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

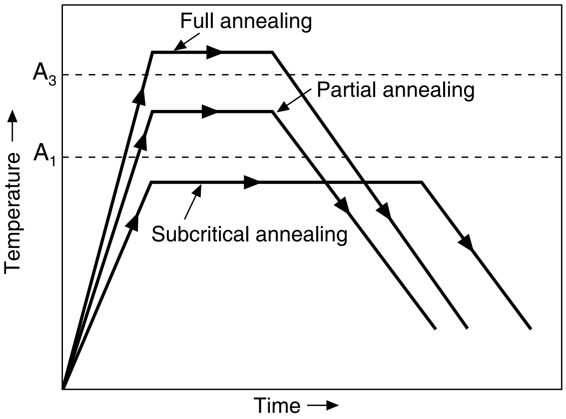


Figure 5.1 Various types of annealing processes classified on the basis of annealing temperature.

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.

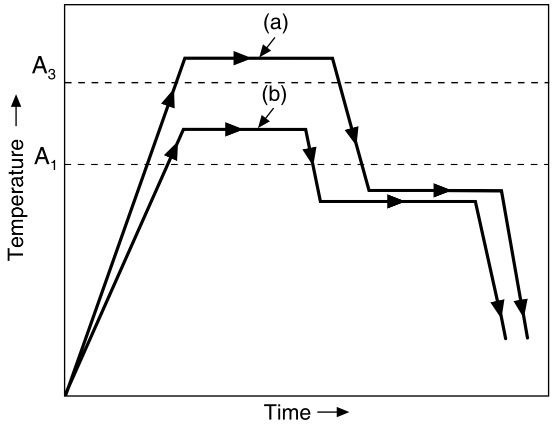


Figure 5.2 **Heat treatment cycle for isothermal annealing of (a) hypoeutectoid steel and (b) eutectoid steel.**

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.

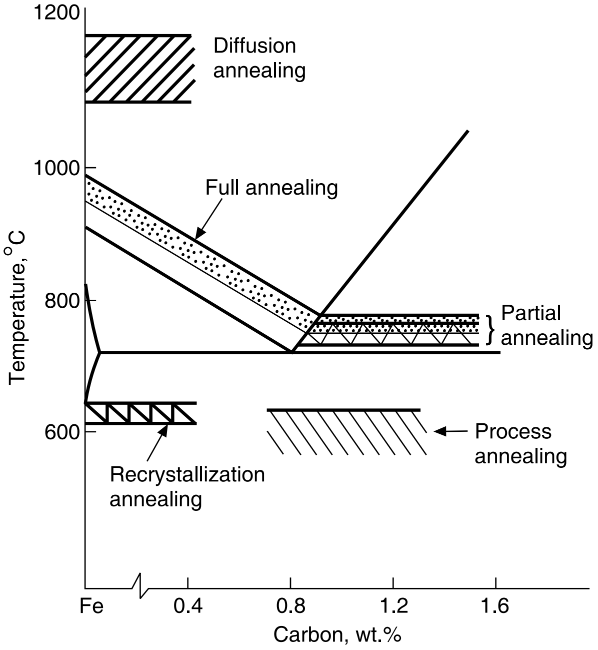


Figure 5.3 Temperature ranges for various types of annealing processes.

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.

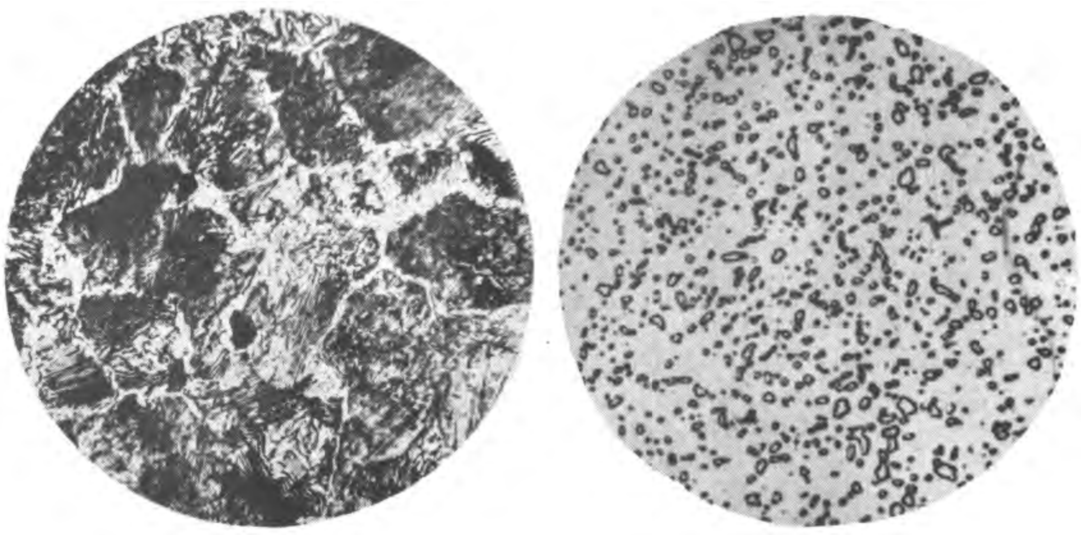
Various methods are available to obtain a spheroidized structure. One such method consists of heating steel to a temperature just below the lower critical temperature, holding at this temperature for prolonged periods, followed by slow cooling. Another method involves heating and cooling steel alternately 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

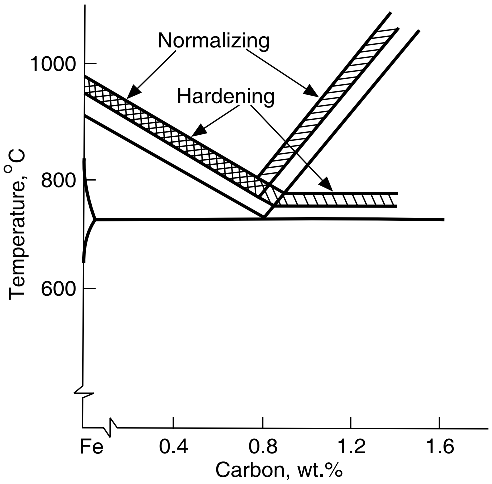


Figure 5.5 Temperature ranges for normalizing and hardening treatment of steels.

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

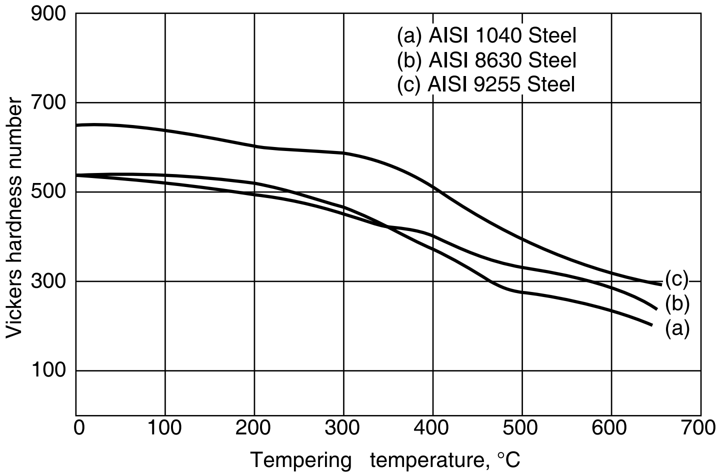


Figure 5.7 Effect of tempering temperature on the hardness of some quenched steels.

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.

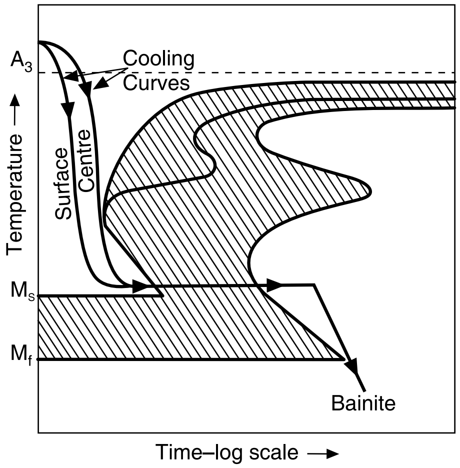


Figure 5.8 Cooling sequence for austempering treatment superimposed on TTT diagram.

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

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.

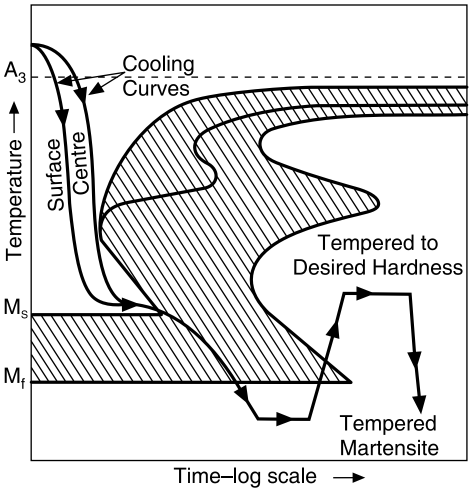


Figure 5.9 Cooling sequence for martempering treatment superimposed on TTT diagram.

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.