the stress corresponding to some specific number of cycles. A typical *S-N* plot for alloy steel heat-treated, medium carbon steel heat-treated, aluminum-copper alloy, and gray cast iron is shown in Fig. 1·27.

Fatigue tests are widely used to study the behavior of materials not only for type and range of fluctuating loads but also for the effect of corrosion, surface conditions, temperature, size, and stress concentration.

1·35 Creep Tests The creep test determines the continuing change in the deformation of a material at elevated temperature when stressed below the yield strength. The results are important in the design of machine parts which are exposed to elevated temperatures. Creep behavior will be discussed in greater detail in Chap. 13.

NONDESTRUCTIVE TESTING

1·36 Introduction A nondestructive test is an examination of an object in any manner which will not impair the future usefulness of the object. Although in most cases nondestructive tests do not provide a direct measurement of mechanical properties, they are very valuable in locating material defects that could impair the performance of a machine member when placed in service. Such a test is used to detect faulty material before it is formed or machined into component parts, to detect faulty components before assembly, to measure the thickness of metal or other materials, to determine level of liquid or solid contents in opaque containers, to identify and sort materials, and to discover defects that may have developed during processing or use. Parts may also be examined in service, permitting their removal before failure occurs.

Nondestructive tests are used to make products more reliable, safe, and economical. Increased reliability improves the public image of the manu-

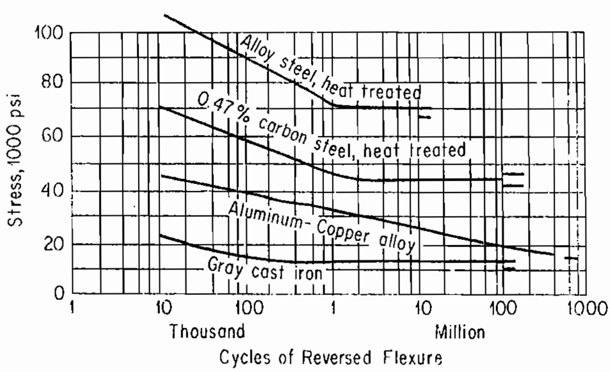


Fig. 1·27 Typical S-N (stress-cycle) diagrams. (From "Metals Handbook," 1948 ed., American Society for Metals, Metals Park, Ohio.)

facturer, which leads to greater sales and profits. In addition, manufacturers use these tests to improve and control manufacturing processes.

Before Wold War II, nondestructive testing was not urgent because of the large safety factors that were engineered into almost every product. Service failures did take place, but the role of material imperfections in such failures was not then fully recognized, and, therefore, little concentrated effort was made to find them. During, and just after, World War II the significance of imperfections to the useful life of a product assumed greater importance. In aircraft design, in nuclear technology, and in space exploration, high hazards and costs have made maximum reliability essential. At the same time, there has been extensive growth of all inspection methods in industrial and scientific applications.

There are five basic elements in any nondestructive test.

1 Source A source which provides some probing medium, namely, a medium that can be used to inspect the item under test.

2 Modification This probing medium must change or be modified as a result of the variations or discontinuities within the object being tested.

3 Detection A detector capable of determining the changes in the probing medium.

4 Indication A means of indicating or recording the signals from the detector.

5 Interpretation A method of interpreting these indications.

While there are a large number of proven nondestructive tests in use, this section will concentrate on the most common methods and on one recent development. The most common methods of nondestructive testing or inspection are:

Radiography
Magnetic-particle inspection
Fluorescent-penetrant inspection
Ultrasonic inspection
Eddy current inspection

1·37 Radiography of Metals The radiography of metals may be carried out by using x-rays or gamma rays—short-wavelength electromagnetic rays capable of going through relatively large thicknesses of metal. Gamma rays may be obtained from a naturally radioactive material such as radium or a radioactive isotope such as cobalt-60. Gamma radiation is more penetrating than that of x-rays, but the inferior sensitivity limits its application. There is no way that the source may be regulated for contrast or variable thickness, and it usually requires much longer exposure times than the x-ray method.

X-rays are produced when matter is bombarded by a rapidly moving stream of electrons. When electrons are suddenly stopped by matter, a

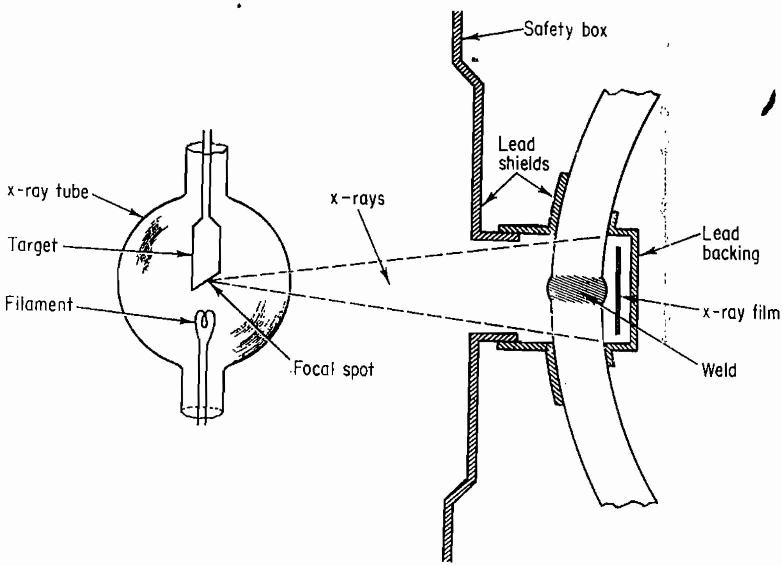
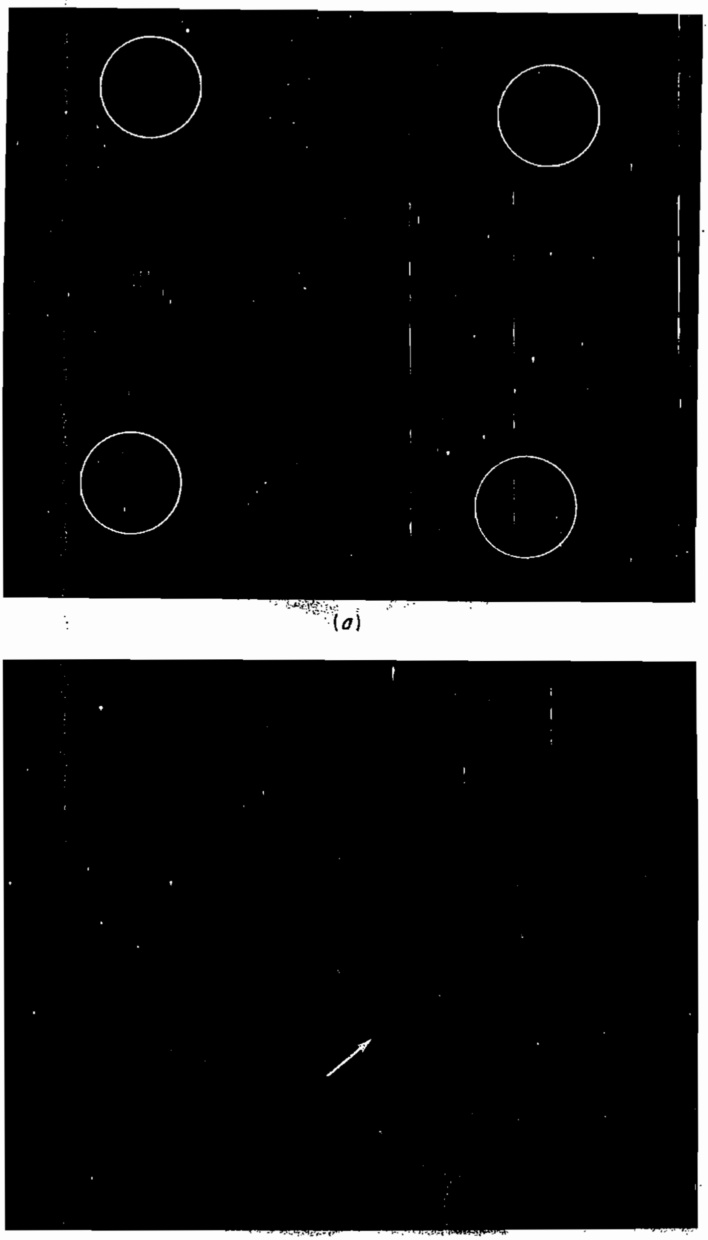


Fig. 1·28 Schematic representation of the use of x-rays for examination of a welded plate. (From "Basic Metallurgy," vol. 2, American Society for Metals, Metals Park, Ohio, 1954.)

part of their kinetic energy is converted to energy of radiation, or x-rays. The essential conditions for the generation of x-rays are (1) a filament (cathode) to provide the source of electrons proceeding toward the target, (2) a target (anode) located in the path of electrons, (3) a voltage difference between the cathode and anode which will regulate the velocity of the electrons striking the target and thus regulate the wavelength of x-rays produced, and (4) a means of regulating tube current to control the number of electrons striking the target. The first two requirements are usually incorporated in an x-ray tube. The use of x-rays for the examination of a welded plate is shown schematically in Fig. 1·28. X-rays are potentially dangerous, and adequate safeguards must be employed to protect operating personnel.

A radiograph is a shadow picture of a material more or less transparent to radiation. The x-rays darken the film so that regions of lower density which readily permit penetration appear dark on the negative as compared with regions of higher density which absorb more of the radiation. Thus a hole or crack appears as a darker area, whereas copper inclusions in aluminum alloy appear as lighter areas (see Fig. 1·29).

While the radiography of metals has been used primarily for the inspection of castings and welded products, it may also be used to measure the thickness of materials. Fig. 1·30 shows a simple radiation thickness gauge.



(a)

(b)

Fig. 1·29 (a) Radiograph of a stainless steel casting; dark spots are shrinkage voids. (b) Radiograph of a brass sand casting; numerous black spots indicate extensive porosity.

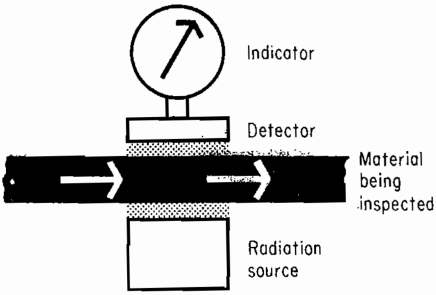


Fig. 1·30 A simple radiation thickness gauge.

The radiation from the source is influenced by the material being tested. As the thickness increases, the radiation intensity reaching the detector decreases. If the response of the detector is calibrated for known thicknesses, the detector reading can be used to indicate the thickness of the inspected material. With a suitable feedback circuit, the detector may be used to control the thickness between predetermined limits.

1·38 Magnetic-particle Inspection (Magnaflux) This is a method of detecting the presence of cracks, laps, tears, seams, inclusions, and similar discontinuities in ferromagnetic materials such as iron and steel. The method will detect surface discontinuities too fine to be seen by the naked eye and will also detect discontinuities which lie slightly below the surface. It is not applicable to nonmagnetic materials.

Magnetic-particle inspection may be carried out in several ways. The piece to be inspected may be magnetized and then covered with fine magnetic particles (iron powder). This is known as the residual method. Or, the magnetization and application of the particles may occur simultaneously. This is known as the continuous method. The magnetic particles may be held in suspension in a liquid that is flushed over the piece, or the piece may be immersed in the suspension (wet method). In some applications, the particles, in the form of a fine powder, are dusted over the surface of the workpiece (dry method). The presence of a discontinuity is shown by the formation and adherence of a particle pattern on the surface of the workpiece over the discontinuity. This pattern is called an *indication* and assumes the approximate shape of the surface projection of the discontinuity. The Magnaglo method developed by the Magnaflux Corporation is a variation of the Magnaflux test. The suspension flowed over the magnetized workpiece contains fluorescent magnetic particles. The workpiece is then viewed under black light, which makes the indications stand out more clearly.

When the discontinuity is open to the surface, the magnetic field leaks out to the surface and forms small north and south poles that attract the

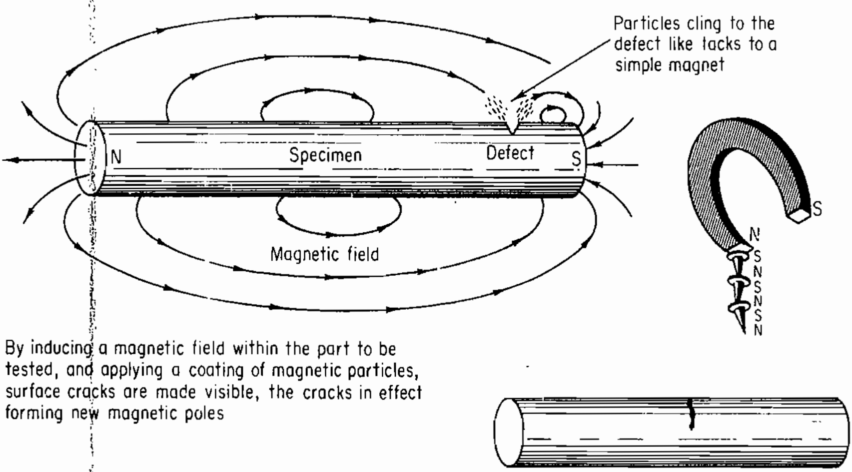


Fig. 1·31 Principle of the Magnaflux test. (Magnaflux Corporation, Chicago, Ill.)

magnetic particles (see Fig. 1·31). When fine discontinuities are under the surface, some part of the field may still be deflected to the surface, but the leakage is less and fewer particles are attracted, so that the indication obtained is much weaker. If the discontinuity is far below the surface, no leakage of the field will be obtained and consequently no indication. Proper use of magnetizing methods is necessary to ensure that the magnetic field set up will be perpendicular to the discontinuity and give the clearest indication.

As shown in Fig. 1·32 for longitudinal magnetization, the magnetic field may be produced in a direction parallel to the long axis of the workpiece by placing the piece in a coil excited by an electric current so that the long axis of the piece is parallel to the axis of the coil. The metal part then becomes the core of an electromagnet and is magnetized by induction from the magnetic field created in the coil. Very long parts are magnetized in steps by moving the coil along the length. In the case of circular magnetization, also shown in Fig. 1·32, a magnetic field transverse to the long axis of the workpiece is readily produced by passing the magnetizing current through the piece along this axis.

Direct current, alternating current, and rectified alternating current are all used for magnetizing purposes. Direct current is more sensitive than alternating current for detecting discontinuities that are not open to the surface. Alternating current will detect discontinuities open to the surface and is used when the detection of this type of discontinuity is the only interest. When alternating current is rectified, it provides a more penetrating magnetic field.

The sensitivity of magnetic-particle inspection is affected by many factors, including strength of the indicating suspension, time in contact with the suspension, time allowed for indications to form, time subject to magnetizing current, and strength of the magnetizing current. Some examples of cracks detectable by Magnaflux or Magnaglo are shown in Fig. 1·33.

All machine parts that have been magnetized for inspection must be put through a demagnetizing operation. If these parts are placed in service without demagnetizing, they will attract filings, grindings, chips, and other steel particles which may cause scoring of bearings and other engine parts. Detection of parts which have not been demagnetized is usually accomplished by keeping a compass on the assembly bench.

1·39 Fluorescent-penetrant Inspection (Zyglo) This is a sensitive nondestructive method of detecting minute discontinuities such as cracks, shrinkage, and porosity that are open to the surface. While this method may be applied to both magnetic and nonmagnetic materials, its primary application

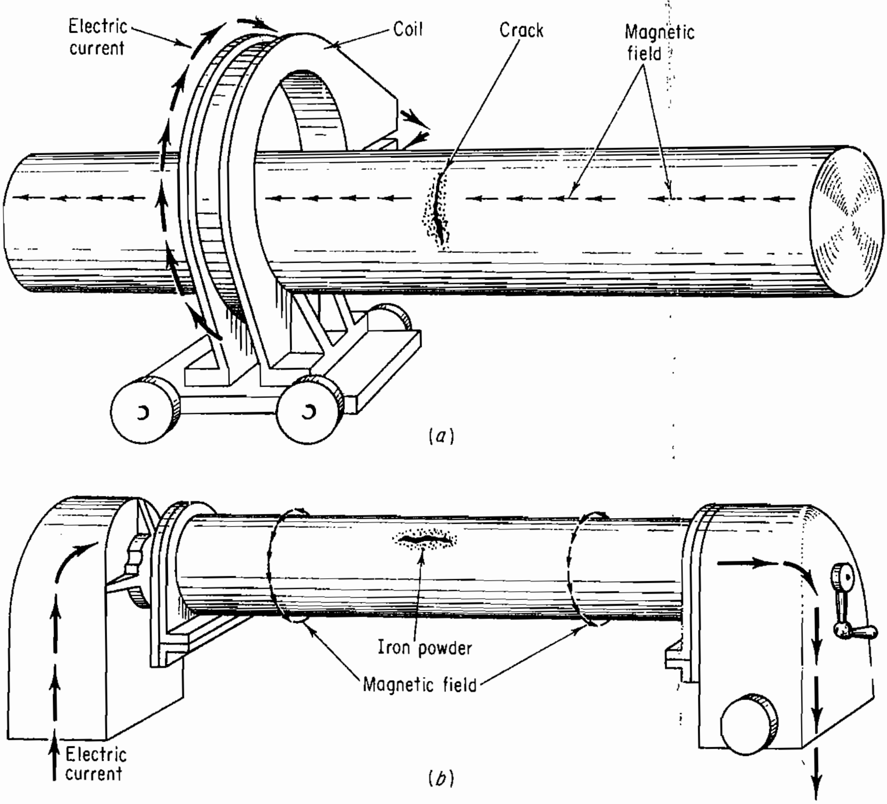
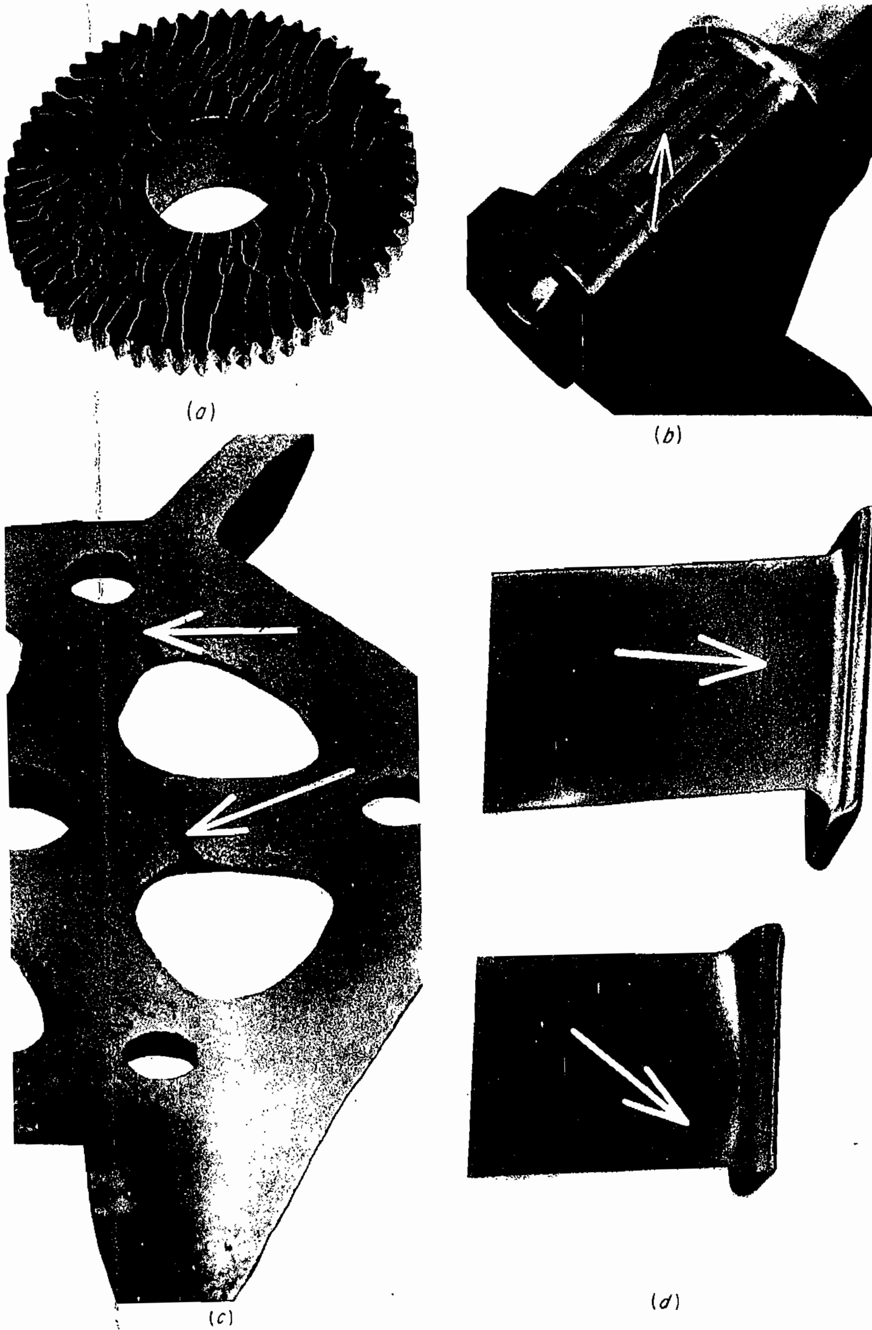


Fig. 1·32 Illustrating two kinds of magnetization: (a) Longitudinal magnetization; (b) circular magnetization. (Magnaflux Corporation, Chicago, Ill.)



(a) (b) (c) (d)

Fig. 1·33 Typical defects revealed by Magnaflux and Magnaglo. (a) Grinding cracks; (b) fatigue crack in an aircraft crankshaft; (c) casting cracks in a lawnmower casting; (d) cracks in critical jet engine blades. (Magnaflux Corporation, Chicago, Ill.)

is for nonmagnetic materials. Penetrant techniques can be used for inspecting any homogeneous material that is not porous, such as metals, glass, plastic, and some ceramic materials.

Parts to be tested are first treated with a penetrant. Penetrants are usually light, oil-like liquids which are applied by dipping, spraying, or brushing, or in some other convenient manner. The liquid penetrant is drawn into cracks and other discontinuities by strong capillary action. After the penetrant has had time to seep in, the portion remaining on the surface is removed by wiping or washing. This leaves the penetrant in all surface-connected discontinuities. The test part is now treated with a dry powder or a suspension of powder in a liquid. This powder or developer acts like a sponge drawing the penetrant from the defect and enlarging the size of the area of penetrant indication. In order for the inspection process to be completed, the penetrant must be easily observed in the developing powder. One method is to use contrasting colors for the penetrant and developer. A combination of white developer and red penetrant is very common.

Another method is to use a fluorescent penetrant. The major steps in fluorescent penetrant inspection are shown in Fig. 1·34. The steps are exactly the same as described previously except that the penetrating liquid contains a material that emits visible light when it is exposed to ultraviolet radiation. Lamps that emit ultraviolet are called black lights, because the visible light they might normally emit is stopped by a filter, making them appear black or dark purple. When the part to be inspected is viewed under black light, the defect appears as a bright fluorescing mark against a black background. Figure 1·35 shows a nonmagnetic stainless steel valve body being tested by fluorescent penetrant.

Fluorescent penetrant inspection is used to locate cracks and shrinkage in castings, cracks in the fabrication and regrinding of carbide tools, cracks and pits in welded structures, cracks in steam- and gas-turbine blading,

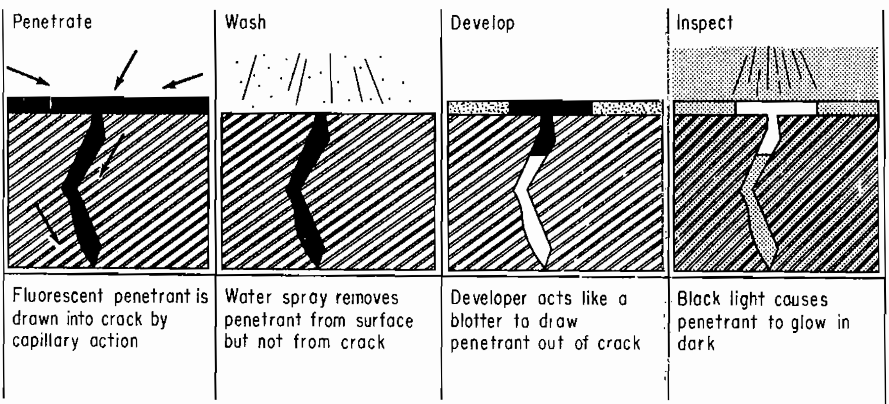


Fig. 1·34 Major steps in fluorescent-penetrant inspection.

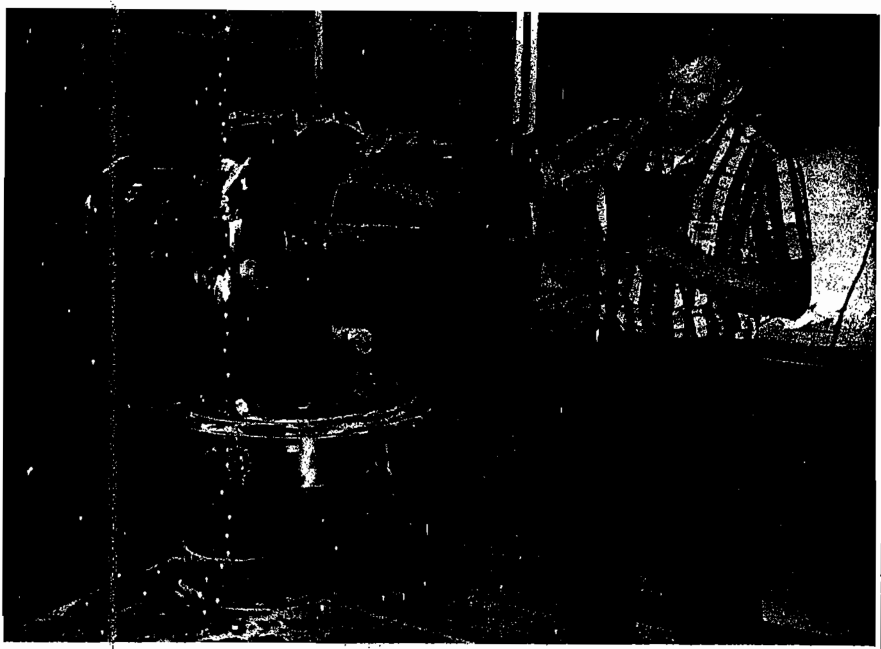


Fig. 1·35 Nonmagnetic stainless steel valve body being inspected by fluorescent penetrant. (Magnaflux Corporation, Chicago, Ill.)

and cracks in ceramic insulators for spark plugs and electronic applications.

1·40 Ultrasonic Inspection The use of sound waves to determine defects is a very ancient method. If a piece of metal is struck by a hammer, it will radiate certain audible notes, of which the pitch and damping may be influenced by the presence of internal flaws. However, this technique of hammering and listening is useful only for the determination of large defects.

A more refined method consists of utilizing sound waves above the audible range with a frequency of 1 to 5 million Hz (cycles per second)—hence the term ultrasonic. Ultrasonics is a fast, reliable nondestructive testing method which employs electronically produced high-frequency sound waves that will penetrate metals, liquids, and many other materials at speeds of several thousand feet per second. Ultrasonic waves for nondestructive testing are usually produced by piezoelectric materials. These materials undergo a change in physical dimension when subjected to an electric field. This conversion of electrical energy to mechanical energy is known as the *piezoelectric* effect. If an alternating electric field is applied to a piezoelectric crystal, the crystal will expand during the first half of the cycle and contract when the electric field is reversed. By varying the

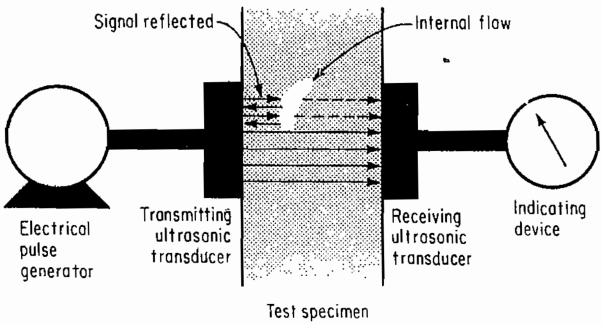


Fig. 1·36 The through-transmission and pulse-echo methods of ultrasonic inspection.

frequency of the alternating electric field, we can vary the frequency of the mechanical vibration (sound wave) produced in the crystal. Quartz is a widely used ultrasonic transducer. A transducer is a device for converting one form of energy to another.

Two common ultrasonic test methods, the through-transmission and the pulse-echo methods, are illustrated in Fig. 1·36. The through-transmission method uses an ultrasonic transducer on each side of the object being inspected. If an electrical pulse of the desired frequency is applied to the transmitting crystal, the ultrasonic waves produced will travel through the specimen to the other side. The receiving transducer on the opposite side receives the vibrations and converts them into an electrical signal that can be amplified and observed on the cathode-ray tube of an oscilloscope, a meter, or some other indicator. If the ultrasonic wave travels through the specimen without encountering any flaw, the signal received is relatively large. If there is a flaw in the path of the ultrasonic

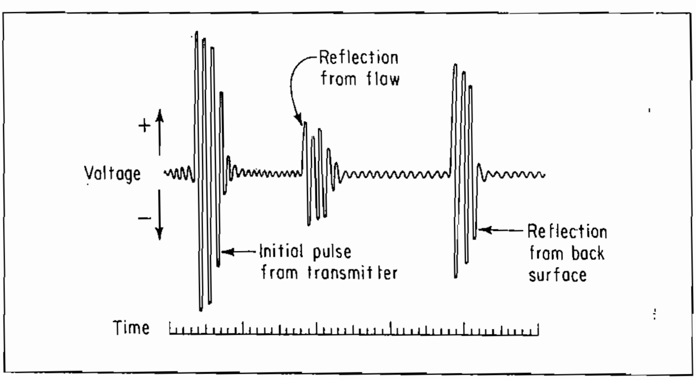


Fig. 1·37 Oscilloscope pattern for the pulse-echo method of ultrasonic inspection.

wave, part of the energy will be reflected and the signal received by the receiving transducer will be reduced.

The pulse-echo method uses only one transducer which serves as both transmitter and receiver. The pattern on an oscilloscope for the pulse-echo method would look similar to that shown in Fig. 1·37. As the sound wave enters the material being tested, part of it is reflected back to the crystal where it is converted back to an electrical impulse. This impulse is amplified and rendered visible as an indication or pip on the screen of the oscilloscope. When the sound wave reaches the other side of the material, it is reflected back and shows as another pip on the screen farther to the right of the first pip. If there is a flaw between the front and back surfaces of the material, it will show as a third pip on the screen between the two indications for the front and back surfaces. Since the indications on the oscilloscope screen measure the elapsed time between reflection of the pulse

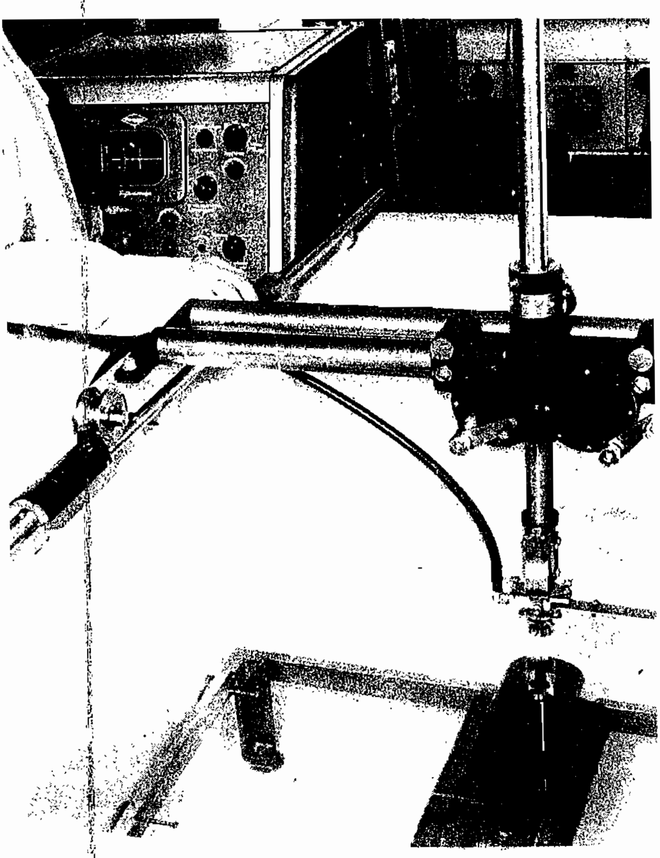


Fig. 1·38 Ultrasonic inspection by immersion in a water tank. (Fansteel Metallurgical Corporation)

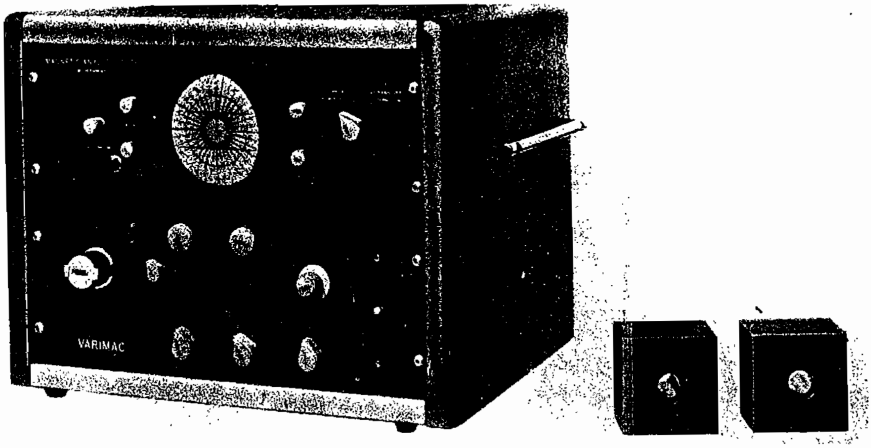


Fig. 1·39 An eddy current tester and two encircling coils. (Magnetic Analysis Corporation, Mount Vernon, N.Y.)

from the front and back surfaces, the distance between indications is a measure of the thickness of the material. The location of a defect may therefore be accurately determined from the indication on the screen.

In general, smooth surfaces are more suitable for the higher-frequency testing pulse and thereby permit detection of smaller defects. Proper transmission of the ultrasonic wave has a great influence on the reliability of the test results. For large parts, a film of oil ensures proper contact between the crystal searching unit and the test piece. Smaller parts may be placed in a tank of water, oil, or glycerin. The crystal searching unit transmits sound waves through the medium and into the material being examined (Fig. 1·38). Close examination of the oscilloscope screen in this picture shows the presence of three pips. The left pip indicates the front of the piece, the right pip the back of the piece, and the smaller center pip is an indication of a flaw.

Ultrasonic inspection is used to detect and locate such defects as shrinkage cavities, internal bursts or cracks, porosity, and large nonmetallic inclusions. Wall thickness can be measured in closed vessels or in cases where such measurement cannot otherwise be made.

1·41 Eddy Current inspection Eddy current techniques are used to inspect electrically conducting materials for defects, irregularities in structure, and variations in composition. In eddy current testing, a varying magnetic field is produced if a source of alternating current is connected to a coil. When this field is placed near a test specimen capable of conducting an electric current, eddy currents will be induced in the specimen. The eddy currents, in turn, will produce a magnetic field of their own. The detection unit will measure this new magnetic field and convert the signal into a volt-

TABLE 1·8 Major Nondestructive Testing Methods

INSPECTION METHOD	WHEN TO USE	WHERE TO USE
Eddy current	Measuring variations in wall thickness of thin metals or coatings; detecting longitudinal seams or cracks in tubing; determining heat treatments and metal compositions for sorting.	Tubing and bar stock, parts of uniform geometry, flat stock, or sheets and wire.
Radiography: x-rays	Detecting internal flaws and defects; finding welding flaws, cracks, seams, porosity, holes, inclusions, lack of fusion; measuring variations in thickness.	Assemblies of electronic parts, casting, welded vessels; field testing of welds; corrosion surveys; components of nonmetallic materials.
Gamma x-rays	Detecting internal flaws, cracks, seams, holes, inclusions, weld defects; measuring thickness variations.	Forgings, castings. tubing, welded vessels; field testing welded pipe; corrosion surveys.
Magnetic particle	Detecting surface or shallow subsurface flaws, cracks, porosity, nonmetallic inclusions, and weld defects.	Only for ferromagnetic materials; parts of any size, shape, composition, or heat treatment.
Penetrant	Locating surface cracks, porosity, laps, cold shuts, lack of weld bond, fatigue, and grinding cracks.	All metals, glass, and ceramics, castings, forgings, machined parts, and cutting tools; field inspections.
Ultrasonic pulse echo	Finding internal defects, cracks, lack of bond, laminations, inclusions, porosity; determining grain structure and thicknesses.	All metals and hard nonmetallic materials; sheets, tubing, rods, forgings, castings; field and production testing; inservice part testing; brazed and adhesive-bonded joints.

* Metals Progress Data Sheet, August 1968, American Society for Metals, Metals Park, Ohio.

ADVANTAGES	LIMITATIONS
High speed, noncontact, automatic.	False indications result from many variables; only good for conductive materials; limited depth of penetration.
Provides permanent record on film; works well on thin sections; high sensitivity; fluoroscopy techniques available; adjustable energy level.	High initial cost; power source required; radiation hazard; trained technicians needed.
Detects variety of flaws; provides a permanent record; portable; low initial cost; source is small (good for inside shots); makes panoramic exposures.	One energy level per source; radiation hazard; trained technicians needed; source loses strength continuously.
Economical, simple in principle, easy to perform; portable (for field testing); fast for production testing.	Material must be magnetic; demagnetizing after testing is required; power source needed; parts must be cleaned before finishing.
Simple to apply, portable, fast, low in cost; results easy to interpret; no elaborate setup required.	Limited to surface defects; surfaces must be clean.
Fast, dependable, easy to operate; lends itself to automation, results of test immediately known; relatively portable, highly accurate, sensitive.	Requires contact or immersion of part; Interpretation of readings requires training.