Second Edition

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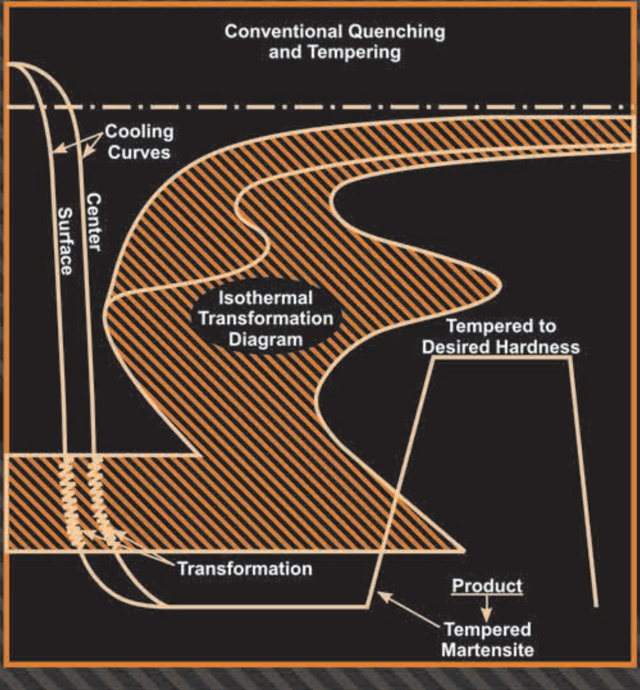
HEAT TREATMENT

Principles and Techniques



T.V. Rajan • C.P. Sharma
Ashok Sharma

Heat Treatment

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Principles and Techniques

SECOND EDITION

T.V. Rajan, C.P. Sharma and Ashok Sharma
Department of Metallurgical and Materials Engineering
Malaviya National Institute of Technology
Jaipur

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HEAT TREATMENT: Principles and Techniques, Second Edition
T.V. Rajan, C.P. Sharma, and Ashok Sharma

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Foreword

Heat treatment originated as an ancient art in man's attempts to improve the performance of materials in their practical applications. In present day metallurgical practice, heat treatment has come to represent a whole class of techniques—involving thermal, mechanical and chemical treatment—by which the desired properties of structural materials are obtained to suit a variety of applications. In the evolution of heat treatment, much of the empiricism has been eliminated by the progress in the systematic understanding of materials structure and structure-property relationships. Properly designed and implemented, the process of heat treatment results in optimum modifications in the composition and distribution of phases; and corresponding changes in physical, chemical and mechanical properties are thus achieved in substantial measure. To the technologist this means that within the constraints of available resources, he has the capability to considerably extend the service performance of materials. On the other hand, to the materials scientist, heat treatment continues to be a fascinating field, providing opportunities for ingenuity in design with the increasing availability of new techniques.

The book is mainly addressed to engineering undergraduates. The authors, who have drawn from their long years of experience in teaching Metallurgy, should be complimented on the comprehensive coverage they have offered on heat treatment, with emphasis both on the theoretical and practical aspects. The introductory chapters are devoted to physical metallurgy and the general principles of heat treatment. This is followed by discussions on the available range of heat treatment processes, including chemical treatment and thermomechanical treatment, on furnace systems used in heat treatment, and the significance of temperature measurement and control. While a major part of the book is devoted to the heat treatment of steels, there is also a detailed discussion on non-ferrous metals and alloys, including nickel and titanium alloys. The importance of inspection and quality control for ensuring final product quality, and of energy economy in designing processes and systems has been emphasized.

The authors have selected and presented the topics in a coherent and systematic manner, and in this, they have shown commendable awareness and imagination, with the result that this textbook for students of engineering will be equally valuable as a reference for the practising engineer and the technician on the shop floor.

C.V. Sundaram
Director
Indira Gandhi Centre for Atomic Research
Kalpakkam

Preface

Necessary modifications have been carried out in presentation of transformations in iron-cementite phase diagram to make the text more comprehensible and cogent. In view of critical role played by retained austenite in heat treatment of steels, elaborate discussions have been included in this revised edition. Plasma nitriding, salt bath nitrocarburizing, boronizing, chromizing and toyota diffusion processes which are important chemical heat treatment processes for steels have been dealt with in detail. Air pollution that accompanies heat treatment has been covered along with Energy Economy.

Necessary corrections and additions have been carried out wherever necessary based on suggestions received from various quarters from time to time. Number of objective as well as other types of questions have been included at the end covering entire text to enable student to assess his grasp and depth of knowledge in the subject of Heat Treatment.

With these modifications and additions it is hoped that the book will meet the needs of all sections of readers to their satisfaction.

T.V. Rajan
C.P. Sharma
Ashok Sharma

Preface to the First Edition

Metals and alloys develop requisite properties by heat treatment which plays a critical role in achieving appropriate microstructure that imparts the desired characteristics in a given material. Hence, the study of heat treatment is of great significance.

The need for a text covering the fundamental aspects of the theory and practice of heat treatment has been felt since long. This book has been written to fulfil such a need.

A knowledge of Physical Metallurgy is essential for understanding the theory of heat treatment. This aspect is therefore dealt with in the beginning. Iron-carbon phase diagram which is fundamental to heat treatment of steels and cast irons has then been considered in detail. This is followed by a discussion on the principles and processes of heat treatment of steel.

The concept of hardenability, and quenchants and their significance are analyzed subsequently. Surface hardening processes, including latest innovations like laser hardening, have been covered. As thermomechanical treatment has assumed considerable importance in recent times, a chapter is devoted to this aspect. Heat treatment furnaces and atmospheres and temperature measurement and control are also dealt with.

As the knowledge of defects that arise during heat treatment and possible remedies is essential for carrying out the process satisfactorily, a discussion on this aspect has been included.

Similarly, since the practising engineer is specifically interested in heat treatment of commercial steels, this has been given an exhaustive treatment. Also, there is an extensive coverage on the heat treatment of various types of cast irons in view of the growing importance of this class of material.

Progressively, the rote of non-ferrous metals and alloys as engineering material is increasing and, 'therefore, there is an indepth discussion in the text on the heat treatment of these, with particular reference to aluminium, magnesium, titanium, copper and nickel alloys. The importance of inspection and quality control is discussed in detail, followed by an analysis of the procedures for testing heat treatment components. Finally, the various methods of achieving energy economy during heat treatment have been included.

The Appendices at the end are meant to provide useful information. The Bibliography listing the classical as well as modern texts on heat treatment should benefit those who wish to delve deeper into the subject.

The book is intended primarily as a text for the undergraduate and postgraduate students of Metallurgy. Besides, it would be useful for the students of Mechanical, Production and Chemical Engineering, who are required to have a basic knowledge of heat treatment. The needs of students of Diploma and Associate Membership of professional engineering bodies have also been taken care of while choosing the contents. In addition, the practising engineers and technical personnel should find this volume valuable for obtaining the necessary information.

We would consider our efforts fruitful if the text serves the needs of the student and the professional.

T.V. Rajan
C.P. Sharma
Ashok Sharma

1

Introduction

Most of the engineering properties of metals and alloys are related to their atomic structure, crystal structure and microstructure. Mechanical properties are structure-sensitive in nature and their magnitude depend largely on size, shape and distribution of various microconstituents. Equilibrium microstructure can be predicted for an alloy with the help of an equilibrium diagram. Mechanical properties can be changed by varying the relative proportions of microconstituents. In practice, change in mechanical properties is achieved by a process known as *heat treatment*. This process consists of heating a metal or alloy to a specific predetermined temperature, holding at this temperature for required time, and finally cooling from this temperature. All these operations are carried out in solid state. Sometimes, it becomes necessary to repeat these operations to impart some characteristics. Therefore, heat treatment may be defined as *heating and cooling operation*(*s*) *applied to metals and alloys in solid state so as to obtain the desired properties*.

Heat treatment of metals is an important operation in the final fabrication process of many engineering components. The object of this process is to make the metal better suited, structurally and physically, for some specific applications. For example, an annealing treatment may be necessary between deep drawing operations particularly when excessive cold working has been carried out.

All metals can be subjected to thermal cycling. But the effect of thermal cycling may differ from one metal to another. For example, heat treatment has significant impact on steels, and their properties may be changed considerably by definite heating and cooling cycles. In contrast, there is hardly any effect of thermal cycling on properties of hot rolled copper.

Heat treatment may be undertaken for the following purposes:

(i) Improvement in ductility
(ii) Relieving internal stresses
(iii) Refinement of grain size
(iv) Increasing hardness or tensile strength and achieving changes in chemical composition of metal surface as in the case of case-hardening.

Other beneficial effects of heat treatment include improvement in machinability, alteration in magnetic properties, modification of electrical conductivity, improvement in toughness and development of recrystallized structure in cold-worked metal.

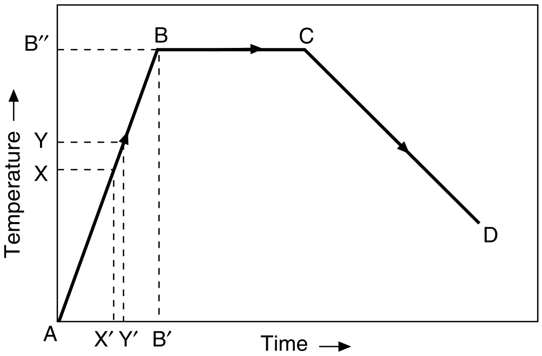


Figure 1.1 **Graphical representation of a simple heat treatment cycle (rate of heating = XY/X′Y′ = AB″/AB′ = constant).**

There are a number of factors of paramount importance which are to be considered when heat treating a metal or alloy. Some of them are the temperature up to which the metal/alloy is heated, the length of time that the metal/alloy is held at the elevated temperature, the rate of cooling, and the atmosphere surrounding the metal/alloy when it is heated.

Any heat treatment process can be represented graphically with temperature and time as coordinates. Figure 1.1 describes a simple heat treatment cycle, whereas Figures 1.2 and 1.3 represent some complex heat treatment cycles.

Figure 1.1 is the simplest possible heat treatment cycle in which the metal/alloy is heated, held at the elevated temperature for some time, and then cooled to room temperature.

Figure 1.2 shows a typical heat treatment cycle suitable for a precipitation hardenable alloy. In this case, the alloy is heated and held at predetermined high temperature. This step is termed as solutionizing. The alloy is then cooled rapidly to room temperature by quenching. The quenched alloy is heated and held at a moderately high temperature above the room temperature, followed by slow cooling. The last step, i.e. heating to and holding at a moderately high temperature is termed as ageing or more specifically as artificial ageing. It is because some precipitation hardenable alloys get hardened even at room temperature. Such alloys are known as natural age hardenable alloys. Duralumins are natural age hardenable alloys.

Figure 1.3 represents a typical heat treatment cycle for carburizing process. The low carbon steel is heated in the temperature range of austenitic region, in contact with some carbonaceous material. It is held at this temperature for some time and then quenched. The

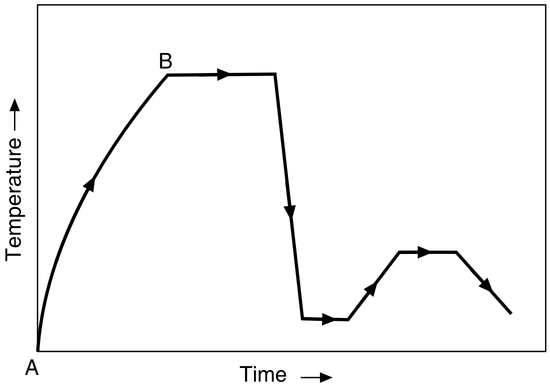


Figure 1.2 **Generalized heat treatment cycle for precipitation hardenable alloy.**

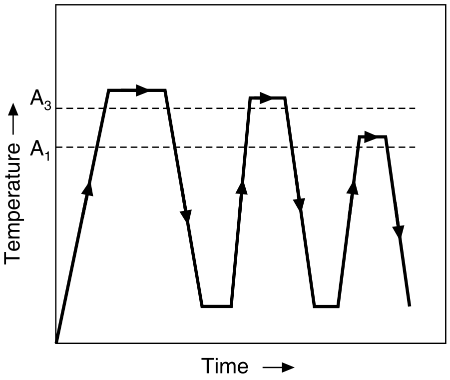


Figure 1.3 **Typical heat treatment cycle for carburizing process.**

quenched steel is reheated to a temperature slightly lower than the one employed in the first step. After holding for some time, it is rapidly cooled to room temperature. In the last step, the steel is again heated to about 750°C (which is just above the lower critical temperature), held at this temperature and then quenched. By these three steps, a hard case and tough core are obtained in the carburized steel.

HEAT TREATMENT PROCESS VARIABLES

Heat treatment temperature, holding time, and rate of heating and cooling are some of the parameters which affect the heat treatment processes, and are commonly referred to as *heat treatment process variables*. The required magnitude of these variables depend on the chemical composition, size and shape of the object and the final properties desired in the metal/ alloy.

In general, the object to be heat treated is put into a heat treatment furnace at room temperature. This furnace is then heated up to a predecided temperature. The average rate of heating is the total increment in temperature divided by the total time taken. The rate of heating can also be calculated for various stages by considering appropriate ranges of temperature. If the heating is done at a constant rate, the temperature-time relationship is represented by a straight line such as *AB* of Figure 1.1. In practice, however, the rate of heating is not constant throughout the complete temperature interval. It is higher in the lower temperature range and decreases gradually as the temperature rises. For such a condition, temperature-time relationship is described by a typical curve *AB* as shown in Figure 1.2. Although, in general, heating of an object is carried out in a single furnace, there are many instances when more than one furnace is used. For example, if the chemical composition of the alloy to be heat treated is such that either the base metal or alloying elements are prone to oxidation or the alloy exhibits tendency towards grain growth at high temperature, the heat treatment will result in poor yield and unsatisfactory mechanical properties.

In order to minimize the problem of oxidation or grain growth, two heat treatment furnaces are employed. In one furnace, the object is heated to a temperature up to which there is no appreciable oxidation or grain growth. The object is then transferred to the second furnace maintained at heat treatment temperature. This practice reduces the total time of holding near the higher heat treatment temperature and thus the above mentioned problems are reduced. The temperature-time relationship for such a heating cycle is shown in Figure 1.4.

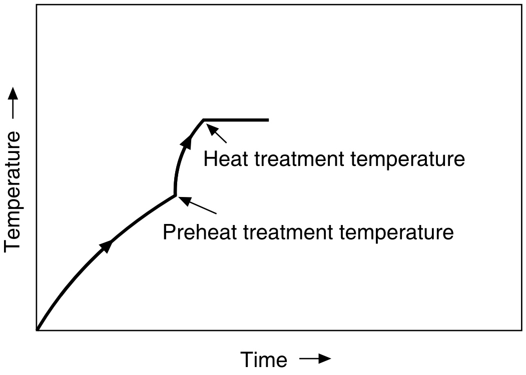


Figure 1.4 A complex heat treatment cycle.

In addition to the mode of heating up to heat treatment temperature, the rate of heating is also of significance. The heating rate depends on the size and shape of the object and the thermal conductivity of the alloy. Fortunately, almost all metallic alloys have good thermal conductivity and thus, in general, this parameter plays only a marginal role. However, for some alloys such as stainless steels, thermal conductivity is an important factor while arriving at the rate of heating. The larger the size of the object, the lower shall be the rate of heating. It avoids development of internal stresses due to thermal gradient. Secondly, low heating rates ensure homogeneity of the structure and reduce holding time at heat treatment temperature. Complicated shapes, sharp cornered objects, and objects with variable sections are also heated slowly. Some alloys, such as high carbon steels and austenitic stainless steels, are also subjected to slow heating rates. Smaller sized and simple shaped objects can be heated with higher heating rates and homogeneity of the structure can be ensured in such cases by increasing the holding time. Also, for the alloys which are prone to oxidation at high temperatures of heat treatment, faster rates of heating are recommended at high temperature range.

Heat treatment temperature is governed mainly by chemical composition of the alloy, prior heat treatment, if any, and the final properties required. For example, for supercritical heat treatments, steel is heated above the upper critical temperature. This temperature is also known as austenitizing temperature, and can be determined, for carbon steels, by the iron-cementite phase diagram. For carbon steels, this temperature decreases first with increasing carbon content up to eutectoid composition and again rises with increasing carbon content. Theoretically, at this temperature, steel should be fully austenitic with the smallest grain size. With rapid heating, actual austenitizing temperature is raised as compared to the theoretical value obtained from iron-cementite phase diagram, whereas in practice, this temperature is lowered on fast cooling. Hence, during heat treatment practice, temperatures which are slightly higher than the temperature determined from the phase diagram are employed. The austenite formed on heating near (just/slightly above) the equilibrium temperature is inhomogeneous in nature. In the case of alloy steels, some alloying elements or their compounds do not dissolve or diffuse with ease. Such steels require higher heating temperatures for homogenization of austenite. Iron carbide, in general, dissolves readily in gamma-iron as compared to carbides of strong carbide-forming elements.

Once the heat treatment temperature is decided, holding time is generally provided at a rate of 2 to 3 minutes per millimetre of section thickness. For an object with variable section thickness values, the holding time is determined on the basis of the thickest section. As already mentioned, objects which are heated up with high heating rates require longer holding time. Heat treatment temperature and holding time are somewhat related in the sense that an increased heat treatment temperature results in reduction of holding time. Similarly, lowering of heat treatment temperature demands an increase in holding time. High alloy steels and alloys, heavily enriched with alloying elements, are kept for more time at heat treatment temperature than plain carbon steels and thinly enriched alloys. In such cases, holding time may be increased by 25 to 40 percent.

As far as cooling from heat treatment temperature is concerned, the mode of cooling as well as the rate of cooling are governed by those factors which control the heating mode and rate, as already discussed. Heavy sections, complicated shapes, objects with variable section thickness, and highly enriched alloys are cooled slowly. Extremely slow cooling results in the development of a structure as is evident from the equilibrium phase diagram. The size, shape, distribution and relative proportions of microconstituents can be controlled over a wide range by varying the cooling rates. Up to a certain limit, higher cooling rate results in a structure which should exist according to the equilibrium diagram. By increasing the cooling rates beyond this limit, structures that are produced will consist of either non-equilibrium products or the high temperature phase(s) retained by sudden quenching.

QUESTIONS

1.1 Explain the term heat treatment. How does heat treatment alter the mechanical properties of an alloy?

1.2 Enumerate the purposes for which heat treatment is employed.

1.3 Discuss the statement—All metals and alloys cannot be heat treated in order to enhance/alter mechanical properties.

1.4 Comment on the statement—Only mechanical properties and not physical properties can be altered by heat treatment.

1.5 Name various heat treatment process variables. Discuss the significance of holding time at heat treatment temperature.

1.6 Explain why some steels are heated in stages to heat treatment temperature.

1.7 Enumerate the precautions that a heat treater should take while heat treating a component of complicated shape having sharp corners and variable section sizes.

1.8 Draw a typical heat treatment cycle for a precipitation hardenable alloy and explain it.

1.9 While heat treating alloy steels are generally heated slowly. Why?

1.10 For identical shape and size, compare the heat treatment schedule for high carbon, medium carbon and low carbon steels.

2

Nature of Metals and Alloys

INTRODUCTION

Before beginning a study of heat treatment of metals and alloys, one should have a clear idea about nature of metals. One can prepare a list of many items made of metals and alloys of daily life. The list will probably include aluminium pots, rolled sheet of mild steel for making the body of refrigerator, scooter and car, steels for making parts, such as gears, pistons, crank shafts of locomotives, copper wire conductors, agricultural implements made of steel and cast irons, aeroplanes made of aluminium and magnesium alloys, and many others. In spite of knowing so much about metals, it is not an easy task to define a metal accurately. Chemists define metals in terms of acids and bases. The base is metal oxide or hydroxide. When metals react with acid, they liberate one or more atoms of hydrogen from acid. Physicists as well as chemists agree that metals have bright lustre (ability to reflect light), good electrical and thermal conductivity, malleability and ductility. In general all metals show all these properties. At the same time, there are non-metals which show one or more of the above mentioned properties. Besides this, metals among themselves show large variation with respect to these properties. For example, lead at room temperature is very soft while tungsten at room temperature is very hard and brittle.

The basic property associated with metals is high electrical and thermal conductivity. This distinguishes them from non-metallic substances. Amongst commonly used engineering metals the best conductor of electricity is copper. However, silver is the best electrical conducting metal. Lead, on the other hand, has poor conductivity. It has electrical conductivity which is one-twelfth of copper. When we compare the conductivity of non-metals such as diamond with copper, it is observed that conductivity of diamond is 10^{-9} times that of copper. Such a large difference in conductivity is due to electrons in metals which can move freely in conduction bands. In non-metals, free movement of electrons under the influence of external electrical field does not take place. Thus, it can be concluded that in metals electrons can move freely and permit flow of current under the action of a potential difference.

In general, the words metal and alloy are interchangeable. However, for engineering and scientific work, metals are metallic elements which are almost pure. Each metal has its own characteristics such as atomic weight, atomic volume, atomic number, melting point and density. By chance it may be possible that an alloy may have the same colour, melting point and density as a pure metal. However, X-ray diffraction techniques distinguish them clearly from parent metals. A very simple way of identification is chemical analysis as alloys contain more than one element.

An alloy may be defined as a combination of two or more elements. The element that is in major quantity should be a metal while the others may be metals, non-metals or combination of both. The resulting material should have metallic characteristics. Brass, bronze and steel are typical examples of alloys.

2.1 CRYSTAL STRUCTURE

A discussion of properties of metals and alloys has to start with consideration of the atom itself. However, the interrelations between individual atoms and heat treatment is far fetched. For a sound understanding of the principles of heat treatment, it is sufficient to go up to the level of crystals rather than atoms.

All metals are crystalline in nature, where atoms are arranged in a definite periodic order. When a solid is composed of only one crystal, it is called single crystal. When a solid is composed of several crystals, it is called a polycrystalline material. In fact, the individual crystals get aggregated to form the solid mass of a polycrystalline substance.

The term grain is used to denote a single crystal in polycrystalline aggregate. In general grains do not have perfect outward form.

On the basis of periodic arrangement of atoms, crystals are grouped into seven crystal structure systems. Cubic, tetragonal, orthorhombic, rhombohedral, hexagonal, monoclinic and triclinic are the seven crystal structure systems. Most of the metals and alloys belong to cubic and hexagonal crystal structure systems and hence are being discussed here.

In a crystal structure, the smallest unit is the unit cell which characterizes the specific arrangement and location of atoms. When the unit cell is repeated in three directions, complete arrangement of atoms in crystal becomes apparent.

2.1.1 Cubic Crystal Structure

Three types of unit cells with cubic crystal structure are possible: simple cubic (SC) structure, body centred cubic (BCC) structure, and face centred cubic (FCC) structure (Figure 2.1).

Simple Cubic ln this case, atoms are located at all the corners of the unit cell.

Body Centred Cubic Structure In the BCC structure, 8 atoms are at corners of the unit cell and 1 atom is at the body centre position. Na, Cr, Mo and W are examples of the elements having BCC crystal structure [Figure 2.1(b)].

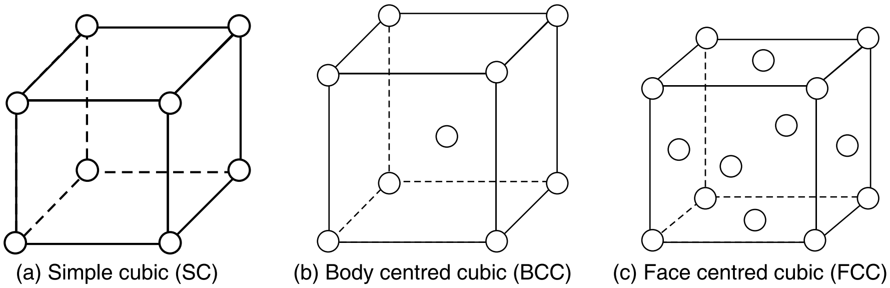

(a) Simple cubic (SC) (b) Body centred cubic (BCC) (c) Face centred cubic (FCC)

Figure 2.1 Unit cells.

Face Centred Cubic Structure In the FCC structure, 8 atoms are arranged at the 8 corners of the unit cell and 6 atoms at the 6 face centres. Cu, Ag, Au, Al, and Ni are the examples of the FCC elements.

2.1.2 Hexagonal Close Packed Crystal Structure

The arrangement of atoms in the hexagonal close packed (HCP) structure is illustrated in Figure 2.2. Be, Ti, Mg and Zn are some of the examples of metals that solidify into the HCP structure.

Generally, the FCC metals are soft, ductile and easily deformable, while the BCC and HCP metals are comparatively brittle and difficult to deform. Table 2.1 shows the crystal structures and lattice constant of some of the common metals.

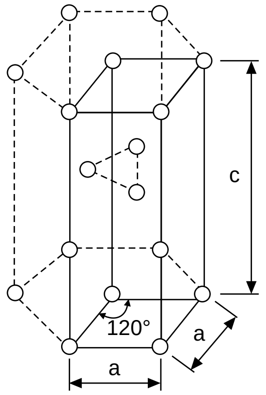


Figure 2.2 HCP (hexagonal close packed) structure.

Table 2.1 Crystal Structures and Lattice Constants of Some Common Metals

Element	Crystal structure	Lattice constant (Å)	Temperature of measurement of lattice constant (°C)
Aluminium	FCC	4.0490	20
Cobalt β	FCC	3.552	20
Copper	FCC	3.6153	20
Gold	FCC	4.0783	20
γ-iron (extrapolated)	FCC	3.571	20
γ-iron (908–1403°C)	FCC	3.656	950
Lead	FCC	4.9495	20
Nickel	FCC	3.5238	20
Silver	FCC	4.0856	20
α-iron	BCC	2.8664	20
Molybdenum	BCC	3.1466	20
Titanium β	BCC	3.33	900
Cadmium	HCP	2.9787	20
Cobalt α	HCP	2.507	20
Magnesium	HCP	3.2092	20
Zinc	HCP	2.664	—

2.2 PROPERTIES OF METALS AND ALLOYS—ROLE OF HEAT TREATMENT

Metals occupy a significant position among engineering materials because of their chemical, physical and mechanical properties. Passivity and corrosion resistance are some of the chemical properties. The physical properties include density, electrical conductivity and thermal conductivity. Tensile and compressive strength, hardness, ductility, resistance to fatigue, impact and abrasion resistance are some of the mechanical properties. In every engineering application, a suitable combination of these properties is required. Physical, mechanical and chemical properties are greatly affected by alloying additions and thermal treatment. For example, when about 4.5 percent copper is added to aluminium and heat treated, the alloy so formed and treated has very high hardness and strength. This is in contrast to pure aluminium which is soft. In many alloys, properties depend largely on their thermal and mechanical history in addition to their chemical composition. In other words, thermal treatment can change mechanical properties of alloys considerably as a result of the modifications that occur due to thermal treatment.

An engineer should have good knowledge about the basic properties of metal and alloys. The successful use of materials for various applications depend on a sound knowledge of these aspects. Properties of alloys can be improved by changing the chemical composition and by proper heat treatment. This understanding helps to reduce the cost of components and make their use economical. An important part of this information is the understanding of heat treatment processes and how they alter the properties. These aspects of heat treatment are discussed in detail in the chapters that follow.

2.3 NATURE OF ALLOYS

In physical metallurgy, the theory of alloys has been developed from fundamental principles. The nature of atoms that constitute an alloy decides the nature of the alloy. Thermodynamic principles are used extensively in arriving at the rules that govern formation of alloys. In the following sections, classification of alloys on conventional basis is carried out. Also, only binary alloys are taken up for discussion.

Pure metals have definite freezing point. When some element is added to a pure metal, the alloy so formed, in general, will solidify either at a higher or a lower temperature as compared to the pure metal. This may also give rise to such a condition that the alloy freezes over a range of temperature. In such cases, solidification proceeds progressively on cooling. Thus, most alloys do not freeze at a constant temperature.

Alloys are produced by melting techniques. Alloying additions of definite quantities are made to base metal. All the constituents are melted together in melting furnace. Solubility of metals constituting an alloy is of importance in this context.

Most of the metals form complete homogeneous solution in liquid state. (Lead-copper and lead-aluminium systems are exceptions to this. In liquid state, both these systems separate into two liquid layers.) When such alloys are cooled from liquid to solid state, there are three possibilities with regard to their solubility in each other: (i) Two metals may show complete solid solubility; (ii) two metals may have no solid solubility; and (iii) two metals may have limited solid solubility.

Solid solutions are formed under possibility (i) and possibility (iii) mentioned above. Solid solutions can be of two types: Substitutional solid solutions and interstitial solid solutions.

Substitutional Solid Solutions

There is direct substitution of the solvent atoms by those of the solute atoms. Crystal lattice of solvent is retained. The only change in the crystal lattice is that of the lattice parameters. Cu-Ni solid solution is a typical example of this type. In this case, Ni atoms substitute for the Cu atoms and form substitutional solid solution with copper. Figure 2.3 shows the arrangement of atoms in a substitutional solid solution. In this figure, hatched circles show solute atoms while empty circles show atoms of base element.

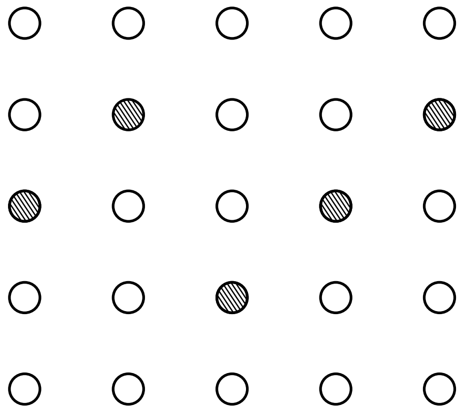


Figure 2.3 Arrangement of atoms in substitutional type of solid solution.

Interstitial Solid Solutions

These are formed when the size of the solute atom is very small as compared to the size of the solvent atoms. Hydrogen, boron, carbon and nitrogen form interstitial solid solution with a number of metals. Carbon in solution in α-iron and γ-iron form interstitial solid solutions which are popularly known as ferrite and austenite, respectively. In interstitial solid solutions, solute atoms occupy the interstitial sites in the crystal structure of the solvent metal. Figure 2.4 shows the arrangement of atoms in interstitial solid solutions. In this figure, the dark smaller circles represent solute atoms while empty circles represent atoms of base element.

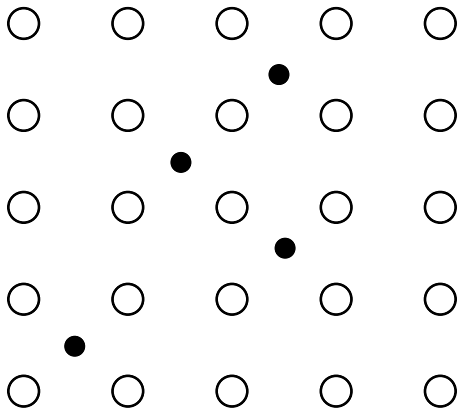


Figure 2.4 Arrangement of atoms in interstitial type of solid solution.

Hume-Rothery Rules

The rules governing the formation of substitutional solid solutions are called Hume-Rothery rules. According to these rules, the following factors affect solid solubility: (i) size, (ii) crystal structure, (iii) valency, and (iv) electrochemical nature of the species. We now discuss each of these factors.

Size Factor Formation of substitutional solid solution is favoured if the size difference between solute and solvent atoms does not exceed a value of 15 percent. When the solute atom is introduced in the crystal lattice of the solvent, lattice strains are introduced. The smaller the size difference between the solute and solvent atoms, the less will be the strains in the parent lattice. Accordingly, the chances of formation of substitutional solid solution are higher. A 15 percent limit has been arrived at empirically. This limit is based on the observations made in known solid solutions. If the size difference between the solute and solvent atoms exceeds 15 percent limit, then the lattice strains will be so high that the formation of substitutional solid solution will not be feasible. In such cases, the solute atoms will have separate identity and will be present as second phase particles in the matrix of the parent phase. For example, lead is insoluble in copper and is present as second phase particles in the form of globules.

Crystal Structure lf two elements have the same crystal structure, then both of them will try to form a substitutional solid solution. This factor should not be viewed in isolation. For instance, considering the Cu-Ni binary system, the size factor effect is favourable. In addition, they also have the same crystal structure, namely, FCC. Due to these two favourable conditions, it is expected that Cu and Ni will form a continuous series of solid solution. This is what is observed in practice.

Valency (Relative valency effect) According to this rule, a metal of higher valency has tendency to dissolve to a large extent in a metal of lower valency than the extent to which the latter dissolves in the former. This rule is a general one and is applicable only for alloys of the univalent metals, such as Cu, Ag, and Au with those of higher valency. For example, in the Cu-Zn system, the solubility of Zn (valency + 2) in Cu (valency + 1) is about 40 percent. In contrast, the solubility of copper in zinc is negligible.

Electrochemical Factor Metals are arranged in electromotive series. Metals occupying higher position in the series are more electropositive. The metals occupying lower positions are electronegative with respect to those occupying higher positions. If two metals are positioned far apart in the electromotive series, the two can be considered relatively as electropositive and electronegative elements, and there is a strong chemical affinity between the two. Under such conditions, the two metals are likely to form a chemical compound rather than solid solution. Further, the larger the difference in the position of any two elements in the electromotive series, the greater the stability of the compound formed.

The electronegativity of the elements in the periodic table increases from left to right in any period and from bottom to top in any group. Therefore, if magnesium of group II is alloyed with elements of group IV, such as silicon, tin or lead, the formation of compound of the type Mg_2 (Si, Sn or Pb) will take place. The order of stability will be Mg_2Pb, Mg_2Sn and Mg_2Si in ascending order as it is obvious by their melting points: 550, 778 and 1085°C, respectively. The extent of solid solubility is very small in all these cases.

2.3.1 When Two Metals Show Complete Solid Solubility

When two metals show complete solid solubility, an isomorphous system is formed (see Section 2.4.1). Since solid solution is a homogeneous phase, its microstructure would resemble that of a pure metal.

2.3.2 When Two Metals have No Solid Solubility in Each Other

When a solid solution is not formed, the formation of compounds may take place. The phases which form in the intermediate regions of the phase diagram may give rise to the formation of compounds. The compounds may be (i) electrochemical compounds, (ii) size factor compound, or (iii) electron compounds. These are now discussed.

Electrochemical Compounds

The important characteristics of electrochemical compounds are: (i) They follow the valency laws; (ii) the range of solid solubility is small; (iii) they have high melting points; and (iv) their crystal structures correspond to specific chemical compounds such as NaCl or CaF_2.

The range of solid solubility decides whether the intermediate phase is a solid solution or compound. If the phase exists over a narrow range, then it is called a compound; if the phase exists over a wide range, it is referred to as a solid solution. Magnesium-based compounds, such as Mg_2Pb, Mg_2Sn or Mg_2Si, are common examples of electrochemical compounds and satisfy these conditions.

Size Factor Compounds

These compounds are formed when there is appreciable difference in the atomic diameters of the participating elements. There are two types of size factor compounds, namely, interstitial and substitutional. If

$$\frac{\text{radius of interstitial atom}}{\text{radius of metal atom}} = 0.41$$

then interstitial solid solutions are formed. Again, if

$$0.59 > \frac{\text{radius of interstitial atom}}{\text{radius of metal atom}} > 0.41$$

interstitial compounds are formed. Borides, carbides and nitrides of transition metals are examples of this category. These phases occur over a small range of composition having a mean formula of type of M_2X or MX (M denotes symbol of solvent metal and X of solute element). Carbides and nitrides of titanium, zirconium, vanadium, niobium and tantalum are the examples of the ones which crystallize into NaCl type of structure. If

$$\frac{\text{radius of interstitial atom}}{\text{radius of metal atom}} > 0.59$$

then the distortion in the parent lattice is too large and, consequently, more complex crystal structure results. For example, in Fe_3C (iron carbide), the ratio is 0.63, and it has a complex structure.

When the difference in the sizes of atoms of two elements is about 20 to 30%, it is possible to achieve efficient packing of the atoms provided the crystal structure common to the Laves phase is adopted. In this phase, each 'A' atom has 12 'B' atoms and 4 'A' atoms as neighbours. They have the common formula AB_2. Further, each B atom is surrounded by 6 like and 6 unlike atoms.

Electron Compounds

These compounds are formed at specific electron to atom (e/a) ratio. W. Hume-Rothery and coworkers pointed out that the (e/a) ratio controls formation of certain intermediate phases which are termed as electron compounds. Besides this (e/a) ratio is important in governing the limit of primary solid solutions. The three (e/a) ratios corresponding to specific crystal structures in an alloy system are 3/2, 21/13 and 7/4.

The β-brass phase (CuZn) having the BCC structure has an (e/a) ratio of 3/2. Other examples of this category are Cu_3Al (BCC), Cu_5Si (β-manganese, complex cubic), and Ag_3Al (CPH). In the case of Ag-Al system, the Ag_3Al structure gets 3 valency electrons from the aluminium, and one each from silver atoms which give rise to an (e/a) ratio of 6 electrons to 4 atoms. This is the same as e/a = 3/2.

The γ-brass phase (Cu_5Zn_8), which has a complex cubic structure, is an example of electron compound having (e/a) ratio of 21/13. Other examples are Cu_9Al_4 and $Cu_{31}Sn_8$.

$CuZn_3$ which is ε-brass phase, has an HCP structure corresponding to (e/a) ratio of 7/4. Other examples of this category are Cu_3Sn and Cu_3Si.

2.3.3 When Two Metals are Soluble to Limited Extent in Solid State

In addition to the possibilities of formation of solid solution over a complete range of composition and of compounds, the third possibility is that of partial solid solubility of two elements in each other. Copper and nickel have complete solid solubility in all proportions and both of them have the FCC structure. However, with an increase in the difference of size factor, the solid solubility limits are changed. For example, the Cu-Ag system (eutectic system) exhibits only partial solid solubility. Such a system can be understood with the help of the relevant phase diagram.

2.4 PHASE DIAGRAMS

Depending on the number of components (metals) that constitute an alloy, binary, ternary, quarternary and complex multicomponent phase diagrams are required for studying the corresponding system. Only binary phase diagrams are discussed in this section.

Freezing of binary alloys from molten state generally occurs as a continuous process over a range of temperature and, even after completion of solidification, some constitutional changes occur in an alloy. These changes which take place during and after solidification of the alloy can be represented graphically by taking temperature on the Y-axis and composition on the X-axis. These graphs are known as phase diagrams, equilibrium diagrams or constitutional diagrams. Knowledge of these diagrams is very helpful in controlling and understanding heat treatment processes. With the help of phase diagrams it is possible to estimate the temperatures at which melting commences and is completed. Also, the possible phase changes that take place by varying the composition or temperature of the alloy can be studied with the help of these diagrams. However, the rate of reactions and structural arrangement of phases are not revealed by phase diagrams.

The word *equilibrium* has been used to denote the fact that during investigations the rate of change of temperature or of composition is extremely slow. This ensures that the alloy comes to a state of rest before a variable such as temperature is changed. But this situation is rarely met with in practice. Nevertheless, these diagrams are very helpful in revealing the path through which changes are likely to take place. Phase changes in commercial alloys of industrial importance can be studied with the help of phase diagrams which incorporate isomorphous, eutectic, eutectoid and peritectic reactions.

2.4.1 Isomorphous System

In this binary system, both elements are soluble in all proportions, both in liquid and in solid states. All alloys belonging to such a system will give rise to a single liquid phase on melting and a single solid phase on freezing. The single phase solid solution so formed is normally denoted by alpha (α). At any point in the α-range, the two metals dissolve in each other at crystal lattice level, they cannot be distinguished from each other under microscope, and their microstructure resembles that of a pure metal. Figure 2.5 is a typical example of an isomorphous system, namely, the nickel-copper phase diagram.

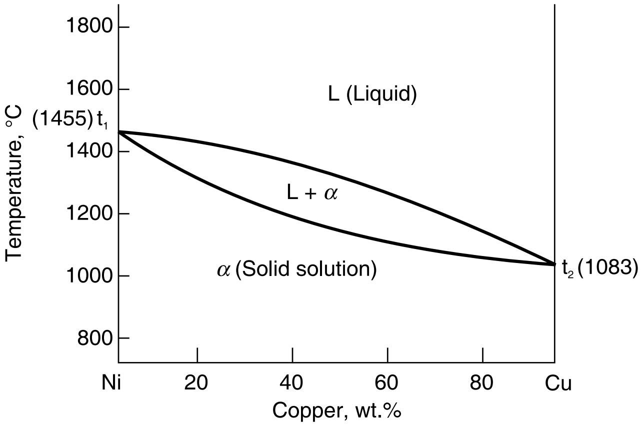


Figure 2.5 Nickel-copper phase diagram.

2.4.2 Eutectic System

In this system, the two elements are completely soluble in all proportions in the liquid state. On cooling, two possibilities may arise: (i) the two elements are completely insoluble in the solid state; (ii) the two elements are partly soluble in the solid state. These reactions can be shown as

$$\text{Liquid (L)} \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} A + B \text{ (possibility (i))}$$

where A and B are metals, and

$$\text{Liquid (L)} \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \alpha + \beta \text{ (possibility (ii))}$$

where α is A rich solid solution and β is B rich solid solution.

These reactions take place at a fixed temperature, called eutectic temperature, and the composition of participating phases is also fixed. Gibb's phase rule can be applied to this equilibrium system. This rule states that for a system consisting of a number of phases in equilibrium, $P + F = C + 2$, where P is the number of phases in equilibrium with each other, F is the degree of freedom, and C is the number of components. For the metallurgical system, pressure is normally maintained constant at one atmosphere. Hence, one degree of freedom is excluded, and the modified phase rule for condensed system is $P + F = C + 1$. This rule is very helpful in studying phase diagrams. On applying the modified phase rule to eutectic equilibrium, the degree of freedom (F) becomes zero. In this case, $P = 3$, $C = 2$. On substituting these values in the equation $P + F = C + 1$, F comes out to be zero. This clearly indicates that the three phases coexist at a single temperature. This temperature is the melting point of the eutectic alloy. Since the three phases also have a fixed composition, the system is invariant. The term eutectic refers to the lowest melting alloy in the entire alloy system. The characteristic feature of eutectic alloy is that it melts at fixed temperature just like a pure metal. Cooling curves for the eutectic alloy and pure metal are identical. Eutectic alloys have very good casting characteristics such as excellent fluidity and minimum porosity. Figures 2.6 and 2.7 show the phase diagram of Bi-Cd and Pb-Sn system, respectively. Both are of the eutectic type.

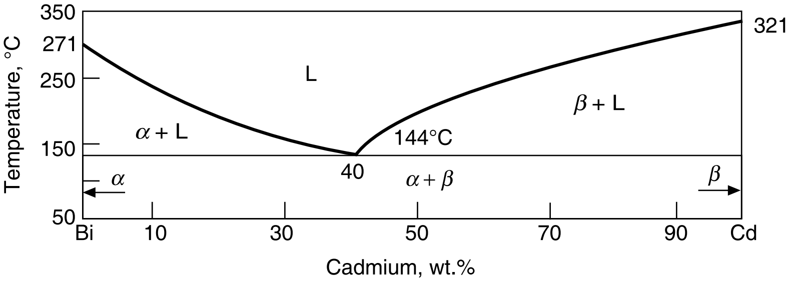


Figure 2.6 Bismuth-cadmium phase diagram.

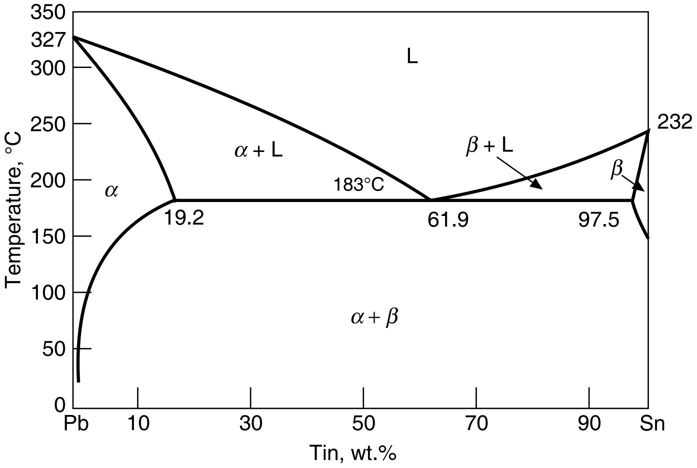


Figure 2.7 Lead-tin phase diagram.

It may be observed that the Bi-Cd system comes under category 1 of the eutectic system since both the metals are completely insoluble in each other. The two metals appear as mechanical mixture in the eutectic.

It is seen that Sn and Pb are partially soluble in each other in solid state. The Pb rich and Sn rich solid solutions are designated as α and β, respectively. In the solid condition, in the two-phase field region, the alloy consists of mechanical mixture of α and β.

2.4.3 Eutectoid System

This is a solid state transformation, i.e. solid-to-solid transformation. In this case, one solid solution on cooling changes to two solids:

$$\gamma \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \alpha + \beta$$

which is the generalized representation of the eutectoid reaction. The temperature at which this reaction takes place is called eutectoid temperature, and the particular composition is known as eutectoid composition of the alloy. The microstructure of the alloy having eutectoid composition shows alternate layers of α and β. Comparing this structure with that of the eutectic alloy, it can be seen that both of them have similar appearance. Hence, at times eutectic and eutectoid microconstituents are microstructurally indistinguishable.

Eutectoid reaction occurs in the Fe-Fe_3C phase diagram at a temperature of 723°C. In this case, austenite changes to pearlite:

$$\left(\gamma \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \alpha + \mathrm{Fe_3C}\right).$$

The microstructure of pearlite shows completely lamellar structure which consists of alternate layers of ferrite and cementite. This is discussed in detail in Chapter 3.

2.4.4 Peritectic System

Ag-Pt is a typical example of the peritectic system. Figure 2.8 depicts the Ag-Pt phase diagram. Peritectic reaction is a common feature of some of the more complex phase diagrams, e.g. the one at the Cu-Zn system.

Peritectic reaction is represented as

$$\mathrm{L} + \beta \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \alpha \cdot$$

In general, peritectic reactions are rarely completed during normal solidification. This is due to the fact that primary β crystals are covered by the layers of α, which prevent the diffusion process. Therefore, on cooling, unreacted β-phase may be seen in peritectic alloys.

2.4.5 Phase Diagram Showing the Presence of Intermetallic Compounds

Figure 2.9 shows the presence of the intermetallic compound Mg_2Sn which contains 29.08 percent magnesium. The melting point of this compound is 778°C which can be lowered by the addition of either magnesium or tin. The equilibrium diagram consists of two eutectic phase diagrams which are joined together.

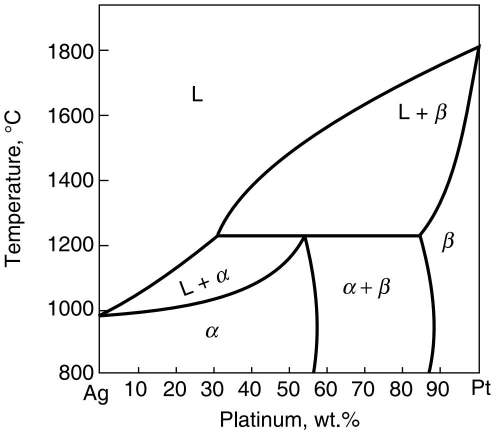


Figure 2.8 Silver-platinum phase diagram.

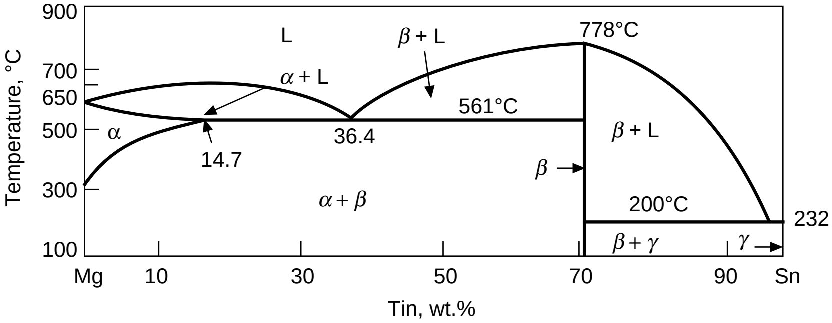


Figure 2.9 Magnesium-tin phase diagram.

2.5 METALLOGRAPHY

Metallography is the study of the internal structure of metals and alloys under microscope at different magnifications. Useful information on grain size, shape and distribution and on percentage of various constituents in the structure can be obtained by metallographic techniques.

Preparation of the sample is necessary for revealing the microstructure of a given specimen. There are two types of metallographic examinations. They are: (i) Macroexamination where the structure is observed with naked eye or under low magnification (×5); and (ii) microexamination where small areas at high magnification (50 to 2000 ×) are observed for this purpose.

2.5.1 Macroexamination

Macroexamination reveals the following:

(i) Segregation of impurities (for instance, antimony in bearing metals and sulphur and phosphorus in steel)

(ii) Presence of non-metallic inclusions, e.g. sulphides and oxides
(iii) Grain size
(iv) Fabrication techniques (for instance, casting, rolling, forging and welding).
(v) Casting defects (e.g. blow holes, pipe formation seams and laps).

Sulphur Print

An indication of the distribution and segregation of sulphur in steels and cast irons can be detected with the help of a silver bromide paper. In this process, first of all the specimen is ground plain and polished with emery papers of successively finer grades. The surface so obtained should be free from dirt and grease. A piece of bromide paper is soaked for 2 minutes in 3% sulphuric acid. The bromide paper is taken out of acid solution and excess acid is wiped off with the help of blotting paper. Now bromide paper with sensitized side is placed in intimate contact with polished surface of the specimen for one or two minutes. During this period, the sulphides react with sulphuric acid and evolve H_2S gas, which stains bromide paper. After this, the bromide paper is removed and washed in water for about 3 minutes and fixed in 20 percent hypo for about 5 minutes. It is finally washed in water for 15 to 20 minutes and dried. The intensity of brown stains on bromide paper indicates the degree of segregation of sulphur. This technique has a limitation. It is not applicable to non-ferrous metals and high alloy steels.

Phosphorus Print

Segregation of phosphorus in steels is detected by phosphorus printing. In this case, a piece of photographic paper is soaked in an aqueous solution of ammonium molybdate (containing 5 gm of ammonium molybdate per 100 cc of water) plus 35 cc of nitric acid (having a density of 1.2). The photographic paper is then taken out and the excess solution is wiped off and the paper is placed with sensitized surface in intimate contact with the polished surface of the specimen. The paper is removed after 5 minutes and developed in an aqueous solution containing 35 percent HCl plus 5 cc saturated stannous chloride solution plus a small quantity of alum. The complex phospho-molybdate, occurring over certain areas as a result of the process associated with the first stage is partly reduced during development. As a result, there is a change in the colour of the molybdates from yellow brown to blue. The blue areas so formed on the paper correspond to phosphorus rich areas on the surface of steel. The intensity of the staining indicates the amount of phosphorus present as segregation.

Macroetching

Macroetching of metals involves deep etching with a suitable reagent that reacts selectively with metal structure. The structure so revealed can be examined by naked eye or at a low magnification. The surface of metal to be examined is ground and polished with the help of emery paper. After this, the metal is immersed in the reagent until the structure is clear. Alternatively, the metal surface may be swabbed with the reagent The metal surface is then washed in water and methylated spirit and finally dried.

Following are the macroetching reagents used for different types of alloys to reveal different kinds of structures.

(i) *Fry's reagent* This reagent is used to reveal overstrain (strains beyond elastic limit) regions in mild steels. It is necessary to heat the specimen to about 230°C for 30 minutes before etching. Etching time varies from 2 to 22 hours. The composition of Fry's reagent is as follows:

Cupric chloride	90 gm
Hydrochloric acid	120 cc
Water	100 cc

(ii) *Humphrey's reagent* This reagent is used to reveal dendritic and fibrous structure in steel. In this case, the prepared steel sample is first immersed in Heyn's reagent (10 gm copper ammonium chloride plus 100 cc water) for about 2 minutes. Then the sample is transferred to Humphrey's reagent. The sample is kept immersed in this reagent for 1/2 hour to 4 hours, while the bath is kept under agitation. The copper coating deposited on the sample is removed with cotton wool. The surface is then washed with spirit and dried. The Humphrey reagent contains the following:

Copper ammonium chloride	10 gm
Concentrated hydrochloric acid	5 cc
Water	100 cc

(iii) To study segregation in steel, the reagent used has the following analysis:

Iodine	10 gm
Potassium iodide	20 gm
Water	100 cc

(iv) The reagent recommended for macroetching of aluminium and its alloys contains the following:

Hydrofluoric acid	10 cc
Nitric acid	1 cc
Water	200 cc

(v) For copper, brass and bronze, the reagent contains the following:

Nitric acid	45 cc
Water	50 cc
Potassium dichromate	0.2 gm

2.5.2 Microexamination

Preparation of metal samples for microexamination involves a number of steps, such as sampling, flattening, grinding, polishing and etching. The sample for microexamination of metals and alloys is cut with the help of hacksaw to a suitable size, say measuring 10 mm dia. ×10 mm to 20 mm dia. ×20 mm. (If samples are too small to be handled with ease, they are mounted on a bakelite or lucite base for preparation.) The sample so cut is filed and ground. Grinding may be carried out either manually or on a grinding wheel. Further polishing is carried out on various grades of emery papers (silicon carbide). Subsequently, grades of emery papers with increasing fineness are used. The next stage is the final polishing which is carried out on a rotating disc covered with a sylvet or billiards cloth, which is soaked in water, sprinkled with a slurry of alumina or calcined magnesia. The disc rotates at a speed of 100–400 rpm. When the polished surface of the sample becomes scratch-free and mirror like, it is taken for etching. Only after etching, does the internal structure of metal become apparent under microscope. This is due to the fact that chemical attack by etchant varies from phase to phase. For example, in steel, the etchant (3% nital, i.e. solution 3% of concentrated nitric acid in absolute methyl alcohol) reacts differently with ferrite and cementite. So these phases are distinguished separately under microscope. Grain boundaries are attacked more easily and at a faster rate by etchant. Therefore, they look as thin dark lines under microscope. Similarly, chemical attack of non-metallic inclusions by etchants varies widely with different types of inclusions. After etching, the sample is washed in running water and alcohol, and then dried in hot air.

Table 2.2 lists some etching reagents in common use.

2.6 METALLURGICAL MICROSCOPE

Microscope is an important tool for a metallurgical engineer. Metallurgical microscope is very helpful in determining the size, shape and distribution of various phases, including inclusions in metals. Grain size determination is also made with the help of metallurgical microscope. All these studies have a great bearing on the mechanical properties of metals. No structure property correlation can be made without the help of metallography.

Construction of a metallurgical microscope is similar to that of a biological microscope, except the manner by which the specimen is illuminated. Metallic specimens are opaque to light. These specimens are polished and etched. Reflected light from the surface of the specimen reveals microscopic details. In contrast, in the case of biological microscope, transmitted light reveals the structural details of biological specimens.

Different types of metallurgical microscopes are available. All of them work on the principle of reflection of light from the specimen surface. Figure 2.10 shows typical metallurgical microscope and its working principle. Such a microscope essentially consists of two parts: the compound microscope, and the electrical illuminating system. A beam of light from illuminating source enters into the tube of microscope from the side. The light falls on the surface of right prism and is reflected downwards. The reflected light passes through the objective lens of microscope and falls on the surface of metallic specimen, the surface reflects back the light. The reflected light again passes through the objective lens and reaches the eye piece. Magnified virtual image is formed during the process. The objective lens resolves the structure of metal, whereas the eye piece magnifies the image formed by the objective.

The whole body of microscope is mounted on a base or foot. A draw tube carrying the eye piece at its top slides in the upper end of the body tube of the microscope. Body tube is connected to the upper end of the limb with the help of rack and pinion device. By sliding the draw tube, the distance between the eye piece and objective lens changes. This helps in proper focusing of the specimen.

During coarse adjustment, the body tube is lowered or raised to get the correct focus. The final stage of coarse focusing is always carried out by lowering the head to the level of stage. The stage then approaches the cover glass. Fine adjustment helps in final focusing of the specimen.

Table 2.2 Etching Reagents for Microscopic Examination

Etching reagents	Composition		Metals and alloys which can be etched	Etching time (seconds)
Nitric acid (nital)	Conc. nitric acid Absolute methyl or ethyl alcohol	4 cc 96 cc	Carbon steels and cast irons	10–30
Picric acid (picral)	Picric acid Absolute methyl or ethyl alcohol	4 gm 96 cc	Carbon steels and low alloy steels (etch pearlite, do not reveal ferrite grains)	15–60
Hydrochloric acid + nitric acid + water	Hydrochloric acid Nitric acid Water Pickling restrainer (flour trace) (used at about 70-80°C)	10 cc 3 cc 100 cc	18/8 stainless steel	15–60
Ferric chloride	Ferric chloride Conc. hydrochloric acid Water	10 gm 30 cc 200 cc	Copper and its alloys such as bronzes, high zinc brasses and aluminium bronze	
Ammonium hydroxide + hydrogen peroxide	Ammonium hydroxide Water Hydrogen peroxide	5 parts 5 parts 2 parts	Copper and its alloys	
Hydrofluoric acid + nitric acid	Hydrofluoric acid Nitric acid Water	2 cc 5 cc 100 cc	Aluminium and its alloys	15–60 (use freshly prepared solution)
Ethylene glycol + nitric acid	Ethylene glycol Distilled water Conc. nitric acid	75 cc 24 cc 1 cc	Magnesium and its alloys	

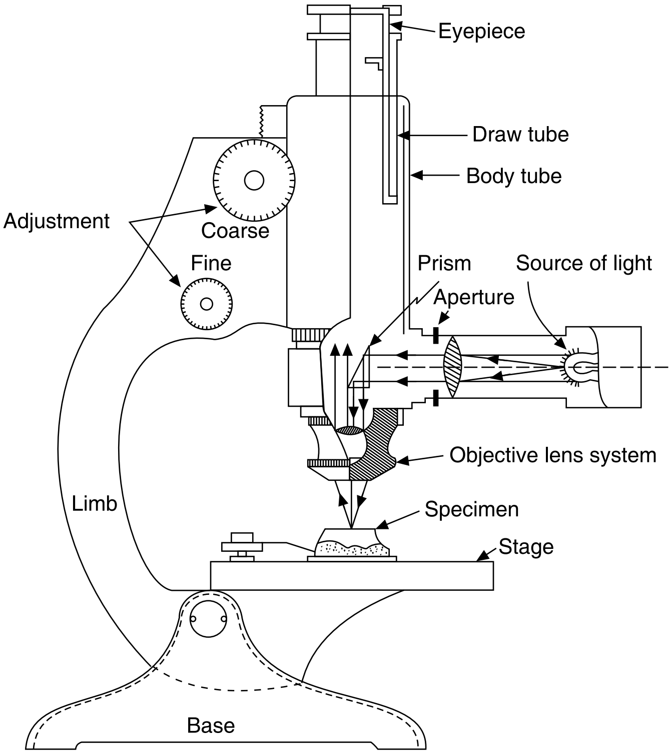


Figure 2.10 A typical metallurgical microscope.

The eye piece is easily detachable and is available with varying powers such as ×5, ×8, ×10, ×12, etc. These numbers are marked on the holder of the eye piece. If the objective lens enlarges the microstructure by 50, the eye piece further magnifies the image formed by objective by 5, 8, 10 times, and so on. The total magnification is the power of objective multiplied by the power of eye piece. Thus the microstructure is magnified by $50 \times 5 = 250$ times, when the objective lens with a magnification of 50 is used in combination with an eye piece having a power of ×5.

A permanent record of microstructures can be obtained with the help of a photographic camera, which may be mounted above the eye piece.

Magnification depends on the focal length. The shorter the focal length of the lens, the greater will be the magnification of structure. The resolving power of an objective lens is its ability which makes it possible to see distinctly two separate lines in a structure. It is expressed as the number of lines per centimetre, which can be separately resolved. Human eye cannot resolve distances less than 0.1 mm. Therefore, magnification by microscope is increased to see distinctly the details of an object.

The resolution δ is related to wavelength λ of illumination, refractive index μ of medium between the lens and specimen and the numerical aperture by the equation

$$\delta = \frac{0.5\lambda}{\text{numerical aperture}} = \frac{0.5\lambda}{\mu \sin \alpha}$$

where α is half the angle subtended by the maximum cone of light rays coming to the objective lens. The numerical aperture is the quantitative measurement of light gathering power of an objective lens.

The ability of a lens to give clarity and sharpness to images of object a little out of focus is measured in terms of depths of focus which is of great significance when the surface of the object is not perfectly plain. It is inversely proportional to numerical aperture. It may, at times be observed that, when the image of the flat surface of the specimen is projected on to a screen, the centre may be sharply focused whereas the edges appear blurred. This situation is due to the curvature of field produced by the objective. To overcome this problem, a special eye piece may be used. Compensation is thus obtained to give a sharp definition over the whole field of view. This is called the flatness of field, which can also be increased by reducing the aperture. This results in increased depth of focus. Correspondingly, there is a decrease in resolving power.

2.7 ELECTRON MICROSCOPE

In the ordinary metallurgical microscope, the maximum magnification that can be achieved is in the range of ×2000. When microstructural details beyond ×2000 are required (say, between ×2000 and ×200,000), we go for an electron microscope in which light rays are replaced by a beam of electrons. A beam of electron is obtained by accelerating thermal electrons from a filament by applying a high voltage. According to De Broglie's principle, wavelength of beam of electrons is related to applied voltage by the formula

$$\lambda \approx \sqrt{\frac{150}{\text{Applied voltage}}}\ \text{Å}$$

The optimum resolution of an electron microscope is of the order of 10 Å. The depth of focus in this case is almost infinite.

The electron microscope essentially consists of an electron gun and condenser and projector lens (see Figure 2.11). For passage of electron beam, vacuum is necessary. Electrons are emitted by a hot tungsten filament cathode and are accelerated to form a high velocity beam. The electron beam can be focused by electric or magnetic fields which act as lenses.

Current-carrying coils act as the source of electric field. The coils are completely enclosed in a soft-iron shroud. There is a narrow gap in the bore. The focal lengths are fixed physically as required. The arc is actually controlled by altering the current through the coils.

An objective lens enlarges the image about 40 times, and this is further magnified 40 times with the help of

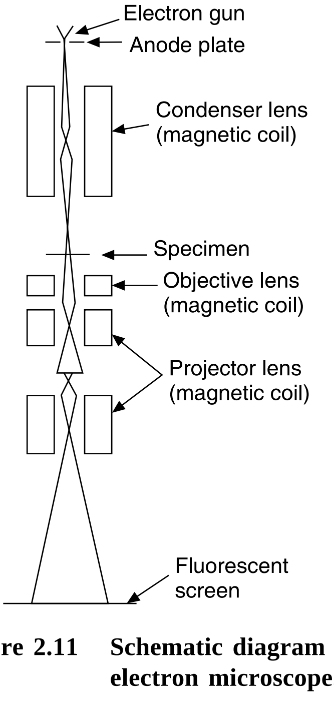


Figure 2.11 Schematic diagram of electron microscope.

the first projector lens. The second projector lens magnifies the image by about 50 times. The image is projected on a fluorescent screen or a photographic plate or film.

The following points should be kept in mind to ensure defect-free image by electron microscope:

(i) Velocity of electrons should be uniform.
(ii) Concentration of electrons at all points should be small to avoid mutual repulsion.
(iii) Image-forming rays should have a small divergence.
(iv) Object and image must be small.
(v) Lens pole pieces should be free of constructional defects.
(vi) Optical and magnetic alignment should be accurate.

For transmission electron microscope, thin foils of the metal are used as specimen. The thickness of thin foils varies from 1000 to 2000 Å. The specimen is prepared either by ion bombardment or by electropolishing technique.

2.8 IMPERFECTIONS IN METAL CRYSTALS

A crystal is made up of atoms, ions or molecules, which are arranged in a repetitive pattern in three dimensions. In an ideal crystal, this arrangement is regular and perfect throughout the crystal, while in a real crystal this situation does not exist. During crystallization from molten metal and processing of solid metals and alloys, lattice distortions and other imperfections creep in, which make crystals irregular. Because of the presence of these imperfections, physical and mechanical properties of engineering metals are greatly affected. Hence, there is always some discrepancy between theoretically computed and the real strength of metals. The extent and degree of imperfections can be changed by heat treatment process. Therefore, it is necessary to have some idea about imperfections in metals. Different types of imperfections in metals can be grouped as (i) point defects, (ii) line defects, (iii) surface defects, and (iv) volume defects. These are now discussed.

2.8.1 Point Defects

In crystal lattice, point defect is completely local in its effect. A vacant lattice site is a typical example of point defect. When point defect gets introduced in crystal lattice, internal energy of the crystal increases. The number of vacancies at equilibrium present in a crystal at a given temperature can be determined by the equation

$$n_0 = Ne^{-\Delta E / kT}$$

where

n_0 = number of vacancies per mole
N = total number of atomic sites per mole
ΔE = activation energy for formation of vacancy
k = Boltzmann constant
T = temperature in absolute scale.

Vacancies, interstitialcies and impurities are examples for point defects in a crystal, which will be now discussed.

Vacancies When there is a vacant site or unoccupied atomic position within a crystal lattice, a vacancy is said to exist in the crystal lattice. Vacancies are atomic sites from which the atoms are missing, and exist in metal at all temperatures above absolute zero. Vacancies play a great role in diffusion of atoms in the crystal lattice. They help in transport of atoms. For example, many industrial processes such as annealing, homogenization, precipitation of second phase particles, and case carburizing require large scale migration of atoms in the crystal lattice.

Vacancies arise from thermal vibrations. They are also introduced during solidification. There is slight distortion in lattice planes due to vacancy because atoms surrounding a vacancy have tendency to come closer.

When vacancies are generated by displacement of atoms from crystal lattice site to the surface, a Schottky defect is formed. Figures 2.12(a) and 2.12(b) show vacancy and Schottky imperfection in a crystal, respectively.

Interstitialcies When an atom is displaced from a regular site and occupies an interstitial site, an interstitialcy is formed. The atom may be a parent atom or a foreign atom. Interstitialcy also gives rise to lattice distortion because interstitial atom tends to push the surrounding atoms apart. The smaller the size of the interstitial atom relative to the parent atom, the smaller is the lattice distortion in the crystal. Figure 2.12(c) shows interstitialcy point defect.

When an ion is displaced from the crystal lattice into an interstitial site, a Frankel defect is formed as in Figure 2.12(d).

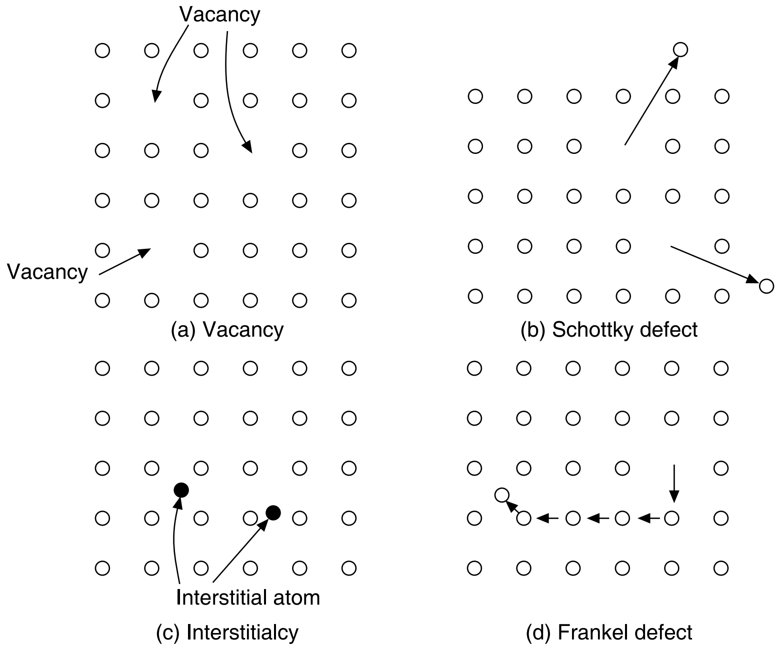
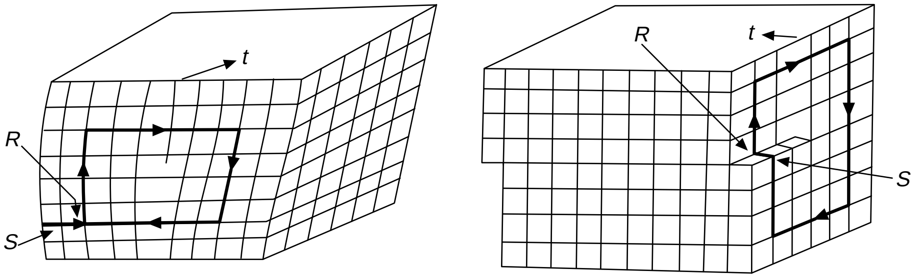


Figure 2.12 Various types of point defects.

Impurities lmpurities are foreign atoms which are present in the crystal lattice. Impurity atoms may occupy either interstitial or substitutional position. An interstitial impurity is a small atom which occupies an interstitial void space between atoms at lattice points of the crystal. When a foreign atom substitutes a parent atom in the crystal lattice, a substitutional type of defect is generated. Both interstitial and substitutional impurities create distortions in the lattice.

2.8.2 Line Defects

Line defects are also known as dislocations. Dislocation is the region of localized lattice disturbance between slipped and unslipped regions of a crystal. Due to lattice disturbances, elastic strain fields and stresses are associated with dislocations. Metals deform plastically by the mechanism of slip. Slipping is facilitated in the presence of dislocations. Strain hardening, creep, fatigue and fracture are the mechanical phenomena, in which dislocations play a major role. Dislocations are of two types: edge dislocation and screw dislocation. Figure 2.13(a) shows an edge dislocation in which the burger's vector lies perpendicular to the dislocation line. A burger circuit is drawn around the dislocation line and the vector required to close the circuit, *RS*, is known as the burger vector of the dislocation. An edge dislocation moves in the direction of the burger vector (slip direction). It has an extra row of atoms either above or below the slip plane in crystal. When the extra row of atoms is above the slip plane, it is called positive and is denoted by sign ⊥. When the extra row of atoms is below the slip plane, it is called negative edge dislocation and is represented by sign ⊤. In edge dislocation, the atoms above the edges are in compression and those below are in tension as shown in Figure 2.13(a). An edge dislocation undergoes gliding in crystal and produces a slip step of one atom width at the edge of the crystal.



(a) Edge dislocation (b) Screw dislocation

Figure 2.13 Line defects.

Figure 2.13(b) shows a screw dislocation. Here, the burger vector is parallel to the dislocation line and distortion is of shear type. The distortion follows a helical path, and it may follow right-hand (positive) or left-hand (negative) screw rule. Positive and negative dislocations are shown by clockwise and anticlockwise signs, respectively. Screw dislocation shows cross slip, where it moves from one slip plane to another.

Two dislocations (either edge or screw) of opposite signs, if present on the same plane, attract each other and can annihilate each other.

Dislocations are introduced in a crystal due to growth accidents, thermal stresses, phase transformations and segregation of solute atoms. The dislocation density in annealed crystal is about 10^6 to 10^{10} mm^{-3}. Perfect crystals, which are totally free from dislocations, are called whiskers and have very high strength.

2.8.3 Surface Defects

Grain boundaries, tilt boundaries, twist boundaries, coherent and incoherent precipitate interfaces are categorized under surface defects.

During solidification of metal, nucleation and growth process starts. During this process, crystals nucleate and grow at different points. When the growing surfaces of these two crystals meet, some atoms are caught in the boundary region of two crystals and do not belong to any one of the two crystals. This region of atoms is called grain boundary (see Figure 2.14). At grain boundaries, atomic packing is imperfect. Thickness of the grain boundary can be estimated by field ion microscopy. When the orientation difference between two adjacent crystals is more than 10 to 15°, the boundary is termed as high-angle grain boundary.

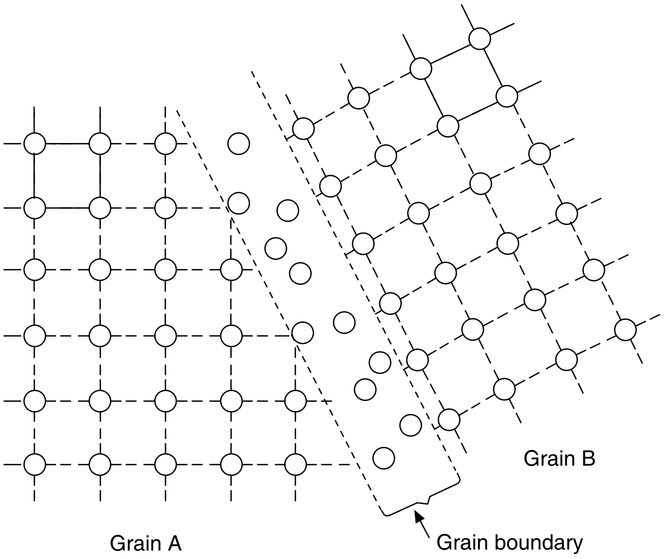


Figure 2.14 Grain boundary.

Tilt boundaries are low-angle grain boundaries, and the orientation difference between two adjacent crystals is less than 10°. This may be regarded as an array of parallel edge dislocations of same sign arranged one below the other.

Twist boundaries are also low-angle grain boundaries but in this case an array of screw dislocations are present instead of edge dislocations.

When the arrangement of atoms on one side of a boundary is a mirror image of that of the other side, twin boundary is formed.

In some instances, crystal structures of the two phases may be similar and the lattice parameters may be nearly equal. In such cases the boundary between the two grains (called an interface) is coherent. There is one-to-one correspondence of atoms at the interface. When such matching does not exist at the interface, the interface is said to be incoherent.

2.8.4 Volume Defects

Inclusions and stacking faults constitute volume defects. When there is a discrepancy in the packing sequence of the rows of atoms, stacking fault results. For example, for an FCC metal the stacking sequence is of *ABC ABC ABC* ... . If the sequence changes to *ABC AB ABC* in practice, then stacking faults (which are usually introduced by deformation of annealed metals and alloys) occur.

A stacking fault occurs when a metal crystal has two adjacent crystallo-graphic planes which do not fit in the normal geometric pattern within the system. Stacking faults may be caused either by slip or some other mechanism.

2.9 SIGNIFICANCE OF IMPERFECTIONS IN HEAT TREATMENT

The role of imperfections in heat treatment is very important. Imperfections account for crystal growth, diffusion mechanism, annealing and precipitation. Besides this, other metallurgical phenomena, such as oxidation, corrosion, yield strength, creep, fatigue and fracture, are governed by imperfections. Imperfections are not always harmful to metals. Sometimes they are generated to obtain the desired properties. For example, carbon is added in steel as interstitial impurity to improve the mechanical properties, and these properties are further improved by different heat treatment processes.

QUESTIONS

2.1 Differentiate between metals and non-metals.

2.2 Define an alloy.

2.3 What is a solid solution? Give examples of solid solutions.

2.4 Copper can dissolve any amount of nickel in solid state and vice versa. Justify the above statement with the help of Hume Rothery Rules for the formation of solid solutions.

2.5 Find out electron-to-atom ratio for the following compositions: Ag_3Al, Cu_5Zn_8, Cu_9Al_4, $CuZn_3$, Cu_3Sn.

2.6 What information do we get from the study of phase diagrams?

2.7 What is metallography? Discuss the importance of metallography with special reference to heat treatment.

2.8 What is the role of imperfections in heat treatment?

3

Iron-Cementite Phase Diagram

INTRODUCTION

The alloys of iron are very important for engineering applications. Steel and cast iron are the important alloys of iron with carbon. Besides this, various alloying elements are also added to obtain alloy steels and alloy cast irons with required properties. This chapter deals with the allotropic forms of iron, microstructure, and phase transformations in iron-cementite and iron-graphite system. The effect of alloying elements on the Fe-Fe_3C phase diagram is also discussed.

3.1 ALLOTROPIC CHANGES IN IRON

Allotropy is characterized by changes in crystal structure of iron at a definite transformation temperature. Iron has three allotropic modifications. α, and δ with body centred cubic structure, and γ-iron with face centred cubic structure.

To study allotropic modifications, molten iron is allowed to cool slowly in an insulated crucible and the cooling curve is plotted, as shown in Figure 3.1. At temperatures above 1540°C, iron is in liquid form. At 1540°C, iron starts freezing. The temperature remains constant till freezing is completed. After completion of solidification, the temperature of solid iron drops down with uniform rate until a temperature of 1395°C is reached. Between 1540°C and 1395°C, the solid iron is known as delta (δ) iron with a body centred cubic structure. From the cooling curve, it is evident that a phase transformation takes place at 1395°C. Delta iron changes to gamma (γ) iron with face centred cubic structure at this temperature. On further cooling, there is uniform rate of drop of temperature from 1395°C to 910°C, indicating that there is no change in crystal structure in this temperature range. At 910°C, another phase change is indicated, which corresponds to transformation of gamma iron to alpha (α) iron, with a body centred cubic structure. The alpha form of iron is magnetic and stable at all temperatures below 910°C, including room temperature. Beta (β) iron, which is a non-magnetic version of alpha iron, is identical to alpha iron in crystal structure, and exists from 910°C to 768°C. The temperature at which paramagnetic beta iron transforms to ferromagnetic alpha iron is termed as Curie temperature. These changes are reversible. On heating from room temperature to 1400°C, the transformations occur in reverse order.

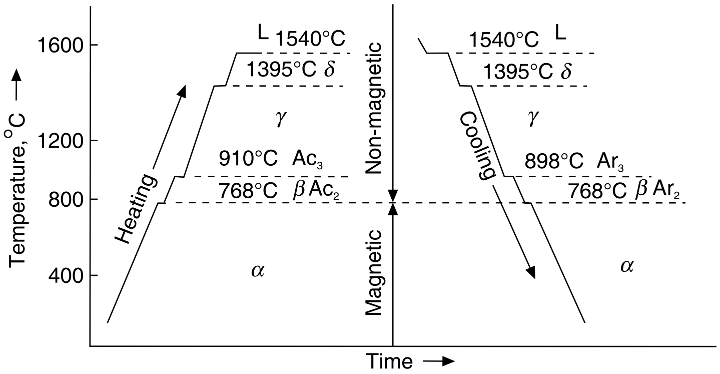


Figure 3.1 Heating and cooling curves for pure iron.

Under normal rates of cooling, actual transformations take place at temperatures which are lower than the equilibrium temperatures indicated above. Similarly, transformations occur at temperatures higher than the equilibrium temperatures while heating is carried out under normal rates. These temperature lags are termed as thermal hysteresis in analogy with the hysteresis that is observed during magnetization and demagnetization cycles.

3.2 TRANSFORMATION TEMPERATURES: NOTATION

The following symbols are used for iron and steel:

Ac_m = In hypereutectoid steel, the temperature at which the solution of cementite in austenite is completed during heating.
Ac_1 = The temperature at which austenite begins to form during heating.
Ac_2 = The temperature at which the α-iron changes to non-magnetic β-iron. (This is not important for heat treatment studies.)
Ac_3 = The temperature at which transformation of α-iron to austenite is completed during heating.
Ac_4 = The temperature at which austenite transforms to delta ferrite during heating.

(Ae_m, Ae_1, Ae_3, Ae_4 are the corresponding temperatures of phase changes at equilibrium.)

Ar_{cm} = In hypereutectoid steel, the temperature at which precipitation of cementite starts during cooling.
Ar_1 = The temperature at which transformation of austenite to ferrite or to ferrite plus cementite is completed during cooling.
Ar_2 = The temperature at which non-magnetic (β-iron changes to ferro-magnetic alpha iron (α-ferrite) during cooling.
Ar_3 = The temperature at which austenite begins to transform to ferrite during cooling.
Ar_4 = The temperature at which delta ferrite transforms to austenite during cooling.
Ar' = The temperature at which transformation of austenite to pearlite starts during cooling.

The letters indicated above are from French words and have the following meaning:

A stands for arrêt (i.e. arrest).
c denotes chauffage (i.e. heating).
r denotes refroidissement (i.e. cooling).

3.3 RECALESCENCE

This is a phenomenon which is observed in iron or steel during transformation of gamma iron on cooling/super cooling. This is revealed by the reglowing of the metal surface due to the sudden increase in the temperature caused by the quick liberation of latent heat of transformation. Decalescence is sudden decrease in the temperature due to reverse phase change in this system.

3.4 IRON-CEMENTITE PHASE DIAGRAM

This is also known as iron-carbon equilibrium diagram. But the term *iron-carbon* is incorrect in a strict sense because the phase which constitutes the binary phase diagram is cementite, and not carbon or graphite. The term iron-cementite is also not strictly correct because the cementite phase is metastable. In metallurgical practice both the terms, namely, iron-carbon and iron-cementite phase diagrams are used.

In the phase diagram, temperature is plotted against composition. Any point on the diagram therefore represents a definite composition and temperature. The phase diagram indicates the phase(s) present and the phase changes that occur during heating and cooling. The relative amounts of the phases that exist at any temperature can also be estimated with the help of lever rule.

The solubility of carbon varies in different forms of iron. In delta iron, maximum solid solubility of carbon is 0.1 percent. In gamma iron, the maximum solid solubility of carbon is 2.03 percent. Austenite is a solid solution of carbon in face centred cubic iron and solute atoms occupy interstitial positions in this lattice. In α-iron, carbon has a limited solid solubility of about 0.008 percent at room temperature. The maximum solubility of carbon in ferrite is 0.025 percent. The solid solution of carbon in α-iron is known as ferrite. The word “ferrite” is derived from the Latin word “ferrum” which stands for iron. There are three reactions which occur in iron-cementite phase diagram (see Figure 3.2): (i) peritectic reaction, (ii) eutectic reaction, and (iii) eutectoid reaction. These reactions are now discussed.

Peritectic Reaction In the alloy containing 0.15 percent carbon, the initial crystals of δ-solid solution and the whole of liquid phase is completely transformed to form austenite on cooling at 1492°C:

$$L + \delta \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \gamma\,(\text{austenite})$$

Eutectic Reaction Alloy with carbon content 4.33 percent (point *C*); the liquid is transformed into austenite and cementite on cooling at 1147°C. That is

$$L \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \gamma + \text{Fe}_3\text{C}$$

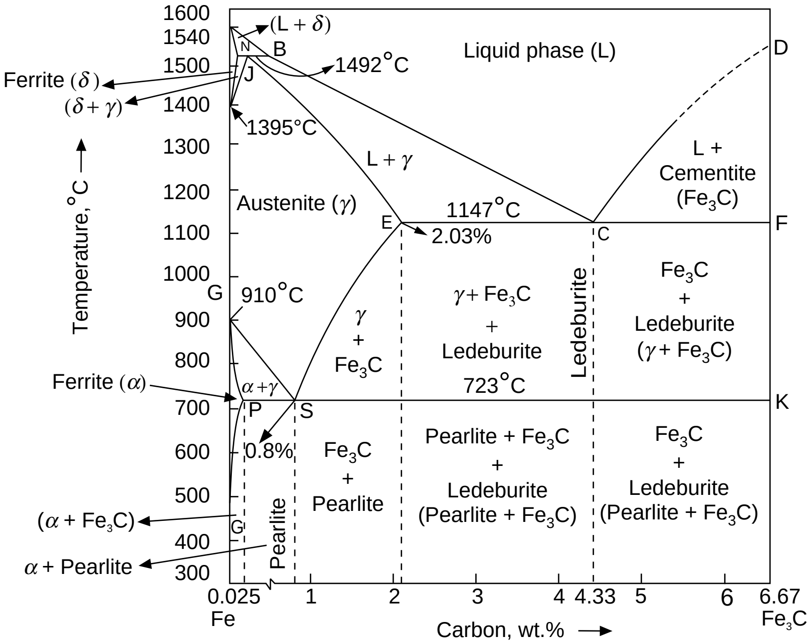


Figure 3.2 Iron-cementite phase diagram.

where Fe_3C is the compound, known as cementite. It contains 6.67 wt.% carbon. The eutectic of austenite and cementite is known as ledeburite.

Eutectoid Reaction In iron-carbon alloy with 0.8 percent carbon (point *S*), the austenite is transformed into ferrite and cementite by eutecioid reaction on cooling at 723°C. Thus,

$$\gamma \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \alpha + Fe_3C$$

The eutectoid of ferrite and cementite (Fe_3C) is known as pearlite. The ferrite and cementite phases occur as alternate layers.

Depending upon the carbon content and the reactions occurring in the iron-cementite phase diagram, the alloys of iron are broadly divided into two groups: steel and cast iron.

3.4.1 Steels

There are three major categories of steels. (Carbon in steels may be present up to 2.03 percent, but it rarely exceeds 1.3–1.4 percent.) These are: (i) low carbon steels (carbon upto 0.3 percent), (ii) medium carbon steels (carbon from 0.3 percent to 0.6 percent), and (iii) high carbon steels (carbon more than 0.6 percent).

Steels with carbon content from 0.025 percent (point *P*) to 0.8 percent (point *S*) are called hypoeutectoid steels. Steel with a carbon content of 0.8 percent is known as eutectoid steel. Steels with carbon content greater than 0.8 percent are called hypereutectoid steels.

Transformations in Hypoeutectoid Steels

There are solid state transformations in these steels. They are the transformation of gamma iron to alpha iron and the decomposition of austenite. Line GS in the phase diagram shows the temperatures where transformation of austenite to ferrite starts. Below this line, ferrite is separated out of the austenite. The critical points that make up line GS are shown by Ar_3 (in cooling) and AC_3 (in heating). Line ES indicates the variation in the solubility of carbon in austenite with the temperature and, in cooling, corresponds to the temperature at which separation of cementite from austenite starts. Point *S* is called the eutectoid point and here the degree of freedom is zero. When point S (0.8% C) is reached during cooling, the austenite decomposes to 100 percent lamellar pearlite at 723°C. Pearlite is a eutectoid mixture of two phases: ferrite and cementite. The critical point where austenite decomposes to pearlite is denoted by Ar_1 (in cooling) and Ac_1 (in heating). The line PQ shows the variation in solubility of carbon in alpha iron with the temperature and, in cooling, corresponds to starting of precipitation of surplus cementite out of ferrite.

The limiting composition for getting pearlite is 0.025 percent carbon. With carbon content less than this amount, no pearlite will be formed. The alloy will contain only ferrite grains.

Steels containing carbon between 0.025 percent to 0.8 percent would contain varying amount of ferrite and pearlite and their relative proportions depend on carbon content. Let us take the case of heating upto austentic region followed by slow cooling of component X_1 containing 0.4 percent carbon [Figure 3.3(a)]. In the austenitic range, this alloy consists of a uniform interstitial solid solution. Each grain contains 0.4 percent carbon dissolved in the

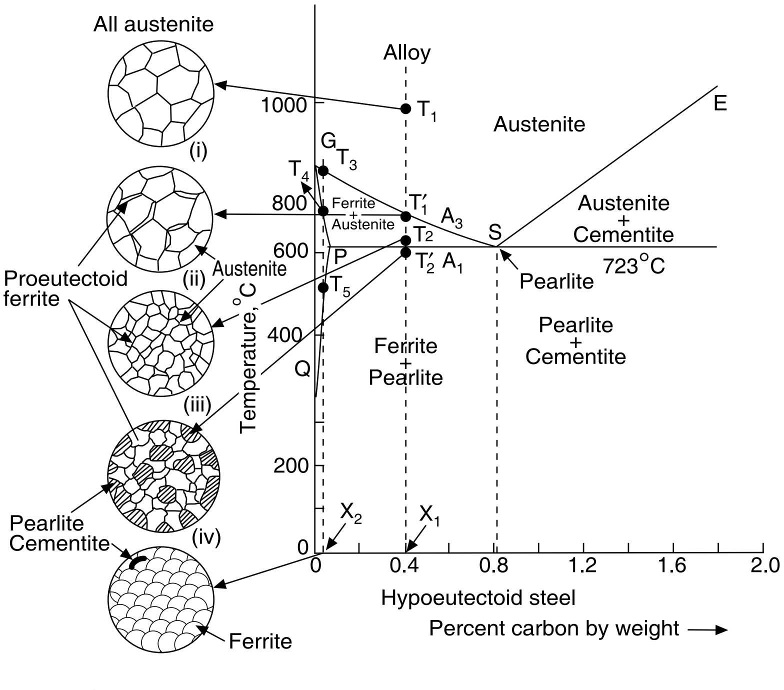


Figure 3.3(a) Part of iron-cementite phase diagram showing microstructural changes during the slow cooling of 0.4% carbon steel and steel containing less than 0.025% carbon.

interstitial spaces of the FCC iron lattice structure. Upon slow cooling, nothing happens until the line GS is crossed at temperature T'_1 where component X_1 cuts the GS line. Proeutectoid α-ferrite starts separating out along line GP, and the composition of austenite moves along line GS. Therefore, at temperature T'_1 ferrite begins to form at the austenite grain boundaries. Since ferrite can dissolve very little amount of carbon, in those areas that are changing to ferrite the carbon must come out of solution before the atoms rearrange themselves to BCC structure. The carbon which comes out of solution is dissolved in the remaining austenite, so that, as cooling progresses and the amount of ferrite increases and the remaining austenite becomes richer in carbon. PS line is the eutectoid-temperature line (723°C) and is the lowest temperature at which FCC iron can exist under equilibrium conditions. Just above the PS line (T_2), the microstructure consists of austenite and proeutectoid ferrite. At the eutectoid temperature, the remaining austenite, of the total material which contains 0.8 percent carbon decomposes to pearlite by the eutectoid reaction. Thus,

$$\underset{(0.8\%\ \text{C})}{\text{Austenite}} \ \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \ \underbrace{\frac{\text{Ferrite}}{(0.025\%\ \text{C})} + \frac{\text{Cementite}}{(6.67\%\ \text{C})}}_{\text{Pearlite}}$$

Only austenite transforms to pearlite at eutectoid temperature. Therefore, when the reaction is complete at temperature T'_2, the microstructure will consist of pearlite and ferrite.

The eutectoid decomposition of austenite takes place at a constant temperature of 723°C, because at this point the degree of freedom is zero. ($F = C - P + 1 = 2 - 3 + 1 = 0$, where F is the degree of freedom, C is the number of components and P is the number of phases.)

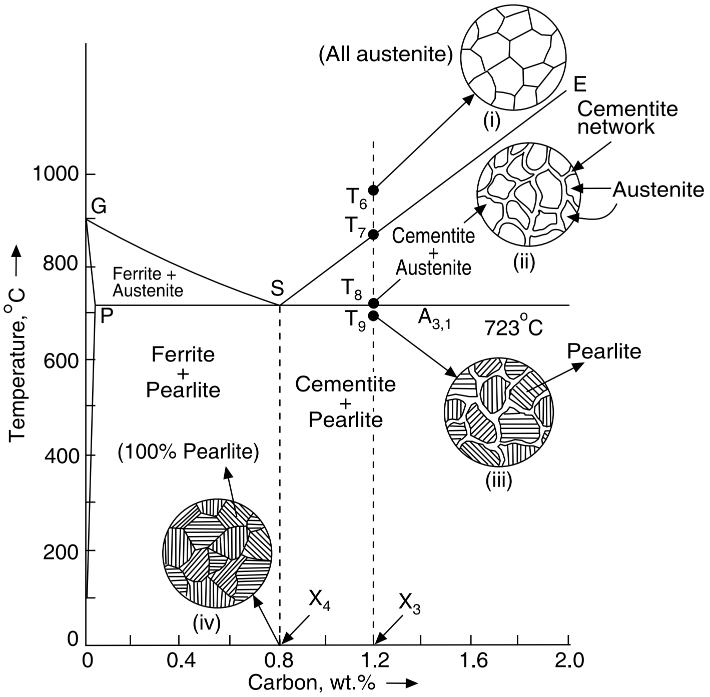


Figure 3.3(b) **Part of iron-cementite phase diagram showing microstructural changes during the slow cooling of 1.2% carbon steel and 0.8% carbon steel.**

Transformations in a Steel Containing Less Than 0.025% Carbon

Now let us take another steel of composition X_2 (see Figure 3.3). In this steel, carbon content is less than 0.025 percent. This alloy begins to transform to α at T_3°C and transformation is completed at T_4°C. No change in this structure occurs between T_4°C and T_5°C. At T_5°C, the vertical composition cuts the solvus line PQ. Excess carbon, thus rejected, separates out as Fe_3C. Hence, the microstructure is predominantly α (ferrite) a with small amount of Fe_3C. If the cooling rate is higher than the equilibrium rate, then enough time is not available for cementite to separate, and the microstructure is 100 percent ferrite. The ferrite is supersaturated as its carbon content is higher than the one according to the solvus line of the equilibrium diagram.

Transformations in Hypereutectoid steels

Consider a steel X_3, containing 1.2 percent carbon [Figure 3.3(b)]. The phase present in the steel in the austenitic condition is FCC iron with carbon forming interstitial solid solution. The composition is uniform throughout each grain. As the temperature is lowered from T_6, phase transformation starts at temperature T_7 which is the point of intersection of vertical line at X_3 and the line ES. At this temperature, austenite is fully saturated with carbon. As the temperature is lowered below T_7 (for example T_8) solubility of carbon in austenite starts moving along ES. The excess carbon comes out in the form of proeutectoid cementite. This cementite is precipitated primarily along the grain boundaries. This leads to formation of grain boundary network of cementite in the hypereutectoid steel. As the steel attains the eutectoid temperature (A_3), eutectoid transformation takes place in the austenite and pearlite is formed. Below A_3 (for example, T_9) the microstructure consists of pearlite with network of cementite.

Transformations in Eutectoid Steel

Let us consider a steel containing 0.8 percent carbon [X_4 in Figure 3.3(b)]. On cooling at eutectoid point S (723°C), all austenite will transform into 100 percent pearlite. So, the microstructure at room temperature will reveal alternate layers of ferrite and cementite, called pearlite.

$$\underset{(0.8\%\ \text{C})}{\gamma} \quad \underset{723^\circ\text{C}}{\overset{\text{Cooling}}{\rightarrow}} \quad \underset{(0.025\%\ \text{C})}{\alpha} \quad + \quad \underset{(6.67\%\ \text{C})}{Fe_3C}$$

Figures 3.4(a), (b) and (c) shows the microstructures of hypoeutectoid, eutectoid, and hypereutectoid steels.

3.4.2 Cast Irons

Cast irons can be divided into two main groups on the basis of the nature of carbon persent in them. They are white cast irons and grey cast irons. In white cast irons, carbon is present in the combined form as cementite and in grey cast irons, it is present in free form as graphite. Under normal conditions, carbon has a tendency to combine with iron to form cementite. However, under very slow rate of cooling, during solidification, carbon atoms get sufficient time to separate out in pure form as graphite. In addition, certain elements promote decomposition of cementite. Their presence help in the formation of graphite. These elements are called graphitizers. Silicon and nickel are two commonly used graphitizing elements.

Based on the Fe-Fe_3C phase diagram, cast irons can be classified into three groups: eutectic, hypoeutectic, and hypereutectic cast irons. Eutectic cast iron contains 4.3 percent carbon.

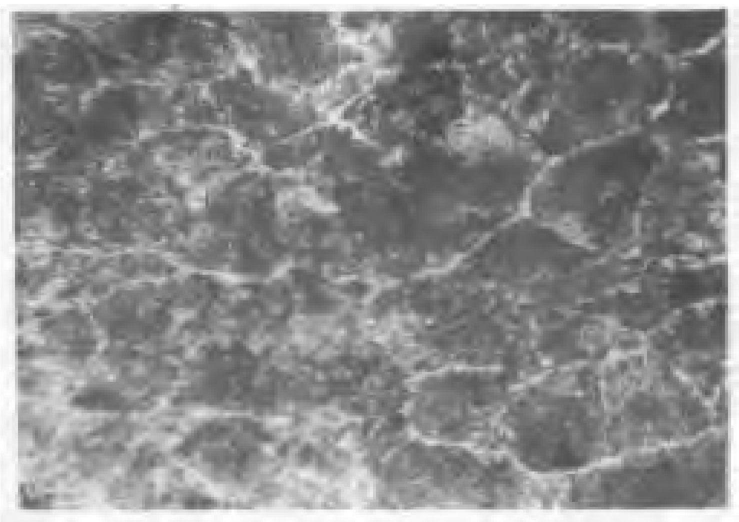
Transformations in Hypoeutectic Cast Iron

In this case, a structure just below 1147°C consists of proeutectic austenite and ledeburite (eutectic mixture consisting of austenite and cementite). On further cooling in the temperature range 1147°C–723°C, excess carbon comes out as cementite from proeutectic and eutectic austenite. Therefore, at the eutectoid temperature, both eutectic and proeutectic austenite would contain 0.8 percent carbon and would decompose by the eutectoid reaction to pearlite. Hence, the final microstructure would be the same as the high temperature microstructure, except that wherever austenite was present, pearlite would now be present.

(a) Hypoeutectoid (ferrite + pearlite), ×500

(b) Eutectoid steel (pearlite), ×1000

Figure 3.4 (*contd.*)



(c) Hypereutectoid steel (pearlite with network of cementite), ×500.

Figure 3.4 Microstructures of steels.

Transformations in Hypereutectic Cast Iron

In this case the structure just below 1147°C consists of proeutectic cementite and ledeburite. On further cooling in the temperature range 1147°C–723°C, excess carbon comes out as cementite from the eutectic austenite. Proeutectic cementite will remain as such since it does not undergo any further change on cooling. Austenite from eutectic rejects excess carbon as cementite. At 723°C, the austenite contains 0.8 percent carbon. At 723°C, eutectic austenite transforms into pearlite. Thus, the final microstructure will reveal proeutectic cementite present as plate and transformed eutectic consisting of pearlite plus cementite.

Transformations in Eutectic Cast Iron

Eutectic cast iron solidifies at 1147°C. In the temperature range 1147°C–723°C the solid alloy consists of ledeburite eutectic, i.e. austenite and cementite. As the temperature decreases, the solubility of carbon in γ-iron decreases, as indicated by the cementite line. Consequently, excess carbon is rejected from austenite and comes out in the form of cementite. On further cooling, proeutectoid cementite separates out of the austenite, and at 723°C austenite containing 0.8 percent carbon transforms to pearlite by eutectoid reaction.

The microstructure of eutectic cast iron at room temperature is identical to that at the high temperature structure. However, there is a distinct difference. In place of austenite, the transformed product, namely, pearlite, will be observed. The cementite that separates out on cooling the alloy between 1147°C and 723°C joins the existing cementite. The eutectic structure consisting of austenite and cementite can be visualized as forming alternate layers of the two phases. Therefore, the final structure will be transformed ledeburite.

The reactions during transformations in eutectic cast iron, on cooling, are as follows:

$$\underset{(4.3\%\ \text{C})}{\text{L(liquid)}} \xrightarrow[1147^\circ\text{C}]{\text{Cooling}} \underset{(2.03\%\ \text{C})}{\gamma} + \underset{(6.67\%\ \text{C})}{\text{Fe}_3\text{C}}$$

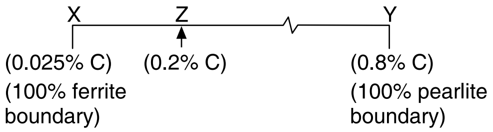
$$\underset{(0.8\%\ \text{C})}{\gamma} \xrightarrow[723^\circ\text{C}]{\text{Cooling}} \underset{(0.025\%\ \text{C})}{\alpha} + \underset{(6.67\%\ \text{C})}{\text{Fe}_3\text{C}}$$

Figures 3.5(a), (b) and (c) show the microstructures of hypoeutectic, eutectic and hypereutectic cast irons.

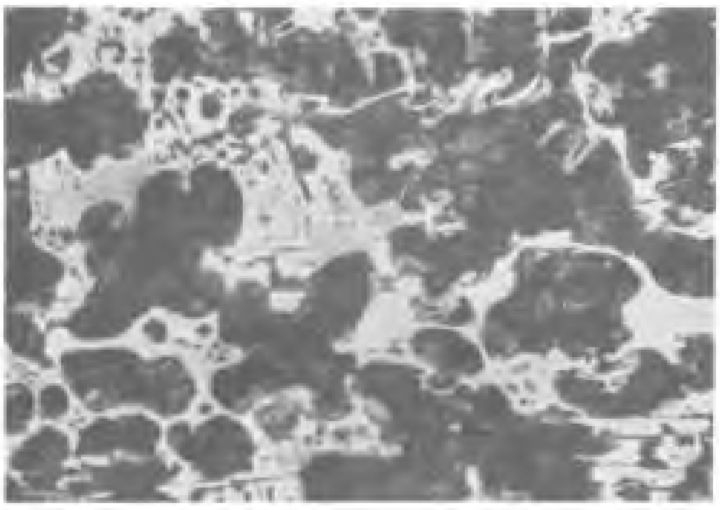
3.4.3 Lever Rule

With the help of this rule, the relative amount of the coexisting phases or microconstituents at a particular temperature can be worked out. We now give four examples of this.

EXAMPLE 1 The relative amount of ferrite and pearlite in 0.2 percent carbon steel can be found with the help of this rule, as in the following representation.



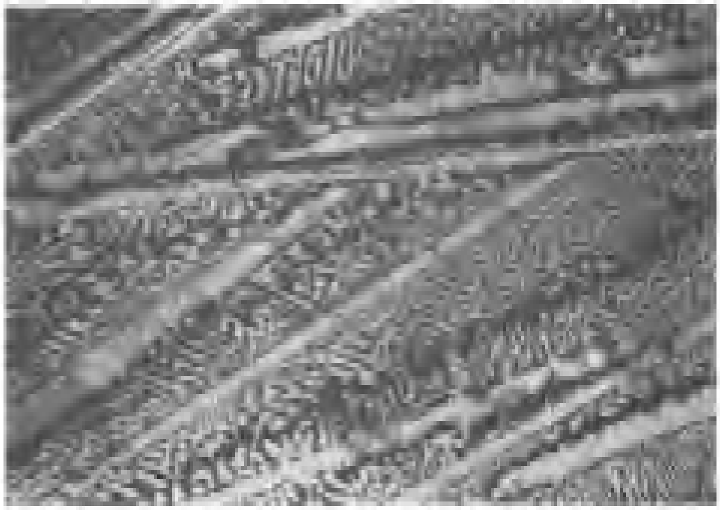
Here, YX is the lever arm. Fulcrum is at point Z. The fraction of α in the 0.2 percent carbon steel is given by the ratio of the lever arm length on the other side of the fulcrum, i.e. YZ to the total length of the lever arm (XY).



(a) Hypoeutectic cast iron (ledeburite + pearlite + cementite), ×200

Figure 3.5 (*contd.*)

(b) Eutectic cast iron (ledeburite), ×100



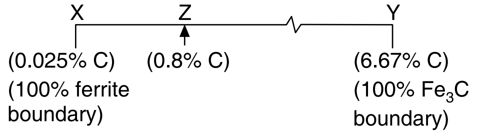
(c) Hypereutectic cast iron (ledeburite + primary cementite), ×200

Figure 3.5 Microstructures of cast irons.

Thus,
$$\text{percent } \alpha = \frac{YZ}{XY} \times 100 = \frac{0.8 - 0.2}{0.8 - 0.025} \times 100 = 77.4\%$$

$$\text{percent pearlite} = \frac{ZX}{XY} = \frac{0.2 - 0.025}{0.8 - 0.025} \times 100 = 22.6\%$$

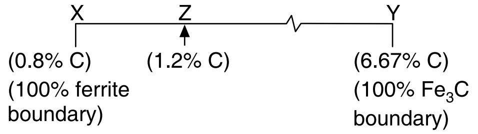
EXAMPLE 2 The relative amount of ferrite and cementite in a steel containing 0.8 percent carbon can be worked out as follows:



$$\text{percent ferrite} = \frac{6.67 - 0.8}{6.67 - 0.025} \times 100 = 88.34\%$$

$$\text{percent cementite} = \frac{0.8 - 0.025}{6.67 - 0.025} \times 100 = 11.66\%$$

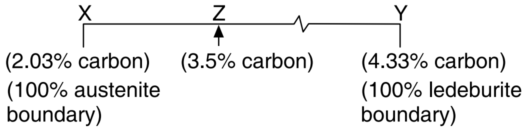
EXAMPLE 3 The relative amount of proeutectoid cementite and pearlite in a steel containing 1.2% carbon can be calculated as follows:



$$\text{percent pearlite} = \frac{6.67 - 1.2}{6.67 - 0.8} \times 100 = 93.2\%$$

$$\text{percent cementite} = \frac{1.2 - 0.8}{6.67 - 0.8} \times 100 = 6.8\%$$

EXAMPLE 4 The relative amount of austenite and liquid in cast iron containing 3.5 percent carbon at eutectic temperature can be estimated as follows:



$$\text{percent proeutectic austenite} = \frac{4.33 - 3.5}{4.33 - 2.03} \times 100 = 36.1$$

$$\text{percent ledeburite} = \frac{3.5 - 2.03}{4.33 - 2.03} \times 100 = 63.9$$

Similarly, for other compositions, the relative amounts of different phases can be calculated.

3.4.4 Iron-Graphite Phase Diagram

The process by which the stable phase, namely graphite, is formed in cast iron (or steel) is known as graphitization. At all temperatures, the following reaction takes place:

$$Fe_3C \xrightarrow{\text{Cooling}} 3Fe + C \text{ (graphite)}.$$

At low temperatures, however, the reaction occurs so slowly that Fe_3C remains as such. At higher temperatures, the graphitization of the iron carbide occurs. In the presence of silicon, graphitization becomes faster. Aluminium and nickel, which are also graphitizers, form additional centres for crystallization of graphite flakes. So, the stable phase, graphite, forms either by separating out of the liquid (or solid) solution, or as a result of decomposition of metastable cementite.

Figure 3.6 is an iron-graphite phase diagram. As the liquid alloy (say having 3.2% C) cools to 1153°C, dendrites of austenite phase starts forming in the liquid. At 1153°C the liquid reaches eutectic composition and solidifies as a eutectic mixture of austenite and graphite. This is called primary stage of graphitization. Upon subsequent slow cooling, additional graphite forms from the austenite and eutectoid graphite is formed in the temperature interval from 738°C to 723°C.

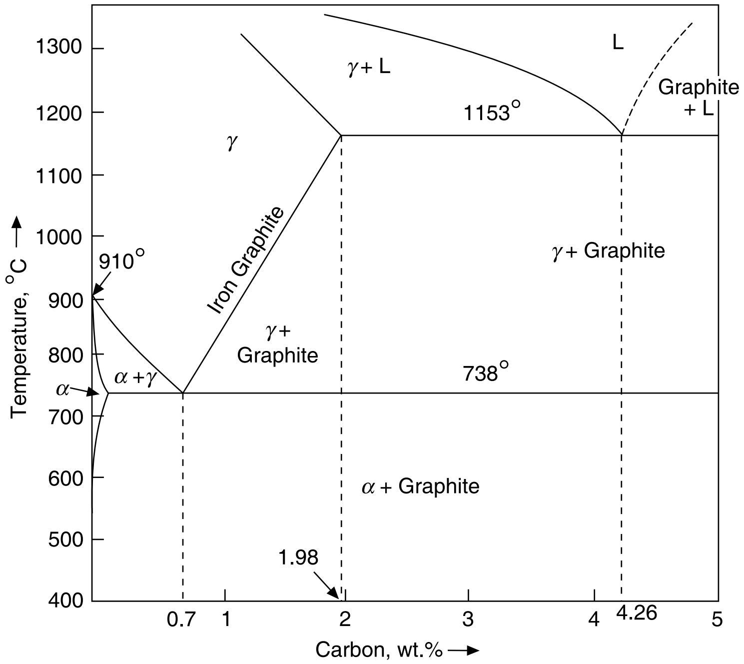


Figure 3.6 Iron-graphite phase diagram.

Separation of secondary graphite from the austenite is called the inter-mediate stage of graphitization. Formation of eutectoid graphite, as well as the decomposition of eutectoid cementite into graphite and ferrite, is called the secondary stage of graphitization. A major amount of graphite precipitates during the primary stage of graphitization. While during intermediate and secondary stage of graphitization, the additional graphite merely adds to the pre-existing graphite flakes and increases its size. If austenite is supercooled below 723°C, it decomposes with the separation of a ferrite-cementite mixture. The prolonged heating at high temperatures of cast iron containing carbon in combined form also leads to graphitization, i.e.

decomposition of cementite into graphite and ferrite at temperature below 738°C, or into graphite and austenite at higher temperature. Composition and cooling rate are two factors which determine the type of structure formed on cooling of cast iron. Rapid cooling inhibits precipitation of graphite partially or completely and promotes formation of cementite. If liquid cast iron is supercooled below 1147°C, cementite is precipitated. The precipitation of graphite from the liquid phase is possible only at very slow cooling rates, i.e. when the degree of supercooling does not exceed 5°C.

Since a cast iron containing coarse graphite flakes has low strength, various methods are used to improve the graphite distribution. Finer graphite tends to form when the alloy is superheated just before casting. A finer flake size can also be produced by adding inoculants like ferrosilicon and calcium-silicon in very small amounts which promote graphitization.

Graphite nodules, rather than graphite flakes, will form if the molten alloy is treated with magnesium or cerium. This results in formation of spheroidal graphite (SG) cast iron.

The rapid cooling prevents graphitization of cementite in white cast iron, but if the casting is reheated to about 875°C and held there for long time, then graphite is slowly produced in the form of temper carbon. This is called malleable cast iron.

3.4.5 Effect of Alloying Elements on the Fe-Fe_3C Phase Diagram

A study of the effect of alloying elements on the Fe-Fe_3C phase diagram is very helpful in understanding the various heat treatment processes of alloy steels. By knowing the behaviour of such elements on the Fe-Fe_3C diagram, it is possible to evolve suitable heat treatment cycles to obtain alloy steels with desired properties. Alloying elements affect the relative stabilities of alpha and gamma iron as also on critical points (A_4, A_3, and A_1)and carbon content. From the point of view of their effect on austenite and ferrite, the alloying elements can be grouped in two classes. They are:

(i) Elements which tend to stabilize ferrite. These are called ferrite stabilizers, e.g. Cr, W, Mo, V, and Si.
(ii) Elements which tend to stabilize austenite. These are called austenite stabilizers. Mn, Ni, Co, and Cu are some elements which fall under this category.

Ferrite Stabilizers

These elements stabilize ferrite. They are more soluble in alpha-iron than in gamma-iron. Most of these elements have the BCC crystal structure, the same crystal structure as that of alpha-iron. They decrease the amount of carbon present in the gamma-iron, and thus favour formation of larger quantity of carbide in the steel for a given carbon content. These elements reduce the austenite region in the Fe-Fe_3C phase diagram by lowering the A_4 point and raising the A_3 point until the A_4 and A_3 points meet and form a closed gamma loop.

The austenite phase may not appear in a steel at any temperature when sufficiently large quantities of such elements are added. For example, by adding 12.8 percent or more of chromium, the austenite phase disappears and the δ-ferrite and α-ferrite merge to give a continuous ferrite from room temperature up to the melting point. Such steels cannot be heat treated in the conventional way because the austenite phase is not available for solid-solid phase transformation. They can be strengthened only by cold working-annealing cycle.

However, it is possible to reintroduce austenite phase in such a steel by addition of austenite stabilizers like nickel. For example, addition of 2% Ni to 18% Cr steel makes the steel heat-treatable.

The approximate compositions at which austenite phase altogether disappears due to addition of ferrite stabilizer elements are given in Table 3.1.

Table 3.1 Quantities of Elements Required for Stabilization of Ferrite

Element	Cr	Si	W	Ti	Mo	V
Composition (wt.%)	12.8	2	6	0.75	4	2

All the elements except Si listed in Table 3.1 have the BCC structure. Silicon is diamond cubic in structure.

Figure 3.7 Shows the Fe-Cr phase diagram.

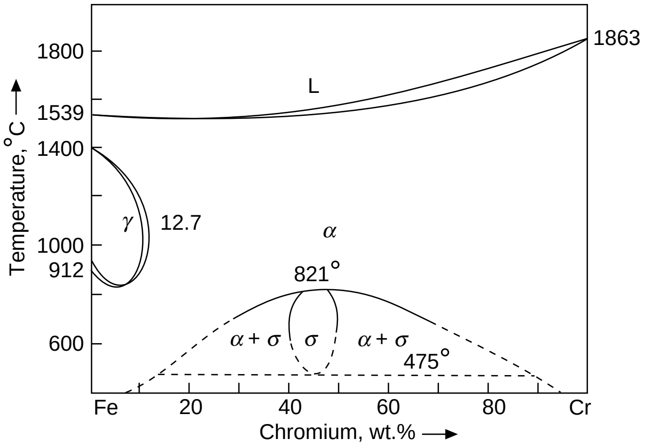


Figure 3.7 Iron-chromium phase diagram incorporating gamma loop.

Austenite Stabilizers

Manganese, nickel, and copper are austenite stabilizing elements. These elements enlarge the austenitic region, make it stable phase even at room temperature, and shift the critical points. The A_4 point is shifted upward and the A_3 point downwards. As a result, the range of stable austenite is increased. Carbon has also similar effect, as can be observed from the Fe-Fe_3C phase diagram. Austenite stabilizers also restrict the separation of carbide. Figure 3.8 shows the Fe-Ni phase diagram. The general trend of effect due to addition of austenite stabilizing elements can be seen from Figure 3.9, which shows the effect of manganese on austenite phase boundaries of the Fe-Fe_3C phase diagram. The carbon content of the eutectoid composition is reduced and also the A_1 temperature. Thus the austenite phase field is enlarged.

The ferrite stabilizing elements (e.g. chromium), on the other hand, reduce the austenite phase field and may even cause its complete removal. This is shown in Figure 3.10 for chromium. The eutectoid temperature increases while the eutectoid composition shifts to lower carbon content.

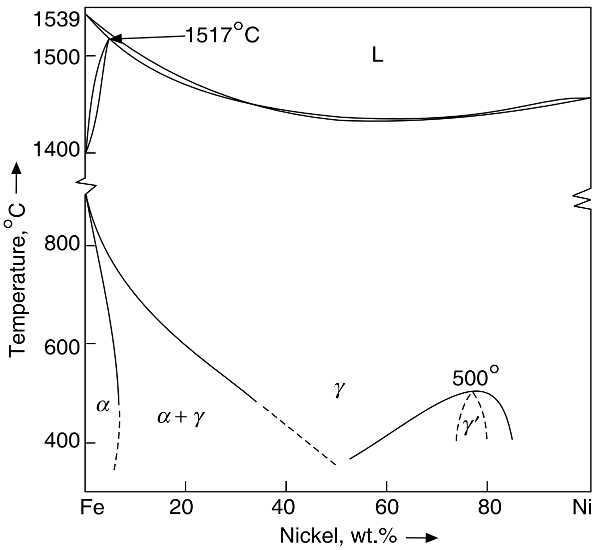


Figure 3.8 Iron-nickel phase diagram (illustrating stabilization of the austenite phase by nickel).

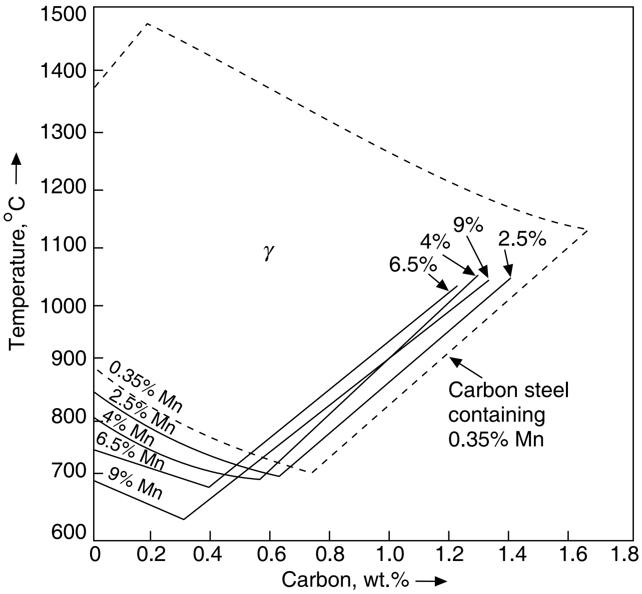


Figure 3.9 Effect of manganese on austenite phase region.

Effect on Eutectoid Temperature and Composition

Different alloying elements may influence the eutectoidal transformation in one or more of the following ways: effect on temperature and effect on carbon content of the eutectoid composition.

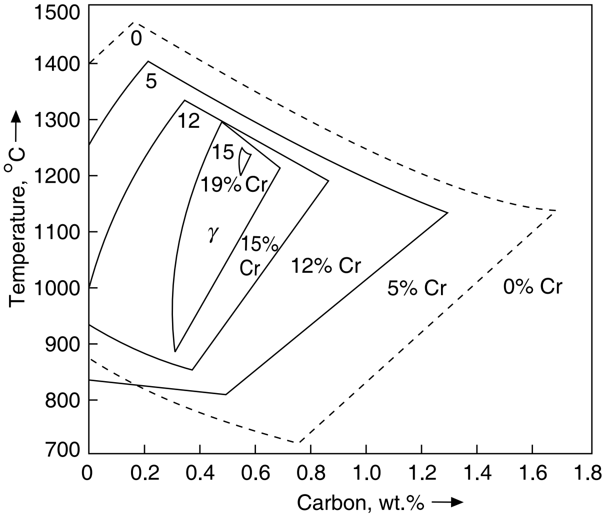


Figure 3.10 Effect of chromium on austenite phase region.

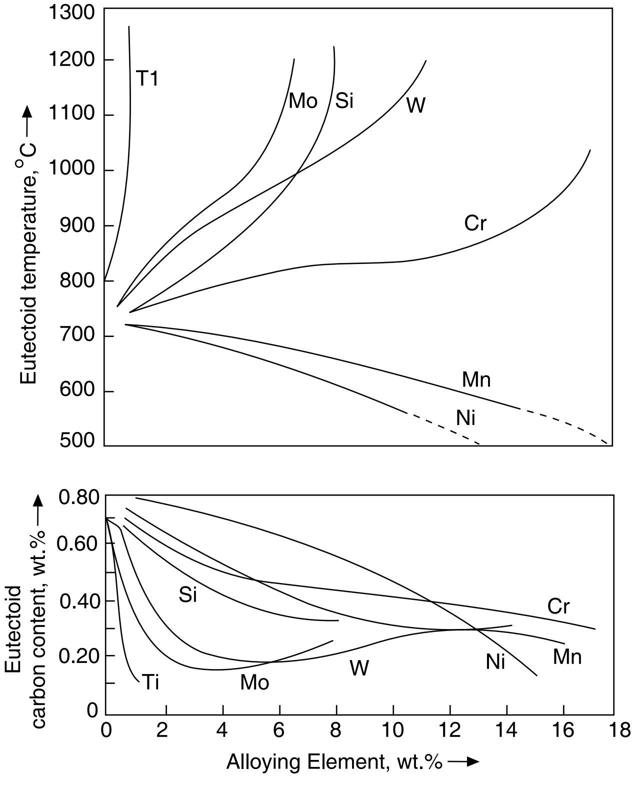


Figure 3.11 Effect of various alloying elements on the eutectoid temperature and composition.

Effect on Temperature Figure 3.11 shows the effect of different alloying elements on eutectoid temperature. Being an austenite stabilizer, nickel lowers eutectoid temperature. Three percent nickel lowers the eutectoid temperature by about 30°C. When chromium, which is a ferrite stabilizer, is added, the eutectoid temperature is raised. Ti and Mo are most effective in this context. Twelve percent chromium raises eutectoidal temperature to about 800°C from 723°C.

Effect on Carbon Content of the Eutectoid Composition Both austenite and ferrite stabilizers lower the carbon content of eutectoid composition. In plain carbon steel, eutectoidal composition corresponds to 0.8 percent carbon.

3.5 CLASSIFICATION OF STEELS

In general, steels may be classified into two broad groups: plain carbon steel and alloy steels.

Plain carbon steel is that steel in which carbon is the main element which governs the properties of steel. Other elements which are associated in the steel are kept below a certain limit so that they do not influence properties of steel. On the other hand, alloy steels are those steels in which one or more elements are added to impart some peculiar characteristics. In such steels, carbon and alloying elements, contribute towards properties of steels.

Plain carbon steel and alloy steels can be further subdivided on the basis of various factors. Plain carbon steel can be further classified on the basis of carbon content, structure at room temperature at slow cooling, quality and application. It may be recalled that a steel having 0.8 percent carbon is called eutectoid steel and it has a completely pearlitic structure on slow cooling.

Hypoeutectoid steels contain proeutectoid ferrite and pearlite, while hypereutectoid steels contain proeutectoid cementite and pearlite. These divisions are not so precise for many reasons. So, for all practical purposes, these can be classified into low, medium and high carbon steel:

Low carbon steel up to 0.3% C
Medium carbon steel from 0.3% C to 0.6% C
High carbon steel from 0.6% C to 2.03% C

These constitute over 90% of the total steel production and in that the mild steels take the major share. Plain carbon steel may contain several other elements like Al, Mn, Si, P, S, and so on, but their individual contents are below the critical limits above which the properties of steel are significantly affected.

Low carbon steel is easily weldable and has good workability but show poor response to heat treatment. It is mainly used for sheets, strips, structural sections, case hardening, etc.

Medium carbon steel has good strength, toughness and its response to heat treatment is also good. It is mainly used for such applications as gear and connecting rods, laminated springs, and so on.

High carbon steel has good strength and is used as tool steel, prestressed concrete wire, etc.

The quality of any steel, in general, depends on S and P contents, the degree of the oxidation and cleanliness. In the case of plain carbon steel, S and P are main factors which control the quality of steel. A quality steel has S and P contents, each 0.04% max. Steel with content of these elements less than 0.025% is known as high quality steel. Steels having S and P between 0.04 percent and 0.06 percent are known as ordinary quality steels.

Plain carbon steels are used successfully where strength and other requirements are not absolutely essential. At ordinary temperature and in an atmosphere, which are not of a severely corroding nature, the performance of plain carbon steels is quite satisfactory. However, the relatively low hardenability of the plain carbon steels limits the strength that can be attained except in relatively small cross-sections.

Following disadvantages limit the usefulness of plain carbon steels:

(i) Low hardenability
(ii) Major loss of hardness on tempering
(iii) Low corrosion resistance and oxidation resistance
(iv) Low strength at elevated temperature.

The most common and practical method of overcoming the deficiencies of the plain carbon steel is to employ alloy steels.

Alloy steels are those in which one or more elements are added to steel for enhancing further the prominent characteristics of the plain carbon steels or to ensure specific properties. These added elements are known as alloying elements. Based on their four features, alloy steels can be classified as follows:

(i) Classification on the basis of the amount of alloying element:
    (a) Low alloy steel in which the total alloying content is less than about 5 percent.
    (b) Medium alloy steel in which the total alloying content is in the range of 5–10 percent.
    (c) High alloy steels in which the total alloying content is above 10 percent.
(ii) Classification on the basis of composition: Depending on the alloying elements, alloy steels are classified into nickel steels, chromium steels, Cr-Ni steel and Cr-Ni-Mo steels. They are classified according to the presence of various alloying elements.
(iii) Classification on the basis of structure: Various structures such as martensite, austenite, or bainite constitute steels. Accordingly, they are called martensitic steel, austenitic steel, and so on.
(iv) Classification on the basis of application; Corrosion resisiant steel, heat resistant steel, magnetic steel, tool steel, electrical steel, etc.

Alloying elements are added with a view to impart a number of desirable properties in steels. Some of these properties are (i) to increase hardenability, resistance to softening on tempering, resistance to corrosion and oxidation, and to increase resistance to abrasion; (ii) to improve high temperature properties; and (iii) to achieve the desired constituents (e.g. stabilization of austenite at room temperature) and higher elastic ratio and endurance strength.

Alloy steels, however, are normally costly. They require more careful handling during manufacturing, heat treatment and mechanical working. Alloy steels have greater tendency for retention of austenite. The retained austenite decomposes at a later stage, leading to dimensional changes and introduction of internal stresses. Certain grades of alloy steels are also prone to temper brittleness.

QUESTIONS

3.1 How are the critical temperatures in steel designated? What is the critical range?

3.2 Draw Fe-Fe_3C phase diagram and label the phase fields. Discuss in brief the different reactions that take place in this system.

3.3 Explain the cooling sequence of a 0.6% “carbon” steel from liquid state to room temperature in detail.

3.4 Compute the following:

(a) Percent pearlite and cementite in a steel containing 1.2% carbon.
(b) Percent austenite and ledeburite in cast iron containing 3.5% carbon.
(c) Percent ferrite and cementite in a steel containing 0.8% carbon.

3.5 Discuss in brief the effect of alloying elements on Fe-Fe_3C phase diagram.

4

Principles of Heat Treatment of Steels

INTRODUCTION

As already mentioned, the properties of steel are related to its structural make-up. The desired levels of mechanical properties can be obtained by altering the size, shape and distribution of various constituents. This is achieved in practice by the process of heat treatment. In general, the structural make-up of any steel consists of transformed product(s) from austenite. Depending on various parameters, transformed products from austenite may be pearlite, bainite or martensite. Not only the presence of these phases microconstituents but also the morphology of these products is of significance in deciding the resultant properties. Therefore, it is very important, before proceeding for a heat treatment process, to know about the nature of austenite and its subsequent transformation behaviour. In fact, such a study is essential in order to learn the theory of heat treatment practice. The following sections deal with various aspects of heat treatment theory.

4.1 FORMATION OF AUSTENITE ON HEATING

Formation of austenite is a preliminary step for any heat treatment process. Austenite is formed on heating an aggregate of ferrite and pearlite, ferrite and cementite or cementite and pearlite, depending on whether the steel is of hypoeutectoid, eutectoid or hypereutectoid type, respectively. Formation of austenite in eutectoid steel differs from that of hypoeutectoid and hypereutectoid steels in the sense that in the former case it occurs at a particular temperature (Ac_1) whereas for the latter it takes place over a range of temperature (see Figure 4.1).

Let us consider the formation of austenite from a mixture of ferrite-cementite in a eutectoid steel. Normally, this mixture in eutectoid steel occurs as pearlite. Figure 4.2 shows the microstructure of lamellar pearlite which consists of alternate lamellae of ferrite and cementite. The orientation of these layers varies for different grains. These layers are in direct contact with each other. The intermetallic compound cementite has 6.67 weight percent carbon, whereas ferrite is almost pure iron, free of carbon. Though a carbon gradient exists, the structure is thermodynamically stable at room temperature and above. This is so because carbon diffusion rates are practically insignificant up to 200°C. As the temperature increases to higher values, but below eutectoid temperature, carbon atoms have a tendency to diffuse into ferrite. But the rate of this diffusion is extremely slow and for all practical purposes, it has no perceptible effect. Maximum content of carbon in ferrite is about 0.025 percent at eutectoid temperature. Below this temperature, it is still less and decreases to a value of about 0.008 percent at room temperature. On heating to eutectoid temperature, BCC iron (α-Fe) lattice changes to FCC iron (γ-Fe) lattice. The maximum solubility of carbon in FCC iron is about 2 percent. Therefore, at this temperature, regions around the cementite layer will be enriched with carbon because of diffusion. The maximum diffusion of carbon atoms will take place from the cementite at the ferrite-cementite interface. As sufficient number of interfaces are available, austenite nuclei will be formed at the interfaces. By gradual dissolution of carbon of cementite into gamma iron, primary austenitic/grains are formed. These primary austenitic grains dissolve the surrounding ferrite and austenitic grains grow at the expense of ferrite (see Figure 4.3).

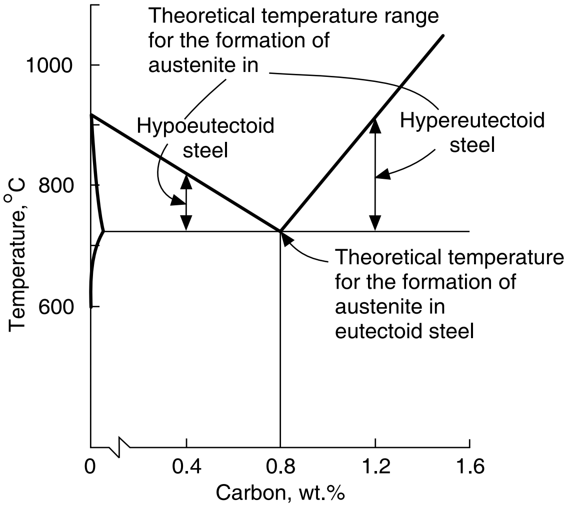


Figure 4.1 Temperature ranges for the formation of austenite on heating for steels.

Figure 4.2 Microstructure showing lamellar nature of pearlite (×1200).

These processes, i.e. the formation of primary austenitic grains and their growth by dissolving ferrite, continue till all ferrite and cementite dissolve to form austenite. The growth

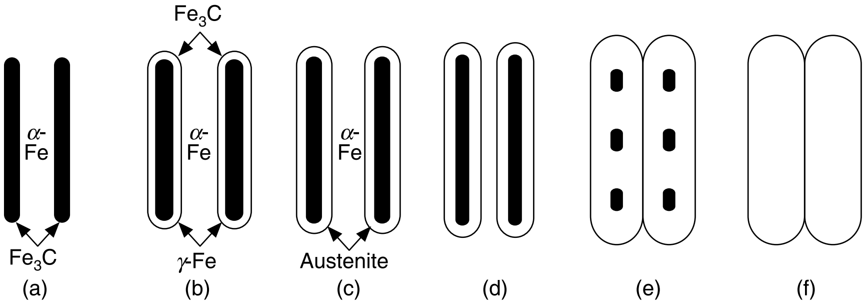


Figure 4.3 Steps associated with transformation of pearlite to austenite.

rate of austenite is higher than the rate of dissolution of the cementite into austenite because austenitic grain growth takes place because of the transformation of alpha iron to gamma iron and diffusion of carbon atoms from austenite to ferrite. This explains the experimentally observed fact that dissolving of ferrite is completed before that of cementite. The austenite thus formed at eutectoid temperature is not homogeneous. The carbon concentration is higher in these regions which are adjacent to the original cementite lamellae than those which are adjacent to the ferrite mass. Chemically homogeneous austenitic grains are obtained by holding steel above the eutectoid temperature. The holding time should be sufficient so that carbon atoms may diffuse and result in uniform distribution of carbon atoms. Figure 4.4 is a pictorial representation of the statement.

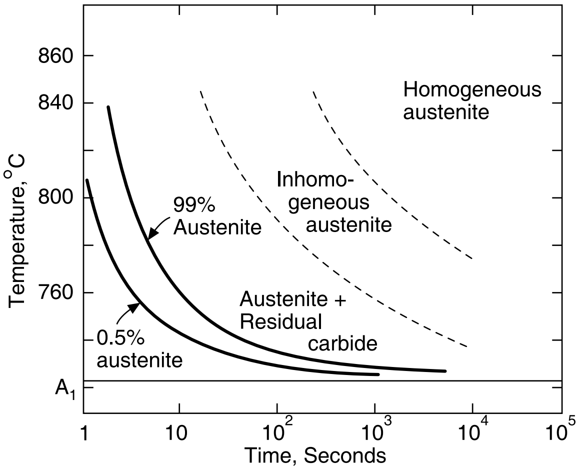


Figure 4.4 Effect of temperature and time on the austenite formed from pearlite in 0.3% carbon steel.

Transformation to austenite on heating hypoeutectoid and hypereutectoid steels is somewhat different from the above condition because of the presence of proeutectoid ferrite and proeutectoid cementite, respectively, along with pearlite. Transformation of proeutectoid ferrite and pearlite, in the case of hypoeutectoid steels, can be understood with the help of the

Fe-Cementite phase diagram. On very slow heating, austenite nuclei are formed just above the eutectoid temperature. More nuclei will form with increase in temperature. Therefore, at first the austenitic grains will grow by the growth of initially formed austenitic grains and then by the growth of newly formed austenite nuclei. The process will continue till the upper critical temperature (A_3) is reached. The austenite present at this temperature will be non-homogeneous due to the presence of embedded cementite particles within the austenitic grains. For hypoeutectoid steels, growth of primary austenitic grains take place at the expense of proeutectoid ferrite. Further, austenite nuclei are also possibly formed at grain boundaries of ferritic grains. In hypoeutectoid steels, cementite dissolves into the ferrite which in turn transforms into austenite. In the case of hypereutectoid steels, the transformation proceeds in a similar way with the difference that austenitic grains grow by dissolving proeutectoid cementite.

Theoretically, though pearlite must transform to austenite completely at eutectoid temperature, it does not happen so in practice. Complete dissolution of cementite of pearlite into austenite takes place over a range of temperatures. On parallel lines, it has been experimentally observed that dissolution of proeutectoid ferrite or proeutectoid cementite is not completed at A_3 or A_{cm} respectively. It, therefore, becomes essential to heat eutectoid, hypoeutectoid and hypereutectoid steels above A_1, A_3 and A_{cm}, respectively, in order to get homogeneous austenite.

4.1.1 Kinetics of Formation of Austenite

In practice, it is not possible to heat a steel with equilibrium rate of heating. The formation of austenite on heating always occurs at a temperature higher than that predicted by the Fe-Cementite phase diagram. Heating of steel to austenitizing temperature is the first and foremost step of almost all heat treatment processes. Also, the grain size of austenite at heat treatment temperature largely controls the resultant mechanical properties after heat treatment. Therefore, the study of kinetics of formation of austenite is of great importance.

A simple approach to the study the kinetics of austenite formation is to heat a number of steel samples to different temperatures above the eutectoid temperature. The size of samples is restricted so that they may attain the required temperature in a very short period. Heating is done by immersing samples in constant temperature baths. A number of samples are immersed in a constant temperature bath and are taken out one by one after a definite interval of time, followed by immediate quenching which will result in the formation of martensite from transformed austenite. The amount of martensite formed will depend on the amount of transformed austenite which in turn will depend on the temperature at which the steel sample has been heated and the holding time at that temperature. As already mentioned, the temperature in this case will be above the eutectoid temperature. Thus, the percentage of transformed austenite with time for a given temperature can be known. The same sequence of operation is employed for different temperatures. The results of such a process are shown in Figure 4.5.

It can be easily concluded that the lower the transformation temperature, the more is the time required to complete the transformation. The results of Figure 4.5 can be reproduced with the help of the temperature-time diagram (Figure 4.6). The percentage of the transformed austenite on heating can also be determined by various other methods. Any property which

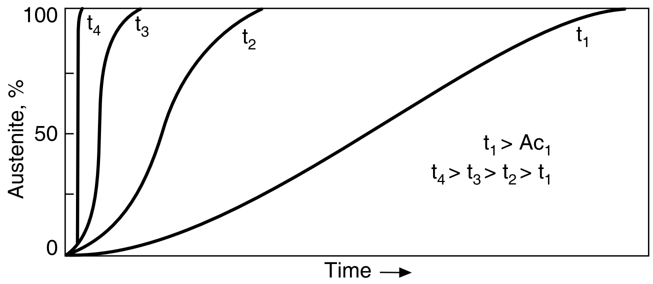


Figure 4.5 Transformation of pearlite to austenite as a function of time at different temperatures.

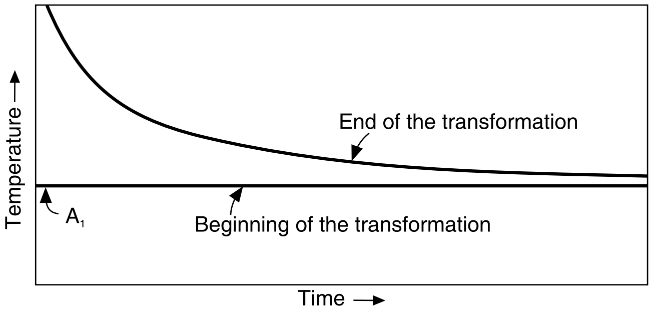


Figure 4.6 Effect of temperature on the time required for completion of transformation of pearlite to austenite.

changes with the formation of austenite, and/or with martensite formed by quenching of transformed austenite, can be utilized for this purpose. Some examples are change in hardness value, volume, magnetic property and internal stresses.

One important limitation of Figure 4.6 is that it does not reveal the effect of superheating on the kinetics of transformation. In fact, under practical conditions of heating, transformation occurs at a temperature above the eutectoid temperature, and not at eutectoid temperature. It will be useful to remember that equilibrium temperatures are raised on heating and lowered on cooling. Figure 4.7 shows the relationship between transformation temperature and transformation time. The relationship has been derived by taking into consideration the effect of superheating. An analysis of Figure 4.7 leads to the following conclusions:

(i) Transformation is completed in a short period at high transformation temperature.
(ii) For higher heating rates, transformation will start at higher temperature, whereas for slower heating rate, transformation will start at lower temperature.
(iii) For any given practical rate of heating, the formation of austenite will occur over a range of temperature, and not at a constant temperature.
(iv) For the formation of austenite at a constant temperature, the heating rate should be extremely slow, and the two curved lines will converge to a single point located at eutectoid temperature line.

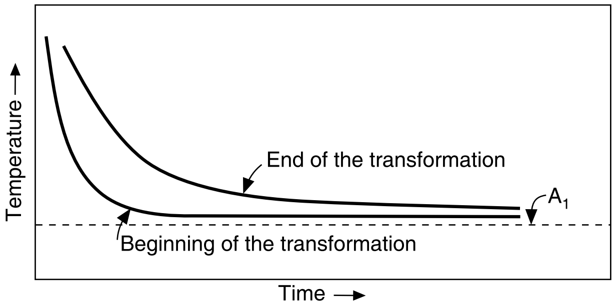


Figure 4.7 Effect of temperature on the time required for start and completion of transformation of pearlite to austenite.

The end of the transformation curve does not reveal any information about the nature (homogeneity) of austenite. The curved line only ensures that all the pearlite has been transformed into austenite. In order to attain a homogeneous austenite, the steel has to be heated to still higher temperatures. Here it is important to emphasize on the austenite transformation temperature. There should not be any confusion regarding it on the basis of Figures 4.6 and 4.7. Austenite is formed as soon as the eutectoid temperature is attained. Firm curved lines of Figure 4.7 only represent the fact that, for a given temperature, most of the pearlite will be transformed into austenite within the time interval between the two curved lines.

The process of austenite formation on heating proceeds by nucleation and growth reaction. Therefore, the factors which can vary either the rate of nucleation or the rate of growth or both will change the kinetics of austenite formation. Two such parameters are transformation temperature and holding time at transformation temperature. The effect of these parameters has already been described in this section. In addition, there are some other factors which control the kinetic of transformation. We now discuss some of these factors.

As already mentioned, the austenite nuclei are formed at the interface of ferrite and cementite as soon as the eutectoid temperature is reached. Therefore, the kinetics of austenitic transformation is governed, to a great extent, by the nature of the pearlite. The number of possible austenite nuclei will increase with the increase in the interfacial area. The interfacial area can be increased in two ways: by increasing the cementite contents, and by decreasing the interlamellar spacing. The former condition, i.e. increase in cementite contents, can be met with by increasing the carbon contents. This is the reason why high carbon steels austenitize more rapidly than low carbon steels. The closer the ferrite-cementite lamellae, the higher will be the rate of nucleation. Also, the carbon atoms have to diffuse for smaller distances in order to enrich low carbon regions. Therefore, the rate of growth of primary austenitic grains will also be higher in this case. This explains why pearlitic structure with less interlamellar spacing is transformed faster to austenite. The kinetics of austenitic transformation for coarse pearlitic structure is slow for the reason given above. The kinetics of austenitic transformation from granular pearlite is slower than that of lamellar pearlite for same reasons. The kinetics of transformation will further decrease with increase in the size of globular cementite particles. Quenched structure will also transform to austenite more rapidly than the granular pearlitic structure.

The foregoing discussion was in relation to carbon steels. For alloy steels, the kinetics, in addition to the nature of pearlitic structure, is also dependent on the nature of alloying element(s). Kinetics of formation of austenite is slowed down in the presence of carbide forming elements. This is so because alloy carbides dissolve in the austenite with greater difficulty than iron carbide.

4.2 AUSTENITIC GRAIN SIZE

Nuclei of austenite are formed as soon as a steel is heated to eutectoid temperature. These nuclei grow into primary austenitic grains. The process of nucleation and growth takes place simultaneously and continues till all the ferrite and cementite transform to austenite. At the end of the transformation, only austenitic grains are present in the structure. The size of these austenitic grains is referred to as original grain size. In practice, a steel is heated above the critical temperature to ensure the homogeneity of austenite, This heating above the critical temperature results in considerable growth of original austenitic grains. The grain size of austenite thus obtained is known as the actual grain size of austenite. The actual austenitic grain size is therefore dependent on the temperature to which steel has been heated up and holding time at this temperature. Until and unless specified, the grain size of steel, in general, means actual austenitic grain size and the same convention has been followed in this text. In fact, many properties of steel are dependent on actual austenitic grain size or simply grain size of steel. Tensile strength, yield strength, toughness, hardenability and machinability can be altered considerably by varying the grain size of steel.

Depending on the tendency of steel to grain growth, steels can be classified into two broad groups: inherently fine grained steels, and inherently coarse grained steels. Inherently fine grained steel resists the growth of austenitic grains with increasing temperature. The kinetics of austenitic grain growth is very slow and the steel remains fine grained even at temperatures as high as 1000°C or 1050°C. On the other hand, grains of inherently coarse grained steel grow abruptly (see Figure 4.8) with increasing temperature, and so a steel with coarse grains is obtained. Apparently, there is some mechanism which checks the austenitic grain growth in inherently fine grained steels and it is absent in inherently coarse grained steels. The terms inherently fine grained steels and inherently coarse grained steels do not essentially mean that the former will always possess finer grains than the latter. On heating above a particular temperature which essentially depends on chemical composition and deoxidation practice, it is possible to get coarser grains in inherently fine grained steel as compared to inherently coarse grained steels. This is possible only when the mechanism, which has been effective below this temperature, is no more effective above this temperature.

It is now understood that it is the presence of ultramicroscopic particles of oxides, carbides and nitrides which prevent grain growth. These particles are refractory in nature, i.e. they can withstand high temperatures and are generally present at grain boundaries of austenite. Therefore, they act as barriers to the growth of austenitic grains. This explains the experimentally observed fact that steels which are either deoxidized with aluminium or treated with boron, titanium and vanadium, i.e. carbide and nitride forming elements, are the inherently fine grained variety. Intensive grain coarsening of inherently fine grained steels above a particular temperature is due to the dissolution of ultrafine particles of carbides, oxides and

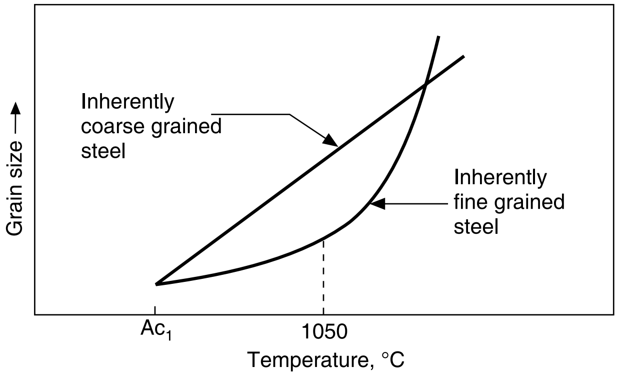


Figure 4.8 Comparison of austenitic grain growth characteristics of inherently fine grained and coarse grained eutectoid steel.

nitrides in the matrix (austenite). After dissolution, no particles are left to offer resistance to grain growth.

Due to the limited effect of temperature on the austenitic grain growth, inherently fine grained steels can be hot worked at higher temperatures or can be heated to higher temperatures for heat treatment purpose without any danger of grain coarsening.

The most popular and widely accepted method for designating the austenitic grain size has been developed by the American Society of Testing Materials. In this designation system, grain size is expressed by grain size index, N. It is given by the relation

$$n = 2^{N-1}$$

where n is the average number of grains per square inch at 100× magnification. The grain size index is estimated by comparing the grain structure of the given specimen with the chart showing standard grain size structures. Some such ASTM charts are shown in Figure 4.9. As the grain size index number increases, grain size becomes fine. Table 4.1 shows the relationship between grain size index and the number of grains.

Table 4.1 ASTM Grain Size

ASTM No. (Grain size index)	Mean number of grains/in^2 at 100 ×	Grains/mm^2
1	1	16
2	2	32
3	4	64
4	8	128
5	16	256
6	32	512
7	64	1,024
8	128	2,048
9	256	4,096
10	512	8,200

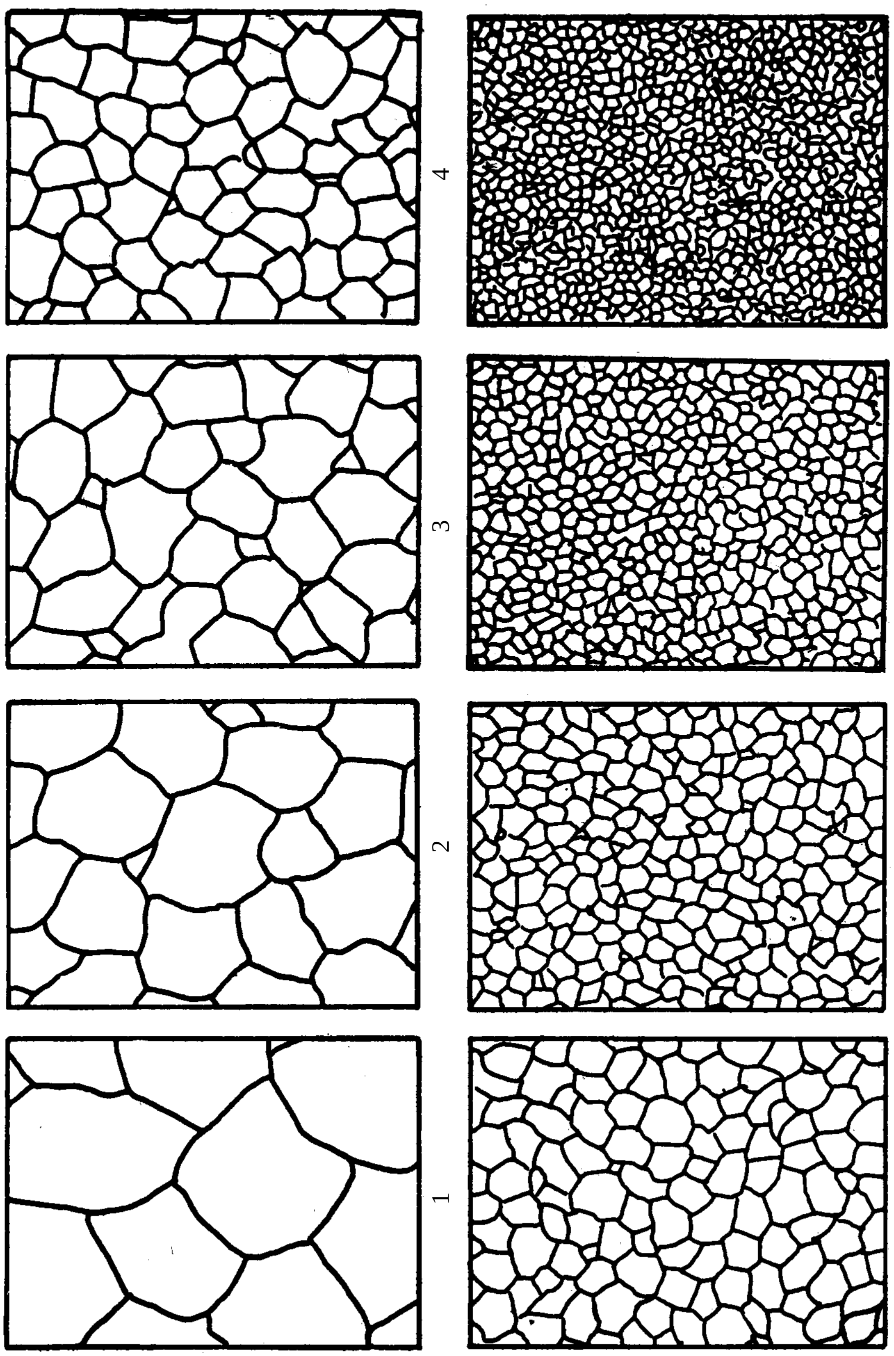


Figure 4.9 **ASTM charts for grain size.**

According to the modified ASTM standard, the ASTM grain size number (G) is related to the number of grains per mm^2(n_a) at 1× by the equation:

$$G = -2.9542 + 1.4427\ l_n\ n_a$$

4.3 DETERMINATION OF AUSTENITIC GRAIN SIZE

The measurement of austenitic grain size is now becoming a regular practice. The diiference in the properties of two steels having the same chemical composition and subjected to similar heat treatment can be explained on the basis of austenitic grain size. Since austeniteis generally not the stable phase at room temperature, methods have been developed to reveal prior austenitic grain boundaries. Revelation of austenitic grain boundaries is based on two distinctly different techniques, one involving change in chemical composition and the other in which change in chemical composition does not take place.

When austenitic grain boundaries are revealed either by carburization or by oxidation, there is change in chemical composition. Carburization method is applicable to only those steels which can be case carburized. The principle involved in this method is the production of hypereutectoid case and cooling it in such a way that excess cementite forms network around the austenitic grains. The method consists of carburizing steel at 925°C for 8 hours, followed by slow cooling in the furnace itself. The steel remains packed in the carburization medium during cooling. The process is also referred to as the McQuaid-Ehn method. Longer carburizing period and slow cooling up to room temperature, involved in this process, result in the precipitation of carbides at the grain boundaries. This precipitation of carbides at grain boundaries facilitates the estimation of the grain size. Oxidation method is employed for plain carbon and low alloy steels. The steel is oxidized under oxidizing atmosphere at an elevated austenitizing temperature. This is followed by quenching, resulting in the oxidation of austenitic grain boundaries which are clearly revealed at room temperature by etching.

The methods which do not involve change in chemical composition consist of heat treating steel. In these methods, either network of ferrite or cementite or of transformed product is formed at austenitic grain boundaries. Hypoeutectoid and hypereutectoid steels consist of pearlite and ferrite or pearlite and cementite, respectively. On slow cooling, depending on the carbon content, either ferrite or cementite will be formed as proeutectoid constituent. Separation of the proeutectoid constituent generally takes place at austenitic grain boundaries. Under a specific set of favourable conditions, rejected ferrite or cementite may form a complete or almost complete network around the austenitic grains. On further cooling to eutectoid temperature, the austenite will transform to pearlite.

Eutectoid steel has no excess constituents to be rejected. However, under specific conditions, a network of fine nodules of pearlite around the austenitic grains can be developed. This network can be preserved and the remaining austenite can be transformed into martensite by quenching. Now, prior austenitic grain boundaries can be easily revealed by etching with a suitable etchant. In the etched structure, light martensite and dark pearlite are clearly differentiated.

Etching contrast method is generally employed for fully hardened, or hardened and slightly tempered steels consisting of martensite or tempered martensite, respectively. The method consists of etching the specimen prepared for metallography by specific etchant which, in general, is a solution of 5 ml hydrochloric acid, 1 gm picric acid and 100 ml ethyl or methyl alcohol. This etchant develops an excellent contrast between differently oriented martensitic grains, thus enabling establishment of prior austenitic grain boundaries.

4.4 IMPORTANCE OF AUSTENITIC GRAIN SIZE

With the knowledge of grain size, it is possible to predict the response of steel to heat treatment and behaviour during working or under various stress conditions to which it may be subjected during service. We now discuss the effect of grain size on various properties of steel.

The dependence of yield stress on grain size is expressed by the well known Hall-Petch equation

$$\sigma_0 = \sigma_i + K_y D^{-1/2}$$

where σ_0 is the yield stress, σ_i the frictional stress opposing motion of a dislocation, K_y the extent to which dislocations are piled up at barriers, and D is the average grain diameter. Therefore, the finer the grain size, the higher will be the yield stress. In fact, grain refinement is the only commercially available conventional technique which improves strength and ductility at the same time. The relationship between yield stress and grain size has been used extensively in the development of high strength low alloy (HSLA) steels.

Grain size has a marked influence on the impact transition temperature. An increase in grain size raises the impact transition temperature, and thus makes the steel more prone to failure by brittle fracture. The effect of grain size on the impact transition temperature is more pronounced in the case of low carbon steels.

It is not possible to derive a mathematical relationship between creep strength and grain size since change in grain size for creep study, i.e. high temperature strength, is always accompanied by other changes. However, in general, a coarse grained steel has better creep strength above the equicohesive temperature. Below this temperature, fine grained steels exhibit superior creep strength. It has been observed that cast steels have improved creep strength over forged steels. The basic coarse grain size of cast steel is believed to be responsible for this. Similar reasoning is given for better creep strength of silicon deoxidized steels as compared to aluminium deoxidized steels.

Fatigue strength, similar to creep strength, does not exhibit any basic relationship with grain size. However, fine grained steels have higher fatigue strength as compared to coarse grained steels. This is true provided the temperature of the test piece is not so high that creep is a predominant phenomenon.

Coarse grained steel has better hardenability than fine grained steel. The reason for this is that coarse grained steel has fewer grain boundaries. Grain boundaries are the region where the rate of diffusion is high. Consequently, formation of pearlite, which is a diffusion controlled process, starts at grain boundaries. With smaller grain boundary area in coarse grained steels, preferential formation of martensite from austenite takes place on cooling. It will further be relevant to note that pearlite formation (see Section 4.7) proceeds by nucleation and growth mechanism. Austenitic grain boundaries act as nucleation sites for pearlite formation.

Coarse grained steels have better machinability than fine grained steels. Coarse grained steel has reduced toughness, which is understood to be the source of providing small discontinuous chips during machining.

4.5 DECOMPOSITION OF AUSTENITE

Austenite is a solid solution of carbon in gamma (FCC) iron. In the case of alloy steels, austenite may also have other elements dissolved in it in addition to carbon. As mentioned in Section 4.1, single-phase austenite is stable above the A_3, A_1 and A_{cm} temperatures for hypoeutectoid, eutectoid and hypereutectoid steels, respectively. Below the A_1 temperature, the mixture of ferrite and cementite is thermodynamically stable. On cooling a eutectoid steel below eutectoid temperature, austenite will decompose to an aggregate of ferrite and cementite. The transformation of austenite on cooling is a complex process in' the sense that compositional as well as configurational changes are involved. Carbon present in the austenite adjusts itself in such a way that at one end it leaves behind an almost carbon-free phase (ferrite) and on the other it combines with iron to form cementite. Similarly, large scale redistribution of alloying elements takes place when the solubility of the element is restricted in alpha iron, and/or there is a strong tendency for the element to form carbide(s). Also, the crystal structure of gamma iron will change to that of alpha iron. The process of austenitic decomposition becomes more and more complicated for hypoeutectoid and hypereutectoid steel as proeutectoid ferrite and proeutectoid cementite separate out in these two types of steel, respectively, before eutectoid decomposition of austenite. The process of decomposition of austenite to a ferrite-cementite aggregate is essentially a diffusion controlled process and proceeds by nucleation and growth mechanism. Therefore, any factor, which is able to vary either the rate of nucleation/the rate of growth or both, is also able to change the nature of ferrite-cementite mixture. Some of these factors are: nature of austenite under consideration, the temperature of transformation and the presence of alloying elements. The more the homogeneity of austenite, the better is the probability of getting a lamellar structure. A heterogeneous austenite may result in the transformation of austenite to spheroidized structure. With lowering of the transformation temperature, a harder and finer aggregate of ferrite and cementite results. Diffusion is a time and temperature controlled process. The rate of diffusion decreases with decreasing transformation temperature. At considerably low transformation temperature, the rate of diffusion decreases to such a level that austenite transforms by a diffusionless process. Cooling rate after the completion of austenitic transformation is of no metallurgical significance. Rapid cooling after completion of transformation will simply decrease the overall time.

It can be concluded on the basis of the foregoing discussion that supercooled austenite transforms either to a mixture of ferrite and cementite or to a product formed by diffusionless process. This product is known as martensite. Martensite possesses the same chemical composition as that of parent austenite but has a different crystal structure. This structure is body centred tetragonal (BCT) in contrast to face centred cubic (FCC) crystal structure of austenite. Martensite is a hard and brittle phase with entirely different properties than the other constituents commonly found in steels. It has been discussed in detail in Section 4.9. Ferrite-cementite mixture produced by the decomposition of austenite by diffusion process can be divided into two broad classes: pearlite and bainite. Pearlite is formed by the nucleation of cementite and ferrite plates and therefore the resultant structure is lamellar in nature which can be easily seen with the help of an optical microscope. The alternate plates of ferrite and cementite can be resolved at levels of magnification obtainable in optical microscopes. The mechanism of formation of bainite differs from that of pearlite and the structure is accicular, and not lamellar, in nature. Bainite is generally formed within an intermediate temperature range. The upper limit of range coincides with the minimum temperature of pearlite formation and the lower limit approaches the temperature at which formation of martensite starts. In majority of steels, the temperature range of formation of bainite overlaps the corresponding ranges for other products. Only in a few alloy steels, a clear-cut delineation between pearlitic, bainitic and martensitic temperature ranges exists. An important feature that distinguishes pearlitic and bainitic transformation is that the former involves diffusion of both iron and carbon atoms during transformation whereas the latter involves only diffusion of carbon atoms. Austenite to pearlite and bainite transformations have been dealt with in detail in Sections 4.7 and 4.8, respectively.

4.6 TIME-TEMPERATURE TRANSFORMATION CURVES

The temperature of transformation controls the nature of decomposed product (of austenite) which in turn decides the resultant properties of steel. Therefore, the study of transformation temperature effect on the nature of decomposed product is of much importance. The kinetics of austenitic transformation can be studied best at a constant temperature rather than by continuous cooling. The constant temperature transformation is also referred to as isothermal transformation which is studied by the following experiment. A number of small samples are taken from the steel under consideration. These samples are heated to predetermined austenitizing temperature and are held at this temperature for a sufficiently long period so as to obtain a homogeneous austenite. These austenitized samples are transferred quickly to another bath maintained at a constant temperature below eutectoid temperature, selected for the study of kinetics of transformation. These samples are taken out one by one from the subcritical temperature bath after different time intervals and are quenched immediately. The quenching of samples results in the formation of martensite from the untransformed austenite. By this technique, the amount of transformed austenite can be determined as a function of time at constant temperature. The amount of transformed austenite will increase by allowing samples to remain in constant temperature bath for longer time. After a particular time, all the austenite will transform to an aggregate to ferrite and cementite at a given temperature. Figure 4.10 shows the effect of time on the amount of transformed austenite for a given transformation temperature T. It is clear from the figure that the transformation of austenite does not start immediately on quenching austenitized sample to a constant temperature bath. Transformation of austenite to ferrite-cementite mixture occurs after a definite time (equals to t_1 of Figure 4.10). This time during which transformation does not proceed is known as incubation period. The magnitude of incubation period provides a qualitative idea about the relative stability of supercooled austenite. Smaller incubation period corresponds to lesser stability of austenite.

Figure 4.10 has one important limitation, i.e. it only correlates the amount of transformed austenite with transformation time for a constant temperature. Both time and temperature of austenitic transformation have significant impact on the nature and morphology of transformed product. Thus, a diagram which can include all the three parameters, i.e. time, temperature and transformation, will be of great importance, specially to the heat treaters. Such a diagram is known as time temperature transformation (TTT) diagram. This diagram is also popularly known as isothermal transformation (IT) diagram or the C-curve. In fact, the TTT curve is an extension of isothermal transformation of austenite diagram (see Figure 4.10).

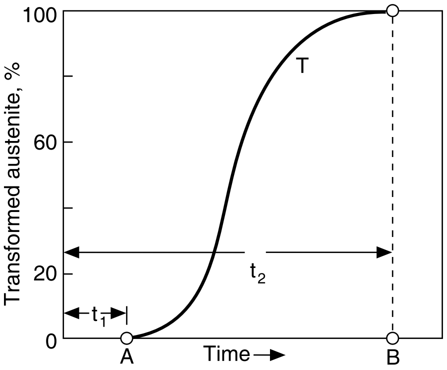


Figure 4.10 Isothermal transformation of austenite to pearlite.

For the construction of the TTT curve for a steel, a large number of small samples of the steel (say, eutectoid steel) are procured. These samples are treated in a way similar to that already mentioned for the study of isothermal transformation of austenite. The only difference now is that the same process is repeated a number of times at varying transformation temperatures instead of a single temperature. The results are shown in Figure 4.11. The amount of transformed austenite at various time periods for different transformation temperatures can be known in this way. The temperature T_1 is greater than T_2, T_3, T_4, T_5,..., and is near to the eutectoid temperature. It can be analyzed from Figure 4.11 that the higher the transformation temperature, the more is the incubation period and time required for completion of the transformation. Incubation period and transformation time decrease with the lowering of transformation temperature. However, after a particular temperature (corresponding to T_4 of Figure 4.11), the decreasing trend is reversed and both incubation period and transformation time increase again with further lowering of transformation temperature. The minimum that is observed in the incubation period can be explained as follows. With decrease in the isothermal transformation temperature, the austenite becomes more unstable. The driving force for the austenite to pearlite transformation increases. Accordingly, the rate of nucleation increases. However, with decrease in transformation temperature, the rate of diffusion, which is an exponential function of temperature, decreases.

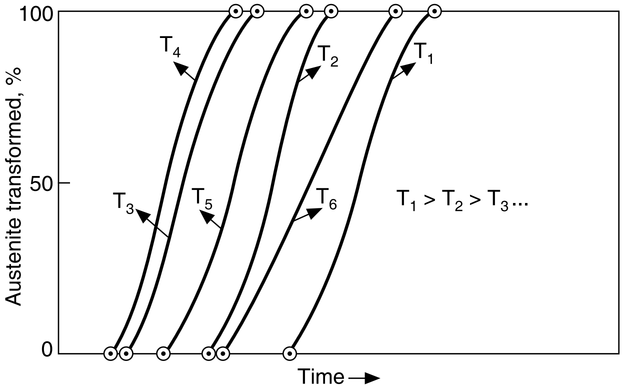


Figure 4.11 Isothermal transformation of austenite to pearlite at different temperatures.

Transformation rate depends on the overall effect of the rate of nucleation and rate of diffusion. The temperature at which the incubation time is minimum (T_4 in the above case)' is the one below which the increase in nucleation rate by decrease in temperature is more than offset by decrease in the diffusion rate as a result of decrease in temperature. Consequently, any further decrease in temperature increases the incubation time. These aspects will be considered in detail in Section 4.7.2.

As already stated, below a particular transformation temperature, the rate of diffusion becomes practically insignificant and if transformation temperature is lowered below this limit, a diffusionless product, namely, martensite, will be formed. Formation of martensite takes place instantaneously at a particular transformation temperature.

From the result of Figure 4.11, another diagram (i.e. Figure 4.12) can be constructed with time and temperature as abscissa and ordinate, respectively. Figure 4.13 shows the TTT diagram for a eutectoid steel.

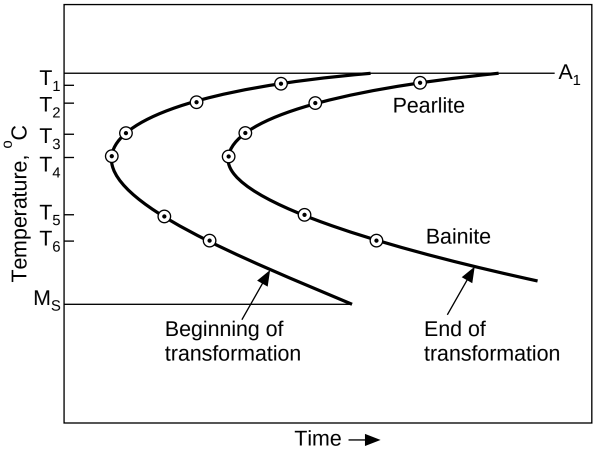


Figure 4.12 TTT diagram for transformation of austenite for steel.

Figures 4.14 and 4.15 represent the TTT diagrams for hypoeutectoid and hypereutectoid steels, respectively. A common feature of these TTT diagrams is that proeutectoid phase (ferrite for hypoeutectoid and cementite for hypereutectoid steels) separates out in upper temperature region. For hypoeutectoid steels, ferrite starts separating out from the austenite as soon as austenite is cooled below the upper critical temperature (A_3). The amount of proeutectoid ferrite decreases as austenite is undercooled more and more below the upper critical temperature. After a certain degree of undercooling, austenite will transform directly to pearlite. On further cooling, there will be no surplus ferrite.

Similarly, cementite is separated out in hypereutectoid steels from austenite on cooling below the upper critical temperature (A_{cm}). The amount of cementite decreases with increased degree of supercooling and finally reduces to zero when austenite is cooled below a particular temperature.

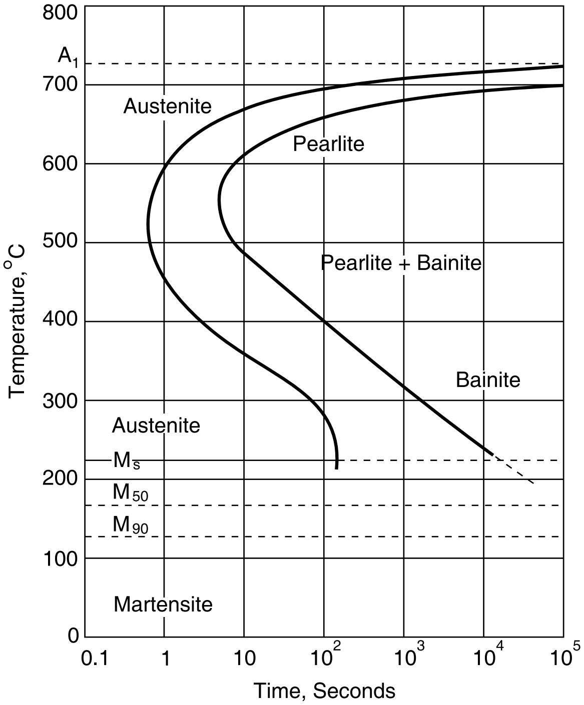


Figure 4.13 TTT diagram for eutectoid steel.

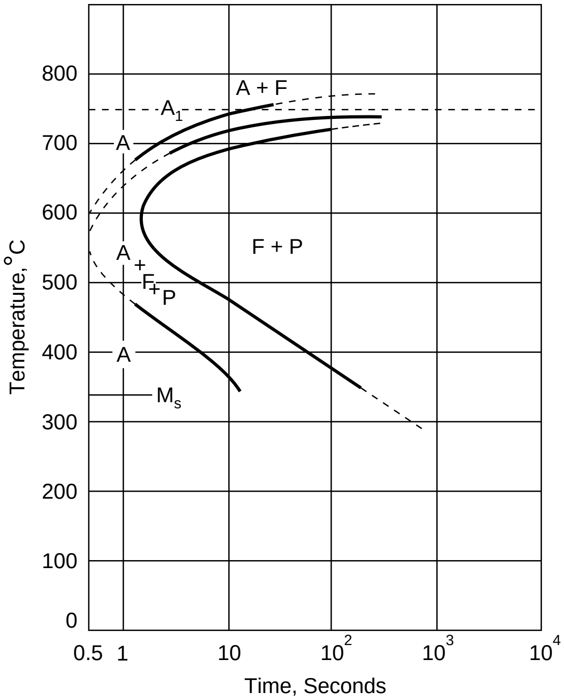


Figure 4.14 TTT diagram for hypoeutectoid steel.

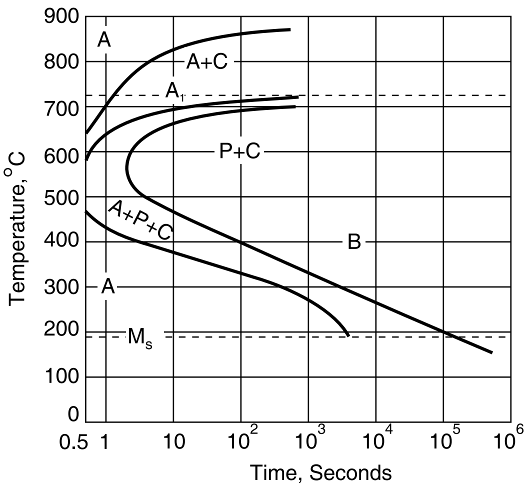


Figure 4.15 TTT diagram for hypereutectoid steel.

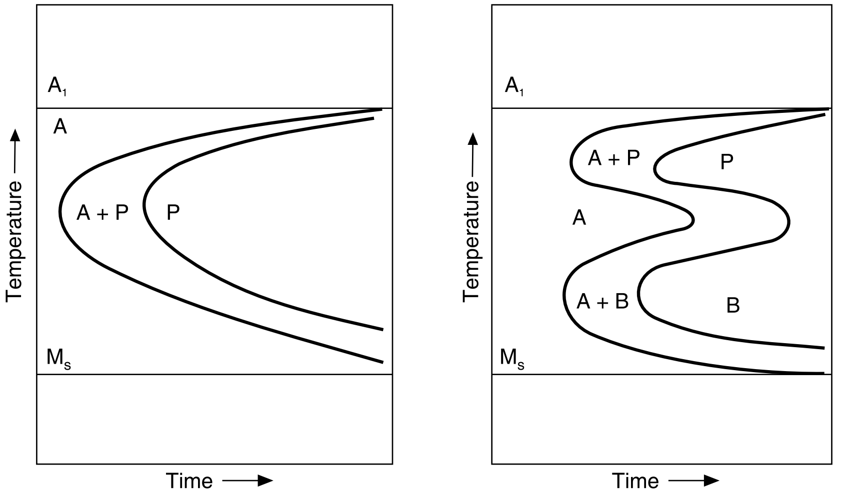
4.6.1 Effect of Alloying Elements on TTT Diagram

Almost all alloying elements, except cobalt, decrease both the tendency for and the rate of decomposition of austenite. The reason for this is obvious for austenite stabilizing elements. Ferrite stabilizers do the same job by forming carbides. Alloy carbides are more stable than cementite, and hence they retard the diffusion of carbon which in turn decrease the rate of decomposition of austenite. Strong carbide formers have more pronounced effect on the retardation of austenite decomposition than the weak carbide formers. Since pearlitic transformation involves diffusion of both carbon and metallic atoms (see Section 4.7), the effect of alloying elements is much more pronounced in pearlitic region. The effect is less pronounced in bainitic region as bainitic transformation (see Section 4.8) involves diffusion of carbon atoms only.

The TTT diagrams for alloy steels can broadly be classified into four types as shown in Figure 4.16. The first type of TTT diagram [Figure 4.16(a)] is similar to that of carbon steel. There is practically no difference in the pattern of austenite decomposition in the presence of non-carbide forming elements. However, in the presence of carbide forming elements, supercooled austenite decomposes to a mixture of ferrite and carbides rather than to an aggregate of ferrite and cementite.

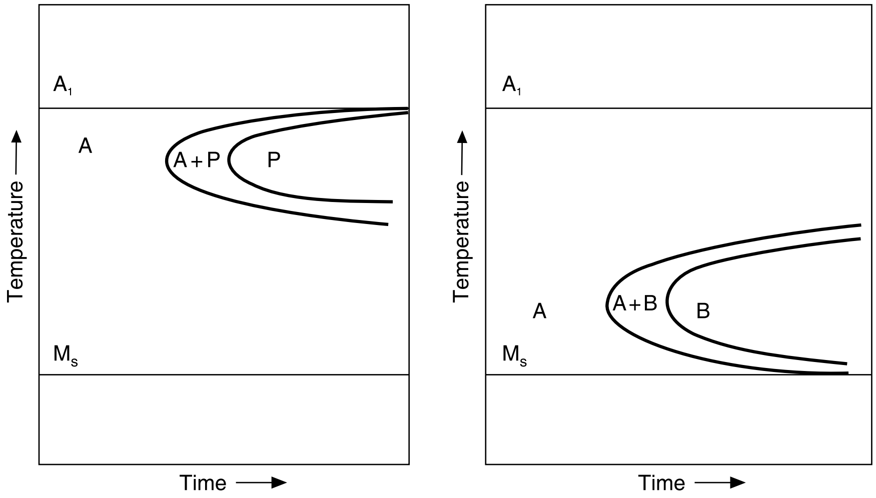
The second type of TTT diagram [Figure 4.16(b)] differs from the remaining TTT diagrams as it consists of two minima with respect to the stability of austenite. The upper bay (at higher temperature) corresponds to the transformation of austenite to pearlite, whereas the lower bay corresponds to the transformation of austenite to bainite. Very few steels exhibit such a TTT diagram. The two types of TTT diagrams discussed above are, in general, observed for low alloy steels.

The third type of TTT diagram [Figure 4.16(c)] is peculiar in the sense that bainitic region is not present. This implies that bainite cannot be formed in such steels. Such a TTT diagram is obtained, in general, for high alloy steels, specially those in which the start of martensitic



(a) with resemblance of plain carbon steel

(b) with both pearlitic and bainitic bays



(c) without bainitic bay

(d) without pearlitic bay

Figure 4.16 Various types of TTT diagrams for alloy steels.

transformation temperature has been shifted to sub-zero region. In such steels, stable austenitic structure is obtained at room temperature.

The fourth type of TTT diagram [Figure 4.16(d)] does not exhibit pearlitic bay. Here, under normal cooling conditions, either bainite or martensite is formed.

4.6.2 Continuous Cooling Transformation

The TTT diagrams have gained great importance from heat treater's point of view. This is due to the simple reason that these diagrams are extremely useful as they give information about the hardening response of steels and the nature of transformed products of austenite at varying degrees of supercooling. These diagrams have been of great practical importance to some special heat treatment processes such as austempering (see Section 5.7) and isothermal annealing (Section 5.2.2).

In practice, however, transformation during heat treatment occurs by continuous cooling, and not isothermally. Thus, TTT diagrams have limited applications. For most of the heat treatment processes, these diagrams are useful only qualitatively, and not quantitatively. A diagram, which can correlate transformation, temperature and time during continuous cooling, will be of real value to heat treaters.

Continuous cooling transformation (CCT) diagrams can be obtained by a technique which is similar to that for TTT diagrams except that, in the case of CCT diagrams, points of start and end of austenitic transformation are recorded on continuous cooling. For the construction of CCT diagram for a eutectoid steel, a large number of small samples are heated above the lower critical temperature (A_1) to get a completely austenitic structure. From this temperature, specimens are cooled at a constant cooling rate, and points corresponding to start and finish of pearlite are determined. By repeating the same process at various cooling rates, different sets of start and end points for pearlitic transformation are obtained. On joining start and end points, two curves, similar to those in TTT curves, corresponding to start and end of transformation, are obtained. Thus, a CCT diagram is obtained. The CCT diagram for eutectoid steel is shown in Figure 4.17.

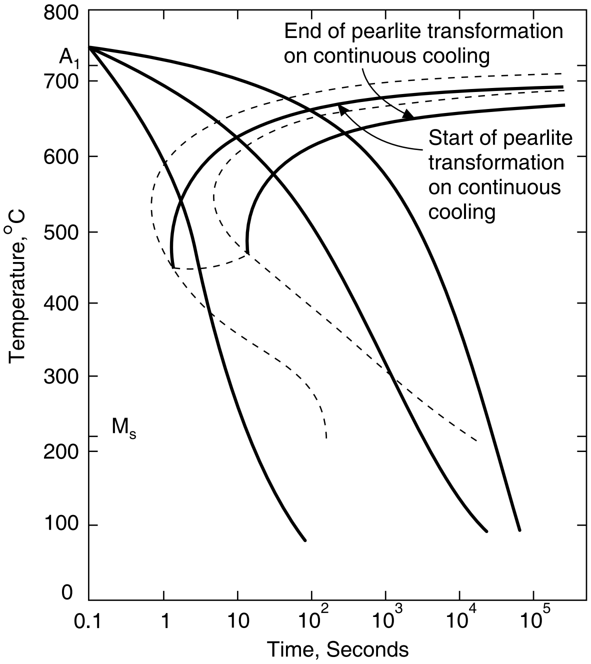


Figure 4.17 CCT diagram for eutectoid steel.

4.7 PEARLITIC TRANSFORMATION

Pearlite is an eutectoid mixture of two phases, namely, ferrite and cementite. The microstructure of pearlite is shown in Figure 4.2. It consists of alternate layers of ferrite and cementite. It is an important constituent of steel and is present in almost all the steels which have been slowly cooled. The mechanical properties of annealed or normalized hypoeutectoid steels mainly depend on this constituent. Pearlite is formed by cooling austenite of eutectoid composition just below the lower critical temperature. The pearlite, thus formed, consists of about 88 percent ferrite and 12 percent cementite. It is important to point out at this stage that in spite of the lamellar structure, ferrite is a continuous phase.

One of the most interesting features of austenite to pearlite transformation is that the transformation product (pearlite) consists of two entirely different phases. One phase, i.e. ferrite, has very low carbon content and for all practical purposes, it can be considered almost pure iron, whereas the second phase, i.e. cementite (Fe_3C), is an intermetallic compound of iron with 6.67 wt.% carbon. Such a transformation is possible only by the redistribution of carbon atoms of austenite on cooling. The redistribution takes place by diffusion of carbon atoms. Thus, the pearlitic transformation is essentially a diffusion controlled phenomenon and proceeds by nucleation and growth mechanism.

Another aspect to be considered in this context is: Which one of the two phases (ferrite and cementite) nucleates first? The nucleus which is formed first is referred to as active nucleus for pearlitic transformation, provided it is present in the transformed product and has lattice orientation relationship with parent austenite. It has not been possible till date to specify with certainty as to which one of the two phases nucleates first. Also, there is no theory which can explain all the characteristics associated with pearlitic transformation such as lamellar nature, temperature dependence of interlamellar spacing and of kinetics of transformation and, finally, the effect of alloying elements on interlamellar spacing and on kinetics of transformation. However, it is a well established fact that active nuclei for austenite to bainite transformation are ferrite crystals. Active nuclei for pearlitic transformation are generally taken to be cementite platelets. This assumption can offer an explanation for the lamellar nature of pearlite. An orientation relationship between cementite and austenite has also been found, which confirms that cementite platelets are active nuclei for pearlitic transformation.

4.7.1 Mechanism of Transformation

The most widely accepted mechanism of pearlite formation is due to Mehl and his coworkers. According to them, the active nucleus for austenite to pearlite transformation is cementite. Some of the reasons in favour of their proposal are based on the following observations:

(i) Orientation relation between pearlitic ferrite and parent austenite is different from that of proeutectoid ferrite and parent austenite. Therefore, ferrite cannot be active nucleus. This is in contrast to bainitic transformation where ferrite has an orientation relation with parent austenite.

(ii) Formation of pearlite is affected by the presence of undissolved cementite particles whereas the presence of ferrite does not exhibit any such effect,

(iii) Proeutectoid cementite as well as pearlitic cementite platelets are, in general, parallel to a high index (or low atomic density) plane of austenite.

Many doubts have been raised about Mehl's hypothesis. The assertion that cementite is an active nucleus for the transformation was challenged. According to Smith's generalized hypothesis, "pearlitic ferrite as well as pearlitic cementite can have any orientation relationships with the parent austenite except for those which allow the formation of interfaces which are partially coherent with the parent austenite". Both cementite and ferrite can be active nucleus and, consequently, formation of pearlite can be initiated by either of the two. In general, ferrite will form first in hypoeutectoid steels and will then nucleate pearlite, whereas cementite will form first in hypereutectoid steels and then nucleate pearlite.

The most popular model for the formation of pearlite has been proposed by F.C. Hull and R.F. Mehl. This model explains the lamellar nature of pearlite. Figure 4.18 shows the mode of formation of pearlite colony from austenite. According to the Hull-Mehl model, the cementite platelet is nucleated first at the austenitic grain boundaries. The diffusion of carbon atoms from the austenite surrounding the cementite platelet takes place, and thus the cementite platelet grows. The carbon diffusion results in lowering of carbon in austenite and, Consequently, austenite transforms to ferrite. The transformation of austenite to ferrite takes place only when the carbon content of austenite reaches some minimum critical value. Thus, ferrite nucleates at the interface of cementite and adjacent austenite and grows along the surface of the cementite plate. Since ferrite is almost carbon-free phase, the growth of ferrite is accompanied by the rejection of carbon. In this process of ferrite growth, the austenite adjacent to ferrite is enriched with carbon. The enrichment of austenite continues till a new platelet of cementite nucleates. Growth of this cementite platelet lowers the carbon content of the adjacent austenite and again ferrite is nucleated. Such a sequence of formation of cementite and ferrite continues, resulting in a lamellar structure.

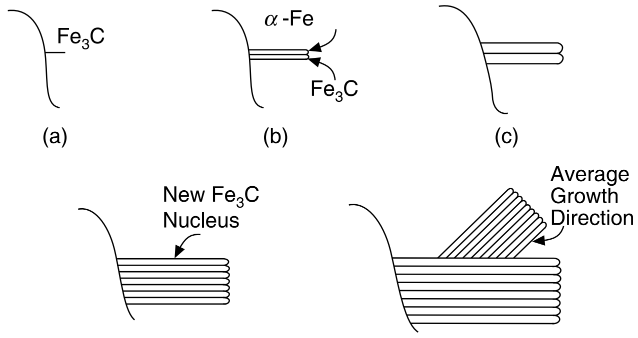


Figure 4.18 Successive stages in formation of pearlite from austenite.

New colonies of pearlite are also formed at the interfaces between the already formed colonies and the adjacent parent austenite. These colonies also grow in the same manner as already discussed. In this way, a pearlite colony grows by simultaneous edge-wise and side-wise growth by repeated nucleation. This process of nucleation of new colonies and growth of existing ones continues till the complete austenitic grain is consumed and converted into a pearlite nodule which is generally spherical in shape as pearlitic colonies are formed with almost equal growth rates along and perpendicular to the lamellae directions. During growth, a pearlitic colony may meet an adjacent pearlitic colony (colonies), and a common boundary results. Prior to formation of such a boundary, the growth rate for pearlitic colonies is constant and so the colonies are almost of the same size. Some parent austenite remains in between pearlite nodules which may grow by consuming such an austenite. With this final stage of pearlite growth, austenite to pearlite transformation is completed.

4.7.2 Kinetics of Transformation

At a lower critical temperature, the free energy of austenite is equal to the free energy of pearlite. Therefore, at this temperature, transformation of pearlite from austenite will be completed in infinite time. In other words, the austenite to pearlite transformation rate will be zero for all practical purposes at this temperature. It is therefore essential to undercool the austenite below the equilibrium (A_1) temperature. Below the lower critical temperature, the free energy of pearlite is lower than that of austenite and so the pearlite is thermodynamically stable. The lower the free energy of pearlite, the more is the stability of the pearlite. Free energy of pearlite will be less at lower temperatures, and hence the stability of pearlite can be increased by increasing the degree of supercooling or, in other words, by lowering the transformation temperature. This means that the rate of austenite to pearlite transformation increases with lowering of transformation temperature.

The decomposition of austenite to pearlite proceeds by the redistribution of carbon atoms of austenite into ferrite and cementite, and is essentially a diffusion controlled process. The rate of diffusion of carbon atoms decreases exponentially with decreasing temperature. This implies that lower transformation temperature retards the rate of transformation. There may be a transformation temperature for which the diffusion rate for carbon atoms may be too small to result in the diffusion controlled transformation. In general, for all practical purposes, the rate of carbon diffusion is negligible below 200°C. This means that undercooling affects the rate of transformation in two ways: On the one hand, increased degree of undercooling increases the transformation rate by providing a greater difference in free energies of austenite and pearlite (curve b of Figure 4.19). On the other hand, increased degree of undercooling reduces the transformation rate by lowering the rate of carbon diffusion (curve a of Figure 4.19). The combined effect is shown as curve c in Figure 4.19.

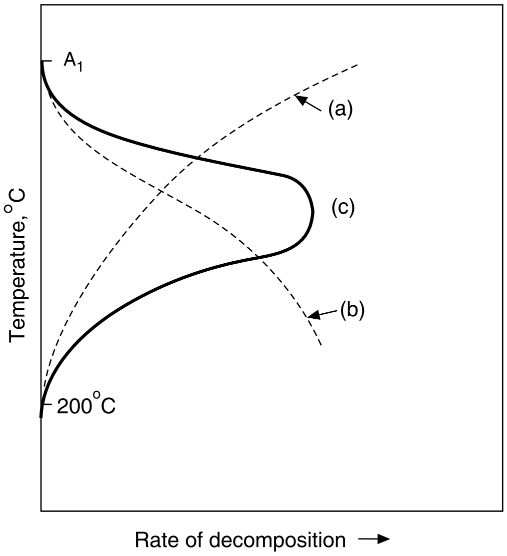


Figure 4.19 Effect of temperature on rate of transformation of austenite.

The austenite to pearlite transformation is completed by nucleation and growth mechanism. The rate of transformation is governed by both the rate of nucleation (*N*) and the rate of growth (*G*), which are in turn controlled by transformation temperature. The rate of nucleation is expressed as total numbers of nuclei appearing per unit time in a unit volume of untransformed austenite. Both the rate of nucleation and the rate of growth are zero at eutectoid temperature. They also tend to be zero below 200°C, as shown in Figure 4.20.

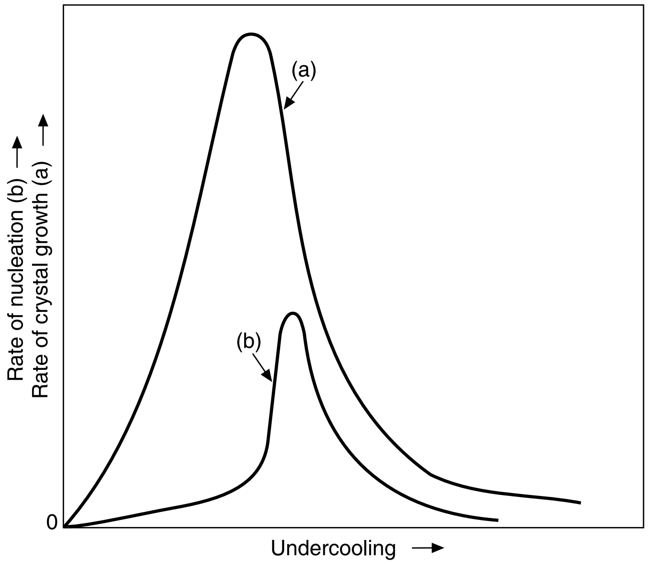


Figure 4.20 Effect of degree of undercooling on the rates of nucleation and growth.

4.7.3 Effect of Alloying Elements on Transformation

Transformation of austenite to pearlite in alloy steels is more complicated than in carbon steels. Almost all alloying elements, whether ferrite stabilizers or austenite stabilizers, except cobalt, lower both the rate of nucleation and the rate of growth. As compared to carbon, alloying elements diffuse very slowly.

Carbon and alloying elements partition to ferrite and carbide phases on decomposition of austenite. The partitioning approaches equilibrium value at higher transformation temperatures, say, in the vicinity of eutectoid temperature. As transformation temperature decreases, the amount of carbon and alloying elements present in ferrite and carbide phases deviate from equilibrium partitioning. Stable carbides, in general, possess higher metal to carbon ratio. As the diffusion rate for metallic atom is much slower than carbon atom, the formation of stable carbides during pearlitic transformation will be feasible only at higher transformation temperatures.

4.7.4 Interlamellar Spacing

Interlamellar spacing of pearlite is of great significance as it affects the mechanical properties of steel. Interlamellar spacing is a function of transformation temperature alone, provided all other parameters are kept constant. This implies that interlamellar spacing can be assigned a definite value for a given transformation temperature. The lower the transformation temperature, the smaller is the interlamellar spacing. The smaller the interlamellar spacing, the stronger is the steel. Interlamellar spacing is less for both hypoeutectoid and hypereutectoid steels than for eutectoid steel. Alloying elements, except cobalt, increase the interlamellar spacing. The simple reason for this is that alloy steels transform at higher temperatures. This, in turn, increases interlamellar spacing.

One of the interesting features of interlamellar spacing is that it is structure-insensitive in nature, i.e. it does not depend on austenitic grain size and the degree of homogeneity of the austenite.

4.8 BAINITIC TRANSFORMATION

The term *bainite* refers to a mixture of ferrite and carbide. This ferrite-carbide mixture has a basic difference with respect to pearlite. It is not lamellar in nature. Also, the distribution of carbides is on finer scale. Hence, higher magnifications than those required for resolution of pearlite are required in order to resolve the bainite which is formed within a specific temperature range. The upper limit of the range is just below the minimum temperature for pearlitic transformation which, in general, is below the nose of the TTT curve for a given steel. The lower limit of the temperature range is above the M_s temperature, i.e. above the temperature at which martensite formation starts. For a eutectoid steel, bainite forms from the undercooled austenite in the temperature range of 200–500°C. Transformation of austenite to bainite occurs only below a definite temperature, known as B_s temperature. Only a few alloy steels exhibit the presence of sharp B_s, temperature. For such steels, two separate bays, one each for pearlite and bainite, exist. Austenite can be transformed into bainite either isothermally or by continuous cooling in such a case. Figure 4.21 shows the TTT curve for an alloy steel having separate pearlitic and bainitic bays. However, for carbon steels and most of the alloy steels, pearlitic and bainitic bays overlap, and austenite transforms to pearlite or martensite, depending on the cooling rate. In such steels, bainite cannot be produced by continuous cooling. It can be formed by cooling austenite at a sufficiently high rate so that its transformation to pearlite is suppressed. The austenite is then held in the bainitic range (see Section 5.7). Austenite to bainite transformation completes at a definite temperature designated as B_f, the end temperature of bainitic transformation. Figure 4.21 illustrates the isothermal transformation to bainite.

4.8.1 Mechanism of Bainitic Transformation

The presence of incubation period for bainitic transformation implies that the transformation is diffusion controlled. However, formation of bainite starts at a temperature at which the diffusion of iron atoms is very slow (almost zero for all practical purposes), but the diffusion of carbon atoms is very important. No significant diffusion of metallic atoms (alloying elements) is possible at this temperature. This means that, in addition to diffusion, some other mechanism is also involved in bainitic transformation. It has been observed that the formation of bainite is always accompanied by surface distortion. This implies that shear processes are also involved in bainitic transformation. Thus, the bainitic transformation is complex by nature as both diffusion controlled and diffusionless (shear) processes are involved. It exhibits features common to both types of transformations. When austenite is undercooled below the B_s temperature, carbon atoms redistribute in the austenite by diffusion. This redistribution leads to the formation of regions with varying carbon concentrations in austenite. Some of these

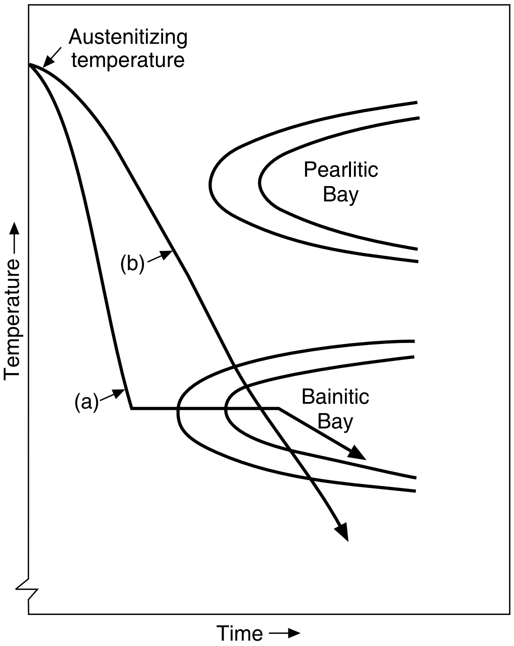


Figure 4.21 Formation of bainite by isothermal transformation of austenite.

regions are enriched in carbon whereas others are depleted in carbon. Such a difference in carbon concentration will result in the development of stresses. The M_s (the start of martensitic transformation) temperature for austenitic regions with low carbon content lies in between the B_s and B_f temperatures. Here, low carbon austenitic regions transform to martensite (ferrite) by diffusionless (shear) process. It is important to note here that low carbon austenite, which transforms to ferrite by shear process, is itself produced by diffusion process. A portion of the carbon enriched austenitic regions does not transform on cooling from holding temperature to room temperature. Such a portion may transform partially to martensite. Thus, a characteristic feature of bainitic transformation is that it is never completed. A structure consisting of bainite and martensite or bainite and retained austenite is obtained. Precipitation of carbides may occur from the carbon enriched austenitic regions, depending on the degree of saturation. The carbon depleted austenitic regions thus obtained by the precipitation of carbides now transform to ferrite by shear mechanism. Such a condition is favourable in the upper region of the intermediate transformation temperature range. As ferrite has very low solubility for carbon, the transformed ferrite will be supersaturated with carbon. The degree of supersaturation increases with decrease in transformation temperature. As carbon diffusion is intensive in the bainitic transformation region, carbon may precipitate out from the supersaturated ferrite. This happens when the bainitic transformation proceeds in the lower region of the transformation range. Thus, in spite of the fact that mechanism of transformation for bainite is same over the entire temperature (B_s–B_f) range, various bainitic structures can be obtained within the bainitic temperature range, depending on the transformation temperature.

4.8.2 Bainitic Structures

The two typical structures of bainite are referred to as upper and lower bainites. The upper bainite is feathery, whereas the lower bainite is accicular in appearance. Figures 4.22 and 4.23 show the microstructures of upper and lower bainite, respectively. The names upper and lower bainites signify that the former is formed in the upper region and the latter in the lower region of the bainitic transformation temperature range. The microstructure of upper bainite consists of lath-shaped ferrite with precipitated carbides parallel to the needle axis. This structure differs considerably from that of lower bainite which consists of ferrite plates within which carbides have been precipitated at an angle to the major axis of the plate. The sequence of formation of upper and lower bainites is shown in Figures 4.24 and 4.25, respectively.

Figure 4.22 Microstructure of upper bainite (×500).

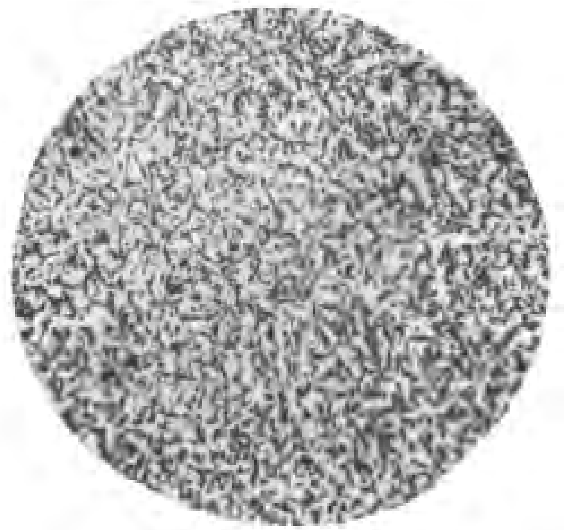


Figure 4.23 Microstructure of lower bainite (×500).

Both upper and lower bainites are nucleated by ferrite, i.e. ferrite is an active nucleus for both. This ferrite is formed by the transformation of low carbon austenitic regions to ferrite as discussed in Section 4.8.1. This ferrite is coherent with the parent austenite. The ferrite thus nucleated grows into bainitic plate on cooling to and holding at a temperature in the bainitic region. The bainite plate so formed is surrounded by austenite which is enriched in carbon. The diffusion of carbon is significant in bainitic transformation temperature range, and specially in the upper region of the range. Carbon diffusion takes place in the carbon enriched austenite

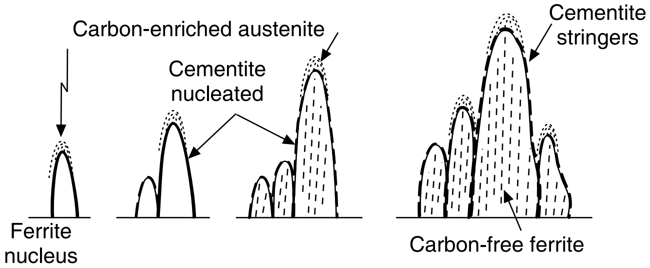


Figure 4.24 Stages in formation of upper bainite.

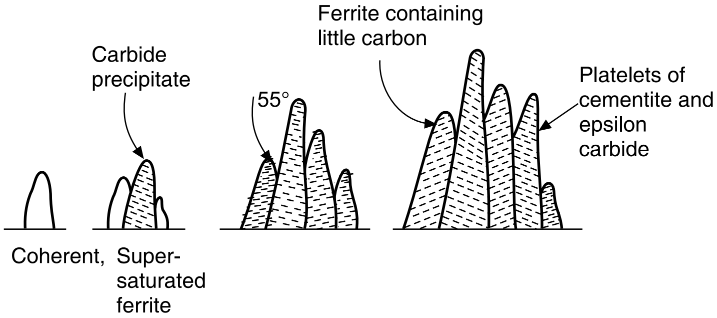


Figure 4.25 Stages in formation of lower bainite.

surrounding the bainitic plate, giving rise to the formation of cementite (carbide) at the austenite-bainite interface. The formation of cementite results in the depletion of carbon from the austenite. Low carbon austenitic region thus obtained transforms to ferrite by the shear mechanism. In this way, the growth of the existing bainitic plates and nucleation of new bainitic plates proceed simultaneously. Therefore, the diffusion of carbon in carbon enriched austenite surrounding the bainitic plate is the most important (controlling) step in the formation of upper bainite. The transformation temperature has an important effect on the morphology of upper bainite. This change in the morphology of upper bainite is due to the sympathetic nucleation of ferrite laths. These laths are in intimate contact with each other. The formation of upper bainite is accompanied by multiple surface relief. It confirms that the upper bainite is formed by sympathetic nucleation. A number of lattice orientation relationships have been found between ferrite and precipitated cementite in the upper bainite. Majority of these relationships match with those existing in the tempered martensite.

The lower bainite differs from the upper bainite with respect to the transformation temperature. The lower bainite is formed at the transformation temperature which lies within the lower region of the bainitic transformation temperature range. In contrast to the upper bainite, the diffusion of carbon in supersaturated ferrite (formed from low carbon austenite by shear mechanism) is the controlling step in the formation of lower bainite. Carbides are precipitated from supersaturated ferrite in the case of lower bainite. The nature of the precipitated carbide, in addition to being dependent on chemical composition of steel, is also a function of transformation temperature and transformation time. A lattice orientation relationship has also been observed between the bainitic ferrite and cementite in the lower bainite. This means that bainitic cementite has been precipitated out from the ferrite, and not from the austenite. The same fact has been confirmed by the presence of epsilon carbide in some alloy steels. Epsilon carbide cannot be precipitated from austenite. This is the reason why in lower bainite, carbides are formed at a definite angle to the major axis (generally growth direction) of the bainitic plate.

4.9 MARTENSITIC TRANSFORMATION

The transformation temperatures for the austenite to pearlite and to bainite are such that diffusion of carbon is quite intense. The diffusion rate of carbon decreases with the lowering of temperature, and at about 200°C, the diffusion rate of carbon becomes negligible. Austenite, when undercooled below this temperature (200°C), transforms to a product known as martensite. This transformation differs from that of pearlitic and bainitic transformations as no diffusion is involved. During transformation, gamma iron changes to alpha iron. As no diffusion of carbon and other metallic atoms can take place at such a low transformation temperature, the chemical composition of alpha iron will be the same as that of gamma iron. As solubility of carbon is more in gamma iron than in alpha iron, the alpha iron thus formed becomes supersaturated. Accordingly, martensite is defined as a supersaturated interstitial solid solution of carbon in alpha iron. Carbon atoms are present at the octahedral interstices. Martensite does not have simple body centred cubic crystal structure, it has body centred tetragonal structure. The tetragonality of martensite is essentially due to the presence of carbon. Figure 4.26 shows the relationship between carbon content of martensite and tetragonality (c/a ratio) of the martensite.

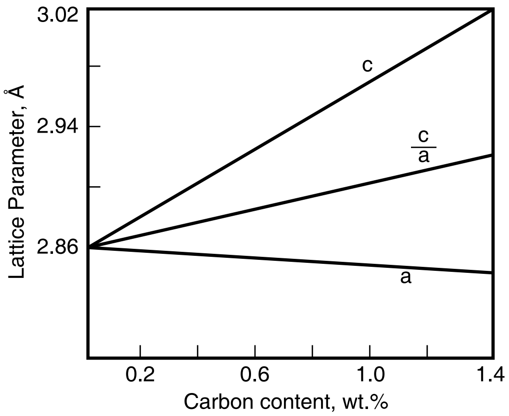


Figure 4.26 Effect of carbon contents on tetragonality of martensite.

4.9.1 Mechanism of Transformation

Martensite is formed by quenching austenite. On quenching, the rate of diffusion is lowered to such an extent that no phase transformation dependent on diffusion can take place. Hence, basically, martensitic transformation is a diffusionless transformation. It is a displaceable transformation that takes place by cooperative movement of a large number of neighbouring atoms. Each atom moves over a distance which is less than one interatomic distance. In this process, the atoms maintain their neighbourhood undisturbed. A large driving force is required for the reaction to take place. The driving force is provided by free energy change accompanying the transformation. The magnitude of the driving force increases with decrease in the temperature of transformation. This is achieved by quenching operation. Although the displacement of individual atoms is less than one interatomic distance, the total displacement increases as one moves away from the interphase boundary. Such build-up of displacements finally results in macroscopic slip. The slip can be observed as relief structure on the surface of martensite.

4.9.2 Kinetics of Transformation

The transformation of undercooled austenite to martensite starts at a definite temperature, M_s, and proceeds over a range of temperatures. The amount of martensite depends on the transformation temperature, as shown in Figure 4.27. More austenite is transformed into martensite by lowering the transformation temperature. The increased amount of martensite is due to the formation of new platelets of martensite, and not due to the growth of existing platelets of martensite. More and more austenite transforms to martensite on lowering the temperature, below M_s temperature until a temperature is reached at which transformation comes to an end. It is difficult to say that all the austenite has transformed to martensite at this temperature. Some amount of austenite remains untransformed. This temperature, denoted by M_f is referred to as the end temperature for martensitic transformation. Cooling of steel below M_f temperature does not result in any further transformation, and the quantity of martensite, already formed up to M_f temperature, remains unchanged. Though the amount of martensite is dependent on the transformation temperature, the velocity of the transformation is, in general, independent of transformation temperature and is extremely fast. Each platelet of martensite is formed approximately in a fraction of a microsecond, and a fraction of a millisecond is sufficient for the completion of the transformation.

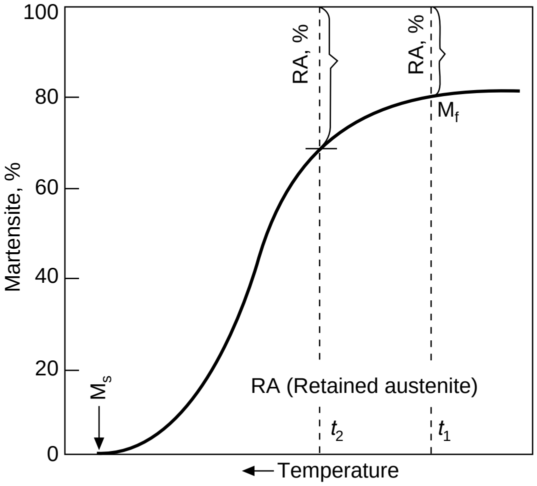


Figure 4.27 Effect of temperature on transformation of austenite to martensite.

The martensitic transformation is independent of holding time. Exceptions to this are a few alloy steels which transform to martensite isothermally. For a given transformation temperature, a portion of undercooled austenite transforms to martensite at a very rapid rate, almost instantaneously. After this transformation, there is, in general, no further transformation at this temperature, irrespective of the length of holding time.

4.9.3 M_s-M_f Temperatures

Martensitic transformation starts at M_s temperature and ends at M_s temperature. The M_s temperature is a definite temperature for a given steel. This temperature depends on the chemical composition of steel. The relationship between M_s temperature and the chemical composition is as shown in the following equation:

$$\begin{aligned} M_s\ (°C) = {} & 561 - 474(\%C) - 33(\%Mn) - 17(\%Ni) \\ & -17(\%Cr) - 21(\%Mo) \end{aligned} \tag{4.1}$$

Almost all alloying elements, except cobalt and aluminium, lower the M_s temperature (see Figure 4.28). It is clear from equation (4.1) that carbon has a most profound effect on M_s temperature. The higher the carbon content of steel, the lower is the M_s temperature. The effect of carbon on M_s temperature is shown in Figure 4.29.

The M_s temperature can neither be raised nor lowered by varying cooling rates. Austenitizing temperature to which the steel is heated prior to the transformation affects the M_s temperature. It affects both the chemical composition of the austenite and the austenitic grain size. The higher the austenitizing temperature, the greater is the probability of dissolution of carbides in the austenite. This increased carbon content decreases the M_s temperature. On the other hand, increase in austenitizing temperature results in a bigger austenitic grain size which in turn raises the M_s temperature. Thus, there are two opposing effects of change in austenitizing temperature on M_s. Depending on the predominance of the effect of one or the other, there is either an increase or a decrease in the M_s temperature due to rise in austenitizing temperature.

The temperature at which martensitic transformation ends, i.e. M_f, in contrast to the M_s temperature, is dependent on the cooling rate and can therefore be varied by changing the

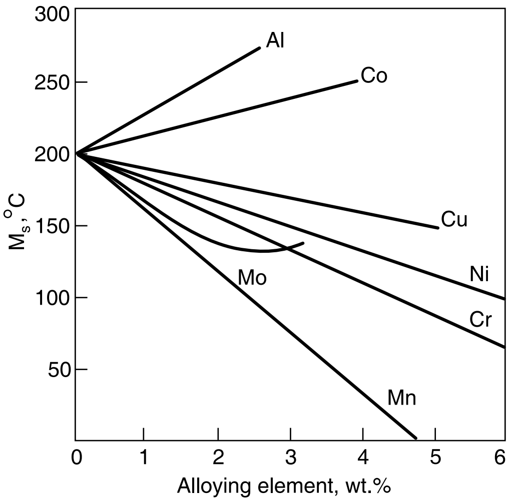


Figure 4.28 Effect of alloying elements on M_s temperature of a steel containing 1% carbon.

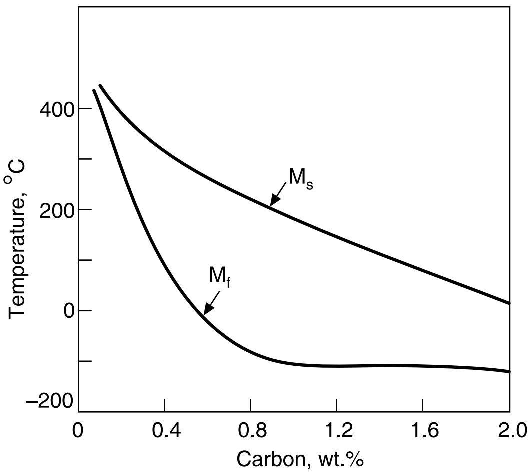


Figure 4.29 Effect of carbon content on M_s and M_f temperatures of steel.

cooling rate. Slower cooling rates result in considerable lowering of M_s temperature. This is the reason why in most TTT diagrams, the M_f temperature is not indicated. It cannot be measured precisely as reaction rates are too slow in its vicinity. Just as in the case of M_s temperature, the M_f temperature is also lowered with increased carbon content of steel, as shown in Figure 4.29.

4.9.4 Effect of Applied Stress on Transformation

The kinetics of martensitic transformation is markedly influenced by the introduction of external or internal stresses. The M_s temperature may be lowered or raised by the application of stresses. If applied stress favours the formation of martensitic plates by lowering the driving force for the reaction, the M_s temperature is raised. If applied stress checks the formation of martensitic plates, it will result in the lowering of M_s temperature. However, in general, application of stress does not result in lowering of M_s temperature. This is so because a number of habit planes (Section 4.9.7) on which formation of martensitic plates can take place, exist. Therefore, the applied stress will favour one or the other martensitic plate.

Plastic deformation of the matrix results in the formation of martensite at a temperature above the M_s temperature. The maximum temperature at which martensite can be formed by plastic deformation is denoted by M_d. The amount of martensite formed by plastic deformation is a function of transformation temperature. For a given plastic deformation, the amount of martensite formed increases as temperature is lowered from M_d to M_s.

4.9.5 Athermal and Isothermal Martensites

One of the distinguishing features of martensitic transformation is that the transformation proceeds on continuous cooling below the M_s temperature. Transformation stops as soon as cooling is interrupted, i.e. steel is held at a constant temperature between the M_s and M_f temperatures. Transformation will now proceed only on further cooling. Martensite thus formed is known as athermal martensite. Athermal transformation occurs in almost all carbon steels.

It is now well established that martensite can also form isothermally. In general, the amount of isothermally transformed martensite has been observed to be low. Extra low carbon-iron base alloys and high alloy steels can be transformed into martensite isothermally. Steels suitable for isothermal transformation, in general, possess low transformation temperatures. At lower transformation temperatures, transformation continues for long periods. However, the amount of martensite decreases with the decrease in transformation temperature and only a part of austenite transforms to martensite. Thus, a considerable amount of austenite is retained. This retained austenite may be transformed into martensite on reaching room temperature.

Depending on the morphology (shape) of martensite phase, two types of martensite, namely, lath martensite and plate martensite are observed in steels. In lath martensite, martensite is present in strip form. The maximum length of the strip is limited to the distance between the grain boundary of the austenitic grain. Thickness of the strip usually lies in between 0.10 and 0.20 μm. Several parallel packets of laths are present within an austenitic grain. Laths are characterized by high dislocation density and low angle grain boundaries between them. Lath martensite is more frequently formed in low and medium carbon steels or low/medium carbon grades of low alloy steels having alloy contents on lower side.

Plate martensite is formed in high carbon steels and high alloy steels. Plate martensite is popularly known as lenticular martensite because of its lens type shape. The length of initially formed martensite plate, similar to lath martensite, extends between grain boundary of the austenite grain. The plates which are formed later extend from grain boundary of the austenite grain and boundary of existing plates.

4.9.6 Reversibility of Transformation

Martensitic transformation is reversible. Martensite can be reverted to austenite on heating above the M_s temperature. The essential condition for the reversibility of martensite is that there should not be any change in chemical composition of martensite during heating. Only a few iron base alloys containing carbon as an impurity fulfil this requirement. Most of the steels do not satisfy this condition. The reason for this is that martensite in steels is supersaturated solid solution of carbon in alpha iron, and it decomposes at a very rapid rate on heating.

4.9.7 Habit Planes

Martensitic transformation is characterized by a well established relationship between the orientation of parent austenite and the transformed martensite. Habit planes are those planes of the parent austenitic lattice on which martensitic plates are formed and which lie parallel to the physical plane of the martensitic plate. A habit plane is not distorted by the martensitic transformation, though along it shear displacement takes place during transformation. The habit planes for low, medium and high carbon steels are (1 1 1), (2 2 5) and (2 5 9), respectively.

4.9.8 Bain Distortion Model

Martensite has body centred tetragonal (BCT) structure with a maximum (c/a) ratio of 1.08. A body centred tetragonal lattice can be obtained from face centred cubic lattice, as shown in Figure 4.30. This body centred tetragonal lattice will have a (c/a) ratio equal to 1.40. The (c/a) ratio is 1.00 for body centred cubic lattice. This means that the body centred tetragonal lattice of martensite is closer to the body centred cubic lattice.

E.C. Bain observed that a body centred cubic lattice can be obtained from face centred cubic structure by a simple mechanical process consisting of compression parallel to the *c*-axis and expansion along the remaining two axes. Application of the Bain distortion model results in the conversion of face centred cubic lattice to body centred cubic lattice with minimum possible movements of atoms.

Although the Bain distortion model has been widely accepted, as it explains the atomic movement involved in the martensitic transformation, it has several major drawbacks. The model neither involves shear—a characteristic feature of martensitic transformation—nor does it explain the observed orientation relationship and well established existence of habit planes. No undistorted plane is available in the Bain distortion model, and hence it is not possible to explain invariant plane strain associated with martensitic transformation.

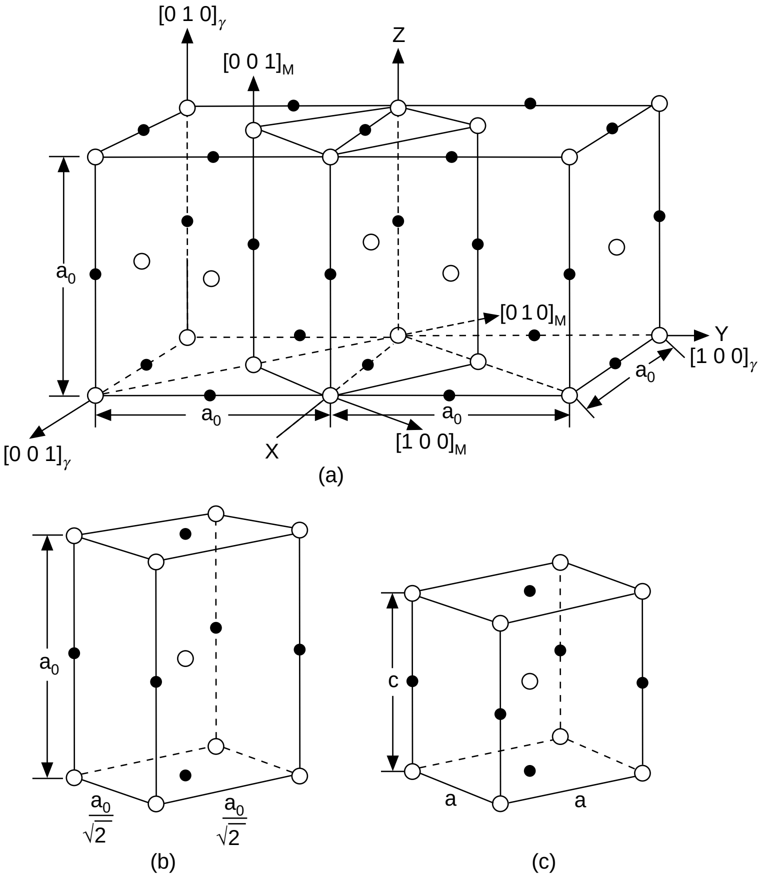


Figure 4.30 Diagram illustrating Bain distortion model.

4.9.9 Hardness of Martensite

In plain carbon steels, the hardness of martensite is essentially due to the presence of carbon. The hardness of martensite increases as carbon contents increase. Figure 4.31 shows the relationship between hardness of martensite and carbon content. It is evident from the figure that some minimum carbon content should be present in order to have a reasonable hardness after martensitic transformation. In order to develop maximum hardness by martensitic transformation for a given carbon content, it is essential that all carbon should be present in austenite, and cooling rate should be sufficiently high to produce martensitic structure.

The reasons for high hardness of martensite are not very clear. Two factors, which may account for it, are internal strains within the alpha iron lattice due to the presence of excess carbon contents, and plastic deforrmation of parent austenite surrounding the martensitic plate.

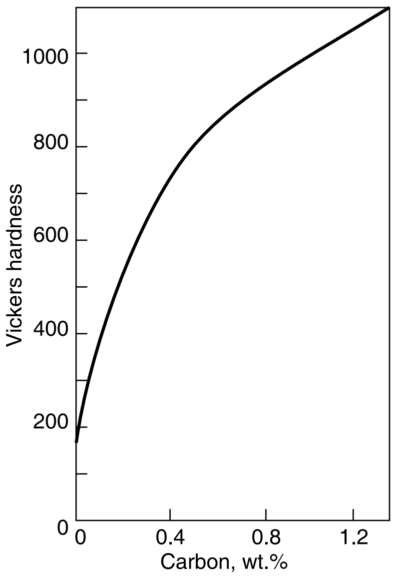


Figure 4.31 Effect of carbon content of steel on hardness of martensite.

The hardness of martensite is dependent on chemical composition of steel as chemical composition controls M_s and M_f temperatures. High carbon steels have lower M_s and M_f temperatures than low carbon and medium carbon steels. This is the reason why the amount of retained austenite is more in high carbon steels. The variation in amount of retained austenite with respect to carbon content is shown in Figure 4.32. The amount of retained austenite in high carbon steels is also dependent on the rate of cooling within the martensitic temperature range. The shaded area of Figure 4.32 shows the effect of cooling rate on the amount of retained austenite. With increase in proportion of retained austenite, the hardness decreases since austenite is a soft phase.

As already stated, all alloying elements, except cobalt and aluminium, lower M_s and M_f temperatures and, therefore, more austenite is retained in high alloy steels than in low and medium alloy steels. For most of the low alloy steels, the hardness of martensite is dependent only on carbon. This implies that Figure 4.31 is also valid for low alloy steels. For all practical purposes, the hardness corresponding to the carbon content of low alloy steel can be utilized.

Low carbon steels are similar to high carbon steels since they do not develop fully martensitic structure. However, the reason for this is not the presence of retained austenite. Due to insufficient hardenability of low carbon steel, the structure consists of martensite plus non-martensitic product(s). Therefore, both high carbon and low carbon steels exhibit lower hardness values than those shown by Figure 4.31.

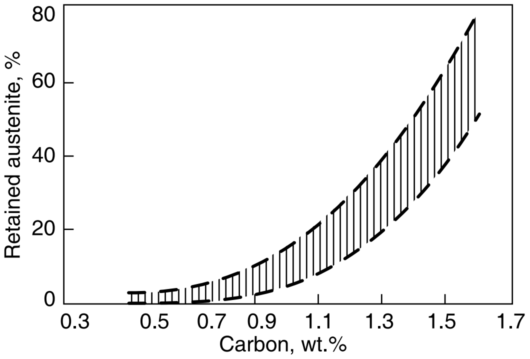


Figure 4.32 Effect of carbon content of steel on percentage retained austenite in quenched steel.

The fact that steels with lower M_s temperatures suffer from the presence of retained austenite does not imply that steels with higher M_s temperatures are desirable for the development of better hardness values. Steel with higher M_s temperature is undercooled to a lesser extent and, therefore, considerable amount of heat energy is retained within the steel, which results in self tempering of steel. Self-tempering in turn results in lowering of hardness.

4.10 RETAINED AUSTENITE

Austenite that is present in the ferrous alloys even after the completion of the heat treatment process is referred to as retained austenite. In simple words, retained austenite is the untransformed austenite. Such a situation is more frequently encountered in hardened steels. Austenite transforms to martensite on rapid cooling (quenching) below M_s temperature but above M_f temperature. As austenite to martensite transformation never goes to completion, some amount of austenite is present in the hardened steel.

Both M_s and M_f temperatures decrease with increase in carbon content (Figure 4.29). Therefore, amount of retained austenite in hardened steels increases with increase in carbon content (Figure 4.32). All alloying elements, except aluminium and cobalt, lower the M_s temperature (Figure 4.28) and hence enhance the amount of retained austenite. Therefore, both high carbon steels and high alloy steels are more prone to the presence of retained austenite. Unfortunately, both high carbon steels and high alloy steels are preferred steels for making, forming and cutting tools, and wear resistant components. These steels are generally hardened from somewhat higher temperatures so that all the carbon and alloy contents are in solid solution in austenite at heat treatment temperature. Such a practice further enhances the amount of retained austenite for two reasons. Firstly, M_s temperature gets lowered as all the carbon and alloying elements are present in austenite and secondly austenite to martensite transformation is hampered by the excess stresses developed in the steel on quenching due to relatively higher heat treatment temperatures.

Retained austenite differs from the original austenite in the sense that it has much higher dislocation density and also many other imperfections. These imperfections can be attributed to the localized deformation of the retained austenite by the surrounding martensitic crystals.

The soft and ductile retained austenite, when present in large proportions, lowers the overall hardness and strength of the steel. Therefore, the very purpose of hardening heat treatment is lost. Properties and reliability of the hardened part further worsen when this retained austenite gets transformed to bainite or martensite due to one or the other reason during service. Such a transformation results in the dimensional changes and even distortion which is highly undesirable in case of precision measuring tools, dies, etc. Being non-magnetic in nature, retained austenite affects the magnetic properties of the steels.

Presence of retained austenite sometimes can be employed for some useful applications by carefully controlling the amount of retained austenite. Non-distorting steels have been developed by carefully controlling the amount of retained austenite so that volume contraction due to formation of austenite from ferrite-carbide aggregate on heating and the volume expansion due to austenite to martensite transformation may balance each other. The excellent dimensional stability shown by these steels is due to the presence of retained austenite. Similarly, steels having retained austenite can be straightened by mechanical working operations.

However, presence of retained austenite, in general, is undesirable and thus it should be as low as possible if not completely absent in the steel. Two heat treatment processes are commonly employed for eliminating or reducing the retained austenite content of the steel. One such heat treatment process is ‘sub-zero treatment’. As a result of sub-zero treatment, retained austenite gets transformed to martensite. Sub-zero treatment has been described in detail in Section 5.9. Another heat treatment process is ‘tempering’. During second stage of tempering, also known as medium temperature tempering (refer Section 5.6.1), retained austenite transforms to bainite.

QUESTIONS

4.1 For an eutectoid steel, describe the mechanism of formation of austenite on heating.

4.2 Discuss the effect of following on the kinetics of formation of austenite on heating:

(a) Carbon content
(b) Presence of carbide-forming elements
(c) Interlamellar spacing of pearlite
(d) Prior heat treatment.

4.3 Explain the terms—(i) actual grain size of austenite, (ii) inherently fine grained steels, and (iii) grain size index. For an ASTM grain size index of 4, indicate approximate number, of grains per square inch/square millimetre.

4.4 Describe dependence of mechanical properties of steels on grain size.

4.5 Explain the construction of TTT diagram according to the first principle. Why it is called S-curve?

4.6 Draw isothermal transformation and continuous cooling diagrams for an eutectoid plain carbon steel and label various phase fields/regions. Of the two, which one is of greater industrial importance and why?

4.7 Explain the term active nucleus. Name the active nucleus for (i) pearlitic transformation, and (ii) bainitic transformation. Give reasons in support of your answer.

4.8 Explain the term interlamellar spacing of pearlite. Enlist parameters which control the interlamellar spacing of pearlite.

4.9 Austenite to bainite transformation is referred to as intermediate transformation. Why? Compare mechanical properties of bainitic structure with those of pearlitic and martensitic structures.

4.10 Distinguish between upper and lower bainite. Describe microstructural features and mechanical properties of each.

4.11 Describe the mechanism of formation of upper and lower bainite.

4.12 Explain why martensite is hard? What is the crystal structure of martensite? Show the positions of carbon atoms in unit cell of martensite.

4.13 Calculate the volume change associated with austenite to martensite transformation in one percent carbon steel.

4.14 Write notes on the following:

- (a) Bain distortion model
- (b) Athermal and isothermal martensite
- (c) Lath martensite and plate martensite.

4.15 Comment on the following statements:

- (a) Martensitic transformation is reversible
- (b) Amount of retained austenite is high in high carbon steels and high alloy steels
- (c) Martensitic transformation does not proceed to completion.

5

Heat Treatment Processes for Steels

INTRODUCTION

The area of application for any metal or alloy is limited by its properties. These properties can be varied within limits by several methods, namely, mechanical working, alloying, grain size control and heat treatment. The importance of heat treatment has been dealt with in Chapter 1. Heat treatment affects mechanical properties either by allotropic transformation or by changing relative solubilities of element(s) in the base metal. The theory of allotropic transformation, generally encountered in ferrous metals, has already been discussed in Chapter 4. Heat treatment practices for commercial steels are discussed in Chapter 14. (The theory and practice of heat treatment for non-ferrous metals and alloys are dealt with in Chapter 16.) Steel is the most important and versatile engineering alloy. It finds numerous applications. Heat treatment plays an important role in such a wide acceptance of steel as an engineering material. Properties of steel can be controlled and varied over a very wide range by heat treatment. Thus, a thorough understanding of heat treatment of steel is very important. In the sections that follow, we discuss various heat treatment processes.

5.1 STRESS RELIEVING

As the name suggests, this process is employed to relieve internal stresses. No microstructural changes occur during the process. In this sense, it differs from other subcritical treatments in which structural improvement takes place. Internal stresses are those stresses which can exist within a body in the absence of external forces. These are also known as residual stresses or locked-in stresses. Internal stresses are developed during different operations like solidification of castings, welding, machining, grinding, shot peening, surface hammering, cold working, case hardening, electroplated coatings, precipitation and phase transformation. Internal stresses under certain conditions can have adverse effects. For example, steels with residual stresses under corrosive environment fail by stress-corrosion cracking, whereas, in general, failure by stress-corrosion cracking occurs under the combined action of corrosion and externally applied stresses. These stresses also enhance the tendency of steels towards warpage and dimensional instability. Fatigue strength is reduced considerably when residual tensile stresses are present in the steel. The problems associated with internal stresses are more difficult in brittle materials than in ductile materials.

The process of stress relieving consists of heating steel uniformly to a temperature below the lower critical temperature, holding at this temperature for sufficient time, followed by uniform cooling. Uniform cooling is of utmost importance as non-uniform cooling will itself result in the development of internal stresses. Thus the very purpose of stress relieving will be lost. For plain carbon steels and low alloy steels, maximum stress relieving temperature is generally limited to about 600°C. Higher temperatures are employed for high alloy steels. Hardened and tempered steels, if service conditions demand, can be stress relieved by heating up to a temperature which is lower than tempering temperature by 25–30°C. The extent to which stresses can be relieved depend on the temperature employed and holding time.

5.2 ANNEALING

Annealing, in general, involves heating to a predetermined temperature, holding at this temperature, and finally cooling at a very slow rate. The temperature, to which steel is heated, and the holding time are determined by various factors such as the chemical composition of steel, size and shape of steel component and final properties desired. Annealing can form either the final treatment or a preparatory step for further treatment. The various purposes of this treatment are to (i) relieve internal stresses developed during solidification, machining, forging, rolling or welding; (ii) improve or restore ductility and toughness; (iii) enhance machinability; (iv) eliminate chemical non-uniformity; (v) refine grain size; and (vi) reduce the gaseous contents in steel.

Annealing treatment can be classified into groups, based on temperature of treatment, phase transformation that takes place during treatment, and the purpose of the treatment. All the groups based on these three criteria are interrelated.

Depending on heat treatment temperature, annealing treatment can be subdivided into three classes, namely, full annealing, partial annealing and subcritical annealing. For full annealing, steel is heated above the upper critical temperature (A_3) and then cooled very slowly. Partial annealing, also known as incomplete annealing or intercritical annealing, involves heating of steel to a temperature lying between lower critical temperature (A_1) and upper critical temperature (A_3 or A_{cm}). The steel may be cooled very slowly from the annealing temperature, or it may be cooled in air from a temperature at which or above which all the austenite has been transformed into pearlite. Subcritical annealing, as the name suggests, is a process in which the maximum temperature to which steel is heated is always less than the lower critical temperature (A_1). These processes have been represented in Figure 5.1. In subcritical annealing, no phase transformation takes place. Only thermally activated phenomena, such as recovery, recrystallization, grain growth, agglomeration of carbide and softening occur in this process. The rate of cooling from a subcritical temperature is of little significance since practically there is no variation as far as microstructure and final properties are concerned.

On the basis of phase transformation features, annealing can be of two types. The first type or first-order annealing is associated with a peculiar characteristic that heat treatment is performed on the steel with the sole aim of achieving some properties. As such, no specific importance is given to phase transformation accompanying the treatment. In other words, any

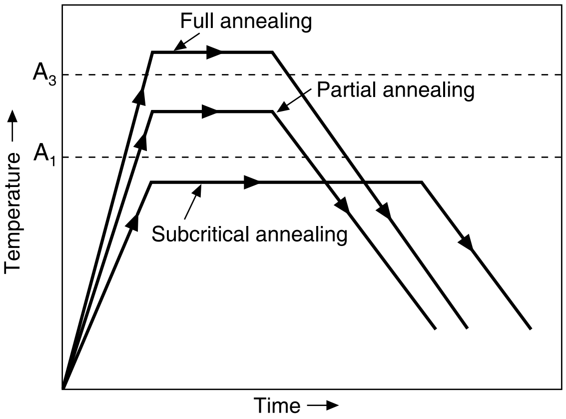


Figure 5.1 Various types of annealing processes classified on the basis of annealing temperature.

change in the characteristics of steel achieved by this type of annealing is not correlated to phase transformation. This is the reason why a wide range of temperature is available for this type of annealing. It can be performed at a wide range of temperatures above or below the critical temperatures. The second type or second-order annealing differs from the first type in the sense that the end results in the former are essentially due to phase transformation which takes place during the treatment. For this reason, the temperature range for this treatment is restricted as compared to the first type. Only temperatures above the upper and lower critical temperatures can be utilized for this type of annealing.

Depending on the specific purpose, annealing is classified into various types, e.g. diffusion annealing, spheroidizing annealing, full annealing and recrystallization annealing. The prefix with the word annealing describes the basic purpose of the type of annealing. Various annealing processes are discussed in the following sections.

5.2.1 Full Annealing

The term *annealing*, until and unless specified, means full annealing. It consists of heating steel to austenitic region, followed by slow cooling. Steel is heated to about 30–50°C above the upper critical temperature (A_3) for hypoeutectoid steels. The steel is held at this temperature for predetermined time, followed by cooling at a very slow rate such as cooling in the furnace itself or in a container made of a heat insulating material. Due to such a slow cooling rate, equilibrium structures as predicted by equilibrium diagram are obtained in the steel. The steel is heated above the upper critical temperature in order to get a homogeneous austenitic structure.

Alloy steels, specially those containing strong carbide forming elements, need higher annealing temperatures than plain carbon steels and other alloy steels. The upper limit of holding temperature is generally restricted to Ac_3 + 50°C in order to check grain coarsening. Steel will become very soft after this treatment. Since a completely austenitic structure can be obtained by heating eutectoid steel above the lower critical temperature (A_1), eutectoid steel is heated 30–50°C above the lower critical temperature for full annealing treatment. This treatment results in a structure consisting of lamellar pearlite. The interlamellar spacing will depend mainly on the annealing temperature and the cooling rate. This process, in general, is not employed for hypereutectoid steels. The reason for this is that heating above the upper critical temperature A_{cm} followed by slow cooling will result in considerable coarsening of austenitic grains, formation of coarse lamellar pearlite and network of cementite on the grain boundary. Neither coarse pearlite nor cementite network at grain boundaries is desirable. Such a structure has inherent brittleness and poor mechanical properties. The objective of the treatment is to improve ductility, remove internal stresses completely, get enhanced magnetic and electrical properties, and refine the grain structure. The austenitic grain size is minimum just above the upper critical temperature (A_3) for hypoeutectoid steels and above the lower critical temperature (A_1) for eutectoid steel. This treatment improves the machinability of medium carbon steels to a great extent. Almost all castings, rolled stocks and forgings are subjected to this treatment in order to attain enhanced mechanical properties by refinement of grains and transformation of dendrites to equiaxed grains and elimination of segregated zones. The prolonged heat treatment cycle, involved in this process, makes it quite expensive. This is one of the main drawbacks associated with this process.

5.2.2 Isothermal Annealing

In this process, hypoeutectoid steel is heated above the upper critical temperature (A_3) and held for some time at this temperature. This is done in order to get a completely austenitic structure and to eliminate any temperature gradient within the steel component. The steel is then cooled rapidly to a temperature less than the lower critical temperature (A_1). This temperature is usually chosen between 600°C and 700°C. Fast cooling can be achieved by rapidly transferring steel to another furnace maintained at the desired temperature. The required temperature is one at which supercooled austenite has minimum stability within the pearlitic region. The steel is held at this temperature till all the austenite gets transformed to pearlite. After all the austenite is transformed into lamellar pearlite, steel is cooled in air. In fact, cooling rates from this temperature are immaterial as no further transformation will take place. However, the magnitude of internal stresses developed within the steel will vary with cooling rate. The prefix "isothermal" associated with annealing implies that transformation of austenite takes place at a constant temperature. For all practical purposes, the microstructure is equivalent to that obtained by full annealing. The major advantage of this process over full annealing is that the time required for heat treatment cycle is cut short to a considerable extent. Shorter heat treatment cycle makes the process cheaper than full annealing process. The eutectoid steel is first heated to above A_1 temperature, and then it is rapidly cooled to a temperature lower than A_1. Steel is held at this temperature till austenite to pearlite transformation is complete. Finally, steel is cooled in air. Hypereutectoid steel is, in general, not subjected to this treatment. The reason for it is the same as discussed for full annealing. Thus, isothermal annealing can be viewed as modified full annealing process. It results in more homogeneous structure as transformation takes place at a constant temperature throughout the steel.

This process not only improves machinability in general, but also results in a better surface finish by machining. The process is of great use for alloy steels as these steels have to be cooled slowly. However, it has one important limitation. It is suitable only for small-sized components. Heavy components cannot be subjected to this treatment because it is not possible to cool them rapidly and uniformly to the holding temperature at which transformation occurs.

For this reason, structure will not be homogeneous and mechanical properties will vary across the cross-section. Figure 5.2 represents heat treatment cycle for isothermal annealing.

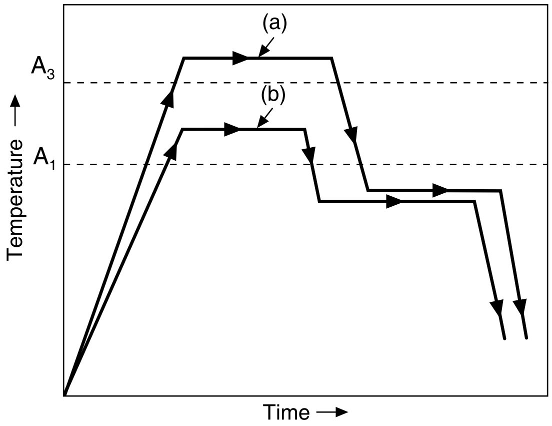


Figure 5.2 **Heat treatment cycle for isothermal annealing of (a) hypoeutectoid steel and (b) eutectoid steel.**

5.2.3 Diffusion Annealing

This process, also known as homogenizing annealing, is employed to remove any structural non-uniformity. Dendrites, columnar grains and chemical inhomogeneities are generally observed in the case of ingots, heavy plain carbon steel casting, and high alloy steel castings. These defects promote brittleness and reduce ductility and toughness of steel. In diffusion annealing treatment, steel is heated sufficiently above the upper critical temperature (say, 1000–1200°C), and is held at this temperature for prolonged periods, usually 10–20 hours, followed by slow cooling. Segregated zones are eliminated, and a chemically homogeneous steel is obtained by this treatment as a result of diffusion. Heating to such a high temperature results in considerable coarsening of austenitic grains and heavy scale formation. The coarse austenite thus obtained further transforms to coarse pearlite on cooling, which is not a desirable structure as mechanical properties are impaired.

The coarse grained structure can be refined either by plastic working for ingots or by employing a second heat treatment for castings. Hypoeutectoid and eutectoid steel castings are given full annealing treatment, whereas hypereutectoid steel castings are either normalized or partially annealed for this purpose. Scaling results in loss of metal and, therefore, heating is done in a controlled manner and the temperature is so chosen that holding time is minimized. Higher temperatures, longer holding periods, slow cooling rates, excessive scaling, and necessity for a second heat treatment make this process highly expensive.

5.2.4 Partial Annealing

Partial annealing is also referred to as intercritical annealing or incomplete annealing. In this process, steel is heated between the lower critical temperature (A_1) and the upper critical temperature (A_3 or A_{cm}). It is followed by slow cooling. Generally, hypereutectoid steels are subjected to this treatment. The resultant microstructure consists of fine pearlite and cementite instead of coarse pearlite and a network of cementite at grain boundaries, as observed in the case of full annealing. The reason for this is that grain refinement takes place at a temperature of about 10 to 30°C above Ac_1 for hypereutectoid steels. As low temperatures are involved in this process, it is less expensive than full annealing which involves higher temperatures. Hypoeutectoid steels are also subjected to this treatment in order to improve their machinability. However, all hypoeutectoid steels cannot be given this treatment. Steels with coarse structure of ferrite and pearlite or with widmanstätten structure are not suitable for this treatment. This is so because only partial phase transformation takes place in this process. A considerable amount of ferrite remains untransformed, and only a part of it along with pearlite transforms to austenite. This coarse or accicular untransformed ferrite results in poor mechanical properties.

5.2.5 Recrystallization Annealing

Practically all steels, which have been heavily cold worked, are subjected to this treatment. The process consists of heating steel above the recrystallization temperature, holding at this temperature and cooling thereafter. It results in decrease in hardness or strength and increase in ductility. The desired extent of reduction in cross-sectional area is possible with the adoption of cold-work-recrystallization anneal cycle(s). The process is used both as an intermediate operation and as a final treatment. The treatment is very important and is frequently employed in industries manufacturing steel wires, sheets and strips. The final structure, after the treatment, consists of strain-free grains produced at the expense of deformed original grains. The temperature for recrystallization annealing is not fixed, as is the case with other annealing processes such as full annealing or process annealing. Recrystallization temperature, and also recrystallization annealing temperature, depends on chemical composition, amount of prior deformation, holding time and initial grain size. A minimum amount of deformation is essential to cause recrystallization. The amount of deformation should be such that sufficient number of lattice defects are developed in the crystal. These defects initiate the nucleation for the production of new grains. The larger the degree of deformation, the lower is the recrystallization temperature. Recrystallization can be achieved at lower temperatures by increasing the holding time. However, the effect of temperature is more predominant than that of holding time. So, it is always desirable to raise recrystallization temperature instead of increasing holding time. A fine structure can be developed in the steel by deforming it heavily and heating to a temperature just above the recrystallization temperature. High carbon steels and alloy steels require higher recrystallization temperatures. The process may also result in the agglomeration of carbide particles.

5.2.6 Process Annealing

In this treatment, steel is heated to a temperature below the lower critical temperature, and is held at this temperature for sufficient time and then cooled. Since it is a subcritical annealing, cooling rate is of little importance. The purpose of this treatment is to reduce hardness and to increase ductility of cold-worked steel so that further working may be carried out easily. It is an intermediate operation and is sometimes referred to as in-process annealing. The process is less expensive than recrystallization annealing. It differs from recrystallization annealing in the sense that complete recrystallization of cold-worked steel may or may not take place in this treatment. Parts which are fabricated by cold forming such as stamping, extrusion, upsetting and drawing are frequently given this treatment as an intermediate step(s). The heating temperatures for various annealing treatments are shown in Figure 5.3.

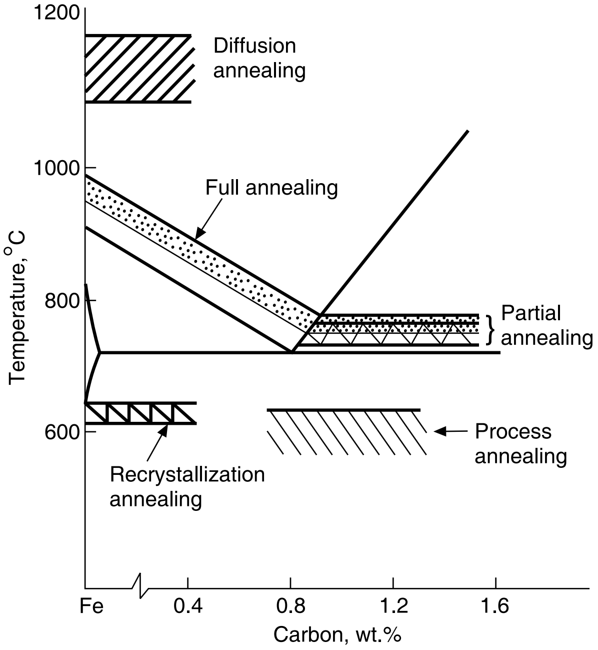


Figure 5.3 Temperature ranges for various types of annealing processes.

5.3 SPHEROIDIZING

Spheroidizing is a heat treatment process which results in a structure consisting of globules or spheroids of carbide in a matrix of ferrite. In other words, ceroentite of lamellar pearlite in the case of hypoeutectoid and eutectoid steels, and both lamellar and free cementite in the case of hyper-eutectoid steels, coalesce into tiny spheroids. The degree of spheroidization depends on heat treatment temperature and holding time. The process can be completed in short time by increasing the treatment temperature. However, selection of proper temperature is very important. With high spheroidization temperatures, dissolved carbide particles can reappear as lamellae during cooling.

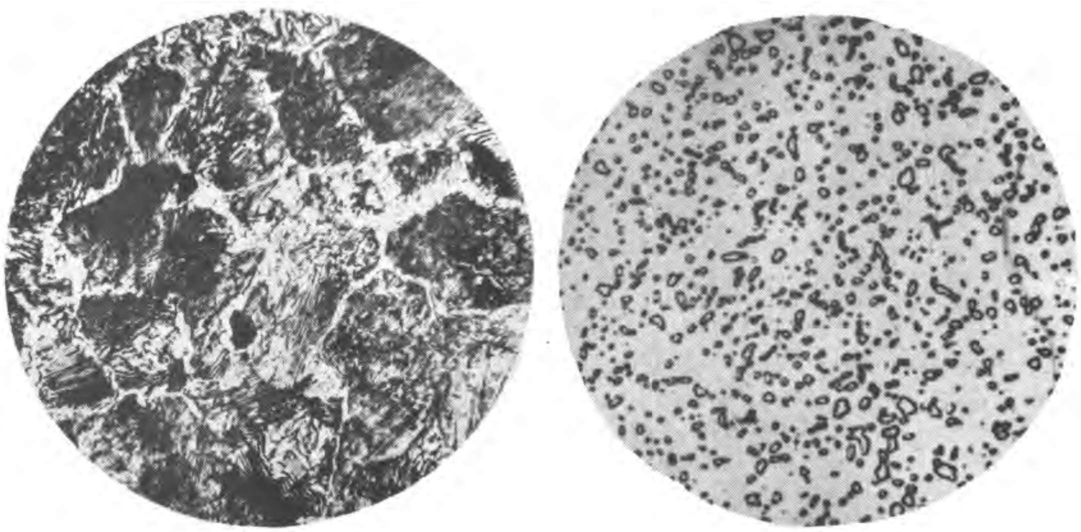
Various methods are available to obtain a spheroidized structure. One such method consists of heating steel to a temperature just below the lower critical temperature, holding at this temperature for prolonged periods, followed by slow cooling. Another method involves heating and cooling steel alternately just above and below the lower critical temperature. Isothermal annealing can also be employed for this purpose in order to save time and energy. It consists of heating of steel to a temperature above the lower critical temperature, followed by slow cooling to a temperature below the lower critical temperature, and holding at this temperature for a period till the shape of all carbide particles changes into spheroids.

The spheroidizing treatment is also carried out by heating steel above the lower critical temperature. This results in a completely spheroidized structure. The extent to which steel is to be heated above the lower critical temperature depends on the chemical composition of steel. Eutectoid steels are heated to about 20–30°C above the lower critical temperature, whereas hypereutectoid steels are heated 30–50°C above the lower critical temperature. Hypereutectoid alloy steels require still higher temperatures. Medium carbon steels can be spheroidized either by heating just above or below the lower critical temperature.

High carbon steels and alloy steels are frequently spheroidized in order to improve machinability and ductility. Low carbon steels are not generally spheroidized. However, the aim is to make these steels suitable for severe deformation in case they are spheroidized. Low carbon steels, on spheroidization, become very soft and gummy (sticky). Spheroidization of these steels does not therefore improve their machinability.

It has been observed that fine lamellar pearlite coalesces more easily than coarse pearlite. Very fine pearlite spheroidizes still more readily. Quenched structures, consisting of fine and well dispersed carbide phase, show greatest spheroidization rates. This means that finely distributed carbide phase is best suited for such a treatment. Cold working of steel, prior to the treatment also helps in accelerating the rate of spheroidization.

In certain cases, a preheat treatment is necessary. For example, a network of carbide at grain boundaries is present in annealed hypereutectoid steel microstructure [Figure 5.4(a)]. Such a steel is first normalized in order to eliminate carbide network and then spheroidized. Spheroidized structure is shown in Figure 5.4(b). Similarly, a very coarse structure is to be modified so as to have finer structure (by normalizing) prior to spheroidization.



(a) Annealed (with network of cementite), ×800

(b) Spheroidized (with cementite in form of spheroids), ×800

Figure 5.4 Hypereutectoid steel.

5.4 NORMALIZING

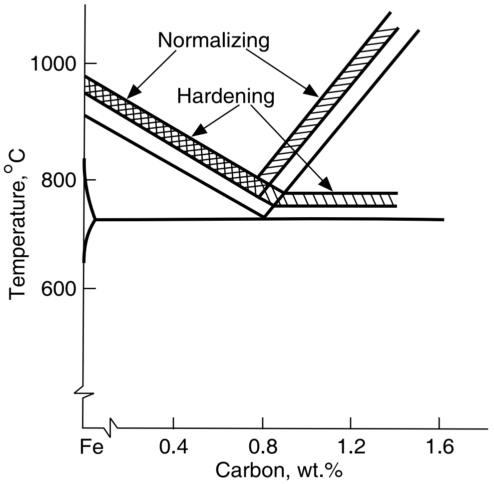


Figure 5.5 Temperature ranges for normalizing and hardening treatment of steels.

Normalizing is a process of heating steel (Figure 5.5) to about 40–50°C above upper critical temperature (A_3 or A_{cm}), holding for proper time, and then cooling in still air or slightly agitated air to room temperature. In special cases, cooling rate can be controlled either by changing air temperature or air volume. After normalizing, the resultant microstructure should be pearlitic. This is particularly important for some alloy steels which are air hardening (martensite forms on air cooling) by nature. For such steels, cooling in air does not lead to normalized structure. Slower cooling rates are required. Since the temperature involved in this process is more than that for annealing, the homogeneity of austenite increases and it results in better dispersion of ferrite and cementite in the final structure. This dispersion results in enhanced mechanical properties. The grain size is finer in normalized structure than in annealed structure. Grain size of normalized steel is governed by section thickness. As cooling rates differ considerably from case to core, there is variation in grain size of normalized steel over its cross-section. Refinement of grain size is one of the most important objectives of normalizing and it is, to a great extent, practised commercially. Rolled and forged steels, possessing coarse grains, due to high temperatures involved in these operations, are subjected to normalizing treatment for grain refinement.

Another important application of this process is its adoption as post treatment after achieving a homogeneous structure. Generally, heavy castings, including ingots, suffer from chemical inhomogeneity. For its elimination, steel is heated to a temperature which is higher than that recommended for normalizing. The casting is held for sufficient period of time so that chemical homogeneity is achieved by diffusion. It is then followed by air cooling. In fact, cooling rates are not of much importance in this case because the treatment is generally followed by a second cycle of treatment. The aim of the second heat treatment cycle is to refine the coarse grained structure developed to high temperature heat treatment. Refining is done by normalizing steel at lower temperature. Some internal stresses are developed in these heavy castings/ingots because of large section thickness which results in variation in cooling rates from case to core.

Normalized steels are generally stronger and harder than fully annealed steels. Correspondingly, the machinability of steels shows an improvement on normalizing. Steels are soft in annealed condition and tend to stick during machining. By normalizing, an optimum combination of strength and softness is achieved, which results in satisfactory level of machinability in steels. This method of improving machinability is specially applicable to hypoeutectoid steel. It has been observed that carbide gets precipitated at grain boundaries and forms continuous network, particularly in hypereutectoid steel by annealing. Normalizing is a very effective process to eliminate this carbide network. Such a network is quite stable, and not eliminated by annealing treatment since there is reprecipitation during cooling. Due to the shorter time available during cooling, this network does not appear in normalized structure. Normalizing treatment is frequently applied to steels in order to achieve any one or more of the objectives, namely, grain refinement, improvement in machinability, and enhanced mechanical properties such as hardness, strength and toughness.

5.4.1 Normalizing versus Annealing

Normalized steels are harder than annealed ones. Relatively rapid cooling in the case of normalizing results in higher degree of supercooling. Therefore, austenite decomposes at relatively lower temperatures, resulting in better dispersion of ferrite-carbide aggregate. Also, the amount, of pearlite is more. Both of these factors result in higher strength and hardness. So, where these properties are desired, annealing treatment cannot be employed, and normalizing should be done. Prolonged heat treatment time and higher energy consumption make the annealing treatment more expensive than normalizing. Thus, normalizing is the preferred treatment in industries. Cooling rates are not critical for normalizing as in the case of annealing. They can be increased considerably in order to cut short the total time for treatment. The only point to be considered is that cooling should result only in production of equilibrium microconstituents. After a particular temperature is attained, which is well below the lower critical temperature, steel may be quenched. Normalized steel has lower impact transition temperature than annealed steel. This is essentially due to the finer grain size of normalized steel. Annealing improves the machinability of medium carbon steels, whereas normalizing improves machinability of low carbon steels.

5.5 HARDENING

Certain applications demand high tensile strength and hardness values so that the components may be successfully used for heavy duty purposes. High tensile strength and hardness values can be obtained by a process known as *hardening*. Hardening treatment consists of heating to a predetermined temperature, usually known as hardening temperature (see Figure 5.5), holding at that temperature, followed by rapid cooling such as quenching in water, oil or salt baths. The high hardness developed by this process is due to the phase transformation accompanying rapid cooling. The term *rapid cooling* simply does not mean that cooling rate is higher than that adopted in annealing and normalizing. What it really means is that cooling rate is equal to or more than the upper critical cooling rate. Rapid cooling results in the transformation of austenite at considerably low temperatures into non-equilibrium product. The product of low temperature transformation of austenite is martensite which is a hard microconstituent of steel. The term *hardening by quenching* is used for this process in order to differentiate it from other hardening processes.

The hardening temperature (Figure 5.5) depends on chemical composition. For plain carbon steels, it depends on carbon content alone. Hypoeutectoid steels are heated to about 30–50°C above the upper critical temperature, whereas eutectoid and hypereutectoid steels are heated to about 30–50°C above the lower critical temperature. Ferrite and pearlite transform to austenite at hardening temperature for hypoeutectoid steels. This austenite transforms to martensite on rapid quenching from hardening temperature. The presence of martensite accounts for high hardness of quenched steel. If hypoeutectoid steel is heated to a hardening temperature equivalent to that for hypereutectoid steel, the structure will consist of ferrite and austenite. This will transform to ferrite and martensite on quenching. Ferrite, a very soft phase, lowers the hardness of hardened steel considerably. Thus, the very purpose of hardening, i.e. attainment of improved mechanical properties, is lost. This is also known as incomplete hardening, and is not usually employed in practice. The preferred hardening temperature for hypereutectoid steel lies between the lower critical temperature (A_1) and the upper critical temperature (A_{cm}). The advantage gained from hardening temperature in this range is two-fold. The first is related to the presence of cementite in hardened steel. The cementite in a martensitic matrix accounts for several desirable properties. Wear resistance is one of them. The fact that both martensite and cementite are hard constituents is responsible for high wear resistance of the resulting microstructure. Cementite is harder than martensite and so wear resistance of the two-phase microstructure is better than what is achieved by martensite alone. The second advantage of this hardening temperature is the attainment of fine martensite in the final structure. In fact, heating of hypereutectoid steel above the upper critical temperature (A_{cm}) for hardening is detrimental because such a high temperature will result in coarsening of austenitic grains and decarburization at the surface. Coarse austenite will transform to coarse accicular martensite (microstructure, Figure 5.6) which has poor mechanical properties. Decarburized surface responds poorly to hardening treatment. In addition to these factors, quenching from such a high temperature will introduce severe internal stresses into the hardened steel.

Figure 5.6 Microstructure showing coarse accicular martensite (×300).

The main purpose of hardening tool steel is to develop high hardness. This enables tool steel to cut other metals. High hardness developed by this process also improves wear resistance. This may be the sole aim of the process for components such as gears, shafts and bearings. Tensile strength and yield strength are improved considerably by hardening structural steels. In the case of structural steels, yield strength is more important than tensile strength as it measures the safe limit of maximum allowable stresses. The higher the yield strength, the greater is the magnitude of stress to which a part can be subjected in service. Since yield strength is the limit of stress up to which elasticity is maintained, an increase in yield strength results in increase of stress level which the material can withstand without loss of elasticity. This is a very important property of springs.

Because of rapid cooling, high internal stresses are developed in the hardened steel. Therefore, hardened parts are seldom used in as-hardened condition. Also, in hardened condition, steels are generally brittle. Hardening, in general, is always followed by another treatment known as tempering which reduces internal stresses and makes the hardened steel relatively stable. Hardening followed by tempering results in improved wear resistance, optimum combination of strength and ductility and enhanced elastic characteristics.

5.5.1 Factors Affecting Hardening Process

The properties of steel developed by hardening depend on various factors. Important among these factors are (i) chemical composition of steel, (ii) size and shape of the steel part, (iii) hardening cycle, i.e. heating rate, hardening temperature, holding time and cooling rate, (iv) homogeneity and grain size of austenite, (v) quenching media, and (vi) surface condition of steel part. All these factors are interrelated. In fact, these factors affect almost all heat treatment processes and are of great importance for hardening treatment, due to rapid cooling, which results in the transformation of austenite to non-equilibrium product.

Chemical composition of steel largely determines the hardening temperature since critical temperature depends on it. In the case of alloy steels, the hardening temperature has to be controlled closely, and depends on the nature and amount of alloying element(s). Comparatively larger amount of retained austenite is present in the hardened steels containing austenite stabilizing elements. The presence of retained austenite greatly reduces strength. The presence of alloy carbides increases wear resistance of the hardened steel to a great extent. The reason for this is that, in general, alloy carbides are harder than cementite. The higher the content of carbide forming element(s) in a given alloy steel, the larger is the volume fraction of carbides in the hardened steel and correspondingly higher is the wear resistance. Hardened alloy tool steels having alloy carbide(s) in a martensitic matrix, apart from excellent wear resistance, have many important characteristics such as longer tool life, increased cutting ability and stability at elevated temperature.

Larger parts or parts with variable thickness of sections are heated at a very slow rate so as to avoid thermal gradient between outer and inner layer or between thick and thin sections. These parts should be held at the hardening temperature for sufficient time in order to attain uniform temperature throughout the volume. Cooling rates should be so chosen that complete hardening may take place with minimum of defects associated with hardening process. Sharp corners or regions where dimensional change takes place are more prone to quench cracks or warpage. For larger parts, martensitic transformation will not proceed simultaneously throughout the volume. This will result in production of high magnitude of internal stresses due to volume change (associated with austenite to martensite transformation) occuring first in the case and then in the core.

For complete hardening, hardening temperature should be such that homogeneous austenite with minimum grain size is produced. This is achieved by heating hypoeutectoid steel to

30 to 50°C above Ac_3 temperature. Eutectoid and hypereutectoid steels are heated to 30 to 50°C above Ac_1, temperature, as already explained in Section 5.5. Cooling rate equal to or greater than the upper critical cooling rate results in complete hardening. Ideally, cooling rate should be just equal to the upper critical cooling rate. Cooling rates more than the critical cooling rate will simply result in development of larger internal stresses without any other advantage. This is not desirable. Slow heating rates are desirable in some cases. However, slow heating rates are to be avoided in cases where the problem of oxidation and decarburization is encountered. In such cases, steel component is heated in two stages. To start with, it is heated to an intermediate temperature which is lower than the required austenitizing temperature. The component is soaked at this temperature for a sufficiently long time. Heating to this lower temperature does not result in either excessive oxidation or decarburization. Now the steel part is transferred quickly to another furnace maintained at the desired temperature. This practice reduces the time for which steel part has been kept at high temperature. In this way, the problem of oxidation and decarburization is minimized. Steel components which are heated to hardening temperature at slow heating rates require less holding time for homogenization. On the other hand, steel components or small sections which get heated up rapidly, need longer holding time.

The properties of hardened steel depend to a large extent on the nature of austenite, because martensite in the quenched steel is formed by direct transformation of austenite. Homogeneity and grain size of austenite play an important role as far as final properties are concerned. A detailed discussion on this aspect is given in Section 4.9.

A desired quenching medium is one which provides a cooling rate higher than the (upper) critical cooling rate. Quenching medium characteristics, such as its temperature, specific heat, thermal conductivity and latent heat of vaporization, affect the cooling rate to a great extent. The effect of these characteristics and the mechanism of heat removal from the quenching medium are dealt with in detail in Chapter 7.

The condition of the surface of steel component also affects hardening characteristics. The presence of oil, grease, scale and other foreign particles on the surface is not desirable. Oil and grease burn during heating and leave behind residue which is a bad conductor of heat. Thus the spot(s), where this residue exists, will cool at a slower rate than the rest of the surface. This may lead to incomplete hardening. Similarly, the presence of scale or foreign particles also results in variable cooling rates within the mass.

5.5.2 Hardening Methods

Rapid cooling is carried out in order to obtain martensite in hardened steel. Austenite to pearlite or bainite transformation is suppressed in this process. This means that higher cooling rates will be required only in that temperature range within which unstable austenite decomposes to ferrite-cementite aggregate. Once this range is crossed, austenite will transform to martensite even on slow cooling. Therefore, it is not essential to rapidly cool the steel component throughout the complete range of temperature from hardening temperature to quenching medium temperature. Minimum possible cooling rate will develop the lowest internal stresses in the hardened steel. Large magnitude of internal stresses may either lead to distortion of piece or to the formation of internal or external cracks.

Hardening can be employed on steel component in several ways, depending on quenching procedures. Various quenching methods based on hardening are (i) conventional or direct quenching, (ii) quenching in stages in sequence in different media, (iii) spray quenching, (iv) quenching with self-tempering, (v) austempering or isothermal quenching, and (vi) martempering (stepped quenching).

Conventional quenching is the simplest and extensively used hardening method. It consists of quenching the steel component from hardening temperature in the quenching medium. The part is allowed to cool up to the temperature of quenching bath. In addition to severe internal stresses, steel parts also develop tendency towards distortion and cracking due to drastic cooling rates involved in this process. Cooling rate can be controlled by adopting less severe quenching media, say, oil in place of water. However, such a control has its own limitations. Only smaller sections can be hardened in quenchants having lesser quenching power. The process is frequently adopted for simpler shapes. Intricate shapes cannot be successfully hardened by this process.

Quenching in stages in sequence in different media consists of quenching steel part from hardening temperature to a bath maintained at a predetermined temperature which is higher than the M_s temperature. The medium used, in general, is water. The part is then transferred quickly to a milder quenching medium where it is cooled to room temperature. Oil and air are much preferred quenching media for second quenching. Internal stresses developed in this process are considerably less than those found in direct quenching. This is mainly due to two reasons. Firstly, the severity of cooling is reduced. Secondly, internal stresses developed (due to austenite to martensite transformation in stages from surface to centre) are also reduced.

Spray quenching is a specific hardening method in which the steel part is cooled rapidly from the hardening temperature by spraying quenchant continuously. In this case, the rate of heat extraction from the steel part is much higher as compared to direct quenching process. The reason for this is that a continuous stream of quenchant is always in contact with the steel surface. Thus there is no probability for formation of liquid vapour film over the steel surface. The process is best suited for selective hardening. Water is the most commonly used quenchant for this process.

Hardening is always followed by tempering in order to have an optimum combination of hardness, strength and toughness. Properly hardened and tempered steel part has, in general, uniform mechanical properties throughout the section. This condition is not desirable for all applications. For example, certain applications, specially those involving impact loading, require a soft and tough core with hardened and toughened case. This condition can be attained by a process known as quenching with self-tempering. It is also referred to as time quenching. In this process, steel part is quenched from the hardening temperature. The part is withdrawn from the quenching bath after some time without allowing it to cool completely in the quenching medium. In this way, considerable amount of heat will be retained in this central portion. The component is now cooled in a mild quenching medium such as oil or air. The first quenching results in the formation of martensite. The depth up to which martensite forms will depend to a great extent on the time period for which the part has been allowed to remain in the quenching bath. Cooling during second quench will result in homogenization of temperature. The core will now be cooled at a. much reduced rate. Thus the core will undergo austenite to pearlite transformation in place of austenite to martensite transformation. The already formed martensite will be tempered by itself without any additional tempering treatment during second cooling. Thus, the process results in a tough core with a hardened and toughened case.

This hardening process is frequently used for chisels, sledge and hand hammers, centre punches, shafts, collars and gears. It is also a useful process for hardening components with intricate shapes. The only problem associated with this process is the close control of time in the first quench. It is very difficult to know the heat contents of the piece after the first quench. Thus it is difficult to control the tempering temperature for the martensite. Tempering temperature cannot be measured accurately in this case. An estimation of temperature is carried out by observing the temper colour of the surface. Hardness of tempered martensite can be controlled by immersing the piece into water after a particular time, depending on the temper colour of the surface. This prevents overheating of steel above the required temperature.

Isothermal quenching and stepped quenching are discussed separately in Sections 5.7 and 5.8, respectively.

5.6 TEMPERING

As mentioned in Section 5.5, hardening treatment develops maximum hardness, excellent wear resistance and high strength levels in the steel. At the same time, it affects adversely properties such as ductility, toughness and impact strength. It also imparts brittleness to steel because of the internal stresses developed by quenching. The extent of brittleness depends on the chemical composition and cooling rate. The degree of brittleness rises with increasing carbon content and severity of cooling rate. Thus, steel in as-hardened state is unsuitable for some service conditions and, therefore, rarely used as such. A relatively stable state can be attained by providing thermal energy to the steel. This results in decrease in internal stresses and reduction in the degree of brittleness. Such a process, which consists of heating hardened steel below the lower critical temperature, followed by cooling in air or at any other desired rate, is known as *tempering*.

Tempering treatment lowers hardness, strength and wear resistance of the hardened steel marginally. However, this marginal loss is adequately compensated by advantages gained by relieving of internal stresses, restoration of ductility and toughness and transformation of retained austenite. The higher the tempering temperature, the more is the restored ductility and tougher the steel. However, due attention should be paid towards hardness, strength and wear resistance properties. This is the aim of hardening treatment. Proper tempering treatment results in optimum combination of mechanical properties. Elastic properties of steel are also affected by this treatment. Hardening followed by tempering is the only conventional heat treatment process suitable for improving elastic limit of steel.

5.6.1 Structural Changes during Tempering

A number of structural changes take place during tempering treatment. These changes include isothermal transformation of retained austenite, ejection of carbon from body centred tetragonal lattice of martensite, growth and spheroidization of carbide particles and formation of ferrite-carbide mixture. Depending on the range of tempering temperature, the treatment proceeds to various stages.

The first stage of tempering is also referred to as low temperature tempering. The maximum temperature to which steel is heated is restricted to about 250°C at this stage. This results in the formation of a low carbon martensite and a carbide by transformation of high carbon martensite. This decomposition of high carbon martensite proceeds essentially by nucleation and growth. The carbon content of the product martensite (low carbon martensite) is independent of the carbon content of the original martensite. Carbon content decreases with increase in tempering time. It continues till the carbon of product martensite reaches a value equal to 0.30 percent carbon. This amount of carbon in martensite leads to a stable state within this temperature range and this martensite does not decompose further.

The carbide precipitated from the high carbon martensite during the first stage of tempering is not cementite. This carbide is known as epsilon (ε) carbide which has a hexagonal closed packed structure. The carbon content of epsilon carbide is more than that of cementite (Fe_3C), and the chemical formula is approximately $Fe_{2.4}C$. The carbon atoms are located at octahedral interstices and arrange themselves in such a fashion that each one is separated from the other with a maximum possible distance. Epsilon carbide forms at low temperature range in which martensite is metastable. Hence, the carbide particles are very fine in size. The carbon contents of the original martensite also affect the temperature range of formation of epsilon carbide.

As far as mechanical properties are concerned, marginal decrease in hardness value takes place at this stage. Strength improves considerably. Toughness also improves but to a lesser degree as compared to strength. Excellent wear resistance and reduced internal stresses are the characteristics of hardened steel tempered in this range. The treatment is useful for high carbon and low alloy steels used for manufacturing cutting and measuring tools. Case hardened steels are also subjected to this treatment.

The second stage of tempering consists of heating steels in the temperature range varying from 350 to 500°C. During this stage, retained austenite transforms to bainite. This bainite differs from conventional bainite in the sense that it consists of ferrite and epsilon carbide. Another name given to this stage is medium temperature tempering. Ductility and toughness increase by this treatment with a corresponding decrease in hardness and strength. The steel develops maximum elastic properties during this stage and the process is best suited for coil and laminated springs.

The third stage of tempering is also popularly known as high temperature tempering. It consists of heating steel within a temperature range of 500 to 680°C. Heating to such high temperatures results in the formation of ferrite-cementite mixture. Martensite changes to ferrite by losing its carbon. Carbon thus released combines with epsilon carbide which in turn transforms to cementite. All these changes occur with the help of diffusion and nucleation. Steel, thus treated, has better tensile, yield and impact strength than annealed or normalized steel and is free from internal stresses. The process is best suited for medium carbon and medium carbon low alloy steels due to their optimum heat treatment response. Connecting rods, shafts and gears are frequently subjected to this treatment. Figure 5.7 shows the effect of tempering temperature on hardness of quenched steel.

5.6.2 Effect of Alloying Elements on Tempering

Almost all alloying elements enhance the ability of steel to resist softening during tempering. In other words, for a given hardness, alloy steels require higher tempering temperatures than carbon steels. The same fact may be stated also for a given tempering cycle, i.e. an alloy steel will have higher hardness than a plain carbon steel of same carbon content. It is not possible

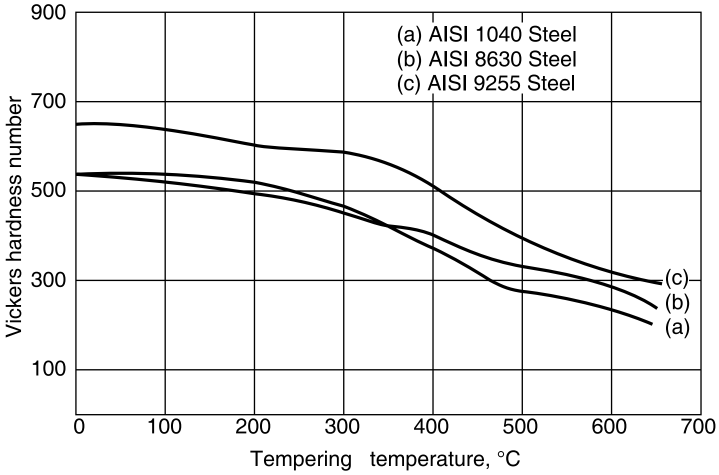


Figure 5.7 Effect of tempering temperature on the hardness of some quenched steels.

to derive a quantitative relationship between alloy content and the resistance to softening as a number of variables are associated with the treatment. Alloy steels do not exhibit any appreciable change in properties at low tempering temperatures, say up to 150°C.

Alloying elements can, in general, be classified into two classes, namely, carbide forming elements and non-carbide forming elements such as nickel, aluminium, silicon and manganese, which enter into ferrite and/or austenite. Thus, they have very little impact on the tempered hardness of steel. The hardening observed in such alloy steels is essentially due to the solid solution hardening effect. Steels with carbide forming elements, such as chromium, molybdenum, tungsten, vanadium, tantalum and titanium, resist softening considerably because of the formation of respective alloy carbides. Also, the martensite formed in alloy steels is much more stable. The reason for this is that the martensite is formed from a highly alloyed austenite at lower transformation temperatures. Lower transformation temperature is a consequence of lowered M_s temperature due to the presence of alloying elements (see Section 4.9).

For some highly alloyed steels, improvement in hardness values has been observed on tempering at elevated temperatures, which is contrary to the basic nature of tempering process. Such a behaviour is referred to as secondary hardening. This hardening results from the formation of alloy carbides. These alloy carbides are formed at higher temperatures and are harder and more stable than cementite. Formation of cementite depends only on diffusion rates of carbon, which is sufficiently high even at lower temperatures. Thus, cementite is easily formed at lower temperatures. The reason why alloy carbides are formed only at higher temperatures is the lower diffusion rates of alloying elements. The diffusion of solute atoms is too slow at lower temperatures to cause any carbide formation. It is significant only at high temperatures which permits formation of alloy carbides.

5.6.3 Temper Brittleness

One of the important objectives of tempering steel is to get an optimum combination of strength and toughness. Since it is a subcritical treatment, cooling from tempering temperatures can be done at any desired rate. It has been found that certain types of steels, either on cooling slowly or on holding for prolonged periods within a specific tempering temperature range (usually between 400°C and 660°C), show a marked decrease in toughness values. This phenomenon is known as temper brittleness. Another name given to it is temper embrittlement. The degree of embrittlement depends on the cooling rate from the embrittlement range. The higher the rate of cooling, the lesser will be the degree of embrittlement. Many theories have been put forward to explain this behaviour, but none can explain all the features associated with it. However, some methods of commercial importance have been developed to reduce the ill effect of temper embrittlement. An interesting feature of this embrittlement is that most of the mechanical properties, such as hardness, tensile strength, yield strength, fatigue strength and ductility as measured by percentage elongation, are not affected significantly. Temper brittleness is a reversible phenomenon. It can be eliminated by heating steel above the embrittlement range followed by rapid cooling.

Temper brittleness does not occur in carbon steel, but has been widely observed in alloy steels. Steels with phosphorus, antimony, tin and arsenic are highly prone to this phenomenon. The tendency is considerably reduced and practically eliminated in the absence of these elements. This is the reason why it is emphasized that the presence of stray elements other than those deliberately added should be carefully guarded against. This will ensure elimination of embrittlement. If the presence of embrittlement elements is suspected, molybdenum, titanium and zirconium are to be added so as to suppress embrittlement. Certain elements such as nickel, manganese, chromium and silicon are also known to enhance the susceptibility of steel to embrittlement.

5.6.4 Temper Colours

Hardened steel, when heated in oxidizing atmosphere for the purpose of tempering, exhibits various colours on the surface. The colours are caused by the formation of iron oxide film. The colour of oxide film is a function of oxide film thickness which, in turn, is a function of tempering temperature and holding time at this temperature. As the oxide film thickness increases, colour changes from light straw to grey. Table 5.1 indicates temper colour and tempering temperatures.

Table 5.1 Temper Colours

Temperature (°C)	Temper colours
220	Straw yellow
240	Light brown
270	Brown
285	Purple
295	Dark blue
310	Light blue
325	Grey
350	Grey-purple
375	Grey-blue
400	Dull grey

5.7 AUSTEMPERING

This is a special heat treatment process in which austenite is transformed into bainite. The cooling sequence for austempering superimposed on TTT diagram is shown in Figure 5.8. In general, austenite is either transformed into pearlite or martensite during conventional heat treatment processes involving continuous cooling. The nature of TTT diagram is such that a given cooling curve cuts the C-curve either above the nose or does not intersect the curve at all. In the former case, pearlite is formed. Martensite is formed in the latter case. Austempering consists of heating steel to above the austenitizing temperature. It is then quenched in a bath maintained at a constant temperature above M_s point and within the bainitic range (200 to 400°C, in general). The steel is quenched and maintained at a constant temperature in the bath itself till all the austenite is transformed into bainite. After complete transformation, steel is taken out of the bath and is cooled in air or at any desired rate to room temperature. Since the process involves transformation of austenite to bainite at constant temperature, it is also known as isothermal quenching or isothermal hardening. The preferred temperature of the quenching bath is generally on the lower side of bainitic range. This results in the formation of lower bainite which has better mechanical properties than tempered martensite, and hence austempered components rarely need tempering.

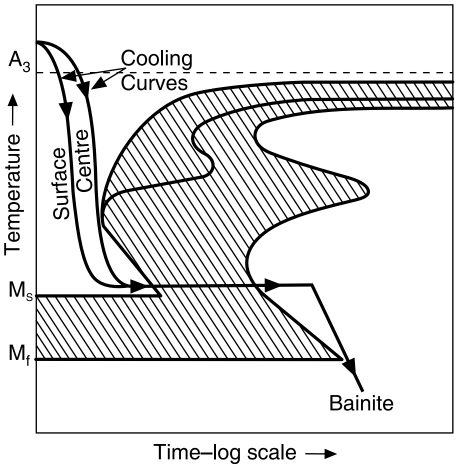


Figure 5.8 Cooling sequence for austempering treatment superimposed on TTT diagram.

The process, as compared to conventional hardening and tempering treatment, results in better ductility at high hardness levels, improved impact and fatigue strength and freedom from distortion. Since bainite is formed at constant temperature, the properties of austempered steels are uniform throughout the section. Two important parameters which control the process are cooling rate for the first quench and holding time in the quenching bath. Steel must be cooled at such a rate that austenite to pearlite transformation cannot take place. In other words, the cooling rate has to be faster than the upper critical cooling rate. Thus, cooling rate imposes restrictions on the steel composition and size. Limitation on size is necessary since the part is required to attain uniform temperature of the quenching bath rapidly. Therefore, only comparatively thin sections can be austempered successfully. The suitability of a given steel for austempering can be determined with the help of TTT diagram. Only that steel, for which austenite to pearlite transformation is comparatively slow, is suitable. The nose of the TTT curve should be sufficiently away from the temperature axis. Also, the time required to complete austenite to bainite transformation should be within reasonable limits. Very few alloy steels fulfil these requirements.

5.8 MARTEMPERING

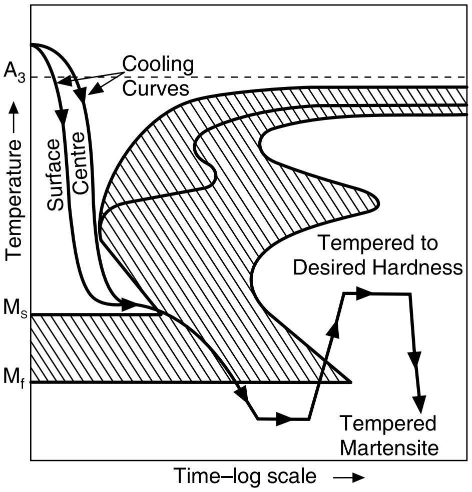


Figure 5.9 Cooling sequence for martempering treatment superimposed on TTT diagram.

Similar to austempering, martempering involves heating the steel to the austenitizing temperature, followed by quenching in a constant temperature bath maintained above M_s point. The usual temperature of the bath lies between 180°C and 250°C. Steel is held in the bath till temperature throughout the section becomes uniform and is equal to the bath temperature. As soon as this temperature is attained, steel is withdrawn and cooled in air. The cooling rate should be sufficiently high and holding time considerably short to prevent transformation of austenite to pearlite or to bainite. Martensite is formed in the second stage, namely, during cooling in air. The cooling sequence for martempering superimposed on TTT diagram is shown in Figure 5.9. Martempering results in minimum internal stresses, reduced tendency towards distortion and cracking and improved mechanical properties as compared to conventional quenching and tempering treatment. The resultant microstructure of martempered steel is martensite. In order to improve properties, martempered steels are generally tempered.

Since the success of the process depends on the formation of martensite, alloy steels are best suited for the process. Almost all alloying elements, except cobalt, increase hardenability. Any steel, which can be hardened by oil quenching, can be martempered successfully. Smaller sections of these steels which can only be hardened by water quenching can also be employed for this process. A large number of steels satisfy these requirements. Another advantage of using alloy steels is that alloying elements increase incubation period. This results in availability of sufficient holding time.

5.9 SUB-ZERO TREATMENT

The resultant microstructure of a fully hardened steel should consist of martensite. In practice, it is very difficult to have a completely martensitic structure by hardening treatment. Some amount of austenite is generally present in the hardened steel. This austenite existing along with martensite is referred to as retained austenite. Conventional metallography does not reveal the presence of retained austenite till it exceeds 20 percent. The presence of retained austenite greatly reduces mechanical properties and such steels do not develop maximum hardness even after cooling at rates higher than the critical cooling rate. The amount of retained austenite depends largely on the chemical composition of steel. For plain carbon steels, the amount of retained austenite increases with the rise in carbon contents. Figure 4.32 shows the effect of carbon on the amount of retained austenite. The problem of retained austenite is more complex in alloy steels. Most of the alloying elements increase the content of retained austenite.

The effect of alloying elements on martensitic transformation has been discussed in detail in Section 4.9.

Strength can be improved in hardened steels containing retained austenite by a process known as sub-zero treatment or cold treatment. Retained austenite is converted into martensite by this treatment. This conversion of retained austenite into martensite results in increased hardness, wear resistance and dimensional stability of steel. When hardened steel is left with retained austenite, it is likely to get transformed into martensite during subsequent thermal cycling. Such transformation leads to unpredictable dimensional changes. Hence, for dimensional stability, it is necessary to eliminate retained austenite by sub-zero treatment. The process consists of cooling steel to sub-zero temperature which should be lower than the M_s temperature of the steel. M_f temperature for most steels lies between –30°C and –70°C. During the process, considerable amount of internal stresses are developed in the steel, and hence tempering is done immediately after the treatment. This treatment also helps to temper martensite which is formed by decomposition of retained austenite during sub-zero treatment. This treatment has been found to be less effective if performed on steels which have been kept at room temperature for several hours or mildly heated, say up to 100 or 150°C, after the hardening treatment. The reason for this is that the stability of austenite is increased considerably by these two processes. The austenite so stabilized does not transform to martensite completely. Therefore, sub-zero treatment must be performed just after the hardening treatment. Mechanical refrigeration units, dry ice, and some liquefied gases such as liquid nitrogen can be used for cooling steels to sub-zero temperatures.

This treatment is employed for high carbon and high alloy steels used for making tools, bearings, measuring gauges and components requiring high impact and fatigue strength coupled with dimensional stability. Case hardened steels, which have a tendency to retain austenite, are also subjected to such treatment.

5.10 PATENTING

The special heat treatment given to medium carbon, high carbon and low alloy steels wire rod is called *patenting*. The process consists of heating the material well above the austenitizing temperature to ensure formation of homogeneous austenite. After soaking for sufficient time at this temperature, the steel is quenched in a bath maintained at a constant temperature. For a given steel, the quenching bath temperature is kept in the vicinity of the nose of TTT curve. This results in transformation of austenite to fine pearlite. Once the transformation is complete, the steel is cooled either in air or by spraying water. In some cases, a small amount of upper bainite has been observed. Lead bath or salt baths are commonly used for quenching the steel. The common temperature of the bath ranges from about 450°C to 550°C. The process is mainly used for wires, ropes and springs.

The higher the soaking temperature (which is always above the austenitizing temperature), the greater is the stress developed, making the steel susceptible to distortion and quench cracks. This is particularly dangerous for high carbon steels. On the contrary, use of too low temperature is again not desirable as it imparts poor mechanical properties, especially ductility, as measured by percentage elongation and percentage reduction in area. Patenting heat treatment results in a homogeneous and fine pearlitic structure. Such a structure is capable of heavier drafting during wire drawing than is possible with common heat treatment processes. Since low carbon steels can be drawn heavily in as-annealed condition, patenting heat treatment is not employed for such steels.

QUESTIONS

5.1 Draw typical heat treatment cycles for subcritical annealing and isothermal annealing. Also describe the processes.

5.2 Differentiate between:

(a) process annealing and recrystallization annealing
(b) diffusion annealing and spheroidizing
(c) normalizing and annealing
(d) stress-relieving and tempering.

5.3 With the help of a suitable diagram, show normalizing and hardening temperature ranges for plain carbon hypereutectoid steels. What is the criteria for the selection of these temperature ranges?

5.4 Discuss the merits and demerits of the following hardening processes:

(a) direct quenching
(b) auto-tempering
(c) interrupted quenching.

5.5 Explain why hardening by quenching is followed by tempering treatment? How do mechanical properties vary with tempering temperature?

5.6 Describe the structural changes that take place during tempering. Is there any fourth stage of tempering? Which type of steels exhibit secondary hardening and why?

5.7 What is meant by temper brittleness? Why does it occur? Are there any remedies for it? Discuss.

5.8 With the help of a suitable diagram, explain the process of martempering. How does it differ from austempering?

5.9 What do the microstructures of martempered and austempered steels consist of? What are the limitations of the two processes?

5.10 Describe the following processes:

(a) Sub-zero treatment
(b) Patenting.

6

Hardenability

INTRODUCTION

When a piece of steel of any appreciable size is heated to austenitizing temperature and then quenched, the cooling rates during quenching vary across the cross-section. The cooling rates at the surface and centre are not the same. The difference in these rates increases with rise in the severity of quench or decrease in the speed of heat abstraction. At the centre of the cross-section, the cooling rate is slowest. This may give rise to the formation of pearlite. Martensite may be formed on the surface, and hence a gradient of hardness exists from the surface to the centre, as shown in Figure 6.1.

Since each grade of steel has its own transformation characteristic, there are different depths of penetration of hardness across the cross-section. Hardenability of steel is a measure of this property. It may be defined as the susceptibility of the steel to hardening when quenched, and is related to the depth and distribution of hardness across a cross-section. It is not related to maximum hardness, and the terms hardness and hardenability should be clearly distinguished. Figure 6.2 shows that steel A has greater hardenability, while steel B has maximum hardness but less hardenability.

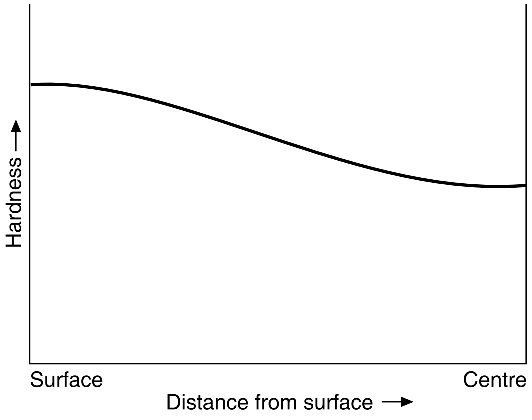


Figure 6.1 **Typical variation of hardness from surface to a centre of a quenched and hardened steel.**

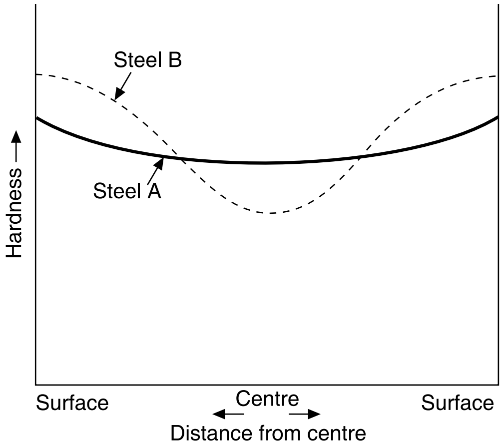


Figure 6.2 **Comparative hardenability and maximum hardness of two steels A and B.**

The maximum hardness depends on the carbon content in the steel. It can be achieved by fulfilling the following conditions:

(i) All the carbon is in solution in austenite.
(ii) Critical cooling rate is achieved.
(iii) No retained austenite is present after quenching.
(iv) No autotempering of martensite takes place.

Hardenability, on the other hand, depends on the addition of alloying elements and grain size of austenite. Besides this, the coolant used for quenching, the size of the specimen, and the criterion used for assessment of hardenability also affect the extent of hardenability.

If drastic cooling is carried out, martensite can also form at the centre of the cross-section of steel because the cooling rate at the centre may exceed the critical cooling rate, and the steel may harden throughout the cross-section. However, drastic quenching may give rise to other undesirable effects such as warping and cracking of the steel. Therefore, hardenability of steel is reflected by its ability to harden (by forming martensite) throughout its cross-section while avoiding drastic quenching.

On the basis of hardenability, steels can be divided into shallow hardening and deep hardening steels. In shallow hardening steels, depth of hardness is limited to a small distance from the surface of the specimen. Carbon steels are shallow hardening type. In deep hardening steels, hardening is uniform throughout the cross-section. A number of alloy steels come under the category of deep hardening steels. In shallow hardening steels, the narrow zone near the surface transforms to martensite. Pearlitic transformation occurs in and around the centre. In intermediate zones, the austenitic transformation takes place in two temperature ranges. Part of transformation occurs at high temperature and the remaining at low temperature. In these intermediate zones, the hardness depends on the relative amounts of the martensitic and pearlitic phases. In deep hardening steels, formation of martensite extends deep into the section.

The martensitic and pearlitic regions can be easily distinguished in the steel section by (i) etching the steel section and viewing the microstructure; (ii) sudden fall in hardness due to increase of pearlitic content in the narrow zone of split transformation; and (iii) by fracture of the sample (martensite breaks with brittle fracture, whereas pearlite breaks with ductile fracture). Microstructurally, steel contains 50 percent martensite and 50 percent pearlite at the brittle-to-ductile-transition temperature.

6.1 SIGNIFICANCE OF HARDENABILITY

For heat treatment, hardenability is a very useful and important property of steel. It determines the rate at which the given steel should be quenched. This also tells about the maximum hardness that can be achieved on the surface of steel of larger cross-section bars, subjected to drastic quenching.

6.2 RELATIONSHIP OF HARDENABILITY WITH TRANSFORMATION RATES

In general, the hardness of steel increases as the transformation temperature decreases. Low temperature transformation products and lower bainite and martensite, when tempered, shown improved ductility and toughness at a given level of strength. To get the benefit of these it is desirable that prior transformation at higher temperatures to pearlite be prevented. In other words, the cooling rate should be very rapid to avoid high temperature transformation, even at the nose of the TTT diagram. This rate, which just allows the transformation of austenite to martensite, is known as (upper) critical cooling rate, and is one of the methods of expressing hardenability. As already explained, cooling rates are different at the surface and the centre of steel bar. This is shown in Figure 6.3 where the cooling curves are plotted to represent paths followed by the surface and the centre of steel bar (about 5 cm in diameter) which is quenched in iced brine. Two other curves, representing the critical cooling rate and the rate at which 50 percent martensite and 50 percent pearlite are formed, are also shown in the figure.

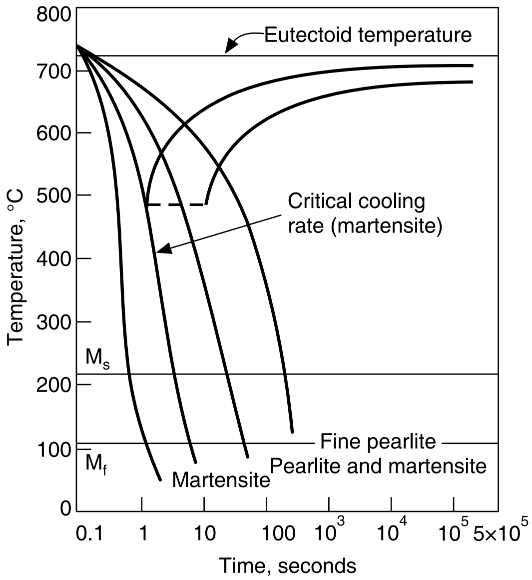


Figure 6.3 **Different microstructures produced due to difference in the cooling rate at the surface and the centre of a cylindrical bar.**

While the microstructure changes with distance along the diameter, there is a corresponding change in the hardness of the steel bar. This observation can be made by taking a circular cross-section of the quenched steel bar and noting the hardness at different points along a diameter. By plotting these results, we get a curve as shown in Figure 6.4. The hardness at the surface is R_c 65, and corresponds to martensitic structure. The pearlitic structure near the centre has hardness around R_c 40. On this figure, hardness of R_c 54 corresponding to hardness of eutectoid steel containing 50 percent martensite and 50 percent pearlite, is drawn as a horizontal line. This horizontal line intersects the hardness curve at the region where the variation of hardness is sharp. Thus, the distance from the surface where the specimen gets cooled at a rate which produces 50 percent martensite can often be subjected to precise experimental measurement. The position corresponding to 50 percent martensite and 50 percent pearlite can be easily measured and can be used as a criterion for measuring the depth to which a steel has hardened with a given quenching medium.

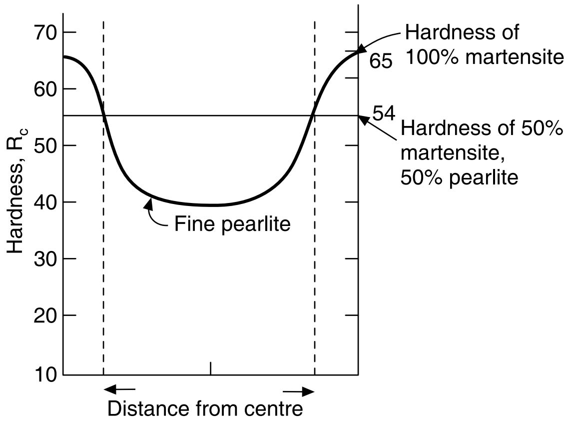


Figure 6.4 **Variation of hardness along the diameter of a quenched cylinder.**

6.3 DETERMINATION OF HARDENABILITY

Hardenability of steel is determined by the following methods:

(i) Grossman's critical diameter method
(ii) Jominy end quench test
(iii) Estimation of hardenability from chemical composition
(iv) Fracture test.

6.3.1 Grossman's Critical Diameter Method

The depth at which 50 percent martensitic and 50 percent pearlitic structure is obtained in a steel bar depends on a number of parameters such as composition, grain size of austenite, the severity of quench and the size of the bar.

M.A. Grossman gave a direct method of measuring hardenability in terms of critical diameter. In this method, a number of steel bars of different diameters are quenched under identical conditions (see Figure 6.5). The length of each bar must be at least five times the diameter to avoid end effects. All the bars with smaller diameters are effectively hardened throughout. If carbon content is ≥ 0.6 percent, a hardness of about R_c 65 is obtained throughout the section. As the diameter of the rod increases, the cooling rate at the centre of steel bar decreases and gives rise to a soft core containing pearlite. Due to this the hardness value decreases. The portion of the section which contains more than 50 percent martensite is considered to be hardened region. That portion which consists of less than 50 percent martensite is regarded as unhardened region. In round bar, the area containing less than 50 percent martensite is called unhardened core. The largest diameter rod (1.5 inches) has only fine pearlite at the centre. The zone of 50 percent martensite can be easily distinguished by etching. The hardness changes most rapidly at a value of R_c 54 which is the hardness for 50 percent martensite and 50 percent pearlite. This inflection point is taken as the transition region between the hardened and unhardened parts of the cross-section of the steel bar. In the given examples, the bar having diameter of 1 inch shows at its centre 50 percent martensite and 50 percent pearlite. This diameter is called the critical diameter (*D*). The critical diameter of the bar is 1 inch. (Bars whose diameters are more than the critical diameter will not harden throughout.) Its value depends on the composition of the steel and means of quenching. The

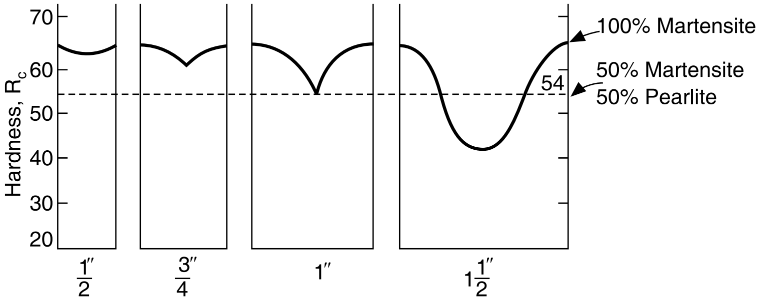


Figure 6.5 **Rods of different diameters 1/2″, 3/4″, 1″ and 1½″ hardened to various depths on quenching in the same medium.**

importance of critical diameter is that it is the measure of the hardenability of a steel. Addition of alloying elements can greatly increase the critical diameter of the steel.

Severity of Quenching Media

It is preferable to express the hardenability of steel in such a way that the effect of quenching medium can be eliminated. This can be achieved if some standard quenching condition is considered for reference. Grossman defined an ideal quenching medium and an ideal critical diameter that corresponds to quenching in ideal medium. The critical diameter corresponding to an ideal quenching medium is called the ideal critical diameter and is denoted by D_I. The quenching conditions can be expressed quantitatively with the help of thermodynamic considerations involved in heat transfer. The severity of quenching medium is indicated by the heat transfer equivalent H and is given by the relation

$$H = \frac{\text{heat transfer coefficient between steel and medium}}{\text{thermal conductivity of the steel}}$$

The ideal quenching medium is the one that removes the heat from the surface of the steel as fast as the heat flows to the surface from the interior portion of the steel bar. Thus, at every instant, the temperature of surface of steel is equal to the temperature of quenching medium. Such a quenching medium does not exist in practice. However, cooling action of such ideal medium on steel can be compared with other quenching media. The most rapid cooling rate is possible at $H = \infty$.

The heat flow from the centre to the surface of the steel occurs at a finite rate and is determined by the thermal conductivity of steel. In actual quenching media, such as water, oil, and brine, the ideal situation does not exist.

When steel at high temperature is immersed in a liquid medium, a vapour blanket forms at the surface of the steel which slows down the rate of heat transfer from the steel to the medium. Agitation or movement of the steel relative to medium removes the vapour blanket and thus increases the rate of cooling. Oil, water and brine are cooling media with severity of quench in ascending order. The viscosity of the liquid also affects quenching efficiency. For example, the lower viscosity of water permits the vapour blanket to be removed faster than oil. In a brine quench (e.g. about 12 percent NaCl dissolved in water), the presence of salt particles causes a series of small explosions to occur near the vapour blanket, and these explosions therefore, violently agitate the liquid medium near the surface of the steel. In air cooling, the rate is slower than in any liquid quenching medium. Agitation of the quenching medium or movement of steel relative to medium helps to remove the vapour blanket and increases the quenching efficiency. The H-values for some typical quenching media and condition are given in Table 6.1.

The relation between critical diameter (D_c), ideal critical diameter (D_I), and severity of quench (H) can be determined from thermodynamic considerations. These relations are shown in Grossman's master graph (Figure 6.6). In this figure, the ideal critical diameter D_I is plotted as the abscissa, and the critical diameter D_c is plotted as the ordinate. A number of curves are plotted in this graph and each belongs to different rates of cooling. In every case, the rate of cooling is measured by the H-value or the severity of quench.

Table 6.1 *H*-Values for Some Quenching Media

H-Value	Quenching medium	State of medium
0.02	Air	Still
0.04	Air	Agitated
0.20	Poor oil quench	No agitation
0.35	Good oil quench	Moderate agitation
0.50	Very good oil quench	Good agitation
0.70	Strong oil quench	Violent agitation
1.00	Poor water quench	No agitation
1.50	Very good water quench	Strong agitation
2.00	Brine quench	No agitation
5.00	Brine quench	Violent agitation
∞	Ideal quench	

From this master graph, by knowing the value of D_c, the corresponding value for D_I can be found out. For example, assuming D_c = 1 inch and H = 5 (for agitated brine quench), the ideal critical diameter or hardenability works out to 1.2 inches with the help of Figure 6.6.

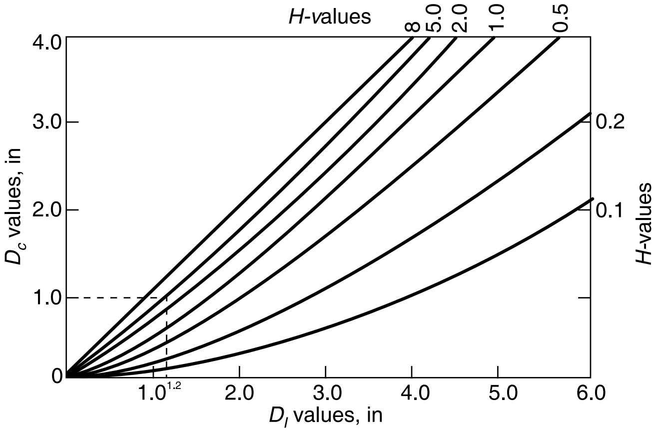


Figure 6.6 The relation between ideal critical diameter (D_I) and critical diameter (D_c) that can be fully hardened by using a quenching medium with a given cooling power *H*.

From Figure 6.6, it can be observed that

$$D_I = D_c \text{ for } H = \infty$$
$$D_I > D_c \text{ for } H < \infty$$

6.3.2 Jominy End Quench Test

The Grossman method of determining the ideal critical diameter D_I is cumbersome and time consuming as a large number of steel bars of varying diameter are to be quenched and tested. This method is a fundamental one and is helpful in explaining the concept of hardenability and ideal critical diameter D_I.

A relatively convenient and the most common method of determining the hardenability of a steel is the end quench test. This is also called the Jominy test. In this test, a steel bar of

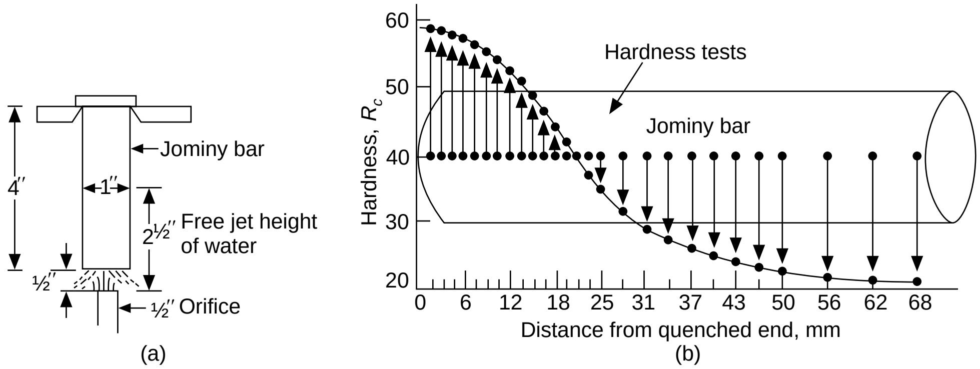


Figure 6.7 (a) Experimental set-up for Jominy end quench test. (b) Hardness variations in quenched Jominy bar.

1 inch diameter and 4 inches long is heated to proper austenitizing temperature. After being soaked for sufficient time, the specimen is quickly placed in a fixture, as shown in Figure 6.7(a). A water jet is opened quickly. Water comes out at a constant pressure through an orifice of 1/2 inch diameter. The distance between orifice and the bottom end of the steel bar is kept at 1/2 inch. The free jet height is 2.5 inches, and the temperature of water is kept around 24°C. A stream of water strikes the lower end of the specimen. The end quenching is continued for about 20 minutes to cool the bar nearly to ambient temperature. The cooling rate is very rapid at the lower end and decreases gradually with increase in distance from the lower end where complete martensitic formation occurs. After quenching, two shallow flat surfaces of 0.02 inch deep are ground 180° apart on the test bar. The hardness is determined at intervals of 1/16 inch along one end of the flat surface of the bar. Near the quenched end, this interval is reduced to 1/32 inch as hardness impressions are smaller and hardness value may vary rapidly. Curves are then plotted showing hardness against distance from the quenched end [see Figure 6.7(b)]. With 50 percent martensite (in 0.8 percent carbon steel), hardness value of R_c 54 is obtained. This distance is measured from the quenched end in units of 1/16 inch. This is called the Jominy distance.

Figure 6.8 shows the master plot between ideal critical diameter D_I and the distance from the quenched end under specific conditions. When the distance from the quenched end is 5/16 inch at R_c 50, it is shown by $J_{50} = 5$. Let 50 percent martensite be formed in steel bar having 0.8 percent carbon at 5/32 inch in an ideal quenching medium. Then the corresponding value for hardenability or ideal critical diameter is 1.4 inches (see Figure 6.8).

Figure 6.9(a) shows the typical Jominy curves for a number of AISI steels (see Table 6.2). A Jominy curve is strictly valid

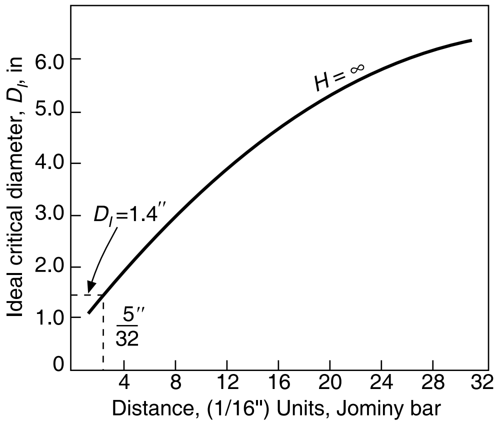


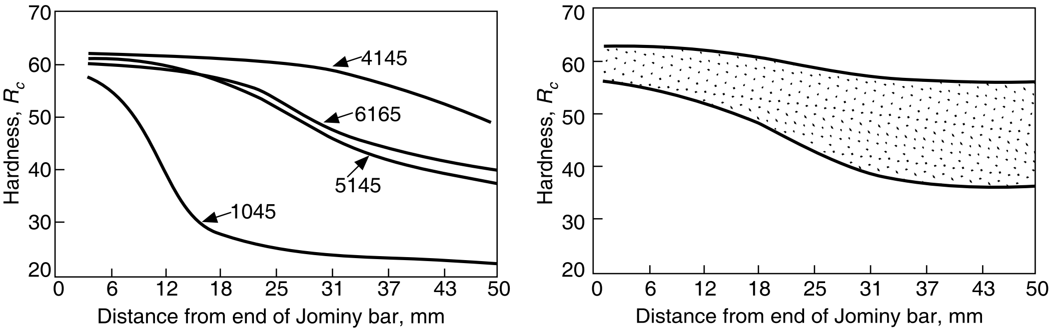
Figure 6.8 The relationship between the Jominy distance and the critical diameters for an ideal quenching medium ($H = \infty$).

only for a given heat of a particular steel because there is tolerance range in chemical composition, which allows an appreciable range in hardenability. Figure 6.9(b) represents the hardenability band for AISI 4145H steel. Hardenability curves for all heats of the steel will lie within this range. For many commercial grades of alloy steels, hardenability limits, as specification standards, have been adopted by the Society of Automotive Engineers. These limits are termed as hardenability bands.

Table 6.2 Brief Description of Some AISI Steels

AISI number	Average alloy content*	Average hardenability of 0.45% carbon steel; ideal critical diameter (in)	Approximate cost relative to carbon steel
10 XX	None	1.1	1
13 XX	1.8–2.0% Mn	3.3	1.2
41 XX	0.5–1.0% Cr, 0.2–0.3% Mo	6.3	1.3
43 XX	0.5–0.8% Cr, 1.8% Ni, 0.3% Mo	7.5 (0.4% C)	1.6
51 XX	0.8–1.l%Cr	3.3	1.2
61 XX	0.8–1.0% Cr, 0.1–0.2% V	3.7	1.4
86 XX	0.6% Ni, 0.5–0.7% Cr, 0.2% Mo	4.0	1.4
87 XX	0.6% Ni, 0.3% Cr, 0.3% Mo	4.4	1.4
92 XX	1.4–2.0% Si, 0.6–0.9% Mn, 0.0–0.7% Cr	2.7 (0.55% C)	1.3

*All the steels contain less than 1.0% Mn, 0.05% P, 0.05% S, 0.35% Si, and residual amount of other elements unless otherwise specified.



(a) Jominy curves for a set of 0.45% carbon steels (b) Hardenability band for AISI 4145 H steel.

Figure 6.9 Representation of Jominy hardenability data.

Attempts have been made by several workers to correlate the cooling rates at different distances along the quenched end of a Jominy bar with the cooling rates at different distances inside the cylindrical steel bar. It can be concluded that, if hardness value at different distances in two steel bars are the same, then the cooling conditions are also identical at those positions. Figure 6.10 shows the relationship between cooling rates of surface, centre and intermediate

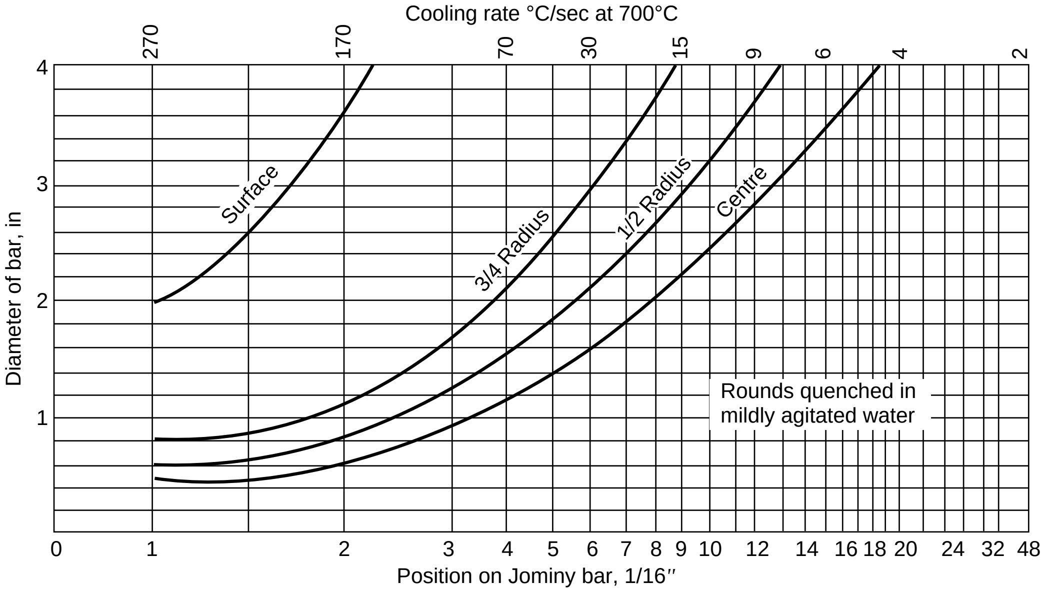


Figure 6.10(a) **Relationship between cooling rates at surface, centre and intermediate positions, size of the bar and distance from quenched end of end-quench test bar which are round in shape and quenched in water.**

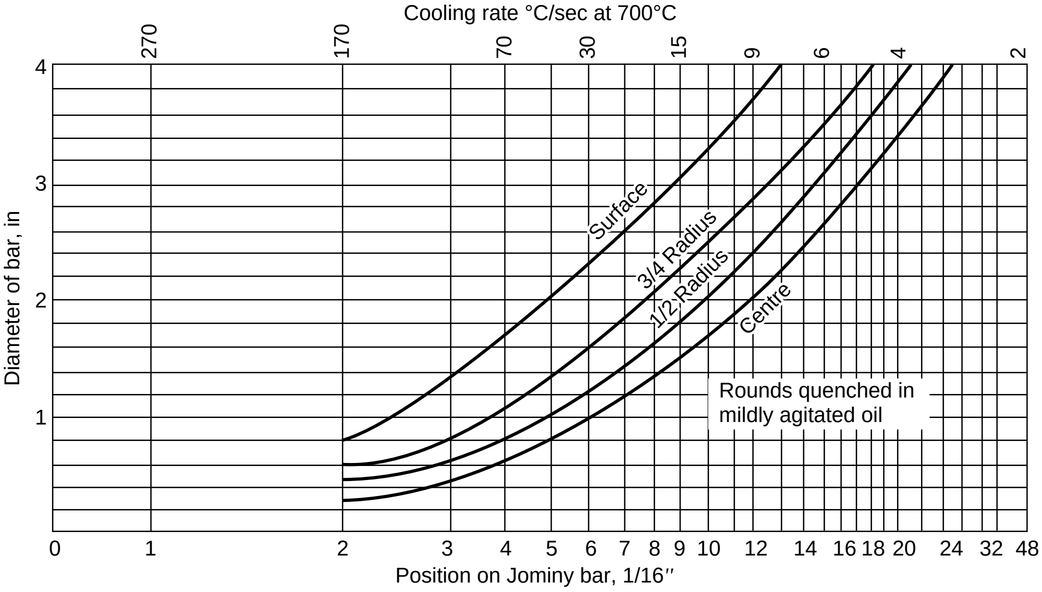


Figure 6.10(b) **Relationship between cooling rates at surface, centre and intermediate positions, size of the bar and distance from quenched end of end-quench test bar which are round in shape and quenched in oil.**

positions, bar sizes and distance from the quenched end of a Jominy bar, for water and oil quenching of round bars. The scale at the top of the end-quench graph gives the cooling rates for the distances from the Jominy test. This correlation is important as it gives interconversion of the two important methods of explaining hardenability.

6.3.3 Estimation of Hardenability from Chemical Composition

Although the ideal critical diameter is generally determined experimentally, it is also possible to estimate it from chemical composition and the grain size of steel. This method is based on the fact that the hardening of steel is controlled basically by the carbon content. Every steel has a base hardenability which depends only on carbon content and grain size. Alloying additions change the rate of reaction. Furthermore, the effect of each alloying element is independent of other alloying elements. The effect is also independent of carbon content and grain size.

Figure 6.11 gives base hardenability in terms of ideal critical diameter. It is clear from the figure that, as the carbon content and grain size decrease, the base diameter value also declines. The effect of alloying elements on the hardenability is shown in Figure 6.12. Molybdenum, manganese and chromium are

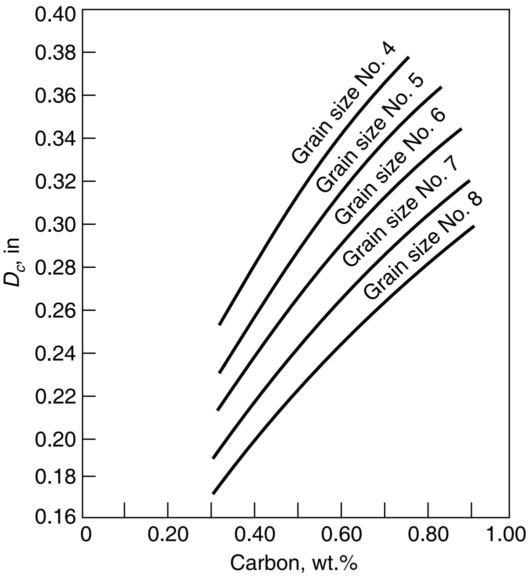


Figure 6.11 **Base diameter as a function of carbon content and grain size.**

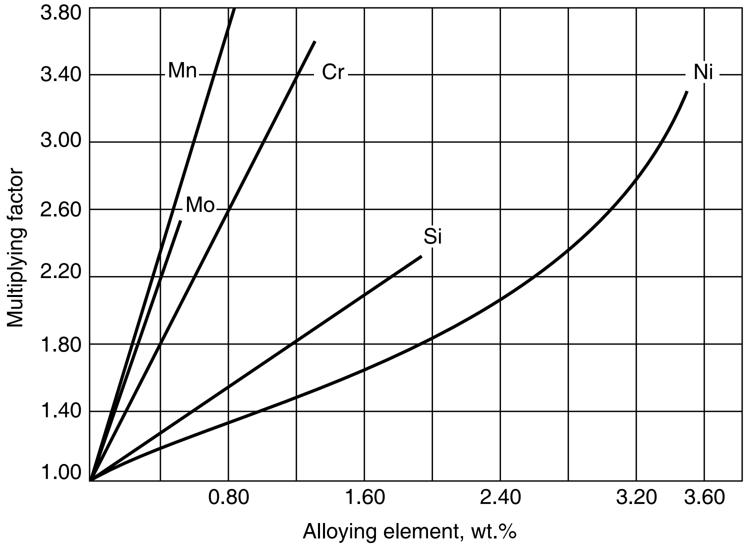


Figure 6.12 **Multiplying factors *F* as a function of weight percent for a set of alloying elements.**

seen to be very effective. The base diameter obtained from Figure 6.11 is multiplied by the multiplying factors F for each of the alloying elements given in Figure 6.12.

$$D_I = D_c \text{ (base diameter)} \times F_{\mathrm{Mn}} \times F_{\mathrm{Cr}} \times F_{\mathrm{Ni}}.$$

For example, for a steel of grain size ASTM 8, with 0.5 percent carbon, 0.6 percent manganese, 1 percent chromium and 2 percent nickel, D_I = 0.22 (from Figure 6.11) × 3.00 (Mn factor from Figure 6.12) × 3.17 (Cr factor from Figure 6.12) × 1.77 (Ni factor from Figure 6.12) = 3.70 inches.

Sulphur and phosphorus are present in low concentrations in steel as impurity. Their combined effect can be ignored in most of the cases. Multiplying factors for sulphur and phosphorus are unity.

6.3.4 Fracture Test

There is a contrast in the nature of fracture undergone by martensitic and pearlitic regions. Whereas martensite formed on the case exhibits brittle fracture, the pearlite formed in the core undergoes ductile fracture. Where there is changeover from martensitic to pearlitic structure, there is corresponding sharp change from brittle to ductile fracture. It is similar to a sudden change in hardness or microstructure as one passes from martensitic to pearlitic region. This region of sudden change is the one that contains 50 percent pearlite and 50 percent martensite. The method based on the nature of fractured surface is successful when the transformation process is quick and a sharp boundary is formed. When the transformation is sluggish, the method cannot be applied since the gradient in hardness is gradual, and it is not possible to get a clear demarcating boundary.

6.4 FACTORS INFLUENCING HARDENABILITY

A steel is said to have high hardenability if austenite of the steel is transformed into martensite, even at relatively slow cooling rates. Any factor, which shifts the nose of the C-curve of CCT diagram to right (see Figure 6.3), makes it easier to form a martensitic structure at a slower cooling rate. All common alloying elements (except cobalt) move the nose of the C-curve to the right. Therefore, they are said to increase the hardenability of the steel. Thus, the shifting of the nose of the C-curve is associated with an increase in hardenability of steel. This statement can also be understood from another angle, i.e. any variable which checks the formation of pearlite increases the hardenability of a steel.

Basically, the hardenability of steel depends on the effect of austenitic grain size, carbon content, and alloying elements, which we now discuss.

6.4.1 Effect of Austenite Grain Size

In many heat treatment processes, the first step is to heat the steel component to the austenitic region. This process is called austenitization. Austenite starts to form when the steel is heated above A_{C1} temperature. The kinetics of this transformation also depends on the starting microstructure, i.e. the previous thermal history. In this process, austenite grains form by nucleation and growth process at cementite and ferrite interfaces. In the beginning, the number of austenite grains formed is large because of the larger interfacial area available for nucleation. Later on, because of the high mobility of atoms at high temperature, the growth of austenite grains takes place. The size of the austenite plays an important role in determining the hardening response of steel. It is clear from Figure 6.11 that fine grained steel shows lower hardenability. This is so because there are more number of sites for heterogeneous nucleation of pearlite provided by the austenitic grain boundaries. This increases the probability of pearlite nucleation. Once austenite to pearlite transformation takes place, the austenite to martensite transformation is suppressed. Accordingly, hardenability decreases.

Coarse grained steel provides less nucleating sites for pearlite transformation. But the use of coarse grain size to increase the hardenability of steel is not recommended. The increase in hardenability is associated with some undesirable changes in properties, such as poor impact properties, quench crack susceptibility, and loss of ductility.

6.4.2 Effect of Carbon Content on Hardenability

Figure 6.11 shows that hardenability of steel is greatly influenced by carbon content. Variation of base hardenability is shown as a function of carbon content and grain size (ASTM Nos. 4-8). In spite of this, pure Fe-C alloys have very low hardenability and the base diameter for a eutectoid steel and ASTM No. 8 is only 0.28 inch. Normal quench will not be effective to harden this steel. Practically, in the commercial grade carbon steel, there is always some amount of manganese and other alloying elements, which increases the hardenability of steel.

Beyond 0.8 percent carbon, hardenability (in hypereutectoid steels) decreases. This is due to the fact that austenitization in this case is carried out in the two-phase region, i.e. autenite plus cementite below A_{cm}. Under such conditions, transformation to austenite is partial. A small amount of cementite remains undissolved. The undissolved carbides restrict the hardenability.

6.4.3 Effect of Alloying Elements

An important role of alloying elements (except cobalt) is to shift the nose of the C-curve to the right in the TTT diagram. This increases the hardenability of steel even at slow cooling rates. To be effective, the alloying elements must be dissolved in austenite. The presence of cobalt is helpful for nucleation and growth of pearlite. Therefore, steels containing this element are difficult to harden. Hardenability depends not only on the presence of alloying elements but also on the mode of distribution of the alloying elements. Undissolved inclusions, such as carbides or nitrides, non-metallic inclusions and inhomogeneity of austenite, decrease the hardenability of steel. On the other hand, the dissolved elements in austenite and homogeneity of austenite increase the hardenability of steel.

Figure 6.13 shows the effect of chromium on the hardenability of steel.

The rate of formation of austenite is directly proportional to temperature. This increases with rise in temperature. Firstly, ferrite transforms to austenite. This is followed by dissolution of carbides after which the austenite remains inhomogeneous. At such places where initially ferrite was present, the concentration of carbon remains low. Therefore, the time required for complete homogenization is much longer than the time required for the formation of say 99 percent of austenite. In the case of alloy steels, homogenization of austenite takes even longer time as the rate at which alloy carbides dissolve is much slower. A carbide forming

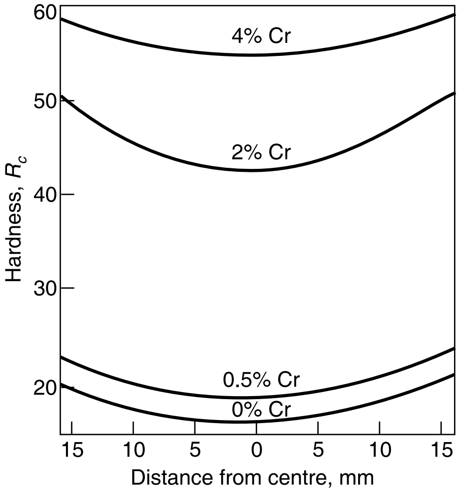
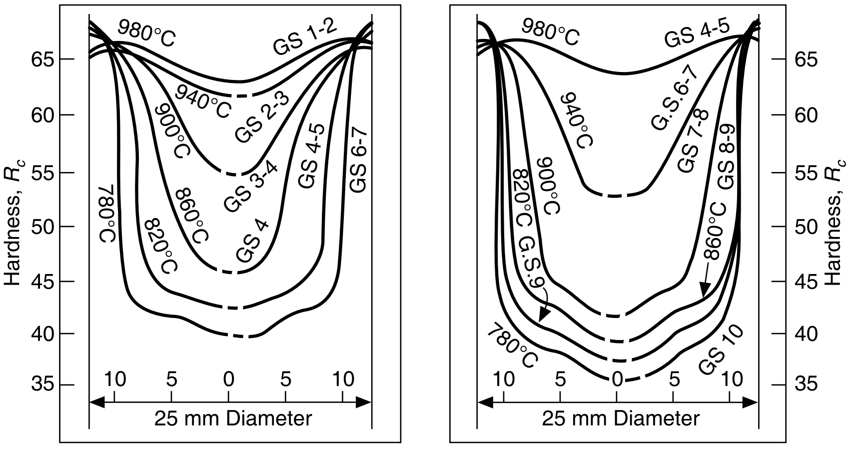


Figure 6.13 **Variation in hardness from end to end of oil quenched 40 mm 0.35% carbon steel bar with different chromium contents.**

element which is not dissolved in austenite has no effect on hardenability, except that it may check the grain growth. So, in such cases hardenability of steel is reduced. Because of the presence of undissolved carbides, the percentage of alloying element and carbon decreases in austenite. Quenching from higher temperature increases hardenability due to coarsening of austenite grains and dissolution of carbides which cannot be dissolved in austenite at lower temperatures. Therefore, such carbides are not preferred for hardening. For example, vanadium carbide dissolves in solution at about 1050°C, whereas niobium carbide dissolves at about 1150°C. These temperatures are quite high in comparison to the temperature of dissolution of other carbides in austenite. Even after the dissolution of these carbides, there remains the problem of homogenization of austenite, which is a very slow process as diffusion of these elements is itself very sluggish. Therefore, a steel in which vanadium is present will tend to be fine grained; that is, coarsening of austenite grains will not occur until a very high temperature is attained. Heating to high temperature is not economical, and it reduces the impact properties of heat treated steels. Figure 6.14 shows the effect of vanadium on hardenability as compared with a plain carbon steel. From Figure 6.14, it is clear that the coarser grains of plain carbon steel have more hardenability than the vanadium steel when heated more or less to the same temperature. For example, when both



Carbon steel Vanadium steel

Figure 6.14 **Variation of hardness across 25 mm, 0.9% carbon steel bar, and 0.9% carbon, 0.27% vanadium steel bar.**

steel samples are heated to 900°C and quenched, the austenite grain size of plain carbon steel is 3–4, whereas that of vanadium steel is 7–8.

The role of non-metallic inclusions in steel is to check the austenitic grain growth. The non-metallic inclusions may enhance the pearlitic nucleation and growth process because of their fine distribution. Thus, their presence lowers the hardenability of steel. Fine grained steels are heated to high temperature and soaked for a long time for grain coarsening and consequent improvement in hardenability. Such heat treatment may not lead to improvement in hardenability in some cases. This may be due to the presence of non-metallic inclusions which promote a high rate of nucleation of pearlite.

Boron in very minute concentrations (0.001–0.003%) has pronounced effect in improving the hardenability of steels. It is believed that boron dissolved in austenite segregates along the grain boundaries of austenite and thus restricts the nucleation of proeutectoid ferrite.

As the compositions of commercial steels are specified over a range, the hardenability also varies over a range. For example, AISI 8640 steel has the following composition limits:

Carbon	0.38–0.43%
Manganese	0.75–1.00%
Silicon	0.20–0.35%
Nickel	0.40–0.70%
Chromium	0.40–0.60%
Molybdenum	0.15–0.25%

Let us take first the maximum values of respective elements and find out their respective multiplying factor from Table 6.3. (Figure 6.12 gives the graphical method to find out the multiplying factor.)

Percentage of element	*Multiplying factor*
1.00% Mn	4.333
0.35% Si	1.245
0.70% Ni	1.255
0.60% Cr	1.255
0.25% Mo	1.750

The base hardenability is 0.1976 (for 0.4% carbon steel and ASTM grain size No. 8). The total hardenability is given by

$$D_I = 0.1976 \times 4.333 \times 1.245 \times 1.255 \times 2.296 \times 1.75 = 5.40 \text{ inches}$$

For minimum composition values, the multiplying factors are as follows:

Percentage of element	*Multiplying factor*
0.75% Mn	3.500
0.20% Si	1.140
0.40% Ni	1.146
0.40% Cr	1.864
0.15% Mo	1.450

The base hardenability for 0.38% carbon steel is 0.1974. The total hardenability of steel is given by

$$D_I = 0.1974 \times 3.5 \times 1.14 \times 1.146 \times 1.8640 \times 1.45 = 2.44 \text{ inches}$$

Table 6.3 Hardenability Multiplying Factors

Percent carbon	Grain Size			Mn	Si	Ni	Cr	Mo
	6	7	8					
0.05	0.0814	0.0750	0.0697	1.167	1.035	1.018	1.1080	1.15
0.10	0.1153	0.1065	0.0995	1.333	1.070	1.036	1.2160	1.30
0.15	0.1413	0.1315	0.1212	1.500	1.105	1.055	1.3240	1.45
0.20	0.1623	0.1509	0.1400	1.667	1.140	1.073	1.4320	1.60
0.25	0.1820	0.1678	0.1560	1.833	1.175	1.091	1.54	1.75
0.30	0.1991	0.1849	0.1700	2.000	1.210	1.109	1.6480	1.90
0.35	0.2154	0.2000	0.1842	2.167	1.245	1.128	1.7560	2.05
0.40	0.2300	0.2130	0.1976	2.333	1.280	1.146	1.8640	2.20
0.45	0.2440	0.2259	0.2090	2.500	1.315	1.164	1.9720	2.35
0.50	0.2380	0.2380	0.2200	2.667	1.350	1.182	2.0800	2.50
0.55	0.273	0.251	0.231	2.883	1.385	1.201	2.1880	2.65
0.60	0.284	0.262	0.241	3.000	1.420	1.219	2.2960	2.80
0.65	0.295	0.273	0.251	3.167	1.455	1.237	2.4040	2.95
0.70	0.306	0.283	0.260	3.333	1.490	1.255	2.5120	3.10
0.75	0.316	0.293	0.270	3.500	1.525	1.273	2.62	3.25
0.80	0.326	0.303	0.278	3.667	1.560	1.291	2.7280	3.40
0.85	0.326	0.312	0.287	3.833	1.595	1.309	2.8360	3.55
0.90	0.346	0.321	0.296	4.000	1.630	1.321	2.9440	3.70
0.95				4.167	1.665	1.345	3.0520	
1.00				4.333	1.700	1.364	3.1600	

These two values of hardenability for the same grade of steel show that hardenability varies over a wide range.

QUESTIONS

6.1 Differentiate between hardness and hardenability.

6.2 Define and explain the term severity of quench.

6.3 What are the various methods of determining hardenability?

6.4 Discuss how hardenability is affected by:

(a) austenite grain size
(b) carbon content
(c) presence of alloying elements.

6.5 Explain why hardenability is improved by coarsening of austenite grain size.

6.6 Describe the Jominy end quench method of determining hardenability.

7

Quenchants

INTRODUCTION

As applied to the heat treatment of steels, quenching is a process of rapid cooling of steel from austenitizing temperature. Quenching results in the transformation of austenite to martensite (a non-equilibrium constituent). During cooling, heat must be extracted at a very fast rate from the steel piece. This is possible only when a steel piece is allowed to come in contact with some medium which can absorb heat from the steel piece within a short period. Under ideal conditions, all the heat absorbed by the medium should be rejected to the surroundings immediately. A medium that is used for quenching is known as a quenchant. The ease with which martensite formation takes place, i.e. the effectiveness of a quenching process, largely depends on the characteristics of the quenchant used. In addition to it, some other factors, such as chemical composition of the steel, design of steel component, and surface conditions of steel component, also control the efficiency of the quenching process. (These factors have already been discussed in Section 5.5.1.) Once a quenching medium is selected, the properties of quenched steel is largely determined by the manner in which the medium is used. (Various quenching methods have already been dealt with in Section 5.5.2.) Most of the quenchants commonly used are liquids. Air and gases are used in special cases.

7.1 REMOVAL OF HEAT DURING QUENCHING

The mechanism of removal of heat from the work-piece as a result of quenching is not as simple as that associated with annealing or normalizing. The removal of heat during quenching is complex in the sense that heat is removed in three stages. As soon as a work-piece comes into contact with a liquid coolant (quenchant), the surrounding quenchant layer is instantaneously heated up to the boiling point of the quenchant and gets vaporized due to the high temperature of the work-piece. This vapour forms an envelope around the work-piece and thus checks further cooling of the work-piece. This is so because the vapour film is a poor conductor of heat. The work-piece is cooled at this stage by conduction and radiation through the vapour film. Only the surface of the work-piece is cooled considerably prior to the formation of this vapour envelope. This is referred to as the first stage of cooling and is named *vapour blanket stage*.

The first stage is followed by the second stage known as *vapour transport cooling stage* or *liquid boiling stage*. The temperature of the work-piece comes down, though very slowly, in the first stage and, consequently, the vapour film is no longer stable below a particular temperature. This is the start of the second stage. As soon as the vapour film is broken, the quenchant comes in contact with the surface of the work-piece and is immediately pushed away from it in the form of bubbles. Fresh coolant now comes in contact with the work-piece surface and the process is repeated. It continues till the temperature of the surface of the work-piece comes down to below the boiling point of the liquid. Very rapid cooling takes place at this stage as the quenchant is always in contact with the surface of the work-piece.

The third stage is known as liquid cooling stage or convection stage. It starts when the temperature of the surface of the work-piece becomes equal to the boiling point of the quenchant. Cooling at this stage takes place by both conduction and convection processes. The rate of cooling is the slowest at this stage. Figure 7.1 shows the cooling curve for a work-piece quenched in a liquid coolant.

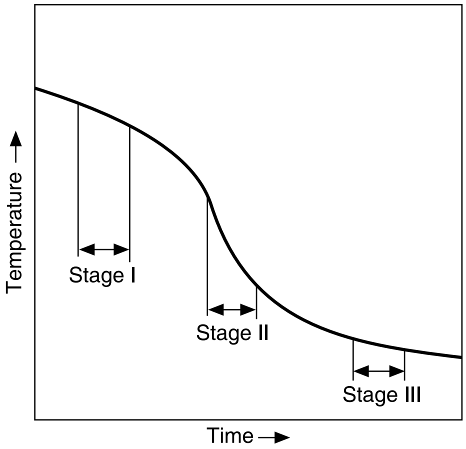


Figure 7.1 Various stages of heat removal during quenching.

7.2 CHARACTERISTICS OF QUENCHANTS

The effectiveness of a quenchant depends largely on its characteristics. Some of the factors which control quenching characteristics are as follows:

(i) Temperature of the quenchant
(ii) Latent heat of vaporization
(iii) Specific heat of the quenchant
(iv) Thermal conductivity of the quenchant
(v) Viscosity of the quenchant
(vi) Degree of agitation of the quenching bath.

The effect of these parameters on quenching is worth considering in detail.

The temperature of the quenching medium is of great significance. In general, the third stage is seriously affected by change in the temperature of the quenchant. The higher the temperature of the coolant, the shorter will be the time required for attainment of thermal equilibrium between the coolant and the work-piece. Thus, cooling rates are slowed down and so higher temperatures are generally employed where distortion or cracking problems are pronounced. Water is used in the temperature range 20–40°C. There is a rapid loss of the cooling power of the water as temperature is raised above 60°C. General purpose mineral oils, used as quenchants, are normally used in the temperature range 50–80°C. Hot quenching oils are used in the temperature range 100–150°C, whereas marquenching oils are used above 150°C.

The latent heat of vaporization of a liquid is defined as the amount of heat required to convert a unit mass of the liquid into vapour without any change in temperature. It varies for different liquids. Quenchants with relatively low latent heat of vaporization will be converted into vapour easily. This will promote the first stage of cooling. In addition, profound fuming will take place on quenching, and there may be a pollution problem. Also, the consumption of the quenchant will be high. On the other hand, quenchants with high latent heat of vaporization will restrict the duration of the first stage. However, most of the heat from the work-piece will be confined to the quenchant itself and the temperature of the quench bath will rise significantly. This will lower the cooling rate.

The specific heat of a substance is defined as the quantity of heat required to raise the temperature of unit mass of the substance through one degree. A quenchant with lower specific heat will be heated up at a faster rate than the one with a higher specific heat. Therefore, a quenchant with low specific heat cannot be used for mass production because of the significant variation in the temperature of the quenchant. However, it can be employed for mass production with installation of proper cooling arrangement. Quenchants with high specific heats can be employed successfully for mass production.

The ability of a material to conduct heat from one part to the other as well as to an adjacent body when in physical contact with each other is referred to as thermal conductivity. The higher the thermal conductivity of a quenchant, the more rapid will be the transfer of heat from it to the surroundings. lt will result in lowering of quenchant temperature and, consequently, faster cooling of the work-piece.

The higher the viscosity of the quenchant, the slower will be the cooling rate since heat transfer from the work-piece to the quenchant as well as within the mass of quenchant will be poorer. A quenchant with lower viscosity is employed where faster cooling rate is required. Low viscosity in a quenchant also restricts the duration for which the first stage of cooling occurs.

The higher the degree of agitation, the better will be the uniformity in the properties of the work-piece. Agitation of quenching bath results either in the complete elimination of the vapour envelope around the work-piece or reduction in the duration of the existence of this film envelope. The work-piece thereby permits fast removal of heat. It also helps in maintaining uniform temperature throughout the quenching bath and relatively fast removal of heat from the quenchant to the surroundings.

7.3 QUENCHING MEDIA

Some of the widely employed quenching media are water, aqueous solutions, oils, molten salts and air. In addition to these, media such as polymer solutions, molten metals and gases are also used but to a lesser extent. We now discuss a few common quenchants.

7.3.1 Water

Water is the most popular quenching medium because of its low cost, availability in abundance and easy handling. No pollution problem is associated with the use of water and it can be easily disposed of. Water has maximum cooling rate amongst all common quenchants except aqueous solutions. Water can therefore be successfully used for carbon steels, alloy steels and non-ferrous alloys. Most of the non-ferrous alloys, especially precipitation hardenable type, are solution annealed, followed by water quenching. The layer of scale formed on the surface during heating is also broken by water quenching, thus eliminating an additional process of surface cleaning.

In practice, the applicability of water as quenching medium is restricted only to plain carbon steels and a few grades of low alloy steels. These steels are characterized by low hardenability values. For deep hardenable steels, water quenching generally results in development of cooling rates higher than the critical cooling rate. Such a cooling rate generally leads to development of excessive internal stresses in the quenched piece, leading to distortion, or even to development of cracks. High cooling rate obtained by water quenching also puts limitation on the shape of the object to be heat treated. Complicated shapes cannot be water-quenched for obvious reasons. Thus, only articles with simple geometrical shapes can be water-quenched.

Another major disadvantage associated with water quenching is that vapour blanket stage is quite stable for prolonged periods. The duration of the period increases with the complexity of shape of work-piece as complicated shapes favour vapour entrapment. This problem can be minimized or eliminated by agitating the quenching bath.

Best results are obtained by using water at room temperature, i.e. in the temperature range 20–40°C. Increase in the temperature of water results in lowering the cooling power of water (see Figs. 7.2 and 7.3). Water-quenched objects are prone to get rusted. So they are either dressed or coated with some rust preventive chemical.

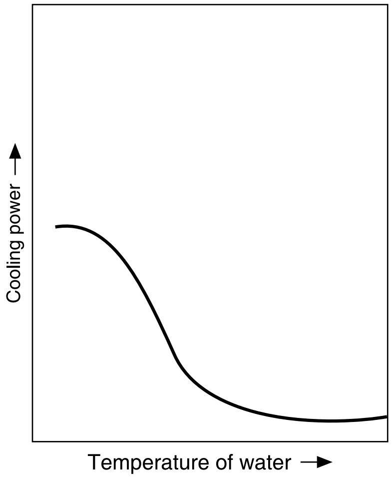


Figure 7.2 Effect of temperature of water on cooling power.

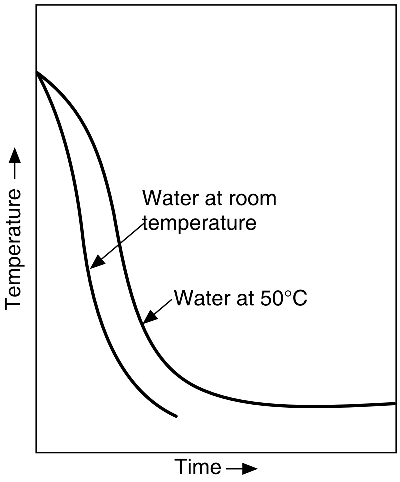


Figure 7.3 Effect of temperature of water on cooling curve of quenched steel specimen.

7.3.2 Aqueous Solutions

Addition of highly ionized salts to water decreases the viscosity of water and reduces the duration of vapour blanket stage. Both these parameters help in improving the cooling power of water and minimize the necessity of agitating the quenching bath. However, by increasing the degree of agitation, the cooling rate may be increased further. In this way, the possibility of formation of soft spots arising from the presence of steam pockets is reduced to a great extent.

Aqueous solutions of salts such as sodium chloride and calcium chloride are referred to as brine solutions, whereas solution of sodium hydroxide is referred to as caustic solution. Such solutions are of great use, especially for shallow hardenable grades of steels. Though the cooling rates are high in these solutions, distortion is less severe than in water quenching. Just as in the case of water, these solutions too are commonly used at room temperature. However, maximum cooling power is obtained when the temperature of aqueous solution is maintained at about 20°C. Aqueous solutions, both brine and caustic with about 5–10 percent concentration are in general use. However, the concentration of the solutions varies in commercial practice. In fact, no relationship between concentration of solution and cooling power of any type is readily available.

These solutions have certain disadvantages over water. They are costlier than water due to the extra cost of the salts. The corrosive nature of these solutions is a major limitation. Due to this, the cost of handling equipments such as quench tanks and pumps increases. Special attention should be paid to the periodical checking of handling equipments and to solution which in turn raises the labour cost. Production of corrosive fumes not only pollutes the atmosphere but also affects the human skin and service life of nearby equipments.

7.3.3 Oil

Most of the oils used as quenchants are mineral oils. These are, in general, paraffin based and do not possess any fatty oils. Quenching in oils provides slower cooling rates as compared to those achieved by water quenching. The slow cooling rate developed during oil quenching reduces the possibility of introduction of hardening defects in the quenched work-piece. The temperature difference between the case and core of the work-piece is less for oil quenching than for water quenching.

Quenching oils are graded according to their viscosity values. Commonly used quenching oils have the viscosity values of about 100 SUS (Saybolt Universal Seconds) at 40°C. For these oils, the duration of the first stage is found to be longer than the corresponding value achieved by water quenching. In addition to this, the cooling rate in the second stage is also considerably lower, and the duration of this stage is shorter than that associated with water quenching. On account of all these factors, these oils are not considered well suited as quenchants where severe quenching is desired. However, they offer less distortion. For majority of applications, these oils are used at temperatures varying from room temperature to 65°C. However, in certain cases, specially where slow cooling rates are required, oils are maintained in the temperature range 65–95°C.

For obtaining faster cooling rates, oils with viscosity values as low as 50 SUS at 40°C are employed. These oils are referred to as fast quenching oils. The duration of the first stage is considerably less for these oils than for common oils. The initial cooling rate associated with these oils approach the value developed by water quenching.

Hot quenching oils generally possess viscosity values in the range 250–3000 SUS at 40°C. These include plain and inhibited mineral oils, which are generally used in the temperature range 100–150°C. Use of these stable oils results in low distortion and cracking. These oils are very well suited to quenching intricately shaped objects.

Marquenching oils have viscosity values more than 2000 SUS at 40°C. These oils are inhibited to provide excellent oxidation and thermal stability. Marquenching oils are generally used at temperatures higher than 150°C. These oils have specific advantages such as uniform cooling rate, minimum possible distortion and cracking.

The presence of water as an impurity in quenching oils is most undesirable. It may lead to development of non-uniform hardness distribution, distortion and cracks. Water can be removed by heating oils to 130°C for about 4 hours.

Oil-water emulsions are sometimes used as quenchants. However, this practice is not common. Cooling characteristics of these emulsions are not well established till date, and thus they are not reliable quenchants. These emulsions have all possible drawbacks due to water and oil quenching and hence are inferior.

7.3.4 Air

Many alloy steels are capable of getting hardened by cooling either in still air or blast of air. Such steels are popularly known as air hardening steels. These steels are almost free from distortion problem. However, the problem of oxidation during cooling (quenching) may be encountered in practice. Many grades of tool steels are subjected to air hardening. Cooling rates may be improved upon by using air-water mixtures.

7.3.5 Gases

The use of gases as quenchant results in development of intermediate cooling rates which are faster than those associated with still air and slower than those developed by oil quenching. A fast moving stream of gas removes the heat from the work-piece at a much faster rate than by still air quenching. Among different gases that may be considered for this purpose, namely, hydrogen, helium, nitrogen and argon; hydrogen possesses maximum cooling efficiency, followed by helium, nitrogen and argon in decreasing order of cooling powers. In general, only nitrogen is used as quenchant. The reasons for this are: Hydrogen is not safe to use, helium is quite expensive, and argon possesses the lowest cooling efficiency.

The cooling efficiency of gaseous quenchants can be raised to a significant extent by using a fast moving stream of gas mixed with droplets of water. Here, fine droplets of water provide additional source for the heat extraction from the work-piece surface. These droplets will always be in contact with surface of work-piece, and very efficient and effective cooling of work-piece will take place. Due to continuous flow of gas stream, there is no possibility of formation of vapour envelope around the work-piece.

7.3.6 Salt Baths

Since long, salt baths have been used as quenchants in commercial practice, specially for tool steels. Salt bath is the best suited quenching medium for a steel with good hardenability and thin sections. Some of the advantages offered by salt bath quenchants are as follows:

(i) Temperature is uniform throughout the bath.
(ii) There is uniformity in the rate of heat transfer from the work-piece.

(iii) There is no danger of oxidation, carburization or decarburization during cooling.
(iv) Selective hardening can be performed.

Some common salt baths are $NaNO_3$, 50% $NaNO_3$ + 50% KNO_3, 50% $NaNO_3$ + 50% KNO_2 and 20% NaOH + 80% KOH.

7.3.7 Synthetic Quenchants

Synthetic quenchants are relatively a new introduction in the field of quenchants. Commonly available synthetic quenchants are generally oxyalkylene polyglycol based, polyalkylene glycol based or polyvinyl pyrolidone based organic materials. Polyalkylene glycol based materials are more commonly used as quenchants. These organic materials are water soluble and, therefore, quenchants with widely differing characteristics can be developed by varying the concentration of the solution. Attainment of desired cooling rates, better heat transfer characteristics, and inverse solubility are the salient features of these quenchants. Inverse solubility is a unique feature of these quenchants, and it enables a thin film of glycol to wet the hot work-piece as it is quenched. This helps in two ways: Firstly, it results in the suppression of formation of vapour envelope around the work-piece. Secondly, it provides uniform rate of heat transfer, resulting in minimum distortion in the work-piece. As the temperature of the work-piece comes down, the thin film of glycol dissolves and thereby permits fast removal of heat from the work-piece. These quenchants are very safe as there is no danger of fire hazards or pollution. They are used at room temperature. For varying cooling rates, concentration of the solution is changed. Slower cooling rates can be achieved by increasing the concentration. Agitation of the bath may be avoided. The consistency of the results is one of the important factors enhancing the popularity of quenchants. These are well suited for mass production since rise in bath temperature is much less than in oil baths because of the high specific heats of these quenchants.

QUESTIONS

7.1 Explain the mechanism of heat removal from a work-piece during quenching.

7.2 Water is the most commonly used quenching medium. Why?

7.3 Explain why oil is considered to be a slower quenching medium than water? How does effectiveness of oil depend on its viscosity, specific heat and latent heat of vaporization?

7.4 Name a few commonly employed salt baths as quenchants. Salt baths, though expensive, are very useful quenchants. Comment.

7.5 What are synthetic quenchants? Enumerate the advantages offered by these quenchants. Give reasons in support of your answer.

8

Chemical Heat Treatment of Steels

INTRODUCTION

Chemical heat treatment is the process used to achieve different properties in core and steel components. There are situations in which the requirement is such that the outer surface should be hard and wear resistant and the inner core more ductile and tougher. Such a combination of properties ensures that the component has sufficient wear resistance to give long service life and at the same time has sufficient toughness to withstand shock loads. Such combination can basically be achieved by two different methods.

The first method is known as thermochemical treatment because the surface composition of the steel changes by diffusion of carbon and/or nitrogen (as in carburizing and nitriding) and sometimes by other elements. The second method involves phase transformation by rapid heating and cooling of the outer surface (flame hardening, induction hardening and electron beam and laser hardening). The aim of both methods is the same.

Components which are surface hardened include ball and tapered bearings, gears, bushings, rock drill bits, dies, gun barrels, cam shafts, crank pins, valve rocker shafts and axles. In this chapter, various thermochemical treatments are considered. Chapter 9 summarizes important surface hardening treatments which do not involve any change in chemical composition.

8.1 CARBURIZING

This is the most widely used process for surface hardening of steels. It is carried out on low carbon steels which contain from 0.10% to 0.25% carbon and are known as carburizing steels. Examples of such steel grades are AISI 1018, 1117, 4023, 4118, 5015 and 8620.

Generally, carburizing is carried out in the temperature range 900–930°C, and the surface layer is enriched with carbon up to 0.7–0.9 percent. In this process, carbon is diffused into steel by heating above the transformation temperature and holding the steel in contact with a carbonaceous material which may be a solid medium, a liquid or a gas. Under such conditions, carbon is absorbed in solid solution in austenite. As the solubility of carbon is more in austenitic state than in ferritic state, fully austenitic state is essential for carburizing. The surface hardness depends on the relationship of hardness (VPN) with carbon content which differs slightly for different grades of steels, as shown in Figure 8.1. Carburizing can be

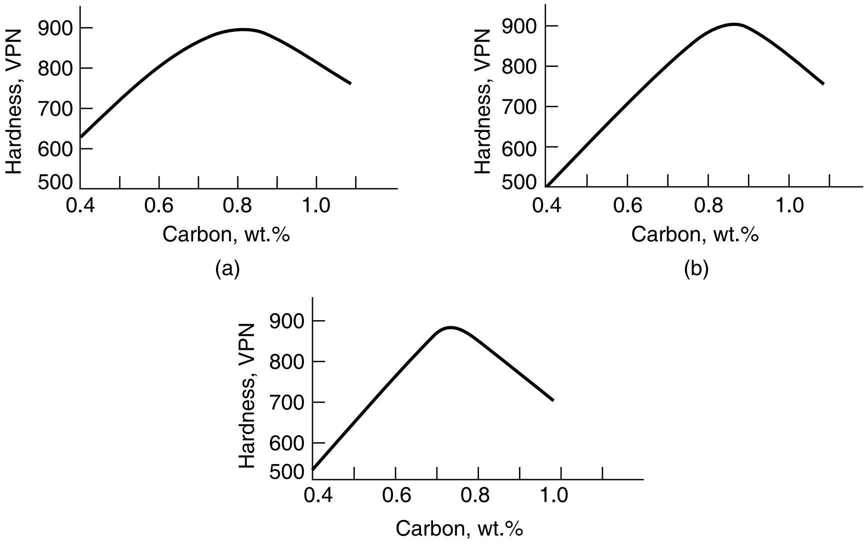


Figure 8.1 Relationship between hardness and carbon content for carburized steels in quenched condition. (a) plain carbon steel (En 32). (b) C-Mn steel (En 201). (c) Ni-Cr steel (En 351).

divided into three categories according to the carbonaceous material used: pack carburizing, liquid carburizing, and gas carburizing, which we now discuss.

8.1.1 Pack Carburizing

This method of carburizing is also known as solid carburizing. It is the oldest method of carburizing steel components. In this process, steel components to be heat treated are packed with 80 percent granular coal and 20 percent $BaCO_3$ as energizer in heat resistant boxes and heated at 930°C in furnace for a specific period of time which depends on the case depth required. Such a high temperature in furnace helps in absorption of carbon at the outer layer. The following reactions take place:

(i) Energizer decomposes to give CO gas to the steel surface:

$$BaCO_3 \rightarrow BaO + CO_2$$
$$CO_2 + C \rightarrow 2CO$$

(ii) Carbon monoxide reacts with the surface of steel:

$$2CO + Fe \rightarrow Fe(C) + CO_2$$

(iii) Diffusion of carbon into steel.

(iv) CO_2 formed in step (ii) reacts with "C" in the coal:

$$CO_2 + C \rightleftharpoons 2CO$$

For a given steel at a given temperature, the depth of penetration is dependent on diffusion and can be related to the time t by the equation

$$\text{Case depth} = k \sqrt{t}$$

where k is a constant.

Generally, carburizing time varies from 6 hours to 8 hours, and case depth obtained varies from 1 mm to 2 mm. In this process, the results depend on the quality of coal. So, there is some element of uncertainty. Here, temperature and case depth control are less than in liquid and gas carburizing.

8.1.2 Liquid Carburizing

Liquid carburizing is also popularly known as salt bath carburizing. In this process, carburizing occurs through molten cyanide (CN) in low carbon steel cast pot type furnace heated by oil or gas. Bath temperature is maintained between 815°C and 900°C. The life of pot depends on quality of material, operating temperature and mode of operation, viz. whether it is continuous or intermittent. Continuous and automatic processes give good end results. The bath surface is covered with graphite or coal to reduce radiation losses and excessive decomposition of cyanide.

Different salt mixtures used in this process are named according to their carbon potential activity. Besides sodium or potassium cyanide, the bath contains (i) sodium and potassium chlorides, and (ii) barium chloride which acts as an activator.

The reactions in cyanide salt bath are as follows:

$$\mathrm{BaCl_2 + 2NaCN \rightarrow Ba(CN)_2 + 2NaCl}$$
$$\mathrm{Ba(CN)_2 + Fe \rightarrow Fe(C) + BaCN_2}$$

Some beneficial nitrogen diffusion may also take place through oxidation of CN to CNO.

In liquid carburizing, heating time is short and heat transfer is rapid. There is complete uniformity of the carburized layer in the component. This process gives a thin and clean hardened layer (0.08 mm thick). However, extensive safety precautions are required to avoid explosions.

8.1.3 Gas Carburizing

This is the most widely used method of carburizing. It is carried out in retort type, sealed quench type, or continuous pusher type furnaces. These furnaces are either gas fired or are heated electrically. Gas carburizing temperature varies from 870°C to 950°C.

Gas atmosphere for carburizing is produced from liquid (methanol, isopropanol) or gaseous hydrocarbons (propane and methane). An endothermic gas generator is used to supply endothermic gas. A mixture of propane or methane with air is cracked in hot retort of an endogas generator to form carrier gas, whose dew point is adjusted at about +4°C by proper gas/air ratio. The approximate composition of this gas is as follows:

Nitrogen	40%
Hydrogen	40%
Carbon monoxide	20%
Carbon dioxide	0.3%
Methane	0.5%
Water vapour	0.8%
Oxygen	in traces

Such a gas acts as a 'carrier gas' for the process. Furnace chamber is purged with this gas to maintain a slightly positive pressure. This in turn prevents infiltration of air from atmosphere. This gas also prevents oxidation of the steel during heating. When the material reaches carburizing temperatures, propane or methane is introduced to maintain a specific carbon potential. Carbon potential is computed by measuring the dew point or carbon dioxide, by infra-red absorptiometry or oxygen, by an electrolytic potential technique using a zirconia probe.

During gas carburizing, the following reactions take place:

(i) $C_3H_8 \rightarrow 2CH_4 + C$ (cracking of hydrocarbon)
(ii) $CH_4 + Fe \rightarrow Fe(C) + 2H_2$
(iii) $CH_4 + CO_2 \rightarrow 2CO + 2H_2$
(iv) $2CO + Fe \rightarrow Fe(C) + CO_2$

Carburizing occurs mainly due to conversion of CO to CO_2 through reaction (iv). Hydrogen reacts with CO_2 and increases CO concentration by the reaction

$$H_2 + CO_2 \rightarrow CO + H_2O$$

Traces of O_2 are also present due to the following reactions:

$$2CO_2 \rightarrow 2CO + O_2$$
$$CO_2 + Fe \rightarrow Fe(C) + O_2$$

Average concentrations of CO_2, H_2O, and O_2 are 0.2 percent, 0.5 percent, and 10^{-14} ppm, respectively.

One of the recent developments in the gas carburizing technique is the use of nitrogen as a carrier gas. Normally, nitrogen gas is used with some minor additives. Carbon potential is controlled by adjusting the level of oxidizing constituents. Currently, the cost of equipment for this modified process is high. Also, skilled and well trained operators are required for successful operation of the process. Small and medium industries cannot afford to have such high investment for this process. Therefore, these industries produce carburizing atmosphere *in situ* by supplying liquid hydrocarbons into the furnace above 700°C. The carbon potential is controlled by regulating liquid flow rates.

8.2 VACUUM CARBURIZING

The first commercial application of vacuum carburizing started in the early 1970s. Vacuum carburizing is a process of carburizing, carried out either in vacuum or in reduced pressure. The main advantage of the process lies in the tremendous energy saving associated with it.

Carburizing in vacuum or reduced pressure is carried out in two stages. In the first stage, carbon is made available to the steel for absorption. In the second stage, diffusion of the carbon takes place within the steel piece and results in appropriate concentration of carbon and depth of carburizing. In vacuum carburizing, there is accurate control on the amount of carbon absorbed. Also, as the process takes place at a relatively higher temperature, carbon absorption is quite rapid.

To start the process, the job is introduced into the furnace which is then evacuated. After achieving the required degree of vacuum, the furnace is heated up to a carburizing temperature which lies in the range 925–1050°C. In this temperature range, austenite which is formed is unsaturated with respect to carbon. A gaseous hydrocarbon such as methane or propane is then introduced into the furnace. The quantity of the gaseous hydrocarbon which is introduced into the furnace depends on the size of the article to be heat treated, the area of the surfaces to be carburized, the depth of the case desired, and the concentration of carbon to be introduced. As compared to conventional atmosphere carburizing, only about 1 percent of the volume of gaseous hydrocarbon is required for an identical case carburization.

As soon as the hydrocarbon in gaseous form comes in contact with the surface of the job, it cracks. As a result, a very thin layer of extremely fine carbon is deposited on the surface. This carbon is immediately absorbed by the steel till saturation is attained. The process continues till sufficient carbon is absorbed and the required case depth is formed. The inflow of gas is then stopped and the excess gas is removed by vacuum pumps. At this point, the second stage or controlled diffusion cycle commences. During this stage the required carbon concentration is formed. Vacuum carburizing can be carried out either by continuous flow of gas during the carburizing cycle or by short cycles of carburizing and diffusion.

Currently, the most popular batch type of vacuum carburizing furnace in use is a two-chamber unit, incorporating an oil quenching system in conjunction with a cooling zone. Figure 8.2 gives the relationship between carburizing time and case depth for vacuum carburizing.

Metallographic studies of cases produced by vacuum carburizing have shown that they are almost free from oxides, microcracks and decarburization.

Vacuum carburizing is basically an energy saving process. Vacuum carburizing cycles are shorter than conventional carburizing cycles. Other factors responsible for saving of energy are as follows:

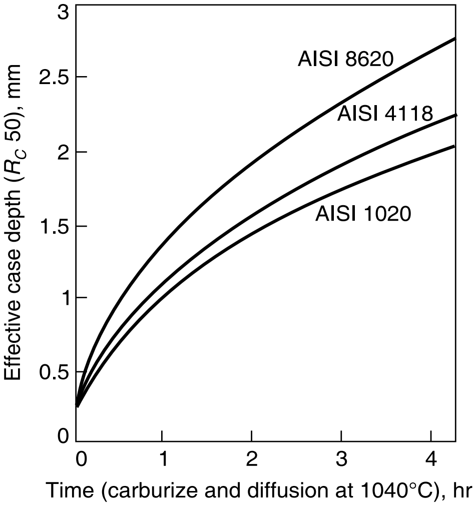


Figure 8.2 Total carburizing time and case depth for various carbon and alloy steels (all values were established on as-quenched samples).

(i) Since heating is carried out by radiation, there is improved efficiency due to the presence of vacuum.
(ii) Heat zones occupy less volume.
(iii) It is not necessary to keep the furnace on throughout the process. It can be heated and cooled rapidly as and when required.
(iv) Absence of atmosphere.
(v) The quantity of gas required is only about 1 percent of the requirement in conventional processes.

The main limitation of the vacuum carburizing process is that only batch type units are available at present. Also, there is a limitation on the size of the work-piece due to the limited size of vacuum furnace.

8.3 POST-CARBURIZING HEAT TREATMENTS

While carburizing at 900–930°C, overheating may occur both in the core and the outer case of the steel due to the prolonged nature of operations. This may cause grain coarsening throughout the cross-section. Therefore, in most of the cases, the steels require specific treatment after carburizing. The objectives of this post-carburizing heat treatment are to (i) improve the microstructure and refine coarser grains of core and case of carburized steel; (ii) achieve high hardness at the surface; and (iii) break the carbide network in the carburized case, which may be formed due to higher carbon content (1.0% carbon). (Network of carbide imparts brittleness to the case.)

In cases where steel is inherently fine grained (e.g. Al-killed), the work-piece is heated above Ac_1 temperature and directly quenched. If the steel is coarse grained throughout the cross-section, then double heat treatment may be required to improve the properties of the case and core. In such cases the steel is first heated above Ac_3 (900°C) temperature and normalized to refine the grain size in the core. The additional advantage of this step is that the carbide network also dissolves on heating and does not appear after quenching. The second step of heat treatment consists of heating the work above Ac_1 temperature (760–780°C), followed by quenching.

By the second heat treatment, refining and hardening of case are achieved. On quenching, the austenite transforms to martensite at the surface of steel. The core does not harden during second heat treatment and remains fine grained and tough. These heat treatment cycles are shown in Figure 8.3 and their characteristic effects discribed in Table 8.1.

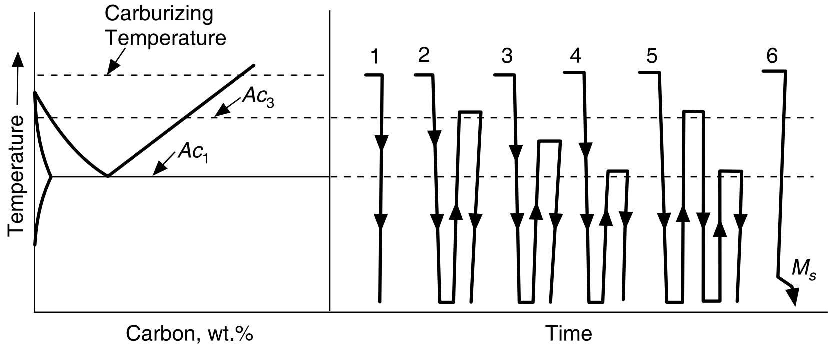


Figure 8.3 Schematic representation of post-carburizing treatments subsequent to carburizing and the case and core characteristics obtained.

A procedure has been devised to obtain maximum case hardness and very fine grain size. The heat treatment cycle for this is shown in Figure 8.4. The steps involved are as follows:

Step 1 Work-piece is heated to about 1040°C (about 120°C above the normal range) for a short time, followed by quenching in oil bath.

Step 2 Tempering at about 370°C for converting retained austenite into bainitic microstructure.

Step 3 Rapid austenitizing by induction beating just above Ac_3 temperature, followed by oil quenching.

Step 4 Final step consists of tempering at about 180°C.

Table 8.1 Effect of Various Post-carburizing Heat Treatments on the Characteristics of Case and Core

	Treatment	Case characteristics	Core characteristics
1	Direct quenching	Unrefined, excess carbide gets dissolved; austenite is retained and distortion limited	Unrefined but hardened
2		Refined, solution of excess carbide favoured; austenite retention is promoted in highly alloyed steels	Refined, maximum core strength and hardness
3		Refined, some solution of excess carbide takes place (i.e. carbides get partially dissolved)	Partially refined, stronger and tougher than heat treatment 4
4		Refined, excess carbide is not dissolved .	Unrefined, soft and machinable
5		Refined and hardened	Refined, low hardenability
6	Interrupted quenching	Unrefined, solution of excess carbide favoured; austenite is retained and distortion minimized	Fully hardened

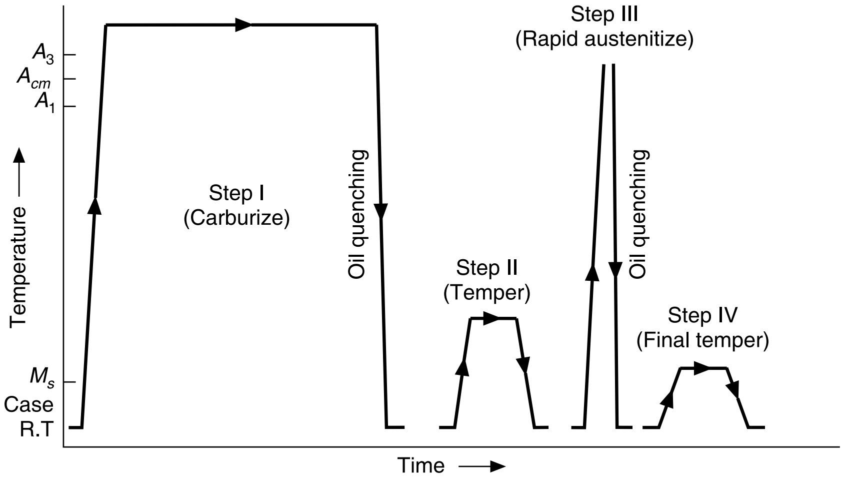


Figure 8.4 Recommended heat treatment cycle for maximizing case hardness along with grain refinement.

This four-step treatment gives maximum case hardness (around 900 DPH) with very fine grained case and core.

In fact, in all cases the final operation in the heat treatment of carburized parts is tempering at about 160–180°C. When high alloy steels are case hardened, problem arises due to retention of austenite. This sharply reduces the hardness. A sub-zero treatment may be given to such steels to convert retained austenite into martensite.

8.4 CYANIDING AND CARBONITRIDING

In cyaniding and carbonitriding processes, the surface layer of steel (with 0.3–0.4% C) is hardened by addition of both carbon and nitrogen.

Cyaniding is carried out in a liquid bath of NaCN. If the process is carried out in a gaseous atmosphere, it is called carbonitriding.

8.4.1 Cyaniding

In this process, the parts to be heat treated are immersed in a liquid bath (at 800–960°C) of NaCN with the concentration varying between 25% and 90%. The measured amount of air is passed through the molten bath. NaCN reacts with the oxygen in the air and is oxidized. The basic reactions in the bath are

$$2NaCN + O_2 \rightarrow 2NaCNO$$
$$2NaCNO + O_2 \rightarrow Na_2CO_3 + CO + 2N$$
$$2CO \rightarrow CO_2 + C$$

Carbon and nitrogen so formed in atomic form diffuse into the steel and give thin wear resistant layer of the carbonitride ε-phase. Usually, this process requires 30–90 minutes for completion.

For obtaining case depth from 0.5 mm to 2 mm, the process is carried out at higher temperature (950°C) in a bath containing 8% NaCN, 82% $BaCl_2$ and 10% NaCl. This process takes 1.5–6 hours for completion. For case depth from 0.13 mm to 0.35 mm, the bath is maintained at 850°C with the following concentration:

NaCN = 30%
NaCl = 35%
Na_2CO_3 = 35%
(Soda ash)

The higher the temperature at a given cyanide level, the higher is the percentage of carbon diffusion (up to 0.8–1.2% C) into the surface of steel as compared to nitrogen (0.2–0.3%). After cyaniding, the pieces are taken out and are quenched in water or oil. For thick sections, mineral oil is preferred for quenching. The final operation is low temperature tempering. After heat treatment, the case has a hardness of 850 VHN. This process is less time consuming. Because of the high heat transfer coefficient in liquid bath and uniform bath temperature, distortion of pieces is less. This process is not suitable for hardening those parts which are subjected to shock, fatigue and impact because nitrogen addition has adverse effects on such properties of steels.

8.4.2 Carbonitriding

This process is specifically used for improving wear resistance of mild, plain carbon or very low alloy steels.

Carbonitriding is carried out at lower temperatures (in the range 800–870°C) in a gas mixture consisting of a carburizing gas and ammonia. A typical gas mixture contains about 15% NH_3, 5% CH_4 and 80% neutral carrier gas. Carbon and nitrogen are diffused at the same time into the surface of the steel in the austenitic-ferritic condition and gives case thickness of the order of 0.05–0.75 mm. Nitrogen is more effective in increasing hardenability of the case as compared to carbon. Nitrogen content of the steel depends on ammonia content and temperature.

After carbonitriding, quenching is done in oil to avoid cracking. This is followed by tempering at 150–180°C. Heat treatment produces a case having a hardness of 850 VHN.

In this process, surface hardenability, wear resistance and corrosion resistance are better than in the carburizing process. But the time required for heat treatment is longer than that for carburizing.

8.5 NITRIDING

Nitriding is most effective for those alloy steels which contain stable nitride forming elements such as aluminium, chromium, molybdenum, vanadium and tungsten. Examples of popular medium-carbon alloy steels which are used for nitriding are: 708A37 and 817A40 to B5970: Part 2. The typical composition of such steel is 0.1–0.5% C, 0.75–1.25% Al, 1–1.5% Cr, and 0.2% Mo.

Nitriding is carried out in a ferritic region below 590°C. So there is no phase change after nitriding. Before nitriding, proper heat treatment should be given to steel components (hardening by heating to 930°C and quenching in oil, then tempering at 650°C) to develop bainitic structure, which increases the strength and toughness of the core. All machining and grinding operations are finished before nitriding. The portions which are not to be nitrided are covered by thin coating of tin deposited by electrolysis. The coating checks diffusion of nitrogen due to its surface tension. Anhydrous ammonia gas is passed into the furnace at about 550°C, where it dissociates into nascent nitrogen and hydrogen. Thus,

$$2NH_3 \rightarrow 2[N]_{Fe} + 3H_2$$

The treatment time varies from 21 hours to 100 hours. Actually, it depends an the desired case depth and size of the steel parts. After nitriding, the steel part is allowed to cool in furnace itself in the presence of ammonia. The furnace container is made of heat resisting alloy steel. The time required for a case depth of 0.5 mm is about 100 hours.

The hardness achieved at the surface of steel varies from 900 VHN to 1100 VHN. The hard layer so formed imparts good wear resistance, hot hardness and corrosion resistance.

During nitriding process, a white layer of Fe_4N (γ' nitride) and Fe_2N (ε nitride) form on the outer layer of surface. This layer is problematic as it is very brittle and tends to crack. Formation of this layer is caused by high nitrogen potential. So this can be avoided by keeping nitrogen potential at the desired level. White layer should be removed from component by mechanical polishing or by boost diffusion techniques.

There are two ways by which white layer can be totally suppressed.

(a) *Floe process* or double-stage nitriding, where a white layer is first produced and then decomposed.

The first stage is carried out between 495 and 525°C for 15–20 hours with around 20% dissociated ammonia to achieve faster growth of nitrided case. The second stage is done between 550 and 565°C with 75–80% dissociated ammonia (atmosphere of low nitrogen potential). The iron nitrides formed in first stage dissociate, so that white layer reduces from

0.05 mm to 0.01 mm, or even gets eliminated. Elimination of white layer means case depth is increased by that thickness. Higher nitriding temperatures in the second stage lower case hardness, increase case depth.

The decomposition of the white layer takes place by means of three fundamental processes:

(i) Diffusion of nitrogen out of the white layer into the vacuum of the ion nitriding vessel.
(ii) Diffusion of nitrogen from the white layer into the diffusion layer.
(iii) Sputtering of the white layer by bombardment with *inert* ions.

The first two processes cause a decomposition of the white layer by a phase transformation of the nitrogen depleted iron nitride γ back to the α(N)-ferrite. The third process results in a reduction of the white layer by a removal of material from the surface. All three processes at the same time contribute to the reduction of the white layer during the second stage. However, the part each process plays varies according to the size of the voltage or the temperature of the work piece.

(b) Ion Nitriding Process or Plasma Nitriding which is described in the following section.

8.6 PLASMA NITRIDING (ION NITRIDING)

Plasma nitriding is also known as ion nitriding process. In this process the steel component to be nitrided acts as cathode (Figure 8.5), the component is heated by electrical heaters to 370 to 650°C. This heating operation is followed by switching on supply of a gas mixture of hydrogen and nitrogen at 1–10 torr. Sufficiently high DC voltage (500–1000 V) is applied between the cathode (component) and anode to form plasma. Current flows between two electrodes and the mixture of hydrogen and nitrogen gas gets ionized. When the part to be treated is subjected to this ionized discharge, the nitrogen ions that are formed bombard the surfaces of the component (cathode) with considerable energy. Part of this energy heats the cathode and allows diffusion of nascent nitrogen inwards from nitrides. The remaining part of energy is used for displacing the secondary electrons from the cathode surface. These secondary electrons gain energy from the applied voltage (potential). Bombarded ions clean the surface, heat the component and gives nascent nitrogen. A glow envelops the component and nitriding starts. Nitrided case depth depends on current temperature and time of nitriding. After ion-nitriding, the

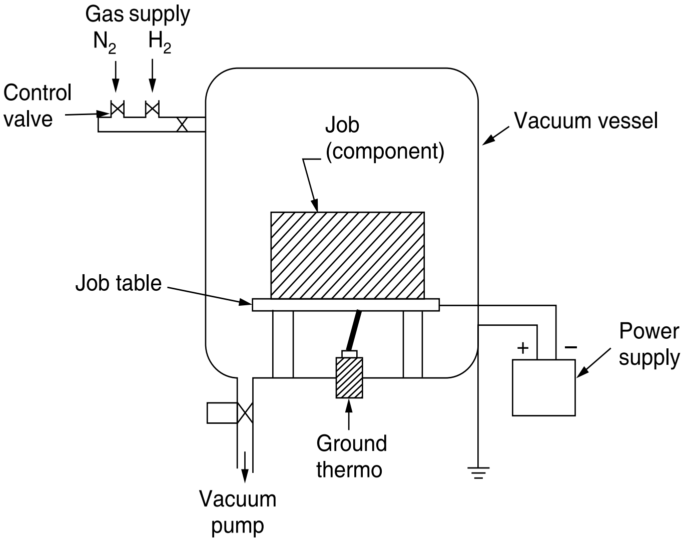


Figure 8.5 Plasma nitriding process.

component is cooled in atmosphere of N_2 gas. For successful plasma nitriding. the glow-discharge current density is to be maintained between 0.5×10^{-3} and 3×10^{-3} amperes/cm^2 by appropriately controlling the glow discharge voltage. Once glow is established, it envelops the part completely and then plasma nitriding takes place. The anode is kept cool by circulating water around it.

Since, in this process, the diffusion of nitrogen can be controlled, it is possible to get a pure diffusion layer without any trace of white layer. That is why, this process is especially suitable for machine components which, in addition to wear, are subjected to high impact, rolling, bending, or twisting stresses. This method is suitable for a wide range of steels starting right from low-alloy steels, nitriding steels, and tool steels and upto the most highly alloyed steels. lon nitriding is carried out after completing all the machining operations according to the need and type of steels. Components to be nitrided by this process are cleaned and degreased to ensure that blocking of the nitriding action does not occur.

This process is characterized by uniform build-up of nitrided cases which are hard but still ductile and core hardness is retained. No dimensional changes of work-piece takes place. The process is completely non-toxic and environmentally clean. It is a low energy consumption and single step operation.

Plasma nitriding is mainly used for ferrous components such as valves, camshafts and piston rods in the mechanical engineering and automotive industries. Other applications are cutting tools or large forming dies. Cast iron parts, such as pump and gear houses, can also be nitrided.

Advantages of plasma nitriding include complex shapes and geometries and components of different sizes can be nitrided. The process provides excellent dimensional stability with no distortion. Steels sensitive to tempering can be nitrided at comparatively low treatment temperatures. The white layer formation is very slow. Even after a longer processing time it remains almost constant at 6 μm. The degree of control of the process allows full exploitation of the non-brittle layer. The fatigue properties of the plasma-nitrided components are markedly improved. Mechanical masking is a feature of the plasma nitriding process. Such a mask can be made of mild sheet, which would be fitted at a distance of approximately 0.5 mm from the area to be masked. These masks have almost indefinite life and can be fitted easily. Since plasma-nitriding can be carried out at lower temperatures, cold work steels can be successfully plasma nitrided to get high absolute wear resistance.

However, the process suffers from some limitations like equipment is complex and needs closer control by skilled workers. The parameters are to be controlled strictly. Equipment cost is high. Different sized and shaped parts cannot be plasma-nitrided together. Moreover, the process that is to be adopted for nitriding of deep surfaces is complex. The rate of growth of case is slow as compared to that formed during salt bath nitriding. Initial investment cost is also high. No quenching facility is available for obtaining better fatigue strength for components made out of unalloyed steels. But besides having these limitations, the process is very attractive because of advantages which score more in comparison to limitations of the process.

8.7 SALT BATH NITROCARBURIZING

In this process, besides nitrogen, carbon atoms are also diffused into the case of steel component at 570–580°C in salt baths. The salt baths are of two types, namely, those containing cyanide and others which do not contain any cyanide. Cyanide-free salt baths are more popular because these are not hazardous. The base salt contains a mixture of sodium and potassium cyanates and carbonates. The time for obtaining a case depth of 10–15 μm is about 1½ hours for low carbon unalloyed steels. Reactions that take place in the bath are as follows:

$$\begin{aligned} 4\text{NCO}^- &\rightarrow \text{CO}_3 + \text{CO} + 2\text{N} + 2\text{CN} \\ \text{XFe} + \text{N} &\rightarrow \text{FexN} \\ 2\text{CN}^- + \text{O}_2 &\rightarrow 2\text{NCO}^- \text{ (regeneration of CN}^-) \\ 3\text{CO}_3 + \text{regenerator} &\rightarrow 6\text{NCO}^- + \text{XH}_2\text{O (regeneration of CO}_3{}^-) \end{aligned}$$

One of the recent developments is to destroy cyanate and the small percentage of cyanide in the drag-out salt. This is achieved by quenching in oxidizing quenching (cooling) salt. Such a treatment eliminates the need for neutralization plant.

This process can be used for any ferrous material; the time taken for treatment is short. However, it is not suitable for very large objects and odd shaped components.

Nitrocarburizing is widely applied in manufacturing of machine components and tools, since improved surface hardness, fatigue strength and corrosion resistance at elevated temperatures are achieved at minimal distortion. Thus, the service life of a part is significantly extended. Moreover, corrosion non-resistant steel grades attain a rather fair corrosion resistance due to compound zone.

Its field of application includes gears and pinion shafts, plastic injection molding screws and barrels, piston rings, aluminium extrusion dies, forging and forming dies, spindles for grinding machines, gun barrels, springs, crankshafts and camshafts and other wear components.

The main advantage of nitrocarburizing over other means of surface hardening is the low process temperature. Components can often be nitrided in the fully hardened and tempered condition without the core properties being adversely affected. An additional advantage of the low temperature process is the low risk of distortion. Moreover, the parts can be machined to final dimensions and do not need costly finishing work such as grinding or straightening after nitrocarburizing. Carbonitride layer has good resistance to adhesive wear.

Limitation of the process is that the typical treated layers are very thin and nitrocarburizing atmospheres/salts are difficult to handle safely.

8.8 BORONIZING

Boronizing is one of the recent methods of surface hardening, which may be applied to any ferrous material but is generally adopted for carbon steels and tool steels. Both pack and gaseous techniques can be applied for surface hardening. In the case of pack process, the components are packed in heat-resistant boxes with mixtures of granules or paste of boron carbide or other boron compounds with additions of activators and diluents at 900–1000°C. Boron diffuses inwards and iron borides (FeB and Fe_2B) layers are formed. On the outer surface, FeB phase forms, while in the interior, Fe_2B phase is formed. FeB phase is more brittle and is not desirable. Higher temperatures, longer treatment times and high alloy steels favour the formation of FeB phase. The boride layers are very hard. The hardness of boride layers produced on carbon steels exceeds that of hard chrome electroplate, hardened tool steels and tungsten carbide. The hardness of boride layers on steel ranges between 1500 and 2100 VHN. Boride layer depths range from 0.012 to 0.127 mm, depending on material and application with the layer depth being matched to the intended application:

- Thick layers (up to 0.127 mm)—for abrasive wear.
- Thin layers (up to 0.025 mm)—for adhesive wear and friction reduction.

The treatment time required for a case depth of 0.15 mm is 6 hours at about 900°C. In this process, treatment temperature is very high, and hence hardening of components before boronizing is not required. Only in the case of tool steels after boronizing, hardening and tempering are required to have the desired mechanical properties.

High hardness can be achieved on steel alloys which is retained up to subcritical temperatures (i.e., 650°C). Heat treatable materials can be fully hardened after boronizing to optimize performance. Boronizing can increase the resistance of low alloy steel to acids such as sulphuric, phosphoric and hydrochloric acids. Boronized austenitic stainless steel has excellent resistance to hydrochloric acid. Boronizing can be selectively applied to only the area that requires hardening. Boronized layer can be polished to a high finish. It can be uniformly applied to irregular shapes.

Boronizing increases tool and mold life by improving resistance to abrasive, sliding and adhesive wear. It reduces the use of lubrication as have low coefficient of friction. But high process temperature may lead to the distortion of the component. Moreover, the component shows poor fatigue and corrosion resistance.

However, due to wear benefits provided by the boronized layer, combined with the broad range of compatible substrates and the cost-effective nature of the process, boronizing is used successfully for general wear resistance of carbon steel components. Additionally, due to its temperature and wear resistance, boronizing is also a good choice for certain tooling applications like in hot forging dies, wire drawing dies, extrusion dies, straightening rolls, ingot molds, etc. It is also used for general components including nozzles, plungers, gears, shafts, and rollers. Oil and gas components (production tubing, valve components, valve fittings, metal seals, coal/oil burner nozzles, etc.) also employ this technique. Other miscellaneous application includes turbine components, pump impellers, ball valves and seats, shaft protection sleeve, and guide bars.

8.9 CHROMIZING

Like boronizing process, chromizing is also used for surface hardening of both carbon and tool steels.

There are two types of chromizing: pack chromizing and gaseous chromizing. The components to be chromized are packed with fine chromium powder and additives. A typical chromizing mixture consists of 60 percent chromium or ferro chrome (with carbon content not exceeding 0.1%), 0.2 percent ammonium iodide, and 39 percent kaolin powder. Diffusion of chromium takes place at 900–1020°C, and chromium carbide is formed on the surface of steel. The treatment time needed for achieving a case depth of 0.02–0.04 mm is 12 hours at 900–1020°C. Hardness of chromium carbide layer is about 1500 VHN.

Hard chromizing

If the steel, which is to be chromized, contains enough carbon (minimum 0.35%), a corrosion and wear resistant chromium layer will be formed on the surface of the work-piece during the chromizing treatment. If necessary, the work-piece can be heat treated after diffusion coating. The structure of the chromized layer is formed of mixed carbides of chromium, characterized by hardness and abrasive resistance.

Soft chromizing

On steel, with low carbon content (< 0.35%), a chromium carbide layer cannot be formed. Instead, a chromium diffusion layer builds up during the chromizing process which can reach up to 200 μm in thickness and a chromium content of up to 35%. The high chromium content endows the work-piece with an excellent resistance against corrosion and oxidation while maintaining its ductility.

Chromizing leads to excellent corrosion resistance under a variety of severe conditions. High temperature oxidation resistance is also improved significantly. Components may undergo bending and flanging operations without spalling. Hardness of chromium carbide layer is about 1500 VHN.

8.10 TOYOTA DIFFUSION (TD) PROCESS

The Toyota Diffusion (TD) process was initially developed by the Toyota Central Research and Development Laboratories to facilitate a surface treatment that created a hard and wear resistant surface for large automotive press tools. In Toyota diffusion process carbide forming elements such as vanadium and niobium are diffused into steels from a salt bath at about 1000°C. Carbide layers 5–12 μm of very high hardness, about 3000 VHN are produced. Table 8.2 summarizes the hardness levels achieved by various surface hardening processes.

Table 8.2 Comparison of Surface Hardness Obtained by Different Surface Hardening Methods

Process	Material	Typical surface hardness, VHN
Carburizing	Wide range of steels	850
Carbonitriding	Carbon steels	850
Nitriding	Cr-Mo steel	650
	Cr-Mo-V steel	900
	Cr-Mo-Al steel	1100
	High-alloy tool steel	1100
Induction and flame hardening	0.4% C steel	500–600
	0.5% C steel	600–700
Boronizing	Mild steel, tool steel	1500
Chromizing	Carbon steel, tool steel	1500
Toyota diffusion process	Tool steel	3000–4000

In Toyota Diffusion process, the component is kept in salt bath of proprietary composition based on borax. The carbide forming elements are added in the form of ferro alloys, e.g. ferro-vanadium. The process is carried out at about 1050°C. After salt bath treatment, the components are quenched and tempered. This process of surface hardening is very appropriate for die and tool steels and is presently widely used in Japan. However, dimensional changes are possible, due to the high temperatures involved.

Extremely high hardness, impact resistance, wear resistance and seizure resistance can be achieved by Toyota diffusion process. The coatings formed by this process are harder than TiC and TiCN and have superior peel strength. The tool life increases and lubricant requirements decreases.

Given the superior wear resistance, high seizure resistance and reduced lubricant requirement that is associated with TD surface treatments, they have historically been used by the automotive industry in specialized press tool applications such as tight radius and deep draw. More recently, however, with the increased use of high strength steels, larger volumes and throughput requirements, automotive companies have been evaluating the use of TD surface treatments more widely on other areas of press tools.

TD surface treatments are not, however, restricted to automotive press tools, they can be applied to a range of engineering components, including shafts, screws, bushes, blades, taps, pins and plugs.

QUESTIONS

8.1 What is case carburizing treatment? What is the surface hardness obtained and approximate carbon content of the carburized case?

8.2 Why it is necessary to toughen the core before hardening the case?

8.3 Specify the advantages of liquid and gaseous media used in case hardening over solid carbonaceous reagents.

8.4 What is vacuum carburizing process? List the advantages and limitations of this process.

8.5 Why post-carburizing heat treatment is necessary for case carburized parts?

8.6 Compare cyaniding and carbonitriding case hardening processes.

8.7 Why a white layer is formed during nitriding? How can it be prevented?

8.8 What is ion-nitriding process?

8.9 Discuss the recent advances in surface hardening processes.

9

Surface Hardening

INTRODUCTION

In this chapter, those surface hardening processes are discussed in which there is no change in the chemistry of the surface of steel component to be surface hardened. These processes are flame hardening, induction hardening, laser hardening and electron beam hardening.

9.1 FLAME HARDENING

Flame hardening is the simplest form of surface hardening heat treatment. This process consists of heating the large work-piece, such as crank shaft, axle, large gear, cam, bending roller, or any other complicated cross-section, by an oxy-acetylene or oxy-fuel blow pipe, followed by spraying of jet of water as coolant. After hardening, reheating of the parts is carried out in furnace or oil bath at about 180–200°C for stress relieving. Such a treatment does not appreciably reduce the hardness at the surface. Hardness in flame hardened steel is due to martensitic and lower bainitic structure.

Overheating of work-piece should be avoided, otherwise, there is danger of cracking after quenching and excessive grain growth in the region just below the hardened surface. The carbon content required for flame hardening steels varies from 0.3 percent to 0.6 percent. High carbon steels can also be hardened by this process, but greater care is required to avoid cracking. Normally, case depth upto 3 mm can be achieved. A high rate of heating is essential for thin cases with proper adjustment of timing of application of flame. For good quality, strict control of heating time and fuel and oxygen consumption is essential.

There are four different methods which are used in general for flame hardening: (i) stationary, (ii) progressive, (iii) spinning, and (iv) progressive-spinning.

In the first, both burner and work-piece are stationary. Progressive hardening is carried out by using a burner combined with a waterspray, as shown in Figure 9.1(a). In this case, the burner moves over the large stationary work-piece. This is followed by quenching. In the spinning method, the work-piece is rotated, while the burner remains stationary. After heating, the flame is removed and quenching is carried out by a water jet. In the progressive-spinning method, the burner moves over a rotating work-piece [see Figure 9.1(b)]. In all the cases, rapid quenching is carried out after heating. There is little scaling, decarburization, or distortion in flame hardening. Since the heating and cooling are very fast, the core remains unaffected.

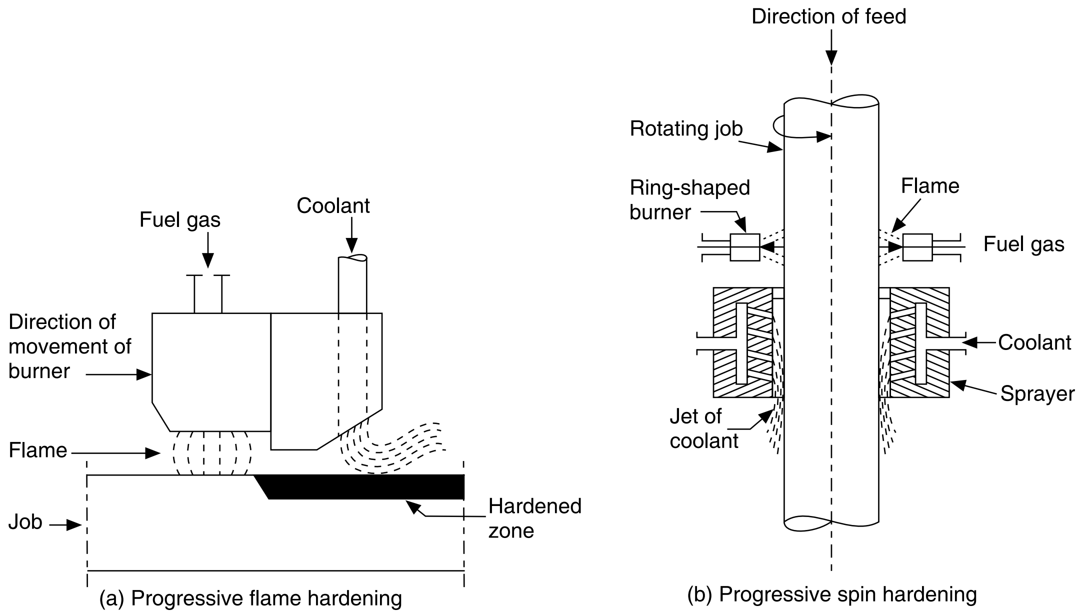


Figure 9.1 Schematic diagram illustrating two principles,

9.2 INDUCTION HARDENING

Induction hardening may be used for local surface heat treatment. Generally, it is used to surface harden crank shafts, cam shafts, gears, crank pins and axles. In this process, heating of the component is achieved by electromagnetic induction. A conductor (coil) carries an alternating current of high frequency which is then induced in the enclosed steel part placed within the magnetic field of the coil. As a result, induction heating takes place. The heat so generated affects only the outer surface of the steel component due to skin effect.

The degree of flow of current on the outer surface of a component depends on the frequency, resistivity and permeability of the component. For a given material, the last two factors depend on temperature. The depth to which the current, penetrates and raises the temperature is given by the following relation for steel components:

$$\text{In cold state (at 20°C)},\ d_{20} = 20/\sqrt{f} \tag{9.1}$$

$$\text{In hot state (at 800°C)},\ d_{800} = 500/\sqrt{f} \tag{9.2}$$

where d is the depth (mm) to which current flows and f is the frequency of current carried by the coil. This frequency is expressed in hertz. This relationship shows that the depth of hardening decreases with increase in frequency. In addition to direct heating of the skin by induced current, there is also some heating of the core due to conduction of heat. Hence, the overall depth of heating is greater than that given by Eqs. (9.1) and (9.2). Accordingly, the overall depth of penetration of heat (d_0, in mm) at 800°C is given by the relation

$$(d_0)_{800} = d_{800} + d_c \tag{9.3}$$

where d_c (mm) is the depth of penetration of heat due to conduction and is given by the relation

$$d_c = 0.2\sqrt{t} \tag{9.4}$$

where t is the heating time (seconds).

In induction hardening, the component is heated usually for a few seconds only. Immediately after heating, the surface is quenched by a jet of cold water. Due to quenching, a martensitic structure is formed, which makes the outer surface hard and wear resistant. Figure 9.2 shows the operation of induction hardening.

In hardening, temperature for plain carbon steel is about 760°C. For alloy steels, higher hardening temperatures are required. For example, for Cr-Mo steels the hardening temperature is about 800°C.

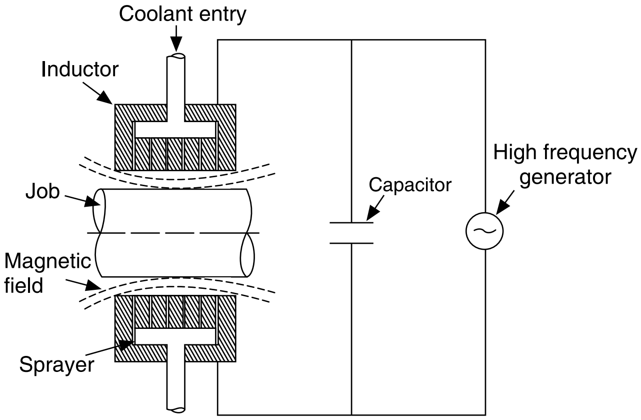


Figure 9.2 Diagrammatic representation of induction hardening process.

A striking feature of induction hardening (which is true of other surface hardening processes also) is that in this process the original toughness and ductility remain unaffected even after heat treatment.

Table 9.1 gives the process conditions for induction hardening of steels.

Table 9.1 Process Conditions for Induction Heating of Steels

Range of desired depth of hardening (mm)	Frequency required (Hz)	Range of power input required (kW)
0.5–1.1	450	15–19
1.1–2.3	450	8–12
1.5–2.3	10	15–25
2.3–3.0	10	15–23
3.0–4.0	10	15–22
3.0–4.0	3	22–25
4.0–5.0	3	15–22

9.3 ELECTRON BEAM HARDENING

This process is used for hardening those components which cannot be induction hardened because of associated distortion. Automatic transmission clutch cams (SAE 5060 steel) are hardened by this process. The work-piece is kept in vacuum at 0.06 m bar pressure. Electron beam is focused on the work-piece to heat the surface. In the beginning, energy input is kept high. With time, power input is reduced as the component gets heated up. This is done to avoid melting. Normally, case depth up to 0.75 mm can be achieved by this method. A mini-computer is used to control voltage, current, beam, dwell time and focus.

9.4 LASER HARDENING

Laser beams are also used for surface hardening treatment. Since these have very high intensity, they may melt the work-piece when they are used at such high intensity. Therefore, a lens is used to reduce the intensity by producing a defocused spot or scans from 1–25 mm wide. A laser beam of 1 kW produces a circular spot whose diameter may vary from 0.50 mm to 0.25 mm. Industrial lasers up to 20 kW are now available. Case depth of about 0.75 mm is obtained by self quenching. The depth of hardening is governed by both time and energy density. In laser hardening process, less time is required than in induction and flame hardening processes, and the effect of heat on the surrounding surface is less, thus leading to less distortion. Some heat patterns are shown in Figure 9.3. No separate quenching media are required since quench is effected by the mass of the surrounding unheated portion. The microstructure of laser-heated steel consists of bainite + ferrite at the surface of the heated spot and pearlite and ferrite in the interior.

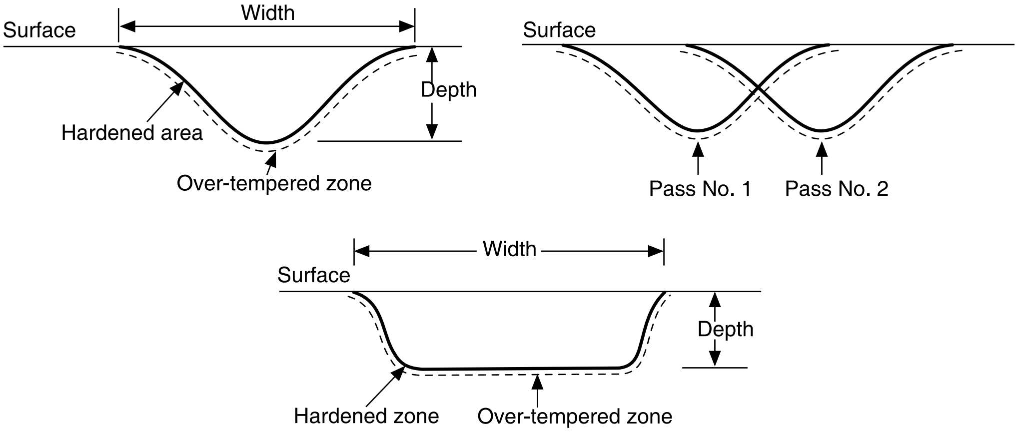


Figure 9.3 Heat effects of three different beam optics, viz. defocused beam, single pass; defocused beam, overlapping passes; and oscillating beam, single pass employed in laser heat treatment.

The relationship between depth of hardening and power is as follows:

$$Y = -0.11 + \frac{3.02P}{(D_b\,V)^{1/2}} \tag{9.5}$$

where

Y = case depth (mm)
P = laser power (W)
D_b = incident beam diameter (mm)
V = traverse speed (mm/s)

However, experimental data show scattering. At a constant value of $P/(D_bV)^{1/2}$ case depth may vary by a factor of 2.

In many countries, the industrial scale application of laser, heat treatment has already commenced. Rapid progress in this area has been achieved because of the availability of high power CO_2 lasers and advanced cost effective laser production techniques.

The main advantages of laser heat treatment are as follows:

(i) It is possible to achieve high production rates since light has no inertia and, consequently, it is possible to obtain high processing speeds with rapid stopping and starting.
(ii) Input distortion is quite low because speciflc energy is very low.
(iii) It is possible to give localized treatment with this process.
(iv) No external quenching is needed. At times external quenching may be adopted for such small parts which have insufficient mass for self-quenching.
(v) There is hardly any contamination during surface hardening treatment.
(vi) It is possible to control the process with the help of a computer.
(vii) Those areas which are difficult to be treated by conventional methods can be easily treated with this technique.
(viii) It is not necessary to carry out any final machining operation subsequent to hardening.

Laser heat treatment is best suited for steel and cast irons. During laser heating, heat transfer takes place by inverse Bremsstrahlung effect, i.e. by interaction of laser beam with the free electrons of the substrate. As a result, the energy state of the electrons of the conduction band is raised.

For successful laser heat treatment, it is necessary that the temperature of the zone which is being hardened must reach closer to the austenitizing range. Further, between the heating and cooling cycles, the substrate must be maintained at the austenitizing temperature for sufficiently long time to ensure adequate diffusion of carbon. Also, there should be enough mass so that the cooling rate achieved by self-quenching is greater than the critical cooling rate required for martensite transformation.

While considering laser heat treatment, it is necessary to apply the same metallurgical concepts as in the case of other conventional heat treating processes. However, there are some basic differences between the laser heat treatment process and other conventional processes. Some of these are as follows:

(i) It is possible to harden low carbon steel with relative ease due to extermely rapid heating and cooling rates associated with laser heating. There is hardly any effect due to differences in hardenability between plain carbon steels and alloy steels since the cooling rates normally achieved during laser heat treatment are much higher than the critical cooling rate required for martensitic transformation.

(ii) It has generally been observed that the level of hardness achieved by laser hardening is higher than that obtained by conventional hardening.

(iii) Laser heat treatment is not well suited for alloys requiring rather long soaking time such as steels containing spheroidal carbides or cast irons rich in graphite instead of pearlite. The large soaking time required for the diffusion of carbon would restrict the operating parameters associated with the laser. Consequently, the process would lose its inherent advantage of rapid heating and cooling rate.

Cast irons with a combination of pearlite and graphite, on the other hand, can be heat treated successfully with lasers. When the pearlite is being dissolved to be converted into austenite and subsequently to martensite, some carbon diffusion takes place out of graphite flakes which will produce martensite around the original graphite flakes. However, the predominant hardening mechanism will be based on austenite formed by dissolution of pearlite.

Some of the major independent process variables connected with laser heat treatment are incident laser beam power, diameter of incident laser beam, absorptivity of laser beam by the coating, and the substrate and transverse speed across the substrate surface. Another important factor in this context is the thermophysical properties of the substrate.

The depth of hardness, geometry of the heat-affected zone, and microstructure and metallurgical properties of the laser heat treated material are the dependent variables.

For efficient laser heat treatment, it is necessary that proper absorption of light energy by the work-piece takes place. All heat transfer calculations for laser processing are based on this absorbed energy.

Melting and key hole formation should be strictly avoided during laser heat treatment. Hence, some absorbent coatings are invariably used during laser heat treatment. Colloidal graphite, manganese phosphate, zinc phosphate and black paint are some of the commonly used absorbent coatings. High absorptivity can also be achieved with the help of a mixer of sodium and potassium silicate. Absorptivity depends on coating thickness, coarseness and adherence to the substrate. Heat transfer between the coating and the substrate also plays an important role in this context.

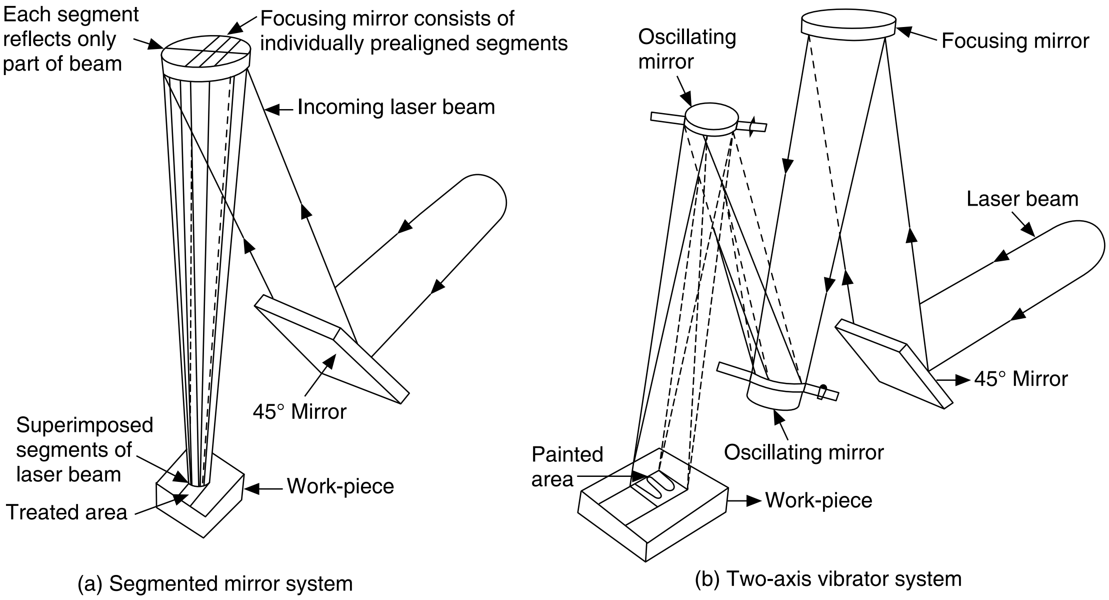
With a given beam diameter and traverse speed, the depth of hardening by laser heat treatment is proportional to the laser power.

The surface heat source is defined by the diameter of the laser beam and distribution intensity.

The power density as also the coverage rate depends on the diameter of the laser beam. For laser heat treatment, a wide beam with uniform intensity distribution is preferable. This in turn ensures uniform case depth.

Different methods of beam manipulation can be adopted to obtain a broad beam with uniform intensity distribution. Different techniques used for this purpose are shown in Figure 9.4.

The interaction time depends on traverse speed. The depth of hardening is inversely proportional to traverse speed. For proper hardening, it is necessary to ensure a minimum interaction time of the order of 10^{-2} s with a power density exceeding 10^3 W/cm^2.



(a) Segmented mirror system (b) Two-axis vibrator system

Figure 9.4 Beam manipulation technique used for laser.

9.5 CASE DEPTH MEASUREMENTS IN STEELS

Case depth (CD) is defined as “the perpendicular distance from the surface of the steel to the point at which the change in hardness, chemical composition or microstructure of the case and core cannot be distinguished". This is the total case depth of steel.

The effective case depth of steel is the perpendicular distance from the surface to that point of core at which hardness values are given in Table 9.2.

Table 9.2 Critical Hardness Values for Defining Case Depth

	Type of steels	Hardness (VHN)	Processes
1.	With %C		
	0.28–0.32	350	Flame or induction hardened
	0.33–0.42	400	
	0.43–0.52	450	
	Over 0.53	550	
2.	Case hardening	550	Carburized, hardened and tempered
3.	Nitriding	Values to be mutually agreed upon	Nitrided and carbonitrided
4.	Carbonitriding	Values to be mutually agreed upon	Nitrided and carbonitrided

Case depth is one of the deciding factors for a steel to be used in practice. Hence, it is necessary to measure the case depth of the steel so that the component can be used in service safely. There are four methods of measuring case depth:

(i) Hardness method
(ii) Chemical method
(iii) Macrostructure method
(iv) Microscopic method.

These methods measure the case depth of the steel which is surface hardened by carburizing, nitriding, carbonitriding, cyaniding or induction and flame hardening processes.

9.5.1 Hardness Method

In this method, hardness values are taken along the case and core. It is a very accurate method since sharp change in hardness across case and core region can be measured. Specimens for this method are prepared by (i) cross-section procedure, (ii) taper-grind procedure, and (iii) step-grind procedure (IS : 6396), which we now discuss.

Cross-section Procedure

The specimen is cut perpendicular to the hardened surface at a predecided area. Care should be taken to ensure that no change in hardness takes place as a result of cutting. The surface area is polished up to 4/0 emery paper.

Figure 9.5 gives the method of measuring case depth for light and medium cases, while Figure 9.6 shows the method of measuring the case depth for medium and heavier cases. The distance of the centre of each impression (formed by hardness measurement) is measured with the help of a suitable optical instrument which is calibrated.

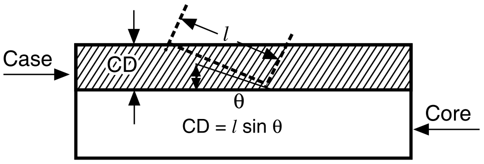


Figure 9.5 **Methods for measuring light and medium cases.**

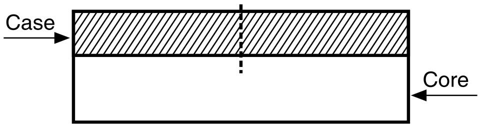


Figure 9.6 **Methods for measuring medium and heavy cases.**

Taper-grind Procedure

This method is suitable for light and medium cases, and is illustrated in Figure 9.7. A shallow taper is ground through the case of steel, and the hardness values are found along the surface of the prepared taper. Care should be taken to avoid reheating, cracking and tempering of steel during cutting while preparing specimen.

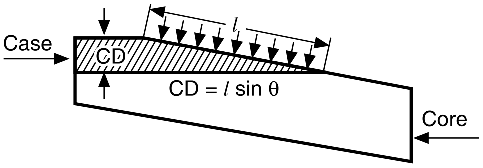


Figure 9.7 **Taper ground specimen for light and medium cases.**

Step-grind Procedure

For medium and heavy cases, step-grind procedure is suitable. In this case, the hardness values are taken in steps of known distances below the surface. Figure 9.8 illustrates the step-grind method. Here, two predetermined depths are ground to ensure that the effective case depth is within specified limits.

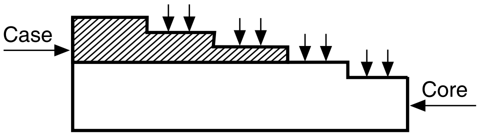


Figure 9.8 **Step ground specimen for medium and heavy cases.**

For all the three procedures we have discussed, special care must be taken during hardness measurement. It is advisable to use such hardness testers whose indentor gives shallow impression so that the hardness values obtained are representative of the surface of the case or core. Testers which produce diamond pyramid having 10 hardness numbers are recommended. Rockwell A and C scales are recommended only for such steels which have high case depth.

9.5.2 Chemical Method

It is a usual practice to apply this method only to carburized cases. It may also be applied to other case-hardening methods which involve change in chemical composition, viz. nitriding and carbonitriding. Carbon content is determined at various depths below the surface of case-hardened specimen. Where hardening is due to formation of nitrides (e.g. nitriding), nitrogen content is estimated. This is the most accurate method of determining case depth.

9.5.3 Macrostructure Method

In this technique, the test specimen is cut perpendicular to the hardened surface. The cut surface is ground and polished through 0/0 to 4/0 emery paper. After this, disc polishing is carried out, which is followed by etching with suitable etching reagent so that case and core regions can be distinguished. The etched specimen is washed in water or alcohol and dried, and is examined under a limited magnification of ×20.

9.5.4 Microscopic Method

In this method, the specimen is cut perpendicular to the hardened surface and the cut surface is ground, polished and etched. The specimen is examined under microscope with calibrated eye piece. The total case depth is the distance from the surface to the point up to which the modified microstructure is observed.

QUESTIONS

9.1 Compare the processes of flame hardening with induction hardening.

9.2 What is a laser hardening process? Discuss the basic difference between laser heat treatment process and other conventional processes.

9.3 Specify the composition of steels recommended for induction hardening.

10

Thermomechanical Treatment

INTRODUCTION

The development of high strength materials, coupled with good formability, has always been the aim of material scientists. The demand for such a combination has increased considerably during the last few decades because of the ever increasing applications in the areas of space, deep sea and high pressure technology. Alloying, mechanical working, heat treatment, grain size control and nuclear irradiations are some of the techniques which may be taken recourse to individually or in combination for this purpose. Individually, each one of them has a limited strengthening effect. In order to attain enhanced properties, various combinations of these unit operations may be adopted advantageously. Thermomechanical treatment is one such combination. As the name suggests, it is a combination of heat treatment and mechanical working. However, this statement does not define the term *thermomechanical treatment* in the strict metallurgical sense since any combination of heat treatment and mechanical working cannot be termed a thermomechanical treatment. The term thermomechanical treatment refers to that treatment in which plastic deformation is carried out in such a way that phase transformation is affected by it.

The principle behind thermomechanical treatment is that plastic deformation results in the production of various crystal defects such as vacancies, dislocations, sub-grain boundaries and stacking faults. These defects severely affect the phase transformation in metals and alloys by providing nucleation sites and aiding diffusion process. These in turn affect the kinetics of phase transformation and morphology of phase(s) formed. Therefore, an important aspect of thermomechanical treatment is that phase transformation should occur under conditions of increased lattice defects. This means that there should be overlapping of the two processes, namely, heat treatment and mechanical deformation. Both processes may either proceed simultaneously or with a time gap. Thermomechanical treatments are equally applicable to both ferrous and non-ferrous materials. As major engineering applications involve the use of ferrous materials, specially steels, much work has been done on thermomechanical treatment of steels, which consists of producing strained austenite and its subsequent transformation to other phases. Lattice defects produced in austenite by deforming will thus be retained, partially or completely, in the transformed structure. Only precipitation hardenable non-ferrous alloys are subjected to thermomechanical treatments. (Thermomechanical treatments for non-ferrous alloys are discussed in Section 10.10. The other sections in this chapter deal with thermomechanical treatment of steels.)

10.1 CLASSIFICATION

Depending on the temperature of deformation of austenite, thermomechanical treatment for steels can broadly be classified into two classes, namely, high temperature thermomechanical treatment (HTMT) and low temperature thermomechanical treatment (LTMT). The former includes deformation of austenite at a temperature above the recrystallization temperature. The austenite is immediately quenched after mechanical working. On the other hand, during low temperature thermomechanical treatment, austenite is supercooled to a temperature below the recrystallization temperature, and then this supercooled austenite is deformed at this temperature. This is followed by rapid cooling immediately after the working. In high temperature thermomechanical treatment, strength levels obtained are higher than the conventional hardening and tempering treatment, but are less than those obtained by low temperature thermomechanical treatment. High temperature thermomechanical treatment is essentially a hot working process, and thus recrystallization eliminates strain-hardening effect to a great extent. For this reason, only small reduction in area, about 20 to 30%, is given, and steel is immediately quenched. Partial strain hardening induces strengthening in this treatment. However, this treatment results in better ductility, as measured by percentage elongation, reduction in area, and impact strength. Low temperature thermomechanical treatment can be regarded as the transformation of cold-worked austenite. Deformation, as indicated by reduction in area, is about 80-90% in this case. This is the reason why strength levels are much higher than those obtained by high temperature thermomechanical treatment. Ductility values achieved by this treatment are comparatively lower. Figure 10.1 is a schematic diagram summarizing the LTMT and HTMT processes.

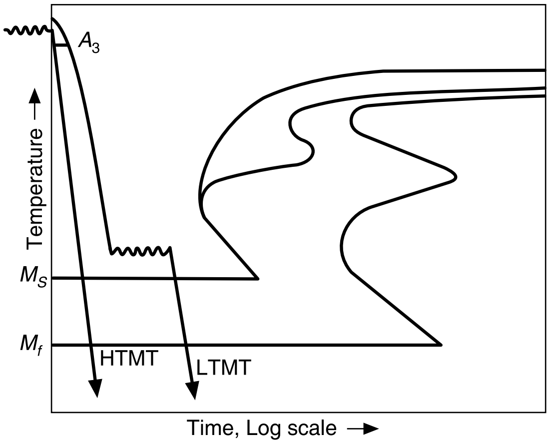


Figure 10.1 Schematic representation of HTMT and LTMT processes.

Another method of classification of thermomechanical treatment is based on the deformation temperature in relation to the critical temperatures of steel. On this basis, the three classes of thermomechanical treatments are the supercritical, intercritical and subcritical treatment. Supercritical thermomechanical treatment consists of deforming the steel in austenitic condition. Deformation is followed by rapid cooling. Recrystallization may or may not accompany deformation of austenite. Intercritical thermomechanical treatment is generally employed only for hypoeutectoid steels. It consists of deforming phase mixture of ferrite plus austenite. On quenching, the deformed dual phase structure gives a structure consisting of ferrite and martensite. Martensite present in the steel imparts directional properties to it. Subcritical thermomechanical treatment, as the name implies, consists of deforming austenite below the lower critical temperature, followed by immediate quenching. Table 10.1 gives the classification of TMT based on critical temperatures.

Table 10.1 Classification of Thermomechanical Treatments (Based on Critical Temperatures)

Class	Temperature range	Examples
Supercritical TMT or high	Above upper critical temperature TMT	Hot-cold working, controlled temperature rolling
Intercritical TMT	Between upper and lower critical temperatures	
Subcritical TMT or low temperature TMT	Below lower critical temperature	Isoforming, ausforming

10.2 CONTROLLED ROLLING

Very high strength levels are obtained by controlled rolling. This process consists of heating steel above the upper critical temperature, i.e. stable austenitic temperature range. Austenite, thus obtained is deformed, and conditions are so maintained that fine grains of recrystallized austenite are obtained. The grain growth tendency is checked by the hot working process variables and by the presence of second phase particles.

Second phase particles are generally carbides of microalloying elements such as niobium, vanadium and titanium. Fine austenitic grains will result in fine ferritic grains in the final structure. Ferritic grains nucleate at austenitic grain boundaries. Thus, the finer the austenitic grains, the better will be the ferritic grains. Therefore, it is very essential to check grain growth during recrystallization. Carbides of microalloying elements not only control the growth of austenitic grains but also retard the rate of recrystallization. However, the carbides of microalloying elements are effective only up to about 1050°C, and so rolling should be performed below this temperature. Heavy deformation during rolling elongates the austenitic grains, thereby increasing the grain-boundary area. This results in the availability of larger number of nucleation sites for ferrite. In order to have maximum strengthening, heavy deformation and low finishing temperature should be chosen. The process is widely employed for high strength low alloy steels.

10.3 HOT-COLD WORKING

Hot-cold working process consists of heating steel above the upper critical temperature. Stable austenite present at this temperature is deformed heavily in such a way that no recrystallization takes place. This non-recrystallized austenite is transformed into martensite by rapid quenching. In this process, work is carried out at minimum possible temperature above the austenitizing temperature. In order to control recrystallization, alloying elements such as vanadium, titanium or niobium are added to steel. The steel so obtained has strong directional properties.

Mechanical properties, such as strength, ductility, impact and fatigue strength, are considerably improved by this process. Since austenitic grain size is minimum at hot working temperature, size of martensitic platelets will also be small, which results in improvement of mechanical properties because of grain refinement. The degree of strengthening depends on the deformation temperature, amount of deformation and chemical composition of steel. Figure 10.2 depicts the hot-cold working TMT cycle.

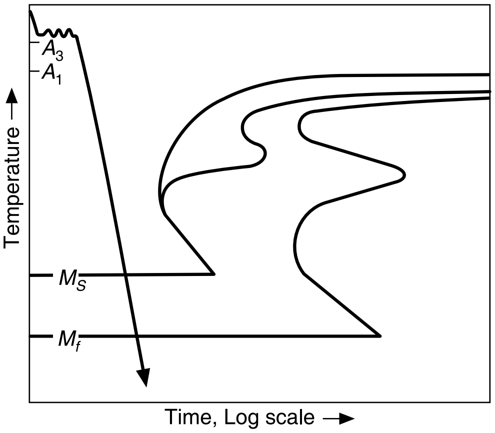


Figure 10.2 Hot-cold working TMT cycle.

10.4 AUSFORMING

Ausforming consists of heating steel above the upper critical temperature so as to get austenite. This austenite is supercooled to a temperature below the recrystallization temperature of the steel. The austenite so supercooled is deformed heavily. It is then quenched to obtain completely martensitic structure. No transformation should take place during deformation of metastable austenite. For this purpose, mechanical treatment should preferably be done at a constant temperature. Tensile strength, yield strength and ductility of ausformed steel are considerably higher than the corresponding values in steels in hardened and tempered condition. Not all steels can be given this treatment. Only steels which possess sufficient gap between pearlitic and bainitic C-curves are suitable for this purpose. This limitation facilitates deformation of metastable austenite. In addition, the pearlitic and bainitic C-curves should have sufficiently long incubation period. This ensures availability of sufficient time for deformation. Figure 10.3 is the TTT diagram for steels suitable for ausforming.

The resultant strength of ausformed steel is not dependent on carbon content of steel. It has, however, been observed that the strengthening effect of the process is small in carbon-free iron alloys. Some minimum amount of carbon, say about 0.05–0.10%, is essential for the success of this process. The strengthening effect of the process is enhanced in the presence of strong carbide forming elements. The presence of alloying elements which raise the stacking fault energy of austenite, for example, nickel, reduces the strengthening effect. In contrast, the strengthening effect associated with ausforming is increased considerably in the presence of elements which reduce the stacking fault energy of the austenite. This is due to the fact that elements, which reduce the stacking fault

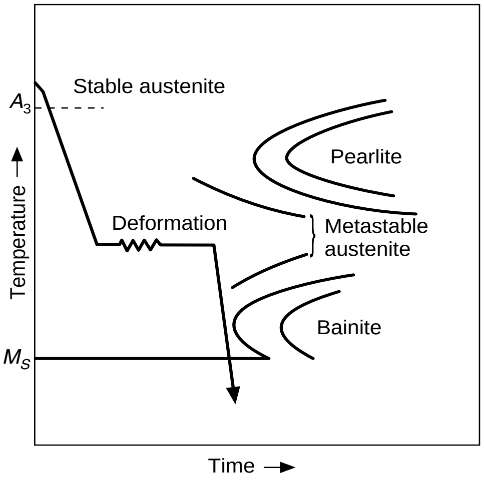


Figure 10.3 Ausforming process.

energy, raise the rate of work hardening and thus make the process more effective. The strengthening mechanism for the ausforming process is not fully understood. None of the theories put forward can explain all the salient features associated with this process. However, it is generally observed that some changes, such as refinement of martensitic grains, alteration of size, amount and distribution of carbides, and increased degree of dislocation density and other defects in the martensite, occur in the process. The extent of strengthening due to ausforming depends mainly on the amount, temperature and rate of deformation. For a given deformation, the strengthening effect increases with decrease in deformation temperature which generally lies between 400°C and 650°C. The greater the degree of deformation, the more is the increment in the strength for a given temperature of deformation. Ausformed steels have improved strength and ductility as compared to conventional hardened and tempered steels.

10.5 ISOFORMING

The isoforming process consists of deforming steel below the lower critical temperature during transformation. The resultant product of transformation may be either fine pearlite or bainite, depending on the prevailing conditions. The process is called isoforming because transformation proceeds isothermally. The steel is first heated above upper critical temperature and then quenched immediately to a temperature of about 650°C, i.e. in the vicinity of nose of the TTT curve (see Figure 10.4). Mechanical working is carried out at this temperature. Sufficient time should be available at this temperature for carrying out the deformation process and for the metastable austenite to transform isothermally to pearlite. Just after the completion of the transformation, steel is quenched. The larger the deformation or lower the deforming temperature, the greater is the level of strength developed in the steel. Bainitic structure can be achieved in the final product in the same way as discussed above with some minor modifications. In this case, stable austenite is supercooled to a temperature range where it transforms to bainite (see Figure 10.4), Steel is deformed during the transformation of metastable austenite to bainite, followed by rapid cooling. The process results in improved and uniform mechanical properties as compared to the properties obtained by conventional hardening and tempering.

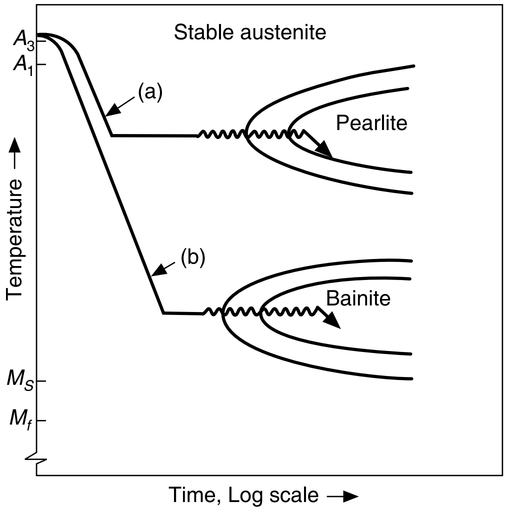


Figure 10.4 Isoforming process.

10.6 MARSTRAINING

In the marstraining process, steel is heated above austenitizing temperature, followed by rapid quenching so as to get a martensitic structure. Since as-quenched martensite is very hard and brittle, it is partially tempered to restore ductility. The ductile martensite thus obtained is cold worked. Only small deformations can be employed in this case because of the rapid rate of work hardening of martensite. This cold-worked martensite is retempered. The second tempering temperature should be lower than the first one. The process produces strain ageing and results in significant improvement in yield strength and tensile strength levels. It is believed that epsilon carbide formed at low tempering temperature dissolves during deformation. The dislocation-carbon interaction thus obtained hinders the movement of dislocations on retempering, and mechanical strength of the steel is improved. Since bainite is relatively soft as compared to martensite, it can be cold worked easily. The strain tempering response of bainite is found to be better than that of martensite in the sense that, for a given strength value, better ductility can be obtained. The first stage of the process, i.e. pretempering, which is carried out to impart some ductility to the steel for cold working, can be dispensed with in the case of strain tempering of bainite.

10.7 CRYOFORMING

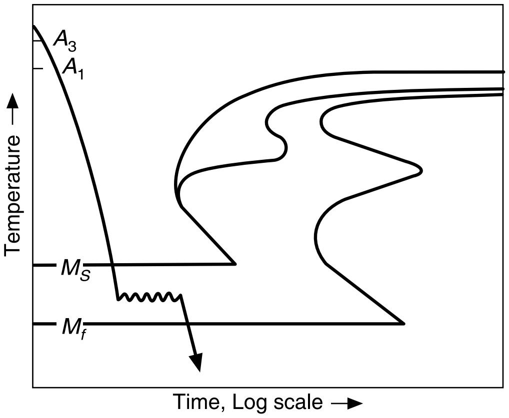


Figure 10.5 Cryoforming.

The cryoforming process is also known as zerolling. It consists of heating steel above the upper critical temperature. From this temperature, steel is rapidly quenched to sub-zero temperature. Then it is plastically deformed at sub-zero temperature, which is accompanied by high rate of work hardening. The transformation of a part of austenite to martensite takes place during deformation, and martensite thus produced has better yield strength, tensile strength and hardness. When austenite gets transformed into martensite at sub-zero temperature, a noise similar to crying is produced. The crying-like sound is produced because both deformation and transformation proceed simultaneously (see Figure 10.5). The process is well suited to steels which cannot be strengthened by cold working because of the high rate of work hardening, resulting in loss of ductility at a rapid rate. The only drawback associated with the process is that a part of austenite is stabilized. This in turn transforms to hard and brittle martensite during service at room temperature. Martensite so formed may cause brittleness.

10.8 PRELIMINARY THERMOMECHANICAL TREATMENT

In this process, steel is plastically deformed. Such steel is rapidly heated to austenitizing temperature, followed by rapid cooling. The treatment does not result in complete elimination of strain-hardening effect developed by deformation given prior to austenitizing. Therefore, the steels thus treated are associated with some strain-hardening effect. The magnitude of residual strain-hardening effect depends on the chemical composition of steel, amount of deformation, rate of deformation, rate of heating to austenitizing temperature, and the austenitizing temperature. Figure 10.6 summarizes the preliminary TMT cycles.

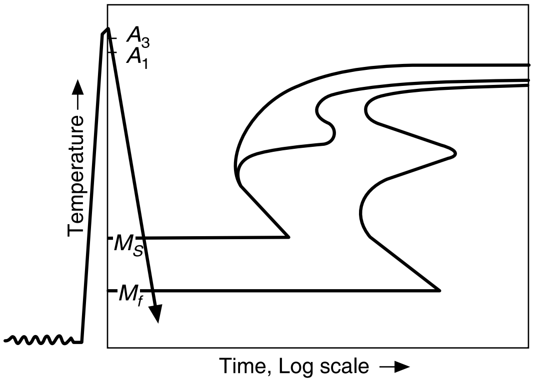


Figure 10.6 Preliminary TMT cycle.

10.9 THERMOMECHANICAL ANNEALING

Thermomechanical annealing consists of heating steel to a temperature just below the upper critical temperature. The metastable austenite thus obtained is plastically deformed as it cools down. The minimum temperature of deformation is just below the lower critical temperature. The process results in a structure consisting of ferrite and well distributed tiny globules of carbides. Such a structure is essential as it improves machinability of alloy steels to a great extent. The structure can be alternatively attained by spheroidizing (see Section 5.3) which is a very lengthy treatment as compared to thermomechanical annealing. Spheroidizing treatment for alloy steels takes long time due to a number of factors. Firstly, alloy steels are heated up and cooled down at slow rates. Secondly, many of the common alloying elements lower down the lower critical temperature, necessitating low temperature spheroidizing cycle and consequent low diffusion rates and low spheroidization speeds. Thermomechanical annealing cycle is shown in Figure 10.7.

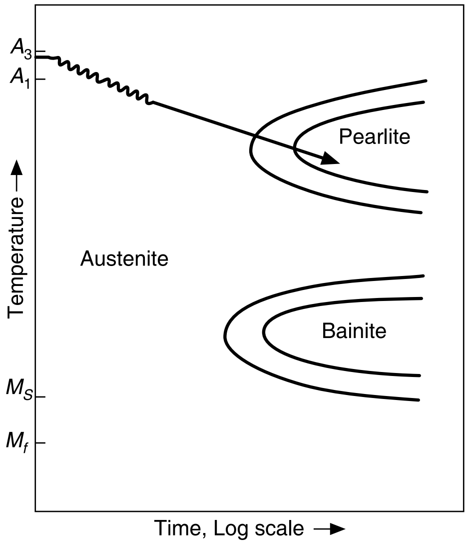


Figure 10.7 Thermomechanical annealing.

10.10 THERMOMECHANICAL TREATMENT OF NON-FERROUS ALLOYS

Thermomechanical treatment of non-ferrous alloys is commonly applied to the age-hardenable alloys. The process consists of plastic deformation of alloys followed by ageing treatment. This is in contrast to thermomechenical treatment applicable to steel, which consists of plastic deformation and simultaneous phase transformation. Significant amount of work has been done on thermomechanical treatment of non-ferrous alloys. Aluminium, copper, and nickel base precipitation hardenable alloys have been successfully subjected to thermomechanical treatment. Tensile strengths so acquired have been found to be many times the tensile strengths obtainable by conventional quenching and ageing treatment. Depending on the temperature of deformation, the process can be divided into two classes, namely, low temperature thermomechanical treatment (LTMT), and high temperature thermomechanical treatment (HTMT). LTMT and HTMT of non-ferrous alloys are shown in Figure 10.8.

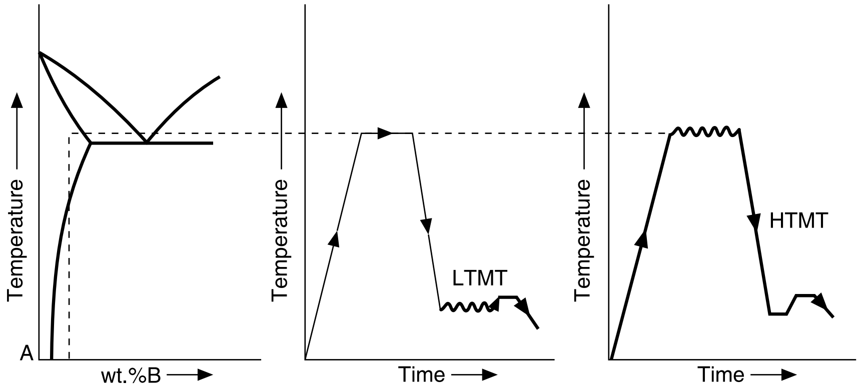


Figure 10.8 LTMT and HTMT cycle for an age hardening alloy.

Low temperature thermomechanical treatment of non-ferrous alloys consists of heating alloy to a single phase structure (solutionizing). From this temperature, alloy is rapidly cooled so that it retains the high temperature phase which is generally a supersaturated solid solution of alloying elements in base metal. This supersaturated solid solution is subjected to cold deformation. The cold-worked alloy is then aged at room temperature or at slightly higher temperatures. For a given alloy, such a treatment results in better yield strength and tensile strength than simple age hardening treatment. However, ductility will be comparatively poor. Tensile strength and hardness values increase as the degree of cold deformation rises. The larger the deformation of as-quenched alloy, the more is the improvement in tensile strength, yield strength, and hardness levels after deformation and ageing.

The strengthening mechanism during low temperature thermomechanical treatment of non-ferrous alloys can be explained on the basis of strain hardening and interaction between crystal defects and precipitated particles. Firstly, cold deformation produces strain-hardening effect. The higher the degree of deformation, the more will be the effect of strain hardening. Certain amount of strain hardening is retained even after heating to ageing temperature. The reason for this is that, in general, ageing temperatures are sufficiently low. So, only the recovery process, and not the recrystallization process, occurs at the ageing temperature. Thus, precipitation hardening takes place with higher initial strength/hardness values. It has been experimentally found that for a given alloy, strength/hardness levels have increased significantly by such a treatment as compared to quenching and ageing treatment. The extent of strengthening effect has been found to be decreasing with lowering amount of deformation and increasing magnitude of ageing temperature. Further, as-quenched supersaturated solid solution, which is thermodynamically unstable, becomes more unstable due to cold deformation. For such a highly unstable alloy, age hardening phenomenon is accelerated. This is due to (i) increased number of potential sites for precipitation, and (ii) enhanced diffusion rate. The defects introduced by cold working contribute to both these factors. The resultant strength/hardness, as usual, also depends on the nature and amount of phase that precipitates out. Cold deformation not only accelerates the precipitation rate from the supersaturated solid solution but also increases the number of precipitated particles and their volume fraction. It increases the probability of precipitation of some phases which would not have been precipitated out in the absence of cold deformation. Experimental observations have also confirmed that the sequence of progress of ageing treatment can be altered by cold deformation. One of the essential conditions for age hardenable alloys, i.e., a precipitate should be coherent with the matrix, is also not met with in cases where as-quenched supersaturated solid solution has been deformed heavily.

High temperature thermomechanical treatment includes heating of the alloy to get a single phase structure. It is followed by deformation of the alloy. The hot deformed solid solution is quenched rapidly and then aged. Hot deformation results in increased dislocation density and strain hardening. Here, the extent of strain hardening will be less than in low temperature thermomechanical treatment because of dynamic recrystallization and dynamic polygonization processes. The desired structure can be developed in hot deformed alloy by controlling the temperature, rate and degree of deformation. The structure may be either strain hardened, recrystallized and polygonized, or mixed.

The high temperature thermomechanical treatment consists of hot deforming solid solution (single phase) in such a way that either non-recrystallized or very feebly recrystallized structure is attained in the hot deformed alloy. Once this non-recrystallized structure is quenched, it will produce a structure with high dislocation density and crystal defects. On ageing, such a structure will develop better mechanical properties, specially tensile and yield strength. Improved properties are obtained by high temperature thermomechanical treatment under a set of optimum conditions. These conditions are as follows:

(i) The structure of hot deformed supersaturated solid solution should be non-recrystallized.
(ii) Dynamic recrystallization during hot deformation should be prevented effectively.
(iii) The degree of supersaturation should be sufficient so that considerable amount of precipitation should take place to induce significant hardening effect.

Optimum combination of strength and ductility is obtained by this treatment. Improved ductility is essentially due to more uniform precipitation from the supersaturated solid solution and very fine grain size. It is important to remember that grain size refinement is one process which improves both strength and ductility.

QUESTIONS

10.1 Any combination of heat treatment and plastic deformation by cold working cannot be referred to as thermomechanical treatment. Discuss.

10.2 What is the basic principle involved in thermomechanical treatment of steels? Give a classification of thermomechanical treatment for steels.

10.3 Conventional hot rolling does not strengthen steel whereas controlled rolling imparts very high strength levels in steels. Why?

10.4 Explain why hot-cold working is categorized as thermomechanical treatment.

10.5 What is ausforming? Enumerate and explain ausforming process variables.

10.6 Is isoforming a high temperature thermomechanical treatment? Compare the microstructure and mechanical properties of isoformed steel with that of a conventionally hardened and tempered steel.

10.7 Which types of steels are best suited for following thermomechanical treatments and why?

(a) Controlled rolling
(b) Isoforming
(c) Cryoforming
(d) Marstraining.

10.8 With the help of a suitable diagram, explain the principle, process and applications of cryoforming.

10.9 What is meant by thermomechanical annealing? Compare it with conventional annealing and spheroidizing.

10.10 Review critically the thermomechanical treatment of non-ferrous alloys.

11

Heat Treatment Furnaces and Atmospheres

INTRODUCTION

The success of heat treatment depends on proper choice of heat treating furnace and the type of atmosphere maintained in this furnace. Heat treatment cycles are effective and result in reproducible properties only when other factors like rate of heating and cooling and uniformity of temperature are ensured according to the requirements. This makes the choice of furnace an important aspect in heat treatment practice. Similarly, it becomes necessary to provide protective atmosphere to ensure that surface deterioration does not take place in reactive metals during heat treatment.

11.1 HEAT TREATMENT FURNACES

Heat treatment furnaces are essentially heating chambers. All heat treatment furnaces basically consist of a heating chamber. Furnace chamber is an enclosure, a refractory vessel, which contains the charge and retains heat. It is heated with some source of heat which should be such that supply of heat to the furnace chamber can be controlled easily. Such a control is essential since maintaining constant temperature for desired time and raising the temperature at the desired rate are two important steps involved in almost all heat treatment operations. Several furnaces, depending on their size and design, heat treatment of components, and on several other parameters, demand for heat circulation arrangement for efficient distribution of heat and introduction of special atmosphere if desired. In certain cases, the charge handling system, for the introduction and removal of charge, constitutes an important auxiliary of the furnace.

11.2 CLASSIFICATION OF HEAT TREATMENT FURNACES

Commonly used heat treatment furnaces may be classified according to use, source of heat, type of work and working environment.

Depending on the use, heat treatment furnaces can be further classified into various heads, such as annealing furnaces, hardening furnaces, tempering furnaces and carburizing furnaces. The basic difference in all these furnaces is based on their capacity to attain the desired temperature and to withstand it with adequate service life. Now-a-days furnaces, which are capable of working over a wide range of temperature, are available, and such furnaces can be used successfully for many heat treatment operations.

According to the source of heat, heat treatment furnaces can be broadly divided into two classes: fuel-fired furnaces and electrically heated furnaces. Fuel-fired furnaces can be further classified depending on the type of fuel, i.e. solid fuel, liquid fuel and gaseous fuel. Solid fuel-fired heat treatment furnaces are no longer in use. Commonly used liquid fuel is fuel oil. Gasoline and kerosene can be used successfully, but they are not being used due to their high cost. Liquid fuels are easy to store and the furnace can be fired at any time. Furnace temperature for such furnaces can be controlled easily with the help of a simple valve connected to the supply line. Oil-fired furnace can attain temperatures as high as 1200°C or more. In fact, oil-fired furnaces are economical only at high temperatures, i.e. in the vicinity of 1000°C. One important limitation of such furnaces is that temperature is not uniform throughout the chamber and so the use of heat circulation arrangement is essential. Gas-fired furnaces have specific advantages over oil-fired furnaces. They are more economical, possess better control of temperature, have simpler design, and can be used up to 1500°C. In fact, as far as efficiency and economy are concerned, gas-fired furnaces are inferior only to electrically heated furnaces. Natural gas, coke-oven gas, water gas, producer gas and refinery gas can be used in such furnaces.

Electric furnaces are most common now-a-days and are being used extensively. Electrically heated furnaces offer certain advantages, such as uniformity of temperature in the furnace chamber, close control of temperature, freedom from pollution, neat and clean working conditions, efficient use of heat energy (i.e. minimum loss of heat energy), minimum requirement of accessories, and ease of starting and closing down. High temperatures can be achieved in electrical furnaces in several ways. Depending on the method of heating, electrical furnaces can be grouped into resistance furnace, arc furnace, induction furnace, plasma arc furnace and electron beam furnace. Resistance furnaces are extensively used for heat treating metals and alloys. In such furnaces, temperature can be controlled easily and to a high degree of accuracy. Depending on the desired temperature, various resistors can be used. A few such resistors are listed in Table 11.1.

Electric arc is capable of producing very high temperatures, say 3000°C or more. However, there are practical difficulties in controlling the temperature so produced. For this reason, electric arc furnaces are mainly used for melting metals and alloys, and not for heat treating purposes. For the same reason, plasma arc and electron beam furnaces are also mainly confined to melting operations. Efforts are being made to utilize these sources of electrical energy towards heat treatment operations. Surface hardening by electron beam is one such example. High frequency induction units are used for surface hardening (induction hardening). However, due to skin effect, these units cannot be used efficiently for other heat treatment processes such as annealing, normalizing and hardening.

According to the type of operation, heat treatment furnaces can be classified into two broad groups, i.e. batch furnace and continuous furnace. In batch furnaces, in general, loading

Table 11.1 Resistors Used in Electrical Resistance Furnaces

Name	Composition	Maximum working temperature (°C)
Constantan	Cu, 40% Ni	900
Nichrome I	Ni, 20% Cr	1100
Nichrome II	Ni, 24% Fe; 16% Cr	950
Alumel	Ni, 3% Mn; 2% Al; 1% Si	1200
Chromel	Ni, 10% Cr	1200
Chromel C	Ni, 23% Fe; 15% Cr; 2% Mn	900
Kanthal	Fe, 25% Cr; 5% Al; 3% Co	1400
Tungsten		2400
Molybdenum		1800
Tantalum		2200
Platinum		1500
Pt–Rh alloy, Pt, 10% Rh		1700
Thoria		2400
Graphite		2000

and unloading of the charge is done manually. These furnaces find wide applicability as these are suitable for varying sizes of work-pieces to be heat treated. Also, with their help, different heat treatment operations can be performed. There is flexibility of operation. These furnaces are ideal for a plant based on job orders and having limited furnaces. The name batch furnace denotes that heat treatment of work-pieces is carried out and completed in various batches. If required, heat treatment process can be varied after each batch. In continuous furnaces, the charge is introduced from one end of the furnace. It is forced to move to another end from which it is discharged. The complete process is adjusted in such a way that discharged component is heat treated to the desired specifications. Such type of furnaces are very well suited for mass production units where parts are subjected to well established heat treatment cycle(s). Only one specific operation is performed in such furnaces. Considerable manual labour is involved in batch type furnaces in loading and unloading of charge. This is minimized to a great extent by using continuous furnace. These furnaces are recommended under conditions of continuous processing and ensure consistent and reproducible quality of heat treated parts. Various batch furnaces and continuous furnaces are discussed in Sections 11.3 and 11.4, respectively. Salt bath furnaces are dealt with in Section 11.5.

According to the work environment, heat treatment furnaces can be divided into two classes, namely, air convection furnaces and controlled atmosphere furnaces. Most of the heat treatment furnaces are of air convection type. Controlled atmosphere furnaces are used only under specific conditions and for limited metals and alloys. The necessity for different controlled atmospheres and their applications are discussed at length in Section 11.6.

11.3 BATCH FURNACES

One of the simplest batch furnaces is the box-type batch furnace (see Figure 11.1). Like box, it has opening (door) at one face only. From the door or gate, work-pieces to be heat treated are introduced and taken out from the same door after completion of the heat treatment operation. The loading and unloading are done manually. For heavy and bulky components, mechanical means are adopted for introduction and discharging. The problem associated with movement of heavy and bulky components has been solved to a great extent by designing box-type batch furnace in such a way that the bottom is movable, i.e. the bottom can be detached/taken out and after loading it can be fitted back. The bottom should be fitted in closely, and proper sealing should be ensured prior to use. Box type batch furnaces have the advantage of flexibility. These can be used over a wide range of operating conditions. In order to have the maximum advantage out of these furnaces, the furnace capacity should be used to the maximum possible extent. These furnaces can be heated up electrically or by any fuel.

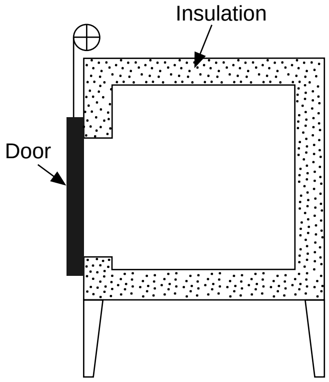


Figure 11.1 Box-type batch furnace.

Muffle furnaces (see Figure 11.2) are very common in use. The most important part of these furnaces is the muffle which is a hollow cuboid made of special refractory material. Any fuel or electrical energy can be used to heat the muffle. Electrically heated muffle furnaces are more popular and are extensively used for the heat treatment of small parts. Here the muffle is surrounded by heating element such as nichrome and kanthal wire. Fuel-fired muffle furnace can be of two types, namely, indirect and direct fuel-fired muffle furnaces. Indirect fuel-fired muffle furnace has advantages over direct fuel-fired muffle furnace for obvious reasons. Less scaling, reduced contaminations, possibility of controlling atmosphere within the muffle, and better uniformity of temperature distribution are some of the advantages.

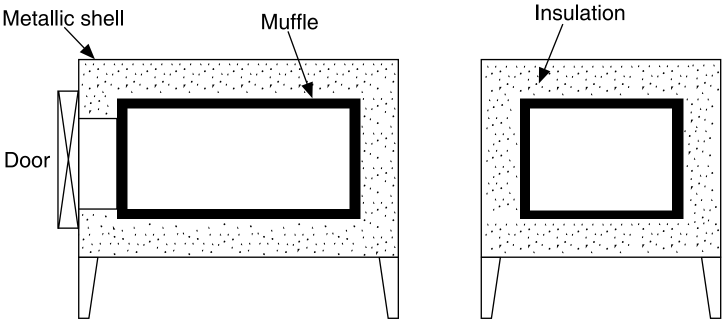


Figure 11.2 Schematic diagram of muffle furnace.

Pit type batch furnace (Figure 11.3) is mainly used for heavy and large parts. This furnace is generally heated up electrically, and is essentially a cylindrical refractory chamber. It is called *pit furnace* because most of its portion lies below the ground level. In this furnace, loading is done mechanically from the top which has an opening.

Bogie hearth batch furnace (Figure 11.4) can be considered as improved (modified) box-type batch furnace. The furnace is specifically suitable for heat treating bulky and heavy

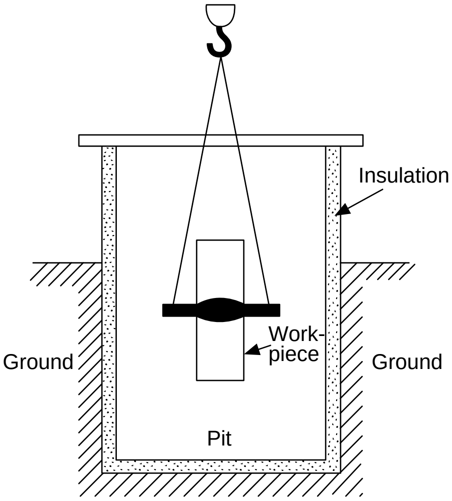


Figure 11.3 Pit furnace.

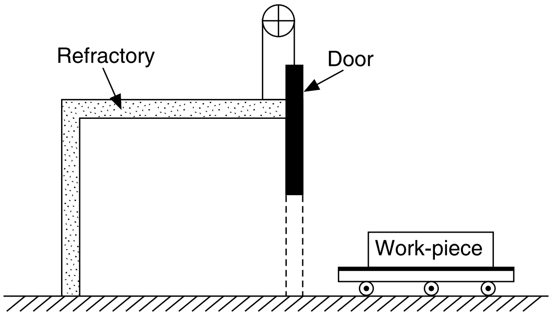


Figure 11.4 Bogie hearth batch furnace.

components although it can also be used for heat treatment of small components. The furnace consists of a refractory topped run-out bogie acting as a hearth, and carries the parts to be heat treated. The bogie should be well within the furnace chamber. Atmosphere within the furnace chamber can be controlled by employing proper sealing.

Lift-off cover furnace (Figure 11.5), also referred to as bell type furnace, is a fixed base furnace and consists of two containers. The base is generally made of heat resisting alloy steel. The work-pieces to be heat treated are put on this base. After loading, one container, called inner container, is placed on the base. Another bell shaped container, known as outer container, is placed over the inner one and the furnace is heated up electrically. The inner container is made of heat resisting alloy steel, whereas the outer one is a metal encased refractory. This furnace is widely used in wire industries for annealing coils of steal wire, steel strips and non-ferrous metals under controlled atmosphere to prevent decarburization or oxidation.

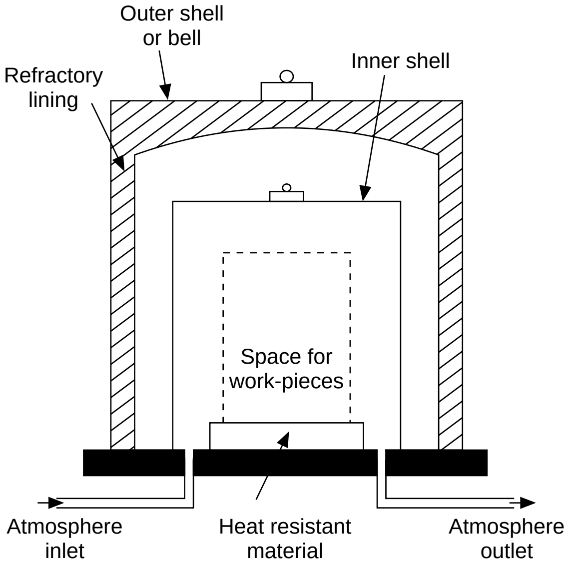


Figure 11.5 Lift-off cover furnace.

11.4 CONTINUOUS FURNACES

Rotary hearth furnaces (Figure 11.6) fall into the group of continuous type furnaces. As the name suggests, these furnaces consist of a rotating hearth. The hearth rotates along its vertical axis. The components to be heat treated are charged through an opening. After completion of the heat treatment cycle, heat treated components are taken out from the same opening or one adjacent to it. The speed of rotation is adjusted in such a manner that heat treatment cycle is completed by the time the hearth undergoes one complete rotation.

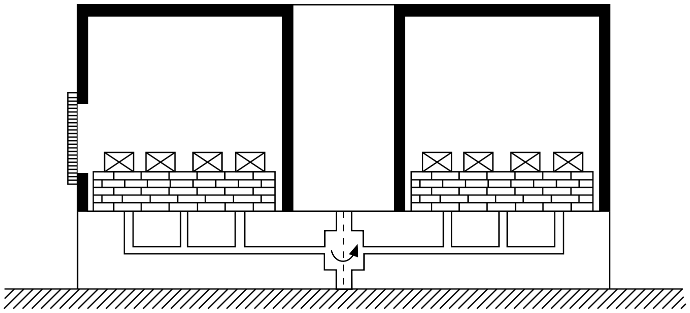


Figure 11.6 Rotary hearth furnace.

Conveyor furnace (Figure 11.7) consists of an endless conveyor belt which moves at a very slow rate. The components to be heat treated are placed on the belt. The component on the belt enters the furnace from one end and comes out from the other. During this movement, the heating cycle is completed. Since the belt is moving continuously, components are either collected in a box or dropped into the quenching tank. These furnaces are generally used for hardening and tempering treatment.

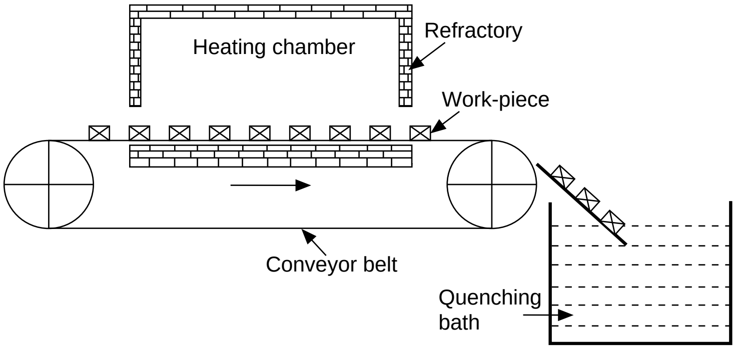


Figure 11.7 Conveyor furnace.

Tunnel furnace (Figure 11.8) is commonly used for annealing. In such a furnace, the charge is loaded on a number of cars. The cars are pushed slowly into the furnace, and pass through the furnace with the help of some mechanical means and finally come back to the starting point as a result of the circular path followed. Thus, a continuous process of movement of cars results in the removal of one car and introduction of next charged car simultaneously.

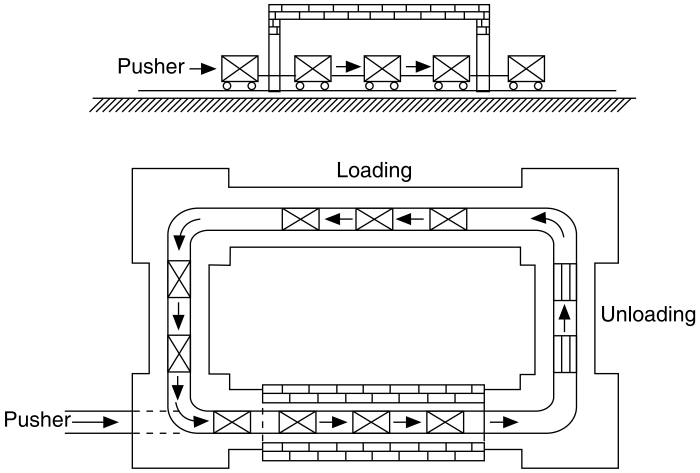


Figure 11.8 Layout of a tunnel furnace.

Rotary furnace (Figure 11.9) is used for heat treating small parts for hardening, tempering, gas carburizing, and so on. It consists of a steel drum with refractory lining, and rotates at a slow speed around its horizontal axis. In general, the horizontal axis of the steel drum is inclined.

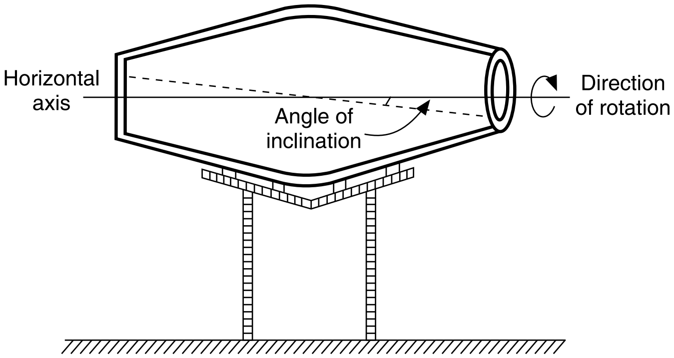


Figure 11.9 Schematic diagram of a rotary furnace.

11.5 SALT BATH FURNACES

Molten salt bath furnaces (Figure 11.10) essentially consist of a container made of ceramic or metal. This container holds molten salt in which work-pieces are immersed. Molten salt bath furnaces can be used within a wide range of temperature (150–1300°C). The commonly used salts are nitrates, chlorides, carbonates, cyanides and caustic soda. The mode of heat transfer to the work-piece is by convection through the liquid bath. As the molten baths possess high heat capacity and heat is transferred by convection, the work-piece is heated up very quickly as compared to conventional furnaces (rate of heating is about five times higher in these furnaces). These furnaces can be heated by fuel or electricity. Electrically heated salt bath

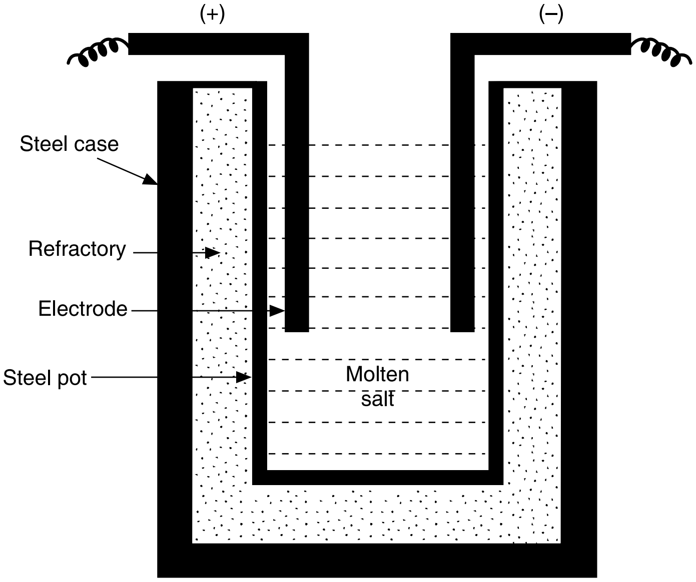


Figure 11.10 Salt bath furnace.

furnaces are much more common in use. These can be classified into three types, namely, externally heated, immersion heating element, and immersed electrode type salt bath furnaces.

Salt bath furnaces are used for various heat treatment operations such as cyaniding, liquid carburizing, liquid nitriding, austempering, martempering, hardening and tempering.

These furnaces offer certain advantages over other furnaces. For example, all work-pieces are at uniform temperature and have identical surroundings. Such a condition results in better surface conditions and consistent and reproducible results. Since work-piece is in direct contact with the molten bath, there is no danger of oxidation and/or decarburization. Selective heat treatment of the work-piece can be performed by immersing only the desired portion of the work-piece. The time consumed in the process is very little. Also, complicated shapes or objects with variable section thicknesses can be heated along with simply shaped objects. Similarly, light and heavy objects can be handled in the same bath.

11.6 CONTROLLED ATMOSPHERES

A controlled atmosphere is defined as a furnace atmosphere that protects the metal from oxidation and maintains the desired properties at the surface of the metal during heat treatment. The composition and distribution of the atmosphere are deliberately controlled to produce specific surface characteristics.

Broadly speaking, controlled atmospheres are either protective or chemically active atmospheres. The aim of protective atmosphere is to prevent oxidation, decarburization or other unwanted chemical changes on the surface of metal, which may otherwise occur during heat treatment.

Bright annealing, normalizing of ferrous and non-ferrous metals and alloys, and atmosphere annealing of black heart malleable cast iron are examples where protective atmosphere is used. In the case of chemically active atmospheres, the aim is to bring change in the chemistry of metal and alloys at the surface or throughout its cross-section. Examples of such type include carburizing and carbonitriding of steel components, decarburization, annealing of white heart malleable cast iron, nitriding, chromizing and gas descaling of hot-rolled steels.

11.6.1 Chemistry of Controlled Atmosphere Processes

Controlled atmospheres generally contain mixtures of gases such as N_2, H_2, H_2O, CO, CO_2 and CH_4. Free oxygen and sulphur compounds are also found in traces as impurities. The level to which these impurities can be tolerated depends on the nature of metal used and operating conditions. The proportions of different gases mixed together decide the properties of controlled atmosphere.

Reactions taking place in the furnace may be grouped as (i) reactions between metal and oxygen, (ii) reactions between metal and carbon, and (iii) reactions between gases. These reactions are now described in detail.

Reactions between metal and oxygen

These reactions are very important since in the majority of cases they form the basis on which techniques are evolved for protecting the metals from oxidation.

The reactions, which control oxidation in a furnace and which are utilized for a process such as bright annealing of low carbon steel, can be written as

$$\text{Metal} + H_2O \rightleftharpoons \text{metal oxide} + H_2$$

$$\text{Metal} + CO_2 \rightleftharpoons \text{metal oxide} + CO \tag{11.1}$$

The composition of these systems at equilibrium is determined by

$$K_1 = \frac{p_{H_2}}{p_{H_2O}}, \qquad K_2 = \frac{p_{CO}}{p_{CO_2}}$$

where K_1 and K_2 are equilibrium constants, p_{H_2}, p_{H_2O}, p_{CO}, and p_{CO_2} are partial pressures of respective gases. Now,

$$\frac{K_2}{K_1} = K_T = \frac{p_{CO} \times p_{H_2O}}{p_{CO_2} \times p_{H_2}} \tag{11.2}$$

where K_T is the equilibrium constant at temperature T. The equilibrium constant K_T is related to temperature by the equation

$$\log_{10} K_T = -\frac{\Delta G^\circ}{4.576T} \tag{11.3}$$

where ΔG° is the free energy of the reaction.

The oxidation/reduction potential depends on the ratio of partial pressure of H_2 to partial pressure of H_2O, and the ratio of partial pressure of CO to partial pressure of CO_2 as expressed by Eq. (11.2). The actual required ratio is decided by the oxide dissociation pressure of the particular metal at the given temperature.

The nature of different metals to oxidize can be shown by graph (Figure 11.11). This shows the variation of oxygen dissociation pressure of common metallic oxides. A point corresponding to the oxygen partial pressure of any atmosphere at a particular temperature can be taken. Those metals which have dissociation pressures lower than this point get oxidized in that atmosphere. On the other hand, those metals which have higher dissociation pressures will not be oxidized.

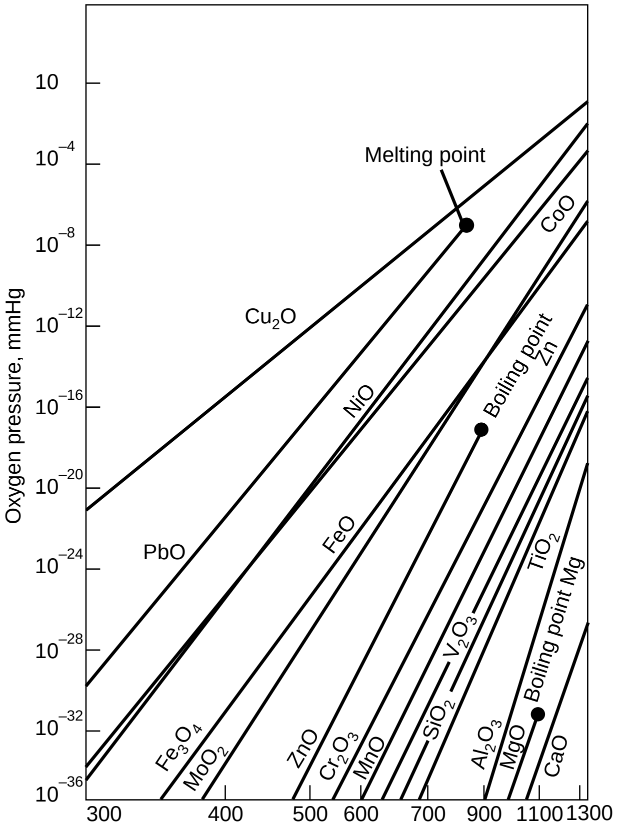


Figure 11.11 Oxygen dissociation pressures of some oxides as a function of temperature.

Atmospheres that have very slight oxygen partial pressure are generally regarded as having no free oxygen. The temperature and the concentration of oxygen bearing gas influence this, and the value can be extremely high as compared to dissociation pressures of metal oxides. Hydrogen and oxygen bearing gases such as water vapour, carbon dioxide and carbon monoxide are contained in many commercial atmospheres. By considering the, relative Concentrations of oxidizing and reducing constituents, it is possible to assess the oxidizing tendencies of these atmospheres. Critical requirements for oxidation of iron by atmospheres containing water vapour and hydrogen and carbon dioxide and carbon monoxide are shown in Figures 11.12 and 11.13, respectively.

Metals and their oxides in pure solid form have been considered in Figure 11.11. The critical atmosphere requirements are affected if the chemical activities are altered in any way. Alloying is one such important factor. It is possible to estimate its effect. Activity of primary metals is reduced by addition of other metals which are less active. The requirements of atmosphere are thus made less exacting. Figure 11.14 shows the quantitative effects as a function of temperature and metals involved. The three binary systems relate to those of commercial importance. It may be observed that in two of the systems, the regions of substantially constant atmosphere requirements correspond to mixed phase fields. On the other hand, the Fe–Ni system is free from such effects. It is also one of those rare systems in which the chemical activity of either metal is equal to its atomic fraction in the alloy. It is also observed in many cases that even when very active elements are present in an alloy in very small quantity, say below 1 percent, they do not significantly affect the critical atmosphere requirements of the base metal. One of the important reasons for these observations is drastically reduced activities at such low concentrations.

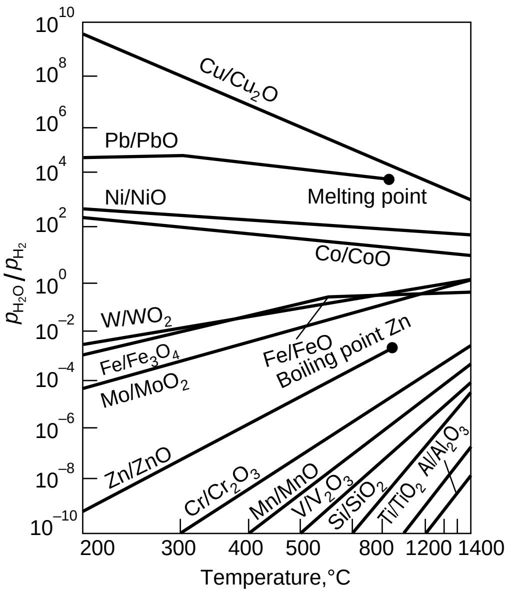


Figure 11.12 **Critical requirements for the oxidation of some metals as a function of temperature in atmospheres containing water vapour and hydrogen.**

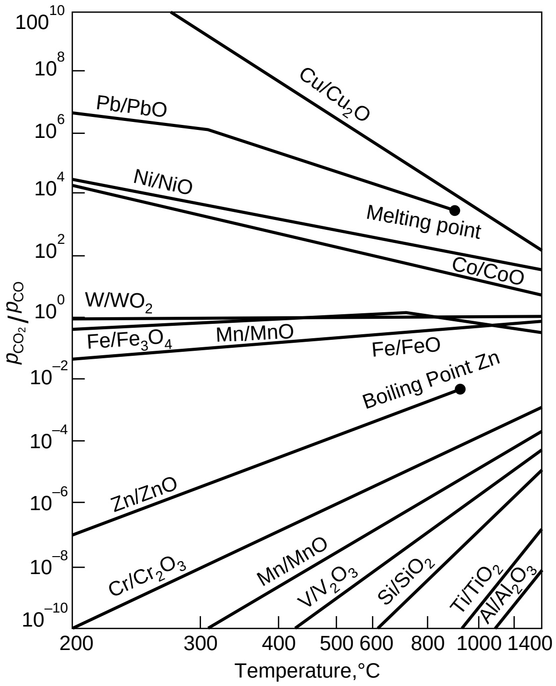


Figure 11.13 **Critical requirements for the oxidation of some selected metals as a function of temperature in atmospheres containing carbon dioxide and carbon monoxide.**

Reactions between metals and carbon

In the case of ferrous alloys, many practical processes involve lowering, maintaining, or raising of the initial carbon level in the material. In other words, carburization or decarburization or their prevention is involved. The common gases which are helpful for carburizing of ferrous materials are carbon monoxide and methane. Gases responsible for decarburization are carbon dioxide, water vapour and hydrogen (up to much lower limit). The following reactions are relevant in this context:

$$2CO + 3Fe \rightleftharpoons CO_2 + Fe_3C$$

$$CH_4 + 3Fe \rightleftharpoons 2H_2 + Fe_3C \qquad (11.4)$$

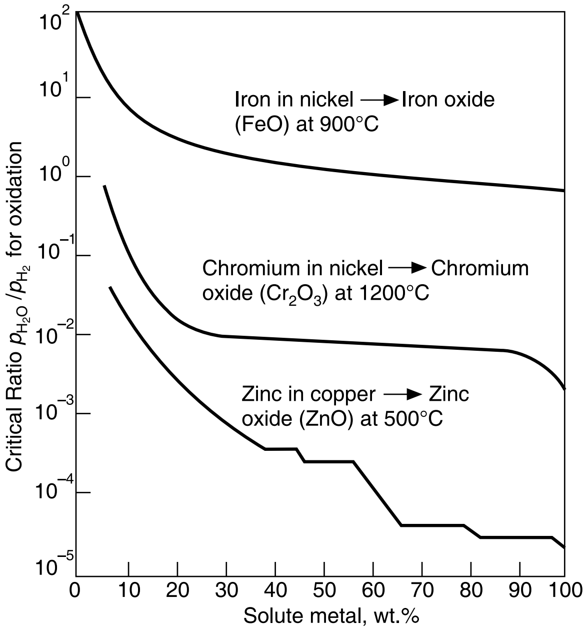


Figure 11.14 Effect of alloying on critical atmosphere requirements for the oxidation of some metals at given temperatures in atmospheres containing water vapour and hydrogen.

for which the equilibrium constants are

$$K_3 = \frac{p_{CO_2}}{p^2{}_{CO}}, \qquad K_4 = \frac{p^2{}_{H_2}}{p_{CH_4}}$$

At a given temperature, the ratio

$$\frac{p^2{}_{CO}}{p_{CO_2}} \quad \text{or} \quad \frac{p_{CH_4}}{p^2{}_{H_2}}$$

can be used for assessing the carbon potential of the atmosphere at a given temperature. These constants involve the second power of the carbon-monoxide and hydrogen content, respectively.

Therefore, in assessing carbon potential or carburizing/decarburizing action of furnace atmosphere, besides the ratio of CO to CO_2, or CH_4 to H_2, the total concentrations should also be considered. Figures 11.15 and 11.16 respectively show the effect of ratios

$$\frac{p^2{}_{CO}}{p_{CO_2}} \quad \text{and} \quad \frac{p^2{}_{H_2}}{p_{CH_4}}$$

on carbon potential in iron with temperature.

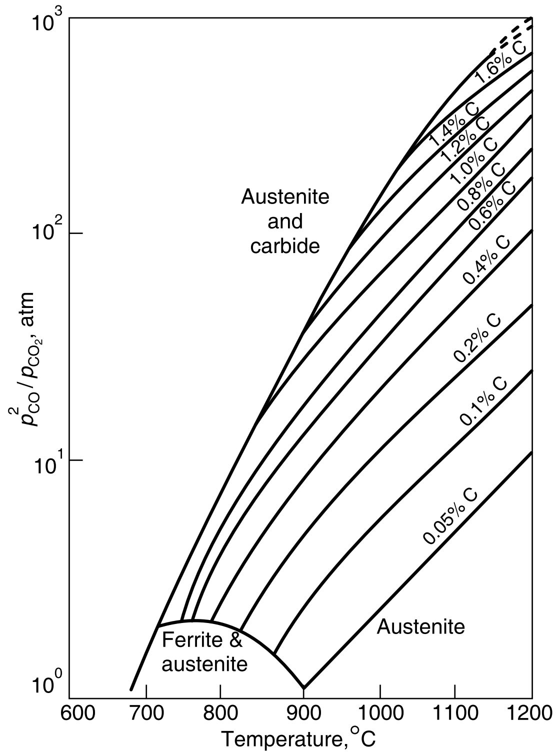


Figure 11.15 Effect of p^2_{CO}/p_{CO_2} ratio on carbon potential in iron as a function of temperature.

It is convenient to estimate the carbon potential of a complex atmosphere at a given temperature. This is carried out by measuring one of the minor constituents. The approximate basic composition is to be kept fixed. It is necessary that the constituents be in equilibrium. Either the carbon dioxide or water vapour content is used as a measure of carbon potential for endothermic gases.

Methane plays an important role in the process of gas carburizing of steels as it is the main source of available carbon; also, it strongly influences soot deposition. However, for assessment of effective carbon potential, it has limited value. The amounts usually present are far in excess of those required for equilibrium with other gases. Accordingly, the carbon potentials are much higher than those which are applied in practice. The following reactions also require due consideration in this context:

$$2CO \rightarrow CO_2 + C \text{ (soot)} \qquad (11.5)$$

$$CH_4 \rightarrow 2H_2 + C \text{ (soot)} \qquad (11.6)$$

These reactions are important, especially in the presence of surfaces that have a catalytic influence on the reactions.

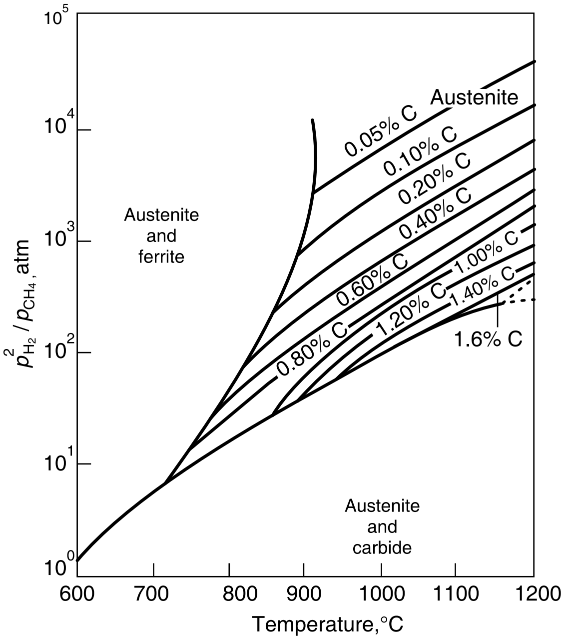


Figure 11.16 Effect of $p_{H_2}^2/p_{CH_4}$ ratio on carbon potential in iron as a function of temperature.

Water vapour is also decarburizing, as is clear from the reaction

$$H_2O + Fe_3C \rightleftharpoons H_2 + CO + 3Fe \qquad (11.7)$$

This reaction requires due consideration in the temperature range 700–750°C.

For non-ferrous metals, the following reaction is very significant:

$$H_2S + \text{metal} \rightarrow H_2 + \text{metal sulphide} \qquad (11.8)$$

This reaction assumes importance when the atmosphere is contaminated with sulphur.

Reactions between gases

Atmospheres containing oxygen, carbon and hydrogen are commonly used to bring about changes in composition for obtaining equilibrium at different temperatures. These effects result from changes in the relative affinities of carbon monoxide and hydrogen for oxygen. Carbon monoxide has greater affinity for oxygen at lower temperatures, while hydrogen has greater affinity for oxygen at higher temperatures, the affinities towards oxygen being equal at about 850°C. At temperatures above 800°C, equilibrium is established by the reaction

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \qquad (11.9)$$

This reaction is called water gas reaction.

Carbon bearing gases present in atmospheres may deposit carbon when temperature changes, though it may be in equilibrium at some other temperature. Carbon monoxide, for example, has a tendency to decompose at low temperatures as was shown by reaction (Eq. 11.5).

If the atmosphere contains water vapour, then the concentration of carbon monoxide can be reduced at low temperature because of water gas reaction. Carbon deposition as soot is a practical problem, particularly in the surfaces that have a catalytic influence on the reactions. The other reaction that also requires attention is reaction (Eq. 11.6).

11.6.2 Commercially Available Atmospheres

The bulk of industrial furnace atmospheres currently in use are: (i) town gas or other fuel gases, (ii) ammonia, (iii) charcoal, (iv) liquid organic mixtures (alcohol base for carburizing), and (v) vacuum.

Prepared Town Gas

Town gas is cheap and is an easily available gas. Atmospheres are prepared by burning a fuel gas with varying amounts of air to give a wide variety of product gases. There are two types of atmospheres where town gas is used, namely, exothermic and endothermic, which we now discuss.

Exothermic Atmospheres Exothermic generators employ partial combustion of town gas, propane, and so on in the presence of air, followed by condensation of excess water vapour.

A range of atmosphere compositions can be produced containing 5–14% CO_2, 1–14% CO, 1–18% H_2 and 0–2% CH_4.

The temperature of the condenser and cooling water determines the content of water vapour, and may correspond to a dew point in the range 5–25°C. Dew points down to –40°C may be obtained by introducing refrigerators and/or dryers to the plant.

By adjusting air-to-gas ratio, both lean (totally burnt) and rich (flammable) exothermic atmospheres may be produced. Generally, rich atmosphere is used for heat treatment of steels, e.g. bright annealing, normalizing and tempering. Lean atmosphere is more commonly used for heat treatment of non-ferrous metals and alloys, e.g. for bright annealing of copper. In this case, at some places sulphur removal is necessary.

These atmospheres have low carbon potential due to the presence of CO_2. Hence, they have limitations at such situations where decarburization is involved. To ensure that the atmosphere is non-decarburizing, CO_2 and water vapour must be removed. When CO_2 and water vapour are removed from the exothermic atmosphere, stripped and dried, exothermic atmosphere is formed. Pure nitrogen and nitrogen-base atmospheres containing controlled amounts of CO and/or hydrogen up to about 25% total come under this category. Initial air-to-gas ratio selected at the generator and the use of a modifying process at a later stage determine the composition. The rich stripped exothermic gas has the composition 10–13% CO, 12–15% H_2, and balance N_2, CO and H_2 give rise to reducing atmosphere and cause carburizing because of the presence of CO. It is more like an endothermic gas. This gas is relatively cheap.

The lean stripped exothermic gas contains 0–3% CO, 0–4% H_2, and balance N_2. It is principally nitrogen containing gas and, when dry, is inert to most of the metals during heat treatment. The advantage is its cheapness, coupled with its non-explosive, non-sooting and non-decarburizing nature.

Carbon dioxide from exothermic atmospheres can be removed by using the following three techniques: (i) mono-ethanolamine (MEA) method, (ii) use of high pressure water, and (iii) molecular sieves method.

(i) *Mono-ethanolamine* (*MEA*) *method*. In this method, CO_2 gas is absorbed in a 15 percent solution of MEA. CO_2 level goes down to about 0.1 percent in exothermic gases. Sulphurous gases are also removed simultaneously. In industries, regenerative plant is also utilized to reuse the MEA gas by driving off CO_2 by heating and venting to air.

(ii) *Use of high pressure water*. In this method, CO_2 is removed by high pressure water. But this method is not very popular because of its high cost. CO_2 level of about 0.1 percent is obtained by using a pressure of about 20 atmospheres.

(iii) *Molecular sieves method.* Molecular sieves are made of granulated artificial zeolite which absorbs both CO_2 and water. By this method, CO_2 level below 0.1 percent is obtained.

Endothermic Atmospheres Endothermic gas is produced by hydrocarbon containing fuel gases with just sufficient air to oxidize the hydrocarbon to CO and H_2. The reactions are as follows:

$$2CH_4 + O_2 + 4N_2 = 2CO + 4H_2 + 4N_2 \tag{11.10}$$

$$2C_3H_8 + 3O_2 + 12N_2 = 6CO + 8H_2 + 12N_2 \tag{11.11}$$

These reactions are carried out at 1075°C in the presence of nickel catalyst.

A typical sample from town gas contains 20–25% CO, 30–45% H_2, 0.5–1.0% CH_4, and 0–1.0% CO_2. Its dew point ranges from –15°C to +20°C. Reactions (11.10) and (11.11) are exothermic, but insufficient to maintain the reaction temperature. Therefore, externally heated retort is used in plant to maintain the temperature. Hence, it is called endothermic.

The atmosphere has a high carbon potential. This can be adjusted by varying gas-to-air ratio. The carbon potential is inversely proportional to the CO_2 content or dew point. Thus, by measuring these quantifies, control over the carbon potential can be maintained.

Endothermic generators are widely used for heat treatment and brazing of carbon steels without decarburization. They are also used for sintering, and as a base gas for gas carburizing and carbonitriding of steels.

Ammonia based Atmospheres

Plenty of anhydrous ammonia is available in liquid form in cylinders. Cracked ammonia is produced when ammonia is dissociated into its constituents by passing it over a catalyst (iron at 560°C, or nickel at 900°C). The reaction that takes place is

$$2NH_3 \rightarrow N_2 + 3H_2 \tag{11.12}$$

Composition of cracked ammonia is 75 percent hydrogen and 25 percent nitrogen. The cracked gas has dew point between –15° and –40°C, depending on the grade of ammonia used. The very high H_2/H_2O ratio gives maximum reducing conditions for the cracked gas.

Burned ammonia is prepared by converting ammonia/air mixture to nitrogen, hydrogen, and water directly over a catalyst at 850°C. The reaction that takes place during burning of ammonia is

$$4NH_3 + 3O_2 + 12N_2 \rightarrow 14N_2 + 6H_2O \tag{11.13}$$

The gas has dew point between +5°C and –70°C.

Pure and cheap atmospheres are produced from ammonia. For bright annealing of strip and wire, burnt ammonia can be used as an alternative to purified partially burnt town gas. For bright annealing of stainless steels, sintering and other applications, cracked ammonia is used.

Charcoal

Charcoal is also used to produce atmospheres by combustion with air or flue gas. When charcoal is burnt in contact with air, the gaseous product which is formed contains 1–3% CO_2, 28–30% CO, 2–8% H_2 and traces of CH_4. Dried atmospheres obtained from charcoal have moderately high carbon potential. But this is very cumbersome because of operating conditions.

Liquid Organic Mixtures

It is possible to obtain a gas of very high carbon potential when certain organic mixtures, especially those based on alcohol, are directly pyrolyzed in a furnace. This gas is very useful for gas carburizing. The associated reaction is

$$\underset{\text{(propyl alcohol)}}{C_3H_7OH} \rightarrow 2CH_4 + CO \tag{11.14}$$

Liquid organic mixtures of commercial use are mostly based on methanol or propanol. Benzole or dipentene is the hydrocarbon that is generally added to this base.

Vacuum

The use of vacuum in a heat treatment furnace chamber is regarded as an alternative form of controlled atmosphere. Under certain working conditions, vacuum is found to be the most suitable protective atmosphere. Vacuum (5–30 mm) is sometimes used for bright annealing steel wire and strip in batch type furnaces. High vacuum (in micron range) is being increasingly used for brazing and annealing of stainless steel and heat resistant steels.

11.6.3 Control of Furnace Atmospheres

Furnace atmospheres can be controlled by using some controllers. There are basically two types of controllers in use for this purpose. These are infrared controllers and gas chromatography controllers. Infrared controllers are used for measuring CO, CO_2 and methane content in atmospheres. The method is quite sensitive and reproducible. The carbon potential of the furnace is calibrated with respect to CO_2 concentration. The controllers based on gas chromatography technique are produced by using the normal principles of gas chromatography, and can estimate the relative proportions of the component gases in the atmosphere. This in turn can be used for the required control.

QUESTIONS

11.1 Give a detailed account of classification of heat treatment furnaces.

11.2 Enumerate salient features of "Lift-off Cover" furnace. What are its various industrial applications?

11.3 Compare the rotary hearth furnace with rotary furnace and describe their utilities in heat treatment.

11.4 Write short notes on the following:

(a) Conveyor furnace
(b) Pit furnace
(c) Muffle furnace.

11.5 Explain advantages offered by salt-bath furnace over other heat treatment furnaces.

11.6 What is the significance of controlled atmospheres in heat treatment?

11.7 Discuss the reaction that take place between the following in furnace under controlled atmospheres:

(a) Metal and oxygen
(b) Metal and carbon
(c) Different gases.

11.8 Give a brief account of various commercially available furnace atmospheres in heat treatment.

12

Temperature Measurement and Control

INTRODUCTION

Accurate measurement and control of temperature are the two important operations involved in heat treating of metals and alloys. Any variation from the desired temperature may lead to development of inferior properties in metals and alloys after heat treatment. Though most of the heat treatment processes involve high temperatures, low temperatures as well as sub-zero temperatures are also involved in some heat treatment processes. Therefore, it is essential to construct a suitable scale of temperature. The results obtained from this temperature scale should be reproducible in nature with a high degree of precision and accuracy. The temperatures involved in heat treating of metals and alloys, in general, varies from –100°C to +1400°C.

12.1 CONCEPT OF TEMPERATURE

Thermal phenomena cannot be described in terms of the three fundamental quantities, i.e. length, mass, and time. A fourth fundamental quantity is needed to explain thermal phenomena. This quantity is referred to as temperature. Till 1843, the quantity of heat was regarded as a fundamental quantity. It was the work of Rumford and Joule (1843–78) which showed that heat is a form of energy and that the quantity of heat can be expressed in terms of three fundamental units.

Temperature is a physical quantity entirely different from quantity of heat. A hot body is considered to be at a higher temperature than a cold body. Therefore, temperature can be used to measure the degree of hotness or coldness. In other words, temperature determines the direction of flow of heat. If two bodies are brought in physical contact with each other, heat will flow from the body at higher temperature to the body at lower temperature. This flow will continue and after some time there will be no further flow of heat. Such a state is explained by stating that both the bodies are in thermal equilibrium. If a number of bodies (or systems) are in thermal equilibrium, the common property of all the bodies can be assigned a single numerical value referred to as temperature. Bodies which are not in thermal equilibrium have different temperatures. Therefore, the temperature of a system can be defined as the property that determines whether or not the system is in thermal equilibrium with the neighbouring system(s).

12.2 MEASUREMENT OF TEMPERATURE

The physical properties of materials change with application of heat. These properties are known as thermometric properties. Any one of these properties can be used for the measurement of temperature. The science and technology dealing with the measurement of temperatures below 500°C is referred to as thermometry, and the instruments used for this purpose are known as thermometers. On the other hand, pyrometry deals with measurement of temperatures above 500ºC, and the instruments used for this purpose are known as pyrometers. For the quantitative measurement of temperature, it is essential to select (at least two) fixed temperatures which must be reproducible in nature. The most important fixed points are the ice point and the steam point. The ice point is defined as the temperature at which ice and air saturated water at normal atmospheric pressure exist in equilibrium. Similarly, steam point is the equilibrium temperature between liquid water and water vapour at one atmospheric pressure. The most popular temperature scale is due to Celsius. In 1742, Celsius suggested the centigrade system of temperature measurement. The two fixed points corresponding to ice and steam points were marked as zero and 100 on the lower and upper ends of the scale, respectively. The interval between the two fixed points was divided into hundred equal parts. Each of these parts was called one degree centigrade or one degree Celsius and was represented as 1°C.

12.3 THERMOMETERS

Thermometers can be grouped into several classes. The classification of thermometers is based on the thermometric property used for the measurement of temperature. Examples of various thermometers are liquid thermometers, gas thermometers, resistance thermometers, vapour pressure thermometers and magnetic thermometers.

Liquid thermometers are based on the principle that the volume of a liquid changes with variation in temperature. Mercury and alcohol thermometers are examples of commercial thermometers belonging to this class. The temperature of general purpose mercury thermometer ranges from –39°C to +357°C. Alcohol thermometer is used to measure temperatures near the ice point. Some of the advantages offered by mercury for use in liquid-in-glass thermometers are due to its low specific heat, good thermal conductivity and uniform coefficient of expansion. Mercury thermometers are generally used for rough and quick work. However, after several corrections, mercury thermometer can be used for precision work. Some of these corrections are due to change of zero point, rapid heating and cooling, exposed stem, inequality of the bore, and thermal capacity and thermal conductivity of the bulb.

The principle that the volume or the pressure of a gas changes with variation in temperature forms the basis of gas thermometers. Callendar’s constant pressure air thermometer, Jolly’s constant volume air thermometer and constant volume hydrogen thermometer belong to this class. In comparison to liquid thermometers, gas thermometers offer certain advantages. These advantages are essentially due to large coefficient of expansion, uniform and regular expansion over a wide range of temperature, and low thermal capacity. Gas thermometers can be used over a wide range of temperature and are suitable for both low and high temperature measurement. These thermometers are not used for routine work as they are bulky and cumbersome.

Bimetallic thermometers are based on the principle of differential expansion of solids. The bimetallic strip consists of two bonded strips. One strip is made of a high expansion metal, and the other of a low expansion metal. When heat is applied, such an arrangement will result in non-uniform expansion along the two strips. This non-uniform expansion is utilized for the measurement of temperature. An industrial bimetallic strip is taken in the form of a spiral. One end of it is fixed and the other end is attached to a pointer which moves over a calibrated scale. In general, invar is selected as a low expansion metal. The metal for the other strip depends on the temperature range of the interest. Yellow brass strip is generally used for low temperatures and nickel or nickel alloys for higher temperatures. Bimetallic thermometers can be used to measure temperatures which vary from –73°C to +537°C.

Vapour pressure thermometers are based on the principle that vapour pressure changes with temperature. For a given temperature, a fixed vapour pressure can be assigned. These thermometers are used for low temperature measurement. The greatest drawback associated with these thermometers is that their useful temperature range is very narrow. The useful temperature ranges are as follows:

Oxygen	–150°C to –210°C
Neon	–246°C to –249°C
Hydrogen	–253°C to –260°C
Helium	–268°C to –272°C

Electrical resistance of a metal changes with temperature. This principle forms the basis of resistance thermometers. Platinum resistance thermometer is capable of measuring temperatures in the range –200°C to +1200°C, with high degree of accuracy. The temperature vs resistance curve for platinum resistance thermometer is almost a straight line. The relationship between temperature and the electrical resistance can be expressed by the equation

$$R_t = R_0(1 + \alpha \cdot t) \qquad (12.1)$$

where R_t is the resistance (in ohms) of the platinum at temperature t °C; R_0 is the resistance of platinum (in ohms) at ice point; α is the temperature coefficient, and t is the temperature in °C. The temperature coefficient α is given by the equation

$$\alpha = R_{100} - R_0/100R_0 \qquad (12.2)$$

where R_{100} is the resistance (in ohms) of the platinum at steam point. The value of α is equal to 0.003915 ohms/°C for high purity platinum. A precise temperature-resistance relationship is given by the equation

$$R_t = R_0(1 + At + Bt^2) \qquad (12.3)$$

where A and B are constants. These constants can be calculated by measuring resistance at several fixed points. These fixed points are, in general, steam point and sulphur point.

The magnetic susceptibility of a substance varies with temperature. Based on this principle, magnetic thermometers are used for the measurement of temperature. These thermometers can primarily be used for measurement of extremely low temperature, generally in the vicinity of –273°C.

12.4 THERMO-COUPLES

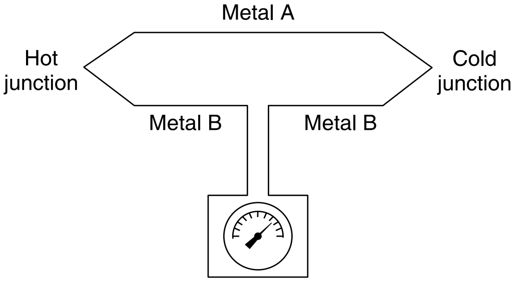


Figure 12.1 Diagram illustrating Seebeck effect.

Thermo-couples are based on the thermo-electric effect. If two dissimilar metals are joined together at both the ends, and these junctions are maintained at different temperatures by heating one junction and keeping the other cold, an electromotive force (emf) is induced in the circuit (see Figure 12.1). This is the well established Seebeck effect. In general, the cold junction is maintained at room temperature or at 0ºC and the hot junction is made to touch the object whose temperature has to be measured. The electromotive force induced will be proportional to the difference in temperature between the two junctions.

A thermo-couple assembly consists of three units, namely, thermo-couple lead wires, and indicator. A thermo-couple is composed of two homogeneous but dissimilar metal wires. The ends of these wires are joined together by soldering, welding or fusing together. Thus, a closed circuit is formed. The free ends of the thermo-couple are connected to lead wires. Other ends of lead wires are connected to a suitable indicator. The indicator measures the electromotive force developed in the circuit. The extension lead wires are generally made of the same materials as the material of thermo-couple wire. This practice is generally adopted for base metal thermo-couples. For noble metal thremo-couples, lead wires are made of copper and/or copper-nickel alloys.

12.4.1 Choice of Thermo-couple Materials

According to the Seebeck effect, any two metals can be selected for forming the thermo-couple. However, in practice, only limited combinations of metals are in use. The choice is limited because of several factors. A few of these factors are as follows:

(i) The metals should be homogeneous.
(ii) The materials under consideration should be resistant to oxidation and corrosion in medium/media and at temperature(s) at which they are supposed to be used.
(iii) The metals should be good conductors, i.e. their electrical resistance should be low.
(iv) The formability of metals to desired shapes, particularly into wires, should be good.
(v) The melting points of thermo-couple materials should be higher than the highest temperature encountered during the service.
(vi) The electromotive force (emf) induced should increase with rise in the temperature or the temperature difference between hot and cold junctions.
(vii) There should be a linear or an almost linear relationship between electromotive force induced and temperature.
(viii) The induced electromotive force should be sufficiently large. This will enable precise and accurate measurement of electromotive force and temperature.
(ix) The induced electromotive force should be reproducible and stable. It should not vary because of physical and chemical changes or contaminations from the surroundings.
(x) The material should not be very expensive.

12.4.2 Thermo-couple Materials

If properly used, thermo-couples are the most versatile and rugged temperature measuring devices. They can be used over a wide range of temperatures-starting from sub-zero temperature to very high temperatures. Currently, thermo-couple materials, which can be used up to 2800°C in neutral atmosphere or vacuum and up to 2200°C in oxidizing atmospheres, are available.

Thermo-couple materials can be broadly divided into two classes, namely, base metal thermo-couples, and noble metal thermo-couples. The base metal thermo-couples include common and relatively inexpensive metals and alloys, e.g. iron, copper, chromel and alumel. The noble metal thermo-couples are made of platinum and platinum alloys. Refractory metals and non-metallic materials are also used now-a-days as thermo-couple materials. Some of the commonly used thermo-couples are now considered.

Copper-constantan thermo-couple is mainly used for low temperature measurements. It can be used only up to 300ºC. A much simpler and cheaper mercury thermometer can be used within this temperature range. Applications of copper-constantan are limited to laboratory and research work. As far as heat treatment is concerned, it can be used successfully for measurement of temperatures for tempering of steel and ageing treatment of some non-ferrous alloys. Iron-nickel and iron-constantan thermo-couple can be used up to 750°C. The iron-constantan thermo-couple is more widely used than the iron-nickel thermo-couple as the latter is more expensive. The upper limit of iron-constantan thermo-couple is restricted since it oxidizes readily above 750°C. However, the upper limit can be raised to 950°C either by protecting it or by imposing reducing atmosphere. This thermo-couple (iron-constantan) can be employed for measuring temperatures involved in the heat treatment of plain carbon steels, low alloy steels and several non-ferrous alloys. Chromel-alumel thermo-couple is very popular and is widely used in the temperature range 25–1100°C. The relationship between temperature and electromotive force induced for this thermo-couple is almost a straight line. It can be successfully used in oxidizing and neutral atmospheres. However, chromel-alumel thermo-couple is susceptible to attack by hydrogen, carbon monoxide, hydrogen sulphide, sulphur dioxide and other reducing gases even when exposed for a very short time. Among base metal thermo-couples, chromel-alumel thermo-couple is best suited for the measurement of temperatures associated with heat treatment of steels. Table 12.1 gives the chemical composition of some thermo-couple materials referred to in this chapter by commercial names.

Table 12.1 Chemical Composition of Some Alloys Used as Thermo-couple Wires

Name of the alloy	Chemical composition
Constantan	Cu, 40% Ni
Chromel	Ni, 10% Cr
Alumel	Ni, 3% Mn; 2% Al; 1% Si
Pt-Rh alloy	Pt, 10% Rh or 13% Rh

Noble metal thermo-couples have many advantages over base metal thermo-couples as they are more reliable, accurate and resistant to corrosion and oxidation. In addition, they can be employed over a wide range of temperatures. Though they are much more expensive than the base metal thermo-couples, the cost is compensated by their high scrap value. Their use is justified by very precise and consistent results needed in research work. Platinum is easily contaminated by lead, bismuth, zinc, arsenic, iron and antimony. Hot hydroxides of alkali and alkaline earth metals, nitrates and cyanides are capable of dissolving platinum which is attacked also by sulphur. For these reasons, platinum-platinum alloy thermo-couples are not used for routine industrial applications. These thermo-couples are generally employed for calibration purposes because of their high degree of accuracy. For the same reason, these are used mainly for research work. Platinum-platinum and 10 percent rhodium alloy thermo-couple are used in the temperature range 300–1500°C. The electromotive force developed is very small, and hence a very sensitive instrument is required for its measurement. Platinum and 6 percent rhodium alloy, platinum and 30 percent rhodium alloy, platinum and 20 percent rhodium alloy, and platinum and 40 percent rhodium alloy thermo-couples can be used up to 1850°C.

To measure temperatures above 2000°C, thermo-couples made of refractory metals, such as tungsten, tantalum, molybdenum, rhenium, niobium, iridium and ruthenium, are used. Table 12.2 gives the melting points of these refractory metals. These metals are used in pure as well as alloy form.

Table 12.2 Melting Points of Some Refractory Metals

Metal	Melting Point (°C)
Tungsten	3410
Tantalum	2996
Molybdenum	2617
Rhenium	3180
Niobium	2468
Iridium	2410
Ruthenium	2310

The following combinations of these metals/alloys are quite popular:

(i) Tungsten-molybdenum
(ii) Tungsten-rhenium
(iii) Tungsten-tungsten and 26 percent rhenium
(iv) Tungsten and 6 percent rhenium-tungsten and 26 percent rhenium
(v) Molybdenum-rhenium
(vi) Tungsten-iridium
(vii) Iridium-iridium and rhodium alloys.

Tungsten constitutes positive electrode in tungsten-molybdenum thermo-couples. A unique feature of these thermo-couples is that induced electro-motive force is negative in the temperature range 0–1300°C. Induced electromotive force is nearly zero at 1300°C; above this temperature, it is positive. These thermo-couples can be used successfully in vacuum and reducing atmospheres. Tungsten and rhenium are common refractory metals used as thermo-couples. They find extensive application because of very low vapour pressures at high temperatures. These thermo-couples (tungsten-rhenium, tungsten-tungsten and rhenium alloys) have a wide range of applications. They can be employed in vacuum, air and reducing atmospheres. Temperatures as high as 2300°C can be measured under inert atmospheres or with short exposures to oxidizing conditions.

Various non-metals which can be considered for constructing thermo-couples include graphite, carbides, borides, nitrides, silicides and oxides. Very few commercial thermo-couples have been made from non-metals and non-metal thermo-couples have more or less been a subject of theoretical importance. The most important reason behind this is that no specific advantage(s) has been offered by these thermo-couples over the conventional thermo-couples. Their range of operation is also covered by a number of metallic thermo-couples. Besides, their processing is somewhat difficult as compared to metallic ones. Further, homogeneity and reproducibility cannot be predicted with certainty. Such a condition demands for the calibration of each individual pair of thermo-couple. From among the non-metallic materials listed, graphite, silicon carbide and boron carbide are of interest, and considerable experimental work has been carried out on these materials.

12.4.3 Temperature Measurement by Thermocouples

The accuracy of the temperature measured by thermo-couples depends on the accuracy with which induced electromotive force can be measured. The electromotive force can be measured either by a millivoltmeter (Figure 12.2) or a potentiometer (Figure 12.3). A millivoltmeter, for all practical purposes, is a sensitive moving coil galvanometer. The pointer of the galvanometer deflects with the current. When connected to a thermo-couple, it measures the current generated in the circuit by the thermo-couple. The scale of galvanometer is calibrated in terms of millivolts. Various sources of error in this method include changes in the resistance of the circuit, spring tension, magnetic field, and' frictional force at the pivot. Due to these limitations, millivoltmeter is not used for research work when a high degree of precision is desired. However, it is used extensively for industrial measurement of temperature where reasonably good accuracy is needed. Measurement by potentiometer is more precise and reliable. In this method, a null point is obtained with the help of a variable resistor. The resistance corresponding to the null point is noted and with its help the induced electromotive force is measured.

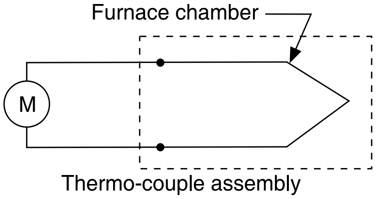


Figure 12.2 Measurement of emf by millivoltmeter.

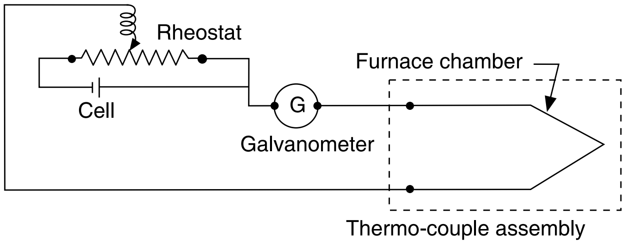


Figure 12.3 Measurement of emf with the help of potentiometer.

12.4.4 Calibration of Thermo-couples

Calibration of a thermo-couple is a very important step. It requires much care and sensitive instruments, and can be done in two ways, namely, calibration at constant temperatures (fixed points) and calibration by comparison with a standard (precalibrated) instrument. The first process is referred to as primary calibration and the second process as secondary calibration.

For primary calibration, the various fixed points used are melting points of copper, nickel, cobalt, platinum, rhodium, iridium and tungsten (see Table 12.3). The use of large numbers of fixed points for calibration provides a high degree of accuracy in determining the temperature-electromotive force relationship. Such a practice also enables the extrapolation or interpolation of the data with reasonably high degree of accuracy. Thermocouples are calibrated in an electric resistance furnace. Sufficient quantity of the metal (in order to have sufficient depth of molten metal on melting to immerse thermo-couple end) is melted in a graphite crucible placed in the constant temperature zone of a resistance furnace. One end of the thermo-couple is immersed into the molten bath. Precautions should be taken to avoid any contact of thermo-couple either with the bottom or the sides of the crucible. Molten liquid is now allowed to cool at a very slow rate. The variation of electromotive force is plotted and so the electromotive force corresponding to the melting point is known. The process is repeated with different metals, and thus a mathematical expression which correlates temperature and electromotive force is obtained.

Table 12.3 Melting Points Used for Primary Calibration

Metal	Melting Point (°C)
Aluminium	660.0
Antimony	630.5
Bismuth	271.3
Cobalt	1480.0
Copper	1083.0
Gold	1063.0
Lead	327.4
Nickel	1453.0
Platinum	1773.5
Rhodium	1966.0
Silver	960.5
Tin	231.9

Primary calibration is quite complex and time consuming. For this reason, commercial thermo-couples, which do not require very high degree of precision, are calibrated by comparison with either primarily calibrated platinum-platinum and 10 percent rhodium thermo-couple or primarily calibrated thermo-couple of the type which is being calibrated. A third possibility also exists, i.e. comparison with a standard instrument. In secondary calibration, in general, a number of thermo-couples for calibration are joined with one another and with a standard thermo-couple. The electromotive force is noted at a fixed reference temperature and some additional temperatures. In this method, a relationship between temperature and electromotive force is obtained for the set of thermo-couples.

12.5 INDIRECT METHODS OF TEMPERATURE MEASUREMENT

Methods involving the use of expansion thermometers, resistance thermo-meters and thermo-couples for measurement of temperature are known as direct methods. In all these methods, the measuring instrument is kept in contact with the object whose temperature is under consideration. Indirect methods do not require any contact between measuring instrument and the object. The temperature of the object can be measured from a distance.

Indirect methods are based on the principle that every object radiates energy to the surroundings. The intensity of the radiation is dependent on the temperature of the object. The higher the temperature of the object, the more is the intensity of the radiation. These radiations are, in general, of mixed wavelengths. The concept of black body is utilized in order to standardize the practice of high temperature measurement by estimating the intensity of the radiation. A black body is one that is capable of absorbing all the electromagnetic radiations, irrespective of their wavelengths falling on it at any temperature. It emits radiations due to its own is considered equal to unity. Though the existence of a perfectly black body is not feasible, conditions approaching the black body conditions can be developed. Two indirect temperature measurement instruments, namely, the optional pyrometer and radiation pyrometer, are now described.

12.5.1 Optional Pyrometer

An optional pyrometer is an instrument in which the intensity of light emanating from a hot body is compared with the intensity of the light from some standard source. The most commonly used optical pyrometer is the disappearing filament type. In this type of optical pyrometer (Figure 12.4), the intensity of the radiation from standard (calibrated) source is varied and matched with the intensity of the radiation from the source whose temperature has to be measured. The intensity of the radiation is judged from the brightness (or the glow) from the object. The pyrometer assembly consists of a filament in which current can be varied with the help of a rheostat. By passing the current through the filament, the temperature of the filament can be raised. The radiations from the filament at different temperatures are calibrated with respect to some standard source at a wavelength of 65 μm. This wavelength corresponds to the wavelength of the red light.

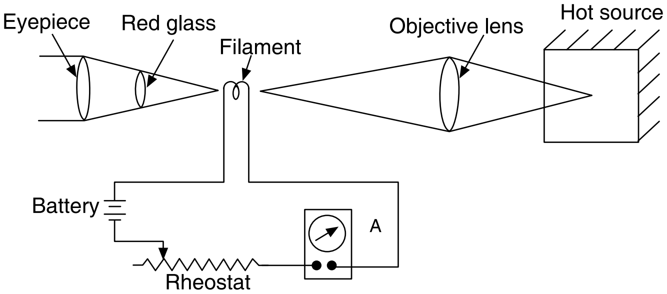


Figure 12.4 Schematic diagram illustrating the principle of working of optical pyrometer.

The operation of the optical pyrometer consists of viewing the object under consideration and focusing at some portion of the hot object. A red glass is introduced in front of the eyepiece. This helps in selecting monochromatic radiation from the hot object. Initially, the filament appears dark with respect to the hot body since it is at a considerably low temperature as compared to the hot body. As the value of current being passed through the filament is increased, it starts glowing with greater brightness. At a particular value of the current, the two glows (namely, from the hot body and the filament) become equal. At this stage, due to perfect matching, the filament will not be visible (see Figure 12.5), and the temperatures of both the hot body and the filament will be same. If more current is passed now, the filament will again be visible with greater brightness of glow.

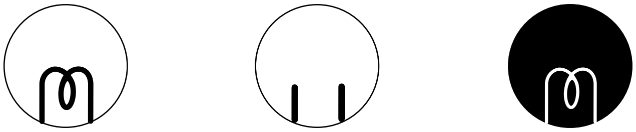


Figure 12.5 Visibility of filament of optical pyrometer under different conditions.

12.5.2 Radiation Pyrometer

Radiation pyrometers are similar to optical pyrometers as far as calibration is concerned. Both are calibrated under a set of conditions approaching to those of black body radiations. However, in radiation pyrometers, all the heat and light radiations (irrespective of their wavelengths) are considered for the measurement of the temperature. In fact, the radiation pyrometer is based on the Stefan-Boltzmann law which states that the rate of emission of radiant energy from the surface of a body is proportional to the fourth power of its temperature in absolute scale.

In radiation pyrometer (Figure 12.6), with the help of a mirror or lens, all the radiated (heat as well as light) energy is focused at a point on a coated sheet within the pyrometer which acts as a black body. This point serves as a hot junction of a thermo-couple and is in contact with a very sensitive thermo-couple. The induced electromotive force is measured by a potentiometer. The electromotive force is calibrated in terms of temperature.

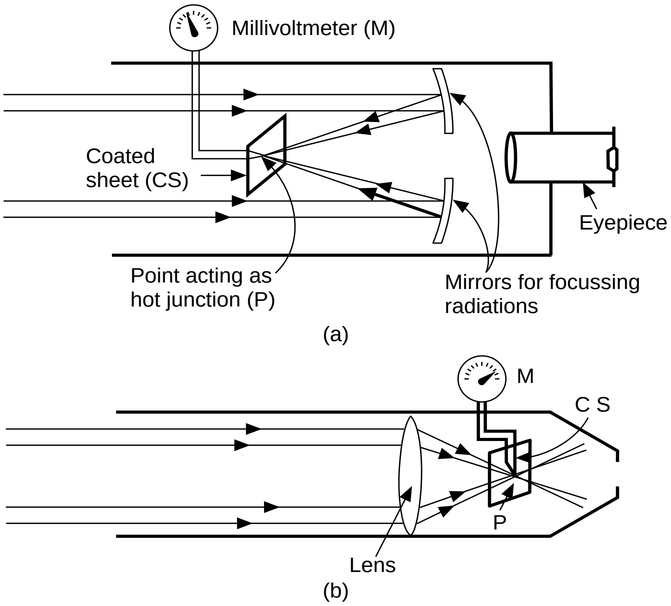


Figure 12.6 Optical ray diagram of radiation pyrometer.

12.6 TEMPERATURE CONTROL

In many heat treatment processes, it is necessary to control the temperatures within definite limits for certain periods of time. Examples are malleabilizing of white cast irons, spheroidizing of steel wires/wire rods and patenting. In certain cases, complete heat treatment cycle is recorded and studied. The purpose of such a study may be to correlate microstructure with mechanical properties of heat treated metal and to modify heat treatment cycle.

In heat treatment furnaces, temperature can be controlled either manually or automatically. The temperature in an electric resistance furnace can be controlled manually with the help of a simple rheostat. By varying resistance, the power supply to the furnace can be controlled, which in turn will control the furnace temperature. In fuel-fired furnaces, the rate of fuel-air supply can be controlled manually, and hence temperature can be regulated. However, in most of the cases, it is essential to measure and control the temperature simultaneously, and for this purpose, automatic temperature controllers are preferred.

The on-off type automatic temperature controller is very popular. The on-off control mechanism (Figure 12.7) ensures automatic shut-off of power supply to furnace as soon as the desired constant temperature is reached. The supply is switched on as soon as the temperature of the furnace comes down below the desired set value. The operation is carried out with the help of an electrical relay. On the temperature panel of on-off type temperature controller, two pointers are used. One pointer is usually painted black while the other red. The red pointer is moved along the temperature scale of the controller and set at a temperature on the scale which has to be maintained in the furnace. As the power supply is switched on to the furnace, temperature of the furnace rises and so the black pointer moves along the temperature scale showing the temperature of the furnace at any moment. When two pointers touch each other (i.e. the desired temperature is reached in the furnace), an electrical relay operates, resulting in cutting off of the power supply to the furnace. Under such a condition, temperature of the furnace will go down with time and, consequently, the black pointer will start moving in the reverse direction. Thus, after some time, the black pointer will not be in contact with the red pointer any more, and the power supply to the furnace will again be restored automatically. In this way, furnace temperature can be controlled within limits for desired periods. The same

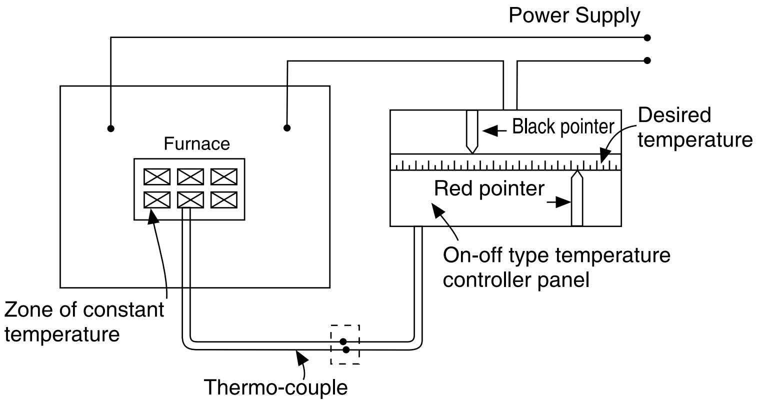


Figure 12.7 Circuit diagram of on-off automatic temperature controller.

principle can be employed for gas and oil-fired furnaces. Here, electrical relay will automatically actuate the fuel-air supply value instead of power supply.

QUESTIONS

12.1 Differentiate between heat and temperature. Explain the principle of measurement of temperature.

12.2 Enumerate the factors governing the selection of thermocouple material.

12.3 Give chemical composition and temperature range of application for the following thermocouples:

(a) Copper-constantan
(b) Chromel-alumel
(c) Platinum-(platinum-rhodium)

12.4 Write notes on the following:

(a) Bimetallic thermometers
(b) Magnetic thermometers
(c) Seebeck effect
(d) Noble metal thermocouples.

12.5 Discuss the following:

(a) Calibration of thermocouples
(b) Temperature measurement by thermocouples.

12.6 With the help of a suitable diagram, explain the principle of working of optical pyrometer.

12.7 How does radiation pyrometer differ from optical pyrometer? Compare the commercial importance of the two.

12.8 Why it is essential to control the temperature of heat treatment furnace?

12.9 Electrical resistance furnaces are most commonly used for heat treatment purpose. Why? Name various resistors used in these furnaces.

12.10 For a jobbing heat treatment shop, which type of furnace(s) would be suitable and why?

13

Possible Defects, Causes and Remedies in Heat Treatment

INTRODUCTION

Heat treatment is the heating and cooling process by which the microstructure and mechanical properties of metals and alloys are improved. When metal fails to achieve the desired properties after heat treatment, the process is said to be defective. Sometimes, the heat treated components may not show the desired properties in spite of adoption of proper procedure. This may be due to unsuitable chemical composition of the alloy. It is necessary to know about the possible causes of the defects associated with heat treatment. These may be due to wrong selection of a material, inherent defect in the material, and/or improper design of a tool or a machine component. Therefore, to have optimum properties in components after heat treatment, the first step is proper selection of raw material and accurate design. This will ensure defect-free components provided proper heat treatment procedure is applied to such a component.

The most common type of defects observed in heat treated steel are as follows:

Low hardness and strength after hardening
Soft spots
Oxidation and decarburization
Overheating and burning
Formation of cracks
Distortion and warping

13.1 LOW HARDNESS AND STRENGTH AFTER HARDENING

When a component is heated up to austenitizing temperature and later on quenched, it may not develop the desired hardness and strength. Actually, on quenching, martensite, which is a hard phase, is formed. To remove its brittleness it is tempered. After tempering, there is marginal softening of martensite. But other mechanical properties are improved. The tendency to crack formation also reduces. Martensite forms only when the cooling rate is rapid. If the cooling rate is slow, other products (e.g. bainite and pearlite which have somewhat lower hardness values) may form. Lower hardening temperature and insufficient soaking time also reduce hardness and strength after hardening.

Besides this, when a given component is rapidly cooled, all austenite may not transform to martensite, and this untransformed austenite also reduces the hardness because it is much softer than martensite. Under these conditions, sub-zero treatment is required, which is usually conducted in –30ºC to –120°C. In such steels the transformation temperature M_f is below the room temperature.

The reasons for low hardness and strength after quenching are as follows:

(i) Lower hardening temperature
(ii) Insufficient soaking time
(iii) Delayed quenching
(iv) Slower cooling rates
(v) Presence of large amount of retained austenite.

Sometimes, low hardness is noticed in steel components after surface hardening treatment such as carburizing, cyaniding and nitriding processes. This may be due to improper carburizing atmosphere, low heat treatment temperature, the presence of excessive retained austenite and large volume of metal in furnace. Therefore, to overcome these, proper carburizing and post-carburizing heat treatment should be done.

13.2 SOFT SPOTS

Sometimes, after hardening operation of steel, the hardness on the surface of the component is not uniform. Hardened steels show varying hardness at different points on their surface. This defect is known as soft spot (Figure 13.1). There are several reasons for occurrence of soft spots. Some of them are as follows:

(i) Formation of vapour blanket between the quenchant and component during quenching, which hinders rapid heat dissipation
(ii) Localized decarburization of steel
(iii) Inhomogeneity of microstructure
(iv) Presence of foreign matters such as dirt and sticky scales on the surface of steel
(v) Keeping of large components in a furnace, leading to non-uniform heating of the component
(vi) Improper handling of component during quenching.

One of the methods of preventing formation of soft spot is adoption of spray quenching practice.

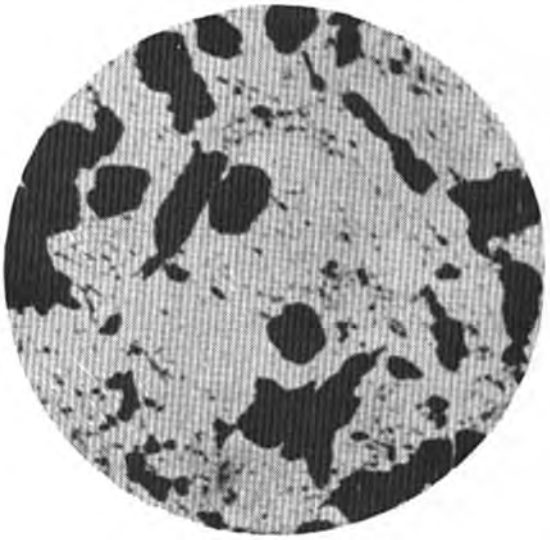


Figure 13.1 Soft spots are seen black in a quenched steel with martensitic matrix (white) (×700).

13.3 OXIDATION AND DECARBURIZATION

When steel is heated to a high temperature in a furnace open to atmosphere, furnace gases such as oxygen, water vapour and carbon dioxide may react with the surface of the steel which is being heated. This may give rise to two surface phenomena: oxidation and decarburization.

Oxidation of steel takes place because of the presence of oxygen, carbon dioxide, and/or water vapour. The possible reactions due to which oxidation occurs are

$$
\begin{aligned}
2Fe + O_2 &\rightleftharpoons 2FeO \\
4FeO + O_2 &\rightleftharpoons 2Fe_2O_3 \\
Fe + CO_2 &\rightleftharpoons FeO + CO \\
3FeO + CO_2 &\rightleftharpoons Fe_3O_4 + CO \\
Fe + H_2O &\rightleftharpoons FeO + H_2 \\
3FeO + H_2O &\rightleftharpoons Fe_3O_4 + H_2
\end{aligned}
$$

The equilibrium relationship between iron and iron oxide in the presence of CO and CO_2 or H_2 and H_2O at the operating temperature determines the degree of oxidation. These four gases also interact according to the reaction

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

This reaction is known as warter gas reaction. The gases in furnace adjust themselves according to the relation

$$K = \frac{p_{CO_2} \cdot p_{H_2}}{p_{CO} \cdot p_{H_2O}}$$

where K is an equilibrium constant.

With high content of CO and low content of water vapour in furnace atmosphere, another reaction known as producer gas reaction normally takes place. This reaction can be represented as

$$2CO \rightleftharpoons CO_2 + C$$

For this reaction, steel behaves like a catalyst at the operating temperatures. As a result, oxidation of the surface of steel takes place.

During oxidation at about 180°C, a thick oxide layer forms on the surface of the steel. When the temperature is raised to about 425°C, porous and loose oxide layer is formed. With growth of such an oxide layer, there is continued disintegration of the component. Therefore, due to oxidation, the quality of the surface of steel component is affected adversely. There are also consequential dimensional changes. Therefore, the nature of furnace atmosphere should be such that there is negligible oxidizing effect. The iron oxide should be reduced by the reactions

$$FeO + H_2 \rightarrow Fe + H_2O$$

$$FeO + CO \rightarrow Fe + CO_2$$

During decarburization, carbon is removed from the steel surface when it is heated to temperatures above 650°C. Carbon reacts with oxygen or hydrogen above 650°C. The depth of decarburization below the steel surface is a function of time, temperature and furnace atmosphere. With decarburization, quenched hardness, wear resistance and fatigue strength are reduced. The reactions involved in decarburization are as follows:

$$\begin{aligned} C + O_2 &\rightleftharpoons CO_2 \\ Fe_3C + O_2 &\rightleftharpoons 3Fe + CO_2 \\ C + CO_2 &\rightleftharpoons 2CO \\ Fe_3C + CO_2 &\rightleftharpoons 3Fe + 2CO \\ Fe_3C + H_2O &\rightleftharpoons 3Fe + H_2 + CO \end{aligned}$$

These reactions are also reversible, and the equilibrium constant determines the ratio of CO to CO_2.

The problem of oxidation and surface decarburization of steel parts may be prevented or minimized by a number of methods. These are:

(i) Steel components may be heated in molten salts, controlled atmosphere or in vacuum. Different types of protective atmosphere which are in use include products of dissociation of ammonia, purified and dried producer gas ($CO–CO_2–N_2$), and a gas mixture containing CO, CO_2, N_2, H_2 and H_2O.
(ii) Decarburized surface layer may be removed by machining after heat treatment.
(iii) Copper layer having thickness in the range 0.013–0.025 mm may be plated on the component.
(iv) In the absence of controlled atmosphere, the steel components may be heated with carburizing agents in boxes or with special surface coatings like borax.
(v) Ceramic coatings may be applied to the components prior to heat treatment.

13.4 OVERHEATING AND BURNING OF STEEL

When steel is heated above the upper critical temperature, coarsening of austenitic grains takes place. Hence, mechanical properties of steel are adversely affected. If grain coarsening is prevented, mechanical properties can be improved by normalizing and annealing treatment. If, however, steel is heated to higher temperatures (i.e. near solidus), or it is held for a very long period, overheating and burning are likely to take place. This affects the properties of steel adversely. Consequently, there is loss of ductility and toughness. Connecting rods or gears may fail prematurely due to fatigue. During overheating, impurities like sulphide inclusions segregate along austenite grain boundaries and cause extensive damage.

Because of overheating, the following changes take place in steel:

(i) A coarse grained microstructure is formed.
(ii) Widmänstatten structure is formed in annealed steel.
(iii) Ductility and toughness are reduced.
(iv) Martensite formed in the hardened steel components gets coarsened.
(v) Surface decarburizing and scaling take place.

When steel is heated in a furnace and temperature crosses the solidus temperature, liquation occurs at the grain boundaries. Under oxidizing conditions, oxide penetration takes place at the surface along the grain boundaries. This phenomenon is called burning of steel. As sulphur and phosphorus lower the liquidus temperature, their presence is restricted to the minimum level. The effect of burning is permanent. Burnt steel becomes a scrap.

Overheating and burning restrict the upper forging temperature which is adopted in industrial practice.

13.4.1 Detection of Overheating and Burning

Nickel fracture test is carried out to observe overheating and burning. The test is conducted preferably in the hardened and tempered condition. The normal fibrous fracture shows slight granularity if the specimen has undergone slight overheating and burning. On the other hand, pronounced overheating produces complete granularity. When steel is burnt, partial fusion is observed in the facets of granular fracture. It is not possible to demarcate clear transition from severely overheated steel to burnt steel. Hence, the two terms are often used to describe the same physical state of the steel.

Figure 13.2 Microstructure of a burnt steel (×850).

Development of granular or faceted fracture in overheated steels also depends to a great extent on the rate of cooling from the overheating temperature. Besides, the subsequent thermal history affects the nature of fractured surface. Very fast or very slow cooling supresses development of this structure. Oil quenching and tempering help to reveal this structure. In this context, it is observed that tempering temperature is very critical for the development of appropriate fractured surface. Thus, non-appearance of facets on the fractured surface does not indicate that the steel had not been overheated or burnt. Metallography is another technique which is used to detect overheating and burning in steels. Thermal history has no effect on metallographic etch test.

The most popular etchant used is a 10% aqueous solution of nitric acid. The steel sample is immersed in etchant for about half a minute, washed and the black surface film swabbed away. This process is repeated thrice after which the steel sample is lightly polished.

The etchant preferentially attacks the prior austenitic grain boundaries. Under microscope, the overheated steel can be identified by the appearance of a network of black grain boundaries with severely attacked grains in the background. Burnt steel, on the other hand, reveals a network of white grain boundaries.

13.4.2 Factors Responsible for Overheating and Burning

The phenomena of overheating and burning are not yet fully understood. But it is widely accepted that overheating occurs only when the steel is heated above a certain minimum temperature. This minimum temperature lies below solidus temperature of the steel under consideration. On the other hand, a sample of steel burns only when its temperature rises above the. solidus temperature and liquation occurs at grain boundaries, i.e. there is incipient fusion. The overheating temperature that causes the defect varies with composition of steel. It also varies with different heats of steel of same composition. High carbon and low alloy steels are more susceptible to overheating in comparison to mild steel. Ni–Cr–Mo and high alloy steels are highly prone to overheating. Even the same steel may show different behaviour towards overheating when it is manufactured by different melting techniques. For example, basic electric steels are more susceptible to overheating and burning than steels of same composition manufactured by open hearth process. So, it is very difficult to establish a direct relationship between overheating and solidus temperatures. Only certain factors can be identified as those responsible for overheating. It has been generally observed that (i) when steels are subjected to heating and forging, their overheating temperatures are raised by about 100ºC; and (ii) steels with higher inclusion content have higher overheating temperatures.

Embrittlement of steels caused by overheating and burning occurs due to segregation "of phosphorus at grain boundaries and its subsequent precipitation (as iron phosphide) at austenitic grain boundaries. Segregation of sulphur also occurs at or near grain boundaries. Segregation of sulphur and phosphorus at high temperature in the austenitic range is responsible for overheating and burning. Sulphur has a predominant role in this context. High sulphur content may therefore enhance overheating and burning tendencies in steels. However, again this is not the sole factor responsible for overheating.

Badly overheated and burnt steels are unserviceable and cannot be reclaimed. Burnt steel is hardly of any use and can only be utilized as scrap. On the other hand, less severely overheated steels can be recovered (i) by repeated normalizing (about 6 times), starting at temperatures 60–100°C more than conventional temperature and with final normalizing treatment at the usual temperature, or (ii) by repeated oil hardening and tempering treatments after prolonged soaking at about 950–1120°C in carburizing atmosphere. But such treatments pose two problems. Firstly, there is substantial alteration of the dimensions of the component due to excessive scaling. Secondly, both the processes are uneconomical.

13.5 QUENCH CRACKS

Sometimes, cracks are formed in steel as a result of stresses produced during transformation of austenite to martensite. The cracks may be small or large. Often, these appear after a steel sample has been quenched. Transformation of austenite to martensite is accompanied by increase in volume. As a result, compressive stresses are introduced and crack appears. The detailed mechanism is considered in this section. Appearance of quench crack is a very serious defect since a steel component with quench crack cannot be used. It has only scrap value.

Steel has a coefficient of linear thermal expansion of 11×10^{-6} K^{-1}. When a steel specimen is cooled from 850°C to 25°C, there is a contraction of about 0.9 percent. During the transformation of austenite to martensite, there is volume expansion. This expansion, expressed as percentage, is equal to $4.64 - (0.53 \times \%C)$. Approximately, the volume expansion is three times the linear expansion. Thus, in a 0.6% carbon steel, the linear expansion is about 1.4% as a result of transformation.

When a steel component of a fully hardenable alloy is quenched from austenitizing temperature, the surface of the component first comes into contact with the quenchant so that the temperature of the outer layer drops below the M_s temperature. Consequently, martensite forms first at the outermost surface. The expansion accompanying martensitic transformation results in plastic deformation of austenite in the inner surface because inherently austenite is a soft phase. On the other hand, its growth at the outer surface is almost unrestricted. Formation of martensite is accompanied by volume increase. This gives rise to stresses at the centre. The yield strength of austenite is low at high temperature so that the stresses are adjusted by plastic flow of the austenite.

As the cooling progresses, the material near the centre of the component crosses the M_s temperature. Martensite is then formed at the centre. The expansion accompanying the newly formed martensite is restricted by the outer layers of martensite formed prior to it. Martensite is too brittle to flow plastically. This gives rise to generation of high internal tensile stresses which are sufficiently large to exceed the tensile strength of the as-quenched martensite present at the outer surface of the component. This is the origin of surface cracks in drastically quenched steels.

It is a well known fact that residual stresses arise due to temperature gradient and lack of simultaneous transformation throughout the cross-section of a component. If cooling is slow, there will be only a small temperature gradient and transformation will occur more or less at the same time throughout the section. Accordingly, lower residual stresses are generated. If alloying elements are added in a steel, the nose of the CCT curve shifts towards the right-hand side, which permits a slower cooling rate. Consequently, the stresses are reduced. This is an important factor that reduces stresses during quenching, which otherwise may give rise to quench cracks.

Residual stresses can be removed by stress relieving operation by reheating steel to relatively low temperature. At 250°C, about 80–85% of stresses are relieved. Higher temperature tempering can relieve all stresses. But once quench cracks are formed, they cannot be removed. Quench cracks, more or less as straight lines, run from the surface toward the centre of the quenched specimen.

13.6 DISTORTION AND WARPING

Distortion refers to changes in the size and shape of heat treated component due to thermal and structural stresses. Warping refers to asymmetrical distortion of component after heat treatment.

Dimensional changes occurring in heat treatment are as follows:

(i) Thermal expansion till AC_1
(ii) Contraction on transformation to austenite
(iii) Thermal expansion of austenite on further heating
(iv) Thermal contraction on cooling to the transformation temperature (M_s in hardening operations)
(v) Expansion on diffusional or diffusionless decomposition of austenite
(vi) Thermal contraction on further cooling to room temperature
(vii) Contraction on tempering of martensite.

These dimensional changes may give rise to distortion in steels. When steel is heated to elevated temperature or cooled slowly, there is a very small temperature gradient. The temperature can be taken as uniform throughout the specimen. Thermal and transformational changes then occur uniformly and simultaneously throughout the section. Hence, there are no chances of internal stresses to develop in the component. When steel component is heated or cooled at a fast rate, internal stresses develop in the steel component because of differential expansion and contraction of steel component. Some layers of the component expand while other layers contract.

Distortion occurs due to the combined effect of thermal and transformation stresses. It refers to dimensional changes after hardening which takes place as a result of volume change during phase transformation. Total distortion occurs because of (i) the presence of residual stresses in the component before heat treatment or (ii) the introduction of internal stresses during heat treatment.

Distortion is one of the most difficult problems associated with heat treatment. It occurs in steel during hardening and tempering. There are two main types of distortion: (i) size distortion which refers to changes in volume, and (ii) shape distortion which relates to changes in geometrical form of the steel component.

Size distortion occurs because of expansion or contraction in steel component, while shape distortion is manifested by changes in curvature such as twisting (warpage) or bending in steel components. A summary of the possible causes of both types of distortion is given in Table 13.1.

Shape distortion is a change of shape, form or geometry of a component without noticeable volume change. For designers and heat treaters, this type of distortion is a much greater problem than size distortion. It can be caused by the presence of residual stresses, sagging, formation of thermal and transformational stresses during heating and quenching, and sharp variation in a section of the steel.

Distortions probuced by thermal and transformational stresses are influenced by the rate of heating, shape, size, wall thickness and geometry of the part, chemical and structural inhomogeneities, the rate of cooling and sub-zero treatment.

13.6.1 Control of Distortion

The risk of distortion during and after heat treatment can be minimized by taking care of the following aspects: design, composition, initial condition, and machining procedure, which we now describe.

Design Abrupt changes, sharp corners and thin walls should be avoided in the component.

Table 13.1 Possible Causes of Size and Shape Distortion during Heat Treatment

Operation	Sequence	Size distortion	Shape distortion
Hardening	Heating and holding at austenitizing temperature	(a) Formation of austenite (b) Dissolution of carbides	(a) Relief of residual stresses (b) Thermal stesses (c) Sagging (due to weight of component, distortion under plastic condition)
	Quenching	Formation of martensite and non-martensitic phases	(a) Thermal stresses (b) Transformation stresses (c) Introduction of residual stresses
Sub-zero treatment	Cooling to and holding at sub-zero temperature and returning to room temperature	Formation of martensite	(a) Thermal stresses (b) Trnasformation stresses (c) Introduction of residual stresses
Tempering	Heating to and holding at tempering temperature	(a) Decomposition of martensite (b) Transformation of retained austenite	(a) Stress relief (b) Thermal stresses
	Cooling from tempering temperature	Transformation of retained austenite	(a) Thermal stresses (b) Introduction of residual stresses

Composition Size distortion can be minimized by proper selection of steel from the point of view of composition.

Initial condition Uniform microstructure in the component and uniform temperature in the furnace should be maintained.

Machining procedure Rough machining to dimensions accounts for size distortion during heat treatment.

13.6.2 Methods to Reduce Distortion during Main Heat Treatment

Size and shape distortion cannot be avoided during main heat treatment. But size distortion can be controlled by proper selection of composition of steel and by adjusting the machining allowance and controlling the amount of various phases present in steel after heat treatment. Shape distortion cannot be avoided during heat treatment because of the large number of factors involved in this case. Therefore, to minimize shape distortion during heat treatment, a number of factors should be taken into account. These are (i) stress relieving, (ii) heating rate, (in) preheating, (iv) quenching media, (v) press quenching, and (vi) trays, fixtures and supports. We now discuss these factors one by one.

Stress Relieving

The presence of residual stresses due to previous machining or forging operation enhances the tendency for distortion. Therefore, these fabrication stresses should be relieved by subcritical annealing or normalizing operation. This is more important for intricate parts with close dimensional tolerances.

Heating Rate

The rate of heating of component should not be very fast. Otherwise, the part may crack or warp since sections having different dimensions heat up at different rates. These differences in temperature can be controlled by preheating the component to a temperature just below the lower transformation temperature of steel. It is not necessary to preheat a component when a muffle furnace is used for austenitizing. Similarly, no preheating is required when a salt bath is used except when the component is large.

For small and symmetrical parts, preheating may be dispensed with when heating is carried out in salt bath. But to avoid any trace of moisture in steel, it is advisable to preheat the steel component to about 100ºC before it is transferred to salt bath.

Preheating

Preheating reduces shape distortion in steels by reducing the thermal stresses produced because of the temperature gradient prevailing between the surface and interior part of a component.

Besides this, preheating results in stress-relief treatment for machined parts. Preheating can be performed between 400°C and 800°C. For a large cross-section and complicated shape parts and for high alloy steels having poor thermal conductivity, it is preferable to carry out two-stage preheating. For example, distortion in industrial saw blade (AISI 1080; 1 m long and 4.5 mm thick) has been successfully reduced by a heat treatment cycle which comprises

(i) preheating for 20 minutes at 650ºC in a salt bath;
(ii) transferring to 870°C salt bath and holding for 20 minutes;
(iii) transferring to austempering salt bath at 345ºC and holding for 20 minutes; and
(iv) air cooling.

In this case, hardness around R_c 50 can be achieved. Slight warping of blade may occur.

Quenching Media

The basic aim in hardening of steels is to get martensitic structure and avoid formation of pearlite and bainite. Therefore, the rate of cooling of heated component should be fast enough to produce fully martensitic structure throughout the section. But faster cooling rate increases the severity of quench. Therefore, it is necessary to use the least drastic quenching medium that produces martensite.

In fact, the choice of quenching medium depends on hardenability, size and shape of the component. Shape distortions can be further reduced during quenching if cooling conditions are made as uniform as possible. Generally, water, brine and conventional oils are used as quenching media. Besides this, salt baths, hot quenching oils and polymer quenchants should be considered. They give very good results.

Press Quenching

Press quenching or die quenching of precision gears and other parts of steel is not common to most of the commercial heat treating industries. During press quenching, distortion is minimized by physical restraint of a part during its rapid cooling from austenitic condition. Quenching jigs are used for this purpose.

After heating, the part is clamped in a jig and placed in a hydraulically operated press. The jig should be preheated to avoid rapid cooling of the surface of the component which comes in contact with the jigs. Along with the closing of the press, oil is flown over the component. As a result, plane shape is maintained during quenching operation.

Trays, Fixtures and Supports

Odd shaped components and unsymmetrical sizes need use of holding trays and fixtures which maintain the shape of components during heating and rapid cooling from austenitizing temperature.

Trays, fixtures and supports are also used to reduce the sagging problem on heating the components to the austenitizing temperature. Parts should lie on a flat surface.

13.6.3 Treatments for Stabilizing Dimensions

Dimensional stability, which is the foremost requirement for gauges and test blocks, may be achieved in heat treatment by single tempering, multiple tempering, cold treatment, seasoning and mechanical shock or vibration technique.

Even after taking all the precautions, it is not possible to avoid distortion or warping completely during or after heat treatment. For example, for long thin components and complicated shapes, there would always be some distortion or warping. Slight distortion can be taken care of by the grinding operation that follows heat treatment. Alternatively, the parts must be straightened.

Table 13.2 summarizes the different types of defects in heat treatment of steels with their causes and remedies.

Table 13.2 Possible Defects, Causes and Remedies in Heat Treatment of Steels

Types of defects and characteristics	Causes	Remedies
1. *Overheating* Causes coarse grained microstructure, Widmänstatten structure in annealed steel, coarse crystallic martensite in hardened steel, reduced ductility and low impact strength value	Heating for long periods at temperatures exceeding normal values	(a) Normal annealing and normalizing for slight overheating (b) Repeated normalizing for about 6 times
2. *Burning* Grain boundaries having (a) regions enriched in carbon in first stage of burning; (b) non-oxidized cavities and blow holes in second stage of burning and (c) iron oxide inclusions in the third stage of burning, resulting in stone-like fracture and poor ductility.	Heating for long duration at high temperature under oxidizing conditions or heating near to melting point of steel	(a) Homogenizing followed by double annealing for first stage of burning (b) Forging followed by annealing for second stage (c) Not remediable if third stage has occurred
3. *Oxidation* Thick layer of scale is seen on the surface of steel component	Oxidizing atmosphere in heating furnace	(a) To use reducing, neutral or protective atmosphere in heating furnace (b) Heating in box with used carburizing agent (c) Heating in molten salt bath
4. *Decarburization* Carbon content decreases in the surface layer of steel component. Hardness and fatigue limits are lower	Oxidizing atmosphere in the heating furnace	(a) Heating in furnace under reducing, neutral or protective atmosphere (b) Heating in box with used carburizing agent or cast iron chips (c) Heating in molten salt bath (d) Removing decarburized layer by machining if machining allowance is available
5. *Excessive Hardness of Hot-worked Annealed Steel*	Excessive cooling rate for simple annealing or insufficient soaking period for isothermal annealing	Repeating annealing with cooling at specified rate

(*Contd.*)

Table 13.2 Possible Defects, Causes and Remedies in Heat Treatment of Steels (cont.)

Types of defects and characteristics	Causes	Remedies
6. *Black Fracture* Free carbon inclusions are seen in the steel	Excessive heating time and slow cooling after annealing	Heating the steel to high temperature and thorough forging
7. *Deformation and Dimensional Changes after Hardening* The higher the hardenability of steel, more severe is the deformation in hardening	Increase in volume of steel due to martensitic transformation	(a) Using steels which are slightly deformed by quenching (b) Cooling slowly in martensitic range (c) Applying surface hardening where possible
8. *Warping* Asymmetrical deformation of component occurs during quenching	(a) Change in volume in heating or cooling (b) Non-uniform heating or cooling of component (c) Internal stresses in the component before heat treatment (d) Lowering component into quenching bath in inclined position	(a) Using alloy steels which are only slightly deformed by quenching (b) Cooling slowly in martensitic range (c) Applying surface hardening wherever possible (d) Annealing, normalizing or tempering at high temperature before hardening (e) Heating uniformly for hardening (f) Quenching as uniformly as possible (g) Keeping component in proper position in quenching bath (h) Using special quenching jigs
9. *Low Hardness after Quenching*	Low hardening, temperate cooling rate, and insufficient soaking period at hardening temperature	Normalizing or annealing, followed by hardening with proper procedure
10. *Soft Spots* Certain portion on the surface of component with lower hardness	(a) Presence of vapour blanket on the surface of component (b) Localized decarburization (c) Inhomogeneity of internal structure after solidification	(a) Using more effective quenchant (b) Annealing or normalizing before hardening for more homogeneous structure (c) Avoiding decarburization in heating

(*Contd.*)

Table 13.2 Possible Defects, Causes and Remedies in Heat Treatment of Steels (cont.)

Types of defects and characteristics	Causes	Remedies
11. *Excessive Hardness after Tempering*	Low temperature or insufficient soaking time in tempering	A second tempering with proper temperature and soaking time
12. *Insufficient Hardness after Tempering*	Too high a tempering temperature	Annealing, rehardening and tempering at normal temperature
13. *Erosion* Reduction in size of component or in respect of form due to loss of material from its surface	Chemical reaction and oxidation of components heated in molten salt baths	(a) Using deoxidizing salt bath with ferro-silicon or borax (b) Proper positioning of component in salt bath
14. *Corrosion* Pitting	(a) High content of sulphuric salts (over 0.7–0.8%) in molten salt bath (b) Bath having become rich in oxygen or iron oxides	(a) Careful control of salt composition (b) Deoxidizing the bath
15. *Quench Crack* External or internal and zig-zag in appearance	(a) Internal stresses (b) Non-uniform cooling	Cannot be remedied but may be prevented by (a) avoiding sharp projections, sharp corners and sudden change in size; (b) eliminating stresses before hardening; (c) heating to minimum suitable temperature for hardening; (d) cooling slowly in martensitic range by using oil as the quenching medium; and (e) quenching followed by tempering immediately

QUESTIONS

13.1 What are the reasons for occurrence of soft spots after hardening operation of steel?

13.2 Why does oxidation of steel component take place during heat treatment?

13.3 What are the various reactions involved in decarburization of steel?

13.4 What type of steels are prone to overheating and why?

13.5 Distinguish between quenching cracks and quenching stresses. How are they caused?

13.6 What are the causes of distortion in steels? Give possible remedies for the same.

14

Heat Treatment of Commercial Steels

INTRODUCTION

Numerous plain carbon and alloy steels are in use today. Each one of them finds a wide range of applications, depending on service requirements, fabricability and economy. Therefore, it is not possible to cover the heat treatment practice for every individual steel and for each application. However, an attempt can be made to arrange steels into some well-defined groups, and generalized heat treatment practice can be discussed for these groups. While Section 14.1 deals with plain carbon steels—their response to heat treatment and applications, Section 14.2 shows how alloy steels respond to heat treatment. Some steels of commercial importance and their heat treatment have also been described in these sections. Section 14.3 describes heat treatment practice for some special steels.

14.1 PLAIN CARBON STEELS

Plain carbon steels are alloys of iron and carbon in which carbon varies from traces to about 2 percent by weight. The upper limit of carbon m plain carbon steels corresponds to the maximum solubility of carbon in austenite. Commercial steels, in addition to carbon, contain elements such as manganese, silicon, sulphur and phosphorus. These elements are always present in all Steels. Sulphur and phosphorus are highly detrimental and are treated as undesirable elements. Exceptions are free cutting steels which contain sulphur as intentionally added element. In general, for most applications, sulphur and phosphorus contents are kept below 0.04 percent maximum (each). Manganese and silicon, though not added intentionally, in the amounts they are present, normally have beneficial effect. On the basis of carbon contents, plain carbon steels can be divided into three classes, namely, low carbon steels, medium carbon steels, and high carbon steels. Their heat treatment is discussed separately under respective heads.

14.1.1 Low Carbon Steels

Low carbon steels contain carbon up to 0.25 percent (by weight). These steels account for about 90 percent of total plain carbon steel output. Low carbon steels are cheap and possess good formability and excellent weldability. These steels are extensively used as sheet and strip steel, structural steel, cold heading steel, free cutting steel and case hardening steels.

Low carbon steels exhibit poor response to heat treatment as a means for improving mechanical properties, particularly tensile and yield strength. The major microconstituent of these steels is ferrite which amounts to about 75 percent (for 0.20 percent carbon) or more than this (for steels containing less than 0.20 percent carbon). This is why only marginal differences in mechanical properties of annealed and normalized low carbon steels are observed in practice. The magnitude of difference in mechanical properties increases with rise in carbon content. In low carbon steels, hardly any martensite is formed on quenching. Thus, for all practical purposes, on hardening by quenching, there is insignificant improvement in mechanical properties. However, it does not mean that low carbon steels are not subjected to heat treatment at all. In fact, many heat treatment processes are an integral part of the manufacturing and fabrication processes of low carbon steels. For the sake of simplicity of discussion, low carbon steels can be grouped into two classes: low carbon steels up to 0.10 percent carbon, and low carbon steels with carbon from 0.10 percent to 0.25 percent.

Low carbon steels with less than 0.10 percent carbon have excellent formability. For this reason, these steels are employed for general engineering constructional work involving severe cold deformation such as bending, rivetting and deep drawing. These steels, in the form of cold-rolled sheets, find applications in automobile, furniture and refrigerator industries. Tin cans, tin plates and galvanized sheets are some other applications of these cold-rolled sheets. Annealing plays an important role during the manufacture of cold-rolled sheets. The manufacturing process essentially consists of a combination of cold working and annealing treatment. In addition to using them as cold-rolled sheets, these steels are employed extensively as soft magnetic material. Though pure iron has excellent magnetic properties, i.e. high saturation induction, high permeability and low coercivity, its uses are limited because of high cost and low strength value as compared to low carbon steels. Removal of last traces of carbon from steel to convert it into pure iron is a costly process. Low carbon steels, which have lower saturation and poor permeability but higher coercivity (i.e. inferior magnetic properties as compared to pure iron), are extensively used due to low cost and higher strength values. These steels find applications such as for yokes in electrical machines and armature in switchgears. Low carbon steels as magnetic material are always subjected to the annealing heat treatment which ensures the attainment of optimum magnetic properties. This annealing differs from conventional annealing (see Section 5.2.1) in the sense that heat treatment temperature is significantly high (1000–1200°C) and holding time is considerably longer in this case. Such an annealing treatment results in alignment of magnetic domains.

Steels with 0.10–0.25 percent carbon possess high strength and toughness values. On case carburizing, these steels develop a hard and wear resistant case with a tough core. Carburized steel is always subjected to further heat treatment to refine case or core or both. These steels are very well suited for light duty general engineering purposes such as welded structures, rivetted structures, forgings and machined parts. Some typical applications include ship plates, boiler plates, cams, shafts, stay bolts, wheel hubs, brake housings and brake pendal levers. These steels are given normalizing heat treatment in order to improve machinability. Table 14.1 gives the chemical compositions and heat treatment temperatures of two types of low carbon steels.

Table 14.1 Heat Treatment Temperatures for a Few Low Carbon Steels

Composition	Annealing temperature (ºC)	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Carburizing temperature (ºC)	Refining treatment after carburizing	Tempering temperature (ºC)
0.10–0.15% C	880–930	880–930	770–800	Water	880–930	Heating to 760–780ºC, followed by water quenching	150–200
0.15–0.20% C	880–920	880–920	770–800	Water	880–930	Heating to 760–780ºC, followed by water quenching	150–200

14.1.2 Medium Carbon Steels

Steels with carbon varying from 0.25 percent to 0.65 percent are referred to as medium carbon steels. The response of these steels to heat treatment is much better than that of low carbon steels. In order to have maximum advantage, these steels are always used in heat treated condition. Depending on their response to heat treatment, medium carbon steels can be divided into two groups. The first group consists of steels with 0.25–0.35 percent carbon, whereas the second group consists of steels with 0.35–0.65 percent carbon. The response of the second group towards hardening treatment is excellent. The response of the first group is not very encouraging. It is for this reason that steels of the second group are generally used in hardened and tempered condition. The desired levels of strength, ductility and toughness can be obtained by a proper combination of hardening and tempering treatment for these steels. Normalizing treatment is employed for improving the machinability of steels included in the first group, whereas the machinability of the second group of steels is improved by annealing.

Steels of the first group are suitable for moderately stressed components. Typical applications include railway couplings, driving rings and flanges, hand tools, sockets, levers, cams, and tubes for bicycles, automobiles and aircraft. Steels of the second group have better strength than those of the first group due to higher carbon contents. For this reason, steels of the second group can be subjected to relatively higher stresses. These steels can be surface hardened by flame or induction hardening. Such hardened steels, in addition to hard and wear resistant cases have very tough cores. Typical applications include spindles of machine tools, gears, bolts, shafts, axles, pinions, cylinders, cylinder liners, cams, crank shafts, keys, machine tools, rifle barrels and ball mill balls. Chemical compositions and heat treatment temperatures of a number of medium carbon steels are given in Table 14.2.

14.1.3 High Carbon Steels

The carbon content of high carbon steels generally varies from 0.65 percent to 1.5 percent. The higher the carbon, more is the strength with attendant brittleness. Therefore, steels with more than 1.3 percent carbon are rarely used in practice. These steels have poor fabricability, formability, machinability and weldability as compared to medium carbon steels. Machinability and formability can be improved to a great extent by a heat treatment process known as spheroidizing annealing (refer Section 5.3). The spheroidizing treatment results in reduction in

Table 14.2 Heat Treatment Temperatures for Medium Carbon Steels

Composition	Annealing temperature (ºC)	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)
0.25–0.30%C	880–900	880–900	$\frac{860-880}{850-870}$	$\frac{\text{Oil}}{\text{Water}}$	500–650
0.30–0.35%C	870–890	870–890	$\frac{850-870}{840-860}$	$\frac{\text{Oil}}{\text{Water}}$	500–650
0.35–0.40%C	860–880	860–880	$\frac{850-870}{840-860}$	$\frac{\text{Oil}}{\text{Water}}$	500–650
0.40–0.45%C	850–870	850–870	$\frac{840-860}{830-850}$	$\frac{\text{Oil}}{\text{Water}}$	500–650
0.45–0.50%C	840–860	840–860	$\frac{830-850}{820-840}$	$\frac{\text{Oil}}{\text{Water}}$	500–650
0.50–0.55%C	830–850	830–850	$\frac{820-840}{810-830}$	$\frac{\text{Oil}}{\text{Water}}$	500–650
0.55–0.60%C	820–840	820–840	$\frac{810-830}{800-820}$	$\frac{\text{Oil}}{\text{Water}}$	500–650
0.60–0.65%C	810–830	810–830	$\frac{800-820}{790-810}$	$\frac{\text{Oil}}{\text{Water}}$	500–650

strength and hardness values. However, the tendency towards brittleness is reduced considerably with attainment of a satisfactory level of ductility.

Steels with 0.65–1.00 percent carbon are frequently used for manufacturing springs. Two common methods adopted for fabricating springs are hot rolling and cold drawing. Springs made by hot rolling process are subjected to hardening and tempering treatment. Hardening and tempering temperatures depend on the chemical composition and final properties required in the spring. A hardness of Rockwell 56 to 60 on C-scale is obtained by hardening and tempering treatment. On account of their low hardenability (as compared to alloy steels), these carbon steels are used for light springs. The cold-drawn springs are generally made by first patenting (refer Section 5.10) the wire rod. The patented wire rod is then cold drawn. The magnitude of cold reduction depends on the final properties required in the spring. More the reduction, the higher is the strength obtained in the spring. Very high tensile strength values, say up to 2750 N/mm^2, can be obtained by a combination of patenting and cold drawing processes. Tempering these steels at 200–250°C results in improvement in elastic limit. Higher tempering temperatures, say about 400°C, are required where service conditions demand enhanced toughness and ductility. Table 14.3 gives chemical compositions and heat treatment temperature of a few high carbon spring steels.

In addition to springs, high carbon steels are also utilized for making gauges, machine knives, piston rings, saws, cutting tools, chisels and hand tools. Heat treatment of these articles is discussed in Section 14.3.

Table 14.3 Heat Treatment Temperatures for a Few High Carbon Spring Steels

Composition	Annealing temperature (ºC)	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)
0.65–0.75% C	810–830	820–850	810–830	Oil or water (depending on Mn-contents and section thickness)	According to use; in general between 400–500
0.75–0.85% C	810–830	820–850	810–830	Oil or water (depending on Mn-contents and section thickness)	According to use; in general between 400–500
0.85–0.95% C	800–820	820–850	800–820	Oil or water (depending on Mn-contents and section thickness)	According to use; in general between 400–500
0.95–1.05% C	800–820	820–850	800–820	Oil or water (depending on Mn-contents and section thickness)	According to use; in general between 400–500

14.2 ALLOY STEELS

Alloy steels are superior to plain carbon steels in several respects. Depending on the nature and amount of alloying element(s), alloy steels, in general, possess (i) better strength, hardness and ductility; (ii) higher fatigue and impact strengths; (iii) better resistance to grain growth and softening during tempering; (iv) excellent high and low temperature properties; (v) enhanced corrosion resistance and wear resistance; and (vi) better electrical and magnetic properties. In this section, general heat treatment practice for various alloy steels grouped on the basis of alloying element(s) present in the steel is analyzed.

14.2.1 Manganese Steels

Steels with more than 1.65 percent manganese are included in alloy steel group. Manganese in the range 1.65–1.90 percent is added to improve tensile strength, hardenability and hot workability of steel. Such an improvement in properties of steel is obtained at almost no extra cost or at marginal increase in cost as manganese is an inexpensive element. The presence of manganese also enhances the response of steel to heat treatment. Optimum mechanical properties in manganese steels are developed by heat treatment. Hardening and tempering treatment results in the best possible properties. However, normalizing treatment improves impact property and is frequently adopted for large forgings and castings.

Low carbon manganese steels (with manganese content ranging from 1.65 percent to 1.90 percent) are generally used for structural purposes in rolled condition without heat treatment. However, medium carbon steels with same range of manganese content are used in heat treated condition. Conventional quenching and tempering treatment gives the best possible mechanical properties. However, normalized steel possesses mechanical properties equivalent to hardened and tempered plain carbon, steels of the same carbon content. Addition of small amounts of alloying elements such as vanadium or molybdenum imparts some additional desirable

Table 14.4 Heat Treatment Temperatures for Medium Carbon–Low Manganese Steels

Composition*	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)
0.30–0.40% C, 1.70–2.00% Mn	850–880	830–860	Oil	530–670
0.30–0.40% C, 1.70–2.00% Mn, 0.20–0.35% Mo	860–890	830–860	Oil	530–670
0.85–0.95% C, 1.70–2.00% Mn	830–850	790–820	Oil	480–520
0.35–0.45% C, 1.70–2.00% Mn, 0.40–0.60% Cr, 0.08–0.15% V	860–890	840–870	Oil	530–670

*Other constituents in these steels are 0.15–0.35% Si, 0.04% S (max) and 0.04% P (max).

characteristics in these steels. A wide range of engineering components are manufactured from these steels. Applications include rails, gears, axles, connecting rods, crankshafts, bolts, nuts, studs, steering levers, aircraft fittings and gun barrels. Chemical compositions and heat treatment temperatures of important medium carbon manganese steels are contained in Table 14.4. High carbon low manganese steels (with manganese content ranging from 1.65 percent to 2.00 percent) constitute an important series of tool steels. This series is popularly known as non-deforming tool steels and has a general composition of 0.9 percent carbon and 1.80 percent manganese. The heat treatment given to these steels is oil quenching from 840°C, followed by tempering at 230°C. These steels possess hard surface, greater depth of hardness, keen cutting edge, high impact strength, and are free from expansion or shrinkage as compared to plain carbon steels of equivalent carbon content.

In spite of many advantages offered by manganese as an alloying element, manganese content in steels is either less than 2 percent or more than 10 percent. This is so because manganese induces tendency towards brittleness. Therefore, steels with 2–10 percent manganese are not in use. Exceptions are nickel substituted austenitic stainless steels.

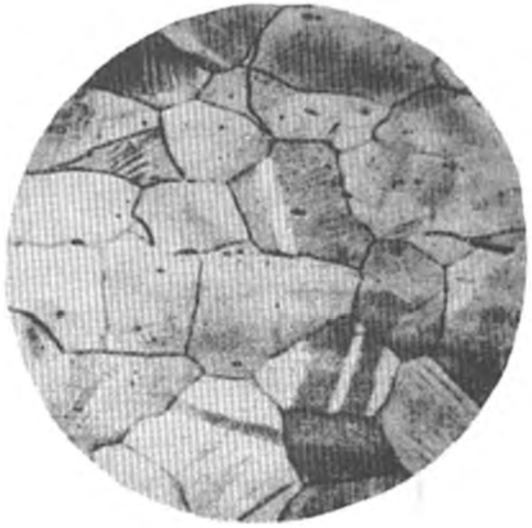


Figure 14.1 Microstructure of as-quenched Hadfield steel (1.4% C and 14.2% Mn) showing austenitic grains; water quenched from 1050°C (×100).

Hadfield steel (microstructure, Figure 14.1) is the only high manganese steel of commercial importance. Hadfield manganese steel contains 1.1–1.4 percent carbon and 11–14 percent manganese. When quenched in water, the structure produced is austenitic provided manganese to carbon ratio in the given Hadfield steel is 10 : 1. This steel, when suitably heat treated, possesses high strength, enhanced toughness and excellent wear resistance. The heat treatment of Hadfield steel consists of heating to about 1000°C, followed by water quenching. This treatment produces a non-magnetic austenitic structure. The steel is neither tempered nor used at elevated temperatures as heating to about 300°C will result in the precipitation of the carbides, which is not desirable. Sometimes, nickel or chromium are added to Hadfield steel to get better properties. Modified Hadfield steel is water quenched from a temperature of about 1050°C.

14.2.2 Silicon Steels

Silicon is present in all steels. Only those steels which contain more than 0.6 percent silicon are termed silicon steels. These steels are characterized by improved elastic properties, excellent electrical and magnetic properties with enhanced resistance to scaling at high temperatures. Since silicon imparts brittleness to the steels, in straight silicon steels, the silicon content is restricted to about 5 percent. A steel with 3–4 percent silicon and less than 0.5 percent carbon is popularly known as electrical steel (microstructure, Figure 14.2). This steel is extensively used for manufacturing cores of electric motors, generators and transformers. For this reason, it is also known as transformer steel. It has higher coercive force than pure iron as silicon atoms go into solid solution and distort iron lattice. Eddy current losses are very low due to higher electrical resistivity of this steel. Carbon affects the properties of this steel adversely. As carbon content decreases, properties are improved; carbon-free iron-silicon alloy has the best properties. Excellent properties are derived from a coarse grained and textured structure. The texture is obtained by repeated cold rolling and annealing. For obtaining coarse grained structure, the steel is annealed at 1100–1200°C under hydrogen atmosphere. This heat treatment constitutes an important step in the manufacturing of cores. Transformer steel is also known as grain-oriented silicon steel. Steel with 1–2 percent silicon is referred to as dynamo steel.

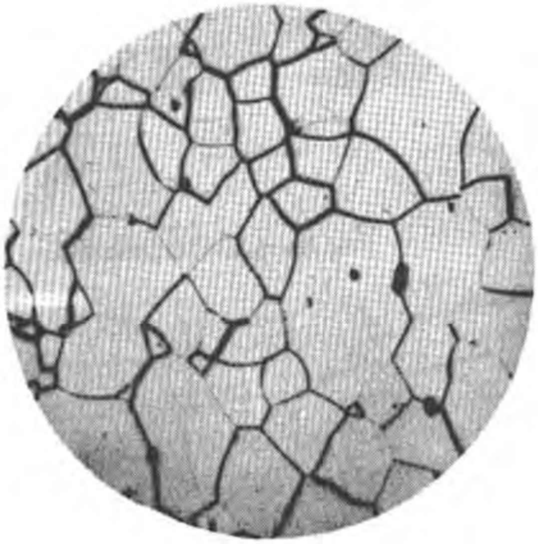


Figure 14.2 Microstructure of annealed silicon steel showing coarse ferritic grains (×150).

Steels with about 2 percent silicon and 1 percent manganese with carbon varying from 0.50 percent to 0.70 percent are of great commercial importance. Properly heat treated steels of this category have high elastic limit and fatigue strength. For this reason, these steels are

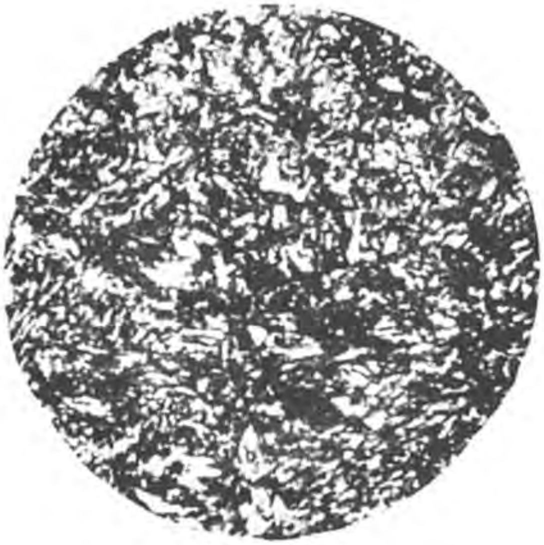


Figure 14.3 Microstructure of oil-quenched silico-manganese spring steel showing tempered martensite. Oil quenched from 870°C and tempered at 450°C (×1000).

well suited for manufacturing springs (microstructure, Figure 14.3), and are widely used as leaf springs, coiled springs, chisels and punches. Some of the shapes into which the spring steels coiled from wires are formed, are given in Figure 14.4. The most frequently adopted heat treatment consists of austenitizing, oil quenching and tempering. Depending on the chemical composition, steel is oil-quenched from a temperature range 840–930°C. Tempering is done within the temperature range 400–550°C. Table 14.5 gives chemical compositions and heat treatment of different grades of silico-manganese spring steels.

Figure 14.4 Various shaped forms of spring steels coiled from wire.

Table 14.5 Heat Treatment Temperatures for Silico-Manganese (Spring) Steels

Composition*	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)
0.45–0.55% C, 1.50–1.80% Si, 0.60–0.80% Mn	840–870	820–850	Water	470–500
0.55–0.65% C, 1.50–1.80% Si, 0.80–1.00% Mn	850–880	830–860	Oil	450–500
0.60–0.65% C, 1.80–2.20% Si, 0.60–0.90% Mn	850–870	830–850	Oil	400–500
0.60–0.70% C, 1.50–1.80% Si, 0.60–0.80% Mn	850–880	830–860	Oil	470–530
0.65–0.75% C, 2.40–2.80% Si, 0.60–0.90% Mn	840–870	820–850	Oil	400–500

*Other constituents are 0.045% S (max) and 0.045% P (max).

14.2.3 Chromium Steels

Low carbon (0.1–0.2% C), low chromium (0.5, 0.75 and 1.0% Cr) steels are generally case carburized. Increasing chromium contents increases the wear resistance of case. However, toughness in the core is somewhat reduced by increasing chromium contents. In order to have optimum properties, these carburized steels are used in heat treated condition. The purpose of post-carburizing heat treatment is to refine the case or core or both. Chemical compositions and heat treatment temperatures of three important types of low carbon low chromium steels are given in Table 14.6.

Medium carbon (0.35% C), low chromium (0.5% Cr) steel finds application in manufacturing gears, jaws of wrenches, machine gun barrels, axles and shafts. The most common heat treatment given to this steel is oil quenching/water quenching, followed by tempering. Heat treated steel has excellent wear resistance and satisfactory level of toughness. The quenching medium depends on the size of the component. Hardening is carried out at about 870°C. Steel with 0.5 percent carbon and 1.5 percent chromium is used for making springs and compressed air tools. This steel is oil-quenched from 850°C and tempered at about 300°C (or at any suitable temperature) so as to get a hardness number of about 44 on Rockwell C-scale. Table 14.7 summarizes the chemical compositions and heat treatment temperatures of some medium carbon low chromium steels.

High carbon, low chromium steels find numerous applications as tool steels. All such steels are, in general, used in heat treated condition. A steel with 0.9 percent carbon and 1.0 percent chromium (microstructure, Figure 14.5) is used for making twist drills, hacksaw blades, knives, hammers and similar products. The heat treatment cycle for this steel consists of heating to 810°C, oil quenching and tempering in the temperature range 250–300°C.

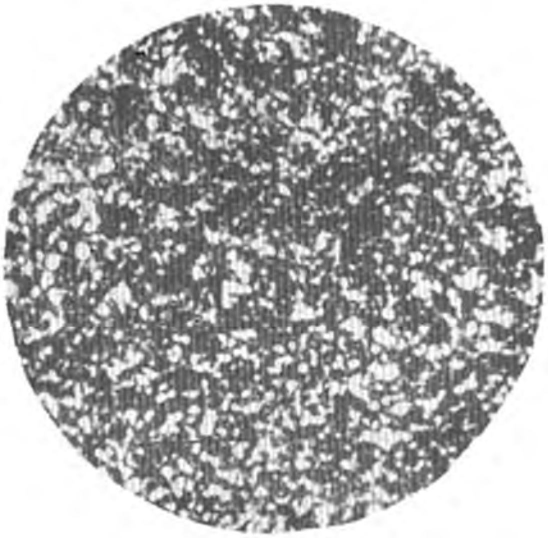


Figure 14.5 Microstructure of quenched and tempered steel containing 0.9% C and 1.0% Cr. Microstructure shows tempered martensite with some carbide particles. Oil quenched from 800°C and tempered at 200°C (×1500).

Table 14.6 Heat Treatment temperatures for Low Carbon–Low Chromium Steels (Carburizing Grades)

Composition*	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Carburizing temperature (ºC)	Refining temperature (ºC)	Tempering temperature (ºC)
0.12–0.18% C 0.30–0.50% Cr, 0.30–0.50% Mn	880–930	760–780	Water	880–930	870–900 followed by AC/OQ/WQ**	150–250
0.15–0.20% C 0.60–0.80% Cr, 0.60–0.80% Mn	870–920	760–780	Water	880–930	870–900 followed by AC/OQ/WQ	150–250
0.15–0.20% C 0.80–1.10% Cr, 1.00–1.30% Mn	850–880	780–820	Oil or water	900–930	870–900 followed by AC/OQ/WQ**	150–250

*Other constituents are 0.10–0.35% Si, 0.05% S (max) and 0.05% P (max).

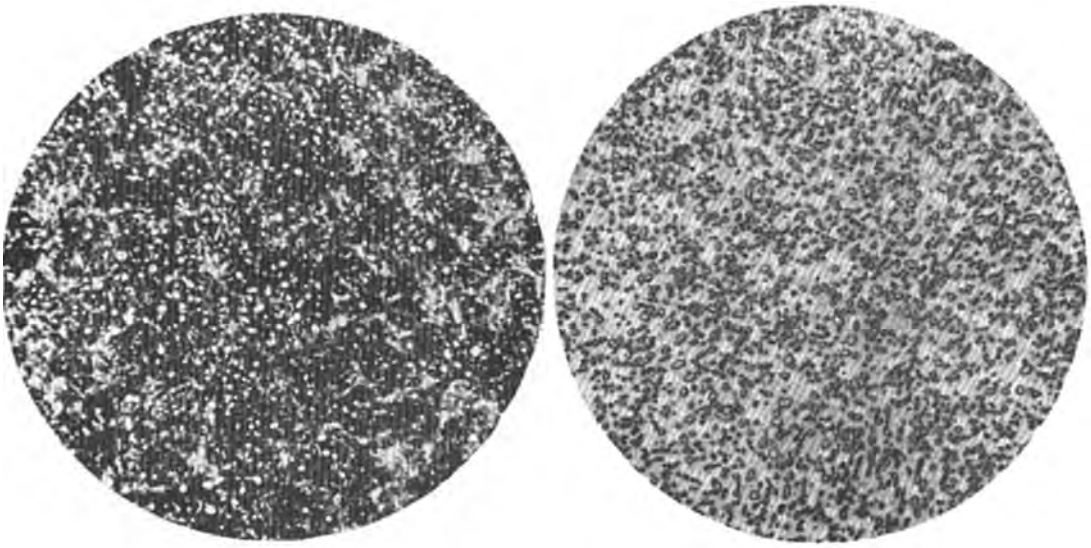
**AC = air cooling, OQ = oil quenching, WQ = water quenching.

A steel with 0.95–1.10 percent carbon and 1.3–1.6 percent chromium (microstructure, Figure 14.6) is comparatively an inexpensive variety used for making ball and roller bearings. This steel is most popularly known as ball bearing steel. It is spheroidized annealed in order to improve machinability. For heat treatment, it is oil quenched from 830°C to 840°C, followed by tempering at 150–160°C in order to achieve a hardness of 62 Rc. In fully heat treated condition, this steel has a high compressive strength and resistance to abrasion. Apart from ball

Table 14.7 Heat Treatment Temperatures for Medium Carbon–Low Chromium Steels

Composition*	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)
0.25–0.30% C, 0.80–1.20% Cr	860–880	860–880	Oil	400–550
0.30–0.35% C, 0.80–1.20% Cr	850–870	850–870	Oil	400–550
0.35–0.40% C, 0.80–1.20% Cr	840–860	840–860	Oil	200–650
0.40–0.45% C, 0.80–1.20% Cr	830–850	830–850	Oil	200–650
0.45–0.55% C, 1.00–1.40% Cr	830–880	830–880	Oil	400–550

*Other consituents are 0.50–0.80% Mn, 0.15–0.40% Si, 0.04% S (max) and 0.04% P (max).



(a) (b)

Figure 14.6 Microstructure of ball bearing steel in (a) quenched and tempered condition, and (b) spheroidized condition, showing tempered martensite and undissolved carbides and globules of carbides, respectively (×500).

and roller bearings, other applications include spindles, cold forming rolls and hardened machine parts. The purpose of chromium addition is to ensure attainment of required hardenability. Therefore, smaller sized components can be made of steels with lower chromium content. Two more popular grades of ball bearing steels contain 0.5 percent and 1.0 percent chromium, respectively. Table 14.8 gives compositions and heat treatment temperatures of typical ball bearing steels.

Table 14.8 Heat Treatment Temperatures for Ball Bearing Steels

Composition*	Hardening temperature (ºC)	Quenching medium	Minimum as-quenched hardness (on Rockwell C-scale)	Tempering temperature (ºC)	Hardness after tempering treatment (on Rockwell C-scale)
0.95–1.10% C 0.04–0.70% Cr,	800–825	Oil	62	150–220	62–56
0.95–1.10% C 0.60–1.20% Cr,	825–840	Oil	62	150–300	62–50
0.95–1.10% C 1.30–0.60% Cr,	840–860	Oil	62	150–400	62–50

*Other constituents are 0.20–0.35% Si, 0.25–0.45% Mn, 0.025% S (max) and 0.025% P (max).

High carbon, low chromium steels are also used as hard magnetic material. Details of heat treatment of a few such steels are contained in Table 14.9.

The properties of low chromium steels can be improved significantly by the addition of alloying elements) such as nickel, molybdenum, vanadium and tungsten. For this reason, complex steels like chromium-nickel, chromium-molybdenum, chromium-vanadium, and chromium-nickel-molybdenum are more commonly used in practice than straight low chromium steels. These steels are discussed in Sections 14.2.7–14.2.9.

Table 14.9 Heat Treatment Temperatures for High Carbon–Low Chromium (Hard Magnetic) Steels

Composition*	Normalizing treatment	Hardening treatment	Ageing treatment for stabilizing structure and magnetic properties
0.95–1.10% C, 1.30–1.60% Cr	Heating to 1000ºC for 5 minutes following by air cooling	Pre-heating to 500–600ºC; final heating to 850ºC for 10–15 minutes followed by oil quenching	5–8 hours ageing at 100ºC
0.95–1.10% C, 2.80–3.60% Cr	Heating to 1050ºC for 5 minutes following by air cooling	Preheating to 500–600ºC; final heating to 850ºC for 10–15 minutes followed by oil quenching	5–8 hours ageing at 100ºC

*Other constituents are 0.20–0.40% Mn, 0.15–0.40% Si, 0.02% S (max) and 0.03% P (max).

Medium chromium and high chromium steels have a large number of applications, e.g. valve steels, tool steels, heat resisting steels and stainless steels. Heat treatment of these steels are discussed under respective heads.

14.2.4 Nickel Steels

As compared to plain carbon steels, nickel steels are characterized by higher tensile strength and toughness values, improved fatigue strength, impact resistance and shear strength. Nickel steels require lower heat treatment temperatures than plain carbon steels, and hence less drastic quenching is needed for obtaining equivalent hardness values.

Low carbon (0.1–0.2% C), low nickel (2.5–3.5% Ni) steels are widely used for case carburizing as these steels have very good core toughness values. Another important group of carburizing nickel steel has slightly increased nickel contents, i.e. 3.5–5.0 percent, whereas carbon level remains the same, viz. 0.1–0.2 percent. These steels have better toughness and strength than those of 3 percent nickel steels but are more expensive. They are used for manufacturing wrist pins, pinions, engine cams, transmission gears, and other parts which are subjected to severe service conditions. Chemical compositions and heat treatment temperatures of a few low carbon, low nickel steels are given in Table 14.10.

Table 14.10 Heat Treatment Temperatures for Low Carbon–Low Nickel (Carburizing Grade) Steels

Composition	Hardening temperature (ºC)	Quenching medium	Carburizing temperature (ºC)	Refining treatment	Tempering temperature (ºC)
0.10–0.15% C, 3.00–3.75% Ni,	760–780	Oil	880–930	Heating to 850–880ºC followed by AC or OQ or WQ*	150–200
0.10–0.15% C, 3.75–4.50% Ni	760–780	Oil	880–930	Heating to 850–880ºC followed by AC or OQ or WQ	150–200
0.10–0.15% C, 4.50–5.50% Ni	760–780	Oil	880–930	Heating to 850–880ºC followed by AC or OQ or WQ	150–200

*AC = air cooling, OQ = oil quenching, WQ = water quenching.

Medium carbon, low nickel (2.5–3.5% Ni) steels are widely used for structural applications. These steels, when properly heat treated, have excellent shock resistance and tensile strength values. Optimum mechanical properties are obtained by hardening and tempering treatment. Hardening is carried out by quenching from 830°C to 860°C, using water or oil as quenching medium. Tempering is done in the range 550–650°C. Various applications of these steels include aeroplane parts, crankshafts, pinion shafts, propeller shafts, turbine shafts, pins, studs and bolts. Table 14.11 contains compositions and heat treatment temperatures of four important types of medium carbon, low nickel steels.

High carbon nickel steels are not very common since nickel is a graphitizer. However, high carbon nickel steels can be used with strong carbide formers.

For most of the applications, nickel is not added alone to the steel. It is generally added in conjunction with some other element(s). This is why nickel-chromium, nickel-molybdenum, and nickel-chromiurn-molybdenum steels are in more common use. This statement is true not only for steels with low nickel contents but also for high nickel containing steels such as valve

Table 14.11 Heat Treatment Temperatures for Medium Carbon–Low Nickel Steels

Composition	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)
0.25–0.35% C, 3.25–3.75% Ni	810–830	810–830	Oil	550–650
0.25–0.35% C, 4.00–4.50% Ni	810–830	810–830	Oil, air	100–250
0.35–0.45% C, 1.00–1.50% Ni	820–850	820–850	Oil	550–650
0.35–0.45% C, 3.00–3.50% Ni	830–860	830–860	Oil	550–650

steels, stainless steels and heat resisting steels. These (high nickel) steels are discussed in Sections 14.2.7–14.2.9.

14.2.5 Molybdenum Steels

Properties of alloy steels can be improved significantly by the addition of molybdenum which improves hardenability, ductility, toughness and elevated temperature properties of the steel. Molybdenum inhibits grain growth and makes the steel less susceptible to temper brittleness. It forms complex carbides which are more stable than cementite. Therefore, molybdenum steels require higher heat treating temperatures.

As molybdenum is an expensive element, straight molybdenum steels, in general, do not contain more than 0.70 percent molybdenum. Three popular grades of molybdenum steels contain 0.15–0.30 percent, 0.30–0.45 percent and 0.45–0.70 percent molybdenum (microstructure, Figure 14.7), respectively.

Low carbon grades of these steels are generally employed for case carburizing. In carburized steels, the main requirements are improved wear resistance of the case and good toughness of the core. These steels are used for shafts, transmission gears, bearing for gears, and bearing axles under moderate service conditions.

With higher carbon contents, these steels can be subjected to heavy duty applications such as coil spring, leaf spring and various other automobile and aeroplane parts.

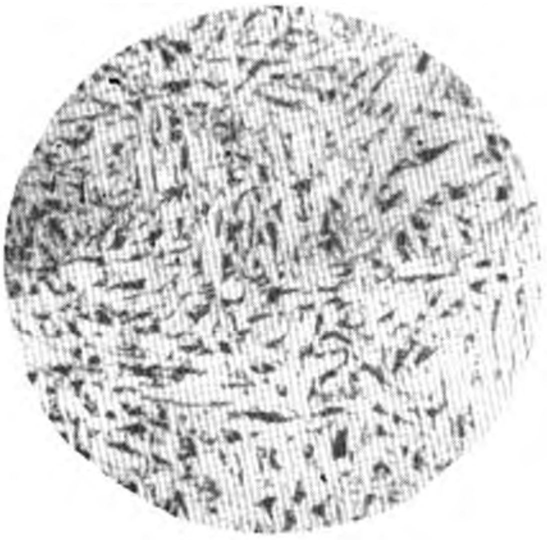


Figure 14.7 Microstructure of as-cast molybdenum steel (with 0.22% C and 0.60% Mo) showing a fine Widmänstatten structure of ferrite (×500).

Heat treatment temperatures for molybdenum steels are generally 10–20°C higher than carbon steels of same carbon contents.

Typical examples of this class of steel include nickel-molybdenum, chromium-molybdenum and nickel-chromium-molybdenum steels. Molybdenum up to 2 percent is present in low alloy creep resisting steels, and up to 2–4 percent in austenitic stainless steels. Molybdenum containing austenitic stainless steels have properties which are superior to the austenitic stainless steels without molybdenum. In some of the tool steels, molybdenum is present in large proportions, say up to 10 percent.

14.2.6 Chromium-Molybdenum Steels

The beneficial effects arising from the presence of chromium in steels are enhanced by addition of molybdenum. For this reason, about 0.25–0.65 percent molybdenum is added to low chromium steels. Applications of chromium-molybdenum are similar to those of corresponding chromium steels. Chromium-molybdenum steels have the added advantages of improved toughness and freedom from temper brittleness.

Low carbon, low chromium-molybdenum steels possess high tensile and creep strength. These steels are, in general, case nitrided. Applications of these steels include aircraft engine cylinders and lightly stressed wear resistant parts for aircraft and automobile construction. In Table 14.12, compositions and heat treatment temperatures of two important varieties of low carbon, low chromium-molybdenum steels are given. Figure 14.8 shows the microstructure of a low carbon, low chromium-molybdenum steel.

Table 14.12 Heat Treatment Temperatures for Low Carbon, Low Chromium-Molybdenum (Case Nitriding Grade)

Composition*	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)	Nitriding temperature (ºC)
0.10–0.20% C, 3.00–3.50% Cr 0.45–0.65% Mo	880–910	880–910	Oil	550–750	520–550
0.20–0.30% C, 3.00–3.50% Cr, 0.45–0.65% Mo	880–910	880–910	Oil	550–750	520–550

*Other constituents are 0.10–0.35% Si, 0.40–0.70% Mn, 0.04% S (max) and 0.04% P (max).

Medium carbon, low chromium-molybdenum steels have high strength, ductility, and good shock resistance. These steels are used for making axles, shafts, connecting rods and other moderately stressed components. They can also be subjected to induction hardening. Table 14.13 summarizes the compositions and heat treatment temperatures of some medium carbon, low chromium-molybdenum steels.

High carbon, low chromium-molybdenum steels are used as cold-worked tool steels. The heat treatment of these steels will be discussed under this group (see Section 14.3.6), High chromium-molybdenum steels find numerous applications. Low carbon and medium carbon, high chromium-molybdenum steels are used as stainless, heat resisting, and valve steels. High carbon, high chromium-molybdenum steels are used extensively for making drawing dies, bushings, shear blades, punches and cold forming rolls.

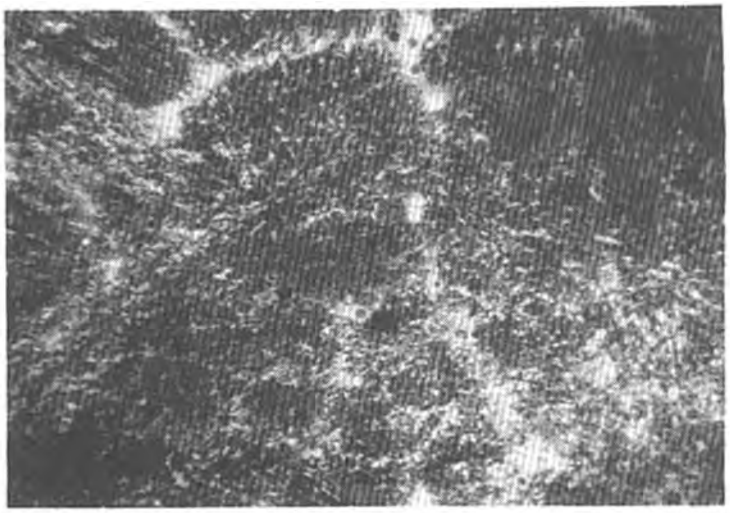


Figure 14.8 Microstructure of as-cast low carbon low chromium-molybdenum steel (0.25% C, 3.0% Cr and 0.5% Mo) showing degenerated pearlite (×500).

Table 14.13 Heat Treatment Temperatures for Medium Carbon, Low Chromium-Molybdenum Steels

Composition*	Annealing temperature (ºC)	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)
0.25–0.35% C, 0.80–1.10% Cr 0.15–0.25% Mo	860–890	860–890	860–890	Oil	450–650
0.30–0.40% C, 0.80–1.10% Cr 0.15–0.25% Mo	860–880	860–880	860–880	Oil	200–250 550–650
0.30–0.40% C, 1.60–1.90% Cr 0.15–0.25% Mo	850–870	850–870	850–870	Oil	550–650
0.35–0.45% C, 0.90–1.20% Cr, 0.20–0.35% Mo	850–880	850–880	850–880	Oil	550–700

*Other constituents are 0.10–0.35% Si and 0.50–0.80% Mn.

14.2.7 Nickel-Molybdenum Steels

Molybdenum, when added to nickel steels, improves hardenability, ductility and toughness. It also checks grain growth and reduces the tendency towards temper brittleness. Applications of nickel-molybdenum steels are similar to those of corresponding nickel steels. Heat treatment temperatures are marginally higher, say about 10°C, than the corresponding nickel steels.

14.2.8 Nickel-Chromium Steels

Nickel-chromium steels have almost all possible advantages and minimum possible disadvantages due to the presence of both the elements. Depending on the chemical composition, these steels exhibit enhanced mechanical properties, excellent corrosion and oxidation resistance, high temperature strength and unique physical properties.

Low carbon, 1.25 percent nickel, 0.75 percent chromium steels are case carburized. In this condition, it has a hard wear resistant case and a tough core. Typical applications are gears, shafts, levers, bearings and races. Low carbon, nickel-chromium steels with 2.0 percent nickel and 0.90 percent chromium have properties which are superior to low carbon, nickel-chromium steels containing 1.25 percent nickel and 0.75 percent chromium. Low carbon steels with about 3.50 percent nickel and 1.50 percent chromium have unusually high hardenability. These steels, when case carburized, possess very hard wear resistant surface with a very tough core. Mechanical properties can be varied over a sufficiently large range with varying heat treatment. The few applications include case hardened gears and pinions, heavy heat treated parts and spline shafts. Compositions and heat treatment temperatures of a few low carbon, nickel-chromium steels are given in Table 14.14.

Table 14.14 Heat Treatment Temperatures for Low Carbon, Nickel-Chromium (Carburizing Grade) Steels

Composition	Normalizing temperature (ºC)	Hardening temperature (ºC); quenching medium	Tempering temperature (ºC)	Carburizing temperature (ºC)	Refining temperature (ºC); quenching medium
0.10–0.15% C, 2.75–3.50% Ni 0.25–0.40% Cr	850–880	760–780 water	150–250	880–930	850–880; air, oil or water
0.10–0.15% C, 3.00–3.75% Ni 0.60–1.10% Cr	850–880	760–780 oil	150–250	880–930	850–880; air, oil or water
0.10–0.15% C, 4.50–5.00% Ni 0.25–0.40% Cr	850–880	760–780 oil	150–250	880–930	850–880; air, oil or water
0.10–0.15% C, 4.00–4.50% Ni, 1.00–1.50% Cr	850–880	760–780 oil	150–250	880–930	850–880; air, oil or water

Medium carbon, 1.25 percent nickel, 0.75 percent chromium steels are hardenable to greater depths than low carbon steels. These steels are used in heat treated condition. One common heat treatment is oil quenching and tempering. Some applications of these steels include crank shafts, propeller shafts, drilling equipment parts and parts of earth moving equipments. Medium carbon, 2.0 percent nickel, 0.90 percent chromium steels have better properties than low carbon and medium carbon, 1.25 percent nickel, 0.75 percent chromium steels. Medium carbon steels with 3.50 percent nickel and 1.50 percent chromium have better mechanical properties because of their high alloy contents. Their properties can be improved by hardening and tempering treatment. In hardened and tempered condition, these steels possess extraordinarily high toughness. For this reason, these steels are employed for heavy duty applications such as highly stressed components in aircrafts and automobiles. Table 14.15 gives the compositions and heat treatment temperatures of some commercially important medium carbon, nickel-chromium steels.

Table 14.15 Heat Treatment Temperatures for Medium Carbon, Nickel-Chromium Steels

Composition	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)
0.30–0.40% C 1.40–1.70% Ni, 0.40–0.70% Cr	850–880	830–850	Oil	550–600
0.30–0.40% C, 2.30–2.70% Ni, 0.60–0.90% Cr	840–870	810–840	Oil	550–650
0.25–0.35% C, 3.25–3.75% Ni, 0.60–0.90% Cr	830–860	810–830	Oil	525–675
0.30–0.40% C, 4.25–4.75% Ni, 1.10–1.40% Cr	830–850	810–830	Oil	525–600

High carbon, nickel-chromium steels are not very common. High nickel-chromium steels constitute the well known series of austenitic stainless steels. High nickel-chromium steels are also used as heat resisting and valve steels.

14.2.9 Nickel-Chromium-Molybdenum Steels

Nickel-chromium-molybdenum steels are sometimes referred to as triple alloy steels. Due to the presence of three alloying elements, these steels have properties which are superior to corresponding double alloy steels, i.e. nickel-chromium, chromium-molybdenum or nickel-molybdenum steels. Low carbon grades of these steels are generally case carburized. Case carburized steels are characterized by very high case hardness and core toughness. These steels are suitable for manufacturing gears, gudgeon pins, shafts, levers, cam shafts, drive wheels, clutch plates, collets and valve rockers. Table 14.16 summarizes compositions and heat treatment schedule of a few carburizing grades of low carbon, low nickel-chromium-molybdenum steels. The microstructure of a low carbon, triple alloy steel is shown in Figure 14.9.

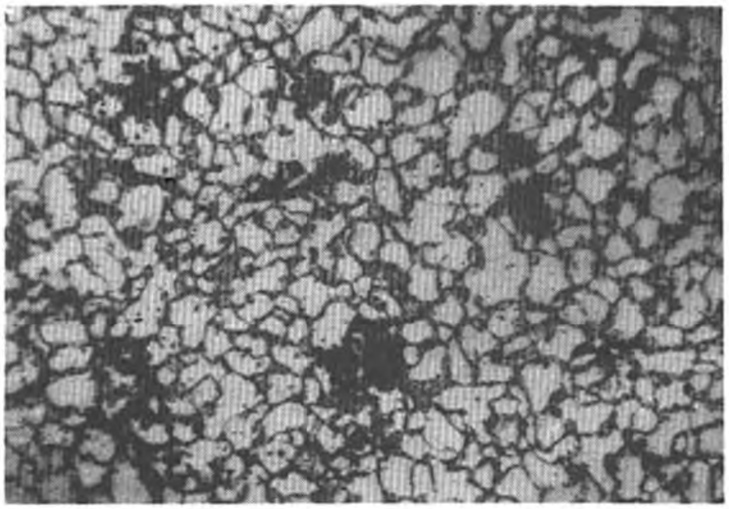


Figure 14.9 **Microstructure of normalized low carbon nickel-chromium-molybdenum steel (0.18% C, 0.60% Ni, 0.55% Cr and 0.22% Mo) showing pearlite and ferrite; normalized from 850°C (×500).**

Medium carbon, low alloy steels have good strength and ductility. The response of these steels to heat treatment is excellent and a wide range of mechanical properties can be attained with the help of suitable heat treatment(s). A general engineering purpose steel has 0.35–0.45 percent carbon, 1.30–1.80 percent nickel, 0.9–1.4 percent chromium, and 0.20–0.35 percent molybdenum. This steel possesses good strength, ductility, toughness and hardenability. Properly heat treated steel has very good resistance to wear and shock. Typical uses include axle shafts, bolts and studs, high duty engine connecting rods and high temperature bolts and oil refining and steam installations.

Medium carbon steels with about 2.50 percent nickel, 0.70 percent chromium and 0.50 percent molybdenum have high hardenability; good strength coupled with high ductility and toughness, fairly good low temperature properties and resistance to shock. Increasing nickel contents to about 3.50 percent (microstructure, Figure 14.10) results in increase in depth of hardening and toughness. Therefore, fairly large

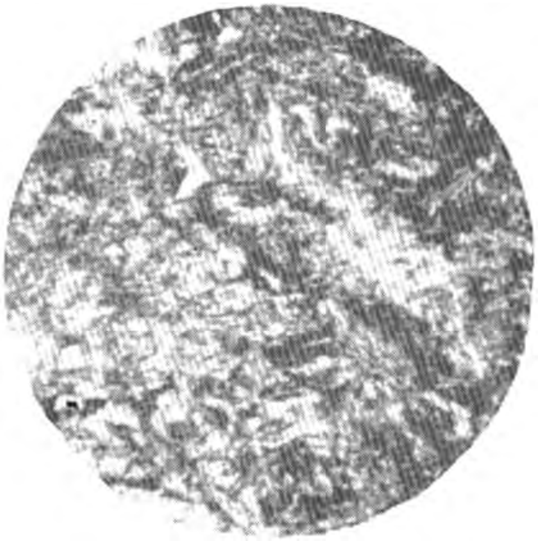


Figure 14.10 **Microstructure of wrought 3.00% nickel-chromium-molybdenum steel (0.30% C, 3.35% Ni, 0.80% Cr and 0.50% Mo). Martensitic structure is observed (×800).**

Table 14.16 Heat Treatment Temperatures for Carburizing Grades of Ni–Cr–Mo Steels

Composition*	Hardening temperature (ºC)	Quenching medium	Carburizing temperature (ºC)	Refining temperature (ºC); quenching medium	Tempering temperature (ºC)
0.10–0.20% C, 0.60–1.00% Mn, 0.60–1.00% Ni, 0.40–0.80% Cr, 0.10% Mo (max)	780–820	Oil	880–930	850–880; air, oil or water	150–200
0.10–0.20% C, 0.50–1.00% Mn, 0.80–1.25% Ni, 0.60–1.00% Cr, 0.10% Mo (max)	780–820	Oil	880–930	850–880; air, oil or water	150–200
0.10–0.20% C, 0.50–1.00% Mn, 1.00–1.50% Ni, 0.75–1.25% Cr, 0.10–0.25% Mo	780–820	Oil	880–930	850–880; air, oil or water	150–200
0.10–0.20% C, 0.40–0.70% Mn, 1.50–2.00% Ni, 0.40–0.60% Cr, 0.20–0.30% Mo	780–800	Oil	880–930	850–880; air, oil or water	150–200
0.10–0.20% C, 0.40–0.70% Mn, 1.80–2.20% Ni, 1.40–1.70% Cr, 0.15–0.25% Mo	780–820	Oil	880–930	850–880; air or oil	150–200
0.10–0.20% C, 0.60–1.00% Mn, 3.00–3.75% Ni, 0.60–1.10% Cr, 0.10–0.25% Mo	760–780	Oil	890–930	850–880; air, oil or water	150–200
0.10–0.25% C, 0.60–1.00% Mn, 3.50–4.50% Ni, 1.00–1.50% Cr, 0.15–0.35% Mo	760–780	Oil	880–930	850–880; air, oil or water	150–200
0.10–0.15% C, 0.60–1.00% Mn, 4.50–5.50% Ni, 0.25–0.40% Cr, 0.15–0.30% Mo	760–780	Oil	880–930	850–880; air, oil or water	150–200

*Other constituents are 0.10–0.35% Si, 0.05% S (max) and 0.05% P (max).

Table 14.17 Heat Treatment Temperatures for Medium Carbon, Ni-Cr-Mo Steels

Composition*	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)	Cooling medium from tempering temperature
0.25–0.35% C, 1.80–2.10% Ni, 1.80–2.10% Cr, 0.25–0.35% Mo	850–880	830–850	Oil	500–700	Air or oil
0.35–0.45% C, 1.20–1.50% Ni, 0.60–0.90% Cr, 0.30–0.45% Mo	850–880	830–850	Oil	500–700	Air or oil
0.40–0.45% C, 0.40–0.70% Ni, 0.60–0.90% Cr, 0.15–0.25% Mo	850–880	830–850	Oil	500–700	Air or oil
0.30–0.40% C, 0.90–1.20% Ni, 0.90–1.20% Cr, 0.15–0.25% Mo	850–880	830–850	Oil	500–700	Air or oil
0.30–0.40% C, 1.40–1.70% Ni, 1.40–1.70% Cr, 0.15–0.25% Mo	850–880	830–850	Oil	500–700	Air or oil
0.25–0.35% C, 2.00–3.00% Ni, 0.50–1.00% Cr, 0.40–0.70% Mo	840–870	820–850	Oil	150–650	Air or oil
0.35–0.45% C, 2.00–3.00% Ni, 0.50–1.00% Cr, 0.40–0.70% Mo	840–870	820–850	Oil	150–650	Air or oil
0.25–0.35% C, 2.75–3.50% Ni, 0.50–1.00% Cr, 0.40–0.70% Mo	850–880	820–850	Oil	550–650	Air or oil
0.25–0.35% C, 3.00–3.75% Ni, 0.50–1.00% Cr, 0.40–0.70% Mo	840–870	830–850	Oil	550–650	Air or oil
0.25–0.40% C, 3.00–4.50% Ni, 0.75–1.50% Cr, 0.20–0.70% Mo	840–870	830–850	Oil	550–650	Air or oil

*Other constituents are 0.50–1.00% Mn, 0.10–0.35% Si, 0.04% S (max) and 0.04% P (max).

sections of such steels can be heat treated in order to develop good mechanical properties. Compositions and heat treatment temperatures of a number of medium carbon, nickel-chromium-molybdenum steels are given in Table 14.17.

High carbon, nickel-chromium-molybdenum steels are not commonly used. High nickel-chromium-molybdenum steels are included in austenitic stainless steels, heat resisting steels and valve steels.

14.3 STRUCTURAL AND TOOL STEELS

Taking into account their uses, steels may be classified into three main classes, namely, structural steels, tool steels, and special purpose steels. In this section, based on their applications, the heat treatment of some categories of steels is discussed.

The three important types of structural steels, namely, hot-rolled steels, cold-drawn and cold-rolled steels and cast steels, their applications and heat treatment are now discussed.

14.3.1 Hot-rolled Steels

In general, hot-rolled structural sections and sheets are not subjected to heat treatment. Since hot rolling itself is a high temperature process, it takes care of a number of heat treatment such as homogenizing, stress relieving and breaking of cast structure.

Thin steel sheets used as dynamo and transformer steel are subjected to specific heat treatment for getting improved magnetic and electrical properties. (The treatment has already been discussed in Section 14.2.2.)

Low carbon steel sheets are annealed or normalized in order to attain a fine grained structure. Medium carbon steel sheets are subjected to spheroidization annealing. High carbon steels in hot-rolled condition are spheroidized to improve the machinability. Alloy steels, specially high alloy steels, in hot-rolled condition are tempered at high temperatures in order to improve machinability.

14.3.2 Cold-drawn and Cold-rolled Steels

In contrast to hot-rolled steels, cold-drawn/cold-rolled steels are always subjected to heat treatment, irrespective of the chemical compositions of the steels. While hot-rolled steels are heat treated after the hot rolling operation, cold-drawn steels are heat treated prior to cold drawing/rolling, in between the cold drawing/rolling cycles and after completing the cold drawing/rolling operations.

For general engineering applications, the heat treatment given prior to cold drawing/cold rolling operation consists of annealing. It imparts maximum softness to the steel so that further reduction by cold working may be facilitated. Exception to this are hypereutectoid steels for which annealed structure is brittle because of the presence of cementite network at grain boundaries. Such a network can be eliminated by normalizing heat treatment. Most of the medium carbon and high carbon steels are spheroidized annealed prior to cold drawing/cold rolling. This imparts ductility coupled with strength. Spheroidizing constitutes an important treatment for objects which are made from cold-drawn/cold-rolled products, specially by machining.

Intermediate heat treatment is essential as it eliminates the effect of strain hardening due to prior cold working and thus makes the product amenable to further processing (cold working) without failure. In general, recrystallization annealing is employed as an intermediate heat treatment.

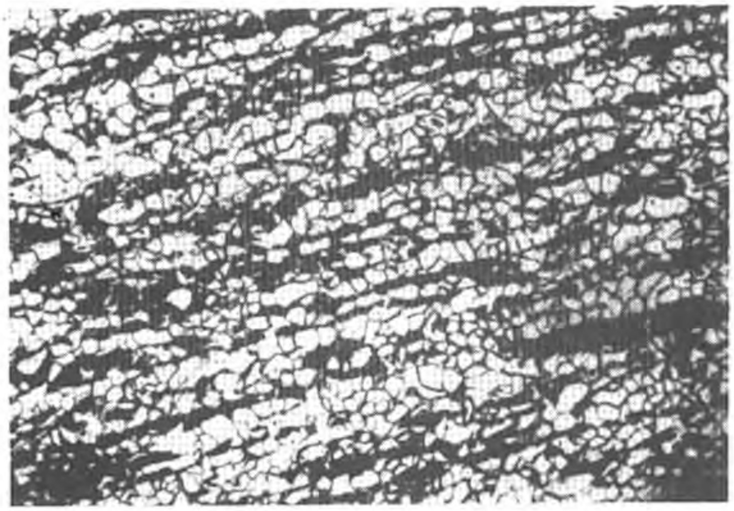
Final heat treatment is chosen in accordance with the properties required in the material. By a proper combination of heat treatment and cold working, different combinations of strength and ductility can be attained.

14.3.3 Structural Steel Castings

Steel castings, in most of the cases, are heat treated to eliminate the cast structure. Cast structure is undesirable for the following reasons:

(i) It is generally coarse and is not desirable (see Figure 14.11).

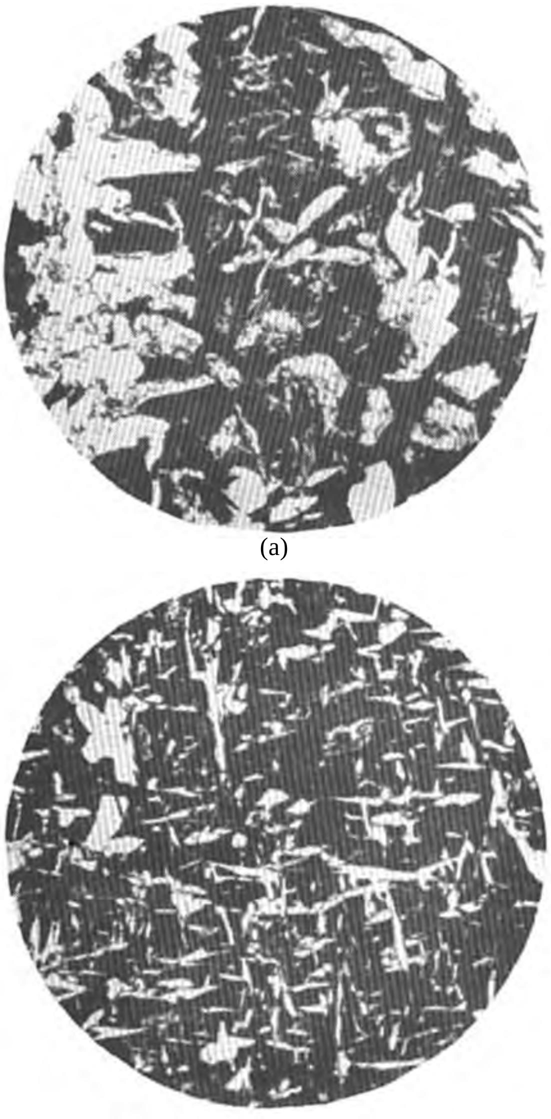
(a)



(b)

Figure 14.11 (a) Microstructure of cast 0.2% plain carbon steel. Pearlite, blocky ferrite and Widmänstatten ferrite are seen (×100). (b) Microstructure of wrought 0.2% plain carbon steel. Fine pearlite is observed (×200).

(ii) It has non-uniformity of chemical composition and of structure.
(iii) It has poor mechanical properties, especially dynamic properties (sometimes), see Figure 14.12
(iv) It has low machinability.
(v) It is always associated with internal stresses due to thermal gradient.


(a)

(b)

Figure 14.12 (a) Microstructure of surface region of cast 0.25% plain carbon steel. Pearlite with ferrite is observed (× 200). (b) Microstructure of centre region of cast 0.25% plain carbon steel. Pearlite with ferrite is observed with changed morphology (× 200).

All these defects can be removed by heat treatment operations. The suitable heat treatment processes have been described in Chapter 5.

Some of the important tool steels, their applications and heat treatment are now considered.

14.3.4 Water Hardening Tool Steels

These are essentially high carbon steels. Carbon content of these steels is as high as 1.40 percent. High carbon steels are characterized by high tensile strength and hardness levels but low ductility and toughness values. Therefore, these steels cannot be subjected to service conditions where impact loading is likely to take place. However, they are extensively used for making tools as these are cheap and possess good machinability and high hardness.

Since machining is an important process in forming of tools, these steels are given spheroidization annealing treatment in order to improve machinability. Spheroidized steel is subjected to water or brine quenching from hardening temperature. Sometimes this treatment results in distortion of the tool. Other problems encountered with these steels, which have hypereutectoid compositions, are of decarburization, possibility of retained austenite in hardened structure, and grain coarsening. These problems demand addition of strong carbide formers such as chromium, vanadium, and molybdenum. The presence of chromium improves both hardness and hardenability—the properties required in most tools. On the other hand, vanadium checks the tendency of steel towards grain coarsening. The structure of hardened steel changes with tempering temperature (see Section 5.6.1). Therefore, tempering temperature has to be chosen carefully. In general, these steels are tempered in the range 170–220°C. Replacement of conventional water or brine hardening heat treatment by martempering (see Section 5.8) leads to development of better mechanical properties in the tools.

Applications of water hardened tool steels include heavy forging hammers, forging dies, large blanking tools, chisels, scissors, knife blades, hand hammers, hot and trimming tools, cutting dies, bending dies, drift punches, lathe centres, milling cutters, boring tools, watch maker’s tools and engraving tools. Compositions and heat treatment temperatures of some water hardening tool steels of commercial importance are given in Table 14.18.

14.3.5 Shock-resisting Tool Steels

As the name suggests, these tool steels are characterized by good toughness. For this reason, the carbon contents of these grades of steel are kept low as compared to water hardening steels. Most of the steels belonging to this group have carbon ranging from 0.5 percent to 0.6 percent. Another important property of tool, i.e. hardness, is imparted by alloying additions. Commonly added alloying elements are chromium, molybdenum and tungsten. These elements not only increase hardness but also improve hardenability to a considerable extent. These steels are water or oil hardened. Tempering temperature depends on the final properties required in the tool. For an optimum combination of toughness and hardness, low temperature tempering is preferred. High temperature tempering is performed where toughness and not hardness is of primary importance.

Table 14.18 Heat Treatment Temperatures for Water Hardening Tool Steels

Composition	Hardening temperature (ºC)	Hardness after hardening (Rockwell C-scale)	Tempering temperature (ºC)	Minimum hardness after tempering (Rockwell C-scale)
0.70–0.80% C	800–820	65–67	As per use; in general between 175–275	56
0.80–0.90% C	790–810	65–67	As per use; in general between 175–275	56
0.90–1.05% C	780–800	65–67	As per use; in general between 175–275	56
1.05–1.20% C	760–780	65–67	As per use; in general between 175–275	56
1.20–1.35% C	760–780	65–67	As per use; in general between 175–275	56
0.85–0.95% C, 0.15–0.30% V	790–810	65–67	As per use; in general between 150–400	48
0.95–1.10% C, 0.15–0.30% V	780–800	65–67	As per use; in general between 150–400	48
1.10–1.40% C, 0.30–0.60% Cr, 0.30% V (max)	790–810	65–67	As per use; in general between 150–400	48

*Other constituents are 0.25–0.35% Mn, 0.10–0.35% Si, 0.03% (max) and 0.04% P (max).

Silicon-manganese steels with about 0.55 percent carbon, 2.0 percent silicon and 1 percent manganese, which have high toughness in hardened and tempered condition, are also included in this group. These steels are considerably cheaper than steels alloyed with tungsten, molybdenum and vanadium. However, due to high silicon contents, decarburization and grain coarsening take place in hardened steels. Applications of these steels include chisels, pneumatic chisels, punches, shear blades and scarring tools; Table 14.19 summarizes compositions and heat treatment temperatures of a few shock-resisting steels.

14.3.6 Cold Work Tool Steels

These steels are mainly employed for making tools intended for cold work applications. Sometimes, steels belonging to this group are referred to as non-deforming or non-distorting steels. In fact, every steel exhibits some distortion or deformation, howsoever small, during hardening heat treatment, and steels of this group are also not exceptions to this. The chemical composition and hardening heat treatment for these steels are so adjusted as to produce minimum possible deformation and, consequently, these are termed as non-deforming steels. These steels have been divided into three groups, namely, oil hardening, air hardening, and high carbon, high chromium type.

Oil hardening steels are basically carbon-manganese steels in which chromium and tungsten are added occasionally to improve hardness, hardenability and wear resistance. These steels

Table 14.19 Heat Treatment Temperatures for Shock Resisting Steels of Different Compositions

Composition	Hardening temperature (ºC)	Quenching medium	As-quenched hardness (Rockwell C-scale)	Tempering temperature (ºC)	Minimum hardness after tempering (Rockwell C-scale)
0.50% C, 1.50% Cr, 2.50% W	900–950	Oil	56–60	150–540	45
0.50% C, 1.00% Si, 0.50% Mo	840–860	Water	60–62	150–260	45
	870–890	Oil	58–60	150–260	54
0.55% C, 0.80% Mn, 2.00% Si	845–870	Water	60–62	150–345	54
	870–910	Oil	58–60	150–345	54
0.55% C, 0.80% Mn, 2.00% Si, 0.40% Mo	845–870	Water	60–62	150–345	54
	870–910	Oil	58–60	150–345	54

are used in oil hardened and tempered condition. They possess good machinability as compared to other cold-worked tool steels, and this enables them to be shaped in complicated shapes by machining to a high degree of precision, such as reamers, taps, press blanking and stamping dies. Compositions and heat treatment temperatures of some important cold work oil hardening tool steels are contained in Table 14.20.

Table 14.20 Heat Treatment Temperatures for Cold Work Oil Hardening Tool Steels

Composition	Hardening temperature (ºC)	As-quenched hardness (on Rockwell C-scale)	Tempering temperature (ºC)	Minimum hardness on tempering (on Rockwell C-scale)
0.90% C, 1.00% Mn, 0.50% W, 0.50% Cr,	790–815	63–65	150–425	50
0.90% C, 1.60% Mn	770–790	63–65	190–260	57
1.45% C, 0.80% Mn, 1.00% Si, 0.25% Mo	790–815	63–65	150–425	50
1.20% C, 1.75% W, 0.75% Cr	790–830	63–66	100–300	58

Air hardening steels are primarily chromium-manganese-molybdenum steels. All these elements considerably improve hardenability and impart air hardening characteristics to the steel. Due to air hardening tendency, distortion of these steels is less than in oil hardening cold work tool steels. Applications are almost similar to those of oil hardening steels. These steels have improved wear resistance and non-deforming properties. Table 14.21 summarizes compositions and heat treatment temperatures of a few cold-worked air hardening tool steels.

Table 14.21 Heat Treatment Temperatures for Cold Work Air Hardening Tool Steels

Composition	Hardening temperature (ºC)	As-quenched hardness (on Rockwell C-scale)	Tempering temperature (ºC)	Minimum hardness on tempering (on Rockwell C-scale)
1.00% C, 1.00% Mo, 5.00% Cr	940–970	61–63	200–375	57
1.00% C, 2.00% Mn, 1.00% Mo, 1.00% Cr	820–860	62–64	150–425	54
0.70% C, 2.00% Mn, 1.25% Mo, 1.00% Cr	820–860	62–64	150–425	54

High carbon, high chromium steels contain minimum amount of 1.0 percent and 12.0 percent carbon and chromium, respectively. These steels do not exhibit grain coarsening up to about 1040°C. The high chromium contents enable the steels to develop martensitic structure on air cooling and, because of this, distortion is much less. These steels are used for larger tools and tools with intricate shapes. In addition to air hardening characteristics, chromium imparts very high hardness and abrasion resistance to the tool due to the formation of chromium carbide. Properties of these steels can be further enhanced by the addition of molybdenum, vanadium and tungsten. Table 14.22 gives the compositions and heat treatment temperatures of typical cold work high carbon, high chromium tool steels.

14.3.7 Hot Work Tool Steels

Depending on the principal alloying element, hot work tool steels can be grouped into three main classes, namely, chromium base, tungsten base, and molybdenum base tool steels. The microstructure of a chromium base hot work tool steel is shown in Figure 14.13.

In contrast to cold work tool steels, these steels are employed for hot working applications such as hot forging and hot extrusion They are also used for fabrication of die casting dies. Therefore, high temperature properties, such as red hardness, wear-resistance, erosion resistance, thermal cracking of reticular type (heat checking) due to severe thermal shocks, are the main considerations for such steels. Red hardness is imparted by tungsten. The larger the tungsten content, the higher is the red hardness and stability of the steel. Chromium improves both

Table 14.22 Heat Treatment Temperatures for Cold Work High Carbon, High Chromium Tool Steels

Composition	Hardening temperature (ºC)	Quenching medium	As-quenched hardness (on Rockwell C-scale)	Tempering temperature (ºC)	Minimum hardness after tempering (on Rockwell C-scale)
1.50% C, 1.00% Mo, 12.00% Cr, 1.00% V	980–1025	Air	61–63	200–375	58
2.25% C, 12.00% Cr	950–980	Oil	62–64	200–375	58
1.50% C, 1.00% Mo, 12.00% Cr, 3.00% Mo	980–1025	Air	60–62	200–375	57
2.35% C, 1.00% Mo, 12.00% Cr, 4.00% V	1010–1065	Air	63–65	150–250 450–550	63 58

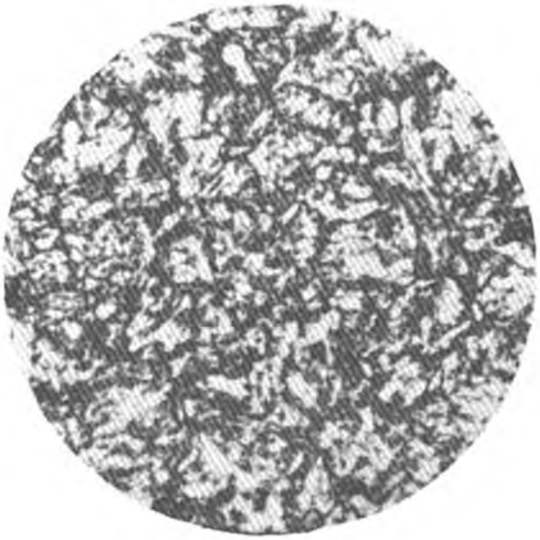


Figure 14.13 Microstructure of a typical chromium based hot work tool steel (0.30% C, 5.15% Cr, 1.45% Mo and 0.40% V) in quenched and tempered conditions. Air cooled from 1010°C and tempered at 625°C (×1000).

hardness and oxidation resistance. Other beneficial alloying elements are molybdenum and vanadium for increasing hardness and high temperature properties. These steels require higher hardening temperatures due to the presence of strong carbide formers. This in turn may cause considerable distortion. Erosion resistance is improved by increasing the carbide contents of the steel. Sometimes, cobalt is added to these steels as it improves the resistance to erosion as well as to heat checking during severe thermal shocks.

Compositions and heat treatment temperatures of chromium base, tungsten base and molybdenum base tool steels are summarized in Table 14.23.

Table 14.23 Heat Treatment Temperatures for Hot Work Tool Steels

Composition	Pre-heat temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)	Working hardness range (Rockwell C-scale)
			Chromium Base		
0.35% C, 5.00% Cr, 0.40% V, 1.50% Mo	810–820	1000–1025	Air	550–650	38–54
0.35% C, 5.00% Cr, 1.50% Mo, 1.00% Mo	810–820	1000–1050	Air	550–650	38–54
0.40% C, 5.00% Cr, 5.00% W	810–820	1000–1075	Air	600–650	40–47
0.40% C, 5.00% Cr, 5.00% W	810–820	1150–1275	Air or oil	600–650	36–49
0.55% C, 7.00% Cr, 7.00% W	810–820	1125–1175	Air or oil	550–675	45–60
			Tungsten Base		
0.35% C, 3.50% Cr, 9.00% V,	810–820	1095–1260	Air or oil	600–675	36–54
0.30% C, 12.00% Cr, 12.00% W	840–850	1200–1275	Air or oil	650–825	30–47
0.25% C, 4.00% Cr, 15.00% W	810–820	1150–1275	Air or oil	550–675	35–44
0.50% C, 4.00% Cr, 1.00% V, 18.00% W	860–880	1175–1275	Air or oil or salt bath	550–675	43–38

(*contd.*)

Table 14.23 Heat Treatment Temperatures for Hot Work Tool Steels (*Contd.*)

Composition	Pre-heat temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)	Working hardness range (Rockwell C-scale)
			Molybdenum Base		
0.65% C, 4.00% Cr, 1.00% V, 1.50% W, 8.00% Mo	780–800	1090–1190	Air or oil or salt bath	550–650	50–60
0.60% C, 4.00% Cr, 2.00% V, 6.00% W, 5.00% Mo	780–800	1120–1220	Air or oil or salt bath	550–650	50–60
0.55% C, 4.00% Cr, 2.00% V, 8.00% Mo	780–800	1090–1190	Air or oil or salt bath	550–650	45–58

14.3.8 High Speed Steels

As the name indicates, these steels are well suited for manufacturing cutting tools which can be operated at high speeds. The service conditions for such cutting tools demand high red hardness and elevated temperature wear resistance. Both these characteristics can be imparted in a steel by alloying it with strong carbide forming elements such as tungsten, molybdenum, chromium and vanadium. Alloying elements should be added in sufficient amounts so that all the carbon may combine with them to form alloy carbides. To some grades of high speed steel, cobalt is added as an alloying element in order to enhance cutting ability of the tool. Cobalt containing high speed steel tools possess superior cutting power than those of cobalt-free high speed steel tools. Materials with poor machinability can be cut successfully with such tools. The total alloy contents, in general, vary from 20 percent to 40 percent in high speed steels. Carbon varies from 0.70 percent to 1.5 percent. Low carbon grades of these steels are tougher than high carbon grades. However, high carbon grades are characterized by higher hardness and wear resistance. Typical applications include high speed cutting tools, heavy cut tools, milling cutters, reamers, deep hole drills, blanking dies, hot forming dies, lathe centres and wearing plates.

One of the most popular grades among all high speed steels is designated as 18–4–1. It contains about 0.7 percent carbon, 18 percent tungsten, 4 percent chromium, and 1 percent vanadium. The heat treatment cycle for this grade of high speed steel is illustrated in Figure 14.14. Figure 14.15 shows the microstructure of 18–4–1 high speed steel.

In view of its high cost and scarcity, tungsten has been replaced partly by molybdenum. Tungsten-molybdenum high speed steels are relatively cheaper than tungsten high speed steels, and are in common use now-a-days. Even the classical, grade of high speed steel (18–4–1) has

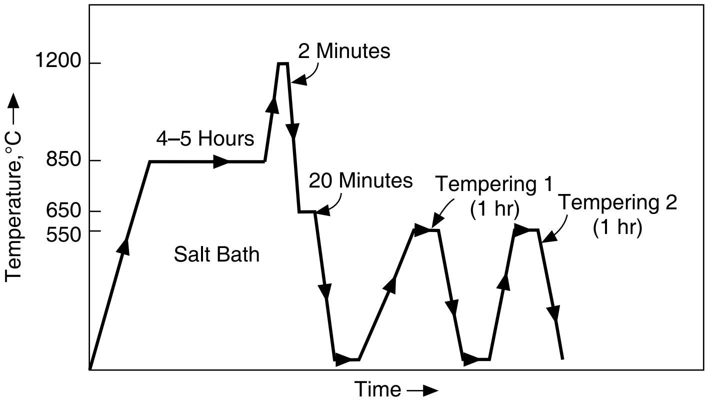


Figure 14.14 A typical heat treatment cycle for 18–4–1 tool steel (high speed steel).

been replaced by tungsten-molybdenum steels. Thus, depending on the composition, high speed steels can be classified into two classes, namely, tungsten base and molybdenum base high speed steels.

All high speed steels are heated to the maximum possible temperature for hardening treatment. However, this temperature should not result in large scale grain coarsening. A high hardening temperature ensures dissolution of all the carbon and alloying elements in the austenite. This highly alloyed austenite transforms to martensite of exactly similar composition on quenching. The martensite, thus formed, which is highly enriched in carbon and alloying elements, has high red hardness and structural stability. Generally, the hardening temperature for high speed steels varies from 1150°C to 1350°C. Heating to such a high temperature poses certain problems like oxidation and decarburization in addition to grain growth. Added to these problems is the poor thermal conductivity of high speed steel. These problems are minimized by heating high speed steels to final hardening temperature in stages. Simpler shapes and smaller-sized tools are heated in two stages. The tool is preheated to about 800°C and then quickly transferred to another furnace maintained at the final hardening temperature. Larger tools or intricate tools are generally heated in three stages. The first step consists of heating to about 400°C, followed by second heating up to about 800°C. The holding time up to 800°C is calculated on the basis of 20–30 seconds per millimetre of diameter or section thickness of the tool. The holding time

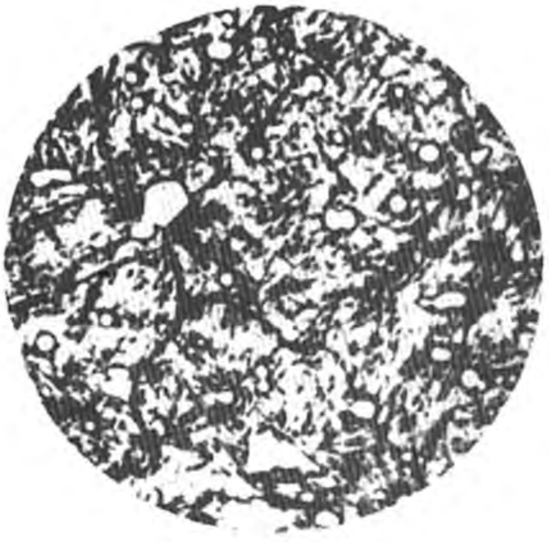


Figure 14.15 Microstructure of quenched and tempered 18–4–1 tool steel (0.7% C, 18% W, 3.9% Cr and 1% V). Tempered martensite is observed (× 1500).

at the final hardening temperature is less and rarely exceeds 5 minutes. Salt bath furnaces are preferred in order to avoid oxidation or decarburization.

High speed steels are either quenched in oil or in stream of air or in salt baths. Normally, direct oil quenching is not practised. High speed steel is first cooled to about 1000°C, and only then it is quenched in oil. This two-step oil quenching avoids formation of quench cracks. Quenched high speed steels may have some retained austenite along with martensite. Such steels are subjected to sub-zero treatment (see Section 5.9). These steels, after sub-zero treatment, are immediately tempered. Tempering is carried out at about 550°C. It has been found that multistage tempering is much more beneficial than single tempering of same duration. Table 14.24 shows compositions and heat treatment temperatures for a few high speed steels.

Table 14.24 Heat Treatment Temperatures for High Speed Steels

Composition	Hardening temperature (ºC)	Quenching medium	As-quenched hardness (on Rockwell C-scale)	Tempering temperature (ºC)
		Tungsten Base		
0.75% C, 18.00% W, 4.00% Cr, 1.00% V	1250–1300	Oil or air or salt bath	64–66	550–600
0.80% C, 18.00% W, 4.00% Cr, 2.00% V	1250–1300	Oil or air or salt bath	63–66	550–600
0.75% C, 18.00% W, 4.00% Cr, 1.00% V, 5.00% Co	1250–1300	Oil or air or salt bath	63–65	550–600
0.80% C, 18.00% W, 4.00% Cr, 2.00% V, 8.00% Co	1250–1325	Oil or air or salt bath	63–65	550–600
0.75% C, 14.00% W, 4.00% Cr, 2.00% V, 5.00% Co	1250–1300	Oil or air or salt bath	63–65	550–600
		Molybdenum Base		
0.85% C, 1.50% W, 8.50% Mo, 4.00% Cr, 1.00% V	1175–1240	Oil or air or salt bath	64–66	540–580

(*contd.*)

Table 14.24 Heat Treatment Temperatures for High Speed Steels (*contd.*)

Composition	Hardening temperature (ºC)	Quenching medium	As-quenched hardness (on Rockwell C-scale)	Tempering temperature (ºC)
0.85% C, 6.00% W, 5.00% Mo, 4.00% Cr, 2.00% V	1190–1240	Oil or air or salt bath	64–66	540–580
1.20% C, 6.00% W, 5.00% Mo, 4.00% Cr, 3.00% V	1175–1225	Oil or air or salt bath	63–66	550–600
1.30% C, 5.50% W, 4.50% Mo, 4.00% Cr, 4.00% V	1175–1225	Oil or air or salt bath	63–66	550–600

A few of the important special purpose steels, their applications, and heat treatment are now discussed.

14.3.9 Stainless Steels

Stainless steels are high alloy steels and possess excellent corrosion and oxidation resistance. Due to these characteristics, these steels find numerous applications in nuclear plants, power generating units, pulp and paper manufacturing plants, food processing units and petrochemical industries.

Stainless steels can be classified into four groups, namely, austenitic, ferritic, martensitic, and precipitation hardening stainless steels. Martensitic stainless steels are straight chromium steels containing 11.5–18 percent chromium. These are the cheapest among the family of stainless steels. Ferritic stainless steels, which are similar to martensitic steels, are straight chromium steels containing 14–27 percent chromium. These steels are superior to martensitic stainless steels in their corrosion resistance but are expensive. Austenitic stainless steels are chromium-nickel steels with a minimum total chromium and nickel contents of 25 percent. In general, minimum 8 percent nickel and 17 percent chromium contents are essential to make the steel completely austenitic in the presence of low carbon contents. These steels, though costly, possess the best possible properties. Precipitation hardening stainless steels, in addition to nickel and chromium, contain molybdenum, copper and aluminium. These steels are strengthened by precipitation of intermetallic compounds. Depending on the matrix, they can be further divided into three groups, namely, austenitic, semi-austenitic, and martensitic steels.

Austenitic stainless steels (microstructure, Figure 14.16) possess optimum combination of strength, ductility and toughness. Hence, they are the most widely used of all varieties of

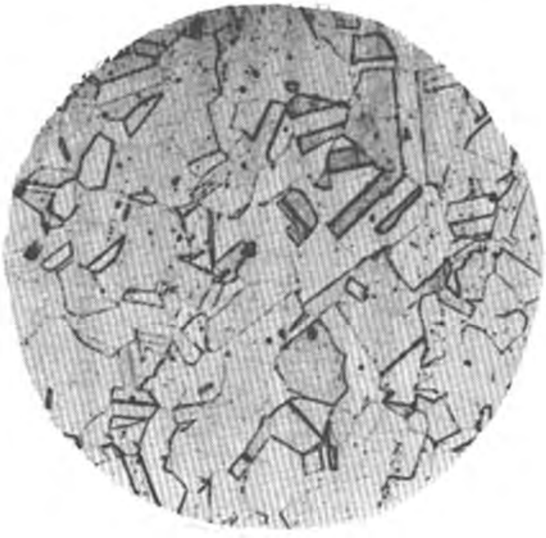


Figure 14.16 Microstructure of wrought 18–8 austenitic stainless steel. Austenitic grains with twinning boundaries are seen (× 200).

stainless steels. There is no phase transformation with temperature for this class of stainless steels. For this reason, they are not subjected to heat treatment operations in order to improve the properties. Cold working is the only strengthening mechanism for these stainless steels. Annealing is done in order to facilitate the cold working process. Stress relieving is also employed on cold-worked and welded parts. When austenitic stainless steels are heated to a temperature range 425–870°C, chromium carbide precipitation takes place at austenitic grain boundaries. Precipitation of chromium carbide will result in depletion of chromium in the matrix adjacent to grain boundaries. Hence, corrosion resistance decreases sharply. Therefore, this temperature range is avoided during heat treatment/welding of austenitic stainless steels. This is also known as sensitization. It can be solved in three ways: (i) by solution treatment, (ii) by controlling carbon content, and (iii) by stabilization. In the first case, steel is heated to sufficiently high temperature so that all carbides get dissolved. From this solution treatment temperature, steel is cooled rapidly. Control of carbon content, in this context, essentially means reduction in carbon content. The lower the carbon content of the steel, the lesser will be the carbide precipitation. Stabilization consists of addition of strong carbide former(s) so that chromium carbide may be replaced by carbides of these elements. In general, titanium or columbium or tantalum is added for this purpose. The relation between carbon content and the quantity of alloying element (for stabilization) is shown in Table 14.25. For some grades of austenitic stainless steels, specially those having high chromium and molybdenum contents, formation of sigma phase takes place in the temperature range 750–850°C. It is a hard and brittle phase which reduces impact strength drastically. Corrosion resistance is also impaired. So, heating within this temperature range should be avoided for such grades of austenitic stainless steels. In Table 14.26, the chemical compositions and heat treatment temperatures of a few austenitic stainless steels are given.

Table 14.25 Relation between Minimum Quantity of Stabilizing Element and Carbon Content

Element	Quantity as function of carbon content
Titanium	5 times
Columbium	10 times
Columbium plus tantalum	10 times

Table 14.26 Heat Treatment Temperatures for a Few Austenitic Stainless Steels

Composition*	Annealing temperature (ºC)	Stress-relieving temperature (ºC)	Remarks
0.15% C (max), 16.00–18.00% Cr, 3.50–5.50% Ni, 5.50–7.50% Mn	1010–1125		Nickel-manganese austenitic stainless steel which has high rate of work hardening.
0.08% C (max), 18.00–20.00% Cr 8.00–10.00% Ni	1010–1125	200–400	Most common grade of austenitic stainless steel used for general engineering applications.
0.25% C (max), 1.50% Si (max), 24.00–26.00% Cr, 19.00–22.00% Ni	1035–1150	200–400	Possesses high temperature strength and scale resistance.
0.08% C (max), 17.00–19.00% Cr, 9.00–12.00% Ni	950–1125	200–400	Titanium stabilized austenitic stainless steel which can be used up to 890ºC during continuous service in air.
0.10% C (max), 25.00–30.00% Cr 3.00–6.00% Ni 1.00–2.00% Mo	950–990		Has better resistance to stress-corrosion cracking. Structure is austenite plus ferrite. Can be age hardened. Hardening temperature is about 730ºC.
0.08% C (max), 0.75–1.50% Si, 17.00–20.00% Cr, 34.00–37.00 Ni	1065–1175		Good resistance to thermal shocks. Used for heat treating fixtures.

*Unless specified, Si is 1.00% (max), Mn is 2.00% (max), S is 0.045% (max), and P is 0.030% (max).

Just as in austenitic stainless steels, there is no phase change in ferritic stainless steels with temperature. Therefore, these steels cannot be subjected to heat treatment processes for strengthening. The composition of these steels is so adjusted as to give ferritic structure at room temperature. High chromium ferritic stainless steels remain ferritic on cooling from high temperatures. However, in the case of relatively low chromium ferritic stainless steels, there is always the possibility of formation of some martensite on cooling from high temperatures. This martensite, though small in amount, affects the mechanical properties, especially ductility and toughness. This is so because martensite is located at the grain boundaries. Hence, addition of strong ferrite formers to these grades of ferritic stainless steels is generally recommended. Properties of ferritic stainless steels are adversely affected by heating in the temperature range 400–450°C. This embrittlement seems to be due to the precipitation of sub-microscopic particles of iron-chromium compound at grain boundaries. It can be checked by rapid cooling above 600°C. The presence of sigma phase and other intermetallic phases decreases toughness and corrosion resistance. Almost all ferritic stainless steels with more than 14 percent chromium suffer from this embrittlement from intermetallic phases. These phases appear on heating to a temperature range 600–1000ºC. These steels should not be selected for service conditions that demand exposure within this temperature range. Heating ferritic stainless steels above 1000°C results in the dissolution of these phases. The compositions and annealing temperatures of important ferritic stainless steels are given in Table 14.27.

Table 14.27 Heat Treatment Temperatures for Ferritic Stainless Steels

Composition*	Annealing temperature (ºC)	Remarks
0.12% C (max), 14.00–16.00% Cr	780–850	Weldable grade; used for nitric acid and nitrogen fixation equipment.
0.12% C (max), 16.00–18.00% Cr	760–820	Deep drawings steel; used for making nitric acid tanks, conbustion chambers and recuperators.
0.12% C (max), 16.00–18.00% Cr, 24.00–26.00% Cr,	785–845	Modified grade with more corrosion resistance than the previous one.
0.12% C (max), 16.00–18.00% Cr, 0.75–1.25% Mo, Nb + Ta = 0.70% (max)	785–845	General purpose ferritic stainless steel for corrosion and heat resisting applications.
0.20% C (max), 18.00–23.00% Cr	700–760	Capable of resisting high temperatures during service without scaling; used for furnace parts.

*For all these grade, Si is 1.00% (max), Mn is 1.00% (max), S is 0.04% (max), and P is 0.03% (max).

In contrast to austenitic and ferritic stainless steels, martensitic stainless steels can be heat treated to improve mechanical properties. Carbon content of martensitic stainless steels is one of the important parameters which controls the properties of heat treated steels. Martensitic stainless steel can be hardened by oil quenching from austenitizing temperature which depends on the chemical composition of steel. For most of the standard grades of martensitic stainless steels, austenitizing temperature lies between 925°C and 1075°C. Due to their high hardenability, these steels can be hardened by air cooling. However, some decrease in ductility and corrosion resistance has been observed in air hardened steels. It is due to the precipitation of carbides at grain boundaries on slow cooling within a temperature range 870–540°C. Therefore, air cooling is performed only for those components whose sizes or shapes are such that the problem of distortion is severe, on oil quenching. Martensitic stainless steels with high carbon contents or nickel contents pose an additional problem, namely, the presence of retained austenite in as-quenched structure. Such grades of martensitic stainless steels are subjected to sub-zero treatment in order to transform retained austenite to martensite. Hardened martensitic stainless steels arc subjected to tempering treatment. Depending on the final properties required, low or medium temperature tempering is carried out. Low temperature tempering results only in stress relieving and does not change the mechanical properties. It is carried out by heating to the temperature range 150–370°C. Medium temperature tempering results in change in mechanical properties. Occasionally, high temperature (just below A_1) tempering is carried out. It imparts maximum softening.

Precipitation hardening stainless steels have either austenitic or martensitic matrix. Steels with martensitic matrix are more common in use than those with austenitic matrix. The austenitic precipitation hardening stainless steels are non-magnetic in nature and have a minimum nickel content of 10 percent. It ensures formation of austenitic matrix which is strengthened by addition of molybdenum, copper, niobium and titanium. Heat treatment of these grades consists of solution treatment so as to get a single phase structure. Solution treatment is carried out by heating the steel to about 1200°C. It is followed by quenching which results in the retention of high temperature phase at room temperature. Quenched steel is then aged at about 750°C. In the aged condition, the structure consists of austenite and intermetallic compounds. Due to high ageing temperature, these steels can be used successfully up to about 650°C.

Table 14.28 Heat Treatment Temperatures for Martensitic Stainless Steels

Composition*	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)	Remarks
0.15% C (max), 11.50–13.50% Cr	925–1025	Air or oil	550–600 or 200–350	General engineering purpose heat treatable steel
0.15% C (min), 12.00–14.00% Cr	975–1075	Air or oil	200–350	High carbon grade of steel mentioned above and used for hand tools and wear-resisting parts.
0.20% C (max), 15.00–17.00% Cr, 1.25–2.50% Ni,	975–1075	Air or oil	550–650 or 225–375	Hardenable high strength steel
0.60–0.75% C, 16.00–18.00% Cr, 0.75% Mo (max)	1010–1075	Air or oil	150–375	Improved grade of above steel

*In these grade, Si, Mn, S, and P are 1.00, 1.00, 0.04, and 0.03 percent (maximum), respectively.

Martensitic grades of precipitation hardening strainless steels are alloyed with copper, molybdenum, aluminium, titanium, niobium and nitrogen. The heat treatment sequence is similar to that described for austenitic grades, i.e. solution treating, quenching and, finally ageing. Martensitic grades are generally aged at relatively lower temperatures (about 450°C) than those adopted for austenitic grades. High nickel steels, known as semi-austenitic precipitation hardening steels, have good formability at room temperature. Tables 14.28 and 14.29 show the chemical compositions and heat treatment temperatures of some martensitic and precipitation hardening stainless steel, respectively.

Table 14.29 Heat Treatment Temperatures for Precipitation Hardenable Stainless Steels

Composition	Hardening temperature (ºC); quenching medium	Post-hardening treatment	Ageing temperature (ºC); time
0.07% C (max), 14.00–15.50% Cr, 3.50–5.50% Ni, 2.50–4.50% Cu 0.15–0.45% Cb + Ta	1025–1050; water		480–550; 4 hours
0.07% C (max), 15.50–17.50% Cr, 3.00–5.00% Ni, 3.00–5.00% Cu 0.15–0.45% Cb + Ta	1025–1050; oil, air	Cool to 30ºC prior to ageing	475–625; 4 hours
0.09% C (max), 16.00–18.00% Cr, 6.50–7.75% Ni, 0.75–1.50% Al	940–975; water	Sub-zero treatment at –70ºC	500–600; 1 hour

14.3.10 Maraging Steels

These steels are essentially high alloy, high strength steels possessing good forming characteristics, weldability, high yield strength to tensile strength ratio and fracture toughness. The chemical composition of a maraging steel is so adjusted that austenite to martensite transformation proceeds even on air cooling. This results in practically insignificant distortion of the steel part. Also, in maraging steel, there is no danger of decarburization on heating.

Maraging steels are basically alloys of iron and nickel. In these steels, minimum 18–20 percent nickel is needed to impart air hardening characteristics. In addition to nickel, cobalt, titanium, beryllium, aluminium, niobium, tungsten and molybdenum are also present in these steels. In maraging steels, carbon is present as an impurity and is generally kept below 0.03 percent. The martensite formed in maraging steels is almost carbon free. The iron-nickel martensite is soft by nature. This martensite has low strength and high ductility. The hardened structure is aged at elevated temperatures. Such an ageing treatment results in the precipitation of intermetallic compounds in a matrix of martensite. Such a structure is responsible for ultra-high strength of maraging steels. Compositions and heat treatment temperatures of important maraging steels are contained in Table 14.30.

Table 14.30 Heat Treatment Temperatures for Maraging Steels

Composition	Solutionizing temperature (ºC); time	Ageing temperature (ºC); time
18.00% Ni, 3.00% Mo, 8.50% Co, 0.20% Ti, 0.10% Al	820; 1 hour	480; 3 hours
18.00% Ni, 5.00% Mo, 7.75% Co, 0.40% Ti, 0.10% Al	820; 1 hour	480; 3 hours
18.00% Ni, 5.00% Mo, 9.00% Co, 0.65% Ti, 0.10% Al	820; 1 hour	480; 3 hours
18.00% Ni, 4.00% Mo, 12.50% Co, 1.50% Ti, 0.10% Al	820; 1 hour	480; 12 hours

14.3.11 Spring Steels

Steels possessing high elastic limit, toughness and fatigue strength are suitable for manufacturing springs. Depending on the service conditions, a number of steels can be used for making springs. High carbon steels are the cheapest among all the grades of spring steels. These steels are used in either hardened and tempered condition or in patented and cold-drawn conditions. Varieties of these steels and their heat treatment have already been discussed in Section 14.1.3.

High quality springs are made from chromium-vanadium steels. Heat treated chromium-vanadium steels develop high elastic limit, toughness, resistance to fatigue and machinability as compared to high carbon steels. These steels are also used in oil hardened and tempered condition. Typical applications include automobile and aircraft engine valve springs, and high quality laminated and coil springs for motor cars. A typical steel belonging to this class contains 0.50% C, 10% Cr, 0.20% V, 0.40% Si and 0.70% Mn. It is oil hardened from 860°C, followed by tempering at about 500°C.

For medium duty applications, leaf and helical springs are generally made from silicon-chromium steels. A representative steel of this class has 0.60% C, 0.70% Si, 0.60% Mn and 0.80% Cr. The heat treatment consists of oil hardening from 830°C, followed by tempering in the temperature range 550–600°C.

Most commonly employed steels for manufacturing springs are silicon-manganese steels (see Section 14.2.2).

The use of chromium-manganese steels for making springs is a relatively recent introduction. These steels are being used increasingly for those applications for which silicon-manganese steels were being used earlier. In other words, these steels provide an alternative to silicon-manganese steels. A steel belonging to this group contains 0.50% C, 0.40% Si (max), 0.80% Mn and 1.0% Cr. Heat treatment consists of oil hardening from 820°C. Tempering is performed at about 400–450°C. Properties of chromium-manganese steels can be improved by the addition of 0.10–0.20 percent vanadium or 0.15–0.25 percent molybdenum, or both.

14.3.12 Valve Steels

High chromium-silicon (Cr + Si ≥ 10%) steels are popularly known as valve steels and are extensively used for manufacturing automobile, aero and marine engine valves. Besides, these steels are also used for making furnace parts, nuts and bolts for high temperature service, tube bending mandrels, tube piercing points, superheater supports and gas turbine parts. These applications imply that chromium-silicon steels can be successfully used as heat resisting steels. In fact, these steels possess very good resistance to heat, corrosion and scale formation. Parts made from these steels can be successfully used up to about 600–650°C. Properties of these steels can be further improved by addition to nickel and tungsten. A chromium-silicon-nickel valve steel has better heat, corrosion, and scale resistance than chromium-silicon steel, and is well suited for making heavy duty outlet valves. It is generally used in hardened and tempered condition. Table 14.31 summarizes the compositions and heat treatment temperatures of a few martensitic valve steels.

Table 14.31 Heat Treatment Temperatures for Martensitic Valve Steels

Composition	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC); cooling medium
0.40–0.50% C, 3.00–3.75% Si, 7.50–9.50% Cr, 0.50% Ni (max), 0.30–0.60% Mn	1000–1050	Air or oil	550–650; air or oil
0.35–0.45% C, 2.00–3.00% Si, 8.00–10.00% Cr, 0.60% Ni (max)	1000–1050	Air or oil	720–800; air or oil
0.35–0.45% C, 2.00–2.75% Si, 9.00–10.50% Cr, 0.50% Ni (max), 0.70–0.90% Mo	1000–1050	Air or oil	760–800; air or oil
0.75–0.85% C, 1.75–2.25% Si, 19.00–20.50% Cr, 0.20–0.60% Mn, 1.00–1.70% Ni	1020–1080	Air or oil	700–750; air or oil

In addition to the martensitic grades of chromium-silicon steels, complexly alloyed austenitic grades of chromium-nickel-silicon-tungsten steels are also used for manufacturing high duty exhaust valves for aircrafts and automobile engines. These austenitic grades cannot be hardened by heat treatment and are used in softened condition. The composition and heat treatment temperatures of three important types of austenitic valve steels are given in Table 14.32.

Table 14.32 Heat Treatment Temperatures for Austenitic Valve Steels

Composition	Softening temperature (ºC); cooling medium from softening temperature
0.35–0.50% C, 1.00–2.50% Si, 1.50% Mn (max), 12.00–16.00% Cr, 10.00% Ni (min) 2.00–4.00% W	950–1020 air, oil or water
0.35–0.45% C, 1.00–2.00% Si, 0.50–0.80% Mn, 13.00–15.00% Cr, 13.00–15.00% Ni, 2.00–3.00% W, 0.40–0.60% Mo, 0.15–0.25% Nb	950–1020; air, oil or water
0.20–0.45% C, 1.00–2.50% Si, 1.00% Mn (max), 17.00% Cr (min), 6.00–12.00% Ni, 2.00–4.00 W	950–1100; rapid cooling (in oil or water)

14.3.13 Heat Resisting Steels

Heat resisting steels are also known as high temperature steels. Since parts made from these steels are exposed to elevated temperature service conditions, such steels should possess high temperature strength and good resistance to oxidation and/or scaling. In addition to these characteristics, dimensional as well as structural stability is of prime importance. Applications of heat resisting steels include components of jet engines, rockets, gas turbines and boilers. A wide range of steels, from plain carbon steels to high alloy steels, can be used as heat resisting steels, depending on the service conditions to which they are exposed.

Plain carbon steels can be successfully subjected to loading up to about 300°C as creep is not significant below this temperature. Low alloy steels are used at higher temperatures. A low alloy steel with about 0.50 percent molybdenum is quite popular due to its low cost and better high temperature properties. The properties of this steel can be improved by addition of chromium or vanadium or both. These elements (Mo, Cr and V) raise the recrystallization temperature of ferrite and thus improve heat resistance. These steels are used for manufacturing steam pipe lines, superheaters, fittings, steam drum, fasteners and for other applications in the temperature range 500–600ºC. Depending on the composition (mainly based on chromium contents), these low alloy steels can be grouped in two classes, pearlitic and martensitic steels.

Table 14.33 Heat Treatment Temperatures for Low Alloy Heat Resisting Steels

Composition	Normalizing temperature (ºC)	Hardening temperature (ºC)	Quenching medium	Tempering temperature (ºC)
		Pearlitic Grades		
0.10–0.15% C, 0.40–0.50% Mo	920–960			680–720
0.10–0.20% C, 0.70–1.00% Cr, 0.40–0.50% Mo	920–950	920–950	Oil	700–740
0.10–0.20% C, 0.30–0.50% Cr, 0.50–0.60% Mo, 0.25–0.35% V	940–980	940–980	Oil or air	650–750
0.10–0.20% C, 0.30–0.50% Cr, 0.70–0.90% Mo, 0.30–0.40% V	950–980	950–980	Oil	630–680
		Martensitic Grades		
0.15% C (max), 5.00–5.50% Cr, 0.45–0.65% Mo		950–980	Oil	650–730
0.15% C (max), 2.00–2.50% Cr, 0.90–1.10% Mo, 0.20–0.35% V		930–960	Air	730–760
0.10–0.20% C, 2.50–3.50% Cr, 0.45–0.65% Mo, 0.25–0.35% V		910–940	Oil	550–750
0.15% C (max), 4.00–6.00% Cr, 0.45–0.65% Mo, 0.40–0.60% V		940–980	Oil	650–700

Pearlitic steels'have low chromium contents and are used in either normalized and tempered condition or in oil quenched and tempered condition. Pearlitic grades of low alloy steels cannot be employed at temperatures above 500–580°C. Martensitic grades of low alloy (Cr–Mo–V) steels are used in hardened and tempered condition. Tempering temperature should be more than the service temperature. Due to higher chromium contents, these steels (martensitic grades) have better heat resistance than pearlitic steels. Table 14.33 provides the compositions and heat treatment temperatures for both grades of low alloy steels.

The heat resistance of steel can be increased by raising the chromium content. This is why both martensitic and ferritic stainless steels are used frequently as heat resisting steels. Martensitic (chromium) steels alloyed with tungsten, vanadium, molybdenum, niobium and titanium are preferred to straight chromium steels because of the better properties that can be achieved in the former. These elements raise the recrystallization temperature of the steel and form strong carbides. For these reasons, these complexly alloyed steels have better heat resistance. Heat resistance can be further improved by the addition of boron, zirconium, cerium and nitrogen. Optimum heat resistance is offered by this class (martensitic) of high chromium steels in hardened and tempered condition (refer to Table 14.34.)

Table 14.34 Heat Treatment Temperatures for High Alloy Martensitic Heat Resisting Steels

Composition	Hardening temperature (°C)	Quenching medium	Tempering temperature (°C)
0.10–0.20% C, 10.00–12.00% Cr, 0.60–0.80% Mo, 0.25–0.40% V	1030–1060	Oil	650–700
0.10–0.20% C, 11.00–13.00% Cr, 0.50–0.70% Mo, 0.15–0.30% V, 0.70–1.10% Nb	1000–1020	Oil	650–700
0.10–0.20% C, 11.00–13.00% Cr, 0.60–0.90% Mo, 1.70–2.20% Nb, 0.15–0.35% V	1050–1100	Oil	650–700

Austenitic heat resistant chromium-nickel steels differ from austenitic stainless steels in the sense that heat resisting steels have higher nickel and chromium contents and are alloyed with tungsten, vanadium, niobium and boron. Such complex steels possess enhanced heat resistance. Austenitic heat resisting steels are regarded as possessing the best heat resistance among all steels and can be used for making components operating at temperatures up to 750°C. Austenitic heat resisting steels are strengthened by precipitation of either carbides or intermetallic compounds. Table 14.35 summarizes compositions and heat treatment temperatures of a few austenitic heat resisting steels.

Chromium-silicon steels also constitute a popular class of heat resisting steels. These steels are also known as valve steels. Heat treatment of these steels has already been described in Section 14.3.12.

Table 14.35 Heat Treatment Temperatures for Austenitic Heat Resisting Steels

Composition	Heat treatment schedule
0.40–0.50% C, 13.00–15.00% Cr, 13.00–15.00% Ni, 2.00–2.75% W, 0.25–0.40% Mo	Annealed at 820°C; microstructure consists of austenite and alloy carbides
0.35–0.45% C, 14.00–16.00% Cr, 6.00–8.00% Ni, 6.00–7.00% Mn, 1.50–2.00% V, 0.65–1.00% Mo	Water or oil quenched from 1150–1200ºC, followed by ageing at 800ºC for 8–10 hours. Microstructure consists of austenite and dispersed alloy carbides.
0.10% C (max), 10.00–12.50% Cr, 18.00–21.00% N, 2.25–2.75% Ti, 0.02% B (max), 0.50% Al (max)	Water or oil quenched from 1060–1080ºC, followed by ageing at 700ºC for 3–8 hours.
0.10% C (max), 10.00–12.50% Cr, 21.00–25.00% Ni, 2.50–3.00% Ti, 1.00–1.50% Mo, 0.02% B (max), 0.80% Al (max)	Oil or air quenched from 1100–1150ºC, followed by ageing at 780ºC for 16 hours, and again ageing at 625ºC for 10–16 hours
0.08% C (max), 12.00–16.00% Cr, 33.00–37.00% Ni, 2.00–4.00% W, 2.50–3.00% Ti, 0.75–2.00% Al, 0.02% B (max)	Normalized at 1150–1180ºC, followed by hardening at 1050ºC. Hardened steel is aged at 830ºC for 8 hours.

QUESTIONS

14.1 Discuss critically the following:

(a) Limitations of plain carbon steels
(b) Classification of alloying elements in steels
(c) Applications of low carbon steels
(d) Structural steels.

14.2 Give microstructure, properties and applications of the following steels:

(a) Fe-0.2C-4Si steel
(b) Fe-lC-1.5Cr steel

(c) Fe-0.1C-1Ni-1Cr-0.1 Mo steel
(d) Fe-0.3C-12Cr steel
(e) Fe-0.08C-18Cr-10Ni-3 Mo steel.

14.3 Discuss the function of

(a) nickel in maraging steel and austenitic stainless steel
(b) chromium in stainless steel and high speed steel
(c) molybdenum in high speed steel and austenitic stainless steel.
(d) manganese in Hadfield steel and austenitic stainless steel
(e) silicon in transformer steel and spring steel.

14.4 Suggest a suitable material of construction, its composition, heat treatment if any, and desired microstructure for the following:

(a) Chiesels and shear blades
(b) Jaw crusher plates
(c) Laminated springs for Railways
(d) Core of a transformer
(e) Container for liquid gases
(f) Food handling equipment
(g) Surgical instruments.

14.5 Compare Hadfield steel and austenitic stainless steel on following lines:

(a) Chemical composition
(b) Heat treatment
(c) Work hardening characteristics
(d) Corrosion resistance
(e) Formability.

14.6 Review applications of tool and die steels as materials of construction.

14.7 Describe "Low Alloy High Strength" steels. Are they different from "High strength low alloy" steels? Explain.

14.8 Discuss "Maraging steels" on following lines:

(a) Chemical composition(s) of commercial importance
(b) Role of alloying element(s)
(c) Heat treatment, if any
(d) Properties and applications.

14.9 Write an essay on the microstructure, mechanical properties and applications of ferritic stainless steels.

14.10 Give representative chemical composition of high speed steel. Why it is named so? Describe typical heat treatment cycle(s) for conventional high speed steel.

15

Cast Irons and Their Heat Treatment

INTRODUCTION

Cast iron is an alloy of iron and carbon with carbon content exceeding 2.03 percent. In the as-cast condition, such alloys cannot be worked at any temperature. Commercial grades of cast irons differ widely in nature and composition. Silicon is an important ingredient in cast iron. Besides silicon, cast irons contain manganese, phosphorus and sulphur.

According to their use, cast irons may be categorized into two main groups, namely, general and special purpose grades. The general purpose grade includes grey cast iron, white cast iron, malleable cast iron and nodular cast iron. These are used for most engineering applications. The special purpose cast iron, called alloy cast iron, is used for extreme heat, corrosion and abrasion conditions.

15.1 GREY CAST IRON

Grey cast iron is obtained by cooling the molten metal slowly during solidification. A large portion of its carbon is present in free state as graphite flakes. The typical grey cast iron contains 2.5–3.5% C, 1.4–2.8% Si, 0.5–0.8% Mn, 0.1–0.9% P, and 0.06–0.12% S. Fractured surface of grey cast iron appears grey because of the presence of graphite. Hence, the alloy is termed grey cast iron.

Carbon, silicon and phosphorus affect the mechanical properties of cast iron significantly. Their combined effect is given by the carbon equivalent value (CEV)

$$\text{CEV} = \text{total carbon}\,\% + \frac{\text{phosphorus}\,\% + \text{silicon}\,\%}{3}$$

Tensile strength of grey cast iron varies from 100 MPa to 340 MPa. In grey cast iron, graphite flakes may be present in ferritic matrix or pearlitic matrix, as shown in Figure 15.1.

The heat treatment given to grey cast iron may be classified into:

(i) stress relieving,
(ii) annealing,
(iii) normalizing, and
(iv) hardening and tempering.

Figure 15.1 Microstructure of grey cast iron (×500).

Stress Relieving

The purpose of stress relieving in grey cast iron is to relieve residual stresses introduced during solidification, due to different cooling rates prevalent at various sections of castings. Residual stresses adversely affect strength and cause distortion and may even result in cracking in some cases. The temperature of stress relieving is kept much below Ac_1 temperature. For maximum stress relief without changing the microstructure, a temperature range 538–565°C is recommended. In this temperature range, about 80 percent of the residual stresses are removed with holding time of about one hour. When held at 590°C, more than 85 percent of the stresses can be removed.

Annealing

The purpose of annealing is to soften the grey cast iron and to improve its machinability by minimizing or eliminating massive eutectic carbides. This treatment reduces the tensile strength of grey cast iron. For example, grade 40 grey cast iron has tensile strength 280 MPa. After annealing, tensile strength comes down to about 210 MPa in this grade of cast iron. This is equal to strength of grade 30 grey cast iron. The extent to which the mechanical properties are reduced depends on annealing temperature, holding time, and the alloying elements present in the iron.

Three types of annealing treatment are given to grey cast iron: ferritizing annealing, full annealing, and graphitizing annealing, which we now discuss.

Ferritizing Annealing To improve machinability in unalloyed or low alloy grey cast iron of normal composition, ferritizing annealing treatment is carried out. In this treatment, pearlitic carbide transforms to ferritic matrix and graphite. Ferritic matrix is soft. Above 590°C, the rate of decomposition of iron carbide to ferrite and graphite increases significantly, and at 760°C the rate of decomposition is maximum. Therefore, for most grey cast irons, the ferritizing annealing temperature is kept between 700°C and 760°C, and the recommended holding time is 1 hour per 25 mm of section. In fact, holding time also depends on chemical composition. It is not advisable to carry out ferritizing annealing below 700°C as the corresponding holding time will be very long. Normally, after ferritizing annealing, the annealed specimens are cooled at a rate varying from 100°C/hour to 300°C/hour.

Full Annealing If alloy content is high in grey cast iron, then it is difficult to decompose iron carbide into ferrite and graphite at 760°C. Therefore, under such conditions, full annealing treatment is adopted. For this treatment, casting is heated to a suitable temperature between 790°C and 900°C and held for about 1 hour. Then it is cooled slowly between 790°C and 680°C.

Graphitizing Annealing The purpose of graphitizing annealing is to convert massive iron carbide into pearlite and graphite. The treatment is carried out at 900-955°C. At this temperature, massive carbide dissolves in austenite which later decomposes to pearlite and graphite on cooling. Above 925°C, Fe_3P may also melt. Holding time varies from 15 minutes to several hours, depending on composition. It is advisable to keep holding time as short as possible while using furnaces without protective atmospheres. Otherwise, at such high temperatures, the grey iron may form scales in the presence of moisture. From annealing temperature to about 535°C, casting is air cooled to get pearlitic structure and, from 535°C to about 285°C, it is cooled at a rate about 110°C/hour.

When good machinability is required, grey iron is furnace cooled from 925°C to 535°C, and subsequently it is cooled to 285°C at the same rate as recommended for the first cycle.

Normalizing

The purpose of normalizing treatment for grey cast iron is to improve mechanical properties such as hardness and tensile strength. This treatment also helps restore as-cast properties which have been modified by other heating processes such as graphitizing or pre-heat and post-heat treatment of welded joints. Normalizing temperature is kept above transformation range, i.e. 885–925°C. Holding time recommended for grey cast iron at normalizing temperature is about 1 hour per 25 mm of maximum section thickness. Heating temperature significantly affects the mechanical properties, e.g. hardness and tensile strength as also the microstructure. Alloying elements such as chromium, molybdenum and nickel enhance the strengthening due to normalizing.

Table 15.1 shows the effect of holding temperatures on hardness and tensile strength of unalloyed, air cooled grey cast iron. The cast iron chosen contains 3.15% C, 2.59% Si, 0.09% P, 0.14% S, 0.88% Mn, 0.01% Cr and 0.10% Ni. It has hardness of 207 BHN and tensile strength of 265 MPa in as-cast condition. The alloyed grey cast iron contains 3.33% C, 2.27% Si, 0.076% P, 0.12% S, 0.72% Mn, 0.44% Cr, 0.36% Ni, and 0.28% Mo. It has hardness of 212 BHN and tensile strength of 265 MPa in as-cast condition.

Hardening and Tempering

The purpose of hardening and tempering in grey iron is to improve its strength and wear resistance. After this treatment, the wear resistance of pearlitic grey cast iron increases four

Table 15.1 Effect of Holding Temperatures on Typical Properties of Air Cooled Grey Cast Irons

Holding temperature (ºC)	Unalloyed grey cast iron		Alloyed grey cast iron	
	Hardness (BHN)	Tensile strength (MPa)	Hardness (BHN)	Tensile strength (MPa)
540	202	210	212	276
595	190	255	210	276
650	138	195	202	266
705	125	180	187	266
760	131	190	170	235
815	150	205	212	295
870	150	205	217	305
925	150	205	223	290
980	150	210	255	340

to five times. Ordinarily, grey iron is furnace or salt-bath hardened from a temperature of about 860–870°C. The transformation range of the particular grey iron decides the temperature to which the casting is to be heated. The transformation range can extend by more than 55°C above the Ac_1 temperature. Approximate Ac_1 temperature of unalloyed grey iron is related to silicon and manganese content by the relation

$$Ac_1\ (^\circ\text{C}) = 730 + 28.0\ (\%\ \text{Si}) - 25.0\ (\%\ \text{Mn})$$

The quenching media used may be water, oil or salt bath. But oil is the popular quenching medium for grey iron. For furnace hardened grey cast iron, water is not preferred as quenching medium because the heat dissipation is so fast that it may cause distortion and cracking in castings. Water soluble polymer quenchants can provide the convenience of water quenching along with slower cooling rates which can reduce the effect of thermal shocks. High alloy grey cast irons can be air quenched. The quenched grey iron may be tempered by reheating to a suitable temperature in the range 150–650°C. Tempering treatment increases the toughness and relieves internal stresses which may be developed during quenching. Due to tempering, hardness decreases.

To achieve maximum toughness in grey iron, tempering temperature of about 370°C is recommended. After tempering at this temperature, the matrix retains a hardness level of 472 BHN. Increase in wear resistance in grey cast iron is achieved by producing a structure consisting of graphite embedded in a martensitic matrix through heat treatment. Soft graphite acts as a lubricant. For increasing strength in grey cast iron, it is not necessary to take recourse to heat treatment because this goal can be achieved by other methods with less cost, such as reducing the silicon and carbon content or adding alloying elements.

Flame or induction hardening of grey iron is not so common as furnace hardening because, for adopting the first two methods, a relatively large content of combined carbon is required since very little time is available for carbon to dissolve in austenite. Water is often used as a quenchant with flame or induction hardening where only the outer case is hardened.

The higher the austenitizing temperature of grey cast iron, the greater will be the dissolution of carbon in austenite and the higher will be the hardness of grey iron after quenching.

In practice, a temperature which is about 90°C higher than the calculated transformation temperature is recommended for austenitizing treatment. This ensures complete austenitization. Beyond this limit, there is a danger of distortion and cracking after quenching of grey iron. Besides this, in alloy grey iron there are chances that retained austenite may be present. The presence of retained austenite is undesirable and is regarded as a defect.

Slow heating through lower temperature range is advisable to avoid cracking. Above 600–650°C, rapid heating according to requirement can be carried out. Up to 650°C, casting is heated in one furnace and then it is transferred to another furnace for austenitizing. This saves 40 minutes of heat treatment time per 25 mm section of casting.

15.2 WHITE CAST IRON

In white cast iron, carbon is present in combined form, i.e. in the form of cementite (Fe_3C). Fractured surface of broken piece of this type of casting has white appearance. Cementite is present as a continuous interdendritic network. This makes the cast iron hard and wear resistant but brittle. As machinability is very poor, it has limited applications. White cast iron has several applications because of its wear resistance as balls for grinding mills, liners for cement mixers, and extrusion nozzles. Typical white cast iron contains 2.5–3.5% C, 0.4–1.5% Si, 0.4–0.6% Mn, 0.1–0.4% P, 0.15% S, and balance Fe.

Large tonnage of white cast iron is used for manufacturing malleable cast iron by means of a graphitizing annealing treatment called malleabilization.

Cast iron castings in which outer Surface is of white iron structure and inner core is graphitic in nature are said to be chilled. Between these two zones, a zone which has both white iron structure and graphite is present. This transition zone is called mottled cast iron. Chilled surface in cast iron can be obtained by rapid cooling of the surface. This is achieved by pouring the molten cast iron in metallic moulds. During solidification, high internal stresses may be developed due to varying cooling rates across the cross-section. These stresses can be relieved by heating white cast iron to about 500–550°C.

The mechanical properties of white cast iron are as follows: tensile strength, 140 MPa to 490 MPa; compressive strength, 1400 MPa to 1750 MPa; and hardness, 375 to 600 BHN.

15.3 MALLEABLE CAST IRON

The composition of malleable cast iron is adjusted, particularly in respect of carbon and silicon content, so as to produce white cast iron completely free from primary graphite. In fact, white cast iron is the starting material from which malleable cast iron is produced by annealing. The chemical composition of white cast iron, which is annealed to get malleable cast iron, is of the following range of percentage composition:

Carbon	2.2–2.8
Silicon	0.8–1.5
Manganese	0.25–0.6
Phosphorus	< 0.18
Sulphur	0.05

There are basically two kinds of malleable cast iron. They are commercially named as white heart and black heart malleable cast iron. The fractured pieces of these two types of malleable cast irons are white and black, respectively. The martix of both types is ferritic. Therefore, they are also called ferritic or standard malleable iron.

Pearlitic malleable irons or alloyed malleable irons are modifications of these two basic types. They have been developed relatively recently, and are used in automotive industry. One essential requirement which is common to all malleable irons is that they should be totally white and free from all primary or free graphite. If any free graphite is present in the starting material, it may give rise to mottled structure which adversely affects the mechanical properties of malleable cast iron after heat treatment. White cast iron consists of cementite (Fe_3C) and pearlite. By the process of controlled annealing treatment, the metastable phase (Fe_3C) decomposes into free carbon and iron as represented by the reaction

$$Fe_3C \rightleftharpoons 3Fe + C$$

The structure so formed consists of aggregates of temper carbon in a matrix of ferrite. This makes the malleable iron ductile, shock resistant and machinable.

15.3.1 Malleabilization of White Cast Iron

White cast iron is used to produce malleable cast iron by the controlled annealing heat treatment (often called malleabilization). The structure of white cast iron consists of massive carbide and pearlite. Heat treatment of white cast iron involves three steps. The first step is nucleation of graphite. This occurs during heating to high holding temperature and in the very beginning during the holding period. Nucleation of graphite is affected by heating rate, section size, chemical composition, pre-heat treatment and the presence of trace elements.

The second step consists of holding the casting at 900–950°C. This is also called the first stage of graphitization (FSG). During heating above transformation temperature, pearlite transforms to austenite. The austenite so formed dissolves some more cementite as the temperature reaches 900–950°C. Graphitization starts at this temperature. Due to graphitization, austenite is depleted in carbon and, therefore, more carbon is dissolved in austenite from neighbouring cementite. This leads to deposition of additional carbon on the existing graphite nuclei. The graphite nuclei grow to almost the same extent in all directions. As a result, graphite assumes the shape of irregular nodules or spheroids. This carbon is known as temper carbon which forms at the interface between primary carbide and saturated austenite at 900–950°C. This is the optimum annealing temperature which gives good results with minimum distortion. High graphitization temperature during first stage results in excessive distortion of castings during annealing. Therefore, high graphitization temperature is not desirable during the first stage. The aim of FSG is to break down all cementite. The time required for FSG is a function of a number of nuclei, solution of carbide and diffusivity of carbon atoms at that temperature. Holding time for FSG varies from 20 hours to 70 hours, as graphitization process is very slow. The microstructure after completion of FSG reveals temper carbon nodules and saturated austenite matrix.

After FSG, castings are rapidly cooled to 740°C to 730°C before entering the second stage of graphitization (SSG), or the second stage of annealing. The rapid cooling cycle requires 2–6 hours. In SSG, the cooling rate must be very slow (1.5–12°C/hour) because the cooling rate should be such that sufficient time is available for transformation of austenite to ferrite and graphite during eutectoid reaction. The graphite so formed gets deposited on the existing temper carbon particles. Higher cooling rate is employed when sufficient number of temper carbon particles are present and when silicon percentage is high in the iron. Once graphitization is completed, no further changes occur during cooling to room temperature. The macrostructure at room temperature consists of temper carbon nodules in ferrite matrix (Figure 15.2).

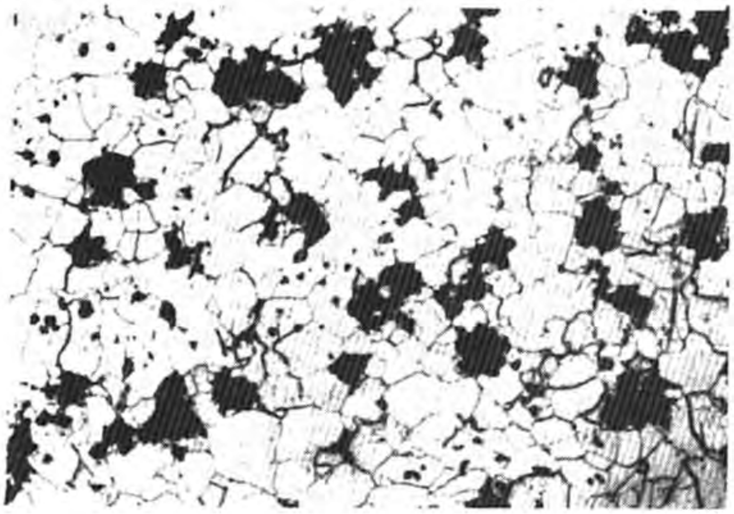


Figure 15.2 Microstructure of black heart malleable cast iron (×100).

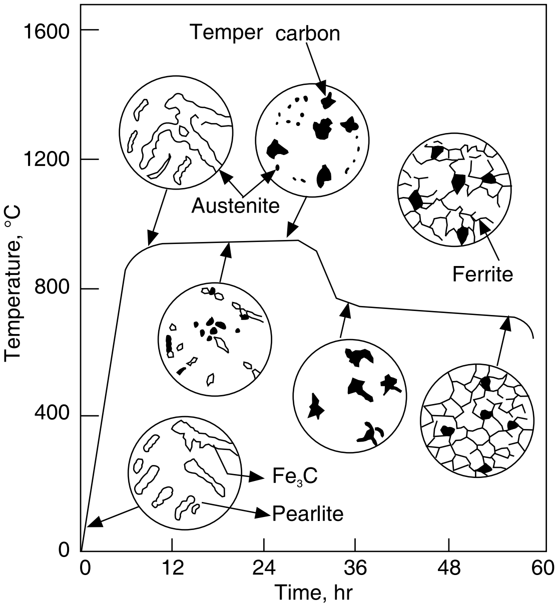


Figure 15.3 Effect of malleabilizing cycle on microstructure showing ferrite matrix.

Various changes in microstructure that take place during controlled annealing (malleabilization) cycle are shown in Figure 15.3. This process is known as *black heart process*. In this process, the charge is packed in heat resistant boxes with sand which serves as a filler and excludes air. Thus, a reducing atmosphere is created during annealing.

For malleabilizing treatment of white heart malleable iron, castings are packed in boxes for heat treatment and voids are filled with iron oxide. In this process, the base metal has usually a high carbon content (i.e. 3% or even more) and a low silicon content (i.e. about 0.6%), and the material is essentially a white cast iron. The castings are annealed in a decarburizing atmosphere to eliminate maximum possible carbon from the surface layers. So, most of the carbon is lost by oxidation. In the case of small castings, carbon is eliminated from the centre also, thus leaving behind an essentially ferritic matrix.

The decarburization in white heart process of heat treatment is carried out with the help of oxygen (either from air or from CO_2/iron ore). Concentration of oxygen which is in contact with casting is so adjusted that scale formation does not take place, whereas carbon from the surface layers get oxidized selectively. Decarburizing process requires prolonged heating in contact with the above mentioned decarburizing agents at above 950°C. At the same time, distortion of the casting due to exposure at high temperature is to be kept at minimum. Castings up to 3 mm thickness may be cooled rapidly from furnace temperature, but thicker sections require controlled cooling through transformation temperature range 700–760°C. For sections more than 12 mm thick, it is recommended that cooling be carried out rapidly to approximately 650°C, followed by reheating to 780°C and controlled final cooling. Gas decarburization process is economical and technically sound for decarburization. In this case, air as well as saturated steam are circulated in the heat treatment furnace.

To avoid oxidation of the iron, a reaction gas is formed from the surface carbon content of about 0.02%. This ensures slightly reducing atmosphere. In addition to normal decarburization process, there is also separation of carbon from ledeburite in the form of temper carbon. The view which is being increasingly adopted is that white heart malleable cast iron which has high carbon content should preferably be annealed in decarburizing atmosphere. So, no decarburization is required in the white heart malleable castings to produce sufficient ductility and machinability. On the other hand, only separation of carbon from ledeburite is sufficient for the purpose. However, some additional properties are achieved by decarburization. Hence, correct combination helps in producing a material with the desired physical properties.

The core of white heart malleable iron at room temperature shows a structure of temper carbon in a matrix of lamellar pearlite. Lamellar pearlite is not desirable as it reduces ductility and impairs machinability. However, if it is changed into globular cementite, it considerably improves ductility and machinability. This requires additional heat treatment. Figure 15.4 shows heat treatment processes to obtain globular cementite. This also reduces the requirement for decarburization treatment.

The average properties of standard malleable iron are tensile strength about 390 MPa, yield strength 250 MPa, and percentage elongation 15 with hardness value of 115 BHN.

15.3.2 Pearlitic Malleable Iron

Pearlitic malleable cast iron is basically a black heart malleable cast iron to which a modified heat treatment cycle is given to get a structure which consists of temper carbon in a matrix of pearlite or tempered martensite. In this case, a controlled quantity of carbon (0.3–0.9%) is retained in combined form. This structure gives high tensile strength (450–700 MPa), and hardenable structure with some reduction in ductility (percentage elongation 16). Hardness is about 163–209 BHN. These properties are valuable for some machinery parts such as rolls, pumps, nozzles, cams and rocker arms; axle and differential housings, cam shafts and crank shafts in automobiles.

Most of the manufacturers of pearlitic malleable iron use the same base metal as the one suitable for ferritic malleable iron and develop pearlitic structure by modified heat treatment

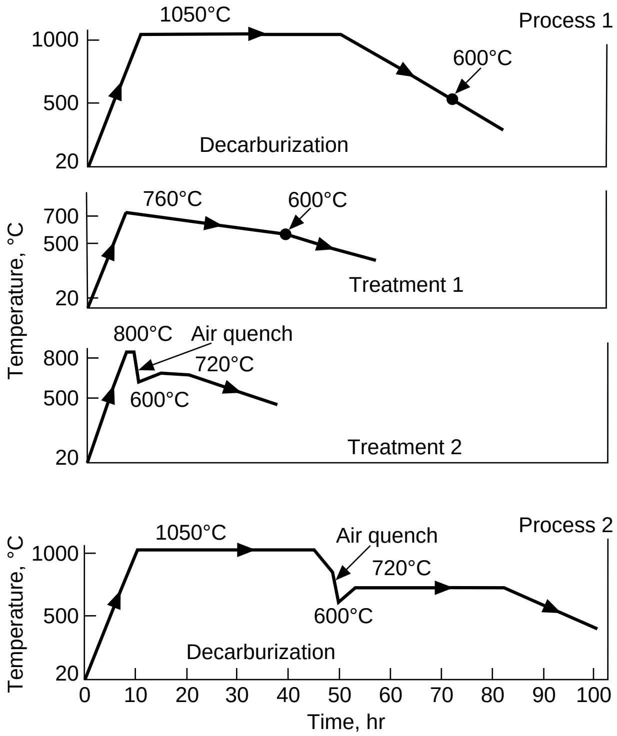


Figure 15.4 Different cycles for nodulizing cementite.

cycle. The advantage is that only one melting control procedure is required, which avoids possible difficulties due to mixing of return, sprue and scrap. However, some manufacturers add alloying elements such as manganese to retain combined carbon throughout the matrix at room temperature with standard malleable annealing practice. Either method can produce castings of good quality, with close adherence to specifications.

In every method of producing malleable cast iron, first stage graphitization is an essential requirement since successful production of pearlitic malleable iron requires complete decomposition of cementite. The possible steps in producing pearlitic malleable iron, after first stage graphitization, can be described as follows:

(i) To reheat after cooling from first stage graphitization to 790–870°C and air quench, which gives rise to 0.75% carbon in combined form in the matrix.

(ii) To air quench from 790-870°C as in step (i), reheat to 840–870°C, and hold there for 1 hour to reaustenitize the matrix and then quench in heated and agitated oil maintained at 85-100°C. This gives rise to martensitic and bainitic matrix with hardness about 550–620 BHN.

(iii) To complete annealing cycle, as in the case of ferritic malleable iron, reheat to 840–870°C, and hold there to dissolve graphite in austenite and then air cool or liquid quench so that the combined carbon content as also the hardness is less in comparison to step (i).

Each practice outlined above has its own merits and demerits. In case (i), the pearlite formed requires minimum number of operations, and the process is used successfully. Relatively thin castings can be subjected to this treatment successfully. In this case, on air cooling, the casting passes through eutectoid range quite fast to retain combined carbon throughout the matrix. The amount of pearlite formed depends on factors such as temperature at which quenching begins and the rate of cooling. Higher quenching temperature and faster cooling rates produce greater amount of pearlite. If the cooling rate is not so fast throughout the transformation range to retain all the carbon in combined form, the areas near the temper carbon will also be graphitized, while the remaining portion will be pearlitic in nature. This structure is called *bull's eye structure* because of its appearance (see Figure 15.5). The higher the austenitizing temperature, more will be the carbon dissolved in cementite from graphite. Subsequent cooling will give rise to more pearlitic structure and develop the desired properties. Most of the pearlitic malleable irons are tempered after air cooling to improve machinability and toughness, and to lower the hardness. Tempering is carried out between 540–650°C for about 2 hours. As compared to martensite, fine pearlite requires longer tempering time. The resulting structure consists of temper carbon and a matrix of tempered pearlite.

Step (ii) is followed to improve the mechanical properties of the matrix. The amount of martensite formed depends on several factors, such as severity of quench, temperature of casting, time of holding at that temperature, thickness of the casting and composition of the iron. Martensitic malleable cast iron is tempered from 230°C to 700°C for 2 hours to improve the properties. Higher austenitizing temperatures (900–930°C) give a more homogeneous austenite which on cooling gives uniform martensite. But precaution should be taken to prevent distortion and cracking.

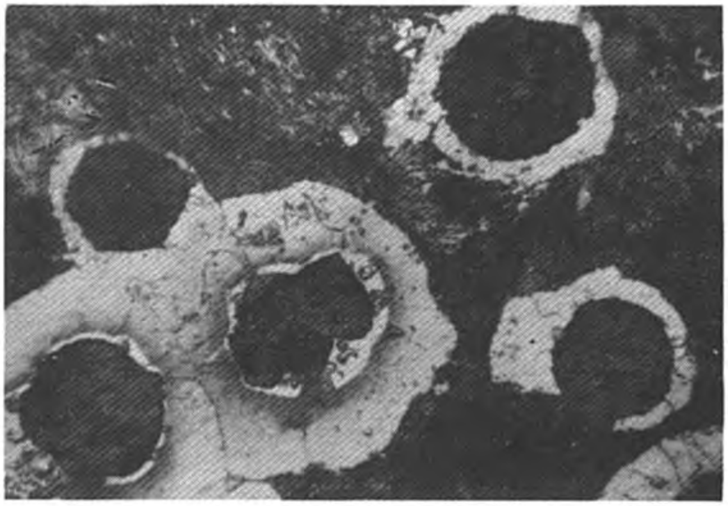


Figure 15.5 Microstructure of malleable cast iron showing bull's eye structure (×500).

Fully pearlitic malleable iron may be surface hardened by either induction heating and quenching or by flame heating and quenching. Laser and electron beam techniques have also been developed for hardening selected areas on the surface of pearlitic and ferritic malleable iron which is free from decarburization.

15.3.3 Special Malleable Iron

A white cast iron of fairly, high carbon, silicon and copper content (2.5–2.8% C, 2.5–3.3% Si, 0.5–0.7% Mn, 1.0% Cu. 0.10% S, 0.10% P, and the remaining Fe) can be obtained by chill casting. Irons of this kind can be malleabilized very rapidly due to high silicon content and the presence of copper. This type of malleable iron is used for manufacturing die cast ductile iron bolts for pipe joints. Copper is added to improve yield strength. This ensures that elongation of bolt does not take place during service. The malleabilizing treatment for such cast iron is as follows:

(i) Heating up to 940°C and holding for 2 hours
(ii) Cooling to 850°C in about 1 hour
(iii) Slowly cooling to 650°C over a period of 3 hours
(iv) Holding at 650°C for 1 hour for obtaining the same temperature throughout casting, followed by air cooling.

The structure obtained by this heat treatment is ferritic. Tensile strength is about 480 MPa, and yield strength 400–450 MPa with elongation of about 1–2 percent.

A malleable iron of ''Ni-resist'' type is poured into chill moulds and graphitized for about two hours at 980°C. This gives an austenitic structure with graphite. The tensile strength is around 500 MPa, yield strength 350 MPa, elongation 5%, and hardness 180–200 BHN.

15.4 SPHEROIDAL GRAPHITE (SG) IRON

Spheroidal graphite iron is also known as nodular iron or ductile iron. This is obtained by making small ladle additions of a modifier such as magnesium or cerium to liquid metal. In the majority of cases, about 0.03–0.06% magnesium is added. Due to the lightness of magnesium, it is added as 1–2% by weight of Ni–Mg alloy. Magnesium content in the alloy is about 10–20%. Nickel is a graphitizer. Magnesium causes the graphite to precipitate in all directions as spheroidal nodules during solidification of the cast iron (see Figure 15.6). Hence, this iron is named as spheroidal graphite iron. Magnesium increases the supercooling of cast iron and consequent chilling. Formation of white cast iron is avoided by double inoculation; magnesium additions make graphite nodular in shape; and ferrosilicon promotes graphitization during solidification. As compared to flaky graphite in grey cast iron, spheroidal graphite does not weaken the matrix considerably. For this reason, the mechanical properties of SG iron are superior to grey iron. In grey cast iron, mechanical properties are poor due to the morphology of graphite, i.e. due to the presence of graphite flakes. The pointed .ends of graphite flakes act as stress raisers.

SG iron has tensile strength of 400–700 MPa, yield strength 270–390 MPa, and percentage elongation 10–20. Approximate chemical composition of SG iron is 3.0–3.6% C, 2.0–2.5% Si, 0.6% Mn, 10.04 max P, 0.04 max S, and balance Fe. Actually, the first condition for production of SG iron is to have very low sulphur and phosphorus content. SG iron is melted in high frequency induction furnace.

The heat treatment procedures usually adopted for SG iron casting are as follows: (i) stress relieving, (ii) annealing, (iii) normalizing, (iv) hardening and tempering, (v) surface hardening, and (vi) austempering. We shall now discuss these one by one.

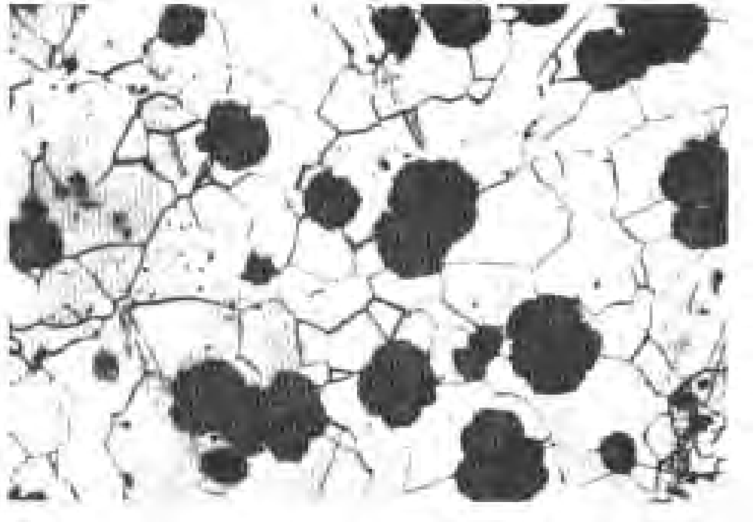


Figure 15.6 Microstructure of ferritic SG cast iron (× 200).

Stress Relieving

SG iron castings of complicated shapes require stress relieving treatment to relieve internal stresses developed after solidification. Internal stresses are relieved at 510–675°C. Holding time at stress relieving temperature is about 1 hour plus 1 hour per 25 mm of section thickness. After this, castings are cooled to 290°C in furnace, followed by cooling in air. Austenitic SG iron can be air cooled from 620°C to 675°C. Stress relieving reduces hardness to some extent. High alloyed SG iron is stress relieved by cooling from 595°C to 650°C.

Annealing

The purpose of annealing heat treatment in the case of SG iron castings is to have maximum ductility and good machinability. After annealing, the microstructure consists of graphite nodules in ferrite matrix.

There are three methods of annealing: (i) Heating the castings to 900–950°C and holding for 1 hour plus 1 hour per 25 mm of section thickness of casting. For heavy casting, the holding time may be up to 8 hours. After this, casting is cooled to 690°C and is kept at this temperature for 5 hours plus 1 hour per 25 mm of section thickness. (ii) In this case, the casting, after being held for 1 hour at 900–955°C, is furnace cooled to 650°C. Cooling rate between 790°C and 650°C should not exceed 20°C/hour. (iii) In both cases (i) and (ii), the matrix obtained is fully ferritic. When impact strength is not of significance, carbides can be tolerated in casting. Under such conditions, castings are heated up to 700°C and held there for 5 hours plus 1 hour per 25 mm of section thickness. After this, castings are cooled to 590°C in furnace. This is a subcritical annealing treatment for SG iron. For superior machinability, Mn, P and alloying elements such as Cr, Ni and Mo should be as low as possible. These are carbide formers. Of these, chromium carbide takes longest time to decompose at 925°C.

Normalizing

The purpose of normalizing is to improve the tensile properties of SG iron. For normalizing, SG iron is heated up to 870–940°C and soaked there for 1 hour. Temperature and soaking time vary with composition, especially with silicon and chromium contents. Normalizing is commonly followed by tempering to achieve the required hardness and to relieve stresses developed during air cooling because of different section sizes of castings. Tempering is carried out at 510–620°C for 1 hour. Tempering after normalizing is also adopted to improve toughness and impact resistance in addition to tensile strength. For this, castings, after air cooling from 870°C to 940°C, are reheated to 425–650°C and soaked for 1 hour. Normally, the microstructure after normalizing consists of fine pearlite and globular graphite. Alloying additions such as nickel, molybdenum and additional manganese help to develop a fully pearlitic structure after normalizing. Martensitic structure is obtained in the case of alloyed castings which are not heavy. Alloying additions increase hardenability. Figure 15.7 shows microstructure of pearlitic SG iron.

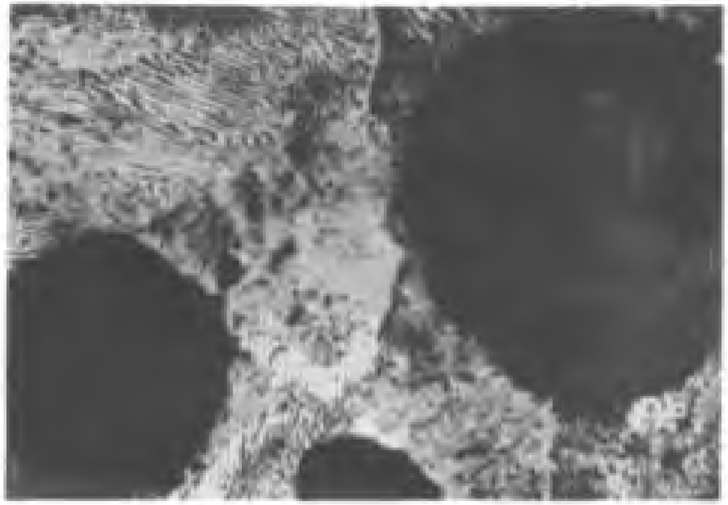


Figure 15.7 Microstructure of pearlitic SG iron (× 500).

Hardening and Tempering

For hardening of SG iron, castings are austenitized at 845–925°C. This is followed by oil quenching. To reduce stresses, oil is preferred as quenchant. Water and brine can also be used in place of oil as quenchant for castings with simple shapes. Castings which have complex shape are quenched in hot oil maintained at 80–100°C to avoid quench cracks. Immediately after quenching, castings are tempered in the range 300–600ºC for 1 hour plus 1 hour per 25 mm section thickness. This is to minimize quenching stresses. Tensile strength of quenched SG iron ranges from 700 MPa to 1000 MPa. The yield strength of such heat treated SG iron varies from 540 MPa to 880 MPa, with elongation of 10–12 percent and hardness of 215–320 BHN. The microstructure of quenphed SG iron reveals the martensitic matrix.

Surface Hardening

SG irons are also flame or induction hardened. Pearlitic type of SG irons are preferred for flame or induction hardening as time required for austenitizing is comparatively small. In the case of steel, some preliminary heat treatment is required before flame or induction hardening. For SG iron also, preliminary heat treatment is required before flame or induction hardening. In the case of pearlitic SG iron, tempering is carried out at 595–650°C for 1 hour plus 1 hour per 25 mm of section thickness to remove virtually all internal stresses before going in for flame or induction hardening. Hardness in this case comes to 600–750 BHN. Some typical applications of flame or induction hardened SG iron include heavy duty applications such as rolls for cold working titanium, ring gears for paper mill drives, and crank shafts and large sprockets for chain drives.

Austempering

To achieve the full potential of SG iron, austempering heat treatment is adopted. It is possible to achieve much higher ranges of tensile strength and elongation by adopting austempering treatment for SG irons.

While taking recourse to austempering, only defect-free SG iron castings should be chosen. Any lapse in quality control of the starting material will result in inferior end product and the very advantage of adopting this heat treatment procedure will be lost.

The process as such is very simple. The first stage consists of soaking the castings at the austenitizing temperature of 850–950°C. The austenitized castings are then quickly transferred to a liquid bath (say salt bath) maintained in the temperature range of 235–425°C. The transformation is allowed to proceed for a period of up to 4 hours when austenite transforms to bainite. The castings are finally cooled to room temperature after transformation.

By adopting austempering instead of conventional hardening and tempering treatment for SG iron, the requirement of alloy content is reduced for the same strength level. Further, the chances of cracking and distortion are also reduced. Thus, it becomes possible to carry out rough or final machining before heat treatment.

Table 15.2 summarizes the properties of austempered ductile irons as compared to other materials.

It is possible to achieve various combinations of high strength, high hardness, limited ductility or lower strength, lower hardness, high ductility by varying the temperature of

Table 15.2 Comparative Properties of Austempered Ductile Irons and Other Materials

Material	Tensile strength (MPa)	Yield strength (MPa)	Hardness (BHN)	Elongation (percent)
Ductile Irons				
Pearlitic and ferritic	400–960	250–610	130–300	28–3
Austempered	800–1600	600–1400	250–480	16–1
Hardened and tempered	600–1300	500–1100	300–400	5–1
Steels				
Hardened and tempered	700–1800	450–1450	210–510	25–8

austempering. The austempered ductile irons have good machinability. It is comparable with that of other ductile irons or low alloy steels. However, in such cases where higher hardness is aimed at by heat treatment, machining should be carried out prior to the heat treatment.

These materials have higher wear resistance than other ductile irons due to the presence of bainite. It may even be better than some steels. However, it has limited wear resistance as compared to white cast iron. For the same reason, the fatigue properties are superior to other ductile irons.

The impact values of austempered ductile irons are much higher than pearlitic ductile irons. They are in fact comparable to those of ferritic ductile irons. The transition of ductile to brittle fracture occurs at a lower temperature range in austempered ductile irons than in pearlitic ductile irons. Current studies on fracture toughness indicate that austempered ductile irons have remarkably higher range of values than those of other ductile cast irons.

Austempered ductile irons have great potentiality for use as gears. The advantageous property of high damping capacity of cast iron will be useful to minimize vibrations and transmission noise. Advantages of austempered ductile irons include high strength and ductility, wear resistance and toughness and better machinability, higher damping capacity and reduced weight in comparison with steel. Table 15.3 lists the possible engineering applications of austempered ductile irons.

Table 15.3 Possible Engineering Applications of Austempered Ductile Irons

Automobiles	Crankshafts Camshafts Steering knuckles Suspension components
Pumps and compressors	Bodies Crankshafts Drive shafts
Railways	Couplings
Agriculture	Undercarriage parts Constructional equipment

Applications of austempered ductile irons based on their wear resistance will include pump castings and impellers of sludge handling equipments, plough shears in agriculture and forestry, friction blocks and locomotive wheels, conveyor rollers and blades and shredders in general machinery.

15.5 ALLOY CAST IRONS

Alloy cast iron contains alloying elements such as nickel, chromium, molybdenum, copper, titanium, aluminium and vanadium which bring about a measurable modification in the physical or mechanical properties such as resistance to corrosion, heat or wear, and strength and hardness. Silicon, manganese, sulphur and phosphorus are not considered alloying elements because they are present in every type of cast iron.

Chromium up to 1 percent increases hardness, strength and depth of chill. Higher percentage of chromium, i.e. 35 percent, makes cast iron resistant to corrosion and high temperature. Copper amounting to 0.25–2.5 percent is added. Copper strengthens the matrix by making massive carbide discontinuous. Molybdenum improves fatigue strength, tensile strength, transverse strength, heat resistance and hardness of cast iron. About 0.25–1.25 percent molybdenum is added. Addition of molybdenum also increases hardenability by retarding the transformation of austenite. Vanadium is a powerful carbide former. It is added from 0.10 percent to 0.25 percent and increases tensile strength, transverse strength and hardness. Nickel addition varies normally from 0.5 percent to 0.6 percent in cast iron. Graphitizing power of nickel is half that of silicon. The main aim of adding nickel to grey cast iron is to retard austenite transformation and to stabilize pearlite. When 1 percent Mo is added, the structure becomes bainitic. When nickel is added between 14 percent and 38 percent to grey iron, it imparts high heat resistance and high corrosion resistance. Due to such a high percentage of nickel, the matrix becomes austenitic.

For improving abrasion resistance, about 4 percent nickel with 1.5 percent Cr is added to white cast iron. The matrix shows martensitic structure.

On the basis of percentage of alloying elements, cast irons are grouped into low alloy (up to 3 percent alloying elements), medium alloy (from 3 percent to 10 percent), and high alloy (above 10 percent) cast irons. The structure of an alloy cast iron may be pearlitic, bainitic, ferritic or austenitic, and graphite in flaky or nodular form.

Typical examples of some alloy cast irons are as follows: (i) Ni-hard martensitic white cast iron, (ii) Ni-resist cast iron, and (iii) chromium-manganese white cast iron. Each of these has specific recommended heat treatment cycle.

15.5.1 Ni-Hard Martensitic White Cast Iron

Wear is a complex phenomenon. It is associated with factors such as generation of heat by friction and impact. These factors determine selection of suitable wear resistant material. For applications requiring wear and abrasion resistance, there may be many materials to choose from. Plain and alloyed white cast iron forms an important group-among wear resistant materials.

The typical microstructure of white cast iron consists of iron carbide in a pearlitic matrix. With hard and brittle iron carbide in a pearlitic matrix, a hardness of around 300–500 BHN can be obtained in plain white cast iron. High hardness and high wear resistance in white cast iron is obtained with increased amount of brittle iron carbide. But this would impair impact resistance. Additions of nickel and chromium to white cast iron gives a very good wear resistant material whose microstructure consists of massive carbides in an austenitic-martensitic matrix. Nickel strengthens the matrix, and the graphitizing effect of nickel can be counteracted by addition of chromium which is a carbide stabilizer. This type of wear resistant material is popular under the trade name ‘‘Ni-hard’’. It is used for parts of large size coal pulverizer, mill liners, grinding media balls and impeller of sand pumps.

Heat treatment for Ni-hard cast iron is of great significance as retained austenite is converted to martensite due to heat treatment. Thus, the desired mechanical properties are improved.

Ni-hard cast iron is grouped as standard Ni-hard, Ni-hard type III and Ni-hard type IV cast iron.

Standard Ni-Hard Cast Iron

In this category, Ni-hard type I and Ni-hard type II cast iron are included. Ni-hard type I cast iron contains 3.2–3.8% C, 0.3–0.5% Si, 0.3–0.7% Mn, 3.5–4.5% Ni, 1.5–2.5% Cr and remaining Fe. The hardness range is 550–600 BHN. The chemical composition of Ni-hard type II cast iron is the same as that of Ni-hard type I except that carbon content is reduced to 2.8–3.2 percent against 3.2–3.8 percent in type I. This lowering of carbon content improves the impact strength of type II from 2.7–5.4 metre kg to 3.4–6.8 metre kg.

Heat treatment of standard Ni-hard consists of stress relieving by heating up to 200–250°C and holding there for 2–4 hours. As a result, internal stresses are removed and the martensite gets tempered. Holding at 275°C for a long time gives bainitic structure besides stress relieving and tempering of as-cast martensite. Due to this, treatment impact life improves significantly besides improvement in hardness. As the retained austenite changes to martensite during heat treatment, there are no chances of dimensional changes during service. This improves the surface stability and imparts spalling resistance. Two-stage heat treatment gives optimum properties. Standard Ni-hard is first heated to 450°C and held there for 4 hours. Then it is air cooled to 275°C and held there for 4 hours. This treatment ensures transformation of retained austenite to martensite.

Figure 15.8 summarizes the result of life-to-fracture drop test carried out on standard Ni-hard in the as-cast as well as double heat-treated condition. It may be observed that double heat treatment not only improves impact fatigue resistance but also narrows down the fluctuations in the results. The use of Ni-hard type II for grinding media and mill linear in mining and cement industry has become feasible because of this treatment.

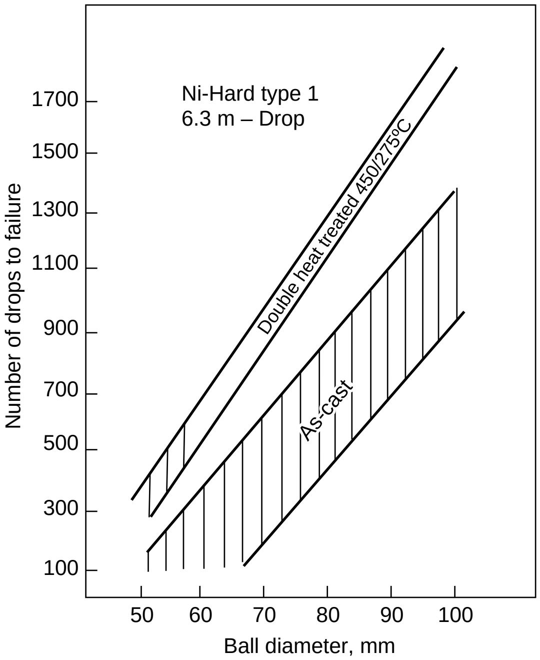


Figure 15.8 Life-to-fracture values for balls of different sizes in standard Ni-hard in the standard as-cast and double heat-treated conditions.

Ni-Hard Type IV

Chemical analysis of Ni-hard type IV cast iron is as follows: 2.8–3.2%C, 1.5–2.0% Si, 0.4–0.6% Mn, 0.1% S, 0.06% P, 5.5–6.5% Ni, 7.0–9.0% Cr and balance Fe. In the as-cast condition, this alloy also contains retained austenite like other types of Ni-hard cast iron. It is necessary to transform this retained austenite to martensite by suitable heat treatment before it is put into actual service. Otherwise, a change in volume with formation of crack will occur during service. Also, this treatment aimed at transformation of retained austenite to martensite will result in increased hardness and wear resistance.

This cast material is heated up to 750°C and held there for 4 hours, followed by air cooling. Partitioning of Ni and Cr in the various phases and their effect on austenite decomposition are responsible for high hardness and toughness. The hardness value obtained is between 550 BHN and 600 BHN. Impact strength is 3.4–7.4 metre kg. Figure 15.9 shows the microstructure of heat treated Ni-hard type IV cast iron.

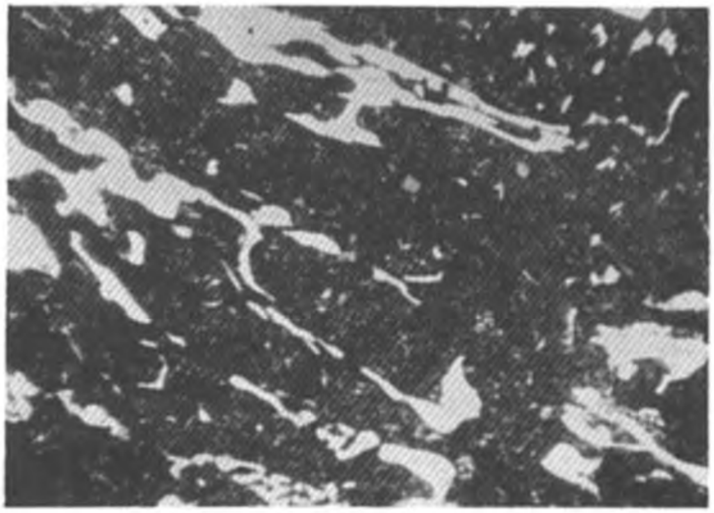


Figure 15.9 Microstructure of heat-treated Ni-hard type IV cast iron (× 1000).

15.5.2 Ni-Resist Cast Irons

These austenitic cast irons possess a stabilized austenite matrix due to the presence of alloying elements such as nickel, copper and manganese. As compared to pearlite, austenitic phase has better corrosion resistance. This class of cast irons includes a wide range of austenitic cast irons, where nickel content lies between 13.5 percent and 36 percent. The two types of Ni-resist cast irons are (i) the flake-graphite corrosion-resistant austenitic cast irons, and (ii) the spheroidal-graphitic corrosion-resistant austenitic cast irons.

In type (i) cast irons, graphite is present in the form of flakes. The composition, mechanical properties, and uses of this grade of cast irons are given in Table 15.4.

In type (ii) cast irons, graphite is present in spheroidal form. Because of the spheroidal form of graphite, these cast irons have high strength and ductility. In all the grades, graphite can be obtained in spheroidal or flakular form. The only exceptions are copper containing grades, namely, type 1 and 1b Ni-resist-cast iron. Trade name, specification, composition, mechanical properties, and uses of spheroidal-graphitic corrosion resistant austenitic grade of cast iron are summarized in Table 15.5.

Nickel, chromium and copper impart corrosion resistance, and nickel and chromium improve wear resistance in Ni-resist cast irons. These cast irons exhibit the following properties:

(i) High resistance to wear due to fine carbide dispersion throughout the structure
(ii) Good erosion resistance to high velocity flow of the liquid and vapour particles in wet steam

Table 15.4 Trade Name, Specification, Composition, Mechanical Properties and Uses of Austenitic Cast Iron–Flake Graphite Grades

Trade names	ISI specification 2749-1964	BS 3648 designation	ASTM A436-61T designation	Composition (percent)						Mechanical properties			Uses
				C	Si	Mn	Ni	Cr	Cu	UTS (MPa)	Elongation (percent)	Hardness (HB)	
Type 1 Ni-R	AFG IA	AUS–101 Grade A	Type 1	3.00 (max)	1.0–2.8	1.0–1.5	13.5–17.5	1.5–2.5	5.5–7.5	170	2.0	130–180	In pump components (e.g. wear rings, paddles in mixer for manufacture of superphosphate and valve seats on aluminium cylinder heads)
Type 1B Ni-R	AFG IB	AUS–101 Grade B	Type 1b	3.00 (max)	1.0–2.8	1.0–1.5	13.5–17.5	2.5–3.5	5.5–7.5	205		150–210	
Type 2 Ni-R	AFG 2A	AUS–102 Grade A	Type 2	3.00 (max)	1.0–2.8	1.0–1.5	18.0–22.0	1.0–2.5	0.5 (max)	170	2.0	120–170	In chemical processes (e.g. handling of caustic and viscose solutions, in rayon production and in soap manufacture)
Type 2b Ni-R	AFG 2B	AUS–102 Grade B	Type 2b	3.00 (max)	1.0–2.8	1.0–1.5	18.0–22.0	3.0–6.0	0.5 (max)	205		170–248	For turbo-charges in diesel engines
Type 3 Ni-R	AFG 5	AUS–105	Type 3	2.60 (max)	1.0–2.0	0.5–1.5	28.0–32.0	2.5–3.5	0.5 (max)	170		120–160	In pumps and other mechanical equipment
Type 4 Ni-R			Type 4	2.60 (max)	5.0–6.0	0.5–1.5	28.0–32.0	2.5–5.5	0.5 (max)	170		150–210	For impellers of pump handling corrosive slurries
Type 5 Ni-R			Type 5	2.40 (max)	1.0–2.0	0.5–1.5	34.0–36.0	0.1–(max)	0.5 (max)	140		100–124	In scientific instruments for low temperature applications
Type 6* Ni-R			Type 6*	3.00 (max)	1.5–2.5	0.5–1.5	18.0–22.0	1.0–2.0	3.5 5.5	170		124–174	In pump components

*Also contains 1.0% molybdenum.

Table 15.5 **Trade Name, Specification, Composition, Mechanical Properties and Uses of Austenitic Cast Iron–Spheroidal Graphite Grades**

Trade names	ISI specification 2749-1964	BS-3468 designation	Equivalent ASTM A439–60T designation	Composition (percent)						Mechanical properties			Uses
				C	Si	Mn	P	Ni	Cr	UTS (MPa)	Elongation (percent)	Hardness (HB)	
Type D2 SG Ni-Resist	ASG2A	AUS–202	D–2	3.00 (max)	1.5–3.0	0.7–1.25	0.08 (max)	18.00–22.0	1.75–2.75	400	8	140–200	In pertrochemical industries, liners for heavy duty diesel engines
Type D2b SG Ni-Resist	ASG2B	AUS–202	D–2b	3.00 (max)	1.5–3.0	0.7–1.25	0.08 (max)	18.0–22.0	2.75–4.00	400	7	150–210	In systems handling corrosive slurries exhaust manifold used for diesel engine
Type D2 /(C)	ASG3	AUS–203	D–2c	2.90 (max)	1.0–3.0	1.8–2.40	0.08 (max)	21.0–24.0	0.50 (max)	400	20	170 (max)	Where maximum ductility is essential
Type D3 SG Ni-Resist	ASG5	AUS–205	D–3	2.60 (max)	1.0–2.80	1.0 (max)	0.08 (max)	28.0–32.0	2.50–3.50	380	6	140–200	In pumps and other mechanical equipment
Type D3A SG Ni-Resist			D–3a	2.60 (max)	1.0–2.80	1.0 (max)	0.08 (max)	28.0–32.0	1.00–1.50	408	10	130–190	In mechanical equipment
Type D4 SG Ni-Resist			D–4	2.60 (max)	5.00–6.00	1.0 (max)	0.08 (max)	28.0–32.0	4.5–5.50	154		202–273	For impellers of pump handling corrosive slurries
Type D5 SG Ni-Resist			D–5	2.60 (max)	1.0–2.80	1.0 (max)	0.08 (max)	34.0–36.0	0.10	380	20	130–185	For low temperature applications
Type D5B SG Ni-Resist			D–5b	2.40–2.60	1.0–2.80	1.0 (max)	0.08 (max)	34.0–36.0	2.00–3.00	380	6	140–190	For low temperature applications

(iii) Good corrosion resistance against a wide range of corrosive media such as alkalies, acids, salts, oils and foods
(iv) High temperature oxidation resistance up to 800°C
(v) High specific electrical resistance
(vi) Uniform thermal expansion
(vii) Moderate strength in flake type grade and good strength in SG grade.

These alloys have a tendency to work harden. Hence they are to be cooled carefully after casting. The same precaution is also to be taken after heat treatment operation. This will ensure that the internal stresses are minimum and also the rate of work hardening that accompanies the operation of removal of metal is also minimum.

The heat treatment processes used for Ni-resist cast iron of both types are now discussed.

Stress Relieving

The purpose of stress relieving is to remove residual stresses developed due to casting or machining operation or both. Stress relieving is carried out at 620–670°C for 1 hour per 25 mm section, followed by air/furnace cooling. About 60% stresses are removed when castings are heated up to 480°C and soaked for 1 hour per 25 mm section thickness. At 670°C, about 95 percent stresses are relieved. Tensile strength, hardness and ductility are not affected by stress relieving.

Spheroidize Annealing

Softening can be achieved by breaking down carbides and converting their shape into spheroids by annealing at 980-1040°C. Holding time varies from half an hour to 5 hours. This treatment lowers hardness, but strength is not adversely affected.

High Temperature Stabilization Heat Treatment

Castings used for high temperature applications (above 480°C) are to be given a stabilization heat treatment. This treatment consists of heating the casting up to 760°C and holding at that temperature for minimum of 4 hours or at 870°C for minimum of 2 hours, followed by furnace cooling to 530°C, and then cooling in air. This treatment removes excess carbon from austenite and dissolved carbides. The carbon so removed gets precipitated as graphite flakes. This prevents distortion in service. Stabilization treatment prior to final machining is very beneficial.

Dimensional Stabilization Treatment

Ni-resist cast irons used for precision machinery and scientific instrument parts require true dimensional stability. In this case, casting is heated up to 870°C and soaked for minimum 2 hours. It is then furnace cooled at a rate of about 45–50°C per hour up to 540°C. It is held for 1 hour at 540°C and then air cooled. After rough machining, it is reheated to about 460–470°C and held there for 1 hour, followed by uniform cooling in air. After this, final machining is carried out. The last step consists of heating to 270–300°C, followed by uniform cooling in air.

Solution Treatment

This heat treatment is carried out occasionally for this group of cast iron. In this case castings are heated up to 950–1000°C and quenched in water or oil. Quench cracking is not likely to take place as no phase changes occur during the process. The strength of SG Ni-resist cast iron is improved by this heat treatment. Improvement in strength can also be achieved by carbide dispersion heat treatment.

QUESTIONS

15.1 Compare the processes of ferritizing annealing and graphitizing annealing.

15.2 How hardening and tempering is carried out for grey cast iron?

15.3 What heat treatment would you recommend for malleable cast iron and why?

15.4 What do you understand by malleabilizing of cast irons?

15.5 Discuss the heat treatment procedures adopted for S.G. iron castings.

15.6 How austempering is achieved in SG iron castings? What are the possible applications of austempered SG iron?

15.7 Discuss the heat treatment processes used for Ni-resist cast irons.

16

Heat Treatment of Non-ferrous Metals and Alloys

INTRODUCTION

Non-ferrous metals and alloys form an important group of materials of industrial importance. Aluminium, copper, lead, magnesium, nickel, and titanium, and the alloys of all these metals are the significant non-ferrous metals and alloys. In addition, there are also a few special purpose non-ferrous metals and alloys. By heat treatment of these metals and alloys, the desired combination of properties is achieved. This, in turn, has gone a long way in their adoption for commercial use.

In this chapter, various types of commercially important non-ferrous metals and alloys and their heat treatment are considered. Among the non-ferrous metals and alloys, the most important one is aluminium and its alloys which are now discussed.

16.1 ALUMINIUM AND ITS ALLOYS

Aluminium and its alloys are used in a variety of cast and wrought forms and conditions of heat treatment. Forgings, sections, extrusions, sheet, plate, strip, foil and wire are some examples of wrought form, while castings are available as sand, pressure and gravity die castings.

To meet various requirements, aluminium is alloyed with copper, manganese, magnesium, zinc, nickel and silicon as major alloying elements. These alloying additions improve the properties of aluminium when added in desired percentages. The AAA (Aluminium Association of America) has classified the wrought aluminium alloys according to a four-digit system. This classification is adopted by the International Alloy Development System (IADS) and by most of the countries in the world. Table 16.1 gives the basis of designation of wrought aluminium alloys in the four-digit system.

The first digit identifies the alloy type. The second digit shows the specific alloy modification. The last two digits indicate the specific aluminium alloy or the purity level in case of pure aluminium.

Table 16.1 Designation of Aluminium Alloys

Alloy number	Major alloying element(s)
1 XXX	Commercially pure aluminium (>99% Al)
2 XXX	Copper
3 XXX	Manganese
4 XXX	Silicon
5 XXX	Magnesium
6 XXX	Magnesium, silicon
7 XXX	Zinc
8 XXX	Other elements such as nickel, titanium, chromium, lead and bismuth
9 XXX	Unassigned

The condition or temper of aluminium alloy can be denoted by specific letters as shown below:

Letter	*Condition of Alloy*
F	As fabricated
O	Annealed
H	Strain hardened by a cold working process
T	Heat treated

The letters H and T are generally shown with some numbers, which indicate more details about the treatment of a particular alloy. For example

H1	indicates only strain hardened;
H2	denotes strain hardened and partially annealed; and
H3	signifies strain hardened and stabilized by suitable annealing.

The second number 2, 4, 6, 8, or 9, if present, shows an increasing amount of strain hardening. For example, H12 denotes quarter hardened, H14 half hardened, and H18 fully hardened condition. Complete designation with treatment, for example, can be written as 5052–H18.

The different tempers produced by heat treatment are shown by letter T combined with-other numbers. This tells about specific heat treatment which has been given to the alloy. The designation is as follows:

T	Age hardened
Tl	Naturally aged after hot working
T2	Annealed (for castings only; for example, adopted to improve ductility of castings)
T3	Solution heat treated, cold worked and naturally aged
T3X	Solution heat treated, cold worked by X% and naturally aged
T4	Solution heat treated, quenched and naturally aged
T5	Artificially aged only
T6	Solution heat treated, quenched and artificially aged
T7	Solution heat treated and stabilized (by an overageing heat treatment)
T8	Solution heat treated, cold worked and artificially aged
T8X	Solution heat treated, cold worked by X% and artificially aged.

When we talk about heat treatment for aluminium alloys, it is generally restricted to the specific operations used to improve strength and hardness of precipitation hardenable wrought and cast aluminium alloys. But all aluminium alloys cannot be heat treated; such alloys are termed “non-heat treatable” alloys. Others are grouped under “heat treatable alloys”. Annealing heat treatment is carried out for both types of alloys. The purpose of this treatment is to increase the ductility. Usually, for non-heat treatable alloys, only complete or partial annealing is carried out. However, a low temperature stabilization treatment is sometimes given to 5 XXX series of alloys. This treatment is designated as mill treatment.

16.1.1 Heat Treatable Aluminium Alloys

Aluminium alloys of this class belong to systems with limited solubility in solid state. These are precipitation hardenable alloys. The main characteristic of this type of alloy system is a temperature-dependent equilibrium solid solubility, which increases with rise in temperature. In addition, the other requirements are possibility of retaining single phase supersaturated solid solution by quenching, and precipitation of coherent/partially coherent phase by decomposition of the supersaturated solid solution.

The examples of this group are as follows:

(i) 2 XXX series of Al-Cu alloys and Al-Cu-Mg alloys (such as 2014, 2024, 2618). In RR 58 alloy (2618 T16) copper and magnesium improve the strength by age hardening. Nickel and iron form the intermetallic compound $FeNiAl_9$, due to which dispersion strengthening occurs. Nickel improves the creep resistance of the alloy.

(ii) 6 XXX series include AI-Mg-Si type alloys. These are used as medium strength structural alloys with added advantages of good weldability, corrosion resistance and immunity to stress corrosion cracking. 6061 and 6063 T6 are common examples of this series.

(iii) 7 XXX series include Al-Zn, Al-Zn-Mg, and Al-Zn-Mg-Cu type alloys. Alloys of this series show pronounced potentiality for age hardening. There is rapid decrease in solubility of zinc with decrease in temperature. Addition of copper to Al-Zn-Mg type alloys reduces the susceptibility to stress corrosion cracking. The examples of this series include 7079 and 7075 T8 which are aircraft materials.

A number of binary aluminium alloy systems show the type of phase diagram which is required for precipitation hardening. They show decrease in solid solubility with lowering of temperature. However, all such alloys do not show actual precipitation hardening characteristics when subjected to age hardening treatment. Al-Si and AI-Mn are typical examples which hardly show any change in mechanical properties as a result of precipitation hardening treatment.

16.1.2 Non-heat Treatable Aluminium Alloys

These alloys do not respond to heat treatment, because they consist of a homogeneous solid solution with or without non-coherent precipitate(s) and show low strength and high ductility. These alloys may be stress hardened. Commercially, pure aluminium (1100), Al-Mn (3003), AI-Mn-Mg, and Al-Si alloys are some examples of this class. These alloys are used as sheet, bar, plate, wire, extrusion, and so on. They are readily bent, formed and welded and possess excellent resistance to corrosion. Tables 16.2 and 16.3 (a and b) show the alloy designation, composition, condition properties and applications of non-heat treatable and heat treatable aluminium alloys, respectively.

16.1.3 Classification of Heat Treatment Processes for Aluminium Alloys

In aluminium alloys, the basic aim of heat treatment is to increase strength and hardness. Depending on the rate of heating, cooling and soaking time at given temperatures, the properties can be varied according to requirement. Main heat treatment processes used for aluminium alloys are as follows: (i) Annealing (for example, recovery, recrystallization, homogenization and high temperature annealing), (ii) solution treatment, and (iii) precipitation hardening, which we now discuss.

Annealing

Annealing of aluminium alloys is carried out to relieve internal stresses caused by cold working. Temperature control is necessary to avoid grain growth. During annealing, the precipitation of the alloying elements may also take place. This complete precipitation gives dimensional stability even at high temperature to the parts in service. There is no appreciable change in mechanical properties. It improves ductility and resistance towards shock, while tensile and yield strength decreases to some extent.

This process can be divided into two subgroups, viz. type I and type II annealing. Type I annealing includes recovery, recrystallization and homogenization. Type II annealing is a high temperature annealing process, also termed phase recrystallization.

Type I Annealing The main purpose of this treatment is to convert the structure of metal to a stable form from an unstable one. This is a spontaneous and irreversible process. For example, a coarse, grained structure produced by this process will not become fine grained until cold working is carried out. In heat treatable aluminium alloys, this process decreases the degree of supersaturation of solid solution. The deciding factors for this process are temperature and time of soaking, and not rate of heating and cooling.

During recovery treatment, most of the elastic distortions in the metal, which are generated during cold working or during fast rate of solidification, are relieved. For this treatment, components are soaked at definite temperature (which varies for different alloys), but below recrystallization temperature of the alloy. Hardness and strength of the alloy decrease due to recovery treatment, while ductility and toughness increase.

Recrystallization annealing treatment is given to wrought semi-finished aluminium alloys to change the structure, i.e. to change the directional grains into equiaxed grains. Thus, isotropy is maintained. Figure 16.1 illustrates the recrystallization of aluminium. This shows the influence of different degrees of deformation on grain size of aluminium at different temperatures.

As the degree of deformation is increased, there is decrease in grain size. Any decrease in the temperature of deformation has also similar effect on the grain size. Hence, such diagrams can give an idea about the appropriate plastic deformation. Further, it also helps in choosing the optimum annealing temperature.

Table 16.2 Composition, Temper, Mechanical Properties and Uses of Non-heat Treatable Aluminium Alloys

Alloy designation	Composition (percent)	Temper*	UTS (MPa)	Yield strength (MPa)	Elongation (percent)	Shear strength (MPa)	Fatigue strength (MPa)	Uses
1100	99% pure aluminium	O	91	35	35	66.5	35	Packing strips, flange, plates cover plates, tubes, etc.
		1/2H	119	98	9	77	49	
3003	1–1.5 Mn, 0.2 Cu, 0.6 Si, 0.1 Zn, 0.7 Fe	O	92	42	30	77	49	Rigid containers
		1/2H	147	126	8	98	63	
5052	2.2–2.8 Mg, 0.15–0.35 Cr, 0.07 Cu, 0.25 Si, 0.4 Fe, 0.1 Mn, 0.1 Zn	O	203	98	25	126	119	Angles, gaskets marine fittings, aircraft fuel tanks
		1/2H	259	203	10	147	133	

*O = soft annealed condition.

1/2H = intermediate temper obtained by varying the amount of cold work after annealing.

Table 16.3(a) Composition, Temper, Mechanical Properties and Uses of Heat Treatable Wrought Aluminium Alloys

Alloy designation	Composition (percent)	Temper	UTS (MPa)	Yield strength (MPa)	Elongation (percent)	Shear strength (MPa)	Fatigue strength (MPa)	Uses
2024	4.5 Cu, 1.5 Mg, 0.6 Mn, 0.05 Si, 0.5 Fe, 0.25 Zn, 0.1 Cr, 0.15 Ti	O	189(182)*	77(77)	20(20)	126(126)	91	Aircraft structures, truck wheels
		T36	504(470)	400(370)	13(11)	294(287)	126	
		T4	476(450)	330(294)	20(19)	287(280)	140	
		T86	(440)	(460)	(6)	294(294)		
6061	1.5 Mg_2Si, 0.25 Cu, 0.25 Cr	O	126(119)	56(99)	25(25)	84(77)	63	General structural aircraft
		T4	245(230)	147(133)	22(22)	168(154)	98	
		T6	315(294)	280(260)	12(12)	210(189)	98	
7075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.4 Si, 0.5 Fe, 0.3 Mn, 0.23 Cr, 0.2 Ti	O	230(224)	105(98)	17(17)	154(154)		
		T6	580(530)	510(468)	11(11)	336(322)	160(90)	Aircraft structures
7079	4.3 Zn, 3.3 Mg, 0.6 Cu, 0.2 Mn, 0.2 Cr	T6	545	475	14	315	160	As aircraft material

*Values given in parentheses correspond to ‘Alclad’ sheets. To improve corrosion resistance, Al-Cu and Al-Zn-Mg alloys are sandwiched between two protective sheets of pure aluminium and rolled to produce a composite known as Alclad.

Table 16.3(b) Composition, Condition, Mechanical Properties and Uses of Heat Treatable Cast Aluminium Alloys

Alloys (percent composition)	Sand cast			Chill cast		Recommended casting practice
	Condition	UTS (MPa)	Elongation (percent)	UTS (MPa)	Elongation (percent)	
5.5 Si, 0.6 Mg	TB*	275	8	310	12	Sand and permanent mould cast
4.5 Cu	TB	215	7	260	13	Sand cast
	TF**	275	4	310	9	Sand cast
12 Si, 1.6 Ni/Cu/Mg	TF	170		275		Sand and permanent mould cast
4 Cu, 2 Ni/1.5 Mg	TF	215		275		Sand and permanent mould cast
7 Si, 0.3 Mg	TB	160	2.5	235	5	Sand and permanent mould cast
	TF	235		275	2	Sand and permanent mould cast
	TF			275	5	Sand and permanent mould cast

*Solution treated only **Fully heat treated

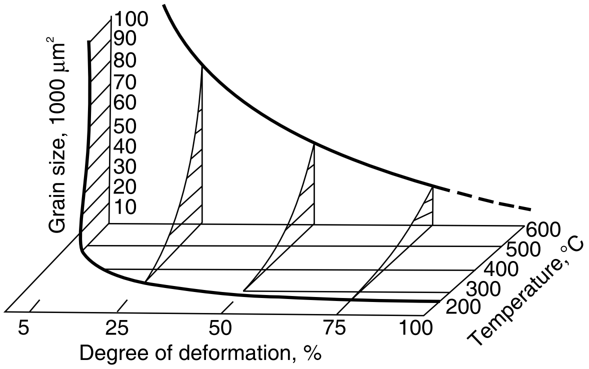


Figure 16.1 Diagrammatic representation of recrystallization of aluminium.

The rapidity of recrystallization process increases with rise in temperature and decrease in original grain size. The diffusion of atoms within the crystal and from one crystal to another takes place above 200°C in aluminium alloys. Therefore, under such circumstances, not only growth of grain and disappearance of some grains take place, but there is also a change in the shape of the grains. During this process, spheroidization of coarser grain also takes place. Such a process can be observed even in cast alloys such as LM–6 (Al, 12% Si) and LM–25 (Al, 7% Si, 0.4% Mg). At high temperatures, the silicon flakes get spheroidized. As such there is no recrystallization in the cast alloys since they are not deformed. In fact, in cast structure each grain is separated by other grains with a very thin non-metallic layer, shrinkages, microvoids and gas bubbles. Wrought alloys do not have such structure. Recrystallization process is possible only for wrought alloys since they are the ones which have undergone deformation.

For a complete and fast rate of recrystallization, the alloy structure should be thermodynamically unstable. Further, there should be good contact between grains, and temperature should be such that it allows enough mobility of atoms among the grains. The previous history of the metal has a great bearing on the process of recrystallization. Some of the manganese containing aluminium alloys exhibit unique phenomena during hot pressing. With a critical deformation, there is formation of coarse grained rim on the deformed material. Duralumin and allied alloys have a tendency to show this type of behaviour.

Industrially, the following steps are taken for obtaining a fine grained equiaxed structure in semi-finished wrought products:

(i) The recrystallization process is interrupted just after nucleation process.
(ii) Fast heating rate is preferred for annealing temperature (for this, nitrate bath is used).
(iii) Recrystallization should be carried out at maximum possible temperature and in minimum time.

Homogenization treatment is given to distribute the alloying additions uniformly throughout the alloy. Thus the adverse effect of segregation is removed by this treatment. As-cast structure is also modified. In so doing, the mechanical properties of the alloy also improve.

Homogenization annealing treatment is given to those semi-finished products which have comparatively high hardness. The aim is to introduce good plasticity before cold and hot working of the ingot. Thus, workability of the alloy improves. This is the first treatment given to ingots. It is a long thermal process which takes about 20–40 hours for completion. Some of the common alloys which are subjected to this type of treatment are: 2017 (Al, 3.8–4.8% Cu, 0.4–0.8% Mg, 0.4–0.8% Mn), 2024 (Al, 3.8–4.9% Cu, 1.2–1.8% Mg, 0.6% Mn), 2014 (Al, 3.9–4.8% Cu, 0.4–0.8% Mg, 0.4–0.8% Mn, 1.0% Si), and 7075 (Al, 5.0–7.0% Zn, 2.0% Cu, 1.8–2.8% Mg, 0.2-0.6% Mn).

The ingots are heated to about 420–520ºC and soaked at this temperature for 20–30 hours in order to homogenize the composition of the alloy and to dissolve such phases which are segregated along grain boundaries and make the alloy brittle. Examples of such phases are $MgZn_2$, Mg_2Si, $A1_2Mg_3Zn_3$ and Al_2CuMg. This type of redistribution of these phases improves the plasticity of the ingot.

When the temperature of homogenization is raised, there is depletion of elements such as manganese in the solid solution. This arises from comparatively high degree of solubility of manganese and other similar elements at the temperature of solidification of the alloys. These elements have low diffusion coefficient. As a result, a supersaturated solid solution in aluminium is formed. In other words, while cooling from molten state, solution heat treatment takes place automatically. The higher the degree of super-saturation, more is the vigour of decomposition of the solid solution. With increase in the temperature and time of homogenization, there is greater extent of depletion of manganese from the solid solution. Side by side, there will be fewer particles of the precipitate rich in manganese, and these particles will correspondingly be coarser. Under these conditions, there is hardly any strengthening effect due to the presence of manganese. The strength of homogenized ingot of semi-finished wrought product so obtained is about 20–40 MPa less than the strength of the ingot which is not subjected to homogenizing treatment (e.g. duralumin).

Type II Annealing In this type of annealing, the alloy is heated above critical temperature and then cooled slowly. Due to this treatment, the shape and size of the grains and nature of distribution of particles of precipitating phases are modified considerably from original structure. We can obtain a fine grained structure which has great bearing on mechanical properties of the alloy. In this case, the change is of reversible type, i.e. the coarse grained structure may change into fine grained, and the reverse of this is also true. The rate of cooling is a major factor besides temperature and soaking time.

Solution Heat Treatment

This involves heating of the alloy to a particular temperature for sufficient time so that alloying elements such as Cu, Si, Mg, and Zn go into solid solution and form single-phase solid solution. Overheating and underheating are to be avoided. Overheating may cause formation of surface blisters, excessive grain growth, and eutectic melting in some alloys. On the other hand, underheating may lead to incomplete solutionizing prior to precipitation. After solutionizing, the alloy is quenched in cold water or hot or boiling water or hot oil or fused salts.

There is an exception to this rule. In the case of aluminium alloys with large manganese content, while the molten alloy is cooled and solidified, the solid solution formed is similar to the one that is obtained by solution treatment. Hence, the subsequent normal process of solution heat treatment effectively causes ageing of the solid solution. Typical examples of such type of alloys are Al, 1.0–1.6% Mn, and Al, 4.5–5.3% Cu, 0.60–1.0% Mn, 0.4% Ti.

During the process, a number of manganese rich precipitates like Al_6Mn, $Al_{12}Mn_2Cu$, $Al_{10}Mn_2Si$ are formed. For these alloys, which are hardened by solution treatment, maximum dissolution of elements which cause strengthening takes place during the heating process.

The factors which affect the final properties of the alloy are soaking temperature, soaking time and cooling rate. Figure 16.2 is the diagrammatic representation of heat treatment process. The soaking temperature is different for various alloys. It depends on the various phases which are present in alloys. Each phase will dissolve in solid solution at different rates. The rate of dissolution increases with rise in temperature. Soaking time is based on the rate of dissolution of alloying elements into solid solution. Soaking time also depends on the conditions under which the alloy is cast. For example, sand cast parts have coarser structure than permanent mould casting. Therefore, a sand casting takes longer time for dissolution of strengthening phases, and the holding time for sand cast alloy is longer (about 12 hours) than permanent mould castings (about 8 hours). Holding time or soaking time also depends on the size and shape of the product.

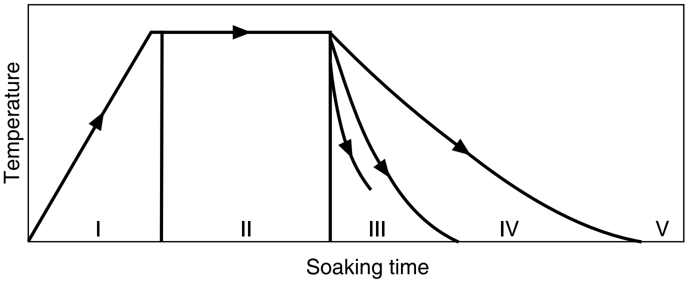


Figure 16.2 Heat treatment process of aluminium alloys. (I, Heating time of alloy; II, soaking time; III, cooling after solution heat treatment; IV, cooling for the process of stabilization; V, cooling for the process of homogenization.

Besides this, prior heat treatment has great influence on the dissolution of the alloying elements during solution heat treatment process. In repeated solution heat treated part, the rate of dissolution increases which in turn decreases holding time of the part. Annealing process has reverse effect on the rate of dissolution and holding time, i.e. it decreases the rate of dissolution of alloying elements and increases holding time of the product. Cooling rates should be fast and to avoid high thermal stresses during quenching, it is better to use hot quenching media such as boiling water, hot oil or fused baths. This produces a minimum of thermal stresses. The process of quenching with prolonged ageing in hot media gives good mechanical properties and this process is called isothermal quenching.

Precipitation Hardening

After quenching, precipitation of second-phase particles occurs. Precipitation with time at room temperature is called natural ageing, whereas precipitation at higher temperatures is referred to as artificial ageing. The hardness after solution treatment is comparatively low. The maximum hardness and strength develops when alloy is aged at a suitable temperature which normally ranges between 120°C and 200°C. In some cases the ageing temperature may be as high as 300°C. Ageing time may vary from 4 hours to 24 hours.

Spontaneous decomposition of supersaturated solid solution takes place during ageing treatment. Ageing temperature and degree of supersaturation play a great role on the final properties of the alloy. The higher the ageing temperature and higher the degree of supersaturation, more intensive will the ageing be. Higher temperature ageing is adopted when more stable phase is required together with dimensional stability. This process is also called stabilizing ageing. Besides mechanical properties, physico-chemical properties are also affected by ageing. This happens due to the metastable structures of the alloy which are formed during ageing of supersaturated solid solution obtained by solution treatment. Rise in temperature changes the atomic positions with corresponding changes in the forces associated with interatomic bonds. At the same time distribution of second phase particles also changes.

With variation in the manufacturing technique of the components, there is variation in mechanical properties at elevated temperatures after heat treatment. Let us, for example, compare the high temperature strength of cast and pressed components of the aluminium alloy containing 4.6–6% Cu, 2.6–3.6% Ni, 1.0% Mg, 0.3% Mn and 0.2% Cr. It can be observed that the pressed components are much superior to the cast components in this respect. On the other hand, the behaviour of cast vis-a-vis pressed components of silumin type alloys is just the opposite. The difference in behaviour is due to the nature of precipitating phases at high temperatures. In the former case, the precipitates that are formed include the $Al_{12}Mn_2Cu$, T (Al_6Cu_3Ni) and $Al_3\ (CuNi)_2$ phases. None of them has any noticeable tendency for growth. In contrast, in the latter case the precipitates, specially the silicon particles, have distinct tendency for growth.

Following steps are associated with the process of precipitation hardening in most of the aluminium alloys:

(i) The first stage preceding the formation of particles of the precipitating phase consists of rearrangement of atoms within the crystal lattice. This constitutes formation of clusters and Guinier-Preston zones. During this process, mechanical properties are improved due to development of microstrains in the lattice.

(ii) Formation of transition structures in the form of modified Guinier-Preston zones (e.g. GP-II zones) and intermediate phases. This may give rise to maximum strengthening in the alloy.

(iii) Formation of stable phase from transition phases whose particles have common boundaries with the grains of the matrix.

(iv) Growth of the certain larger particles at the expense of neighbouring smaller particles. Due to this stress relief takes place in the lattice usually at higher ageing temperatures, which causes considerable decrease in strength and increase in ductility of the alloy.

16.1.4 Heat Treatment of Wrought Aluminium Alloys

Wrought aluminium products are usually supplied in the semi-finished form by the aluminium industries. Non-heat treatable alloys are usually supplied in the form of annealed, semi-hard and hard tempers. For example, 99.3% Al (1230), Al, 1.0–1.6% Mn (3003), and Al, 2,0–2.8% Mg (5052) are supplied in these conditions.

Semi-finished products of heat treatable alloys such as Al, 3.8–4,8% Cu, 0.4–0.8% Mg, 0.4–0.8% Mn (2017), Al, 3.8–4.9% Cu, 1.2–1.8% Mg, 0.3–0.9% Mn (2024), and Al, 5.0–7.0%

Zn, 1.4–2.0% Cu, 1.8–2.8% Mg, 0.2–0.6% Mn, 0.1–0.25% Cr (7075) are supplied to the users in solution heat treated and annealed tempers. Semi-finished products of 2024 type alloys and others may also be supplied in hard temper after solutionizing. This may or may not be aged.

Further, these semi-finished products are shaped into finished products by stamping, extrusion, and other methods of cold working. Recovery, initial and intermediate annealing and precipitation hardening treatment may reduce the number of rejects and can increase productivity of the products.

Annealing of Wrought Alloys

The basic aim of annealing for semi-finished wrought products is to give sufficient plasticity to the product so that it can be cold worked without any problem. The various annealing processes used for semi-finished products of aluminium alloys in industries are: (i) high temperature annealing, (ii) low temperature annealing, (iii) full annealing, (iv) fast annealing, and (v) instantaneous annealing. These are now discussed,

High Temperature Annealing The main purpose of this process is to completely soften the material after cold working. Usually, this process is used for non-heat treatable alloys. The working temperature is around 300–500°C. At such high temperature, recrystallization proceeds at a fast rate. It is essential to avoid grain coarsening during this process. Therefore, care should be taken to restrict holding time and temperature. The optimum values of these two variables differ from one alloy to another. The alloys which are generally given this treatment are (1100), (1230), (3003), (5052), and (5056). The rate of cooling has no bearing on the properties of the alloys.

Low Temperature Annealing This process is useful for non-heat treatable alloys as it increases the plasticity of the cold-worked, semi-finished products. The working temperature is about 150–300ºC. By this treatment, the required strength obtained through work hardening is also maintained. Low temperature annealing is recommended for those alloys which are not suited for high temperature annealing.

Full Annealing This treatment is given to heat treatable wrought alloys such as Al, 3.8–4.8% Cu, 0.4–0.8% Mg, 0.4–0.8% Mn (2017), (2024), Al, 0.4–0.9% Mg, 0.15–0.35% Mn, 0.2–0.6% Cu (6151), and Al, 3.9–4.8% Cu, 0.4–0.8% Mg, 0.4–0.8% Mn, 0.6-1.2% Si (2014). The purpose of full annealing is to impart high plasticity. It is adopted for alloys that have been strengthened by solutionizing and ageing treatment. Temperature for full annealing is chosen between 380°C and 450°C, and holding time is about 10 minutes to one hour.

During this period, the internal stresses are relieved in semi-finished products at large cross-sections. Besides this, the effect of prior cold working is also eliminated during this process. Cooling rate should be fairly slow so that there is sufficient time for diffusion of precipitating phases as also for growth of the particles of precipitating phases. The semi-finished products so annealed can be given a high degree of deformation during cold working.

Fast Annealing A fast annealing treatment is given to semi-finished products, which are in solutionized and aged condition. The aim is to impart plasticity and to relieve partially internal stresses in semi-finished products. The annealing temperature is about 300–415°C, and holding time is 2 to 4 hours. During this period, some growth of precipitated particles take place. Further ageing should be avoided by keeping the annealing temperature at the lower side so that air cooling would not cause ageing.

Instantaneous Annealing This treatment is given to (2017) and (2024) type of alloys for eliminating the effect of cold working in semi-finished products. The working temperature is about 350–380°C, and holding time is very small, i.e. for about 1 or 2 minutes. This is followed by air cooling. The semi-finished product is heated in nitrate baths with water as cooling medium. The product is rinsed in warm water and the moisture from the surface is wiped out. By giving such an annealing treatment, the semi-finished products become amenable to further deformation during cold working.

Strengthening Heat Treatment of Wrought Aluminium Alloys

According to the phases present, heat treatable aluminium alloys are classified as follows: (i) Al-Cu-Mg-Mn system, (ii) Al-Mg-Si and Al-Mg-Si-Cu system, (iii) Al-Zn-Mg-Cu system, (iv) Al-Cu-Mg-Fe-Ni system, and (v) Al-Cu-Mn system. The mechanical properties of these alloys also vary over a wide range. We shall now discuss these systems one by one.

Alloys of Al-Cu-Mg-Mn System These were the first heat treatable alloys to be discovered. They are also known as duralumin. The chemical composition of this type of alloys is Al, 2.5–6.0% Cu, 0.4–2.8% Mg, 0.4–1.0% Mn. Two examples of this system are Al, 3.8–4.8% Cu, 0.4–0.8% Mg, 0.4–0.8% Mn (2017), and Al, 3.8–4.9% Cu, 1.2–1.8% Mg, 0.3–0.9% Mn (2024). These alloys find wide applications in engineering and aircraft industries in the form of forgings, extrusions, sheet, plate, tube and rivets.

These alloys have low corrosion resistance due to the presence of copper. So they are clad on both sides by aluminium of 99.5% purity. A detailed discussion of precipitation hardening during ageing of duralumin alloy (Al, 4.5% Cu, 1.5% Mg, 0.6% Mn) follows. The phases and mechanisms involved for Al-Cu system is considered since duralumin is a complex alloy.

(i) *Precipitation hardening of Al-4.5% Cu alloy.* The precipitation process can be explained by considering the aluminium rich portion of Al-Cu system (see Figure 16.3). The equilibrium solid solubility of copper in aluminium increases as temperature rises. At 250°C, the solid solubility of copper in aluminium is about 0.20%. The maximum solid solubility of copper in aluminium is 5.65% at 548°C eutectic melting temperature.

In precipitation heat treatment, the alloy is first solutionized by heating into a single phase region at about 490–500°C and soaking for sufficient time to permit required diffusion. Copper goes into solid solution completely. (At temperatures below solvus line, the equilibrium state consists of solid solution α plus an intermetallic compound phase θ ($CuAl_2$).) After solution treatment, the alloy is quenched in water to get supersaturated solid solution (SSS). The rapid cooling prevents formation of equilibrium precipitates. If alloy is left at room temperature for sufficiently long time, natural ageing is said to occur. If it is reheated to slightly higher temperatures, say about 130°C, artificial ageing takes place. Due to sluggish diffusion rates at these temperatures, the solute atoms have limited mobility. The atom can move over only a few tens of interatomic distances. This gives rise to formation of fine scale transition structure (100 Å in dimension). The fine precipitates so formed within the matrix lead to local distortions and strain fields which restrict dislocation motion. This, in turn, increases the strength of the alloy.

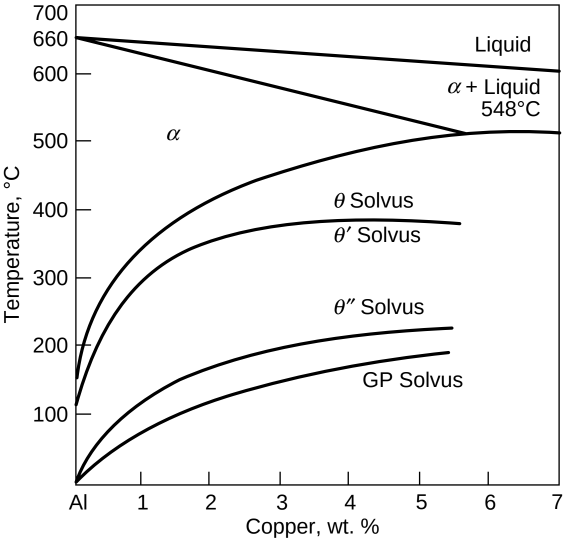


Figure 16.3 Aluminium-copper phase diagram along with metastable phase boundaries at aluminium end.

(ii) *Steps in ageing process.* The several stages associated with ageing are identified by the following sequence:

$$\begin{array}{c} \text{SSS} \rightarrow \text{GP-I zone} \rightarrow \text{GP-II zone (or } \theta'') \\ \downarrow \\ \theta' \\ \downarrow \\ \theta \\ (\text{CuAl}_2) \\ \text{equilibrium phase} \end{array}$$

GP-zone I and GP-zone II constitute the first two transition structures. Age hardening processes are best studied by X-ray diffraction and electron microscopy. The Laue method was adopted by Guinier and Preston and they observed streaks in X-ray pattern df aluminium-copper system. Appearance of these streaks was associated with segregation of copper rich areas in a plate like shape. These are known as Guinier-Preston (GP) zones after the name of the investigators.

Oscillating single crystal X-ray technique using monochromatic radiation has also been successfully applied to study this stage of precipitation in aluminium-copper alloys, by applying the X-ray small-angle scattering (SAS) technique. The structural changes that take place during ageing can be investigated conveniently by transmission electron microscopy with the help of thin foils. The structure of precipitated phases is revealed by electron diffraction studies.

These techniques have revealed that the GP-zones consisting of solute atoms are coherent with respect to the matrix. A coherent precipitate is one in which there is a one-to-one alignment between the two structures. This coincidence of dimensions is achieved only by introducing some lattice distortions. This stage is followed by sequence of formation of partly coherent and by equilibrium non-coherent precipitate which is stable.

Al-Cu alloys show GP-I zones which are ordered copper rich clusters of atoms about 100 Å long and about three atoms thick, segregated on (100) planes of aluminium. They are completely coherent with respect to the matrix of aluminium (see Figure 16.4). Due to difference in atomic radii of two, elastic strain energy develops. GP-I zone gives rise to first hardness peak in Al-4.5% Cu alloy aged at 130°C. This is shown in Figure 16.5. This figure also shows variation of hardness with time for other Al-Cu alloys aged at 130°C.

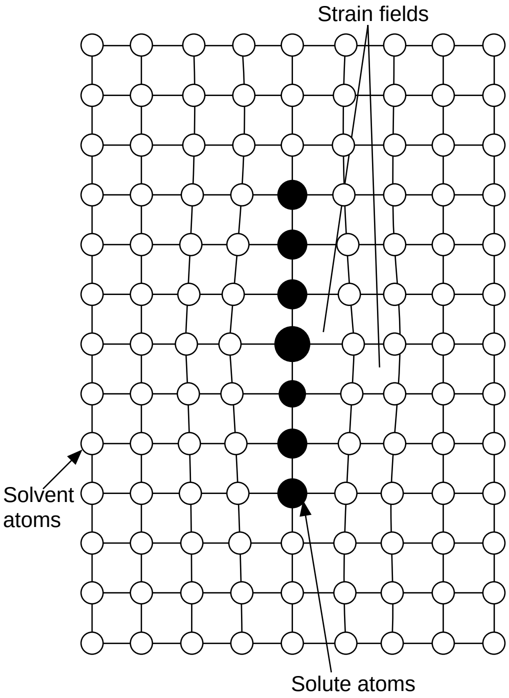


Figure 16.4 Coherency strains associated with presence of solute atoms having larger radii than the solvent atoms.

As the clusters grow in dimensions, an intermediate coherent precipitate (GP-II zone) forms. GP-II zones are about 150 Å thick and 1500 Å in diameter. In this case, coherency is only along diameter of zone. Therefore, it produces compressive strain along thickness. It has tetragonal structure. In this respect it resembles the equilibrium phase $CuAl_2$. Its lattice coincides with the lattice of unit cell of aluminium in *a* and *b* directions with mismatch in the direction, as shown in Figure 16.6. With the growth in the size of the precipitate, there is corresponding increase in the strain field. Accordingly, a second peak in the hardness plot is observed due to emergence of GP-II zones. In the next stage, θ' precipitate (a = 4.04 Å and c = 5.8 Å) appears. With this, coherency is gradually lost and softening of the alloy starts. When the tetragonal equilibrium precipitate $CuAl_2$ (θ) is formed (with a = 6.06 Å and c = 4.87 Å), coherency is lost fully, resulting in complete loss of hardness. This process is termed *overageing*.

If alloy is heated above 200°C after the appearance of the GP-zone, the zones redissolve. So, GP-zones do not exist above 200°C, as is clear from Figure 16.3. This process is called *reversion*. The service temperature of an age-hardened alloy should be less than the ageing temperature to avoid coarsening of precipitate particles.

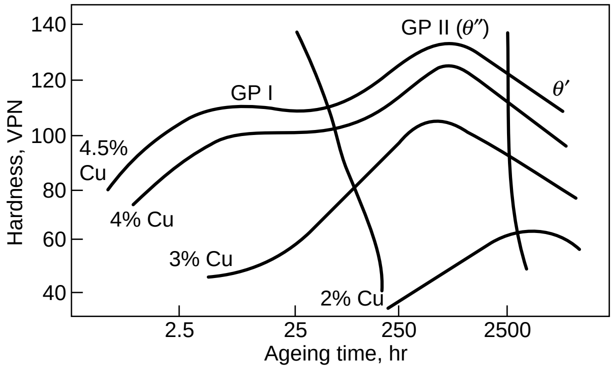


Figure 16.5 Ageing curves for a set of aluminium-copper alloys aged at 130°C.

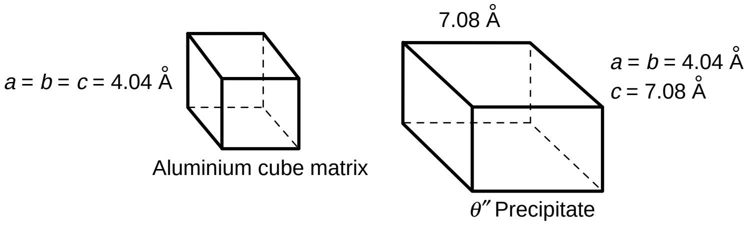


Figure 16.6 Coincidence of the lattice dimensions of θ'' and aluminium.

(iii) *Mechanism of precipitation hardening.* Dislocation theory explains the actual hardening mechanism. The precipitated particles or zones interact with dislocations. The strain fields associated with dislocations interact with the strain fields created around the precipitates or zones. Fine precipitates which are closely spaced hinder the movement of dislocations in the matrix. Moving dislocations can overcome the obstacle either by cutting through the precipitates or by bending and by passing them.

The cutting mechanism is operative when the precipitate particles are small (less than 50 A in size) and are coherent with respect to the matrix. Figure 16.7(a) explains how steps are created at the interface due to such cutting action. Coupled with this, other surface imperfections such as stacking faults are also created within the particle by the cutting mechanism. Both these factors result in increased resistance to dislocation motion.

With larger particles (particle size range is 100–500 Å), the second mechanism, namely, bending of dislocation around the particles and their subsequent bypassing, becomes operative. This is explained in Figure 16.7(b). The mechanism of bypass of dislocation resembles the Frank-Read source. The stress needed for bending at dislocation is inversely proportional to average inter-particle spacing. Hence, when the particles are fine and are closely spaced, there is considerable increase in the level of stress required for bending and bypassing of dislocations. This condition is satisfied when the precipitation hardenabie alloy has been aged to optimum level. When the alloy is overaged, particles become coarse (with size greater than 1000 Å); correspondingly, the dislocations are able to bypass them with ease at low stress levels.

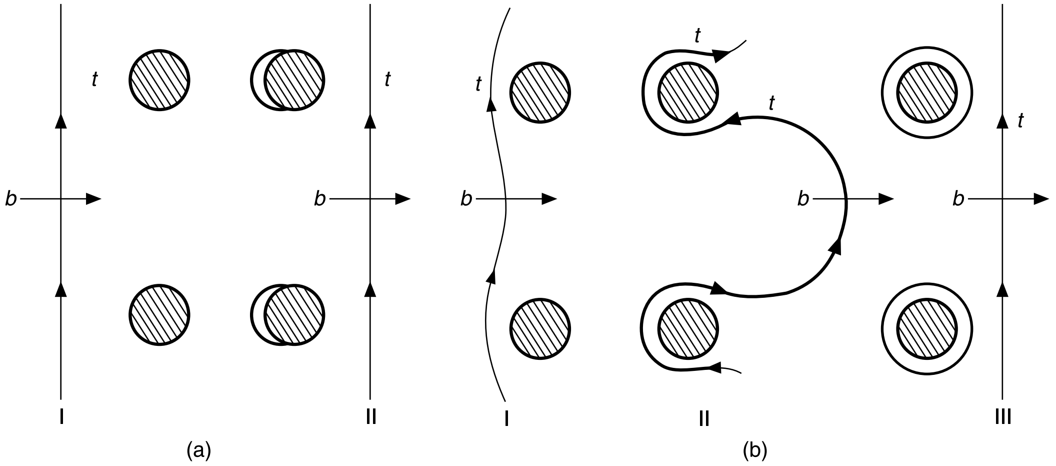


Figure 16.7 **(a) Cutting of precipitate particle by a moving dislocation, (b) Bending of a moving dislocation to bypass precipitate particles.**

Al-Mg-Si Alloys These alloys show medium strength, good formability, satisfactory corrosion resistance, and fair weldability. They are not suitable for elevated temperature service. When Mg and Si are present in correct proportion, the intermetallic compound Mg_2Si forms. These alloys are used in the naturally aged condition or fully heat treated condition. For full ageing, the alloy is solution treated at 516–545°C and quenched in cold water. The quenched alloy may be aged at room temperature. For example, solution treated 6061 alloy is aged for 48 hours at room temperature to obtain T4 temper. Artificial ageing is carried out at 170–180°C for 6–10 hours for T6 treatment of the same alloy. Two important compositions of the alloys of this group are: Al, 0.7% Mg, 1.0% Si, 0.6% Mn and Al, 1.0% Mg, 0.6% Si, 0.25% Cu, 0.25% Cr (6061).

The age hardening in Al-Cu-Mg-Si alloys is due to $CuAl_2$ and $CuAl_2Mg$. In properly heat treated alloy, these phases are very fine and cannot be detected by optical microscope. Mg_2Si phase is also present, but this phase does not dissolve during solutionizing at 500°C and so it does not play any role in ageing process. On quenching, copper has tendency to precipitate on the α (AlMnFeSi) intermetallic phase.

Al-Zn-Mg-Cu System This group of alloys shows maximum strength. The alloys are mainly used in aircrafts in the form of forgings, extrusions and clad sheets. Two compositions of commercial importance in this group of alloys are DTD 5024 (Al, 5.5% Zn, 2.8% Mg, 0.45% Cu, 0.5% Mn) and DTD 5075 (Al, 5.8% Zn, 2.5% Mg, 1.4% Cu, 0.15% Mn, 0.2% Cr).

These alloys are solutionized at about 460–470°C. If alloys are heated above 480°C, melting may occur. Artificial ageing at 110–135ºC is preferred for these alloys. The age hardening phase is $MgZn_2$. This is a very fine phase and cannot be detected by optical microscope. Earlier, there was a problem of stress corrosion susceptibility. But this has been overcome by quenching in molten salt media at 180°C after solutionizing or giving a second ageing treatment at about 165–180°C.

Al-Cu-Mg-Fe-Ni System In these alloys, copper and magnesium are the major alloying additions, besides iron and nickel. The special feature of this group of alloys is their complex composition. These are also known as RR (Rolls Royce) alloys. The composition of two common alloys of this group are: Al, 3.5–4.5% Cu, 0.4–0.8% Mg, 1.8% Ni, 0.5–1 % Fe, 0.5–1.0% Si (2016) and Al, 1.9–2.5% Cu, 1.4–1.8% Mg, 1.1% Ni, 1.0–1.5% Fe, 0.2-0.1% Ti (2618; Rolls Royce designation RR 58).

These alloys have lower copper to magnesium ratio in comparison to duralumin type alloys. They are used for the manufacture of impeller components for compressors, pistons, large ventilator blades, and other components for room temperature and elevated temperature service. The phases which are responsible for strengthening are Mg_2Si and S (Al_2CuMg). Due to higher amount of S (Al_2CuMg) phase and lower amount of Mg_2Si phase, the alloy has better heat resistant property. Due to higher nickel content, Al_6Cu_3Ni phase is formed. It is insoluble in solid solution and so decreases the strength at room temperature. 2016 alloy is solutionized at 530°C, followed by water quenching, while 2618 (RR 58) alloy is quenched from 535°C. Both alloys are artificially aged at 170°C for 10–16 hours. However, it is better to age 2016 alloy at 190°C for 10 hours. Depending on the requirement, the ageing temperature may even be raised to 240°C with ageing time limited to 1 or 3 hours. The forging temperature for these alloys is about 350–480°C. Annealing is done at 430ºC for 3–5 hours, followed by slow cooling.

Al-Cu-Mn System The alloys of this group are marketed in the form of sheets, semi-finished pressed products and forgings. The chemical compositions of two typical alloys of this group are: Al, 6–7% Cu, 0.4–0.8% Mn, 0.1–0.2% Ti, 0.3% Fe, 0.3% Si, 0.1% Zn, 0.05% Mg and Al, 6–7% Cu, 0.25–0.45% Mg, 0.4–0.8% Mn, 0.1–0.2% Ti, 0.3% Fe, 0.1% Zn.

In annealed condition, the phases that exist in the alloy are a-solid solution, $CuAl_2$, T ($Al_{12}Mn_2Cu$), Al_3Ti, and AlSiMnFe. The thicker sections of the second alloy may have S (Al_2CuMg) as an additional phase. Both the alloys show good response to heat treatment. The solutionizing temperature varies from 525°C to 535°C. To make solutionizing more effective, it is advisable to take recourse to step-wise heating. The alloy is held at 500°C for half the holding time. Such step-wise heating is specially recommended for the second alloy. The first alloy may be artificially aged by holding its sheets at 160–170°C for 10–12 hours, followed by air cooling. For press products, holding time is kept 6–12 hours at 220°C, followed by air cooling. Semifinished products of the second alloy are artificially aged at 180–190°C for 12–16 hours, followed by air cooling,

16.1.5 Heat Treatment of Cast Aluminium Alloys

Cast aluminium alloys are also often heat treated. Heat treatment markedly improves the properties of such alloys. Generally, cast alloys require much longer holding time at the solutionizing temperature as compared to wrought alloys. The pressure die casting alloys such as LM2 (Al, 10% Si, 1.5% Cu) and LM24 (Al, 8.5% Si, 3.5% Cu) are not heat treated because in these alloys air is entrapped during casting process and this air may expand and distort the castings at solutionizing temperature.

Cast aluminium alloys may be divided into following groups according to their properties and chemical composition:

(i) *Alloys with high silicon content.* These include binary Al-Si alloy of type LM6, ternary Al-Si-Cu alloy of type LM4 (5% Si, 3% Cu) and quaternary Al-Si-Cu-Mg alloy, e.g. an alloy of composition, Al, 5% Si, 1.5% Cu, 0.5% Mg.

(ii) *Alloys with high magnesium content.* Examples are binary Al-Mg alloy (Al, 10% Mg) and quaternary Al-Mg-Si-Mn alloy (Al, 5.5% Mg, 0.8–1.3% Si, 0.1–0.4% Mn).

(iii) *Alloys with high copper content.* (4% and more). Examples are binary LM11 (Al, 4.5% Cu) and quaternary Al-Cu-Mn-Ti alloy (Al, 4.5–5.3% Cu, 0.6–1.0% Mn, 0.25–0.45% Ti).

(iv) *Alloys with high zinc content.* These include Al-Si-Zn (Al, 6.0–8.0% Si, 10–14% Zn).

(v) *Alloys with complex chemical compositions used for high temperature service.* Examples of such alloys are LM14 (Al, 4% Cu, 2% Ni, 1.5% Mg), also known as 'Y' alloy, and RR 350 (Al, 5% Cu, 1.5% Ni with small additions of Mn, Ti, Sb, Co and Zr).

Alloys with High Silicon Content

Alloys of aluminium-silicon series (e.g. LM4, LM8. and LM25) have best casting characteristics such as small shrinkage, excellent fluidity, good gas impermeability and low tendency for crack formation after solidification. Therefore, these alloys are widely used for production of all types of casting. They also have good corrosion resistance. Table 16.3 shows some of the aluminium casting alloys, including alloys from other groups. Binary (Al, 12% Si) alloy is not heat treatable.

Al-Si-Cu Alloys Addition of copper in Al-Si alloy increases the strength and machinability, but corrosion resistance castability and ductility are adversely affected. Addition of copper to Al-Si alloy makes the alloy heat treatable since copper has precipitation hardening effect. LM4 alloy (Al: 5% Si, 3% Cu) is a typical alloy in this category. This alloy is solutionized at 505–520°C for 6–16 hours, followed by water quenching at 70–80°C. It is then artificially aged at I50–170°C for 6–18 hours. This is a general engineering alloy and can withstand relatively high static loads in fully heat treated condition.

As a result of studies carried out with the aim of maximizing strength with improved casting characteristics, a new alloy, namely, AI (11% Si, 3% Cu), has been developed. This is a low cost secondary material and is used as piston alloy. It can be used safely at elevated temperature since it maintains good level of strength and hardness at high temperatures. In the cast condition, the alloy has tensile strength of 190 MPa with 1.5% elongation. This alloy is artificially aged at 200–210°C for 7–9 hours. After this treatment, tensile strength increases to 250–320 MPa with 2–8% elongation.

Al-Si-Mg Alloys Small quantities of magnesium are added to the cast Al-Si alloys. LM8 (Al: 5.5% Si, 0.6% Mg) and LM25 (Al: 7% Si, 0.3% Mg) are examples of this type of alloys. Besides Mg and Si, elements such as Fe, Mn, Cu, and Zn are present in these alloys as impurities. These alloys are used in carburettor parts, pump castings, and so on. They show superior casting characteristics and properties as compared to Al-Si-Cu alloys. LM25 alloy is solution heat treated at about 535°C for 2–6 hours. The dissolution rate of Mg_2Si phase at solution heat treatment temperature is rapid. Artificial ageing is carried out at 150–180°C for 3–5 hours.

Al-Si-Cu-Mg Alloys The most common alloy of this group contains 4.5-5.5% Si, 1.0–1.5% Cu, 0.35–0.6% Mg, and balance Al. Fe and Zn are present as impurities. These alloys show relatively good casting properties. Gas absorption and cracking tendency are low. This alloy contains $CuAl_2$ phase when copper content is higher and magnesium content lower. On the other hand, Mg_2Si phase is present when the copper content is lower and magnesium content higher. When iron impurity is higher, AlCuSiFe phase may form. This phase neither dissolves properly during solution treatment nor does it contribute to the process of precipitation hardening. On the contrary, $CuAl_2$ and Mg_2Si phases participate fully and contribute to precipitation hardening process. This alloy is solutionized at 525°C for 6 hours, followed by quenching in boiling water. Subsequently, it can be aged at room temperature for 5 days to obtain UTS of 227 MPa and percentage elongation 0.8. If aged for 5 hours at 225°C, its ductility improves. It has then UTS 270 MPa with percentage elongation of 1.4.

Alloys with High Magnesium Content

All commercial aluminium-magnesium (such as Al, 10% Mg) alloys are highly resistant to corrosion. Homogenized alloys have excellent strength (450 MPa) with good ductility (percentage elongation of 10–25). This alloy is used in marine environment as the alloy shows excellent corrosion resistance to sea water. This alloy poses some problems during casting, such as increased tendency for oxidation. Small addition of beryllium lessens this effect. Due to gas-mould interaction, hydrogen is picked during solidification of this alloy. This gives rise to pin hole porosity. This effect can be minimized by using inhibitors in moulds. Five percent boric acid has been used successfully as inhibitor. Besides this, the alloy has a tendency to pick up silicon and iron, which affects its mechanical properties adversely due to formation of intermetallic phases Al_3Fe and Mg_2Si. In spite of these disadvantages, it is preferred for applications involving high vibrational stresses or service in moist atmospheres and marine environments. However, the alloy can be used satisfactorily only up to 50°C.

Intermetallic phase β (Mg_2Al_3) is formed in the alloy LM10 (Al, 10% Mg). The higher the difference in the magnesium concentration between the grain boundaries and the interior of the grains of α-solid solution, the faster will be the rate of dissolution of the β-phase. Hence, it becomes necessary to increase the soaking time for solution heat treatment so as to ensure that the β-phase is fully dissolved in the α-solid solution. This is so because of the localized increase in the magnesium content in the grains. The time required for full homogenization of LM10 alloy at 430°C is 10–20 hours. In contrast, the alloy containing 12 percent magnesium requires corresponding holding time which is 25 percent longer as compared to the time required for the alloy with 10 percent magnesium content.

The alloy, after solutionizing heat treatment, is quenched in hot oil and used in quenched condition. It has high ductility in this condition. This alloy has tendency to age naturally with time. Due to this, the strength increases and ductility decreases with time and the alloy shows embrittling effect. This is due to the precipitation of β-phase along the grain boundaries, which can be avoided by reducing the magnesium content to 8 percent and adding 1.5 percent zinc. This minimizes the natural ageing tendency. When zinc is added, $Mg_3Zn_3Al_2$ phase is formed. So the addition of zinc alters the composition and distribution of the precipitating phase.

Alloys with High Copper Content

The binary aluminium-copper alloys are one of the oldest casting alloys. Now only LM11 (Al, 4.5% Cu) finds application for the manufacture of small machine parts of simple shape of aircraft castings and for castings which have to withstand high stresses. This application is based on good mechanical properties and resistance to shock associated with this alloy. The foundry characteristics and corrosion resistance of these alloys are considerably inferior in comparison to Al-Si type alloys. Alloys with higher amount of copper show tendency towards hot shortness. Therefore, only sand casting is preferred. In order to improve fluidity and to decrease the tendency towards hot shortness, silicon is added up to 3 percent in LM11 alloy. This forms ternary eutectic (α + Si + $CuAl_2$). Binary aluminium alloys with higher copper content consist of α-solid solution plus $CuAl_2$. The higher the copper content and coarser the grain structure, the longer is the holding time required for complete solutionization. Soaking for 15–16 hours is done in normal practice. This alloy should be quenched immediately after solution treatment because diffusion of copper in solid aluminium is comparatively high. Artificial ageing is done at 120–170°C for 12–14 hours. This alloy is getting progressively replaced by others.

Alloys with High Zinc Content

One of the aluminium alloys of this group contains 10–14% Zn, 6–8% Si, 0.1–0.3% Mg. Fe, Mn, and Cu are present as impurities. This alloy is prone to formation of porosity. Hence, the alloy requires modification. It has good casting properties, high fluidity and low linear shrinkage. This is a self-hardening alloy. Solution heat treatment has no significant effect on Al-Si-Zn type alloys. Therefore, such alloys are used in as-cast condition with special solutionizing treatment. Internal stresses of the castings can be removed by heating the alloy to 170–180°C for 5–10 hours or heating to 250–300°C for 3 hours.

Another alloy of Al-Zn-Mg-Cu system, which contains 3.5–4.5% Zn, 1.4–1.75% Mg, and 0.3–0.6% Cu, has very good mechanical properties. This alloy is solutionized at 460–480°C for 3–5 hours, followed by quenching in water. After quenching, it is artificially aged at 160°C for 12–16 hours.

Alloys with Complex Chemical Compositions

In this category comes alloys of type LM4 (Al, 4% Cu, 2% Ni, 1.5% Mg), also known as ‘Y’ alloy. This alloy maintains strength even at high temperatures (300°C), Due to this unique property, it is very popular as piston material. Corrosion resistance of this alloy is quite good. LM4 was developed by the British National Laboratory during World War I, This alloy has certain limitations. It has a tendency towards hot cracking and has low fluidity and high coefficient of linear shrinkage. The phases present in this alloy include $NiAl_3$, Al-Cu-Ni, Mg_2Si, and small amounts of $CuAl_2$. The alloy is solution heat treated at 515ºC. Holding time depends on the structure of the alloy. Fine grained alloy requires 3–5 hours, whereas coarse grained alloy needs 6–10 hours. This alfoy can be either naturally or artificially aged at 100°C The recommended ageing treatment for piston material is ageing at 220°C for 10–16 hours. For complete removal of the internal stresses, the ageing temperature can be raised to 250–300°C.

To overcome the drawbacks of ‘Y’ alloy, a new alloy which contains 4.6–6% Cu, 2.6–3.6% Ni, 0.8–1.5% Mg, 0.10–0.25% Cr, and 0.18–0.35% Mn with impurities like Fe, Si and Zn, has been developed. Addition of chromium and manganese considerably increases the heat resistance of the alloys. As many phases are present in this alloy, its plasticity gets lowered to some extent. This can be improved either by decreasing the amount of Mg, Cr and Mn or by adopting isothermal quenching. Various phases which are present in this alloy are α-solid solution, TNi (Al_6Cu_3Ni), SNi [Al_3 $(CuNi)_2$], and chromium and manganese containing phases. These phases are responsible for making this alloy heat resistant. The alloy is initially solutionized at 500°C for 5 hours, it is further heated to 525°C and soaked for 3–5 hours for final solution treatment. As a result of step-wise heating, better properties are achieved. After final solution treatment, it is quenched in hot water. Components which are to operate at 300–350°C in actual service must be aged at 300°C for 3–7 hours.

16.2 MAGNESIUM ALLOYS

Magnesium (wrought and cast) alloys are very popular in aerospace industries because of their low density (1.8 gm/cc), high strength to weight ratio, good damping capacity, ease of machinability, and relatively high thermal and electrical conductivity. These alloys are processed in the form of castings, forgings and extrusions, and show good dimensional stability up to 100°C.

Wrought forms of magnesium alloys are used in aircraft fuel tanks, ducts, wings and flaps in the form of sheets. The extrusions are used in seat frames. Forgings are used in aircraft engine-bearing caps, housings and socker arm supports. Wrought alloys that can be strengthened by heat treatment are grouped on the basis of their composition as follows:

(i) Magnesium, aluminium and zinc (e.g. AZ80A)
(ii) Magnesium, thorium and zirconium (e.g. HK31A)
(iii) Magnesium, thorium and manganese (e.g. HM21A)
(iv) Magnesium, zinc and zirconium (e.g. ZK60A)

Table 16.4(a) shows the heat treatment, chemical composition and properties of some of the wrought alloys. Due to high strength to weight ratio, magnesium casting alloys are finding increasing applications in aerospace industries for a variety of components such as jet engine parts, landing wheel, helicopter gear box housings, cockpit canopies, missile bodies and rudder. Casting alloys that can be heat treated are grouped (on the basis of compositions) as follows:

(i) Mg-Al-Mn system (e.g. AM100A)
(ii) Mg-Al-Zn (e.g. AZ63A, AZ9IC)
(iii) Mg-R_E (rare earth metals)—Zn-Zr (e.g. EZ33A, ZE41A)
(iv) Mg-R_E (rare earth metals)—Ag-Zr (e.g. QE22A, QH21A)
(v) Mg-Th-Zr (e.g. HK31A, ZH62A).

Table 16.4(b) shows the heat treatment, composition and properties of important cast magnesium alloys.

Solutionizing treatment improves the strength and gives very good toughness and shock resistance to the magnesium alloys. Precipitation hardening after solutionizing treatment of magnesium alloys improves hardness and strength, while toughness is decreased by a marginal extent. In this respect, its behaviour is similar to aluminium alloys. Annealing of wrought products is beneficial because it improves plasticity of the alloy with loss of strength which makes the alloy suitable for fabrication operations. Solutionizing temperature, time, quenching media, artificial ageing temperature and time are important parameters which change the

Table 16.4(a) Heat Treatments, Nominal Composition and Mechanical Properties of Wrought Magnesium Alloys

Alloy designation	Heat treatment	Nominal composition						Tensile strength (MPa)	Yield strength (MPa)	Elongation (percent)	Hardness, BHN (500 kg 10 mm)
		Al	Mn	Zn	Th	Zr	Rare earth				
					Extruded Bars and Shapes						
MIA	F		1.2					250	176	12	44
AZ31B	F	3.0	0.2	1.0				258	197	15	49
AZ61A	F	5.5	0.2	1.0				300	225	16	60
AZ80A	T5	8.5		0.5				370	270	7	80
ZK60A	T5			5.5		0.5		360	300	11	82
					Sheet and Plate Alloy						
AZ31B	H24	3.0	0.2	1.0				285	220	15	73
HK31A	H24				3.52	0.7		250	217	8	
HM21A	T8		0.5		2.0			230	170	10	
ZE10A	H24			1.25			0.17	258	190	13	

Basic temper designation W = solution heat treated; unstable temper; T = heat treated to produce stable tempers other than F, O or H; T2 = annealed (cast products only); T3 = solution heat treated nad cold worked; T4 = solution heat treated; T5 = artificially aged only; T6 = solution heat treated and artificially aged; T7 = solution heat treated and stabilized; T8 = solution heat treated, cold worked and artificially aged; T9 = solution heat treated, artificially aged and cold worked; T10 = artificially aged and cold worked.

Table 16.4(b) Heat Treatments, Nominal Composition and Mechanical Properties of Cast Magnesium Alloys

Alloy designation	Heat treatment	Nominal composition						Tensile strength (MPa)	Yield strength (MPa)	Elongation (percent)	Hardness, BHN (500 kg 10 mm)
		Al	Mn	Zn	Th	Zr	Rare earth				
AM100A	T6	10.0	0.1					270	150	1	69
AZ63A	T6	6.0	0.2	3.0				270	130	5	73
AZ81A	T4	7.5	0.15	0.7				270	82	15	55
AZ91A	T6	9.0	0.2	0.7				270	130	5	70
AZ92A	T6	9.0	0.1	2.0				270	150	3	81
ZK51A	T5			4.5		0.7		270	163	8	65
ZK61A	T5			6.0		0.7			184		68
ZK61A	T6			6.0		0.7			190		70
ZE62A	T5			5.7	1.8	0.7		265	177	4	70
AE41A	T5			4.25		0.5	1.25	204	136	3.5	62
EK30A	T6					0.6	4.0	156	109	3	45
EK41A	T6					0.2	3.0	170	122	3	50
EZ33A	T5			2.7		0.5	3.0	156	109	3	50
HK33A	T6				3.25	0.7		217	102	8	66
HZ32A	T5			0.2	3.25	0.75		184	88	4	55

mechanical properties of the alloy. The optimum combination of these factors considerably improves the strength and hardness of the alloy. The temper designation for magnesium alloys is the same as the one adopted for aluminium alloys.

16.2.1 Types of Heat Treatment

Heat treatment of magnesium alloys is carried out in order to improve mechanical properties or to relieve internal stresses produced during solidification in cast alloys or during cold and hot working, shaping and forming of wrought alloys. Various types of heat treatment which are commonly carried out for wrought and cast magnesium alloys are: (i) Annealing and stress relieving, (ii) solution heat treatment, and (iii) precipitation hardening. We now discuss these three types of heat treatment.

Annealing and Stress Relieving

Depending on the composition, wrought magnesium alloys which have been strain hardened to various degrees, i.e. which are in different tempers, can be annealed in the temperature range 290–245°C by soaking for 1 or 2 hours. By this treatment, a product is obtained in the fully annealed condition. In wrought alloys, mostly forming operations are carried out at elevated temperature. So there is no need of fully annealed wrought material. Table 16.5 shows the annealing temperatures for wrought magnesium alloys.

Table 16.5 Annealing Temperatures for Commercial Wrought Magnesium Alloys

Alloy designation	Remarks	Annealing temperature (ºC)
AZ31B	As fabricated and strain hardened and annealed	345
AZ3IC	As fabricated	345
AZ61A	As fabricated	345
AZ80A	As fabricated and heat treated	385
HM21A	Heat treated	455
HM31A	Heat treated	455
ZK60A	As fabricated and heat treated	290

Internal stresses in wrought magnesium alloys, produced through cold and hot working, welding and other forming techniques, are removed by stress relieving treatment. Table 16.6 gives the optimum stress relieving time and temperature for wrought alloys.

Residual stresses can also be produced in magnesium casting alloys as a result of solidification, non-uniform cooling after heat treatment, or quenching. Machining operations are also responsible for residual stresses in the castings. Therefore, it is preferable to carry out intermediate stress relieving operations before final machining. Stress relieving temperature and time should be such that the mechanical properties are not affected significantly. In this process, the casting is heated from 220ºC to 360°C for 2–6 hours. Mg-Al-Mn and Mg-Al-Zn type alloys of all temper are stress relieved at 260ºC for 1 hour. ZE41A type alloys for all temper are stress relieved at 330°C for 2 hours. By this treatment, there is no major change in the mechanical properties of the alloy.

Table 16.6 Stress-relieving Temperatures and Time for Commercial Wrought Magnesium Alloys

Alloy designation	Heat treatment	Sheet				Extrusions and forgings	
		Annealed		Hard rolled			
		Temperature (ºC)	Time (min)	Temperature (ºC)	Time (min)	Temperature (ºC)	Time (min)
AZ31B		345	120	150	60		
AZ31B	F					260	15
AZ61A		345	120	205	60		
AZ61A	F					260	15
A280A	F					260	15
AZ80A	T5					205	60
HK31A		345	60	290	30		
HM2IA	T5					370	30
HM21A	T8			370	30		
HM21A	T81			400	30		
HM31A	T5					425	60
ZK60A	F	230	180			260	15
ZK60A	T5					150	60

Solution Heat Treatment

In this treatment, the alloying elements dissolve into solution and form a single-phase solid solution. Solutionizing temperature for magnesium cast alloys varies from 350°C to 490°C and soaking time varies from 8 hours to 24 hours. Solutionized components are air cooled. In fact, solutionizing temperature and time depend on the alloy composition, temper and thickness and section size. This treatment improves tensile strength, ductility and toughness. Proof stress and hardness are lowered marginally. Solution treatment should be carried out below the temperature at which eutectic melts. The alloy is further air cooled and is stable at room temperature. At room temperature these alloys do not harden by ageing.

Precipitation Hardening

This treatment is carried out after solutionizing treatment so that the precipitation of some fine, coherent particles takes place. Ageing temperature varies from 130°C to 230°C. Ageing is carried out for 5–16 hours. In some cases, ageing time may be up to 48 hours. The alloy is then cooled in air. With this treatment, strength and hardness of the alloy increases further with some loss in ductility.

16.2.2 Heat Treatment of Mg-Al-Zn Alloys

For solutionizing treatment, Mg-Al-Zn alloys are soaked at a temperature of 260°C. The material is charged into the furnace at room temperature and brought to soaking temperature in about 2 hours by slow and uniform rate of heating.

A typical sand cast alloy AZ92A (Mg, 9% Al, 2% Zn and 0.1% Mn) can be solutionized at about 407–412°C by soaking for 16–24 hours. When complete solutionizing occurs, the alloy becomes single phased. In this case, aluminium is the major alloying element responsible for strengthening. Zinc and manganese are added to improve corrosion resistance. Since zinc and manganese dissolve in α and β solid solutions, this alloy can be considered as a binary alloy of Mg-Al. The solid solubility of aluminium decreases with lowering of temperature. Beta is a brittle intermediate phase ($Mg_{17}Al_{12}$) that occurs in this system. At solutionizing temperature, this phase gets dissolved. At room temperature, the mixture of alpha and beta phase is stable. The eutectic is composed of alpha and beta phase, the alpha phase joins the primary alpha grains, leaving behind the compound ($Mg_{17}Al_{12}$) as white network. This intermetallic compound may be retained on fast cooling and may reappear at a temperature at which the atoms have enough mobility to cause some precipitation of this compound (beta phase) as fine particles within the grains. Artificial ageing is carried out at 218°C for 5 hours. However, care should be taken to check oxidation and occurrence of incipient fusion due to zinc segregation. For this reason, zinc is kept below 3 percent, The use of sulphur dioxide (about 1 percent SO_2 by volume) as protective atmosphere is useful in preventing oxidation in these alloys. Table 16.7 shows time and temperature of solution heat treatment and ageing for some cast magnesium alloys.

16.3 TITANIUM ALLOYS

Titanium and its alloys give a variety of light weight strong materials with good fatigue and corrosion resistance. It is used as substitute for aluminium alloys in aircraft structure subjected to service in the temperature range 200–500°C.

There are two allotropic forms of titanium, namely, alpha (α) titanium having a close-packed hexagonal crystal structure, up to 882°C, and beta (β) titanium having body centred cubic structure which is stable above 882°C. Commercially pure titanium contains residual amounts of oxygen, nitrogen, carbon, iron, and so on. The total amount of residuals does not exceed 0.5%.

Addition of alloying elements to titanium affects the α to β transformation temperature. Aluminium is an α-stabilizer, i.e. when aluminium is added, the α to β transformation temperature is raised. Chromium, molybdenum, vanadium, manganese and iron are some of the well-known β-stabilizers. When these elements are added, the α to β transformation temperature is lowered.

The relative amounts of α and β stabilizing elements in titanium alloy, and the heat treatment determine whether its microstructure would be mainly α, a mixture of α and β, or single phase β over the range of desired temperature. On the basis of phases present, titanium alloy may be of three basic types, namely, α, β, and α-β alloys, α-alloys show excellent weldability, good strength at high and low temperatures, and stability at moderate temperatures for sufficiently long duration. The α-β alloys are two-phase alloys at room temperature and are stronger than α-alloys. They are basically forging alloys. β-aIloys retain their structure at room temperature and can be age-hardened to give high strength. Table 16.8 gives the composition, properties and uses of some of the heat treatable titanium alloys.

Table 16.7 Solution and Ageing Treatment Temperature and Time for Some Cast Magnesium Alloys

Alloy designation	Treatment	Ageing		Solution treatment		Ageing after solution treatment	
		Temperature (ºC)	Time (hr)	Temperature (ºC)	Time (hr)	Temperature (ºC)	Time (hr)
AM100A	Artificially aged only	232	5				
	Solution heat treated			430	16–14		
	Solution heat treated and artificially aged			430	16–24	230	5
AZ92A	Artificially aged only	260	4				
	Solution heat treated only			410	16–24		
	Solution heat treated and artificially aged			410	16–24	218	5
HK31A	Solution heat treated and artificially aged			568	2	204	16
ZE63A*	Solution heat treated and artificially aged			485	10–72	285	16
ZH62A	Artificially aged only	329		2			

*Alloy ZE63A must be solution treated in a special hydrogen atmosphere because its mechanical properties are improved through hydriding of some of its alloying elements. Hydriding time depends on section thickness. As a guideline it may be noted that 6 mm section requires about 10 hours and 19 mm section requires about 72 hours. After solution treatment, these alloys should be quenched in oil, water sprayed or air-blast.

Table 16.8 Titanium Alloys (Heat Treatable): Composition, Properties and Uses

Alloy type and composition (percent)	Form	Condition	Strength		Elongation (percent)	Uses
			UTS (MPa)	Yield (MPa)		
α-alloy Ti-5Al-2.5 Sn	Sheets, bars and forgings	Annealed	800	760	10	Compressor blades and welded assemblies
Near-α alloy Ti-6Al-3Mo-1Zr	Bars and fogings	Heat treated	1200		6	Compressor blades and discs
α–β alloy Ti-6Al-4V	Sheets, bars and forgings	Heat treated	1200	1060	8	Pressure vessels, air frame and engine parts
α–β alloy Ti-4Al-4Mo-4Sn	Bars and forgings	Heat treated	1400	1250	10	Air frame structrual forgings
β-alloy Ti-13V-11Cr-3Al	Sheets, bars and forgings	Heat treated	920	850	10	Fasteners, rivets, sheet metal parts and tubings

16.3.1 Heat Treatment of Titanium Alloys

The purpose of heat treatment of titanium and its alloys is to reduce residual stresses developed during fabrication operation, to get optimum combination of ductility, machinability and dimensional and structural stability, and to obtain improved strength and specific mechanical properties such as fracture toughness, fatigue strength and creep resistance.

α and near-α (containing mainly α stabilizing elements plus less than 2 percent β stabilizing elements) titanium alloys are subjected to stress relieving and annealing heat treatment. High strength cannot be obtained in α and near-α titanium alloys by heat treatment. The commercial β-alloys respond to heat treatment. Ageing at elevated temperature after solution treatment results in decomposition of β-phase, and hence strengthening occurs.

α-β alloys are two-phase alloys and are most popular of the three types of titanium alloys. In the α-β alloys, change in the phase composition, size and distribution due to heat treatment within specified limit improves the strength and other specific properties,

Three types of heat treatment processes are adopted for titanium alloys. They are (i) stress relieving, (ii) annealing, and (iii) solution treating and ageing, which we now discuss.

Stress Relieving

Titanium and titanium alloys are stress relieved to minimize the undesirable residual stresses due to cold working, non-uniform hot forging and solidification. Removal of these stresses helps in maintaining stability of shape and removes unfavourable conditions, e.g. the loss of compressive yield strength (Bauschinger effect). Components can be cooled from stress relieving temperature either by air cooling or by slow cooling. Table 16.9 shows the stress relieving temperature and time for some of the α, α-β and β titanium alloys.

Table 16.9 Stress Relieving Temperature Range and Time for Titanium and Titanium Alloys

Alloy	Temperature range °C	Time (hr)
Commercially pure Ti	480–590	1/4–4
α or near-α alloys		
Ti-8Al-1Mo-1V	590–700	1/4–4
Ti-6Al-2Cb-1Ta-0.8Mo	600–650	1/4–2
α-β alloys		
Ti-6Al-4V	485–645	1–4
Ti-3Al-2.5V	540–650	1/2–2
Ti-8Mn	480–590	1/4–2
β-alloys		
Ti-13V-11Cr-3Al	710–730	1/2–1/4
Ti-10V-2Fe-3Al	680–700	1/2–2

Annealing

Annealing improves fracture toughness, ductility, dimensional and thermal stability and creep resistance. Different types of annealing treatment given to titanium alloys include (i) mill annealing, (ii) duplex annealing, (iii) triplex annealing, (iv) recrystallization annealing, and (v) beta annealing.

Mill annealing, a general purpose annealing treatment, is carried out to improve the properties of mill products. It is not a full annealing treatment. Duplex and triplex annealing treatment improves the creep resistance or fracture toughness by modifying the phases. Recrystallization and beta annealing treatment improves the fracture toughness.

Table 16.10 gives the temperature and time for annealing treatment of titanium and titanium alloys.

Table 16.10 Annealing Temperature Range for Titanium and Titanium Alloys

Alloy	Temperature range (°C)	Time (hr)	Cooling medium
Commercially pure Ti	650–760	1/10–2	Air
α or near-α alloys			
Ti-8Al-1Mo-1V	785	1–8	Air or furnace
Ti-6Al-2Cb-1Ta-0.8Mo	795–900	1–4	Air
α-β alloys			
Ti-6Al-4V	710–790	1–4	Air or furnace
Ti-3Al-2.5V	650–760	1/2–2	Air
β alloys			
Ti-13V-11Cr-3Al	710–790	1/6–1	Air or water
Ti-15V-3Al-3Cr-3Sn	790–810	1/2–1/4	Air

Solution Treating and Ageing

α-β and β-alloys are solution heat treated and aged to obtain a wide range of strength levels. The high temperature β-phase is unstable at lower temperatures. Higher ratio of β is produced by heating an α-β alloy to the solution treating temperature. By quenching, the proportion of phases is maintained. Decomposition of metastable β-phase takes place during subsequent ageing. This results in improved strength levels. β-alloys are normally supplied in the solution treated condition. They require only ageing subsequently.

Solution treatment is to be carried out at a temperature which is high in the α-β field to obtain strong alloy with adequate ductility. Good control of temperature is essential to ensure that the material does not enter into the β-region. In the absence of such precaution, ductility is adversely affected.

β-alloys are quenched in air from solution treating temperature. α-β alloys are quenched in water or a 5 percent brine or caustic soda solution. These quenchants help prevent decomposition of the β-phase by their rapid cooling rates. If the quenching rates are slow, ageing will not be effective. After quenching, ageing of titanium alloys is carried out by reheating to 430–650°C. During ageing, decomposition of the supersaturated β-phase, retained during quenching, occurs. When titanium alloys are aged around annealing temperature, over-ageing occurs. Proper ageing gives high strength associated with good ductility and microstructural stability.

To start with, β transforms to a metastable transition phase termed as ω (omega). This type of transformation is generally observed in highly β-stabilized α-β alloys. The omega phase introduces brittleness in heat treated alloys. Hence, it is better that formation of ω-phase is suppressed. The ω-phase that is formed can be avoided by rapid quenching and fast reheating to ageing temperatures above 430°C.

It is observed that, by addition of aluminium, formation of ω is prevented. This is possibly due to increased sluggishness of β to ω transformation. β-phase can also be stabilized by addition of Mo which also suppresses formation of ω by quenching of β. Al and Sn have also been used successfully in other alloys to prevent formation of ω.

Ti-6A1-4V (α-β alloy) is solution treated at 955–970°C for about one hour. This is followed by water quenching. After quenching, this alloy is reheated to a temperature between 480° and 590°C for 4–8 hours for ageing. This heat treatment gives maximum tensile properties to the alloy. In the heat treated condition, the alloy contains α' (titanium martensite) which has a needle-like structure.

16.4 COPPER AND ITS ALLOYS

Copper and its alloys find wide application in industries as electrical conductor, fuel and oil lines, bearings, automobile radiators, pressure vessels, and so on. They are good electrical conductors, have reasonable strength coupled with good corrosion resistance, and are non-magnetic.

Heat treatment processes which are relevant to copper and copper alloys include homogenizing, annealing and stress relieving. Beryllium bronzes are precipitation hardenable alloys.

Homogenization is carried out at 50°C above upper annealing temperature for 3–10 hours. This treatment is required specially for long freezing range alloys such as tin bronzes, copper-nickel and silicon bronzes. As a result of homogenization, segregation and coring are reduced. Thus, hot and cold ductility of the cast alloys is improved. Stress relieving which is carried out below annealing temperature relieves internal stresses. In general, for wrought copper alloys, stress relieving temperature varies from 190°C to 260ºC,

16.4.1 Heat Treatment of Copper

In the case of pure copper, the heat treatment process which is adopted is annealing. The purpose of annealing is to achieve the original ductility and softness in cold-worked copper. Pure copper is annealed at about 600°C. After holding at this temperature for some time, copper is quenched in cold water. Annealing temperature of copper is higher than its recrystallization temperature (270°C). Water quenching removes scale formation and gives clean surface of copper. Annealing above 600°C does not have any significant effect on copper except that grain coarsening occurs. Grain coarsening is undesirable since it reduces ductility.

16.4.2 Heat Treatment of Brasses

Like pure copper, brasses are also subjected to recrystallization annealing treatment after cold working. By annealing above recrystallization temperature, the original degree of ductility and toughness can be restored in the cold-worked brass. Annealing may be carried out by heating the cold-worked brass at a temperature between 650°C and 700°C, followed by cooling at any suitable rate. Controlled atmosphere is often used while annealing to avoid excessive oxidation and discolouration of the surface of the brass. A low temperature (300°C) annealing heat treatment may be given to brass articles for about one hour to remove internal stresses. Such treatment reduces the tendency for season cracking. By low temperature annealing, tensile strength is maintained within acceptable limits.

16.4.3 Heat Treatment of Bronzes

As in the case of aluminium alloys, beryllium bronzes (copper-beryllium alloys) respond to precipitation heat treatment. Other types of bronzes are not given any heat treatment except annealing at about 500°C.

Beryllium bronzes contain 1.5–2.25 percent beryllium. The solid solubility of beryllium in copper increases with temperature from less than 1 percent at room temperature to more than 2 percent at 815°C. Due to decrease in solid solubility with decrease in temperature, coupled with the possibility of quenching supersaturated solid solution and formation of precipitates with coherency, these alloys are amenable to precipitation heat treatment which greatly improves mechanical properties such as strength and hardness. Copper-beryllium alloys are solutionized at 800°C for about half an hour, followed by quenching in water. They are aged at a temperature between 300–320°C for a period of 2–4 hours. Ageing treatment precipitates second phase particles (γ-phase) uniformly in the matrix. With this process, the hardness of the order of 200–400 BHN can be attained, depending on ageing time. Tensile strength and yield strength also increase. By suitable heat treatment and cold working, tensile strength as high as 1400 MPa can be attained.

16.5 NICKEL ALLOYS

Nickel is a metal having good resistance to corrosion and oxidation. The electrical conductivity of nickel is poor in comparison to copper and aluminium. Nickel finds wide application at those places where high resistance to corrosion and oxidation is required. It is alloyed with Cu, Fe, Cr, Si, Mo, Mn and Al. It is also used as a superalloy.

16.5.1 Heat Treatment of Nickel Alloys

The following heat treatment processes are generally applied to nickel and its alloys: (i) annealing, (ii) stress relieving, (iii) stress equalizing, (iv) solution treating, and (v) age hardening. These processes are now discussed.

Annealing

This treatment is given to nickel alloys to produce a recrystallized grain structure. Annealing also softens the work hardened nickel alloys. Annealing temperature for nickel alloys varies from 700°C to 1200°C, depending on alloy composition and extent of work hardening.

Stress Relieving

Stress relieving is given to work hardened and non-age hardenable nickel alloys to remove or minimize residual stresses. This treatment does not produce a recrystallized grain structure.

Stress relieving temperature varies from 430°C to 870°C. This depends on the composition and degree of work hardening.

Stress Equalizing

This is a low temperature heat treatment process and is given to nickel and its alloys to balance stresses in cold-worked metal or alloy without appreciably affecting the mechanical properties of the cold-worked material.

Solution Treating

This heat treatment is applied to age hardenable nickel alloys before ageing. Because of this treatment, age hardening constituents and carbides diffuse into solid solution.

Age Hardening

This treatment is carried out between 430°C and 870°C on some of the nickel alloys to obtain maximum strength by precipitation of a dispersed phase in the matrix.

Details of solution and ageing treatment for some of the nickel alloys are summarized in Table 16.11.

Table 16.11 Solution and Ageing Treatment for Some Nickel Alloys

Alloy	Solution treatment	Ageing
Nimonic 90 (20% Cr, 18% Co, 2.5% Ti, 1.5% Al, 0.05% C)	8–12 hours at 1080–1180ºC, followed by air cooling	12–16 hours at 700–850ºC and air cooled
Inconel X (15% Cr, 0.85% Co, 6.75% Fe, 0.8% Al, 2.5% Ti, 0.7% Mn 0.04% C)	2–4 hours at 1165ºC, followed by air cooling	24 hours at 860ºC, air cooled, followed by 20 hours at 740ºC air cooled
Hastelloy B (1% Cr, 2.5% Co, 23–30% Mo, 2.6% V, 1.0% Si, 1.0% Mn 0.05% C)	1200ºC, air cooled	
Waspalloy (19.5% Cr, 13.5% Co, 2% Fe, 4.25% Mo, 1.3% Al, 3% Ti, 0.1% C)	4 hours at 1100ºC and air cooled	24 hours at 860ºC and air cooled
Udiment-700 (15% Cr, 18.5% Co, 1% Fe, 2.5–7% Mo 4% Al, 3.5% Ti, 0.15% C)	4 hours at 1200ºC	23 hours at 860ºC and air cooled

Nimonic alloys are heated to 1080–1200°C for about 10 hours and subsequently aged at 700–850°C for 10–16 hours. A supersaturated γ-solution with an FCC lattice forms. Upon ageing, the supersaturated γ-solid solution decomposes and a fine precipitate of γ'-phase, i.e.

Ni (Al) compound, is formed. On longer ageing at 850–900°C, the stable η-phase (Ni_3Ti) is formed, which is of hexagonal type and may cause embrittlement to the alloy. Nimonic alloys lose their hardness very slowly at about 700–800ºC because γ-solid solution has a high recrystallization temperature and the γ'-phase does not coagulate.

QUESTIONS

16.1 What is precipitation hardening? What are the conditions necessary for precipitation hardening to take place in an alloy?

16.2 What is meant by solvus line?

16.3 What is age hardening?

16.4 What is solution treatment?

16.5 Name a few of the important commercial non-ferrous alloys which are age hardenable.

16.6 Explain the various changes in structure that take place when a Al-4.5 wt.% Cu alloy after solution treatment and quenching is aged at about 130°C.

16.7 Explain the mechanisms of hardening by coherent particles.

16.8 Explain why hardening effect is reduced during over-ageing.

16.9 Discuss the heat treatment for sand cast AZ92A (Mg-9% Al-2% Zn-0.1% Mn) alloy.

16.10 Give the possible heat treatments for Ti-6% Al-4% V (α-β alloy).

16.11 Discuss the heat treatment of copper-beryllium alloys.

16.12 Discuss solution and ageing treatment for nickel alloys.

17

Inspection and Quality Control in Heat Treatment

INTRODUCTION

Heat treatment is performed on a material in order to obtain certain desired properties in the material. The properties of interest, in most cases, are mechanical properties. (We have already discussed the principles involved in processes and practices of heat treating ferrous and non-ferrous materials.) Heat treatment is a complex process in itself as a number of variables affect the success of the process. Various heat treatment variables have already been discussed in Chapter 1.

In addition to these factors, various other factors such as proper selection, testing, and initial microstructure of the material, choice of proper heat treatment process, practice, furnace and atmosphere—all these govern the final properties in heat treated material to a great extent. Impact of these variables on the quality of heat treated product will be discussed in Section 17.5. Prior to it, it is essential to consider the fundamentals of inspection and quality control in general.

17.1 INSPECTION

Inspection can be defined in several ways. Simply, it can be defined as a tool to judge the quality of a product. According to Dr. W.R. Spriegel, “Inspection is the process of measuring the quality of a product or service in terms of established standards”. D.S. Kimball defined the term *inspection* by stating “Inspection is the art of comparing materials, products or performances with established standards”. L.P. Alford and H.R. Beatty defined it as the art of applying tests, preferably by the aid of measuring appliances to observe whether a given item of a product is within the specified limits of variability.

Inspection is an important step in any production unit as it decides whether the material or the product under consideration is suitable for use. It separates accepted from rejected items. Therefore, inspection checks entry of defective items from further processing, resulting in the saving of material, time and money. Also, it protects the interests of the producer and customer. It helps the producer by improving reputation and competitive strength, and assists the customer by ensuring supply of quality items. It should be clearly understood that inspection does not include any corrective action. The inspection staff is supposed to give reason(s) for rejecting items, but is not responsible for providing reason(s) for the defect(s) present in the rejected items.

17.1.1 Steps in Inspection

An ideal inspection procedure consists of various steps. These steps are to be carried out in the following sequential order:

Step 1 Interpretation of specifications. This is the first and foremost step in inspection. A careful study of specifications is essential for developing a correct approach to inspection.
Step 2 Measurement of characteristics mentioned in the specification sheet, followed by rating the quality of these characteristics.
Step 3 Comparison of Steps 1 and 2.
Step 4 Judging the conformability.
Step 5 Isolation of conformed cases.
Step 6 Isolation of non-conformed cases.
Step 7 Recording and reporting the data obtained.

17.1.2 Objectives of Inspection

Various objectives of inspection are to

(i) isolate good lots from bad lots,
(ii) isolate good items from bad items,
(iii) study the process (for determining whether the relevant process helps in approaching the specification limits or results in deviation from the specification limits),
(iv) rate the capability of the process,
(v) measure the product quality,
(vi) rate the inspection accuracy,
(vii) measure the degree of precision of the measuring instruments used in inspection,
(viii) procure information about product design, and
(ix) to calibrate measuring standards and instruments.

17.1.3 Manner of Inspection

Inspection may be carried out either at the shop floor stage or in a central inspection room. Floor inspection is a fast process as no material movement is involved in it. It is a cheaper process too as the cost of transportation of the material from the floor to the inspection room is nil. It is highly efficient and most probably the only way of inspection for bulky items. Two main problems associated with floor inspection are: (i) Service conditions at floor are not suitable for precision work; (ii) there is a real possibility of the inspector being influenced by production personnel.

Central room inspection has certain advantages over floor inspection insofar as it can be carried out more precisely and rapidly due to availability of all equipment at one place and the working conditions are better. Minimum possible interference is encountered in central room inspection. It is well suited to incoming materials inspection, finished product inspection, and inspection of high precision and delicate products. However, it is a time consuming inspection as material movement is involved.

In general, both floor inspection and centralized inspection are employed in a production unit, and is known as combined inspection. In this case, some components may be inspected at the floor whereas others are inspected at the central room.

17.1.4 Process of Inspection

The nature of product and the practice adopted for manufacturing it give the answer to the question: When should one inspect? In fact, no general rule can -be made as human factors, economy of concern and management policy also play an important role. However, there are various possibilities for carrying out inspection. These are as follows:

(i) Inspection at the end of each operation
(ii) Inspection of the finished product
(iii) Inspection in between the processes
(iv) Inspection after those operations in which chances of introduction of defects are maximum.

Possibility (iv) will fulfil the main aim of the inspection, i.e. checking the suitability of the item with minimum possible cost.

17.1.5 Inspection Methods

Depending on the nature of the product and the types of tests employed, inspection can be carried out either on each item of the lot or on the samples drawn from the lot under consideration. The former is referred to as cent percent inspection or screening, the latter is known as lot by lot inspection or sampling.

In screening, each item is subjected to inspection and, therefore, probability of any defective piece reaching the customer is zero. However, human factors such as inspector’s fatigue, oversight and carelessness result in inclusion of some defective items in the good lot. Thus the very purpose of cent percent inspection is lost. This inspection method is preferable either for items on which functioning of entire assembly depends or where no risk can be taken. For these reasons, sometimes even 200 percent or 300 percent inspection is performed. Cost of carrying out cent percent inspection is very high compared to sampling. The cost raises further if some test or tests involved are costly in nature. However, for critical items or applications, cost is of secondary importance and reliability is of utmost importance. The process is slow, consumes lot of time, and is not feasible when destructive testing is involved; it poses many complications in mass production units. One of the serious drawbacks associated with cent percent inspection is that quality of the product(s) cannot be improved as feedback is not available from the customer’s end.

In comparison to cent percent inspection, lot by lot inspection has certain merits. The latter is a fast process and any decision regarding acceptance or rejection of the lot can be taken quickly. Total cost of the process is low and, therefore, even expensive tests can be performed. As the process is less time consuming, more and more characteristics can be studied. It is the only inspection method available in cases where destructive tests are involved. However, the process suffers from the serious drawback that some probability of entry of defective items in the accepted lot always exists due to sampling error.

A third method of inspection is known as process inspection. In this method, inspection is carried out at each step, starting from raw material to the finished product. Defective products are located and separated as and when they are identified. Only passed products are allowed to go for the next stage of production process. The method is highly advantageous when cent percent inspection is carried out at the end of each step. It saves both time and money as no further processing of defective items takes place. Defective items can be diverted to some other semi-finished or finished product. As the reason of rejection is known, corrective measures can be taken by the quality control department immediately. However, this inspection method has two serious drawbacks: (i) excessive material handling is needed; (ii) time involved is enormous,

17.1.6 Stages of Inspection

There are three stages of inspection. The first stage of inspection is also known as incoming materials inspection or receiving inspection. In this stage, all the raw materials, parts and other items of interest procured by the purchase department or stores are inspected as per specifications and standards laid down before their actual use or storage. Such an inspection can be carried out either at suppliers or customer's end. It is always advisable to inspect bulk quantity involving large transportation cost at suppliers end. However, most of the suppliers produce test reports of their products and guarantee that the products/items supplied by them conform to test reports. This solves the problem to a great extent.

The second stage of inspection involves inspection at production stage. The inspection is performed at the end of each process of production. The third or the last stage of inspection is related to the inspection of finished goods. Defective items are isolated from the accepted items and stored at a separate place.

17.1.7 Common Characteristics Inspected

Though the testing during inspection depends on the nature and end use of the product and many other factors, a few common characteristics are generally inspected. These characteristics can be classified under the following types of inspection.

(i) *Visual Inspection* It is probably the oldest way of inspection. Visual examination reveals the surface smoothness or roughness and surface defects such as burnt-on sand, misruns and cavities.

(ii) *Dimensional Inspection*
  (a) Linear measurement
  (b) Angular measurement
  (c) Profile measurement
  (d) Surface roughness measurement.

(iii) *Metallurgical Inspection*
  (a) Chemical composition determination
  (b) Strength and hardness measurement

  (c) Study of microstructure and/or macrostructure
  (d) Grain size determination
  (e) Grain flow study
  (f) Case depth measurement
  (g) Measurement of decarburization depth
  (h) Count of non-metallic inclusions.

(iv) *Material Flaws Inspection*
  (a) Leakage testing
  (b) Application of penetrant methods
  (c) Magnetic particle inspection
  (d) Inspection by acoustic methods
  (e) Radiography inspection
  (f) Application of thermal methods
  (g) Electrical methods of inspection.

(v) *Performance Inspection* Performance, in general, is rated by stating expected life under conditions similar to those of service conditions.

17.2 QUALITY

Though it is difficult to define quality, it is a commonly used word in day-to-day life. In general, quality signifies product quality, and can be defined by (i) fitness for use, (ii) conformity to specifications, (iii) consumer's preference, and (iv) degree of excellence.

A product ultimately has to be used somewhere. If it functions well, it is said to be of good quality. But due to obvious reasons, there cannot be any absolute criterion for quality. In most cases, quality is judged by comparing the characteristics of a product with those mentioned in the specification sheet. In this case, if the product characteristics match with the specifications laid down, the product is accepted and is said to be of good quality. Otherwise, the product is referred to as of poor quality and is rejected. However, many examples can be cited to prove that conformity to specifications cannot guarantee its quality in terms of its performance. Since a product is meant for the customer, so the term product quality is more or less related to the choice of the customer. The opinion about the product may differ from customer to customer, and so no rigid definition can be given about the product quality based only on the characteristics of the product. The same product may be of good quality to one customer and of poor quality to another. In general, the term product quality signifies the degree' of its excellence. However, this phrase, i.e. degree of excellence, cannot be used for defining the term product quality as this definition is misleading. A product may show excellent behaviour under some particular set of conditions. The same product may be a total failure under some other set of conditions. Thus, none of the above stated definitions is perfect in themselves, and so the concept of quality requires rethinking.

Product quality has been a very ambiguous term for a long period. There have been rapid and competitive technological advancements during and after the Second World War period all over the world and producers have been compelled to think about product quality. Such a situation has led to the development of a revolutionary concept of product quality. It was realized that, in addition to conformity to the specifications and fitness for use at the time of procurement, there must be some more factors. In other words, there exist some factors which are of great importance to the customer. Some of these factors are ease of installation and operation, safety, reliability, economy of operation, and maintenance and after sales service.

17.2.1 Factors Controlling Quality

Various factors affecting the quality of a product are (i) men, (ii) materials, (iii) machines, (iv) money, (v) market research, (vi) management policy, (vii) product design and production method, (viii) packing and transportation, and (ix) after sales service.

The role of men, materials, machines and money, i.e. capability of investment in a production unit, is well known to everybody. These factors do not require any explanation as far as their importance is concerned.

Currently, rapid technological advancement is taking place. For this reason, it is not possible for a production unit to prosper without either modifying the product or carrying out diversification of the products. In fact, now-a-days, success of a business house largely depends on the efficiency by which it can introduce new techniques and/or developments in its products or explore possibilities of newer product ideas. These aims are fulfilled by market research which is based on well established scientific methods. Market research tells about the nature, demand, and quantity of the product to be manufactured, prospective buyers, and probable competitors. An efficient market research consists of analysis on product, market distribution and competition.

The policy of management controls, to a great extent, the quality standard of a product. Inspection and quality control personnel cannot function efficiently and independently without the support of the management. In the past, higher production even at the expense of quality has been the aim of the management. It is only during the last two or three decades that product quality has been given due consideration. This change in the attitude is essentially a result of competitive market.

Product design and production method are the two major factors which directly govern the final quality of the product. A quality product is developed by efficient combination of both these factors. The best product design may lead to a poor quality product due to faulty production technique. Similarly, even the most efficient product method can result in inferior product because of improper product design.

Good packing is essential especially for products for which surface properties are of great importance. Fatigue strength as well as impact strength largely depend on the surface characteristics of the components and, therefore, such components have to be packed and transported properly. Some products get rusted when exposed to atmosphere even for a day or two. Such products are first dipped into or coated with rust preventive oils and then packed with polythene and jute. Such a packing sequence prevents rusting for sufficiently long periods. Thus, packing and transportation have their own importance and must be given due consideration. Any negligence during packing and transportation may result in irreparable damage to the product.

After sales service is as important as the quality of the product. A poor after sales service results in the loss of goodwill in the market. Now-a-days, it is very difficult to enter into or capture the market, even with superior quality product, without a well established sales and after sales service network.

17.3 QUALITY CONTROL

The simplest word meaning of *quality control* is the control of quality. Since many factors affect the quality of the product (see Section 17.2.1), the control of product quality can be achieved only by controlling all the factors. Therefore, the term quality control can be explained by stating that quality control includes activities which are carried out in order to achieve quality objectives of the concern. Alford and Beatty defined quality control as "Industrial management technique by means of which products of uniform acceptable quality are manufactured". In simpler words, quality control can be defined as a technique adopted for manufacturing products as per customer's demand or as per national or international specifications for a given product.

Quality control not only helps in maintaining uniform quality of the product, but also improves the quality of the product. An efficient quality control results in the reduction in the losses due to defects and reduction in the cost of inspection. In fact, as control becomes more and more effective, the need for inspection decreases. Thus, improved product quality does not necessarily mean increased cost of production. By adopting quality control measures strictly and by improving quality mindedness of concerned persons, a superior quality product can be manufactured at low production cost.

An important distinction between inspection and quality control is that inspection is concerned only with detecting, rejecting and isolating defective items from good items, whereas quality control is responsible not only for taking corrective measures in order to eliminate defects in the product, but also for rectification and/or diversification of already produced defective items. Inspection is closely associated with quality control, but it cannot by itself generate quality. It determines the actual conformity of the product to the specifications. However, inspection does not add any value to the product already produced. Quality control, in contrast, is highly critical in nature. It analyses each and every step to search for answers to what, why and how. It provides not only the reasons for the difference in the desired product quality and actually attained product quality, but also suggests methods by which the desired product quality can be attained economically.

17.3.1 Objectives of Quality Control

The major objectives of quality control are to

(i) study the quality specifications desired by the customer,
(ii) develop a process capable of producing items as per customer's choice at an economical rate,
(iii) take necessary corrective measures if the quality of product deteriorates,
(iv) plan for improvement in product quality, and
(v) find ways for reducing product cost without affecting quality of the product.

17.3.2 Functions of Quality Control Department

The important functions performed by quality control department are to

(i) ensure that products of uniform and specified quality should only reach the customer,
(ii) pass instructions to production personnel regarding the nature of the products and the quality of the work expected from them,
(iii) provide process sheet to all related persons,
(iv) train supervisory staff and operators,
(v) develop quality awareness,
(vi) suggest solutions to various problems encountered during the course of manufacturing,
(vii) evaluate critically the functioning of inspection, design and production departments,
(viii) decide about adoption of various measures for controlling/improving product quality, and
(ix) develop processes with improved product quality without raising product cost.

17.3.3 Advantages of Quality Control

There are many advantages offered by quality control to both manufacturer and customer. Some of the important advantages are as follows:

(i) A process resulting in production of good quality items is streamlined.
(ii) Production of good quality items results in increase in sales volume.
(iii) Uniformity in the product quality is attained.
(iv) Reputation of the concern improves.
(v) Product reliability is enhanced.
(vi) Since defective items are only a few, material wastage is reduced significantly. It reduces overall cost of production. Cost is also reduced due to less reworking of defective items.
(vii) Inspection cost is reduced significantly.

17.3.4 Quality Control—Everybody's Business

Product quality cannot be managed by employing a few inspectors and quality control engineers. Quality of a product depends largely on men, materials, machines, manufacturing process, working conditions, management policy and economy. In fact, the first step to wards quality of a product starts much before the actual manufacturing of the product. A designer designs it. Process planners suggest a flow sheet of manufacturing process. The purchase officer procures materials as per the specifications suggested by customer or quality control personnel. Maintenance personnel ensure smooth functioning of all machines and other equipment prior to their actual use. The production team manufactures it as per the flow sheet with the help of quality control and inspection departments. Sales personnel introduce the product into the market. After sales service department satisfies the needs of the customers after the supply of the product and thus helps in maintaining cordial relations between the manufacturer and customer. Therefore, every department has its own importance. Negligence on the part of any department or person will result in the production of inferior quality product.

Human factors as well as resources of the concern also play significant role. Under identical conditions, a skilled worker can produce better quality product as compared to semiskilled or unskilled worker. Sincerity of the worker also leads to better quality product. Due to obvious reasons, working conditions affect the working efficiency which in turn affect the quality of product. Similarly, use of better machines and high quality materials results in improved product quality. Thus, on the basis of the foregoing discussion, it can be concluded that quality control is the business of everybody and not of a few individuals belonging to quality control and inspection departments.

17.4 STATISTICAL QUALITY CONTROL

One of the simplest and safest methods of controlling quality is to perform cent percent inspection. By this method, defective items are rejected and isolated from good items. However, as discussed in section 17.1.5, the process is not economical, especially in the case of mass production. In certain cases, it is neither practicable nor desirable. Thus, one is forced to switch over to lot by lot inspection, i.e. sampling. The shortcomings of sampling method are minimized by the application of statistics. The use of statistics in controlling quality has resulted in the development of a method to carry out satisfactory inspection. Statistics is concerned with obtaining correct facts from figures. More precisely, statistics can be defined as a science of collecting and tabulating numerical data, or representing data by means of charts or figures, of calculating the mean, median, mode, standard deviation, and so on. When statistics is used as a tool for controlling quality, the technique is known as statistical quality control. Statistical quality control can be defined as a technique of controlling the quality of a product by controlling the very process of production itself with the help of statistics. The first stage of statistical quality control is to determine the control limits (upper and lower limits) of permissible deviations in the quality. This stage results in the attainment of the desired quality of the product. The second stage of statistical quality control is to maintain the product quality within predetermined control limits. The second stage is attained by taking corrective measures as soon as any deviation beyond the control limits is noticed.

Statistical quality control results in establishing quality standards as per customer's specifications. The economy of the process should not be unduly disturbed. Product quality along with customer's satisfaction should be economical to maintain. The technique is efficient in identifying the faults in the process. This results in the reduction in the wastage of material, time and money.

17.5 QUALITY CONTROL IN HEAT TREATMENT

The variables that affect heat treatment process have already been discussed in Chapter 1 and in the earlier sections of this chapter. Obviously, the quality of heat treated product will be governed by these factors. The effect of some of these factors on the quality of heat treated product is now discussed in detail.

17.5.1 Product Design

Product designing for heat treating plays an important role. A properly designed part ensures satisfactory and economical heat treatment. Following factors should be given due consideration during designing:

(i) There should be, as far as possible, no sharp corners.
(ii) No significant variation should be present in section sizes.
(iii) No sharp corners should be seen between thick and thin sections.
(iv) Use of fillets at all corners and junctions should be made a routine practice.
(v) Product design must be free from single internal or external key way.
(vi) There should be no clustering of openings or holes.

In addition to the above mentioned general factors, special precautions are undertaken while designing gears, cutters, dies, shafts and threaded sections.

17.5.2 Heat Treatment Specifications

Heat treatment specifications should also be provided along with design specifications or separately. These specifications should consist of details about various parameters such as hardness, tensile strength, toughness, microstructure, case and core properties, depth of decarburization, appearance of fracture and grain size.

17.5.3 Material Selection

Once the design of the product has been either finalized or procured from the customer, the foremost job is to select a suitable material for the product. The material selected should be able to meet the service conditions and/or technical specifications in heat treated condition. In general, service conditions are not well defined by the customer and in such cases choice of the material lies in the hands of manufacturer. The customer is only interested in technical specifications.

The most suitable material is one which, in addition to conforming to technical specifications, is also economical. A material is said to be economical if its properties just match with the properties listed in the given specification sheet. However, the concept of an economical material is somewhat complex when heat treatment is taken into account. In such a case, the economy of material selection also includes cost of heat treatment and of post-heat treatment operation(s). Some of the post-heat treatment operations are stress relieving, scale removing, machining or grinding and straightening. It is quite possible that the overall cost of finished heat treated product may be much higher for cheaper material than for costly material.

After selecting the material, it should be tested. In general, though the supplier produces a test certificate indicating the characteristics of the material, it is desirable to test the material at one’s end. The standard methods should preferably be adopted for testing the material. However, mutually agreed upon methods will also serve the purpose. Similarly, the sampling technique and the sample size selected should either be as per standard practice (such as the one laid by ISI) or according to mutual consent. Depending on the nature of the product and service conditions, both destructive and non-destructive tests may be performed.

17.5.4 Dimensional Considerations

Due attention should be paid towards dimensions of the part before and after heat treatment. During heat treatment, parts may undergo dimensional changes due to thermal fluctuations and phase transformations. Dimensional changes can lead to excessive distortion in the component. The problem can be controlled by providing allowances in dimensions. The magnitude of allowances depends largely on the nature of the material itself and on the heat treatment process variables, especially temperature and rate of heating and cooling. Allowances should be provided carefully. More allowances need excessive machining or grinding which is not economical because (i) more material is wasted, (ii) more time is needed, (iii) more tools are consumed, and (iv) men and machines are engaged for longer periods. On the other hand, low allowances may not serve the purpose, and in the worst case, heat treated component may have to be rejected.

17.5.5 Selection of Equipment, Instrument and Auxiliary Accessories

Selection of equipment in heat treatment is governed by following factors:

(i) Nature of the operation—batch type or continuous type
(ii) Desired surface characteristics of the product
(iii) Heat treatment process.

Batch type furnaces can be used successfully for different heat treatment processes and for varying sizes of the products. For these reasons, these furnaces are very popular in heat treatment plants based on job orders. Continuous type heat treatment furnaces are well suited for mass production units.

The surface of the parts heat treated in muffle and air chamber furnaces generally get oxidized. Another problem related to surface is decarburization. To avoid this, salt bath furnaces or controlled atmosphere furnaces should be employed for parts requiring good surface characteristics such as bearings, gears and tools. Vacuum furnaces are considered best for protecting surface characteristics.

Some specific heat treatment processes demand for specially designed furnaces and other equipment. Examples are patenting, and bell-type, rotary and conveyor furnaces.

Furnace is essentially a heating chamber. It does not provide any information about what is going on within the chamber. For this purpose, some instruments are needed. Use of proper instruments and instrumentation method is necessary for measuring and controlling temperature of the heat treatment furnace, dew point in case of controlled atmosphere furnace and air or gas pressures.

There should be proper storage arrangement for water and oil. Water tank used for quenching should be of recirculation type so that constant temperature can be obtained. Circulation of water also provides stirring action to some extent. Oil tanks for oil quenching purpose should have mechanical stirring attachment. Similarly, other essential auxiliary accessories should be provided at appropriate places so that heat treatment can be performed successfully.

17.5.6 Heat Treatment Shop Layout

In general, heat treatment is a part of some manufacturing unit such as foundry or wire industry. Very little attention is paid to this section as far as installation of equipment is concerned. A good plant layout results in (i) smooth functioning, (ii) minimum men movement, (iii) minimum materials movement, (iv) minimum production delays, (v) maximum flow of activities of various men, machines and materials at work, (vi) effective utilization of the space, (vii) increased production, and (viii) worker's convenience and job satisfaction.

17.5.7 Heat Treatment Flow Sheet

It has been generally observed that the best product is obtained only when every worker, in addition to knowing his work well, is made familiar with the product and characteristics desired after the operation which he carries out. A detailed flow sheet of the process should be prepared and provided to the supervisors/operators. It will help the person concerned to understand one's own responsibility. An ideal process layout should consist of details about the following:

(i) Materials specification
(ii) Furnace to be used
(iii) Temperature(s) of heat treatment and holding time(s) at heat treatment temperature(s)
(iv) Quantity of the material to be heat treated
(v) Rate of heating
(vi) Heat treatment atmosphere and its characteristics such as dew point, volume fraction in case of mixed gases atmosphere, purity and feeding speed
(vii) Quenchant and its characteristics
(viii) Auxiliary accessories to be used
(ix) Sample size and sampling technique
(x) Tests to be performed on each sample.

17.5.8 Quality of Consumable Items

The quality of the consumables also affects the final properties of heat treated product. The following are a few of the commonly used consumable items:

(i) Neutral salts such as sodium chloride (NaCl), potassium chloride (KCl), and barium chloride ($BaCl_2$). These are used in salt bath furnaces.
(ii) Charcoal, charcoal-barium carbonate mixture, sodium cyanide (NaCN), potassium cyanide (KCN), natural gas and water gas. These are used for carburizing steels.
(iii) Ammonia, ammonia-nitrogen mixture, ammonia-hydrocarbon mixture, sodium cyanide and sodium carbonate mixture. These are used for nitriding or carbo-nitriding steels.
(iv) Water, oil, water-oil emulsion, polymers, and salt baths. These are quenchants.
(v) Degreasing chemicals,
(vi) Cleaning agents.

These items should be procured from reputed concerns or from reliable sources as most of these products are sold in the market by company's trade name, and not by actual chemical composition.

17.5.9 Working of Equipment

Equipment should always be in good working condition. Measuring instruments too should be able to provide accurate and reproducible results. A well established, well planned maintenance scheme is required for smooth and reliable working of equipment and instruments. Even on economical ground, a timely maintenance is profitable. Unplanned/untimely maintenance should be avoided.

In addition to the above mentioned factors, human factors such as good working conditions, efficient supervision, employment of skilled workers, management policy and quality mindedness affect the quality of finished product to a great extent.

17.6 INSPECTION IN HEAT TREATMENT

The importance of inspection has already been described in Section 17.1. Inspection in heat treatment can be divided into three classes, namely, preheat treatment inspection, post-heat treatment inspection, and inspection during heat treatment. Various characteristics to be inspected in each class are as follows:

(i) *Pre-heat Treatment, Inspection*
   (a) Size
   (b) Chemical composition
   (c) Macro and microstructure
   (d) Austenitic grain size
   (e) Hardenability
   (f) Tensile strength, percentage elongation and reduction in area
   (g) Non-metallic inclusions
   (h) Surface flaws.

(ii) *Inspection during Heat Treatment*
   (a) Heat treatment temperature
   (b) Heat treatment time (heating time, soaking time and sometimes cooling time)
   (c) Properties of gas in case of controlled atmosphere process
   (d) Properties of solid, liquid or gaseous materials used in case of hardening (carburizing, nitriding and carbonitriding) processes. Properties of quenchants, if in use.

(iii) *Post-heat Treatment Inspection*
   The characteristics to be inspected are almost the same as the ones included in pre-heat treatment inspection.

QUESTIONS

17.1 Explain the terms—‘Inspection’, ‘Quality’ and ‘Quality control’.
17.2 Enlist common characteristics inspected alongwith purpose involved.
17.3 Name and describe objectives and stages of inspection.
17.4 Comment on the statement “Quality control is everybody’s business”.
17.5 Describe quality control in a heat treatment unit.

18

Materials Testing

INTRODUCTION

Testing of material is one of the important and essential steps for judging suitability for engineering applications after heat treatment. Most of the properties of interest are mechanical properties since heat treatment essentially alters mechanical properties. This chapter is confined to the testing of mechanical properties; non-destructive methods of testing materials have also been included as they constitute an important aspect of testing heat treated components. Many tests and testing methods are in use now-a-days. Detailed discussion of all these tests is beyond the scope of this book. This chapter mainly deals with standard and most commonly used tests.

18.1 HARDNESS TEST

The concept of hardness is quite old. All materials exhibit this property. Hardness has been defined in several ways, based on the principle and the manner in which test is conducted. About 30 methods are used for measuring different types of hardnesses. There are three general types of hardness: scratch hardness, indentation hardness, and rebound or dynamic hardness.

Scratch hardness can be defined as that property of the material by virtue of which it resists wear or abrasion. Mohs' scale of hardness proposed by Friedrich Mohs, consists of 10 standard minerals. It is most commonly used for the measurement of scratch hardness. Each one of the minerals has been assigned a hardness number (see Table 18.1). The softest mineral in this scale is talc whereas the hardest is diamond. Though Mohs' scale finds wide application in the field of mineralogy, it is hardly used for metals and alloys which may have hardness values lying between two consecutive scratch hardness according to Mohs' scale. Thus, comparative hardness values of metals and alloys, which are of great significance, cannot be estimated.

Indentation hardness is a measure of resistance offered by a material to plastic deformation. It is measured by estimating the size of indentation. Indentation hardness measurement involves pressing (forcing) an indenter of known material and of well defined geometry into the surface of the sample/work-piece under certain conditions. The size or depth of indentation so obtained is used as hardness measuring parameter. Indentation hardness test is very common and finds

Table 18.1 Standard Mohs' Scale of Hardness

Mineral	Mohs' hardness
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Orthoclase	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

varied applications in the field of metallurgy. It is most widely used for metals and alloys. Three most common types of indentation hardness tests are Brinell hardness, Vickers hardness, and Rockwell hardness tests.

Rebound hardness is a measure of resistance of the materials to strike and rebound. For determining rebound hardness, an indenter is dropped on the surface of the material under specific set of conditions. The energy of the impact or the height of rebound of the indenter forms the basis of measurement of rebound or dynamic hardness. Shore sceleroscope is the most commonly used rebound hardness tester.

18.1.1 Brinell Hardness Test

Brinell hardness tester (see Figure 18.1) consists of penetrating metal surface by a hardened steel ball (indenter) at a predetermined load. After removal of the load, the surface area of the indentation (see Figure 18.2) is measured. Brinell hardness is obtained by dividing the applied load by the surface area of the indentation. Though Brinell hardness has the same unit as of pressure, it is expressed as a number without assigning any unit. Therefore, the term Brinell hardness number (BHN) is commonly used. The mathematical formula for BHN is given by

$$\text{BHN} = \frac{P}{(\pi D/2)\left(D - \sqrt{D^2 - d^2}\right)} \tag{18.1}$$

where

P = applied load (kg)

D = diameter of the indenter (mm)

d = diameter of indentation (mm)

In general, a hardened steel ball of 10 mm diameter at a load of 3000 kg is used to determine Brinell hardness number of hard metals such as steel. For harder metals, tungsten carbide ball is used in place of hardened steel ball. Smaller steel balls at lower loads are used for the measurement of Brinell hardness number of soft materials. In order to have reproducibility of results in Brinell hardness test, the specific ratio of applied load to square of the diameter of indentation ball (P/D^2) is maintained. This ratio takes care of error(s) arising

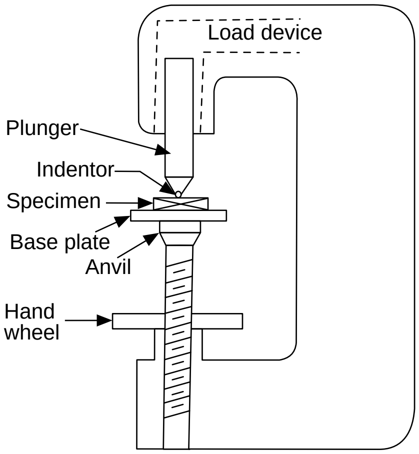


Figure 18.1 **Block diagram of Brinell hardness tester.**

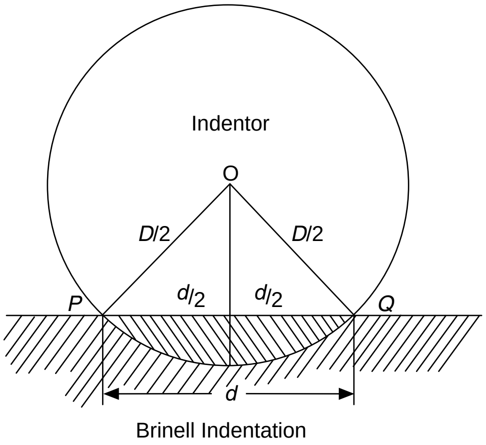


Figure 18.2 **Geometry of indentation by Brinell hardness tester.**

from the use of non-standard ball diameter and load. The ratio of 30, 10, and 2 is specified for steels, non-ferrous metals, and for very soft metals, respectively.

In accurate measurement of diameter of the indentation (*d*), certain problems are encountered. In general, the measured diameter is either greater or lesser than the actual diameter of indentation. It is mainly due to the localized deformation of the metal at the indentation. The localized deformation affects the indentation diameter in two ways (see Figure 18.3), namely, ridging or sinking in. Ridging or piling up is generally observed in cold-worked metals in which the measured diameter is larger than the actual diameter. Contrary to ridging, sinking in usually occurs in annealed metals and alloys and in this case the measured diameter is less than the actual diameter.

(a) Ridging (b) Sinking in

Figure 18.3 Localized deformation in Brinell testing.

In a Brinell hardness tester, specimen is loaded hydraulically. There is a simple mechanical device to vary the magnitude of load. The diameter of the indentation is measured either by a graduated low power microscope or with the help of a graduated screen coupled with vernier scale attached with the machine itself. The surface of the specimen is polished in the same manner as is done for metallographic studies. However, wheel polish is not needed. The specimen is fixed on the test platform as per specified arrangement. The point or spot at which hardness is desired is focused in the microscope. Now the required load is applied. This load is released after 15–30 seconds. The diameter of indentation is read with the aid of microscope. Now Brinell hardness number can be calculated either by substituting the values of different parameters in Eq. (18.1) or with the help of a standard table correlating the diameter of indentation to Brinell hardness number for a given size of indentation ball and applied load.

18.1.2 Vickers Hardness Test

Vickers hardness test is also referred to as Vickers diamond pyramid test. The indenter used in this test is a square base diamond pyramid (see Figure 18.4). The included angle between opposite faces of the pyramid is 136°. The loads generally employed in this test vary from 1 kg to 120 kg, depending on the hardness of the material under test. Therefore, at varying loads, the same indenter can be used for the measurement of hardness of a number of metals and alloys. Just as in the case of Brinell hardness test, Vickers hardness is represented as a number (free from unit). The Vickers hardness number (VHN) is obtained by dividing load by surface area of indentation. The relation between Vickers hardness number and measured parameters is given by the equation

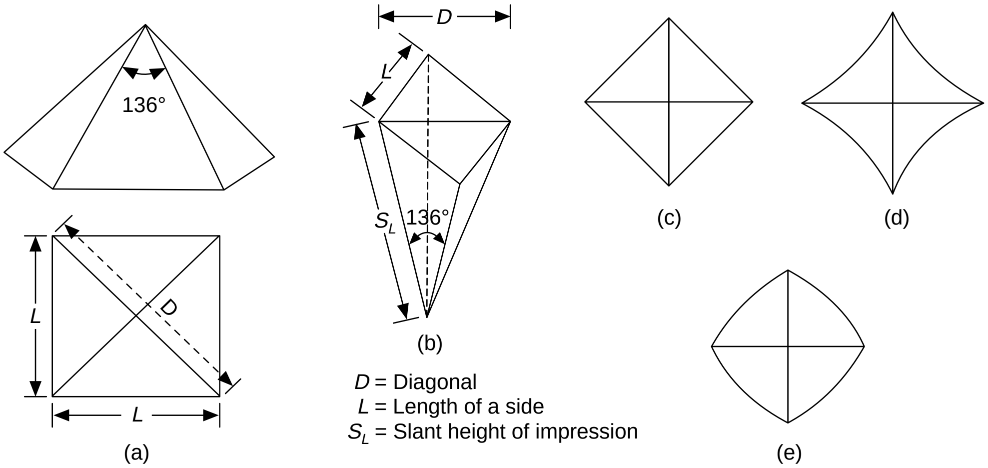


Figure 18.4 **Geometry of (a) indentor; (b) indentation in Vickers hardness tester; (c) perfect indentation; (d) pin cushion indentation (due to sinking in); and (e) barrelled indentation (due to ridging).**

$$\mathrm{VHN} = \frac{1.854P}{D^2} \tag{18.2}$$

where P is the applied load and D is the diagonal length of indentation. Due to the accuracy associated with this test, it is generally used for research and high precision work. The test is not very common for routine tests as it requires a high degree of surface polishing and is time consuming.

18.1.3 Rockwell Hardness Test

This test differs from both the Brinell and Vickers tests in the sense that here the depth of penetration, and not the surface area, is used as the parameter for arriving at the hardness value.

It works on the principle that the depth of penetration varies with the hardness of material. The higher the hardness, the smaller will be the depth of penetration and vice versa. In this test, the depth of penetration is not measured. Instead of that, the hardness values can be read directly on a dial attached to the tester. The readings on the dial gauge are calibrated with respect to the depth of penetration. Thus no calculation is required. The test is rather coarse. Accuracy that can be achieved by this test is not comparable to either Brinell or Vickers hardness test. However, the test is very popular in day-to-day industrial practice. There are two basic reasons for this: Firstly, it is a fast process and, secondly, very small indentation is made on the surface. Therefore, even finished parts can be subjected to this test.

As in the case of Brinell hardness test, several combinations of indenters and loads are used in the Rockwell hardness test in order to determine the hardness of a number of materials varying from soft to hard. A 120° diamond cone, also known as Brale indenter, or 1/16″ and 1/8″ diameter steel balls are generally used as an indenter. Loads of 60 kg, 100 kg and 150 kg are generally used. Depending on the combination of load and indenter, various scales are incorporated in the same dial of Rockwell hardness tester (Figure 18.5). It is very important to write the symbol while denoting Rockwell hardness number. In the absence of such a designation, Rockwell hardness number does not have any meaning. Table 18.2 shows some Rockwell hardness scales and their corresponding load and indenter. A minor load of 10 kg is applied prior to the application of major loads, i.e. 60 kg, 100 kg and 150 kg. Application of minor load serves a number of purposes. For example, it takes care of scratches on the surface or coarse surface finish, and reduces tendency towards ridging or sinking in.

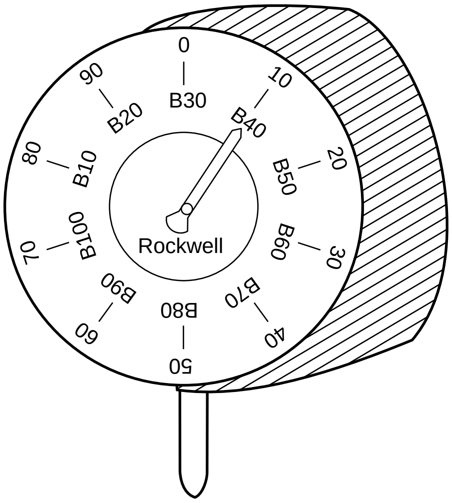


Figure 18.5 Rockwell hardness tester dial.

Table 18.2 Standard Rockwell Hardness Scales (10 kg Minor Load)

Scale	Indenter	Major load (kg)	Dial numerals	Applications
A	Brale	60	Black	For measuring hardness of very hard materials (e.g. cemented carbides, ceramics cermets and case-hardened surfaces)
B	1/16″ diameter ball	100	Red	Copper alloys, aluminium alloys and unhardened steels
C	Brale	150	Black	Hardened steels, cast irons, titanium alloys and case hardened surfaces
D	Brale	100	Black	Razor blades and certain case-hardened surfaces

18.2 TENSILE TEST

Tensile test is one of the most widely performed tests. Various properties of the material that can be determined by tensile test are yield stress, upper and lower yield points, tensile strength, elongation, and reduction in area. Universal tensile testing machine (see Figure 18.6) is frequently used for performing tensile test. Figure 18.7 shows dimensions of a specimen for tensile test. The specimen is subjected to tensile load till fracture occurs. Results of such a tensile test can be represented in the form of engineering stress-strain curve or true stress-strain curve. Figures 18.8, 18.9 and 18.10 show the three types of stress-strain curves. In the engineering stress-strain curve, average longitudinal stress and average linear strain in the tensile specimen are plotted.

The yield stress is defined as the stress at which plastic deformation (elongation/extension) of the tensile specimen takes place at a constant load (see Figure 18.8). Such a behaviour is generally observed in carbon steels, and especially in low carbon steels. This phenomenon can be associated with the presence of small amounts of interstitial impurities, say carbon and nitrogen in case of low carbon steels, and their interaction with dislocations. Some steels, especially alloy steels and hardened steels and non-ferrous alloys, do not show the presence of sharp yield point (see Figs. 18.9 and 18.10). For such steels, proof stress is reported instead of yield stress. Proof stress is that stress at which some small amount of permanent deformation,

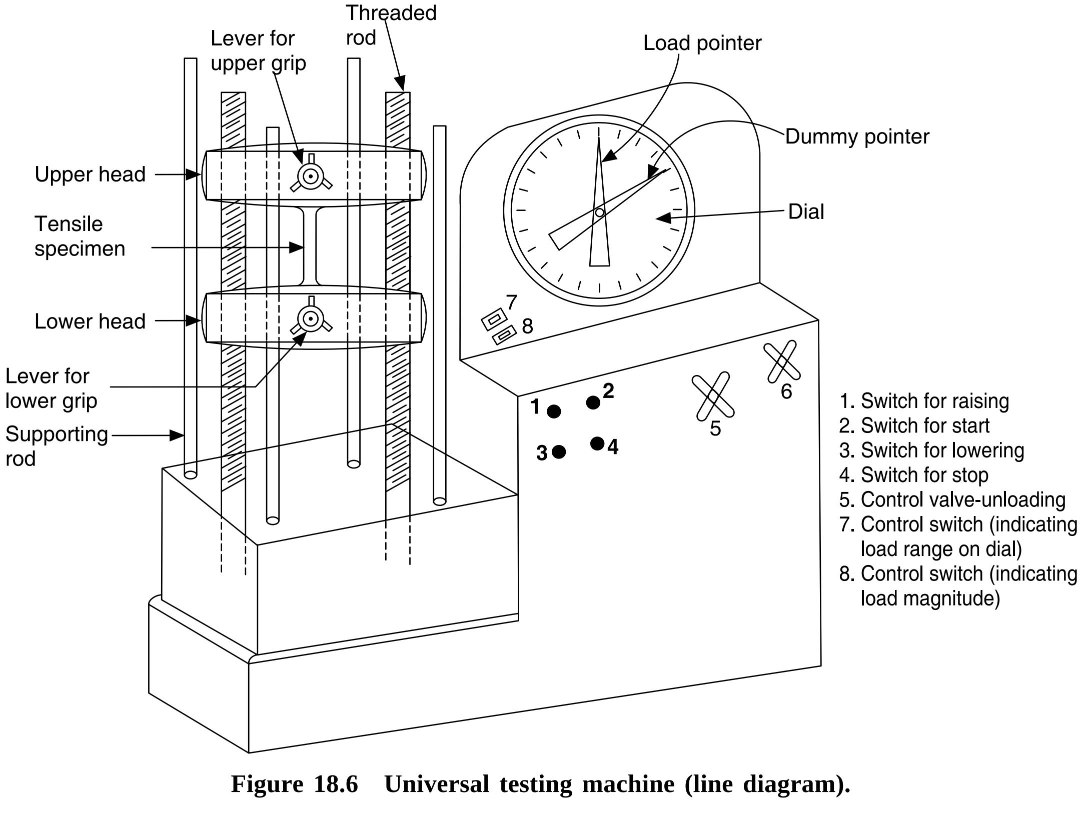


Figure 18.6 Universal testing machine (line diagram).

say equal to 0.2 percent strain, takes place. In other words, it is that stress which produces a permanent elongation of 0.2 percent in the tensile specimen on the removal of load. For structural steels, this property is of prime importance as compared to tensile strength and is always taken into consideration.

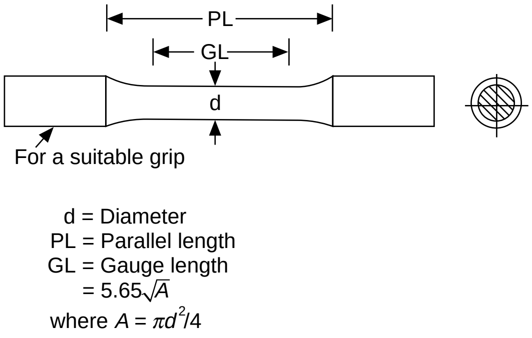


Figure 18.7 Standard tensile test specimen.

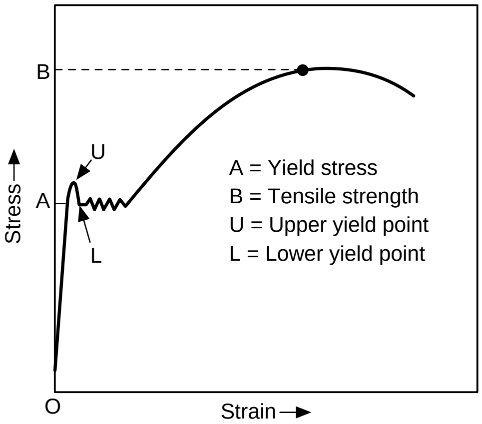


Figure 18.8 Typical stress-strain curve for mild steel.

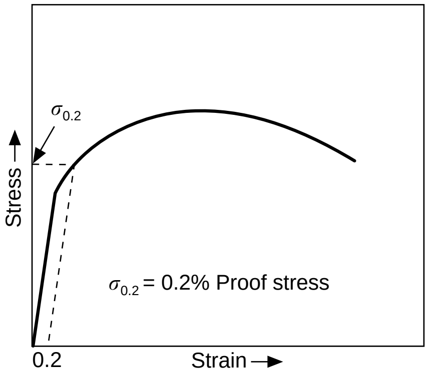


Figure 18.9 General stress-strain curve for ductile materials.

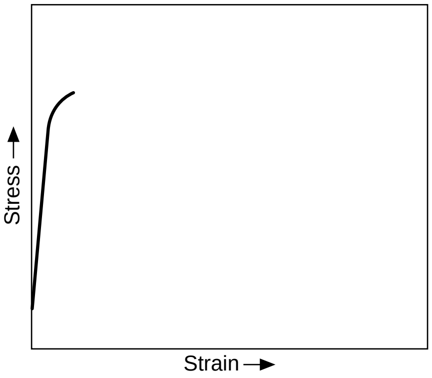


Figure 18.10 General stress-strain curve for brittle materials.

The tensile strength, also known as ultimate tensile strength, is defined as the maximum stress which a material can withstand. It is obtained by dividing maximum load by original cross-sectional area of tensile specimen. Tensile strength value also provides a fairly good idea about hardness and fatigue strength of the material. When two samples of the same material with identical microstructure but with different compositions are taken into consideration, it is observed that their fatigue strengths and hardness bear direct relation to tensile strength. As an example, let us consider steels. The tensile strength in newton per millimetre square (N/mm^2) is related to its hardness (in BHN) as follows:

Tensile strength = 3.242× BHN for heat treated alloy steels
Tensile strength = 3.396 × BHN for heat treated medium carbon steels
Tensile strength = 3.551 × BHN for heat treated low carbon steels

Generally, fatigue strength of most of steels is of the order of 50 percent of tensile strength. Tensile strength is used as design criterion for brittle materials.

Elongation is generally reported as percentage elongation. It is given by change in length per unit length of the tensile specimen multiplied by 100. The change in length is always measured relative to some length marked on the tensile specimen (by marking points) prior to testing. This reference length is referred to as gauge length. Knowledge of gauge length is essential in order to ensure the reproducibility of the results. The gauge length is always reported along with the reported value of percentage elongation. An expression for determining percentage elongation is

$$\text{Percentage elongation} = \frac{L_f - L_0}{L_0} \times 100 \tag{18.3}$$

where L_f is the final length and L_0 the initial length (gauge length).

As in the case of percentage elongation, percentage reduction in area is given by

$$\text{Percentage reduction in area} = \frac{A_0 - A_f}{A_0} \times 100 \tag{18.4}$$

where A_0 is the original cross-sectional area of the tensile specimen and A_f the final cross-sectional area of the tensile specimen.

In addition to these properties, some more characteristics such as Young’s modulus, resilience and toughness can also be determined with engineering stress-strain curve. Young’s modulus, also referred to as modulus of elasticity, can be obtained by dividing the stress by the corresponding strain while the specimen is undergoing deformation within the elastic limit, i.e. when it follows Hooke’s law. Such a calculation gives the slope of the initial linear region of the stress-strain curve. Young’s modulus provides information about the stiffness of the material. In fact, modulus of elasticity is structure-insensitive mechanical property. It depends mainly on the binding forces between atoms. The maximum energy which a material is capable of absorbing within the elastic limit is known as resilience. It is measured by the area within the stress-strain curve up to elastic limit. Toughness is the property of the material which measures the ability to absorb energy in the plastic region. The total area under the stress-strain curve is a measure of toughness for the relevant material.

For research work and in laboratories, Hounsfield tensometer (see Figure 18.11) is most commonly used. Load on tensile specimen in this tester is applied with the help of spring beams. The maximum load which can be applied on tensile specimen in a tensometer is 2000 kg. Other loads (spring beams) available with tensometer are 1000 kg, 500 kg, 250 kg, 125 kg, 62.50 kg, and 31.25 kg. Therefore, a large number of materials can be tested on this machine. For reproducibility of results, samples of standard size should be tested. The tensile strength specifications are summarized in Figure 18.12 and Table 18.3.

Table 18.3 Dimensions of Standard Round Tensile Test Specimens (see Figure 18.12)

	Specimen type							
Parameter	A	B	C	D	E	F	G	H
Gauge length (GL)	11.35	16.05	16.05	22.71	22.71	32.10	32.10	45.41
Parallel length (PL)	12.93	17.65	18.44	25.04	25.83	35.23	36.83	50.11
Gauge diameter (*d*)	3.20	4.53	4.53	6.40	6.40	9.05	9.05	12.80
	3.21	4.54	4.54	6.43	6.43	9.09	9.09	12.85
Diameter of outer shoulder (D_1)	6.55	6.81	9.07	9.60	12.83	13.59	18.14	18.69
	7.21	7.21	10.21	10.21	14.60	14.60	20.42	20.42
Diameter of inner shoulder (D_2)	4.27		5.60		8.58		12.19	
	4.52		6.35		9.07		12.80	
Thickness of outer shoulder (*t*)	2.29	3.81	3.30	5.08	4.57	7.37	6.35	10.16
	3.30	5.33	5.33	7.62	7.11	11.18	9.39	15.24
L (Parallel length + double the thickness of inner shoulder)	19.35		27.53		38.68		54.86	
Radius of curvature (*R*)0.80	0.80	1.20	1.20	1.60	1.60	2.40	2.40	

All dimensions are in millimetre.

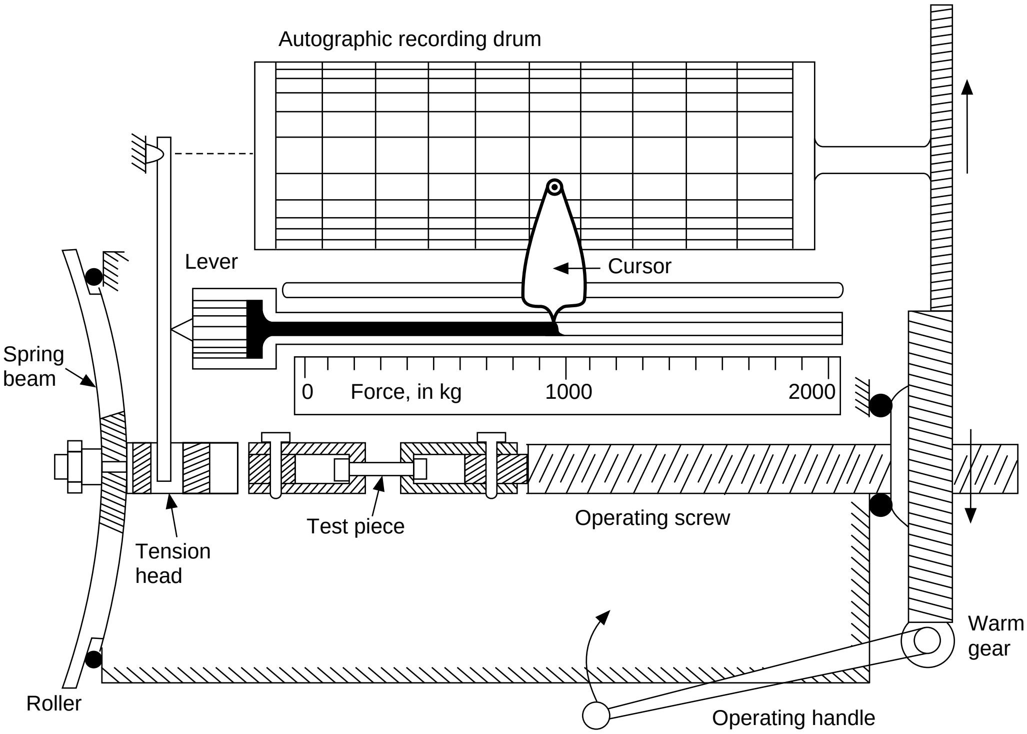


Figure 18.11 Line diagram of Hounsfield tensometer.

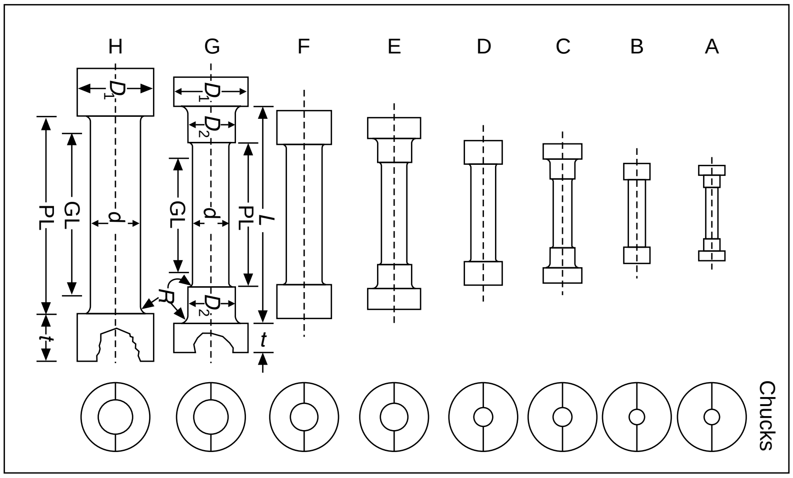


Figure 18.12 **Standard tensile test specimens used in Hounsfield tensometer. (The dimensions are detailed in Table 18.3.)**

18.3 IMPACT TEST

Impact test measures the strength of a material under dynamic loading. Often in actual service, most of the structural components are subjected to dynamic loading. Hence, knowledge of tensile strength alone will not be of sufficient use as a design parameter. In impact test, the material is subjected to sudden (impact) load. For this purpose, in general, a hammer is made to swing from a fixed height and strike the standard impact specimen (see Figure 18.13). Impact strength of a material is defined as the capability of the material to absorb energy just prior to failure under impact loading. Depending on the nature of the standard impact specimen, there are two most common methods for the measurement of impact strength. They are Izod and Charpy impact tests. The dimensions of both types of specimens are shown in Figure 18.14. The Izod specimen may have either square or round cross-section. The specimen has a

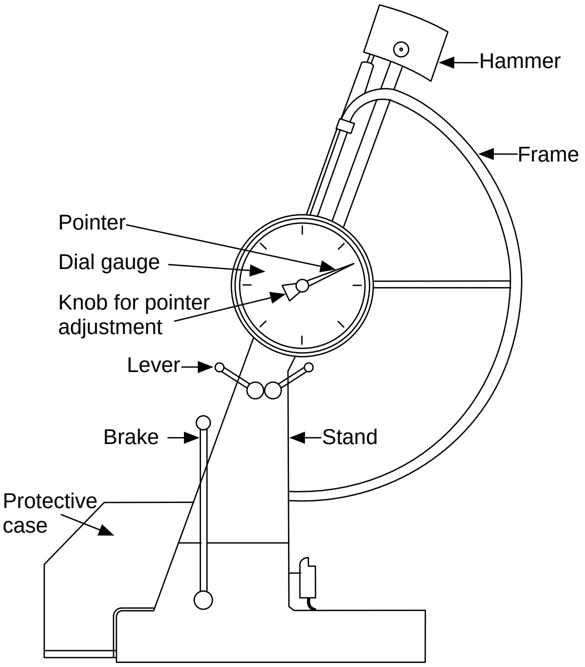


Figure 18.13 **Block diagram of impact testing machine.**

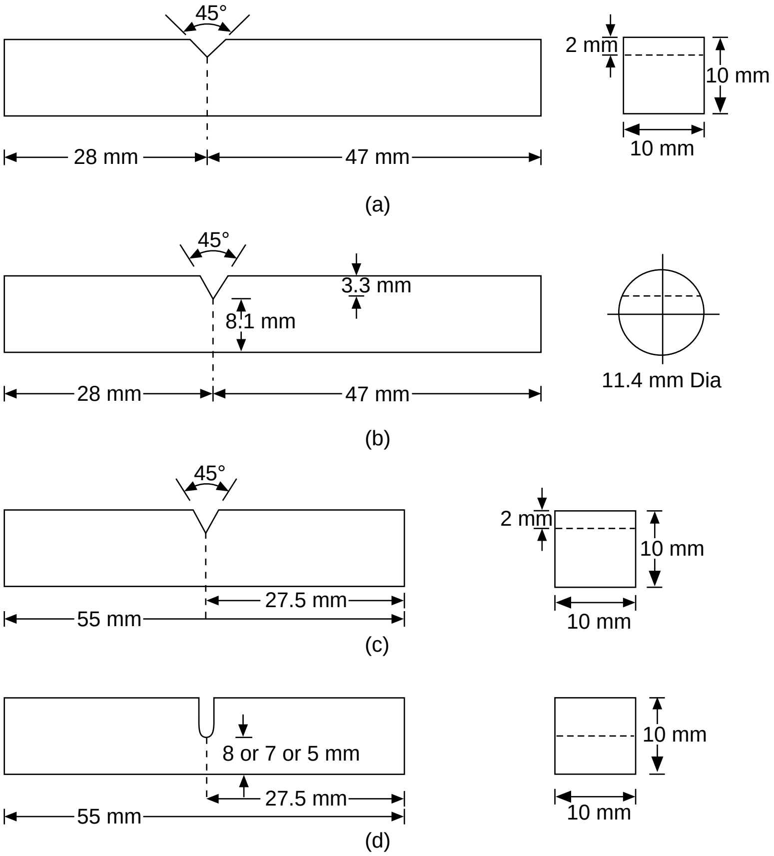


Figure 18.14 (a) Single notch square Izod. (b) Single notch round Izod. (c) Beam (V-notch). (d) Charpy (C-notch) impact test specimens.

V-shaped notch. The depth of notch is 2 mm and included angle is 45°. In this test, a hammer strikes the specimen which is fixed in vertical position (see Figure 18.15). The notch faces the hammer. Charpy impact specimen, square in cross-section, has V-shaped or key hole shaped notch. The specimen is fixed in horizontal position, as illustrated in Figure 18.16. The hammer strikes the impact specimen on the unnotched face.

Impact strength of a material is governed by many factors such as temperature, heat treatment, chemical composition and grain size. Temperature has marked influence on impact strength. As temperature comes down, impact strength also decreases. There is sudden drop in impact strength when a material is cooled below a particular temperature. The temperature at which an otherwise ductile metal changes to brittle is known as ductile to brittle transition temperature. Impact strength is very poor below this temperature. The temperature at which fracture is 50 percent brittle and 50 percent ductile is called fracture appearance transition temperature (FATT). Carbon raises transition temperature significantly in steels. Fortunately, the deleterious effect of carbon is counteracted by manganese. The manganese to carbon ratio should be at least 3 for satisfactory impact strength. Other elements which raise the transition

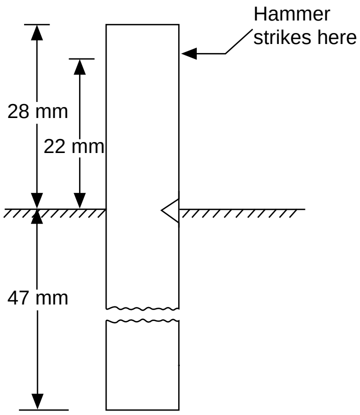


Figure 18.15 Mounting of Izod impact specimen.

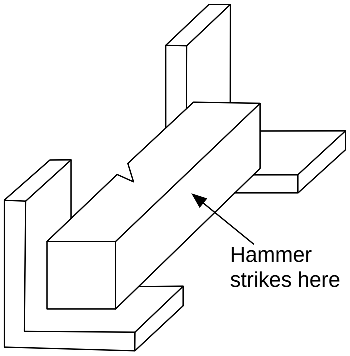


Figure 18.16 Mounting of Charpy impact specimen.

temperature are phosphorus, silicon and molybdenum. Grain size, as discussed in Section 4.4, affects transition temperature significantly. Heat treatment also affects impact strength. A tempered martensitic structure provides the best combination of tensile strength and impact strength.

18.4 FATIGUE TEST

Failure of a metal can take place at much lower stress as compared to tensile strength when it is subjected to repetitive or fluctuating load (see Figure 18.17). Such a failure is referred to as fatigue failure which always results in brittle fracture. It takes place instantaneously without any warning. Many components such as crank shafts, gears, connecting rods, springs and blades of power driven machines, which are subjected to cyclic loading, are prone to failure by fatigue. Such failure has been observed to be promoted mainly by application of sufficiently high tensile stresses, large fluctuation or variation in the applied stress, and a large number of cycles of applied stress.

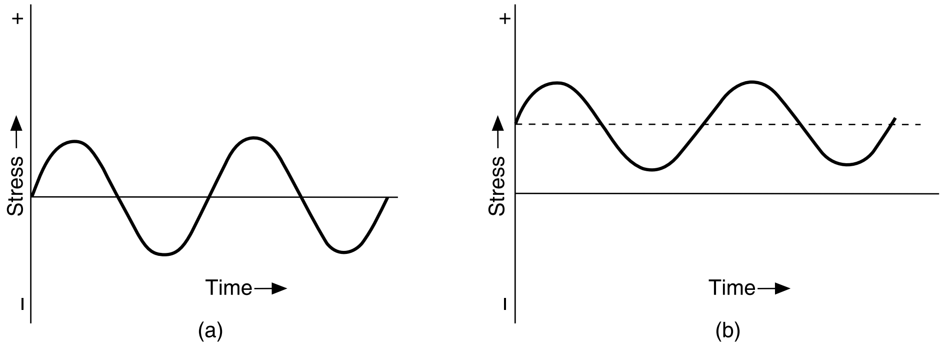


Figure 18.17 Two representative fatigue stress cycles.

The principle of operation of a fatigue testing machine is very simple and can be easily understood with the help of Figure 18.18. The test specimen is mounted on the machine and subjected to rotation. Due to rotation, the upper surface of the test specimen is subjected to tension, whereas the lower surface experiences compression. The rotation of specimen continues till failure occurs. The test is performed for a given metal at varying cyclic stresses. Thus a graph is obtained between cyclic stress and number of cycles. Such a graph or plot is referred to as S-N curve. Figure 18.19 shows a typical S-N curve for ferrous and non-ferrous metals.

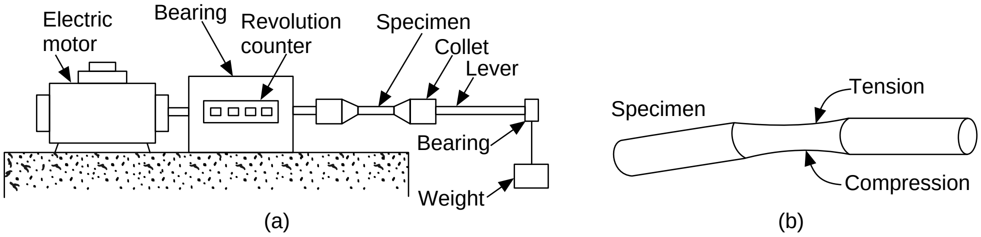


Figure 18.18 Block diagram of fatigue testing machine and stresses developed in test specimen.

Fatigue failure, in general, starts at the surface. Hence, in addition to stress, surface finish should be given due attention for components subjected to cyclic loading. It has been experimentally observed that resistance to fatigue failure can be improved significantly by improving the surface finish, removal of decarburized layer, hardening of surface and electropolishing. Introduction of compressive residual stresses in the surface considerably enhances resistance towards failure by fatigue. Shot peening and surface rolling are two commercial methods available for the introduction of compressive residual stresses in the metal surface. In addition to surface characteristics, certain metallurgical factors such as heat treatment, grain size, presence of alloying element and non-metallic inclusions also affect fatigue strength. The presence of equilibrium products in steel greatly reduces the fatigue strength. In general, a hardened and tempered steel has optimum fatigue properties. Further improvement in fatigue properties can be achieved by a bainitic structure. The effect of grain size on fatigue strength has already been discussed in Section 4.4.

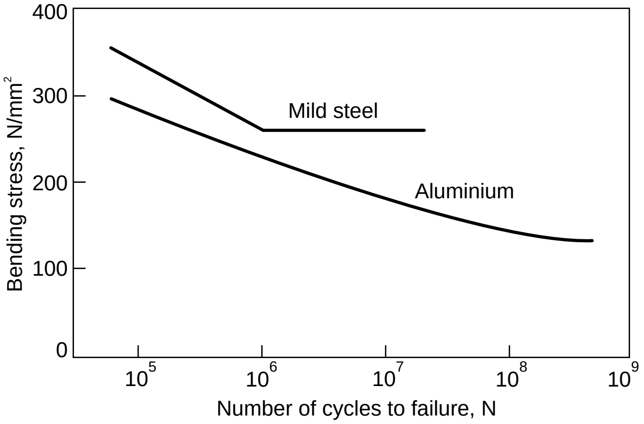


Figure 18.19 Typical S–N curves for ferrous and non-ferrous metals.

18.5 CREEP TEST

Creep is defined as time-dependent plastic deformation (elongation) of the metal at a constant tensile load. The phenomenon is quite significant at elevated temperatures. There is practically no creep deformation at room temperature for most metals and alloys and, therefore, the creep property is generally considered as high temperature property. Deformation at elevated temperature is facilitated by greater mobility of dislocations, availability of more vacancies, introduction of additional slip systems and possibility or grain boundary deformation. A typical creep curve is shown in Figure 18.20. The first stage of the creep curve, also known as primary creep, represents a region with decreasing creep rate. The resistance of the material to creep increases due to strain hardening effect. Hence, primary creep is the predominant creep process at low temperatures and for low stresses. The second stage or steady state creep or secondary creep is a result of balance between two opposing phenomena, namely, strain hardening and recovery. The third stage or tertiary creep is generally the predominant. creep process at high temperatures and for high stresses. The creep properties of steel depend on many factors such as grain size, chemical composition, melting practice, deoxidation practice and micro structure. Coarse grained steels, in general, have better creep strength. The presence of refractory compounds is beneficial in improving creep strength. For this reason, dispersion hardened steel and alloys are much preferred for high temperature applications.

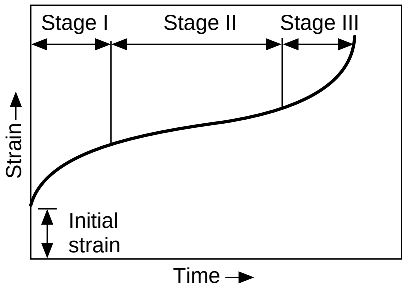


Figure 18.20 Creep curve showing various stages of creep.

The experimental set-up for creep testing, which consists of a furnace, is shown in Figure 18.21. The specimen is enclosed in the furnace and subjected to constant stress. The test is quite similar to tensile test. Four variables of the process, i.e. time, temperature, stress and strain, are noted carefully and a curve is plotted between elongation and test time.

18.6 NON-DESTRUCTIVE TESTING METHODS

A number of situations are encountered in day-to-day industrial practice where it becomes necessary to study the flaws in metallic components without destroying them. Under such circumstances, recourse is taken to non-destructive testing (NDT) technique. This technique makes the use of the component more reliable, safe and economical. Non-destructive testing has two important roles to play: (i) From these investigations, the presence of defects is established, (ii) it is also useful in estimating the nature and extent of defects and arriving at a conclusion about accepting or rejecting the product for service. Non-destructive tests also help in measuring the defect size and distribution, which plays a crucial role in taking the final decision on accepting or rejecting the component. A number of non-destructive tests are available now-a-days to detect the flaws in metallic components. Some of these tests are magnetic particle inspection, liquid penetration inspection, radiographic inspection, ultrasonic inspection and eddy current inspection. Magnetic particle inspection and liquid penetration

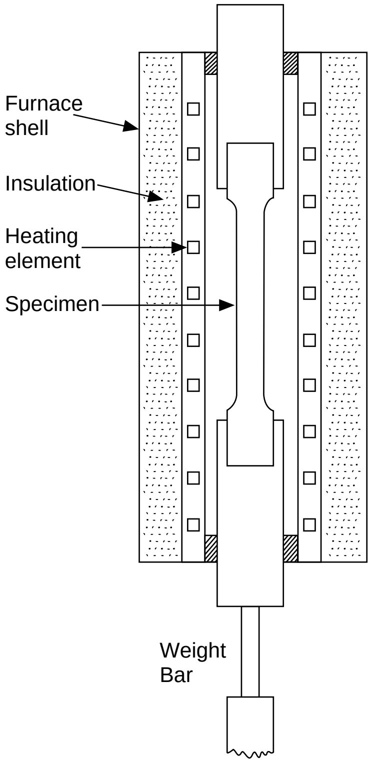


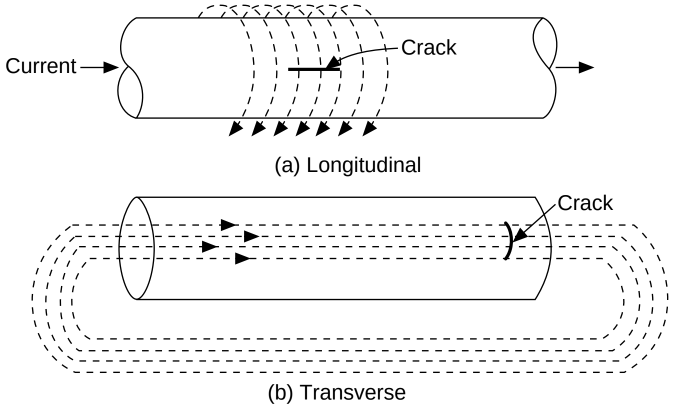
Figure 18.21 Diagrammatic representation of creep testing machine.

inspection are used to detect only surface defects. Radiographic and ultrasonic inspection techniques are useful for studying both surface and internal defects. Eddy current inspection is not as commonly used as the other non-destructive tests.

18.6.1 Magnetic Particle Inspection

This method is used to study surface or near surface defects. The only problem associated with this method is that its use is limited to ferromagnetic materials. A liquid solution containing very tiny magnetic particles is sprayed on the surface being checked and the sample is then subjected to a strong magnetic field (Figure 18.22). Discontinuity at or near the surface of the metal creates free poles. When magnetized, the metal attracts the magnetic particles in the solution used. When the magnetic field is removed, magnetic particles are left behind and get concentrated at those sites, thereby revealing the defects.

The magnetic field is set up in the test piece either by passing a current through it or by using a powerful electromagnet. In the latter case, the magnetic field generated by the electromagnet passes through the material under inspection. Both alternating current and direct current fields can be used. Alternating current field has the advantage of high sensitivity at the surface, brought about by skin effect. Direct current field has a better chance of revealing sub-surface defects. In certain cases, the test piece is encircled by a current-carrying conductor. A magnetic field is in turn generated in the test piece. The magnetic field flux lines should be



(a) Longitudinal

(b) Transverse

Figure 18.22 Principle of operation of magnetic crack detector for detecting cracks.

approximately at 90° to crack for maximum reliability. The test piece should be magnetized twice, successively in two mutually perpendicular directions to take care of any random orientation of the crack. The material to be tested should be as clean and bright as possible. A recent development in this method includes introduction of magnetic tape techniques.

18.6.2 Liquid Penetration Inspection

This method uses coloured (normally red) liquid dyes and fluorescent liquid penetrants to detect large cracks or openings, cold shuts, fatigue cracks and pits. The liquid dye penetrant is sprayed on to the clean surface of the test piece. Excess amount of dye is removed with a cleaner and the surface is washed with water and thoroughly dried. Then a developer is sprayed on the surface, which brings out the colour in the dye penetrant that has penetrated into crack or pin holes.

Similarly, fluorescent liquid is used and is applied to the surface being inspected. After some time, the excess fluorescent liquid is removed with a cleaner and the surface is washed and dried. Then the test surface is viewed under black light whose wavelength lies between the visible and ultraviolet regions of the spectrum. Black light causes penetrant to glow clearly in the dark. Some solvents used in the cleaners and developers contain a high percentage of chlorine to make the liquid non-flammable. Great care is required while using such cleaners and developers in view of health hazards associated with chlorine. Penetrant testing has the advantage that it can be used for all types of materials.

18.6.3 Eddy Current Inspection

Eddy current testing is one of the methods of detecting discontinuities and flaws. The method is based on the principle that when an alternating current carrying conductor coil is brought up near a metallic/conductive specimen, eddy currents are introduced in the specimen due to electromagnetic induction. These eddy currents produce their own magnetic field which opposes the field of the current-carrying coil, thereby increasing its impedance (resistance). Coil impedance can be measured. Whenever any flaw comes under the current-carrying coil, the local eddy current varies in the test piece. This in turn changes the impedance of the coil which actuates a flash light, and thus the position of the flaw can be detected. The magnitude of the induced eddy current is a function of many variables such as magnitude and frequency of the alternating current flowing in the conductor coil, electric and magnetic properties of the test specimen, shape of the test specimen, and metallurgical properties of the test specimen. Because of such complexity, this method has not gained sufficient popularity.

18.6.4 Radiographic Inspection

This is one of the most important techniques for detecting defects such as blow holes and cracks in a material. This technique is also used in estimating the type, location and size of defects. It is an excellent technique because volumetric defects are easily detected and identified. But planar defects are difficult to detect since such defects are thin. However, if the direction of electromagnetic beam is parallel to the plane of defect, identification may be possible as, in this position, it offers maximum thickness to the beam. The disadvantages of this technique are that special safety precautions are to be taken in view of health hazards associated with radiations. Also, the technique is expensive.

X-ray radiography is based on the principle of absorption of X-rays by a body as a function of absorption coefficient μ and thickness t. If I_0 is the intensity of the incident beam and I the intensity of the transmitted beam, then the two are related by the equation

$$I = I_0 \exp(-\mu t) \tag{18.5}$$

The greater the thickness of the body, the lesser will be the intensity of transmitted beam. When the beam passes through blow holes, cracks or similar defects, it has to pass through an effectively thinner section. Accordingly, the transmitted X-rays are of greater intensity in comparison to the X-ray beam passing through the other normal area of the test piece. Thus, on positive print, defects are marked by light areas.

The accelerating voltage needed varies from 50 kV to 24,000 kV in the X-ray tube. In recent years, many advances have taken place in radiographic technique. Now it is possible to obtain sharp radiographic images of defects with the help of microfocus X-ray tubes. It is used at such places where sensitivity and resolution of radiograph is of paramount importance. Microfocus X-ray tubes are available with spot as small as 10 μm in size as compared to spot of 2 mm to 4 mm size in conventional techniques. Some latest advances in the field of X-ray radiography are X-ray television fluoroscopy and digital image storage processing.

Gamma-ray radiography technique makes use of certain radioactive isotopes, namely, cesium 137, cobalt 60, iridium 142, samarium 153, thulium 170, and ytterbium 169. These isotopes give off γ-rays required for the test, γ-ray equipment is more flexible in use than standard X-ray equipment. Ytterbium 169 has been found to be well suited for taking radiographs on steel in the 5–10 mm thickness range.

18.6.5 Ultrasonic Inspection

Those defects which cannot be detected by X-rays or γ-rays can be successfully detected by means of ultrasonic flow detection. In this method, an electronic oscillator sends out alternating current to piezoelectric transducer which converts the electric energy to acoustic energy with same frequency. A frequency of 2.25 megacycle is commonly used. This acoustic wave is then sent to the test piece using suitable liquid couplant. If there is a flaw, say a crack within the test piece, the acoustic wave bounces back from the crack and returns to the same transducer as an echo. The returning echo cyclically strains the crystal, which then responds by generating alternating current of the same frequency that it receives from the echo pulse. The voltage of this alternating current, generated by the crystal, is then amplified and applied to the horizontal plates of cathode ray tube. A small defect returns a small echo, which appears as a short vertical pip on cathode ray oscillograph (CRO) screen, whereas a large vertical defect will appear as a large pip. Figure 18.23 shows the principle of ultrasonic inspection.

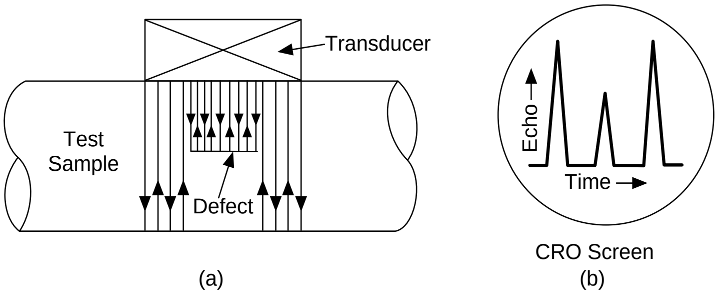


Figure 18.23 Diagram illustrating the principle of ultrasonic testing.

QUESTIONS

18.1 Distinguish between
- (a) elastic limit and proportional limit
- (b) toughness and resilience
- (c) endurance limit and fatigue strength
- (d) ridging and sinking
- (e) upper and lower yield points.

18.2 Draw engineering stress-strain curves for mild steel, cast iron and copper. Give reasons for the differences observed.

18.3 A good estimation of hardness can be obtained by tensile strength data and vice-versa. Explain which one is preferred and why?

18.4 Why do metals undergo creep deformation? Draw a typical creep curve and explain it.

18.5 Enumerate metallurgical factors affecting creep behaviour? How can a metal be strengthened to resist creep deformation?

18.6 Discuss the conditions which lead to fatigue failure. Name the factors controlling the fatigue strength of a metal.

18.7 Draw S–N curves for mild steel and high strength aluminium alloy. Explain the difference in the nature of the two curves.

18.8 Describe dependence of fatigue strength, creep strength and impact strength on microstructure of steel.

18.9 Discuss the effect of temperature, grain size and heat treatment on toughness, fatigue strength and creep strength of steel.

18.10 Give the units for the following:

(a) Brinell hardness
(b) Young's modulus
(c) Toughness
(d) Tensile strength
(e) Creep deformation.

18.11 Name the processes by which resilience, toughness and stiffness can be improved.

18.12 What is a transducer? Differentiate between transmission and pulse echo methods of ultrasonic inspection.

18.13 Enumerate the limitations of the following tests:

(a) Ultrasonic test
(b) Dye-penetrant test
(c) Magnetic particle test
(d) Radiography.

18.14 Compare the X-ray and γ-ray radiographic techniques as non-destructive tests.

18.15 Name the most versatile non-destructive test. Give reasons in support of your answer.

19

Energy Economy in Heat Treatment

INTRODUCTION

Economy in the use of energy during processing is of vital concern from the point of view of conservation of resources and cost of processing. Much attention has been devoted to the subject of energy economy during the last few years, The sources of energy largely availed of are coal, hydroelectric energy and electric power. As far as India is concerned, the resources of natural fuel are expected to last only up to about the middle of the twenty first century. Of the sources of energy in large use, coal occupies a predominant position. Coal reserves in India are expected to last at least up to the end of the twenty first century. Fuel resources are being consumed daily at a much faster rate than the availability of new reserves and, consequently, fuel prices are skyrocketing.

In regard to hydroelectric resources, hardly 40 percent of the hydro resources have been tapped. Besides being costly, in respect of tapping, they create problems of environment.

The main raw material used in generating electric energy is coal. So far nuclear power production has been greatly hampered by the comparatively low availability of uranium and lack of uranium refining technology, apart from the question of cost which is debatable. The use of power as a source of energy is at a very low level. The need for searching for other sources of energy has become paramount and steps have been taken in this regard.

Heat treatment of metals and alloys involves considerable heat energy. The various forms of energy used in heat treatment are gas, oil and electricity for heating furnaces and petroleum products for case hardening.

In the context of high prices of fuels, efficient use of heat energy assumes special significance. It has been observed that a major fraction of the heat energy is just wasted. For example, only 12–13% of the total heat energy is utilized in a gas-fired carburizing furnace. Therefore, there is considerable scope for devising ways and means of reducing this loss. The following are the various measures which can be considered for bringing about fuel economy:

(i) Heat treatment cycle can be reviewed for time saving without affecting the final quality of the product.
(ii) If possible, material can be changed so that heat treatment cycle may be shortened as much as possible.

(iii) Various equipment should be maintained properly so that they can be utilized to their maximum or near maximum efficiency.
(iv) Heat treatment furnaces should be altered in design and/or material so as to get maximum possible utilization of input of heat energy.
(v) Auxiliary equipment should be installed in order to recover heat energy.

All these measures emphasize that proper corrective action should be taken at every possible stage to save energy.

One of the ways of reducing heat (energy) consumption is reduction in weight of the component to be heat treated. This parameter is very important, especially in automobile, aircraft and spacecraft industries. A lighter assembly will consume less energy as compared to the heavier one provided all other parameters are kept constant.

Alteration in the material in use, modification in heat treatment cycle, and switching over to some less heat consuming processes are most probably the factors through which energy economy and saving can be achieved in heat treating.

19.1 ENERGY ECONOMY THROUGH CHANGE OF MATERIAL

Change of material does not essentially mean change of chemical composition. The term is used in a wider sense and, in addition to change in chemical composition, includes use of pre-processed material, pre-heat treated material, castings in place of forgings, high quality or better grade material, and hard facing. A number of alternative materials can be explored, which can eliminate the necessity of heat treatment and result in saving of energy. In some cases, lengthy heat treatment cycle(s) can be shortened. Selection of alternative material will depend largely on the purpose of heat treatment which is given to the original material. This can be understood with the help of the following examples.

If the purpose of heat treatment is only to improve tensile strength, then for simpler shapes, cold drawn steel can serve as a substitute for heat treated steel. The desired tensile strength equivalent to that of normalized or hardened and tempered steel can be achieved by controlling the degree of cold working. An optimum combination of tensile strength and ductility can be achieved in cold drawn steel by a suitable cold work anneal cycle. However, cold-worked steel suffers from non-uniformity of properties, i.e. tensile strength value is different in transverse and longitudinal directions. On the contrary, the tensile strength of normalized or hardened and tempered steel is uniform throughout the cross-section. Elevated temperature drawing eliminates this defect associated with cold working. Drawn steel which is heavily worked at elevated temperature possesses uniform hardness and tensile strength throughout the cross-section.

A properly heat treated high carbon steel can be used successfully in place of case hardened steel for making wear resistant parts. It has been found that heat treated high carbon low chromium steel, known as ball-bearing steel (see section 14.2.3), is capable of replacing nitrided martensitic stainless steels as some wear resistant component. Heat treatment of ball-bearing steel, namely, hardening and tempering, requires only about 20 percent of the energy consumed in nitriding treatment of martensitic stainless steel.

Pre-heat treating of the material is beneficial in many ways. It can induce softness, improve formability, eliminate the heterogeneity of chemical composition, develop desired properties, and result in attainment of a particular grain size. All these factors may facilitate further processing of the material and can result in elimination of heat treatment of intermediate or even finished part. For example, patented high carbon steel wire rod can be cold drawn to about 90 percent reduction in area without any need of intermediate annealing. Hence patented and cold drawn steel wires can by themselves be used for making springs. In many cases, these springs are comparable or even superior to heat treated springs.

Some heat treatment processes such as spheroidizing, annealing and normalizing are carried out to improve formability. Such heat treatment(s) can be easily avoided by proper selection of the material. For example, the necessity of heat treatment to improve machinability can be avoided by the use of free machining grades of steels. Similarly, the use of better cold formable grades of steel may eliminate the necessity of heat treatment in cold forming process. Boron and silicon steels have generally better formability than other steels with equivalent properties.

Use of castings in place of forgings can save sufficiently high amount of energy. Castings can be used either in as-cast or in heat treated condition. Even the energy consumed in heat treating of castings is far far less than that consumed in the process of forging of castings. Malleable iron and ductile iron castings have been used successfully in place of forgings, specially as crank shafts, chain links, gears and track shoes.

Use of hard facing in place of case hardening treatment for improving wear resistance results not only in saving of energy but also in reducing the overall cost.

19.2 ENERGY ECONOMY THROUGH HEAT TREATMENT PRACTICE

There are many ways by which energy can be saved by some modification(s) in heat treatment cycle(s). For example, tempering treatment can be avoided for components made from shallow hardened grades of steel. It has been observed that such a modified practice, neither interferes with the performance during service nor results in development of inferior properties. Thus a reasonable amount of energy can be saved.

Tempering temperature and holding period at tempering temperature should be well established prior to going in for mass heat treatment schedule. It will avoid any overtempering and will not only check the excess softening but also save excess energy consumed due to overtempering. Temperature measurement and control should be precise for this purpose.

In general, heat treatment furnaces are either underloaded or overloaded, Both these conditions result not only in larger consumption of energy but also in poor quality of heat treated parts. In both cases, as the desired properties are not achieved in the heat treated part, a second heat treatment cycle is given to already improperly heat treated parts.

Heat treatment furnaces and auxiliary equipment, which are not in use, should be shut down. However, in cases where energy required for reheating purpose is very high, shut-down should be avoided.

In general, holding period at heat treatment temperature is not given as much importance as it deserves. Longer holding periods do not help in any way, and hence should be avoided in order to save energy.

It has been found that production of deeper case depths than the specified one are in no way harmful to the component. This fact is very important as a number of parts with different case depth requirements can be case hardened at the same time in a single lot with the aim of achieving maximum possible demanded case depth in any of the part. Such a practice results in considerable saving of energy. However, if parts have to be heat treated in different lots because of furnace capacity or some other reasons, the original case depth requirements should be followed.

In some cases, heat treatment cycles may be shortened. For example, duration of malleabilizing cycle can be reduced from about 48–60 hours to about 12–16 hours by proper selection of chemical composition and close control of temperature. Mechanical working, specially cold working, has pronounced effect on the kinetics of phase transformation, and it can be used for modifying heat treatment practice.

Carburizing heat treatment should be avoided as far as possible. The two main reasons for this are: (i) it involves high temperatures; (ii) post-carburizing heat treatment is almost an essential feature of carburizing heat treatment. A lot of energy is consumed in this process. Since it is not practically possible to avoid carburizing heat treatment, attention may be focused on development of such grades of steel which are capable of undergoing direct quenching after carburizing. This is achieved to some extent by the selection of deeper hardenable grades of steel. Carburizing time can be cut short indirectly by using more efficient quenching techniques such as polymer quenching or spray quenching. The merits of these quenching techniques over conventional quenching techniques have already been described in Sections 5.5.2 and 7.3.7.

19.3 ENERGY ECONOMY THROUGH PROCESSING

Energy saving and economy in heat treating can be achieved by changing over to alternative processes. For example, using high temperatures in carburization results in the reduction of duration of heat treatment cycle by a considerable extent. This, in turn, increases the production rate of heat treatment shop and decreases overall gas consumption. Reduction in heat treatment process time, due to high temperature practice, more than compensates for the extra energy required for producing and maintaining higher temperature during the process.

Conventionally case hardened parts can be replaced by hard faced or plated parts for wear resistant purposes. This not only reduces the furnace time but also improves corrosion resistance of the component.

Conventional hardening and tempering treatment for hardening steel, as far as possible, should be replaced by austempering treatment. Austempering heat treatment and its advantages have already been dealt with in Section 5.7.

Medium carbon steels should preferably be induction hardened in place of conventional case hardening. Induction hardening saves energy. This energy saving is possible because (i) energy is needed only to heat the surface area of the part; and (ii) much less energy is lost to the surroundings as rate of heating is very fast. Since the process is almost fully automatic, it is well suited to mass production of parts like gears, crank shafts and armour-plate.

Vacuum carburizing offers many advantages over conventional carburizing process. It saves energy in many ways. Some of the factors responsible for energy saving are: Shorter carburizing cycle as compared to conventional case carburizing; faster rate of heating as heating is done by radiation; almost uniform temperature distribution throughout the furnace chamber because of high quality of insulation; rapid heating and cooling rates (i.e. furnace can be heated up and cooled down rapidly, eliminating the need for keeping furnace hot during non-working hours); and elimination of heat energy required for heating the furnace atmosphere as atmosphere is absent in this case.

In general, conventional hardening processes for improving wear resistance are high temperature processes. Substantial amount of energy can be saved if some low temperature hardening processes are adopted. A few low temperature surface hardening methods are low temperature sulphidizing, low temperature carbo-nitriding and boronizing.

New processes involving less energy consumption should be adopted. Some recent additions to heat treatment (surface hardening) technology include electron beam, laser beam and plasma heat treating. These are very efficient processes from the point of view of energy economy. These heat treatment processes have already been discussed in Chapter 9.

19.4 AIR POLLUTION IN HEAT TREATMENT

Sources of air pollution in heat treatment areas are:

1. Malfunctioning of furnace combustion system.
2. Evolution of vapours and fumes because of unclean surface on the work.
3. Oil mist or vapour generation during cooling of the medium being used.
4. Molten salt pot fumes.
5. Toxic gases emitted from furnaces under special atmospheres.
6. Release of mist and vapours during oil quenching.

The primary source of toxic and hazardous emissions is the carbonitriding process known as *gas cyaniding*. The cyanide salt decomposes into carbonitrates and if these carbonitrates get released into atmosphere they combine with atmospheric moisture to form toxic compounds. The heat treatment furnaces are major contributors to the emission of many toxic pollutants—cyanides, carbon monoxides, nitrogen methane and metallic oxides.

The accepted ways to prevent pollution may be summarized as follows:

1. Correction of operating procedures combined with selection of proper fuel and burner so as to eliminate smoke.
2. Removal of organic material adhering to the workpiece by degreasing prior to heat treatment.
3. Proper selection of oils and control of oil bath temperature so that mists and fumes are not generated during oil quenching.
4. Removal of fumes from molten salt pots by cloth arresters in the bag house. It should be noted that the salt fumes are hygroscopic and corrosive in nature.
5. Properly designed canopy hoods above the heat treatment furnaces to capture effectively the up-draft of hot air.

Appendices

APPENDIX 1 Table for Conversion of Temperature

–459.4 to 0					
°C	°F/°C	°F	°C	°F/°C	°F
–273	*–459.4*		–146	*–230*	–382
–268	*–450*		–140	*–220*	–364
–262	*–440*		–134	*–210*	–346
–257	*–430*		–129	*–200*	–328
–251	*–420*		–123	*–190*	–310
–246	*–410*		–118	*–180*	–292
–240	*–400*		–112	*–170*	–274
–234	*–390*		–107	*–160*	–256
–229	*–380*		–101	*–150*	–238
–223	*–370*		–96	*–140*	–220
–218	*–360*		–90	*–130*	–202
–212	*–350*		–84	*–120*	–184
–207	*–340*		–79	*–110*	–166
–201	*–330*		–73	*–100*	–148
–196	*–320*		–68	*–90*	–130
–190	*–310*		–62	*–80*	–112
–184	*–300*		–57	*–70*	– 94
–179	*–290*		–51	*–60*	–76
–173	*–280*		–46	*–50*	–58
–169	*–273*	–459.4	–40	*–40*	–40
–168	*–270*	–454	–34	*–30*	–22
–162	*–260*	–436	–29	*–20*	–4
–157	*–250*	–418	–23	*–10*	14
–151	*–240*	–400	–17.8	*0*	32

To convert degrees Celsius to degrees Fahrenheit, look up the reading in the middle column and read the equivalent in the right-hand column.

To convert degrees Fahrenheit to degrees Celsius, look up the reading in the middle column and read the equivalent in the left-hand column.

APPENDIX 1 Table for Conversion of Temperature (cont.)

0 to 100

°C	°F/°C	°F	°C	°F\°C	°F	°C	°F/°C	°F	°C	°F/°C	°F
–17.8	*0*	32	–3.3	*26*	78.8	11.1	*52*	125.6	25.6	*78*	172.4
–17.2	*1*	33.8	–2.8	*27*	80.6	11.7	*53*	127.4	26.1	*79*	174.2
–16.7	*2*	35.6	–2.2	*28*	82.4	12.2	*54*	129.2	26.7	*80*	176.0
–16.1	*3*	37.4	–1.7	*29*	84.2	12.8	*55*	131.0	27.2	*81*	177.8
–15.6	*4*	39.2	–1.1	*30*	86.0	13.3	*56*	132.8	27.8	*82*	179.6
–15.0	*5*	41.0	–0.6	*31*	87.8	13.9	*57*	134.6	28.3	*83*	181.4
–14.4	*6*	42.8	0	*32*	89.6	14.4	*58*	136.4	28.9	*84*	183.2
–13.9	*7*	44.6	0.6	*33*	91.4	15.0	*59*	138.2	29.4	*85*	185.0
–13.3	***8***	46.4	1.1	*34*	93.2	15.6	*60*	140.0	30.0	*86*	186.0
–12.8	*9*	48.2	1.7	*35*	95.0	16.1	*61*	141.8	30.6	*87*	188.6
–12.2	*10*	50.0	2.2	*36*	96.8	16.7	*62*	143.6	31.1	*88*	190.4
–11.7	*11*	51.8	2.8	*37*	98.6	17.2	*63*	145.4	31.7	*89*	192.2
–11.1	*12*	53.6	3.3	*38*	100.4	17.8	*64*	147.2	32.2	*90*	194.0
–10.6	*13*	55.4	3.9	39	102.2	18.3	*65*	149.0	32.8	*91*	195.8
–10.0	*14*	57.2	4.4	*40*	104.0	18.9	*66*	150.8	33.3	*92*	197.6
–9.4	*15*	59.0	5.0	*41*	105.8	19.4	*67*	152.6	33.9	*93*	199.4
–8.9	*16*	60.8	5.6	*42*	107.6	20.0	*68*	154.4	34.4	*94*	201.2
–8.3	*17*	62.6	6.1	*43*	109.4	20.6	*69*	156.2	35.0	*95*	203.0
–7.8	*18*	64.4	6.7	*44*	111.2	21.1	*70*	158.0	35.6	*96*	204.8
–7.2	*19*	66.2	7.2	*45*	113.0	21.7	*71*	159.8	36.1	*97*	206.6
–6.7	*20*	68.0	7.8	*46*	114.8	22.2	*72*	161.6	36.7	*98*	208.4
–6.1	*21*	69.8	8.3	*47*	116.6	22.8	*73*	163.4	37.2	*99*	210.2
–5.6	*22*	71.6	8.9	*48*	118.4	23.3	*74*	165.2	37.8	*100*	212.0
–5.0	*23*	73.4	9.4	*49*	120.2	23.9	*75*	167.0			
–4.4	*24*	75.2	10.0	*50*	122.0	24.4	*76*	168.8			
–3.9	*25*	77.0	10.6	*51*	123.8	25.0	*77*	170.6			

100 to 1000

°C	°F/°C	°F	°C	°F\°C	°F	°C	°F/°C	°F	°C	°F/°C	°F
38	*100*	212	160	*320*	608	288	*550*	1022	416	*780*	1436
43	*110*	230	166	*330*	626	293	*560*	1040	421	*790*	1454
49	*120*	248	171	*340*	644	299	*570*	1058	427	*800*	1472
54	*130*	266	177	*350*	662	304	*580*	1076	432	*810*	1490
60	*140*	284	182	*360*	680	310	*590*	1094	438	*820*	1508
66	*150*	302	188	*370*	698	316	*600*	1112	443	*830*	1526
71	*160*	320	193	*380*	716	321	*610*	1130	449	*840*	1544
77	*170*	338	199	*390*	734	327	*620*	1148	454	*850*	1562
82	*180*	356	204	*400*	752	332	*630*	1166	460	*860*	1580
88	*190*	374	210	*410*	770	338	*640*	1184	466	*870*	1598
93	*200*	392	216	*420*	788	343	*650*	1202	471	*880*	1616
99	*210*	410	221	*430*	806	349	*660*	1220	477	*890*	1634
100	*212*	413.6	227	*440*	824	354	*670*	1238	482	*900*	1652
104	*220*	428	232	*450*	842	360	*680*	1256	488	*910*	1670
110	*230*	446	238	*460*	860	366	*690*	1274	493	*920*	1688
116	*240*	464	243	*470*	878	371	*700*	1292	499	*930*	1706
121	*250*	482	249	*480*	896	377	*710*	1310	504	*940*	1724
127	*260*	500	254	*490*	914	382	*720*	1328	510	*950*	1742
132	*270*	518	260	*500*	932	388	*730*	1346	516	*960*	1760
138	*280*	536	266	*510*	950	393	*740*	1364	521	*970*	1778
143	*290*	554	271	*520*	968	399	*750*	1382	527	*980*	1796
149	*300*	572	277	*530*	986	404	*760*	1400	532	*990*	1814
154	*310*	590	282	*540*	1004	410	*770*	1418	538	*1000*	1832

APPENDIX 1 Table for Conversion of Temperature (cont.)

1000 to 2000

°C	°F/°C	°F	°C	°F\°C	°F	°C	°F/°C	°F	°C	°F/°C	°F
538	*1000*	1832	682	*1260*	2300	827	*1520*	2768	971	*1780*	3236
543	*1010*	1850	688	*1270*	2318	832	*1530*	2786	977	*1790*	3254
549	*1020*	1868	693	*1280*	2336	838	*1540*	2804	982	*1800*	3272
554	*1030*	1886	699	*1290*	2354	843	*1550*	2822	988	*1810*	3290
560	*1040*	1904	704	*1300*	2372	849	*1560*	2840	993	*1820*	3308
566	*1050*	1922	710	*1310*	2390	854	*1570*	2858	999	*1830*	3326
571	*1060*	1940	716	*1320*	2408	860	*1580*	2876	1004	*1840*	3344
577	*1070*	1958	721	*1330*	2426	866	*1590*	2894	1010	*1850*	3362
582	*1080*	1976	727	*1340*	2444	871	*1600*	2912	1016	*1860*	3380
588	*1090*	1994	732	*1350*	2462	877	*1610*	2930	1021	*1870*	3398
593	*1100*	2012	738	*1360*	2480	882	*1620*	2948	1027	*1880*	3416
599	*1110*	2030	743	*1370*	2498	888	*1630*	2966	1032	*1890*	3434
604	*1120*	2048	749	*1380*	2516	893	*1640*	2984	1038	*1900*	3452
610	*1130*	2066	754	*1390*	2534	899	*1650*	3002	1043	*1910*	3470
616	*1140*	2084	760	*1400*	2552	904	*1660*	3020	1049	*1920*	3488
621	*1150*	2102	766	*1410*	2570	910	*1670*	3038	1054	*1930*	3506
627	*1160*	2120	771	*1420*	2588	916	*1680*	3056	1060	*1940*	3524
632	*1170*	2138	777	*1430*	2606	921	*1690*	3074	1066	*1950*	3542
638	*1180*	2156	782	*1440*	2624	927	*1700*	3092	1071	*1960*	3560
643	*1190*	2174	788	*1450*	2642	932	*1710*	3110	1077	*1970*	3578
649	*1200*	2192	793	*1460*	2660	938	*1720*	3128	1082	*1980*	3596
654	*1210*	2210	799	*1470*	2678	943	*1730*	3146	1088	*1990*	3614
660	*1220*	2228	804	*1480*	2696	949	*1740*	3164	1093	*2000*	3632
666	*1230*	2246	810	*1490*	2714	954	*1750*	3182			
671	*1240*	2264	816	*1501*	2732	960	*1760*	3200			
677	*1250*	2282	821	*1510*	2750	966	*1770*	3218			

2000 to 3000

°C	°F/°C	°F	°C	°F\°C	°F	°C	°F/°C	°F	°C	°F/°C	°F
1093	*2000*	3632	1238	*2260*	4100	1382	*2520*	4568	1527	*2780*	5036
1099	*2010*	3650	1243	*2270*	4118	1388	*2530*	4586	1532	*2790*	5054
1104	*2020*	3668	1249	*2280*	4136	1393	*2540*	4604	1538	*2800*	5072
1110	*2030*	3686	1254	*2290*	4154	1399	*2550*	4622	1543	*2810*	5090
1116	*2040*	3704	1260	*2300*	4172	1404	*2560*	4640	1549	*2820*	5108
1121	*2050*	3722	1266	*2310*	4190	1410	*2570*	4658	1554	*2830*	5126
1127	*2060*	3740	1271	*2320*	4208	1416	*2580*	4676	1560	*2840*	5144
1132	*2070*	3758	1277	*2330*	4226	1421	*2590*	4694	1566	*2850*	5162
1138	*2080*	3776	1282	*2340*	4244	1427	*2600*	4712	1571	*2860*	5180
1143	*2090*	3794	1288	*2350*	4262	1432	*2610*	4730	1577	*2870*	5198
1149	*2100*	3812	1293	*2360*	4280	1438	*2620*	4748	1582	*2880*	5216
1154	*2110*	3830	1299	*2370*	4298	1443	*2630*	4766	1588	*2890*	5234
1160	*2120*	3848	1304	*2380*	4316	1449	*2640*	4784	1593	*2900*	5252
1166	*2130*	3866	1310	*2390*	4334	1454	*2650*	4802	1599	*2910*	5270
1171	*2140*	3884	1316	*2400*	4352	1460	*2660*	4820	1604	*2920*	5288
1177	*2150*	3902	1321	*2410*	4370	1466	*2670*	4838	1610	*2930*	5306
1182	*2160*	3920	1327	*2420*	4388	1471	*2680*	4856	1616	*2940*	5324
1188	*2170*	3938	1332	*2430*	4406	1477	*2690*	4874	1621	*2950*	5342
1193	*2180*	3956	1338	*2440*	4424	1482	*2700*	4892	1627	*2960*	5360
1199	*2190*	3974	1343	*2450*	4442	1488	*2710*	4910	1632	*2970*	5378
1204	*2200*	3992	1349	*2460*	4460	1493	*2720*	4928	1638	*2980*	5396
1210	*2210*	4010	1354	*2470*	4478	1499	*2730*	4946	1643	*2990*	5414
1216	*2220*	4028	1360	*2480*	4496	1504	*2740*	4964	1649	*3000*	5432
1221	*2230*	4046	1366	*2490*	4514	1510	*2750*	4982			
1227	*2240*	4064	1371	*2500*	4532	1516	*2760*	5000			
1232	*2250*	4082	1377	*2510*	4550	1521	*2770*	5018			

APPENDIX 2 Relationship between Thermo emf (mV) and Temperature (°C) for Chromel-Alumel Thermo-couple

Millivolts	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	Milli-volts	ºC per 0.01 mV
	Degrees Celsius												
0	0	2	5	8	10	13	15	18	20	23	25	0	0.25
1	25	28	30	33	35	37	40	42	45	47	50	1	0.24
2	50	52	54	57	59	62	64	67	69	71	74	2	0.24
3	74	76	79	81	83	86	88	91	93	95	98	3	0.24
4	98	100	103	105	107	110	112	115	117	119	122	4	0.24
5	122	124	127	129	132	134	137	139	142	144	147	5	0.25
6	147	149	152	154	157	159	162	164	167	169	172	6	0.25
7	172	174	177	179	182	184	187	189	192	194	197	7	0.25
8	197	199	202	204	207	209	212	214	217	219	222	8	0.25
9	222	224	227	229	232	234	236	239	241	244	246	9	0.24
10	246	249	251	254	256	259	261	263	266	268	271	10	0.24
11	271	273	276	278	280	283	285	288	290	293	295	11	0.24
12	295	297	300	302	305	307	309	312	314	317	319	12	0.24
13	319	322	324	326	329	331	333	336	338	341	343	13	0.24
14	343	345	348	350	353	355	357	360	362	365	367	14	0.24
15	367	369	372	374	376	379	381	384	386	388	391	15	0.23
16	391	393	395	398	400	403	405	407	410	412	414	16	0.24
17	414	417	419	421	424	426	429	431	433	436	438	17	0.24
18	438	440	443	445	448	450	452	455	457	459	462	18	0.23
19	462	464	466	469	471	473	476	478	480	483	485	19	0.23
20	485	487	490	492	494	497	499	501	504	506	508	20	0.23
21	508	511	513	516	518	520	523	525	527	530	532	21	0.24
22	532	534	537	539	541	544	546	548	551	553	555	22	0.23
23	555	558	560	562	565	567	569	572	574	577	579	23	0.23
24	579	581	584	586	588	591	593	595	598	600	602	24	0.23
25	602	605	607	609	612	614	616	619	621	623	626	25	0.23
26	626	628	630	633	635	638	640	642	645	647	649	26	0.24
27	649	652	654	657	659	661	664	666	668	671	673	27	0.23
28	673	675	678	680	683	685	687	690	692	694	697	28	0.24
29	697	699	701	704	706	709	711	713	716	718	721	29	0.24
30	721	723	725	728	730	732	735	737	740	742	744	30	0.24
31	744	747	749	752	754	756	759	761	764	766	768	31	0.24
32	768	771	773	776	778	780	783	785	788	790	793	32	0.24
33	793	795	797	800	802	805	807	810	812	815	817	33	0.24
34	817	819	822	824	827	829	832	834	837	839	841	34	0.24
35	841	844	846	849	851	854	856	859	861	864	866	35	0.25
36	866	869	871	874	876	879	881	884	886	888	891	36	0.25
37	891	893	890	898	901	903	906	908	911	913	916	37	0.25
38	916	918	921	923	926	928	931	933	936	938	941	38	0.25
39	941	944	946	949	951	954	956	959	961	964	967	39	0.26
40	967	969	972	974	977	979	982	984	987	989	992	40	0.26
41	992	994	997	999	1002	1005	1007	1010	1013	1015	1018	41	0.26
42	1018	1020	1023	1026	1028	1031	1033	1036	1038	1041	1044	42	0.26
43	1044	1046	1049	1052	1054	1057	1059	1062	1065	1067	1070	43	0.26
44	1070	1073	1075	1078	1080	1083	1086	1088	1091	1094	1096	44	0.26
45	1096	1099	1102	1104	1107	1110	1112	1115	1118	1120	1123	45	0.27
46	1123	1126	1128	1131	1134	1136	1139	1142	1144	1147	1150	46	0.27
47	1150	1152	1155	1158	1160	1163	1166	1169	1171	1174	1177	47	0.28
48	1177	1180	1182	1185	1188	1190	1193	1196	1199	1201	1204	48	0.27
49	1204	1207	1210	1212	1215	1218	1221	1224	1226	1229	1232	49	0.28
50	1232	1235	1237	1240	1243	1246	1249	1252	1254	1257	1260	50	0.28
51	1260	1263	1266	1268	1271	1274	1277	1280	1283	1285	1288	51	0.28
52	1288	1291	1294	1297	1300	1303	1305	1308	1311	1314	1317	52	0.29
53	1317	1320	1323	1326	1329	1332	1334	1337	1340	1343	1346	53	0.29
54	1346	1349	1352	1355	1358	1361	1364	1367	1370	1373	1376	54	0.29

The cold junction is assumed to be at 0°C.

APPENDIX 3 Relationship between Thermo emf (mV) and Temperature (°C) for Iron-Constantan Thermo-couple

Millivolts	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	Milli-volts	ºC per 0.01 mV
	Degrees Celsius												
0	0	2	4	6	8	10	12	13	15	17	19	0	0.19
1	19	21	23	25	27	29	31	33	35	36	38	1	0.19
2	38	40	42	44	46	48	50	52	54	55	57	2	0.18
3	57	59	61	63	65	67	69	70	72	74	76	3	0.19
4	76	78	80	82	84	86	87	89	91	93	95	4	0.19
5	95	97	98	100	102	104	106	108	110	111	113	5	0.18
6	113	115	117	119	121	122	124	126	128	130	132	6	0.18
7	132	133	135	137	139	141	142	144	146	148	150	7	0.18
8	150	152	154	155	157	159	161	163	164	166	168	8	0.18
9	168	170	172	173	175	177	179	181	183	185	186	9	0.18
10	186	188	190	192	193	195	197	199	201	202	204	10	0.18
11	204	206	208	210	211	213	215	217	219	220	222	11	0.18
12	222	224	226	228	229	231	233	235	237	238	240	12	0.18
13	240	242	244	246	247	249	251	253	255	257	258	13	0.18
14	258	260	262	264	266	267	269	271	273	275	276	14	0.18
15	276	278	280	282	284	285	287	289	291	293	294	15	0.18
16	294	296	298	300	302	303	305	307	309	311	312	16	0.18
17	312	314	316	318	320	321	323	325	327	329	331	17	0.18
18	331	332	334	336	338	340	341	343	345	347	349	18	0.18
19	349	350	352	354	356	358	360	361	363	365	367	19	0.18
20	367	368	370	372	374	376	377	379	381	383	385	20	0.18
21	385	387	388	390	392	394	395	397	399	401	403	21	0.18
22	403	404	406	408	410	412	413	415	417	419	421	22	0.18
23	421	422	424	426	428	430	431	433	435	437	439	23	0.18
24	439	440	442	444	446	448	449	451	453	455	457	24	0.18
25	457	458	460	462	464	466	467	469	471	473	475	25	0.18
26	475	476	478	480	482	483	485	487	489	491	492	26	0.18
27	492	494	496	498	499	501	503	505	507	508	510	27	0.18
28	510	512	514	515	517	519	521	523	524	526	528	28	0.17
29	528	530	531	533	535	537	538	540	542	544	545	29	0.18
30	545	547	549	551	552	554	556	558	559	561	563	30	0.17
31	563	565	566	568	570	572	573	575	577	579	580	31	0.17
32	580	582	584	586	587	589	591	592	594	596	597	32	0.17
33	597	599	601	602	604	606	608	609	611	613	614	33	0.17
34	614	616	618	619	621	623	624	626	628	629	631	34	0.17
35	631	633	635	636	638	640	641	643	645	646	648	35	0.17
36	648	650	651	653	655	656	658	660	661	663	665	36	0.16
37	665	666	668	669	671	673	674	676	678	679	681	37	0.16
38	681	683	684	686	687	689	691	692	694	695	697	38	0.16
39	697	699	700	702	704	705	707	708	710	712	713	39	0.16
40	713	715	716	718	720	721	723	724	726	728	729	40	0.16
41	729	731	732	734	736	737	739	740	742	744	745	41	0.16
42	745	747	748	750	752	753	755	756	758	760	761	42	0.16
43	761	763	764	766	767	769	771	772	774	775	777	43	0.16
44	777	778	780	782	783	785	786	788	789	791	793	44	0.16
45	793	794	796	797	799	800	802	804	806	807	808	45	0.16
46	808	810	812	813	815	816	818	819	821	823	824	46	0.16
47	824	826	827	829	830	832	834	835	837	838	840	47	0.16
48	840	841	843	845	846	848	849	851	853	854	858	48	0.16

APPENDIX 3 Relationship between Thermo emf (mV) and Temperature (°C) for Iron-Constantan Thermo-couple (cont.)

Millivolts	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	Milli-volts	ºC per 0.01 mV
	Degrees Celsius												
49	856	857	859	860	862	863	865	867	868	870	871	49	0.16
50	871	873	874	876	878	879	881	882	884	886	887	50	0.16
51	887	889	890	892	893	895	897	898	900	901	903	51	0.16
52	903	904	906	908	909	911	912	914	915	917	919	52	0.16
53	919	920	922	923	925	926	928	930	931	933	934	53	0.16
54	934	936	937	939	941	942	944	945	947	949	950	54	0.16
55	950	952	953	955	956	958	960	961	963	964	966	55	0.16
56	966	967	969	971	972	974	975	977	979	980	982	56	0.16
57	982	983	985	986	988	990	992	993	994	996	997	57	0.16
58	997	999	1001	1002	1004	1005	1007	1008	1010	1012	1013	58	0.16
59	1013	1015	1016	1018	1019	1021	1023	1024	1026	1027	1029	59	0.16
60	1029	1030	1032	1034	1035	1037	1038	1040	1041	1043	1045	60	0.16
61	1045	1046	1048	1049	1051	1052	1054	1056	1057	1059	1060	61	0.16
62	1060	1062	1063	1065	1067	1068	1070	1071	1073	1074	1076	62	0.16
63	1076	1078	1079	1081	1082	1084	1085	1087	1088	1090	1092	63	0.16
64	1092	1093	1095	1096	1098	1099	1101	1103	1104	1106	1108	64	0.16

The cold junction is assumed to be at 0°C.

APPENDIX 4 Relationship between Thermo emf (mV) and Temperature (°C) for Platinum-Platinum-10 Percent Rhodium Thermo-couple

Millivolts	0	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	Milli-volts	ºC per 0.005 mV
	Degrees Celsius												
0	0	9	18	26	34	42	50	58	65	73	80	0	0.73
1	147	153	159	166	172	178	184	190	196	202	208	1	0.59
2	265	271	276	282	287	293	298	304	309	315	320	2	0.54
3	374	379	384	389	395	400	405	410	416	421	426	3	0.52
4	478	483	488	493	498	503	508	513	518	523	528	4	0.51
5	578	583	588	593	598	603	608	612	617	622	627	5	0.49
6	675	680	685	690	694	699	704	709	713	718	723	6	0.47
7	769	774	779	783	788	793	797	802	806	811	816	7	0.46
8	861	866	870	875	879	884	888	893	897	901	906	8	0.44
9	950	955	959	963	968	972	977	981	985	990	994	9	0.44
10	1037	1042	1046	1050	1054	1059	1063	1067	1071	1076	1080	10	0.43
11	1122	1127	1131	1135	1139	1143	1148	1152	1156	1160	1164	11	0.42
12	1206	1211	1215	1219	1223	1227	1231	1236	1240	1244	1248	12	0.42
13	1290	1294	1298	1302	1307	1311	1315	1319	1323	1328	1332	13	0.42
14	1374	1378	1382	1386	1391	1395	1399	1403	1407	1412	1416	14	0.42
15	1458	1462	1466	1471	1475	1479	1483	1488	1492	1496	1500	15	0.43
16	1543	1547	1551	1555	1560	1564	1568	1572	1577	1581	1585	16	0.43
17	1628	1632	1656	1641	1645	1649	1653	1658	1662	1666	1671	17	0.43

The cold junction is assumed to be at 0°C.

APPENDIX 4 Relationship between Thermo emf (mV) and Temperature (°C) for Platinum-Platinum-10 Percent Rhodium Thermo-couple (cont.)

Millivolts	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	Milli-volts	ºC per 0.005 mV
	Degrees Celsius											
0	87	94	101	108	114	121	128	134	141	147	0	0.73
1	213	219	225	231	237	242	248	254	259	265	1	0.59
2	326	331	336	342	347	352	358	363	368	374	2	0.54
3	431	436	442	447	452	457	462	467	473	478	3	0.52
4	533	538	543	548	553	558	563	568	573	578	4	0.51
5	632	637	642	646	651	656	661	666	670	675	5	0.49
6	727	732	737	741	746	751	755	760	765	769	6	0.47
7	820	825	829	834	838	843	847	852	857	861	7	0.46
8	910	915	919	924	928	933	937	941	946	950	8	0.44
9	998	1003	1007	1011	1016	1020	1024	1029	1033	1037	9	0.44
10	1084	1088	1093	1097	1101	1105	1110	1114	1118	1122	10	0.43
11	1169	1173	1177	1181	1185	1190	1194	1198	1202	1206	11	0.42
12	1252	1257	1261	1265	1269	1273	1277	1282	1286	1290	12	0.42
13	1336	1340	1344	1349	1353	1357	1361	1365	1370	1374	13	0.42
14	1420	1424	1428	1433	1437	1441	1445	1449	1454	1458	14	0.42
15	1504	1509	1513	1517	1521	1526	1530	1534	1538	1543	15	0.43
16	1589	1594	1598	1602	1607	1611	1615	1619	1624	1628	16	0.43
17	1675	1679	1684	1688	1692	1697	1701	1705	1709	1714	17	0.43

APPENDIX 5 Relationship between Thermo emf (mV) and Temperature (°C) for Platinum-Platinum-13 Percent Rhodium Thermo-couple

Millivolts	0	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	Milli-volts	ºC per 0.005 mV
	Degrees Celsius												
0	0	9	18	26	34	42	50	58	65	73	80	0	0.73
1	145	152	158	164	169	175	181	187	193	198	204	1	0.57
2	259	264	269	275	280	285	290	295	301	306	311	2	0.52
3	361	366	371	376	381	386	390	395	400	405	410	3	0.48
4	458	462	467	472	476	481	486	490	495	500	504	4	0.47
5	550	554	559	563	568	572	577	581	586	590	595	5	0.44
6	638	643	647	651	656	660	664	669	673	677	681	6	0.43
7	724	728	732	736	740	744	749	753	757	761	765	7	0.42
8	806	810	814	818	822	826	830	834	838	842	846	8	0.40
9	886	890	894	898	902	906	910	914	918	921	925	9	0.39
10	964	968	972	976	979	983	987	991	995	998	1002	10	0.38
11	1040	1044	1047	1051	1055	1059	1062	1066	1070	1073	1077	11	0.37
12	1114	1118	1121	1125	1129	1132	1136	1139	1143	1147	1150	12	0.37
13	1187	1191	1194	1198	1201	1205	1209	1212	1216	1220	1223	13	0.37
14	1259	1263	1267	1270	1274	1277	1281	1285	1288	1292	1295	14	0.36
15	1332	1335	1339	1343	1346	1350	1353	1357	1361	1364	1368	15	0.36
16	1404	1408	1412	1415	1419	1422	1426	1430	1433	1437	1441	16	0.36
17	1477	1481	1484	1488	1492	1495	1499	1502	1506	1510	1513	17	0.37
18	1550	1554	1557	1561	1565	1568	1572	1576	1579	1583	1587	18	0.37
19	1624	1627	1631	1635	1638	1642	1646	1650	1653	1657	1661	19	0.37

The cold junction is assumed to be at 0°C.

APPENDIX 5 Relationship between Thermo emf (mV) and Temperature (°C) for Platinum-Platinum-13 Percent Rhodium Thermo-couple (cont.)

Millivolts	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	Milli-volts	ºC per 0.005 mV
	Degrees Celsius											
0	87	94	101	107	114	120	127	133	139	145	0	0.73
1	210	215	221	226	232	237	243	248	253	259	1	0.57
2	316	321	326	331	336	341	346	351	356	361	2	0.52
3	415	419	424	429	434	439	443	448	453	458	3	0.48
4	509	513	518	523	527	532	536	541	545	550	4	0.47
5	599	603	608	612	617	621	625	630	634	638	5	0.44
6	686	690	694	698	703	707	711	715	719	724	6	0.43
7	769	773	777	781	786	790	794	798	802	806	7	0.42
8	850	854	858	862	866	870	874	878	882	886	8	0.40
9	929	933	937	941	945	949	953	956	960	964	9	0.39
10	1006	1010	1014	1017	1021	1025	1029	1032	1036	1040	10	0.38
11	1081	1084	1088	1092	1096	1099	1103	1107	1110	1114	11	0.37
12	1154	1158	1161	1165	1169	1172	1176	1180	1183	1187	12	0.37
13	1227	1230	1234	1238	1241	1245	1249	1252	1256	1259	13	0.37
14	1299	1303	1306	1310	1314	1317	1321	1324	1328	1332	14	0.36
15	1372	1375	1379	1383	1386	1390	1393	1397	1401	1404	15	0.36
16	1444	1448	1452	1455	1459	1462	1466	1470	1473	1477	16	0.36
17	1517	1521	1524	1528	1532	1535	1539	1543	1546	1550	17	0.37
18	1590	1594	1598	1602	1605	1609	1613	1616	1620	1624	18	0.37
19	1664	1668	1672	1675	1679	1683	1687	1690	1694	1698	19	0.37

APPENDIX 6 Table for Hardness Conversion

Vickers hardness number (VHN)	Brinell hardness number (BHN)	Rockwell hardness number		Vickers hardness number (VHN)	Brinell hardness number (BHN)	Rockwell hardness number	
		R_B	R_C			R_B	R_C
940			68.0	590			54.7
920			67.5	580			54.1
900			67.0	570			53.6
880			66.4	560			53.0
860			65.9	550	505		52.3
840			65.3	540	496		51.7
820			64.7	530	488		51.1
800			64.0	520	480		50.5
780			63.3	510	473		49.8
760			62.5	500	465		49.1
740			61.8	490	456		48.4
720			61.0	480	448		47.7
700			60.1	470	441		46.9
690			59.7	460	433		46.1
680			59.2	450	425		45.3
670			58.8	440	415		44.5
660			58.3	430	405		43.6
650			57.8	420	397		42.7
640			57.3	410	388		41.8
630			56.8	400	379		40.8
620			56.3	390	369		39.8
610			55.7	380	360		38.8
600			55.2	370	350		37.7

APPENDIX 6 Table for Hardness Conversion (cont.)

Vickers hardness number (VHN)	Brinell hardness number (BHN)	Rockwell hardness number		Vickers hardness number (VHN)	Brinell hardness number (BHN)	Rockwell hardness number	
		R_B	R_C			R_B	R_C
360	341		36.6	240	228	98.1	20.3
350	331		35.5	230	219	96.7	
340	322		34.4	220	209	95.0	
330	313		33.4	210	200	93.4	
320	303		32.2	200	190	91.5	
310	294		31.0	190	181	89.5	
300	284		29.8	180	171	87.1	
295	280		29.2	170	162	85.0	
290	275		28.5	160	152	81.7	
285	270		27.8	150	143	78.7	
280	265		27.1	140	133	75.0	
275	261		26.4	130	124	71.2	
270	256		25.6	120	114	66.7	
265	252		24.8	110	105	62.3	
260	247		24.0	100	95	56.2	
255	243		23.1	95	90	52.0	
250	238		22.2	90	86	48.0	
245	233		21.3	85	81	41.0	

APPENDIX 7 Table for Conversion of Stress

Ton/in^2	kg/mm^2	N/mm^2	Ton/in^2	kg/mm^2	N/mm^2	Ton/in^2	kg/mm^2	N/mm^2
1	1.6	15	30	47.3	463	59	92.9	911
2	3.2	31	31	48.8	479	60	94.5	927
3	4.7	46	32	50.4	494	61	96.1	942
4	6.3	62	33	52.0	510	62	97.6	985
5	7.9	77	34	53.5	525	63	99.2	973
6	9.5	93	35	55.1	541	64	101	988
7	11.0	108	36	56.7	556	65	102	1004
8	12.6	124	37	58.3	571	66	104	1019
9	14.2	139	38	59.8	587	67	105	1035
10	15.7	154	39	61.4	602	68	107	1050
11	17.3	170	40	63.0	618	69	109	1066
12	18.9	185	41	64.6	632	70	110	1081
13	20.5	201	42	66.1	649	71	112	1097
14	22.1	216	43	67.7	664	72	113	1112
15	23.6	232	44	69.3	680	73	115	1127
16	25.2	247	45	70.9	695	74	116	1143
17	26.8	263	46	72.4	710	75	118	1158
18	28.4	278	47	74.0	726	76	120	1174
19	29.9	293	48	75.6	741	77	121	1189
20	31.5	309	49	77.2	757	78	123	1205
21	33.1	324	50	78.7	772	79	124	1220
22	34.7	340	51	80.3	788	80	126	1236
23	36.2	355	52	81.9	803	81	128	1251
24	37.8	371	53	83.5	819	82	129	1266
25	39.4	386	54	85.0	834	83	131	1282
26	41.0	402	55	86.6	849	84	132	1297
27	42.5	417	56	88.2	865	85	134	1313
28	44.1	432	57	89.8	880	86	135	1328
29	45.7	448	58	91.3	896	87	137	1344

APPENDIX 7 Table for Conversion of Stress (cont.)

Ton/in^2	kg/mm^2	N/mm^2	Ton/in^2	kg/mm^2	N/mm^2	Ton/in^2	kg/mm^2	N/mm^2
88	139	1359	99	156	1529	110	173	1698
89	140	1375	100	158	1544	111	175	1714
90	142	1390	101	159	1559	112	176	1729
91	143	1405	102	161	1575	113	178	1745
92	145	1421	103	162	1590	114	180	1760
93	147	1436	104	164	1606	115	181	1776
94	148	1452	105	165	1621	116	183	1791
95	150	1467	106	167	1637	117	184	1806
96	151	1483	107	169	1652	118	186	1822
97	153	1498	108	170	1668	119	187	1837
98	154	1514	109	172	1683	120	189	1853

APPENDIX 8 Table for Conversion of Energy

ft 1b	kg m	J	ft 1b	kg m	J	ft 1b	kg m	J
1	0.14	1.4	41	5.67	55.6	81	11.2	110
2	0.28	2.7	42	5.81	56.9	82	11.3	111
3	0.41	4.1	43	5.94	58.3	83	11.5	113
4	0.55	5.4	44	6.08	59.7	84	11.6	114
5	0.69	6.8	45	6.22	61.0	85	11.8	115
6	0.83	8.1	46	6.36	62.4	86	11.9	117
7	0.97	9.5	47	6.50	63.7	87	12.0	118
8	1.11	10.8	48	6.64	65.1	88	12.2	119
9	1.24	12.2	49	6.77	66.4	89	12.3	121
10	1.38	13.6	50	6.91	67.8	90	12.4	122
11	1.52	14.9	51	7.05	69.1	91	12.6	123
12	1.66	16.3	52	7.19	70.5	92	12.7	125
13	1.80	17.6	53	7.33	71.9	93	12.9	126
14	1.94	19.0	54	7.47	73.2	94	13.0	127
15	2.07	20.3	55	7.60	74.6	95	13.1	129
16	2.21	21.7	56	7.74	75.8	96	13.3	130
17	2.35	23.0	57	7.88	77.3	97	13.4	132
18	2.49	24.4	58	8.02	78.6	98	13.6	133
19	2.63	25.8	59	8.16	80.0	99	13.7	134
20	2.77	27.1	60	8.30	81.3	100	13.8	135
21	2.90	28.5	61	8.43	82.7	101	14.0	137
22	3.04	29.8	62	8.57	84.1	102	14.1	138
23	3.18	31.2	63	8.71	85.4	103	14.2	139
24	3.32	32.5	64	8.85	86.8	104	14.4	141
25	3.46	33.9	65	8.99	88.1	105	14.5	142
26	3.59	35.3	66	9.12	89.5	106	14.7	144
27	3.73	36.6	67	9.26	90.8	107	14.8	145
28	3.87	38.0	68	9.40	92.2	108	14.9	146
29	4.01	39.3	69	9.54	93.6	109	15.1	148
30	4.15	40.7	70	9.68	94.9	110	15.2	149
31	4.29	42.0	71	9.82	96.3	111	15.4	151
32	4.42	43.4	72	9.95	97.6	112	15.5	152
33	4.56	44.7	73	10.1	99.0	113	15.6	153
34	4.70	46.1	74	10.2	100	114	15.8	155
35	4.84	47.5	75	10.4	102	115	15.9	156
36	4.98	48.8	76	10.5	103	116	16.0	157
37	5.12	50.2	77	10.7	104	117	16.2	159
38	5.25	51.5	78	10.8	106	118	16.3	160
39	5.39	52.9	79	10.9	107	119	16.5	162
40	5.53	54.2	80	11.1	108	120	16.6	163

APPENDIX 9 AISI–SAE Steel Composition

AISI No.	SAE No.	C	Si	Mn	P max	S max	Cr	Mo	Ni	Others
Carbon and Alloy Steels										
C1010	1010	0.08–0.13	0.10 max	0.30–0.60	0.04	0.05				
C1015	1015	0.13–0.18	0.10 max	0.30–0.60	0.04	0.05				
C1020	1020	0.18–0.23	0.10–0.20	0.30–0.60	0.04	0.05				
C1025	1025	0.22–0.28	0.10–0.20	0.30–0.60	0.04	0.05				
C1030	1030	0.28–0.34	0.10–0.20	0.60–0.90	0.04	0.05				
C1035	1035	0.32–0.38	0.10–0.20	0.60–0.90	0.04	0.05				
C1040	1040	0.37–0.44	0.10–0.20	0.60–0.90	0.04	0.05				
C1045	1045	0.43–0.50	0.20–0.35	0.60–0.90	0.04	0.05				
C1050	1050	0.48–0.55	0.20–0.35	0.60–0.90	0.04	0.05				
C1055	1055	0.50–0.60	0.20–0.35	0.60–0.60	0.04	0.05				
C1060	1060	0.55–0.65	0.20–0.35	0.60–0.90	0.04	0.05				
C1065	1065	0.60–0.70	0.20–0.35	0.60–0.90	0.04	0.05				
C1070	1070	0.65–0.75	0.20–0.35	0.60–0.90	0.04	0.05				
C1109	1109	0.08–0.13	<0.10	0.60–0.90	0.04	008–0.13				
B1111	1111	<0.13	<0.10	0.60–0.90	0.07–0.12	0.08–0.15				
B1112	1112	<0.13	<0.10	0.70–1.00	0.07–0.12	0.16–0.23				
B1113	1113	<0.13	<0.10	0.70–1.00	0.07–0.12	0.24–0.33				
C1114	1114	0.10–0.16	<0.20	1.00–1.30	0.04	0.13 max				
C1115	1115	0.13–0.18	<0.20	0.60–0.90	0.04	0.08–0.13				
C1116	1116	0.14–0.20	<0.20	1.10–1.40	0.04	0.16–0.23				
C1117	1117	0.14–0.20	<0.20	1.00–1.30	0.04	0.08–0.13				
C1118	1118	0.14–0.20	<0.20	1.30–1.60	0.04	0.08–0.13				
C1119	1119	0.14–0.20	<0.20	1.00–1.30	0.04	0.24–0.33				
C1120	1120	0.18–0.23	<0.20	0.70–1.00	0.04	0.08–0.13				
C1126	1126	0.23–0.29	<0.20	0.70–1.00	0.04	0.08–0.13				
C1132	1132	0.27–0.34	<0.20	1.35–1.65	0.04	0.08–0.13				
C1137	1137	0.32–0.39	<0.20	1.35–1.65	0.04	0.08–0.13				
C1138	1138	0.34–0.40	<0.20	0.70–1.00	0.04	0.08–0.13				
C1140	1140	0.37–0.44	<0.20	0.70–1.00	0.04	0.08–0.13				
C1141	1141	0.37–0.45	<0.20	1.35–1.65	0.04	0.08–0.13				
C1144	1144	0.40–0.48	<0.20	1.35–1.65	0.04	0.24–0.33				
1320	1320	0.18–0.23	0.20–0.35	1.60–1.90	0.04	0.04				
1321	1321	0.17–0.22	0.20–0.35	1.80–2.10	0.04	0.05				
1330	1330	0.28–0.33	0.20–0.35	1.60–1.90	0.04	0.04				
1335	1335	0.33–0.38	0.20–0.35	1.60–1.90	0.04	0.04				

APPENDIX 9 AISI–SAE Steel Composition (cont.)

AISI No.	SAE No.	C	Si	Mn	P max	S max	Cr	Mo	Ni	Others
1340	1340	0.38–0.43	0.20–0.35	1.60–1.90	0.04	0.04				
1345	1345	0.43–0.48	0.20–0.35	1.60–1.90	0.04	0.04				
2317	2317	0.15–0.20	0.20–0.35	0.40–0.60	0.04	0.04			3.25–3.75	
2330	2330	0.28–0.33	0.20–0.35	0.60–0.80	0.04	0.04			3.25–3.75	
2335	2335	0.33–0.38	0.20–0.35	0.60–0.80	0.04	0.04			3.25–3.75	
2340	2340	0.38–0.43	0.20–0.35	0.70–0.90	0.04	0.04			3.25–3.75	
2345	2345	0.43–0.48	0.20–0.35	0.70–0.90	0.04	0.04			3.25–3.75	
E 2512	2512	0.09–0.14	0.20–0.35	0.45–0.60	0.025	0.025			4.75–5.25	
2515	2515	0.12–0.17	0.20–0.35	0.40–0.60	0.04	0.04			4.75–5.25	
E 2517	2517	0.15–0.20	0.20–0.35	0.45–0.60	0.025	0.025			4.75–5.25	
3115	3115	0.13–0.18	0.20–0.35	0.40–0.60	0.04	0.04	0.55–0.75		1.10–1.40	
3120	3120	0.17–0.22	0.20–0.35	0.60–0.80	0.04	0.04	0.55–0.75		1.10–1.40	
3130	3130	0.28–0.33	0.20–0.35	0.60–0.80	0.04	0.04	0.55–0.75		1.10–1.40	
3135	3135	0.33–0.38	0.20–0.35	0.60–0.80	0.04	0.04	0.55–0.75		1.10–1.40	
3140	3140	0.38–0.43	0.20–0.35	0.70–0.90	0.04	0.04	0.55–0.75		1.10–1.40	
3141	3141	0.38–0.43	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90		1.10–1.40	
3145	3145	0.43–0.48	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90		1.10–1.40	
3150	3150	0.48–0.53	0.20–0.35	0.70 0.90	0.04	0.04	0.70–0.90		1.10–1.40	
E 3130	3310	0.08–0.13	0.20–0.35	0.45–0.60	0.025	0.025	1.40–1.75		3.25–3.75	
E 3316	3316	0.14–0.19	0.20–0.35	0.45–0.60	0.025	0.025	1.40–1.75		3.25–3.75	
4017	4017	0.15–0.20	0.20–0.35	0.70–0.90	0.04	0.04		0.20–0.30		
4023	4023	0.20–0.25	0.20–0.35	0.70–0.90	0.04	0.04		0.20–0.30		
4024	4024	0.20–0.25	0.20–0 35	0.70–0.90	0.04	0.05		0.20–0.30		
4027	4027	0.25–0.30	0.20–0.35	0.70–0.90	0.04	0.04		0.20–0.30		
4028	4028	0.25–0.30	0.20–0.35	0.70–0.90	0.04	0.05		0.20–0.30		
4032	4032	0.30–0.35	0.20–0.35	0.70–0.90	0.04	0.04		0.20–0.30		
4037	4037	0.35–0.40	0.20–0.35	0.70–0.90	0.04	0.04		0.20–0.30		
4042	4042	0.40–0.45	0.20–2.35	0.70–0.90	0.04	0.04		0.20–0.30		
4047	4047	0.45–0.50	0.20–0.35	0.70–0.90	0.04	0.04		0.20–0.30		
4053	4053	0.50–0.56	0.20–0.35	0.75–1.00	0.04	0.04		0.20–0.30		
4063	4063	0.60–0.67	0.20–0.35	0.75–1.00	0.04	0.04		0.20–0.30		
4068	4068	0.63–0.70	0.20–0.35	0.75–1.00	0.04	0.04		0.20–0.30		
4118		0.18–0.23	0.20–0.35	0.70–0,90	0.04	0.04	0.40–0.60	0.08–0.15		
	4119	0.17–0.22	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.20–0.30		
4130	4130	0.28–0.33	0.20–0.35	0.40–0.60	0.04	0.04	0.80–1.10	0.15–0.25		
E 4132		0.30–0.35	0.20–0.35	0.40–0.60	0.025	0.025	080–1.10	0.18–0.25		
E 4135		0.33–0.38	0.20–0.35	0.70–0.90	0.04	0.04	0.80–1.10	0.18–0.25		

4137	4137	0.35–0.40	0.20–0.35	0.70–0.90	0.04	0.04	0.80–1.10	0.15–0.25		
E 4137		0.35–0.40	0.20–0.35	0.70–0.90	0.025	0.025	0.80–1.10	0.18–0.25		
4140	4140	0. 38–0.43	0.20–0.35	0.75–1.00	0.04	0.04	0.80–1.10	0.15–0.25		
4142		0.40–0.45	0.20–0.35	0.75–1.00	0.04	0.04	0.80–1.10	0.15–0.25		
4145	4145	0.43–0.48	0.20–0.35	0.75–1.00	0.04	0.04	0.80–1.10	0.15–0.25		
4147		0.45–0.50	0.20–0.35	0.75–1.00	0.04	0.04	0.80–1.10	0.15–0.25		
4150	4150	0.48–0.53	0.20–0.35	0.75–1.00	0.04	0.04	0.80–1.10	0.15–0.25		
4317	4317	0.15–0.20	0.20–0.35	0.45–0.65	0.04	0.04	0.40–0.60	0.20–030	1.65–2.00	
4320	4320	0.17–0.22	0.20–0.35	0.45–0.65	0.04	0.04	0.40–0.60	0.20–0.30	1.65–2.00	
4337		0.35–0.40	0.20–0.35	0.60–0.80	0.04	0.04	0.70–0.90	0.20–0.30	1.65–2.00	
4340	4340	0.38–0.43	0.20–0.35	0.65–0.85	0.04	0.04	0.70–0.90	0.20–0.30	1.65–2.00	
4608	4608	0.06–0.11	0.25 max	0.25–0.45	0.04	0.04		0.15–0.25	1.40–1.75	
4615	4615	0.13–0.18	0.20–0.35	0.45–0.65	0.04	0.04		0.20–0.30	1.65–2.00	
E 4617	4617	0.15–0.20	0.20–0.35	0.45–0.65	0.025	0.025		0.20–0.30	1.65–2.00	
4620	4620	0.17–0.22	0.20–0.35	0.45–0.65	0.04	0.04		0.20–0.30	1.65–2.00	
E 4620		0.17–0.22	0.20–0.35	0.45–0.65	0.025	0.025		0.20–0.27	1.65–2.00	
4621	4621	0.18–0.23	0.20–0.35	0.70–0.90	0.04	0.04		0.20–0.30	1.65–2.00	
4640	4640	0.38–0.43	0.20–0.35	0.60–0.80	0.04	0.04		0.20–0.30	1.65–2.00	
E 4640		0.38–0.43	0.20.0.35	0.60–0.80	0.025	0.025		0.20–0.27	1.65–2.00	
4812	4812	0.10–0.15	0.20–0.35	0.40–0.60	0.04	0.04		0.20–0.30	3.25–3.75	
4815	4815	0.13–0.18	0.20–0.35	0.40–0.60	0.04	0.04		0.20–0.30	3.25–3.75	
4820	4820	0.18–0.23	0.20–0.35	0.50–0.70	0.04	0.04		0.20–0.30	3.25–3.75	
5015	5015	0.12–0.17	0.20–0.35	0.30–0.50	0.04	0.04	0.30–0.50			
5045	5045	0.43–0.48	0.20–0.35	0.70–0.90	0.04	0.04	0.55–0.75			
5046	5046	0.43–0.50	0.20–0.35	0.75–1.00	0.04	0.04	0.20–0.35			
	5115	0.13–0.18	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90			
5120	5120	0.17–0.22	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90			
5130	5130	0.28–0.33	0.20–0.35	0.70–0.90	0.04	0.04	0.80–1.10			
5132	5132	0.30–0.35	0.20–0.35	0.60–0.80	0.04	0.04	0.75–1.00			
5135	5135	0.33–0.38	0.20–0.35	0.60–0.80	0.04	0.04	0.80–1.05			
5140	5140	0.38–0.43	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90			
5145	5145	0.43–0.48	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90			
5147	5147	0.45–0.52	0.20–0.35	0.70–0.95	0.04	0.04	0.85–1.15			
5150	5150	0.48–0.53	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90			
5152	5152	0.48–0.55	0.20–0.35	0.70–0.90	0.04	0.04	0.90–1.20			
5155		0.50–0.60	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90			
5160	5160	0.55–0.65	0.20–0.35	0.75–1.00	0.04	0.04	0.70–0.90			
E 50100	50100	0.95–1.10	0.20–0.35	0.25–0.45	0.025	0.025	0.40–0.60			
E 50110	51100	0.95–1.10	0.20–0.35	0.25–0.45	0.025	0.025	0.90–1.15			
E 52100	52100	0.95–1.10	0.20–0.35	0.25–0.45	0.025	0.025	1.30–1.60			
6117	6117	0.15–0.20	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90			V 0.10 min
6120		0.17–0.22	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90			V 0.10 min

APPENDIX 9 AISI–SAE Steel Composition (cont.)

AISI No.	SAE No.	C	Si	Mn	P max	S max	Cr	Mo	Ni	Others
6145		0.43.0.48	0.20–0.35	0.70–0.90	0.04	0.04	0.80–1.10			V 0.15 min
6150	6150	0.48–0.53	0.20–0.35	0.70–0.90	0.04	0.04	0.80–1.10			V 0.15 min
6152		0.48–0.55	0.20–0.35	0.70–0.90	0.04	0.04	0.80–1.10			V 0.10 min
80 B 20		0.17–0.23	0.20–0.35	0.45–0.70	0.04	0.04	0.15–0.35	0.08–0.15	0.20–0.40	B 0.0005 min
80 B 25		0.21–0.28	0.20–0.35	0.50–0.75	0.04	0.04	0.15–0.35	0.08–0.15	0.20–0.40	B 0.0005 min
80 B 30		0.27–0.34	0.20–0.35	0.55–0.80	0.04	0.04	0.15–0.35	0.08–0.15	0.20–0.40	B 0.0005 min
80 B 35		0.32–0.39	0.20–0.35	0.65–0.95	0.04	0.04	0.15–0.35	9.0S–0.15	0.20–0.40	B 0.0005 min
80 B 40		0.37–0.45	0.20–0.35	0.70–1.00	0.04	0.04	0.15–0.35	0.08–0.15	0.20–0.40	B 0.0005 min
80 B 45		0.42–0.50	0.20–0.35	0.70–1.00	0.04	0.04	0.15–0.35	0.08–0.15	0.20–0.40	B 0.0005 min
80 B 50		0.47–0.55	0.20–0.35	0.70–1.00	0.04	0.04	0.25–0.50	0.80–0.15	0.20–0.40	B 0.0005 min
80 B 55		0.50–0.60	0.20–0.35	0.70–1.00	0.04	0.04	0.30–0.55	0.80–0.15	0.20–0.40	B 0.0005 min
80 B 60		0.55–0.65	0.20–0.35	0.70–1.00	0.04	0.04	0.30–0.55	0.08–0.15	0.20–0.40	B 0.0005 min
81 B 35		0.32–0.39	0.20–0.35	0.70–1.00	0.04	0.04	0.30–0.55	0.08–0.15	0.20–0.40	B 0.0005 min
81 B 40		0.37–0.45	0.20–0.35	0.70–1.00	0.04	0.04	0.30–0.55	0.08–0.15	0.20–0.40	B 0.0005 min
81 B 45		0.42–0.50	0.20–0.35	0.70–1.00	0.04	0.04	0.30–0.55	0.08–0.15	0.20–0.40	B 0.0005 min
81 B 50		0.47–0.55	0.20–0.35	0.75–1.05	0.04	0.04	0.35–0.60	0.08–0.15	0.20–0.40	B 0.0005 min
8615	8615	0.13–0.18	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8617	8617	0.15–0.20	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8620	8620	0.18–0.23	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8622	8622	0.22–0,25	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8625	8625	0.23–0.28	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8627	8627	0.25–0.30	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8630	8630	0.28–0.33	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8632	8632	0.30–0.35	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8635	8635	0.33–0.38	0.20–0.35	0.75–1.00	0.40	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8637	8637	0.35–0.40	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8640	8640	0.38–0.43	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8641	8641	0.38–0.43	0.20–0.35	0.75–1.00	0,04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8642	8642	0.40–0.45	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8645	8645	0.43–0.48	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
86 B 45		0.43–0.48	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8647	8647	0.45–0.50	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8650	8650	0.48–0.53	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8653	8653	0.50–0.56	0.20–0.35	0.75–1.00	0.04	0.04	0.50–0.80	0.15–0.25	0.40–0.70	
8655	8655	0.50–0.60	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.15–0.25	0.40.0.70	
8660	8660	0.55–0.65	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.15–0.25	0.40–0.70	
8715	8715	0.13–0.18	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70	

8717		0.15–0.20	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70
8719		0.18–0.23	0.20–0.35	0.60–0.80	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70
8720	8720	0.18–0.23	0.20–0.35	0.70–0.90	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70
8735	8735	0.33–0.38	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70
8740	8740	0.38–0.43	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70
8742		0.40–0.45	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70
8745	8745	0.43–0.48	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70
8747		0.45–0.50	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70
8750	8750	0.48–0.53	0.20–0.35	0.75–1.00	0.04	0.04	0.40–0.60	0.20–0.30	0.40–0.70
	9254	0.50–0.60	1.20–1.60	0.50–0.80	0.04	0.04	0.50–0.80		
9255	9255	0.50–0.60	1.80–2.20	0.70–0.95	0.04	0.04			
9260	9260	0.55–0.65	1.80–2.20	0.70–1.00	0.04	0.04			
9261	9261	0.55–0.65	1.80–2.20	0.75–1.00	0.04	0.04	0.10–0.25		
9262	9262	0.55–0.65	1.80–2.20	0.75–1.00	0.04	0.04	0.25–0.40		
E 9310	9310	0.08–0.13	0.20–0.35	0.45–0.65	0.025	0.025	1.00–1.40	0.08–0.15	3.00–3.50
E 9314		0.11–0.17	0.20–0.35	0.40–0.70	0.025	0.025	1.00–1.40	0.08–0.15	3.00–3.50
E 9315	9315	0.13–0.18	0.20–0.35	0.45–0.65	0.025	0.025	1.00–1.40	0.08–0.15	3.00–3.50
E 93I7	9317	0.15–0.20	0.20–0.35	0.45–0.65	0.025	0.025	1.00–1.40	0.08–0.15	3.00–3.50
9347	9347	0.35–0.40	0.20–0.35	0.90–1.20	0.04	0.04	0.30–0.50	0.08–0.15	0.30–0.60
9440	9440	0.38–0.43	0.20–0.35	0.90–1.20	0.04	0.04	0.30–0.50	0.08–0.15	0.30–0.60
9442	9442	0.40–0.45	0.20–0.35	1.00–1.30	0.04	0.04	0.30–0.50	0.08–0.15	0.30–0.60
9445	9445	0.43–0.48	0.20–0.35	1.00–1.30	0.04	0.04	0.30–0.50	0.08–0.15	0.30–0.60
9747	9747	0.45–0.50	0.20–0.35	0.50–0.80	0.04	0.04	0.10–0.25	0.15–0.25	0.40–0.70
9763	9763	0.60–0.67	0.20–0.35	0.50–0.80	0.04	0.04	0.10–0.25	0.15–0.25	0.40–0.70
9840	9840	0.38–0.43	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90	0.20–0.30	0–85–1.15
9845	9845	0.43–0.48	0.20–0.35	0.70–0.90	0.04	0.04	0.70 0.90	0.20–0.30	0.85–1.15
9850	9850	0.48–0.53	0.20–0.35	0.70–0.90	0.04	0.04	0.70–0.90	0.20–0.30	0.85–1.15
‘H’ Steels with Guaranteed Hardenability Bands									
1320 H	1320 H	0.17–0.24	0.20–0.35	1.50–2.00	0.04	0.04			
1330 H	1330 H	0.27–0.34	0.20–0.35	1.50–2.00	0.04	0.04			
1335 H	1335 H	0.32–0.39	0.20–0.35	1.50–2.00	0.04	0.04			
1340 H	1340 H	0.37–0.45	0.20–0.35	1.50–2.00	0.04	0.04			
2330 H	2330 H	0.27–0.34	0,20–0.35	0.55–0.85	0.04	0.04			3.20–3.80
2512 H	2512 H	0.08–0.15	0.20–0.35	0.35–0.65	0.04	0.04			4.70–5.30
2515 H	2515 H	0.11–0.18	0.20–0.35	0.35–0.65	0.04	0.04			4.70–5.30
2517 H	2517 H	0.14–0.21	0.20–0.35	0.35–0.65	0.04	0.04			4.70–5.30
3120 H	3120 H	0.17–0.24	0.20–0.35	0.55–0.85	0.04	0.04	0.50–0.80		1.00–1.50
3130 H	3130 H	0.27–0.34	0.20–0.35	0.55–0.85	0.04	0.04	0.50–0.80		1.00–1.50
3135 H	3135 H	0.32–0.39	0.20–0.35	0.55–0.85	0.04	0.04	0.50–0.80		1.00–1.50
3140 H	3140 H	0.37–0.45	0.20–0.35	0.60–0.95	0.04	0.04	0.50–0.80		1.00–1.50
3310 H	3310 H	0.07–0.14	0.20–0.35	0.35–0.65	0.04	0.04	1.35–1.75		3.20–3.80

APPENDIX 9 AISI–SAE Steel Composition (cont.)

AISI No.	SAE No.	C	Si	Mn	P max	S max	Cr	Mo	Ni	Others
3316 H	3316 H	0.13–0.20	0.20–0.35	0.35–065	0.04	0.04	1.35–1.75		3.20–3.80	
4032 H	4032 H	0.30–0.37	0.20–0.35	0.60–0.95	0.04	0.04		0.20–0.30		
4037 H	4037 H	0.35–0.43	0.20–0.35	0.60–0.95	0.04	0.04		0.20–0.30		
4042 H	4042 H	0.40–0.48	0.20–0.35	0.60–0.95	0.04	0.04		0.20–0.30		
4047 H	4047 H	0.44–0.52	0.20–0.35	0.60–0.95	0.04	0.04		0.20–0.30		
4053 H	4053 H	0.49–0.57	0.20–0.35	0.70–1.05	0.04	0.04		0.20–0.30		
4063 H	4063 H	0.50–0.68	0.20–0.35	0.70–1.05	0.04	0.04		0.20–0.30		
4068 H	4068 H	0.62–0.72	0.20–0.35	0.70–1.05	0.04	0.04		0.20–0.30		
										Cu max
4130 H	4130 H	0.27–0.34	0.20–0.35	0.35–0.65	0.04	0.04	0.80–1.15	0.15–0.25		0.35
4132 H	4132 H	0.30–0.37	0.20–0.35	0.35–0.65	0.04	0.04	0.80–1.15	0.15–0.25		0.35
4135 H	4135 H	0.32–0.39	0.20–0.35	0.60–0.95	0.04	0.04	0.80–1.15	0.15–0.25		0.35
4137 H	4137 H	0.35–0.43	0.20–0.35	0.60–0.95	0.04	0.04	0.80–1.15	0.15–0.25		0.35
4140 H	4140 H	0.37–0.45	0.20–0.35	0.70–1.05	0.04	0.04	0.80–1.15	0.15–0.25		0.35
4142 H	4142 H	0.40–0.48	0.20–0.35	0.70–1.05	0.04	0.04	0.80–1.15	0.15–0.25		0.35
4145 H	4145 H	0.42–0.50	0.20–0.35	0.70–1.05	0.04	0.04	0.80–1.15	0.15–0.25		0.35
4147 H	4147 H	0.44–0.52	0.20–0.35	0.70–1.05	0.04	0.04	0.80–1.15	0.15–0.25		0.35
4150 H	4150 H	0.46–0.54	0.20–0.35	0.70–1.05	0.04	0.04	0.80–1.15	0.15–0.25		0.35
4317 H	4317 H	0.14–0.21	0.20–0.35	0.50–0.70	0.04	0.04	0.35–0.65	0.20–0.30	1.50–2.00	0.35
4320 H	4320 H	0.16–0.23	0.20–0.35	0.40–0.70	0.04	0.04	0.35–0.65	0.20–0.30	1.50–2.00	0.35
4337 H	4337 H	0.35–0.43	0.20–0.35	0.55–0.85	0.04	0.04	0.65–0.95	0.20–0.30	1.50–2.00	0.35
4340 H	4340 H	0.37–0.45	0.20–0.35	0.60–0.95	0.04	0.04	0.65–0.95	0.20–0.30	1.50–2.00	0.35
4620 H	4620 H	0.17–0.24	0.20–0.35	0.40–0.70	0.04	0.04		0.20–0.30	1.50–2.00	0.35
4621 H	4621 H	0.17–0.24	0.20–0.35	0.60–0.95	0.04	0.04		0.20–0.30	1.50–2.00	0.35
4640 H	4640 H	0.37–0.45	0.20–0.35	0.55–0.85	0.04	0.04		3.20–0.30	1.50–2.00	0.35
4812 H	4812 H	0.10–0.11	0.20–0.35	0.30–0.60	0.04	0.04		0.20–0.30	3.20–3.80	0.35
4815 H	4815 H	0.12–0.19	0.20–0.35	0.35–0.65	0.04	0.04		0.20–0.30	3.20–3.80	0.35
4817 H	4817 H	0.14–0.21	0.20–0.35	0.35–0.65	0.04	0.04		0.20–0.30	3.20–3.80	0.35
4820 H	4820 H	0.16–0.24	0.20–0.35	0.45–0.75	0.04	0.04		0.20–0.30	3.20–3.80	0.35
5120 H	5120 H	0.16–0.25	0.20–0.35	0.60–0.95	0.04	0.04	0.65–0.95			0.35
5130 H	5130 H	0.27–0.34	0.20–0.35	0.60–0.95	0.04	0.04	0.80–1.15			0.35
5132 H	5132 H	0.28–0.35	0.20–0.35	0.50–0.85	0.04	0.04	0.70–1.05			0.35
5135 H	5135 H	0.32–0.39	0.20–0.35	0.55–0.75	0.04	0.04	0.75–1.10			0.35
5140 H	5140 H	0.37–0.35	0.20–0.35	0.60–0.95	0.04	0.04	0.65–0.95			0.31
5145 H	5145 H	0.42–0.50	0.20–0.35	0.60–0.95	0.04	0.04	0.65–0.95			0.35
5147 H	5147 H	0.44–0.52	0.20–0.35	0.65–1.00	0.04	0.04	0.85–1.20			0.35

5150 H	5150 H	0.46–0.54	0.20–0.35	0.60–0.95	4.04	0.04	0.65–0.95			0.35
5152 H	5152 H	0.48–0.56	0.20–0.35	0.60–0.95	0.04	0.04	0.90–1.25			0.35
5160 H	5160 H	0.55–0.65	0.20–0.35	0.70–1.05	0.04	0.04	0.65–0.95			0.35
6150 H	6150 H	0.46–0.54	0.20–0.35	0.60–0.95	0.04	0.04	0.80–1.15			0.35 V 0.15 min
8617 H	8617 H	0.14–0.21	0.20–0.35	0.60–0.95	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8620 H	8620 H	0.17–0.24	0.20–0.35	0.60–0.95	0.04	0.04	0.35–0.65	0.15.0–25	0.35–0.75	0.35
8622 H	8622 H	0.20–0.27	0.20–0.35	0.60–0.95	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8625 H	8625 H	0.22–0.29	0.20–0.35	0.60–0.95	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8627 H	8627 H	0.25–0.32	0.20–0.35	0.60–0.95	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8630 H	8630 H	0.27–0.34	0.20–0.35	0.60–0.95	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8632 H	8632 H	0.30–0.37	0.20–0.35	0.60–0.95	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8635 H	8635 H	0.32–0.37	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8637 H	8637 H	0.35–0.43	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8640 H	8640 H	0,37–0.45	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8641 H	8641 H	0.37–0.45	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8642 H	8642 H	0.40–0.48	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8645 H	8645 H	0.42–0.50	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8647 H	8647 H	0.44–0.52	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8650 H	8650 H	0.46–0.54	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8653 H	8653 H	0.49–0.57	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8655 H	8655 H	0.50–0.60	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
8660 H	8660 H	0.55–0.65	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.15–0.25	0.35–0.75	0.35
										Cu max
8720 H	8720 H	0.17–0.24	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.20–0.30	0.35–0.75	0.35
8735 H	8735 H	0.32–0.39	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.20–0.30	0.35–0.75	0.35
8740 H	8740 H	0.37–0.45	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.20–0.30	0.35–0.75	0.35
8742 H	8742 H	0.40–0.48	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.20–0.30	0.35–0.75	0.35
8745 H	8745 H	0.42–0.50	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.20–0.30	0.35–0.75	0.35
8747 H	8747 H	0.44–0.52	0.20–0,35	0.70–1.05	0.04	0.04	0.05–0.65	0.20–0.30	0.35–0.75	0.35
8750 H	8750 H	0.46–0.54	0.20–0.35	0.70–1.05	0.04	0.04	0.35–0.65	0.20–0.30	0.35–0.75	0.35
9260 H	9260 H	0.55–0.65	1.70–2.20	0.70–1.05	0.04	0.04				0.35
9261 H	9261 H	0.55–0.65	1.70–2.20	0.70–1.05	0.04	0.04	0.05–0.35			0.35
9262 H	9262 H	0.55–0.65	1.70–2.20	0.70–1.05	0.04	0.04	0.20–0.50			0.35
9310 H	9310 H	0.07–0.14	0.20–0.35	0.40–0.70	0.04	0.04	1.00–1.45	0.08–0.15	2.95–3.95	0.35
9437 H	9437 H	0.35–0.43	0.20–0.35	0.85–1.25	0.04	0.04	0.25–0.55	0.08–0.15	0.25–0.65	0.35
9440 H	9440 H	0.37–0.45	0.20–0.35	0.85–1.25	0.04	0.04	0.25–0.55	0.08–0.15	0.25–0.65	0.35
9442 H	9442 H	0.40–0.48	0.20–0.35	0.95–1.35	0.04	0.04	0.25–0.55	0.08–0.15	0.25–0.65	0.35
9445 H	9445 H	0.42–0.50	0.20–0.35	0.95–1.35	0.04	0.04	0.25–0.55	0.08–0.15	0.25–0.65	0.35

APPENDIX 10 AISI Stainless Steel Composition

AISI type	C max	Si max	Mn max	P max	S max	Cr	Ni	Mo	Others
Austenitic Stainless Steels									
201	0.15	1.00	5.50–7.50	0.060	0.030	16.0–18.0	3.5–5.5		N 0.25 max
202	0.15	1.00	7.50–10.00	0.060	0.030	17.0–19.0	4.0–6.0		N 0.25 max
301	0.15	1.00	2.00 max	0.045	0.030	16.0–18.0	6.0–8.0		
302	0.15	1.04	2.00	0.045	0.030	17.0–19.0	8.0–10.0		
302 B	0.15	2.00–3.00	2.00	0.045	0.030	17.0–19.0	8.0–10.0		
303	0.15	1.00	2.00	0.20	0.15min	17.0–19.0	8.0–10.0	0.60 max*	
303 Se	0.15	1.00	2.00	0.20	0.060	17.0–19.0	8.0–10.0		Se 0.l5 min
304	0.08	1.00	2.00	0.045	0.030	18.0–20.0	8.0–10.5		
304 L	0.030	1.00	2.00	0.045	0.030	18.0–20.0	8.0–12.0		
305	0.12	1.00	2.00	0.045	0.030	17.0–19.0	10.5–13.0		
308	0.08	1.00	2.00	0.045	0.030	19.0–21.0	10.0–12.0		
309	0.20	1.00	2.00	0.045	0.030	22.0–24.0	12.0–15.0		
309 S	0.08	1.00	2.00	0.045	0.030	22.0–24.0	12.0–15.0		
310	0.25	1.50	2.00	0.045	0.030	24.0–26.0	19.0–22.0		
310 S	0.08	1.50	2.00	0.045	0.030	24.0–26.0	19.0–22.0		
314	0.25	1.50–3.00	2.00	0.045	0.030	23.0–26.0	19.0–22.0		
316	0.08	1.00	2.00	0.045	0.030	16.0–18.0	10.0–14.0	2.0–3.0	
316 L	0.030	1.00	2.00	0.045	0.030	16.0–18.0	10.0–14.0	2.0–3.0	
317	0.08	1.00	2.00	0.045	0.030	18.0–20.0	11.0–15.0	3.0–4.0	
321	0.08	1.00	2.00	0.045	0.030	17.0–19.0	9.0–12.0		Ti 5 × Cmin
347	0.08	1.00	2.00	0.045	0.030	17.0–19.0	9.0–12.0		Nb–Ta 10 × C min
348	0.08	1.00	2.00	0.045	0.030	17.0–19.0	9.0–13.0		Nb–Ta 10 × C min Ta 0.10 max Co 0.20 max
384	0.08	1.00	2.00	0.045	0.030	15.0–17.0	17.0–19.0		
385	0.08	1.00	2.00	0.045	0.030	11.5–13.5	14.0–16.0		
Martensitic Stainless Steels									
403	0.15	0.50	1.00	0.040	0.030	11.50–13.00			
410	0.15	1.00	1.00	0.040	0.030	11.50–13.50			
414	0.15	1.00	1.00	0.040	0.030	11.50–13.50	1.25–2.50		
416	0.15	1.00	1.25	0.060	0.15 min	12.00–14.00		0.60 max*	
416 Se	0.15	1.00	1.25	0.060	0.060	12.00–14.00			Se 0.15 min
420	Above 0.15	1.00	1.00	0.040	0.030	12.00–14.00			
420F	Above 0.15	1.00	1.25	0.060	0.15 min	12.00–14.00		0.60 max*	
431	0.20	1.00	1.00	0.040	0.030	15.00–17.00	1.25–2.50		
440A	0.60–0.75	1.00	1.00	0.040	0.030	16.00–18.00		0.75 max	

440B	0.75–0.95	1.00	1.00	0.040	0.030	16.00–18.00	0.75 max	
440C	0.95–1.20	1.00	1.00	0.040	0.030	16.00–18.00	0.75 max	
501	Above 0.10	1.00	1.00	0.040	0.030	4.00–6.00	0.40–0.65	
502	0.10	1.00	1.00	0.040	0.030	4.00–6.00	0.40–0.65	
Ferritic Stainless Steels								
405	0.08	1.00	1.00	0.040	0.030	11.50–14.50		Al 0.10–0.30
429	0.12	1.00	1.00	0.040	0.030	14.00–16.00		
430	0.12	1.00	1.00	0.040	0.030	16.00–18.00		
430F	0.12	1.00	1.25	0.060	0.15 min	16.00–18.00	0.60 max*	
430F Se	0.12	1.00	1.25	0.060	0.060	16.00–18.00		Se 0.15 min
434	0.12	1.00	1.00	0.040	0.030	16.00–18.00	0.75–1.25	
436	0.12	1.00	1.00	0.040	0.030	16.00–18.00	0.75–1.25	Nb–Ta 5 × C min 0.70 max
442	0.20	1.00	1.00	0.040	0.030	18.00–23.00		
446	0.20	1.00	1.50	0.040	0.030	23.00–27.00		N 0.25 max

*Occasional

APPENDIX 11 AISI Tool Steel Composition

AISI type	C	Mn	Si	W	Mo	Cr	V	Co	Ni	Ai
Tungsten-base High Speed Steels										
Tl	0.75			18.0		4.0	1.0			
T2	0.80			18.0		4.0	2.0			
T4	0.75			18.0		4.0	1.0	5.0		
T5	0.80			18.0		4.0	2.0	8.0		
T6	0.80			20.0		4.5	1.5	12.0		
T8	0.75			14.0		4.0	2.0	5.0		
T15	1.50			12.0		4.0	5.0	5.0		
Molybdenum-base High Speed Steels										
Ml	0.80			1.50	8.00	4.00	1.00			
M2	0.85–1.00			6.00	5.00	4.00	2.00			
M3 Cl. 1	1.05			6.00	5.00	4.00	2.40			
M3 Cl. 2	1.20			6.00	5.00	4.00	3.00			
M4	1.30			5.50	4.50	4.00	4.00			
M6	0.80			4.00	5.00	4.00	1.50	12.00		
M7	1.00			1.75	8.75	4.00	2.00			
M10	0.85–1.00				8.00	4.00	2.00			
M30	0.80			2.00	8.00	4.00	1.25	5.00		
M33	0.90			1.50	9.50	4.00	1.15	8.00		

APPENDIX 11 AISI Tool Steel Composition (cont.)

AISI type	C	Mn	Si	W	Mo	Cr	V	Co	Ni	Ai
M34	0.90			2.00	8.00	4.00	2.00	8.00		
M36	0.80			6.00	5.00	4.00	2.00	8.00		
M41	1.10			6.75	3.75	4.25	2.00	5.00		
M42	1.10			1.50	9.50	3.75	1.15	8.00		
M43	1.20			2.75	8.00	3.75	1.60	8.25		
M44	1.15			5.25	6.25	4.25	2.25	12.00		
M46	1.25			2.00	8.25	4.00	3.20	8.25		
M47	1.10			1.50	9.50	3.75	1.25	5.00		
Chromium-base Hot Work Steels										
H10	0.40				2.50	3.25	0.40			
H11	0.35				1.50	5.00	0.40			
H12	0.35			1.50	1.50	5.00	0.40			
H13	0.35				1.50	5.00	1.00			
H14	0.40			5.00		5.00				
H19	0.40			4.25		4.25	2.00	4.25		
Tungsten-base Hot Work Steels										
H21	0.35			9.00		3.50				
H22	0.35			11.00		2.00				
H23	0.30			12.00		12.00				
H24	0.45			15.00		3.00				
H25	0.25			15.00		4.00				
H26	0.50			18.00		4.00	1.00			
Molybdenum-base Hot Work Steels										
H41	0.65			1.50	8.00	4.00	1.00			
H42	0.60			6.00	5.00	4.00	2.00			
H43	0.55				8.00	4.00	2.00			
Water Hardening Tool Steels										
W1	0.60–1.40									
W2	0.60–1.40						0.25			
W5	1.10					0.50				
Shock Resistant Tool Steels										
S1	0.50			2.50		1.50				
S2	0.50		1.00		0.50					
S5	0.55	0.80	2.00		0.40					
S7	0.50				1.40	3.25				

Low-alloy Tool Steels										
L2	0.50–1.10						1.00	0.20		
L3	1.00						1.50	0.20		
L6	0.70					0.25*	0.75		1 .50	
Low-alloy Dimensionally Stable Cold Work Steels										
01	0.90	1.00		0.50		0.50				
02	0.90	1.60								
06	1.45		1.00		0.25					
07	1.20			1.75		0.75				
Air Hardening Cold Work Steels										
A2	1.00				1.00	5.00				
A3	1.25				1.00	5.00	1.00			
A4	1.00	2.00			1.00	1.00				
A6	0.70	2.00			1.25	1.00				
A7	2.25			1.00*	1.00	5.25	4.75			
A8	0.55			1.25	1.25	5.00				
A9	0.50				1.40	5.00	1.00		1.50	
A10	1.35	1.80	1.25		1.50				1.80	
High-carbon High-chromium Steels										
D2	1.50				1.00	12.00	1.00			
D3	2.25					12.00				
D4	2.25				1.00	12.00				
D5	1.50				1.00	12.00		3.00		
D7	2.35				1.00	12.00	4.00			
Tungsten Diamond Steels										
F1	1.00			1.25						
F2	1.25			3.50						
Plastic Moulding Die Steels										
P2	0.07				0.20	2.00			0.50	
P3	0.10					0.60			1.25	
P4	0.07				0.75	5.00				
P5	0.10					2.25				
P6	0.10				0.40	1.25			3.50	
P20	0.35				0.40	1.25				
P21	0.20								4.00	1.20

*Occasional

APPENDIX 12 EN Steel Composition

EN	C	Si	Mn	P max	S max	Cr	Mo	Ni	Others
				Carbon and Alloy Steels					
1A	0.07–0.15	0.10 max	0.80–1.20	0.070	0.300				
1B	0.07–0.15	0.10 max	0.80–1.40	0.070	0.600				
2	0.20 max	0.30 max	0.80 max	0.060	0.060				
2B	0.12–0.18	0.10–0.30	0.30–0.60	0.040	0.040				
3	0.25 max	0.05–0.35	1.00 max	0.060	0.060				
3A	0.15–0.25	0.05–0.35	0.40–0.90	0.060	0.060				
3B	0.25 max	0.35 max	1.00 max	0.060	0.060				
4	0.20–0.30	0.35 max	1.00 max	0.060	0.060				
4A	0.30 max	0.05–0.35	1.00 max	0.060	0.060				
5	0.25–0.35	0.05–0.35	0.60–1.00	0.060	0.060				
6	0.40 max	0.05–0.35	0.50–0.90	0.060	0.060				
6A	0.40 max	0.35 max	0.50–0.90	0.060	0.060				
7	0.10–0.30	0.35 max	0.70–1.30	0.060	0.180				
8	0.35–0.45	0.05–0.35	0.60–1.00	0.060	0.060				
8M	0.35–0.45	0.25 max	0.90–1.10	0.070	0.200				
9	0.50–0.60	0.40 max	0.80 max	0.040	0.040				
10	0.50–0.60	0.05–0.35	0.50–0.80	0.060	0.060				
11	0.50–0.70	0.35 max	0.50–0.80	0.050	0.050	0.50–0.80		0.50–0.80	
12	0.30–0.45	0.10–0.35	1.50 max	0.050	0.050			0.60–1.00	
13	0.15–0.25	0.10–0.35	1.40–1.50	0.050	0.050		0.15–0.35	0.40–0.70	
14A	0.15–0.25	0.10–0.35	1.30–1.70	0.060	0.060	0.25 max		0.40 max	
14B	0.20–0.30	0.10–0.35	1.30–1.70	0.060	0.060			0.40 max	
15	0.30–0.40	0.10–0.35	1.30–1.70	0.050	0.050			0.30 max	
15A	0.30–0.40	0.05–0.35	1.30–1.70	0.060	0.060				
29	0.15–0.35	0.10–0.35	0.65 max	0.050	0.050	2.50–3.50	0.30–0.70	0.40 max	
30A	0.26–0.45	0.10–0.35	0.40–0.60	0.050	0.050	1.10–1.40		3.90–4.30	
30B	0.26–0.34	0.10–0.35	0.40–0.60	0.050	0.050	1.10–1.40	0.20–0.40	3.93–4.30	
31	0.90–1.10	0.10–0.35	1.10 max	0.050	0.050	1.00–1.50	0.30–0.35		
32	0.10–0.18	0.05–0.35	0.60–1.00	0.050	0.070				
33	0.10–0.15	0.10–0.35	0.30–0.60	0.050	0.050	0.30 max		2.75–3.50	
34	0.14–0.20	0.10–0.35	0.30–0.60	0.050	0.050		0.20–0.30	1.50–2.00	
35	0.20–0.28	0.10–0.35	0.30–0.60	0.050	0.050		0.20–0.30	1.50–2.00	
15B	0.35–0.40	0.05–0.35	1.10–1.30	0.060	0.060				
16	0.25–0.40	0.10–0.35	1.30–1.80	0.050	0.050		0.20–0.35		
16A	0.25–0.30	0.10–0.35	1.30–1.80	0.050	0.050		0.20–0.35		
16B	0.30–0.35	0.10–0.35	1.30–1.80	0.050	0.050		0.20–0.35		
16C	0.35–0.40	0.10–0.35	1.30–1.80	0.050	0.050		0.20–0.55		
17	0.30–0.40	0.10–0.35	1.30–1.80	0.050	0.050		0.35–0.55		

18	0.35–0.45	0.10–0.35	0.60–0.95	0.050	0.050	0.80–1.10			
18A	0.27–0.32	0.10–0.35	0.65–0.80	0.050	0.050	0.80–1.10			
18B	0.30–0.35	0.10–0.35	0.65–0.80	0.050	0.050	0.80–1.10			
18C	0.35–0.38	0.10–0.35	0.65–0.80	0.050	0.050	0.80–1.10			
18D	0.38–0.43	0.10–0.35	0.65–0.80	0.050	0.050	0.80–1.10			
19	0.35–0.45	0.10–0.35	0.50–0.80	0.050	0.050	0.90–1.50	0.20–0.40		
19A	0.35–0.45	0.10–0.35	0.50–0.80	0.050	0.050	0.90–1.20	0.20–0.35		
19B	0.35–0.40	0.10–0.35	0.50–0.80	0.050	0.050	0.90–1.20	0.20–0.35		
19C	0.40–0.45	0.10–0.35	0.50–0.80	0.050	0.050	0.90–1.20	0.20–0.35		
20	0.22–0.50	0.10–0.35	0.40–0.70	0.050	0.050	0.50–1.50	0.40–1.00	0.30 max	
21	0.25–0.35	0.10–0.35	0.35–0.75	0.050	0.050	0.30 max		2.75–3.50	
22	0.35–0.45	0.10–0.35	0.50–0.80	0.050	0.050	0.30 max		3.25–3.75	
23	0.25–0.35	0.10–0.35	0.45–0.70	0.050	0.050	0.50–1.00	0.30 max	2.75–3.50	
24	0.35–0.45	0.10–0.35	0.45–0.70	0.050	0.050	0.90–1.40	0.20–0.35	1.30–1.80	
25	0.27–0.35	0.10–0.35	0.50–0.70	0.050	0.050	0.50–0.80	0.40–0.70	2.30–2.80	
26	0.36–0.44	0.10–0.35	0.50–0.70	0.050	0.050	0.50–0.80	0.40–0.70	2.30–2.80	
27	0.25–0.35	0.10–0.35	0.70. max	0.050	0.050	0.50–1.30	0.20–0.65	3.00–3.75	
28	0.25–0.40	0.10–0.35	0.70 max	0.050	0.050	0.75–1.50	0.20–0.65	3.00–4.50	
Carbon and Alloy Steels									
35A	0.20–0.25	0.10–0.35	0.30–0.60	0.050	0.050		0.20–0.30	1.50–2.00	
35B	0.23–0.28	0.10–0.35	0.30–0.60	0.050	0.050		0.20–0.30	1.50–2.00	
36	0.18 max	0.10–0.35	0.30–0.60	0.050	0.050	0.60–1.10		3.00–3.75	
37	0.17 max	0.10–0.35	0.45 max	0.050	0.050	0.30 max		4.50–5.20	
38	0.16 max	0.10–0.35	0.60 max	0.050	0.050	0.30 max	0.30 max	4.50–5.50	
39A	0.12–0.18	0.10–0.35	0.50 max	0.050	0.050	1.00–1.40		3.80–4.50	
39B	0.12–0.18	0.10–0.35	0.50 max	0.050	0.050	1.00–1.40	0.15–0.35	3.80–4.50	
40A	0.10–0.20	0.10–0.35	0.40–0.65	0.050	0.050	2.90–3.50	0.40–0.70	0.30 max	
40B	0.20–0.30	0.10–0.35	0.40–0.65	0.050	0.050	2.50–3.50	0.40–0.70	0.30 max	
40C	0.30–0.50	0.10–0.35	0.40–0.80	0.050	0.050	2.50–3.50	0.70–1.20	0.40 max	V 0.10–0.30
41	0.18–0.45	0.10–0.45	0.65 max	0.050	0.050	1.40–1.80	0.10–0.25	0.40 max	Al 0.90–1.30
41A	0.25–0.35	0.10–0.40	0.65 max	0.050	0.050	1.40–1.80	0.10–0.25		Al 0.90–1.30
42	0.65–0.80	0.35 max	0.70 max	0.050	0.050				
45	0.50–0.65	1.50–2.00	0.70–1.00	0.050	0.050				
45A	0.53–0.63	1.70–2.00	0.70–1.00	0.050	0.050				
46	0.35–0.45	1.50–2.00	0.60–1.00	0.050	0.050				
47	0.45–0.55	0.50 max	0.50–0.80	0.050	0.050	0.80–1.20			V 0.15 min
48	0.45–0.55	0.10–0.50	0.50–0.80	0.050	0.050	1.00–1.40			
50	0.40–0.50	0.10–0.35	0.50–0.70	0.040	0.040	1.00–1.50			V 0.l5 min
51	0.25–0.35	0.10–0.35	0.35–0.75	0.050	0.050	0.30 max		2.75–3.50	
100	0.35–0.45	0.50 max	1.20–1.50	0.050	0.050	0.30–0.60	0.15–0.25	0.50–1.00	
100A	0.25–0.30	0.10–0.35	1.20–1.50	0.050	0.050	0.30–0.60	0.15–0.25	0.50–1.00	
100B	0.30–0.35	0.10–0.35	1.20–1.50	0.050	0.050	0.30–0.60	0.15–0.25	0.50–1.00	
100C	0.35–0.40	0.10–0.35	1.20–1.50	0.050	0.050	0.30–0.60	0.15–0.25	0.50–1.00	
100D	0.40–0.45	0.10–0.35	1.20–1.50	0.050	0.050	0.30–0.60	0.15–0.25	0.50–1.00	

APPENDIX 12 EN Steel Composition (cont.)

EN	C	Si	Mn	P max	S max	Cr	Mo	Ni	Others
110	0.35–0.45	0.10–0.35	0.40–0.80	0.050	0.050	0.90–1.40	0.10–0.20	1.20–1.60	
111	0.30–0.40	0.10–0.35	0.60–0.90	0.050	0.050	0.45–0.75		1.00–1.50	
111A	0.33–0.38	0.10–0.35	0.60–0.90	0.050	0.050	0.45–0.75		1.00–1.50	
160	0.35–0.45	0.10–0.35	0.30–0.60	0.050	0.050		0.20–0.35	1.50–2.00	
160A	0.38–0.43	0.10–0.35	0.30–0.60	0.050	0.050		0.20–0.35	1.50–2.00	
201	0.18 max	0.05–0.35	1.10–1.50	0.050	0.050				
202	0.18 max	0.05–0.35	1.10–1.50	0.050	0.180				
206	0.12–0.17	0.10–0.35	0.30–0.50	0.050	0.050	0.30–0.50			
207	0.16–0.21	0.10–0.35	0.60–0.80	0.050	0.050	0.60–0.80			
320	0.14–0.20	0.10–tf35	0.40–0.70	0.050	0.050	1.80–2.20	0.15–0.25	1.80–2,20	
325	0.17–0.22	0.10–0.35	0.45–0.65	0.050	0.050	0.40–0.60	0.20–0.30	1.50–2.00	
351	0.16–0.24	0.40 max	0.40–0.70	0.045	0.045	0.50–0.70		0.60–1.00	
352	0.16–0.22	0.40 max	0.60–0.90	0.045	0.045	0.85–1.20		0.80–1.25	
353	0.16–0.22	0.40 max	0.60–0.90	0.045	0.045	0.85–1.20	0.15 max	1.20–1.60	
354	0.14–0.22	0.40 max	0.60–0.90	0.045	0.045	0.80–1.20	0.15–0.30	1.20–1.60	
355	0.14–0.22	0.40 max	0.60–0.90	0.045	0.045	0.80–1.20	0.15–0.30	1.80–2.20	
361	0.13–0.18	0.40 max	0.70–0.90	0.045	0.045	0.40–0.60	0.15–0.25	0.40–0.70	
362	0.18–0.23	0.40 max	0.70–0.90	0.045	0.045	0.40–0.60	0.15–0.25	0.40–0.70	
52	0.40–0.50	3.00–3.75	0.40–0.60	0.040	0.030	7.5–8.5		0.50 max	
54	0.39–0.45	1.40–1.70	0.65–0.75	0.040	0.030	13.0–14.0		13.0–13.5	W 2.50–3.00
56A	0.10 max	1.00 max	1.00 max	0.040	0.040	12.0–14.0			
56AM	0.12 max	1.00 max	1.00 max	0.040	0.040	12.0–14.0			
56	0.10–0.20	0.50 max	1.00 max	0.040	0.040	12.0–14.0		1.00 max	
56C	0.18–0.25	0.50 max	1.00 max	0.040	0.040	12.0–14.0		0.30 max	
56D	0.40 max	0.25 max	0.30 max	0.040	0.040	11.50			
56M	0.30 max	1,00 max	1.00 max	0.050	0.050	12.0–14.0		1.00 max	
57	0.25 max	1.00 max	1.00 max	0.040	0.040	16.0–20.0		1.5–2.0	
58A	0.15 max	1.00 max	2.00 max	0.040	0.040	17.0–20.0		7.0–10.0	
58B	0.15 max	1.50 max	1.00 max	0.040	0.040	17.0–20.0		7.5–10.5	Nb (10 × C) min
58C	0.15 max	0.20 min	2.00 max	0.040	0.040	17.0–20.0		8.0–12.0	Ti (5 × C) min
58D	0.08–0.15	1.00 max	1 .00 max	0.040	0.040	11.0–14.0		11.0–14.0	
58E	0.08 max	0.20 max	2.00 max	0.040	0.040	17.5–20.0		8.0–11.0	
58F	0.08 max	1.00 max	2.00 max	0.040	0.040	17.5–20.0		10.0–14.0	Cb/Ta (10 × C) min
58G	0.15 max	0.20 max	2.00 max	0.040	0.040	17.0–20.0		10.0–14.0	Nb (10 × C) min
58H	0.08–0.12	1.00 max	2.00 max	0.040	0.040	17.0–20.0	1.50–2.50	8.0–12.0	Ti (5 × C) min
58J	0.12 max	0.20 min	2.00 max	0.040	0.040	17.0–20.5	2.50–3.50	8.0–12.0	
59	0.76–0.82	2.00	0.60	0.040	0.030	19.0–20.5		1.2–1.6	
60	0.12 max	1.00 max	1.00 max	0.050	0.050	15.0–19.0		0.50 max	
61	0.12 max	1.00 max	1.00 max	0.050	0.050	19.0–23.0		0.50 max	

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Question Bank

SECTION A

Choose correct answers for the following questions.

1. Chemically homogeneous austenite (on heating) can be obtained by
   (a) heating rapidly and holding for sometime at upper critical temperature.
   (b) heating slowly and holding for sometime at upper critical temperature.
   (c) simply holding for sometime at upper critical temperature irrespective of the heating rates.
   (d) none of the above

2. What type of heating rate will favour the formation of austenite at a constant temperature in an eutectoid steel?
   (a) fast
   (b) extremely fast
   (c) slow
   (d) extremely slow

3. The model proposed by Hull and Mehl is most widely accepted for transformation of austenite to:
   (a) pearlite
   (b) bainite
   (c) martensite
   (d) ferrite

4. The growth rate (in mm per second) for pearlitic transformation is of the order of
   (a) 10^2–10^3
   (b) 10^{-3}–10^{-2}
   (c) 10^{-4}–10^{-3}
   (d) 10^3–10^4

5. Which of the following statements is valid for interlamellar spacing of pearlite?
   (a) It is structure-sensitive in nature.
   (b) It is independent of austenitic grain size.
   (c) It is independent of degree of homogeneity of austenite.

6. Upper bainite is an aggregate of
   (a) ferrite and epsilon carbide.
   (b) ferrite and cementite.
   (c) acicular ferrite and epsilon carbide.
   (d) acicular ferrite and cementite.

7. In general as compared to upper bainite, mechanical properties of lower bainite are
   (a) inferior
   (b) almost similar
   (c) better

8. Feathery structure in heat treated steel, in general, confirms the presence of
(a) lower bainite (b) upper bainite
(c) massive martensite (d) tempered martensite

9. Carbon martensite is a supersaturated solid solution of carbon in
(a) ferrite (b) gamma iron
(c) austenite (d) alpha iron

10. The martensite formed in carbon steels on quenching is referred to as
(a) isothermal martensite (b) athermal martensite
(c) strained martensite

11. The c/a ratio for martensite obtained from austenite, fully saturated with carbon, will be about
(a) 1.08 (b) –1.414
(c) 1.32 (d) 1.732

12. The c/a ratio for martensite obtained from Bain distortion model is
(a) 1.045 (b) 1.320
(c) 1.080 (d) 1.414

13. The growth rate (in mm per second) for martensite transformation is of the order of
(a) 10^{-3} (b) 10^{3}
(c) 10^{6} (d) 10^{-6}

14. For a given steel, M_s temperature is independent of cooling rate employed
(a) independent (b) dependent

15. Most of the alloying elements lower the M_s temperature. However .... raises it.
(a) silicon (b) copper
(c) molybdenum (d) aluminium

16. For a given chemistry of steel, M_f temperature is not a fixed temperature. It can be lowered by .... cooling rate and .... carbon content.
(a) lowering, raising (b) raising, raising
(c) lowering, lowering (d) raising, lowering

17. The plane (2 5 9) is a habit plane for ....steels.
(a) low carbon (b) medium carbon
(c) high carbon (d) all of these

18. When viewed under microscope, etched sample of tempered martensite appears .... as compared to etched sample of as quenched martensite
(a) light (b) dark

19. M_d temperature is the highest temperature at which
(a) martensite can be deformed easily.
(b) martensite will be stable during tempering.
(c) none of the above.

20. Strain induced martensite may form under stress at temperatures
(a) above M_s temperature (b) below M_f temperature

21. The basic step in any heat treatment process is the formation of
(a) ferrite (b) pearlite
(c) austenite (d) martensite

22. In general, for a given temperature, alloying elements in steels diffuse .... in comparison to carbon.
(a) slowly (b) very slowly
(c) quickly (d) very quickly

23. Annealing improves the machinability of
(a) low and medium carbon steels (b) medium and high carbon steels
(c) high and low carbon steels

24. The .... annealing treatment is given to alloy steel ingots to eliminate dendritic structure and to obtain chemical homogeneity.
(a) recrystallization (b) full
(c) isothermal (d) diffusion

25. Annealing temperature for a medium carbon (0.25–0.30%C) steel ranges between
(a) 860–880°C (b) 880–900°C
(c) 920–940°C (d) 940–960°C

26. Spheroidizing treatment raises the toughness and improves the machinability of .... carbon steels.
(a) low (b) medium
(c) high

27. This constituent is always present in almost all normalized/annealed carbon steels,
(a) ferrite (b) pearlite
(c) cementite

28. The two-stage heating schedule up to hardening temperature is employed for high speed steel (18-4-1 type) to ensure
(a) check on grain growth. (b) minimum possible oxidation risk.
(c) both of the above.

29. The range of carbon content, which gives maximum relative increase in hardness of steel on quenching, is
(a) 0.35–0.70% (b) 0.70–1.00%
(c) 1.00–1.20% (d) 1.20–1.50%

30. In order to compare cooling capacity of different quenching media, the cooling capacity of .... water is arbitrarily taken as 1.
(a) non-agitated (b) gently continuously flowing
(c) gently agitated

31. Air can be used as a quenching medium for steels with
(a) low hardenability (b) low alloy content
(c) very high hardenability (d) very high alloy content

32. The amount of retained austenite is high in .... carbon steel.
(a) low (b) medium
(c) high

33. On quenching from a normal hardening temperature, a high speed steel may contain retained austenite in the range,
(a) 2–10% (b) 10–20%
(c) 20–30%

34. As compared to plain carbon steels, the hardening temperature for low nickel steels of a similar carbon content is on the
(a) higher side (b) lower side

35. Tempering treatment for hardened steels is imparted to reduce
(a) toughness (b) internal stresses
(c) hardness (d) tensile strength

36. The second stage of tempering starts at about
(a) 150°C (b) 250°C
(c) 350°C

37. The temperature of secondary hardening for a conventional 18-4-1 high speed steel is
(a) 270°C (b) 370°C
(c) 470°C (d) 570°C

38. The temperature–colour relationship as given in literature under the head 'Temper Colours' is valid for
(a) plain carbon steels only. (b) alloy steels only.
(c) both plain carbon and alloy steels.

39. In general, all alloying elements increase hardenability of steels except
(a) silicon and cobalt (b) cobalt and aluminium
(c) silicon and aluminium (d) boron and silicon

40. Hardenability of steel can be improved by any mechanism which results in shifting of TTT curve
(a) towards the temperature axis.
(b) towards the time axis.
(c) away from the temperature axis.
(d) away from the time axis.

41. The name of M.A. Grossman is associated with
(a) grain size measurement. (b) martensitic transformation.
(c) determination of hardenability. (d) mechanism of precipitation hardening.

42. A steel to be employed in welded condition should have .... hardenability
(a) low (b) high

43. The micro-constituent that is normally produced by patenting treatment is
(a) fine pearlite (b) upper bainite
(c) tempered martensite

44. Patenting is a special heat treatment process for imparting very high strength level coupled with good cold drawability, given to
(a) low and medium carbon steels (b) medium and high carbon steels
(c) high carbon steels only (d) low carbon steels only

45. Austempering is a
(a) thermomechanical treatment.
(b) high temperature tempering treatment.
(c) low temperature tempering treatment.
(d) none of the above.

46. The microstructure of austempered steel consists of
(a) martensite + retained austenite (b) martensite
(c) bainite (d) bainite + retained austenite

47. One of the limitations of austempering treatment is that
(a) fine grained steels alone can be employed.
(b) process is suitable for plain carbon steels only.
(c) steels with high hardenability are best suited.
(d) it can be applied successfully only to thin sections.

48. The process which results in the formation of martensite with a minimum of internal stresses is referred to as
(a) austempering (b) ausaging
(c) martempering (d) maraging

49. In comparison to conventional hardening, the amount of retained austenite is generally .... after martempering.
(a) less (b) more

50. Maraging steels are commonly processed through a heat treatment cycle consisting of cooling from
(a) 820°C and tempering at 570°C for 3 hours.
(b) 920°C and tempering at 480°C for 3 hours.
(c) 820°C and tempering at 480°C for 3 hours.
(d) 920°C and tempering at 570°C for 3 hours.

51. Ausforming is a
(a) heat treatment process (b) thermomechanical treatment
(c) hot deformation process (d) cold deformation process

52. Carburizing is generally carried out in the temperature range of
(a) 800–850°C (b) 850–900°C
(c) 900–950°C (d) 950–980°C

53. .... carburizing is the most effective carburizing process
(a) Pack (b) Liquid
(c) Gas

54. The energizer used along with carburizing compound in pack carburizing is .... carbonate.
(a) barium (b) magnesium
(c) calcium

55. Hot working tool steels can be case hardened by the process of
(a) carburizing (b) carbonitriding
(c) nitriding (d) induction hardening

56. As compared to carburized case, nitrided case is
(a) relatively thin, much harder and has better endurance limit.
(b) relatively thick, much harder and has better corrosion resistance.
(c) relatively thin, much softer and has better endurance limit.
(d) relatively thick, much softer and has better corrosion resistance.

57. The term ‘white layer’ in heat treatment is related to .... process.
(a) case carburizing (b) martempering
(c) case nitriding (d) austempering

58. The best suited steel for case nitriding contains
(a) aluminium (b) chromium
(c) cobalt (d) silicon

59. .... carbon steels are best suited for case nitriding
(a) Low (b) Medium
(c) High

60. Carbides in steel, irrespective of their composition, improve room temperature
(a) fatigue strength (b) impact strength
(c) tensile strength (d) yield strength

61. Temper-embitterment can be counteracted by the addition of
(a) nickel (b) molybdenum
(c) chromium (d) vanadium

62. Blue brittleness is, in general, not observed in
(a) rimmed steels (b) semi-killed steels
(c) killed steels (d) capped steels

63. Blue Brittleness is exhibited by some steels when heated to a temperature range of
(a) 100–200°C (b) 200–300°C
(c) 350–500°C

64. Quench cracks
(a) are generally open cracks. (b) are all internal cracks.
(c) may be both open and internal type.

65. The microstructure of silicon consists of
(a) upper bainite (b) lath martensite
(c) coarse ferrite (d) retained austenite

66. The BIS code .... is used to determine depth of decarburization.
(a) IS-4163 (b) IS-2853
(c) IS-6396 (d) IS-4748

67. Which type of heat treating furnace is superior in respect of greater heat capacity and better uniformity of temperature?
(a) muffle furnace (b) liquid bath furnace
(c) rotary hearth furnace (d) circulating air type furnace

68. The magnitude of internal stresses developed on quenching increases with increase in the
(a) carbon content of steel. (b) alloy content of steel.
(c) austenite grain size.

69. Lath martensite is usually formed in................. carbon steels
(a) high and medium
(b) high and low
(c) low and medium
(d) high

70. In a precipitation hardenable alloy, the precipitation occurs
(a) at grain boundaries
(b) along slip planes
(c) both of the above
(d) none of the above

71. The maximum precipitation hardening effect in an Al-Cu ally would be observed when the copper content is
(a) 2.5%
(b) 4.0%
(c) 5.5%
(d) 7.0%

72. Which one is not a precipitation hardenable alloy?
(a) Cu–2%Be
(b) Mg–2%Pb
(c) 17–7PH
(d) AISI8620 steel

73. In an Al-4%Cu alloy, the strengthening (on precipitation hardening) is due to the precipitation of
(a) Cu_2Al
(b) CuAl
(c) $CuAl_2$

74. .... treatment does not involve quenching after holding at case hardening temperature
(a) Carburizing
(b) Nitriding
(c) Cyaniding

75. It is possible to form martensite in
(a) steels and cast irons
(b) copper and copper based alloys
(c) titanium and titanium based alloys
(d) all of the above.

ANSWERS
SECTION A

1.	(d)	**2.**	(d)	**3.**	(a)	**4.**	(b)	**5.**	(a)	**6.**	(b)	**7.**	(c)
8.	(b)	**9.**	(d)	**10.**	(b)	**11.**	(a)	**12.**	(d)	**13.**	(c)	**14.**	(a)
15.	(d)	**16.**	(a)	**17.**	(c)	**18.**	(b)	**19.**	(c)	**20.**	(a)	**21.**	(c)
22.	(b)	**23.**	(b)	**24.**	(d)	**25.**	(b)	**26.**	(c)	**27.**	(b)	**28.**	(c)
29.	(a)	**30.**	(a)	**31.**	(c)	**32.**	(c)	**33.**	(c)	**34.**	(b)	**35.**	(b)
36.	(b)	**37.**	(d)	**38.**	(a)	**39.**	(b)	**40.**	(c)	**41.**	(c)	**42.**	(a)
43.	(a)	**44.**	(b)	**45.**	(d)	**46.**	(c)	**47.**	(d)	**48.**	(c)	**49.**	(b)
50.	(c)	**51.**	(b)	**52.**	(c)	**53.**	(c)	**54.**	(a)	**55.**	(c)	**56.**	(a)
57.	(c)	**58.**	(a)	**59.**	(b)	**60.**	(c)	**61.**	(b)	**62.**	(c)	**63.**	(b)
64.	(c)	**65.**	(c)	**66.**	(c)	**67.**	(b)	**68.**	(a)	**69.**	(c)	**70.**	(c)
71.	(c)	**72.**	(d)	**73.**	(c)	**74.**	(b)	**75.**	(d)				

SECTION B

Choose whether each of the following statements are true or false.

1. The lamellar nature of pearlite can be explained on the basis of an assumption that cementite platelets are active nuclei for pearlite transformation.

2. In general, the effect of alloying elements is more pronounced on pearlitic transformation in comparison to the bainitic transformation.

3. Martensitic transformation is reversible.

4. Transformation of austenite to martensite occurs instantaneously and so chemical composition and crystal structure of both the parent and product phase are same.

5. Carbon atoms in martensite are present at the tetrahedral interstices.

6. In comparison to carbon steels, all alloy steels, except cobalt steels, have larger inter-lamellar spacing.

7. Temper brittleness can be eliminated by the addition of chromium or manganese to steel.

8. Hardenability is a measure of the maximum hardness attainable in a given steel in the hardened condition.

9. Formation of epsilon carbide during early stage of tempering can be easily confirmed by optical microscopy.

10. Hardenability of steel increases with increasing carbon content.

11. Case hardening treatments are generally confined to low carbon steels.

12. Heat treatment is most probably the only method of strengthening high alloy steels.

13. Like steels, grey cast irons can also be hardened and tempered in order to improve mechanical properties.

14. In an Al-4%Cu alloy, G.P. Zones consist of ultrafine precipitate particles with a well defined chemical composition and crystal structure, different from the chemical composition and crystal structure of the final precipitate.

15. In comparison to salt bath nitriding, gas nitriding requires a longer time and makes the steel brittle.

16. The only limitation of maraging steels is their susceptibility to hydrogen embitterment.

17. The process of formation of G.P. Zones is referred to as precipitation.

18. For a precipitation hardenable alloy, the stage at which the precipitate particles can be just observed with an optical microscope would correspond to the peak hardness.

19. Sub-zero treatment should be performed after holding hardened steel at room temperature for over 3 to 6 hours.

20. The steel subjected to sub-zero treatment should be tempered immediately to reduce stresses developed due to the transformation of retained austenite to martensite.

KEYS

1. T **2.** T **3.** T **4.** F **5.** F **6.** T **7.** F **8.** F
9. F **10.** F **11.** F **12.** F **13.** T **14.** T **15.** T **16.** F
17. F **18.** F **19.** F **20.** T

SECTION C

1. Explain why

   (i) High carbon steels austenitize more rapidly as compared to low carbon steels.
   (ii) Martensite, and not bainite, forms on quenching a plain carbon steel.
   (iii) Normalized steels have better strength and toughness as compared to annealed steels.
   (iv) Mild steel cannot be hardened by quenching.
   (v) Nitriding is a low temperature treatment as compared to carburizing treatment.
   (vi) A double heat treatment is sometimes necessary for case carburized steels.
   (vii) Alloy steels are preferred over plain carbon steels for nitriding.
   (viii) Presence of non-metallic inclusions lowers the hardenability of a steel.
   (ix) There are limited numbers of precipitation hardenable alloys.
   (x) Salt baths are preferred as quenchant for tool steels.

2. Enlist/Name

   (i) Factors affecting decomposition of austenite on cooling.
   (ii) Factors affecting formation of austenite from ferrite-cementite aggregate on heating.
   (iii) Factors controlling the interlamellar spacing of pearlite.
   (iv) Process variables affecting "hardening by quenching" process.
   (v) Ausforming process variables.
   (vi) Any five heat treatment defects (identify the reason and name it in each case).
   (vii) Salts that are commonly used in salt bath furnaces.
   (viii) Some endothermic atmospheres used in heat treatment furnaces and their applications.

SECTION D

1. Calculate the average grain size (diameter) corresponding to ASTM grain size number 10. Find the yield strength of this steel if the yield strength values for this steel with ASTM grain size number 6 and 8 are 80 and 120 kg/mm^2, respectively.

2. What is retained austenite? Enlist the parameters promoting the formation of retained austenite. What is its effect on mechanical properties of steels?

3. Draw a neat sketch explaining the process of heat removal during quenching.

4. (i) Draw heat treatment cycles for a
   (a) Typical maraging steel.
   (b) Conventional high speed steel.
   (ii) Name various processes involved and specify various temperatures.

5. Draw figures explaining the process of ‘Isoforming’ and ‘Martempering’.

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