

CHAPTER 15

METALLURGY AND HEAT TREATMENT

CHAPTER LEARNING OBJECTIVES

Upon completing this chapter, you should be able to do the following:

- *Explain the internal structures of metals.*
- *Identify and explain the use of heat-treating equipment.*
- *Explain the principles of heat treating.*
- *Explain the heat treatment of metals.*
- *Identify heat-treating problems.*
- *Identify and explain hardness tests.*

As a Machinery Repairman, you work with many different types of metals and alloys. The more knowledge you have of metals and alloys, the better you will be able to perform your repair and maintenance duties. The information you have already learned about the characteristics of metals and alloys in chapter 3 will help you better understand the theory of metallurgy and heat treatment.

There have been many books written on metallurgy and heat treatment. This chapter will only be an overview. For more detailed information of the theory and of metallurgy and heat treatment, consult a machinist handbook or any textbook on physical metallurgy.

As with any shop equipment you must observe all posted safety precautions. Review your equipment operators manual for safety precautions and any chapters of *Navy Occupational Safety and Health (NAVOSH) Program Manual for Forces Afloat*, OPNAV instruction 5100.19B, which pertain to the equipment you will be operating.

Metallurgy is the art or science of separating metals from their ores, making and compounding alloys, and working or heat-treating metals to give them certain desired shapes or properties. Metallurgy has been broken down into three branches—chemical metallurgy, physical metallurgy, and mechanical metallurgy.

CHEMICAL METALLURGY deals with the reduction of metals from their ores and the creation of alloys by changing the chemical structure of the base metals. For example, steel is made from iron, which is produced from iron ore. During this process, coke is used as a fuel, and limestone is used as a fluxing agent.

PHYSICAL METALLURGY deals with the nature, structure, and physical properties of metals and alloys. The subject of physical metallurgy includes metallography (study of metals with a microscope), mechanical testing, and heat treatment, which we will discuss later in this chapter.

MECHANICAL METALLURGY deals with the working and shaping of metals through operations such as machining, casting, and forging.

STRUCTURE OF METAL

Throughout your career as a Machinery Repairman, you have become familiar with the physical properties, such as hardness, brittleness, malleability, and ductility, associated with various metals. These properties of metal are directly related to the internal, or atomic, structure of the metals. This section will explain to you how various arrangements of atoms result in these and other properties.

Metals in liquid state have a noncrystalline structural form. The crystals in solid metal are called

GRAINS (irregularly shaped crystals developed from the converging lattices). These irregularly shaped crystals are formed as the metal cools and changes from a liquid state to a solid state. This change of state is called **FREEZING** or **SOLIDIFICATION**. As the metal freezes, its atoms lose the energy of motion they had in the metal's liquid state. The slow-moving atoms become attached to one another, usually in one of four predictable patterns, depending on the type and composition of the metal. These patterns are shown in figure 15-1 and will be discussed in greater detail later in this chapter.

CRYSTALS AND GRAINS

The first groups of atoms to form a pattern create what are called **UNIT CELLS**, or **GRAIN NUCLEI**. The unit cell is the basic building block of the metal. Many unit cells connect in the same pattern that makes up the unit cell and forms a **CRYSTAL**. Crystals then connect to form the metal's **CRYSTALLINE STRUCTURE**.

Under ideal conditions, crystals will be perfectly shaped. Under real world conditions, however, crystal shapes are usually distorted. These typically distorted crystals, or grains, form what is known as the **GRAIN STRUCTURE** of the metal.

The surface of a metal does not indicate its internal grain structure. However, when the metal is fractured, structure will show on the fractured surface. The size of the grains depends upon a number of factors, including the nature of the metal, the temperature to which it is heated, the length of time it is held at a specific temperature, and the rate at which it is cooled from a liquid to a solid. In general, the quicker a metal solidifies, the smaller the grains will be.

The line-shaped areas between adjacent grains are known as **GRAIN BOUNDARIES**. A high state of stress exists at the grain boundaries, due to a mismatch of each lattice. When a metal is deformed, the atoms in the structure slide over one another along certain planes called **SLIP PLANES**. Slip planes are the planes of least resistance to an applied force. Metals with large grains have long slip planes, allowing deformation to occur easily. On the other hand, metals with small grains have short slip planes, making deformation difficult. The plane along which a metal separates when subjected to an applied force is called a **CLEAVAGE PLANE**.

GRAIN SIZE is determined by the number of grains per square inch in a metal magnified 100 times normal size. The number of grains that form depends upon the

rate of cooling from a molten state to a solid state. If a metal cools rapidly, many grains will form, and the size of the grain will be smaller. The smaller the grain, the shorter the slip planes, and the harder and stronger the metal will be. The opposite will occur if the metal is cooled slowly. Grain size, therefore, directly affects the physical and the mechanical properties of metal and can be changed by various heat treatment methods.

Some grains may be seen with the naked eye. Others can only be seen under magnification. The study of the microscopic structure of metals is called **metallography**. Instruments used to magnify grains are called **METALLURGICAL MICROSCOPES**. These microscopes can magnify grains several hundred times their actual size. Additional magnification can be gained through the use of an **ELECTRON MICROSCOPE**, which can magnify up to many thousand times actual size.

Metallurgical microscopes equipped with devices for photographing the microstructure of metals are known as **METALLOGRAPHIC MICROSCOPES**.

SPACE LATTICES

The arrangement of atoms (the most basic unit of matter) in a crystal can be shown by a graphic illustration called a **SPACE LATTICE**. Each of the four line-dot drawings in figure 15-1 is a space lattice. The dots represent atoms, while the lines make the shape easier to visualize.

The space lattices of most metals can be identified as one of the following four types:

1. Body-centered cubic
2. Face-centered cubic
3. Body-centered tetragonal
4. Hexagonal close-packed

Body-Centered Cubic Lattice

The body-centered cubic lattice (fig. 15-1, view A) contains nine atoms, one at each corner of the cube and one at the center of the cube. In this arrangement, each atom is held in position by the force of the remaining eight atoms.

Metals that have the body-centered cubic arrangement are usually stronger, but harder to work cold, than metals that have a face-centered cubic arrangement (discussed next). Some of the body-centered metals are tungsten, molybdenum (MO), vanadium (V),

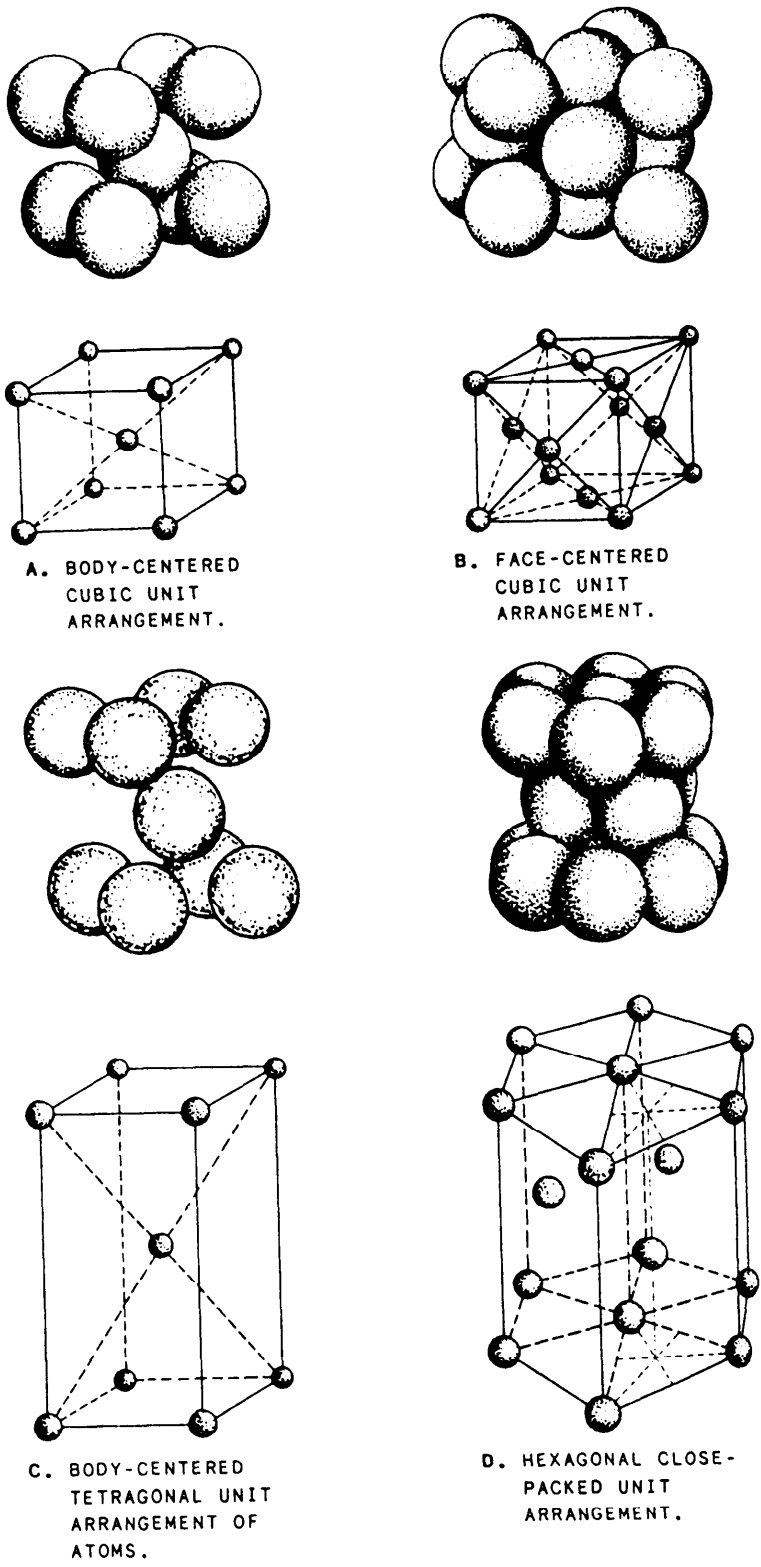


Figure 15-1.—Atom arrangement in a space lattice system.

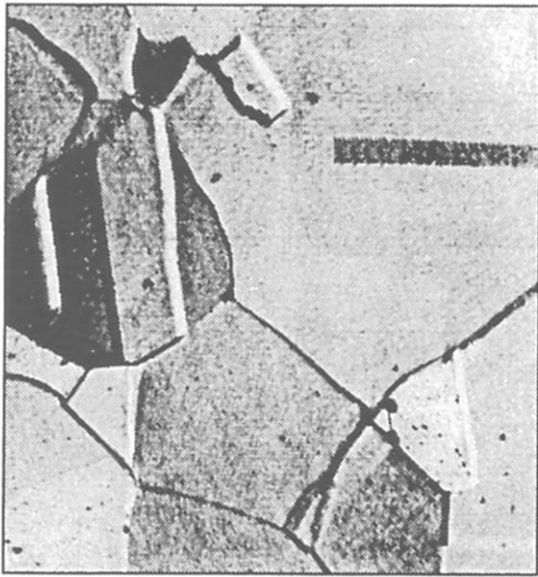


Figure 15-2.—Microscopic structure called austenite magnified 500 times.



Figure 15-3.—Microscopic structure called martensite magnified 2,500 times.

wolfram(W), columbium, and ferrite (or alpha iron) below its hardening temperature.

Face-Centered Cubic Lattice

The face-centered cubic lattice (fig. 15-1, view B) contains 14 atoms, one at each corner of the cube and one at the center of each face of the cube. In this arrangement the atoms are more dense (closely packed) than in the body-centered arrangement. Metals that have a face-centered cubic lattice structure include nickel, aluminum, copper, lead, gold, and silver.

When steel is heated to the hardening temperature, the space lattice units in the grain structure transform from the body-centered cubic form to the face-centered cubic form. In this form it is called austenite or gamma iron (fig. 15-2). At the elevated temperature at which austenite forms, the carbon in steel decomposes from its combined state as cementite (iron carbide) to free carbon. The free carbon then dissolves into the solid hot iron to form a solid solution of uniformly dispersed carbon in iron. This form of iron will dissolve up to a maximum of 2 percent carbon. In contrast, the body-centered (alpha) form of iron (ferrite) will dissolve a maximum of about 0.05 percent carbon.

Body-Centered Tetragonal Lattice

The body-centered tetragonal lattice (fig. 15-1, view C) contains nine atoms and looks like a body-centered cubic lattice stretched in one dimension.

Recall that steel heated to its hardening temperature becomes a face-centered cubic material called austenite. If austenite is quenched at its hardening temperature and cooled rapidly to a temperature of less than 400°F, it will change into MARTENSITE (fig. 15-3) in a body-centered tetragonal arrangement. During the transformation from austenite to martensite, the steel becomes supersaturated with carbon. Because of its extremely high carbon content and the distortion of its structure, martensite is the hardest and most brittle form of steel.

Hexagonal Close-Packed Lattice

The hexagonal close-packed lattice (fig. 15-1, view D) contains 17 atoms. This structure does not have the high degree of symmetry evident in the cubic structure, and as a result this type of structure is very difficult to deform. Metals that have this structure have little plasticity and are very difficult to work cold. Some examples of this type of metal are cadmium (Cd), cobalt (Co), magnesium (Mg), titanium (Ti), zinc (Zn), and beryllium (Be).

Of the four lattices mentioned, the cubic types are the most important. If you understand the role these structures play in the heat-treating process, you will be able to understand better how desired characteristics are given to various forms of steel. The relationship between atomic structure, carbon content, and

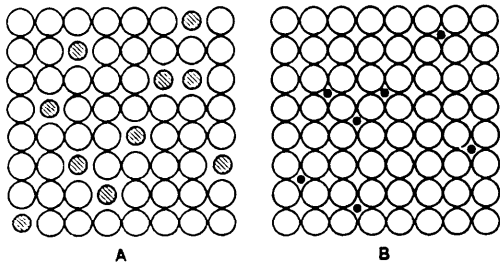


Figure 15-4.—Space lattices of two forms of solid solution.
A. Atoms of one element replace atoms of another element.
B. Atoms of one element fit between atoms of another element.

characteristics of the metal will be discussed later in this chapter.

ALLOTROPY

Some metals may exist in more than one lattice form at a particular temperature. When a metal exists in more than one lattice form it is said to be **ALLOTROPIC** in nature. A change from one lattice structure to another is called an **allotropic change**. The temperature at which allotropic changes take place is called the **TRANSFORMATION TEMPERATURE**. The changes from one form of iron to another are not often instantaneous at a specific temperature. Rather, they generally take place within a range of temperatures called the **TRANSFORMATION TEMPERATURE RANGE**. The temperature of the lower end is called the lower transformation temperature and the temperature of the upper end is called the upper transformation temperature.

INTERNAL STRUCTURE OF METALS

In alloys (substances composed of two or more metals or of a metal and a nonmetal), the internal structure may be in the form of crystals of pure metals, a solid solution, intermetallic compounds, mechanical mixtures, or some combination of these structures.

In a solid solution, the elements are completely dissolved in each other, with the atoms of one element fitting into and forming parts of the space lattice of the other element. Figure 15-4 illustrates two ways in which solid solutions may exist. The atoms of one element may fit into the spaces between the atoms of another element, as indicated in figure 15-4, view B; or the atoms of one element may replace the atoms of another element in the space lattice, as indicated in figure 15-4, view A.

A solid solution in a metal is similar to many solutions you are familiar with. For example: water dissolves salt. The result is a salty liquid. The taste of the salt and the wetness of the water have not changed. As you see, there has been no change of individual properties. However, you cannot see or distinguish which is water and which is salt. The loss of individual identity is apparent. An example of a familiar solid solution is Monel metal. You know from experience that Monel is tough, and yet soft and plastic; the toughness of nickel and the plasticity of copper have been combined in the form of a metallic solid solution.

The individual elements lose their identity in a solid solution. A polished cross section of a material that consists of only one solid solution shows all grains to be of the same nominal composition.

Ferrite and austenite are two solid solutions that are important constituents of steel. **FERRITE** is the name given to a solid solution of alpha iron and carbon. **AUSTENITE** is the term for a solid solution of gamma iron and carbon. Carbon is only slightly soluble in alpha iron but is quite soluble in gamma iron. Alpha iron at room temperature can hold only about 0.007 percent carbon in solid solution. At a temperature of 2,065°F, gamma iron can hold up to about 2 percent carbon in solid solution.

As an introduction to compounds, consider ordinary table salt. The two poisonous elements, sodium and chlorine, are combined chemically to create a new and different substance, sodium chloride, or table salt. Salt, with its own identity and properties, does not resemble either sodium or chlorine.

Similarly, **INTERMETALLIC COMPOUNDS** are combinations of a metal and some other substance such as carbon or sulfur. Under certain conditions, intermetallic compounds form and a new substance with new properties is created in very much the same manner but on a more complicated basis. Perhaps the most important thing to remember about the intermetallic compounds is the loss of identity and the change in properties of the combining elements. The heat treater quite often uses the change in properties offered by compound formations in metals to create compounds with certain desired properties.

One intermetallic compound of great importance in ferrous alloys is known as **IRON CARBIDE** or **CEMENTITE**. This is an extremely hard and brittle compound that is formed by the combination of iron (a metal) and carbon (a metalloid). The formula for iron carbide, or cementite, is Fe_3C . This formula shows that three atoms of iron combine with one atom of carbon to produce one molecule of iron carbide, or cementite

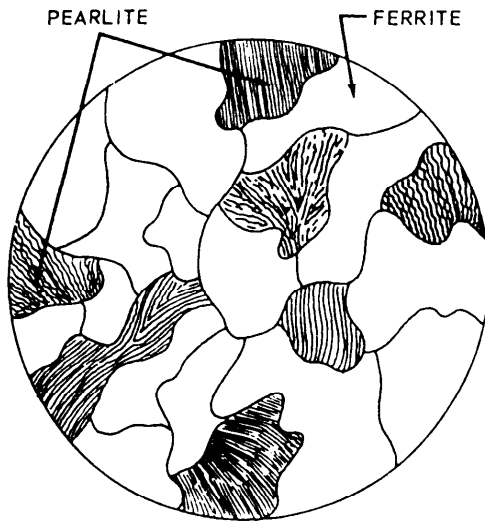


Figure 15-5.—Typical structure of low-carbon steel.

The structure of an alloy is described as being a **MECHANICAL MIXTURE** when two or more structural forms are mixed together but are still separately distinguishable. A mechanical mixture of an alloy is comparable—though on a smaller scale—to the mixture of sand and gravel in concrete.

One of the most important mechanical mixtures that occurs in many steels is known as **PEARLITE**. Pearlite, so called because it has a pearly luster when seen under a microscope, is an intimate mechanical mixture of ferrite and cementite in alternate plates or layers. Ferrite is a solid solution, and cementite or iron carbide is an intermetallic compound; in pearlite, the two are closely mixed to form a characteristically layered structure. When the entire structure of the alloy is in the form of pearlite, the composition is referred to as the **EUTECTOID COMPOSITION**. The pearlitic structure is called the **EUTECTOID** or the **EUTECTOID STRUCTURE**.

The internal structure of an alloy may show various combinations of pure metals, solid solutions, intermetallic compounds, and mechanical mixtures. Many of the combinations that are important in steels and other alloys are the result of heating and cooling of the alloy. Figure 15-5 shows, very much enlarged, a typical combination that occurs when plain-carbon steel containing less than 0.83 percent carbon is heated to a certain temperature and then cooled slowly. This combination consists of the solid solution ferrite and the mechanical mixture pearlite, each in crystal form, distributed throughout the alloy. The relative proportions of ferrite and pearlite in this combination depend largely upon the carbon content of the alloy.

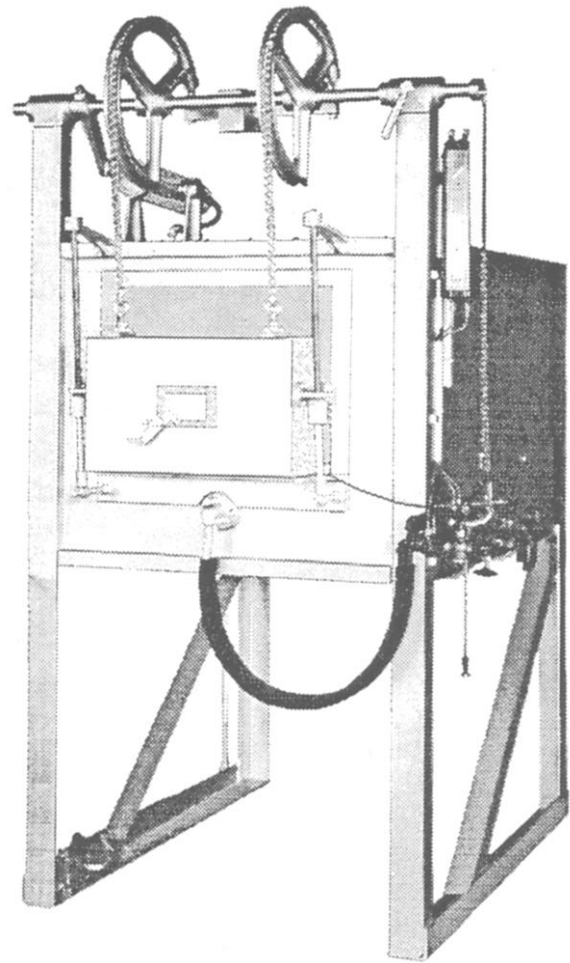


Figure 15-6.—Controlled atmosphere electric furnace used for heat-treating.

HEAT-TREATING EQUIPMENT

The equipment required for heat-treating consists of furnaces or other heating devices, quenching baths or other cooling devices, temperature controls and indicators, and other controls and indicators required for the proper operation of the equipment or for the control of the process. In addition, heat-treating equipment includes tongs and other devices for handling and holding the work while it is being heated or cooled.

Because heat-treating equipment varies so widely, it is not practical to describe or to give operating instructions for different types in this course. The equipment described here is typical of heat-treating equipment you may be required to use, but it does not include all possible types of equipment. If you are required to heat-treat metals, find out all you can about the equipment that is available before you begin to use it. The instructions furnished by the manufacturer are usually your best—and sometimes only—source of authoritative information on a specific item of heat-treating equipment.

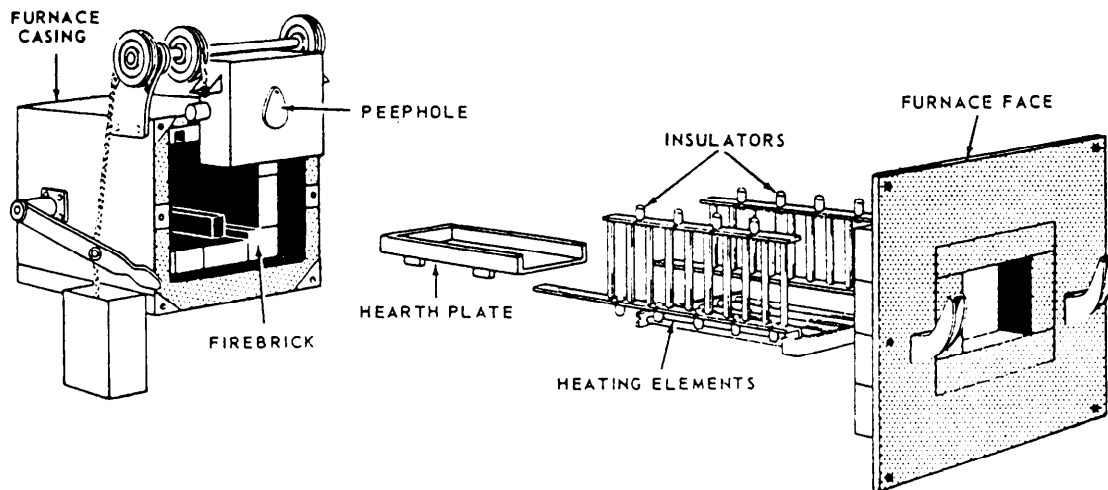


Figure 15-7.—Exploded view of electric furnace used for heat-treating.

HEATING EQUIPMENT

Equipment designed for the heating of metals includes electric furnaces, fuel-fired furnaces, bath furnaces, and devices for the measurement and control of temperature. Improvised heating devices may include oxyacetylene torches, Hauck burners, forges, and temporary ovens constructed of firebrick and sheet asbestos. We will discuss electric furnaces since they are what most Machinery Repairmen will be using.

The gases that circulate through the furnace heating chamber and surround the metal as it is being heated make up the **FURNACE ATMOSPHERE**. By controlling the composition of the furnace atmosphere, you can produce the type of atmosphere best suited for the heating of a particular type of metal. Furnace atmospheres are generally classified as being oxidizing, reducing, or neutral.

An **OXIDIZING ATMOSPHERE** exists when excess air is circulated through the furnace. Some electric furnaces are designed to operate with an oxidizing atmosphere at all times. An oxidizing atmosphere is indicated by bright, clean walls and a clear, transparent atmosphere in the furnace. Metals heated in an oxidizing atmosphere occasionally develop films of metal oxides (scale) on their surfaces. In some cases, this is undesirable; but in other cases, it is desirable because it tends to prevent further decarburization of the metal. Decarburization is a term used to describe the loss of carbon from the surface of ferrous metals with consequent softening of the material.

A **REDUCING ATMOSPHERE** tends to remove oxygen from the surface of the metal. A reducing atmosphere is often desirable in heat treatment since it tends to prevent oxide formation and other surface deterioration. If decarburization of steel is to be

avoided, however, a neutral atmosphere rather than a reducing or oxidizing atmosphere is used.

A **NEUTRAL ATMOSPHERE** is neither oxidizing nor reducing because it contains no oxygen (oxidizing agent) and no carbon monoxide (reducing agent). In reality, other factors often tend to produce either oxidation or decarburization; therefore, an atmosphere that is described as neutral may not always be totally neutral.

The furnace atmosphere may be the result of the deliberate introduction of a gas or a mixture of gases into the heating chamber. When gases are deliberately introduced into the heating chamber for the purpose of controlling the atmosphere, the furnace is said to have a **CONTROLLED** or **PROTECTIVE ATMOSPHERE**.

Electric Furnaces

Electric furnaces with a controlled atmosphere are frequently used for heat-treating on repair ships and tenders. Quite often two such units are used on the same ship. One is a relatively low-temperature furnace used for preheating or tempering, and the other is a higher temperature furnace used for hardening. Both types are equipped with control devices for regulating temperature. The high-temperature furnace may also be equipped with rheostats used to increase the rate of heating. A typical electric furnace for shipboard use is shown in figure 15-6. An exploded view of a slightly different type of electric furnace is shown in figure 15-7.

The outer casing of the furnace is usually made of sheet steel. Just inside the casing is a layer of insulating material, such as mica, spun glass, or asbestos. Inside this insulating material is a lining of refractory material, such as firebrick and insulating brick. The refractory lining insulates the furnace, helps maintain the required

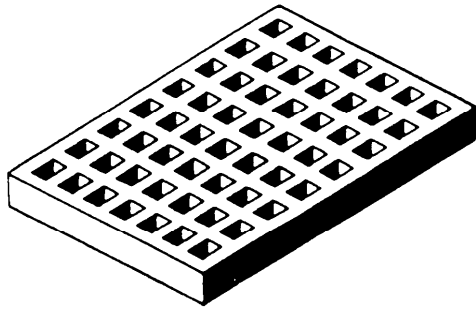


Figure 15-8.—Grid for heat-treating furnace.

high temperatures, and supports the heating elements and the hearth plate.

Hearth plates are placed on the bottom of the heating chamber to support the pieces being heated. Hearth plates must withstand high temperatures without sagging or scaling. They are often made of a special nickel-chromium, heat-resistant alloy. If the furnace is designed for the heat treatment of high-speed steels, the hearth plate may be made of a carbon and silicon.

Grids, usually made of iron-chromium-nickel alloy, keep heavy or long sections of material off the hearth plate. The use of grids ensures more uniform heating of the material and tends to prevent warping. A grid for an electric furnace is shown in figure 15-8.

A special type of electric furnace known as an AIR-CIRCULATING FURNACE is sometimes used for stress-relieving and tempering. Air-circulating furnaces are relatively low-temperature units, usually designed to operate at temperatures ranging from 275° to 1,250°F. Temperature control is both accurate and rapid. The maximum temperature variation is seldom more than plus or minus 5°F, and very rapid changes to a higher or lower temperature are possible.

Temperature Measurement and Control

The measurement and control of temperature are extremely important in all heat-treating processes. Modern heat-treating furnaces are equipped with various devices for indicating (and in some cases recording) temperatures. Most furnaces are also equipped with temperature controllers.

The most commonly used device for measuring the temperature in a heat-treating furnace is the THERMOELECTRIC PYROMETER. This instrument (fig. 15-9) consists of a thermocouple, an extension lead, and an indicating unit. The indicating unit is calibrated in degrees Fahrenheit or Centigrade.

Some pyrometers merely indicate the temperature; others indicate it and record it. Most electric furnaces are equipped with pyrometers that are controllers as

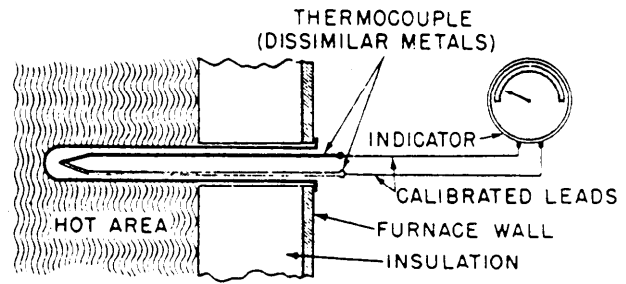


Figure 15-9.—Thermoelectric pyrometer used in heat-treating furnace.

well as measuring devices. This type of instrument can be set to develop and maintain any desired temperature within the limits of the furnace design.

If you are using improvised heat-treating equipment, you will probably not have any accurate way of measuring temperature and will have to improvise methods for determining temperature.

It is possible to estimate the temperature of ferrous metals by noting the color changes that occur when the material is heated. This method is not practical for nonferrous metals since most nonferrous metals melt before they show a color change. At best, the color method of judging temperatures is guesswork. Nonetheless, you should develop some skill in using this technique. It may be the only method you have to estimate temperature when you do not have adequate heat-treating equipment.

The best way to learn to judge the temperature of ferrous metal by color is by heating small samples of clean, polished steel under controlled conditions. This way you can check the color of the sample against the actual temperature. Also, study the color charts that relate color and temperature. Your perception of the colors will be affected by the color and intensity of the light in the furnace or in the room where you are working. Use standard lighting conditions, if possible, when you must estimate the temperature of a metal by observing the color. Charts are available in various handbooks and textbooks on metals. Table 15-1 is a rough guide to the color-temperature relationships of steel.

At temperatures below those given in table 15-1) another type of color determination can be made. If steel is thoroughly cleaned and polished, the surface will appear to change color as the material is heated. An oxide film forms on the polished surface as the steel is heated, and the oxide color corresponds to a certain temperature. Some oxide colors for steel are given in table 15-2.

Table 15-1.—Relationship Between Color and Temperature of Steel

Color	Approximate Temperature (°F)
Faint red, visible in darkness	750
Faint red, visible in daylight	900
Blood red.	1050
Dark cherry	1075
Medium red	1250
Cherry or full red	1375
Bright red	1550
Salmon	1650
Grange	1725
Lemon	1825
Light yellow	1975
White.	2200
Dazzling white	<u>2350</u>

Table 15-2.—Oxide Colors for Steel of Various Temperatures

Color	Approximate Temperature (°F)
Pale yellow.	428
Straw	446
Golden yellow	469
Brown	491
Brown dappled with purple	509
Purple	531
Dark blue	550
Bright blue	567
Pale blue	<u>610</u>

Table 15-3.—Average Cooling Rates of Some Liquids and Gases Used for Cooling, as Compared with Cooling Rate of Water at 65°F

Cooling Medium	Cooling Rate, as Compared to Water at 65°F
10-percent brine solution at 65°F	1.96
10-percent caustic soda solution	1.38
Water at 65°F	1.00
Prepared oil	0.44
Fuel oil	0.36
Cottonseed oil	0.36
Neatsfoot oil	0.33
Sperm oil	0.33
Fish oil	0.31
Castor oil	0.29
Machine oil	0.22
Lard oil	0.19
Circulated oil	0.032
Still air	0.015

Special temperature-indicating crayons or other materials may be available for use in connection with heat treatment. These materials give a much more accurate indication of temperature than can be obtained by merely observing the color of the metal. Temperature-indicating crayons are made of materials that melt rapidly and clearly at specified temperatures. A series of crayons is supplied to cover a wide range of temperatures.

The crayons are easy to use. You select the crayon that is labeled with the temperature you want. As the metal is being heated, stroke the work with the crayon. When the metal is below the temperature rating of the crayon, the crayon will leave a dry or chalky mark on the surface. When the proper temperature is reached or exceeded, the crayon will melt quickly, leaving a liquid smear on the metal. Do not forget that the crayons indicate only the skin or surface temperature of the metal. The interior of the piece may be at quite a

different temperature unless the piece has been soaking for some time.

COOLING EQUIPMENT

The rate of cooling is controlled by selecting an appropriate cooling medium and cooling procedure. The equipment required for cooling includes the substances used for cooling, a tank or other container to hold the cooling medium, and various kinds of tongs, baskets, and other devices for handling and holding the work.

The rate at which a metal cools depends upon a number of factors. The size, shape, temperature, and composition of the material and the temperature and composition of the cooling medium are the major factors involved. The rate at which a cooling medium can absorb heat is also greatly influenced by circulation. When the cooling medium is agitated, the rate of

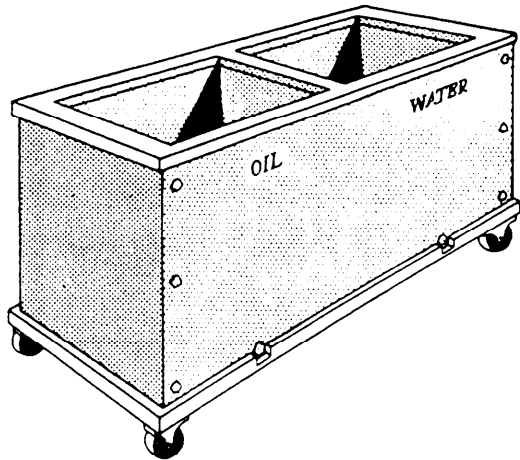


Figure 15-10.—Portable quenching tank for use in heat-treating.

cooling is much faster than when the cooling medium is not in motion. The volume of the cooling medium is also important. As the metal cools, the cooling medium absorbs heat. If the volume is insufficient, the cooling medium will become too hot to cool the work at the required rate. In regular heat-treating shops where the cooling mediums must be used continuously, mechanical cooling systems are used to maintain the cooling medium at the correct temperature.

Liquids, gases, and solids are all used as cooling mediums for heat-treating operations. Table 15-3 shows the relative cooling rates of some commonly used liquids and gases. Solid materials such as lime, sand, ashes, and cast-iron chips are sometimes used when the rate of cooling must be slower than that produced by liquids or gases.

Liquid quenching is accomplished either by STILL-BATH QUENCHING or by FLUSH QUENCHING. In still-bath quenching the metal is cooled in a tank of still liquid. The only movement of the liquid is that caused by the movement of the hot metal. Flush quenching is used for parts that have recesses or cavities that would not be properly quenched by the still-bath method. In flush quenching, the liquid is sprayed under pressure onto the surface of the piece and into every cavity or recess. This procedure is often used to minimize distortion by providing a relatively uniform quench to all parts of the piece.

Portable quenching tanks of the type shown in figure 15-10 are sometimes used in small shops that do not have permanent, built-in equipment. Portable quenching tanks may have one compartment or several. When more than one quenching medium is to be used, the seal between the compartments must be absolutely

tight to prevent mixing of the mediums. Each compartment is equipped with a drain plug, a screen in the bottom to catch scale and other foreign matter, and a mesh basket to hold the parts being quenched. The mesh basket and the wire screen are suspended in the tank and held in position by clips that fit over the rim of the tank. A portable electric pump may be attached to the rim of the tank to circulate the liquid.

Stationary quenching tanks are usually designed to contain only one liquid. In a stationary quenching tank, the mesh basket that holds the work is usually raised and lowered by air pressure and is controlled by a three-way air valve. The basket can usually be positioned at any level and can be raised above the level of the liquid so the parts can be drained after they have been cooled. Stationary quenching tanks usually have built-in electric pumps to circulate the liquid. WATER is often used as a quenching medium for plain-carbon steels and for aluminum and other nonferrous metals. The water must be kept clean by frequent changing. The temperature most often used for water quenching is about 65°F. Normally, the volume of water in the tank should prevent a temperature rise of more than 20°F. When very heavy pieces are being quenched, the temperature rise may exceed 20°F, but it should always be kept as low as possible.

BRINE is used for many quenching operations. At any given temperature, brine cannot hold as much dissolved air as fresh water can hold. With brine, therefore, there are fewer air bubbles or gas pockets on the surface of the work. Brine wets the surface more thoroughly and cools the work more rapidly and more uniformly than plain water.

Brine solutions usually contain from 7 to 10 percent salt by weight or 3/4 of a pound of salt for each gallon of water. The correct temperature for a brine quench ranges from 65° to 100°F. Plain-carbon steels and low-alloy steels are often quenched in brine. High-carbon steels and all alloy steels that are uneven in cross section must be quenched very carefully if brine is the cooling medium. Brine cools the material so rapidly that great internal stresses may develop and crack the work. Brine is not used as a quenching medium for nonferrous metals because of its high corrosive effect on these metals.

OIL is used to quench high-speed steels and oil-hardened steels. It is also the preferred quenching medium for almost all other steels except where the necessary hardness cannot be obtained by such a relatively slow quench. Although nonferrous metals are not normally quenched in oil, they may be in special

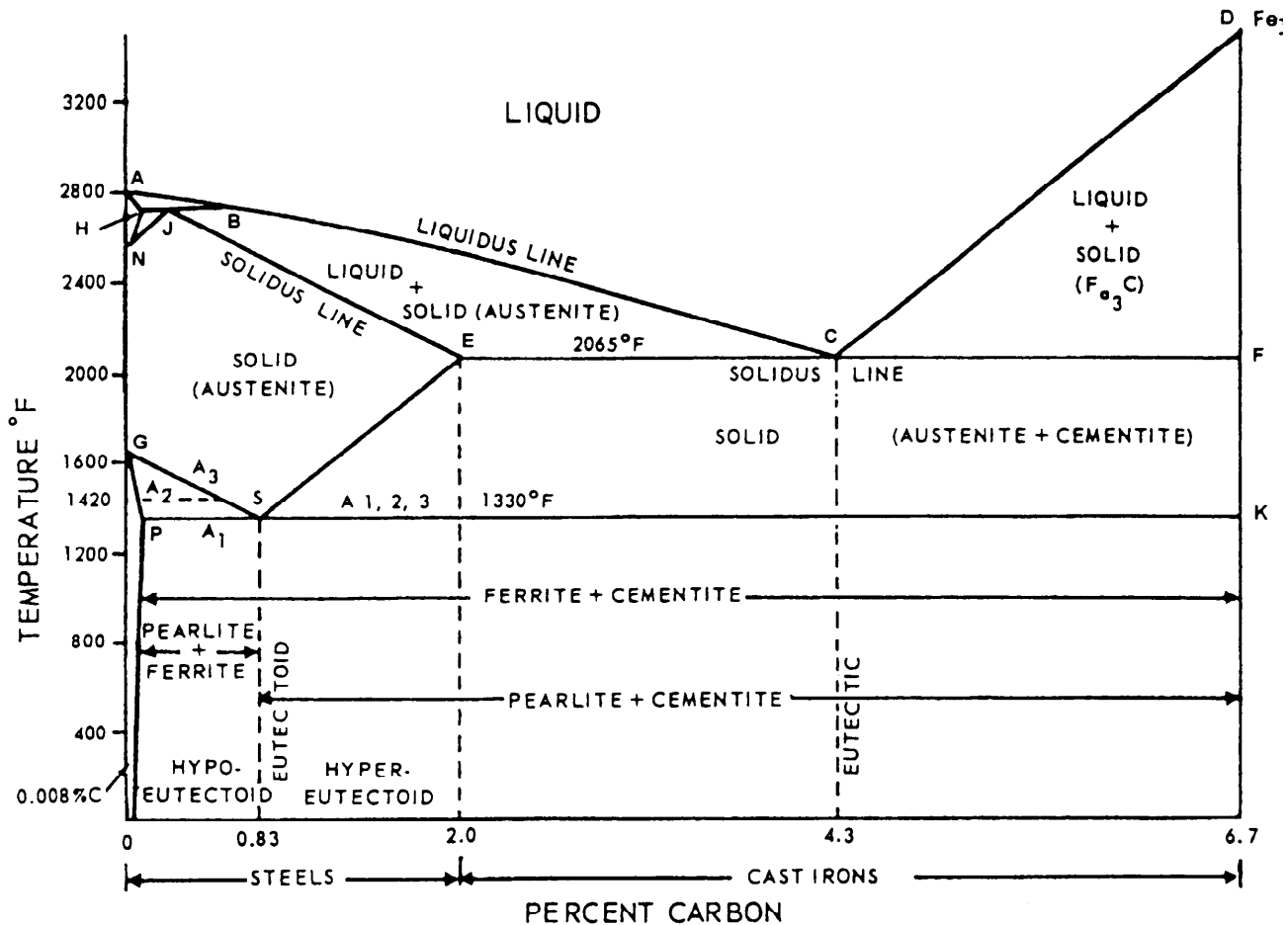


Figure 15-11.—Iron-carbon phase diagram.

cases. A wide variety of quenching oils may be used, including animal oils, fish oils, vegetable oils, and mineral oils. Oils have a slower cooling rate than brine or water but a faster cooling rate than air or solid materials. Quenching oils are usually used in the temperature range of 120° to 150°F.

The chief danger involved in quenching with oil is that a hot metal piece may raise the temperature of the oil to the flash point and cause it to burst into flames. A cover should always be kept near a quenching tank that is used for oil. If the oil flashes into flames, put the cover over the tank immediately to smother the fire.

Some water usually collects in the bottom of the oil tank. The water does no harm if only a small amount is present. If enough water is present that the work extends into the water, the rapid quenching action of the water may cause the piece to crack.

CAUSTIC SODA in water is used for some steels that require rapid quenching. A lo-percent caustic soda solution quenches faster than water, but slower than brine. Nonferrous metals are not quenched in caustic soda solutions.

AIR is used for cooling some high-alloy steels and some nonferrous metals. Both still air and circulating air are used. For either method the work pieces are placed on racks or other suitable containers so all parts are uniformly exposed. Air is often circulated by electric fans arranged to provide uniform cooling. Compressed air is sometimes used to concentrate the cooling on particular areas. Compressed air used for this purpose must be entirely free of moisture. Any moisture in the air produces rapid quenching wherever it touches the metal and may cause cracking or hard spots.

MOLTEN LEAD at temperatures ranging from 650° to 1,100°F is often used as a first-stage quench for high-speed steels. A common practice is to quench high-speed steel in molten lead as soon as the work is removed from the furnace and to follow this quench by cooling the part in still air to about 200°F before tempering. Molten lead is not used as a quenching medium for nonferrous metals.

MOLTEN SALT at temperatures ranging from 300° to 1,000°F is sometimes used as a quenching medium

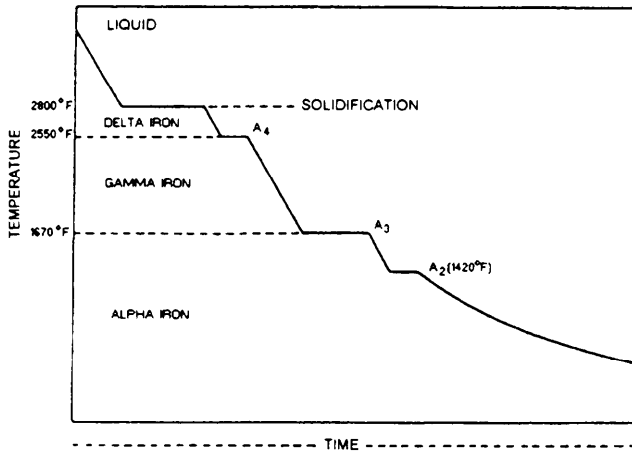


Figure 15-12.—Idealized cooling curve for pure iron.

for steels that tend to crack or distort from more sudden quenches. The final cooling for the temperature of the molten salt bath is accomplished in still air. All traces of the salt must be washed from the steel to prevent corrosion.

SPECIAL PROTECTIVE ATMOSPHERES are used for the first-stage cooling of some steels. The protective atmosphere almost entirely eliminates air from around the metal and thus prevents scaling. When the steel has cooled enough so there is no further danger of scaling, the remainder of the cooling is done in still air.

PRINCIPLES OF HEAT-TREATING FERROUS ALLOYS

As we have seen, the properties of a metal or an alloy are directly related to the metallurgical structure of the material. Since we know that the basic purpose of heat treatment is to **CHANGE** the properties of the materials, let's see how this is done. The following sections deal with basic considerations in heat treatment—equilibrium diagrams, transformation temperatures, and the effects of heating, holding at temperature, and cooling.

EQUILIBRIUM DIAGRAMS

The relationships among the various metallurgical structures that compose alloys and the temperatures at which these structures exist are shown on existing equilibrium diagrams for all major alloy systems. Figure 15-11 shows a simplified equilibrium diagram (also called a phase diagram) for iron-carbon alloys. This type of diagram gives a good overall view of the effects of temperature on the structures of various

alloys. However, you should note that an equilibrium diagram indicates equilibrium conditions—you might say, ideal conditions of very slow and very uniform heating and cooling. The rate and uniformity of heating and cooling affect the internal structure of alloys and alter the relationship between temperature and internal structure. Therefore, equilibrium diagrams represent theoretical rather than actual conditions.

TRANSFORMATION TEMPERATURES

If you allow a molten sample of pure iron to cool slowly and measure the temperature of the iron at regular intervals, an idealized (equilibrium) time-temperature plot of the data will appear as shown in figure 15-12. The horizontal discontinuities (temperature arrests) in this curve are caused by physical changes in the iron.

The first arrest at 2,800°F marks the temperature at which the iron freezes. The other arrests (known as transformation temperatures or critical points) mark temperatures at which certain internal changes take place in the solid iron. Some of these temperatures are very important in the heat treatment of steel.

As was mentioned before, the atoms in all solid metals are arranged in a definite geometric pattern. The atoms in iron immediately after freezing are arranged in the body-centered cubic structure. In this crystal structure the unit cell consists of a cube with an iron atom at each of the eight corners and another in the center. Each of the many individual grains (crystals) of which the solid metal is composed is built up of a very large number of these unit cells, all oriented alike in the same grain. This high-temperature iron is known as delta iron.

At 2,550°F (the A_4 point, fig. 15-12), iron undergoes an allotropic transformation; that is, the arrangement of the atoms in the crystal changes. The new crystal structure is face-centered cubic, and the unit cell again consists of a cube with an iron atom at each of the eight corners, but with an iron atom in the center of each of the six faces instead of one in the center of the cube. This form is known as gamma iron. At 1,670°F (the A_3 point), iron undergoes another allotropic transformation and reverts to the body-centered cubic system. This structure, which is basically the same as the structure of delta iron, is stable at all temperatures below the A_3 point and is known as alpha iron. The arrest at 1,420°F (the A_2 point) is not caused by an allotropic change. It marks the temperature at which iron becomes ferromagnetic and is, therefore, termed the magnetic transition. Above this temperature iron is nonmagnetic.

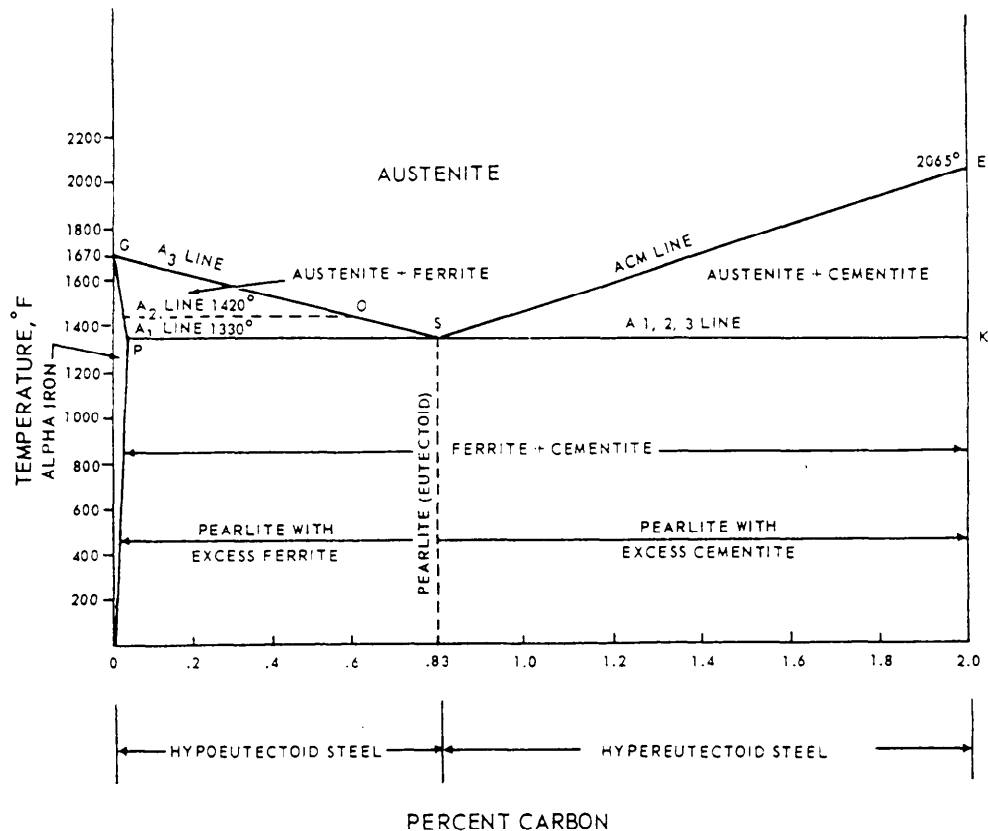


Figure 15-13.—Phase diagram for carbon steels.

These various temperature arrests on cooling are caused by evolutions of heat. On heating, the arrests occur in reverse order and are caused by absorptions of heat. The critical points may be detected also by sudden changes in other physical properties, for instance, expansivity or electrical conductivity.

IRON-CARBON PHASE DIAGRAM

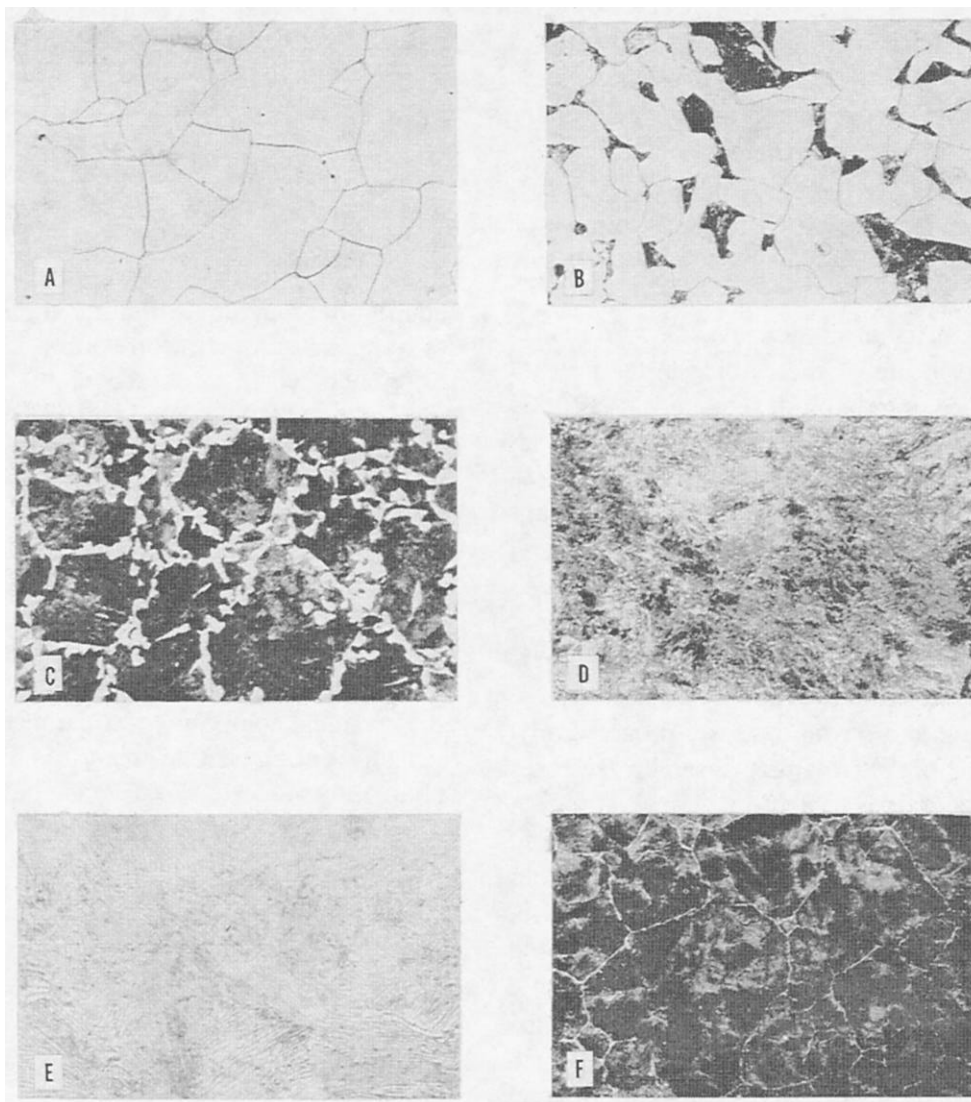
The complete iron-carbon phase diagram represents the relationship between temperatures, compositions, and structures of all phases that may be formed by iron and carbon under an equilibrium condition (very slow cooling). Figure 15-11 illustrates a portion of this diagram for alloys ranging up to 6.7 percent of carbon. The left-hand boundary of the diagram represents pure iron (ferrite), and the right-hand boundary represents the compound iron carbide, Fe_3C , commonly called cementite.

The beginning of freezing (change in state of metal from liquid to solid) of the various iron-carbon alloys is shown by line ABCD (fig. 15-11), termed the LIQUIDUS LINE. The ending of freezing is given by line AHJECF, termed the SOLIDUS LINE. The freezing point of iron is lowered by the addition of carbon (up to 4.3 percent) and the resultant alloys freeze

over a range in temperature instead of at a constant temperature as does the pure metal iron. The alloy containing 4.3 percent carbon, called the eutectic alloy of iron and cementite, freezes at a constant temperature as indicated by point C (fig. 15-11). Eutectic is defined as an alloy or solution having its components in such proportions that the melting point is the lowest possible for this combination of components. Not all alloys are eutectic forming. The formation of a eutectic occurs when a molten alloy or solution of the proper composition freezes. This temperature (in iron) is 2,065°F, considerably below the freezing point of pure iron.

Carbon has an important effect upon the transformation temperatures of iron; it raises the A_4 temperature and lowers the A_3 temperature. This effect on the A_3 temperature is very important in the heat treatment of carbon and alloy structural steels, while the effect on the A_4 temperature is important in the heat treatment of certain high-alloy steels, particularly stainless types.

Solid iron can absorb various amounts of carbon, depending on the crystal structure of the iron and the temperature to which the iron is heated. The body-centered iron (alpha or delta) can absorb very little carbon, whereas the face-centered (gamma) iron can



126.83

Figure 15-14.—Microstructural constituents of slowly cooled carbon steel (all etched with either picral or nital).

absorb a considerable amount as pure austenite, the maximum being about 2 percent at 2,065°F (fig. 15-11, point E). The solid solution of carbon in delta iron is called delta ferrite, and the solid solution of carbon in alpha iron is called alpha ferrite, or, more simply, ferrite.

The physical process by which iron-carbon alloys, especially those containing less than about 0.6 percent of carbon, solidify is rather complicated. All you really need to know, however, is that all iron-carbon alloys containing less than 2 percent of carbon (steel) will, immediately or soon after solidification is complete, consist of single-phase austenite. Cast irons containing greater than 2 percent carbon will consist of two phases immediately after solidification—*austenite* and *cementite*. Under some conditions this *cementite* formed on cooling through the temperature 2,065°F

(ECF in fig. 15-11) will decompose partly or completely into *austenite* and *graphite*.

The part of the iron-carbon phase diagram that is concerned with the heat treatment of steel is reproduced on an expanded scale in figure 15-13. Regardless of the carbon content, steel exists as *austenite* above line GOSE. Steel of 0.83 percent carbon is designated as *eutectoid steel*, and those with lower or higher carbon as *hypoeutectoid* and *hypereutectoid*, respectively.

An *eutectoid steel*, when cooled at very slow rates from temperatures within the *austenitic* field, undergoes no change until the temperature reaches 1,330°F (line PSK) (fig. 15-13). At this temperature (known as the A_1 temperature), the *austenite* transforms completely to a mixture of *ferrite* and *cementite* having a typical lamellar structure (fig. 15-14, view E). The mixture is

known as pearlite, and the A_1 temperature is, therefore, frequently referred to as the pearlite point. Since the A_1 transformation involves the transformation of austenite to pearlite (which contains cementite— Fe_3C), pure iron does not possess an A_1 transformation (fig. 15-13). Theoretically, iron must be alloyed with a minimum of 0.03 percent of carbon before the first minute traces of pearlite can be formed on cooling (fig. 15-13, point P). If the steel is held at a temperature just below A_1 (either during cooling or heating), the carbide in the pearlite tends to coalesce into globules or spheroids; this phenomenon, known as SPHEROIDIZATION, will be discussed later.

A hypoeutectoid steel (less than 0.83 percent carbon), cooled slowly from a temperature above the A_3 temperature, begins to precipitate ferrite when the A_3 line is reached. This ferrite is often called pro-eutectoid, since it forms before the eutectoid temperature is reached. As the temperature drops from the A_3 to the A_1 , the precipitation of ferrite increases progressively, and as the amount of the remaining austenite decreases progressively, its carbon content increases. At the A_1 temperature the remaining austenite reaches eutectoid composition (0.83 percent carbon) and, upon further cooling, transforms completely into pearlite (fig. 15-14, view D). The microstructures of slowly cooled hypoeutectoid steels thus consist of mixtures of ferrite and pearlite (fig. 15-14, views B and C). The lower the carbon content, the higher is the temperature at which ferrite begins to precipitate and the greater is the amount of ferrite in the final structure.

The temperature range between the A_1 and A_3 points is called the transformation range. Theoretically, the critical points in any given steel should occur at about the same temperatures, if the steel is being heated or cooled very slowly. Practically, however, they do not since the A_3 and A_1 points, affected slightly by the rate of heating, are affected tremendously by the rate of cooling. Rapid rates of heating raise these points only slightly, but rapid rates of cooling lower the temperatures of transformation considerably. To differentiate between the critical points on heating and cooling, the small letters *c* (for *chauffage*, meaning heating) and *r* (for *refroidissement*, meaning cooling) are added. The terminology of the critical points thus becomes Ac_3 , Ar_3 , Ac_1 , Ar_1 , and so on. The letter *e* is used to designate the occurrence of the points under conditions of extremely slow cooling on the assumption that this represents equilibrium conditions (Ae_3 and Ae_{cm}).

EFFECTS OF HEATING, HOLDING, AND COOLING

We have seen what happens to the structure of an iron-carbon alloy containing 0.83 percent carbon when it is cooled very slowly so all of the transformations occur at the points indicated on the equilibrium diagram. In the same manner, we could use the equilibrium diagram to find the transformation points or ranges for other iron-carbon alloys containing different percentages of carbon.

If we want to change a metal's properties, we have to create a specific grain structure in the metal. We do this primarily by (1) heating the metal at a certain rate to a certain temperature, (2) holding or soaking it at that temperature for a specified time, and (3) cooling it at a specified rate. Thus the three major factors involved in all heat-treating processes are (1) rate of heating, (2) holding time (or soaking time) at the specified temperature, and (3) rate of cooling. A fourth factor—the chemical composition of the material surrounding the alloy during heat treatment—is important in nearly all treating processes.

The rate of heating determines where the changes will occur in the material as it is heated. Increasing the rate of heating raises the temperatures at which the transformations occur. Within certain limits, the faster the material is heated, the higher its transformation temperatures will be. The temperature to which the material is raised and the time it is held at that temperature affect the size of the grains in the final structure. The rate of heating also partially determines whether or not stresses will be set up in the material by the process of heating.

The holding time (or soaking time) at temperature is important for a number of reasons. The holding time must be sufficient to allow all parts of the piece to come to a uniform temperature, except in those cases involving localized hardening of certain areas. If the rate of heating is very slow, uniformity of temperature may be reached with a short holding time. But if the rate of heating is rapid, a longer holding time will probably be required. In any case, holding time must be sufficient to allow the required transformations to take place. As we have seen, the transformations do not occur instantaneously but require a definite time for completion.

The rate of cooling is tremendously important in most heat-treating processes. Increasing the rate of cooling lowers the temperatures at which the transformations occur; and the lower the transformation temperature, the stronger and harder the final product will be. Very rapid cooling does not allow time for the

transformations to be completed in the normal manner, resulting in quite different structures than those obtained by very slow cooling of the same material. Remember this fact about cooling—if you do not cool a metal properly, you will not get the desired results, no matter how carefully you heat and soak the metal. In addition, very rapid cooling can cause internal stresses in your material, which may lead to cracking.

In plain-carbon steel, the properties of the material are largely determined by the form and distribution of the ferrite and the cementite. Most heat treatment of plain-carbon steels consists of heating the material slightly above its transformation temperature, holding it at this temperature until it is completely austenitic, and then cooling it at the rate required to produce a particular kind of structure. Thus austenite, a solid solution of carbon and gamma iron, might be considered the basis from which all plain-carbon steel structures are derived.

As noted before, the very slow cooling of austenite to room temperature produces structures that are combinations of ferrite and cementite. The particular combination depends upon the percentage of carbon in the alloy. With less than about 0.83 percent carbon, the structure is a combination of ferrite and pearlite. With just about 0.83 percent carbon, the structure is entirely pearlitic. With more than 0.83 percent carbon, the structure is a combination of pearlite surrounded by cementite at the grain boundaries as shown in figure 15-14, view F.

If the steel is cooled rapidly, a different structure will result. The austenite will be retained until the material reaches a temperature of about 430°F. At this point the transformation from austenite to a structure called MARTENSITE begins. Martensite is a very hard and highly stressed structure. It is formed at the moment gamma iron changes to alpha iron. Since gamma iron can hold a great deal more carbon in solid solution than alpha iron can, the change from gamma iron to alpha iron causes a sudden dispersion of carbon. Because the transformation from austenite is so rapid, carbon is trapped throughout the structure in this solid solution.

The rate of cooling is controlled by selecting an appropriate quenching medium and cooling procedure. Fresh water, brine, oil, and caustic soda in water are commonly used for rapid quenching. Slower cooling is obtained by air cooling, by packing, and by furnace cooling. Packing consists of burying the heated metal in sand, ashes, or some other substance that is a poor conductor of heat. Furnace cooling consists of shutting off the heat and leaving the piece in the furnace so the metal and the furnace cool together. Ferrous metals are sometimes cooled in baths of molten lead or molten

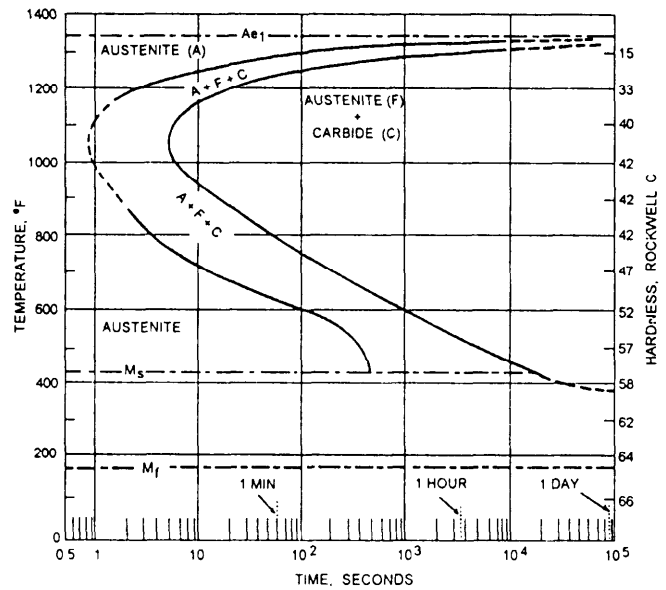


Figure 15-15.—Isothermal transformation diagram (S-curve) for eutectoid carbon steel.

salts. Occasionally, solid materials are used as quenching mediums. In each instance, the quenching medium and the quenching procedure must be selected on the basis of the nature of the material being treated, the size and design of the piece, and the properties that are required in the final product.

Isothermal Transformation

The course of transformation of austenite when the steel is quenched to and held at various constant elevated temperature levels (isothermal transformation) is shown by a diagram known as the isothermal transformation diagram (I-T diagram). This diagram is also called the Bain S-curve or the TTT diagram, for time, temperature, and transformation. Such a diagram for eutectoid carbon steel is shown in figure 15-15. The I-T diagram of a steel is a map that charts the transformation of austenite as a function of temperature and time and shows approximately how a particular steel will respond to any rate of slow or rapid cooling from the austenite state. The products of this transformation will be discussed below.

PEARLITE: Austenite containing 0.83 percent of carbon, cooled quickly to and held at 1,300°F, does not begin to decompose (transform) until after about 15 minutes and does not completely decompose until after about 2 hours (fig. 15-15). Thus, at temperatures just below the critical temperature (A_{c1}), austenite is stable for a considerable length of time. The product of the decomposition of austenite at this temperature is coarse pearlite of relatively low hardness. If the austenite is

quickly cooled to and held at a somewhat lower temperature, say 1,200°F, decomposition begins in about 3 seconds and is completed after about 30 seconds, the resultant pearlite being finer and harder than that formed at 1,300°F. At a temperature of about 1,050°F, the austenite decomposes extremely rapidly, with less than 1 second elapsing before the transformation starts and 5 seconds before it is completed. The resultant pearlite is extremely fine and its hardness is relatively high. This region of the S-curve where decomposition of austenite to fine pearlite proceeds so rapidly is called the “nose” of the curve.

BAINITE: If the austenite is cooled unchanged to temperatures below the nose of the S-curve (1,050°F), the time required for its decomposition begins to increase. The final product of decomposition now is not pearlite, but a new structure called bainite, possessing unusual toughness with hardness even greater than that of very fine pearlite. Depending on the temperature, a certain interval of time is necessary before austenite starts to transform into either pearlite or bainite. Additional time is necessary before the transformations are completed.

MARTENSITE: If the austenite is cooled unchanged to relatively low temperatures (below about 430°F for the eutectoid carbon steel), partial transformation takes place instantaneously; the product of transformation is martensite. Austenite transforms into martensite over a temperature range with the amount that transforms being a function of the temperature. Only minute amounts will transform at about 430°F; practically all of the austenite will be transformed at about 175°F. The beginning of this transformation range is termed the M_s (martensite start) temperature and the end of the range is termed the M_f (martensite finish) temperature, as shown in figure 15-15. As long as the temperature is held constant within the $M_s - M_f$ range, the portion of the austenite that does not transform instantaneously to martensite remains untransformed for a considerable length of time, eventually transforming to bainite.

In ordinary heat treatment of the plain-carbon steels, austenite does not transform into bainite. Transformation of the austenite takes place either above or at the nose of the S-curve, forming pearlite, or in passing through the $M_s - M_f$ range, forming martensite or both. For austenite to be transformed entirely into martensite, it must be cooled rapidly enough so the temperature of the center of the steel, which cools more slowly, is lowered past the nose of the S-curve in less time than is necessary for transformation to start at this temperature. If this is not done, part of the steel

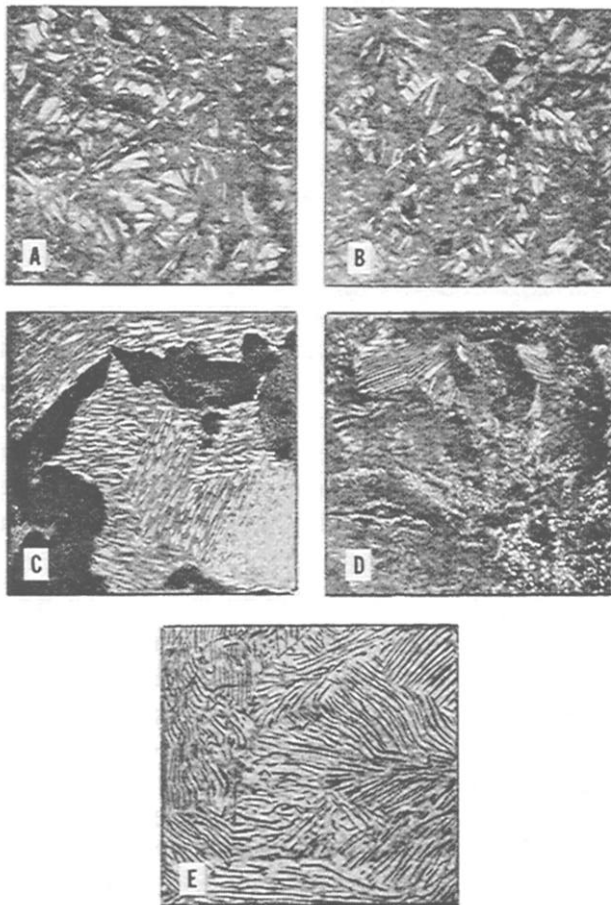
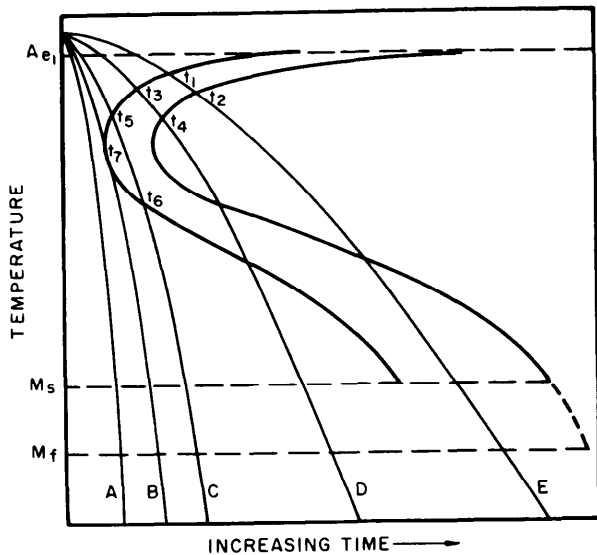
transforms into pearlite at the high temperature and the remainder transforms into martensite at the low temperature ($M_s - M_f$ temperature range). The resulting material will then transform to a nonuniform structure that is usually not desirable.

Continuous Cooling

Figure 15-16 represents a theoretical S-curve on which are superimposed five theoretical cooling curves. Curves A to E represent successively slower rates of cooling that would be obtained, for instance, by cooling in (A) iced brine, (B) water, (C) oil, (D) air, and (E) the furnace.

Steel cooled according to curve E begins to transform at temperature t_1 and completes transformation at t_2 ; the final product is coarse pearlite with relatively low hardness. When the steel is cooled according to curve D, transformation begins at t_3 and is complete at t_4 ; the final product is fine pearlite and its hardness is greater than that of the steel cooled according to curve E. When the steel is cooled according to curve C, transformation begins at t_5 and is only partially complete when temperature t_6 is reached. The product of this partial transformation is very fine pearlite. The remainder of the austenite does not decompose until the M_s temperature is reached. Then it begins to transform to martensite, and completes this transformation at the M_f temperature. The final structure is then a mixture of fine pearlite and martensite (typical of an improperly quenched steel) with a higher hardness than was obtained with the steel cooled according to curve D. The rate of cooling represented by curve B is just sufficient to intersect the nose of the S-curve. Consequently, only a minute amount of austenite decomposes into fine pearlite at temperature t_7 ; the remainder of the austenite is unchanged until the martensite transformation range is reached. If the steel is cooled at a slightly faster rate, so no transformation takes place at the nose of the S-curve, the steel is completely hardened. This particular rate is termed the critical cooling rate and is defined as the slowest rate at which the steel can be cooled and yet be completely hardened. Since this rate cannot be directly determined, the rate indicated by curve B, producing only a trace of fine pearlite, is frequently used as the critical cooling rate. The hardness of the resultant martensite is equivalent to the maximum that can be obtained. Samples cooled at a faster rate, such as that indicated by curve A, are also completely martensitic but are not harder than the sample cooled according to the critical cooling rate.

The rate at which a steel cools through the temperature in the vicinity of the nose of the S-curve is



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Figure 15-16.—Schematic diagram illustrating the relation between the S-curve, continuous cooling curves, and resulting microstructures of eutectoid carbon steels.

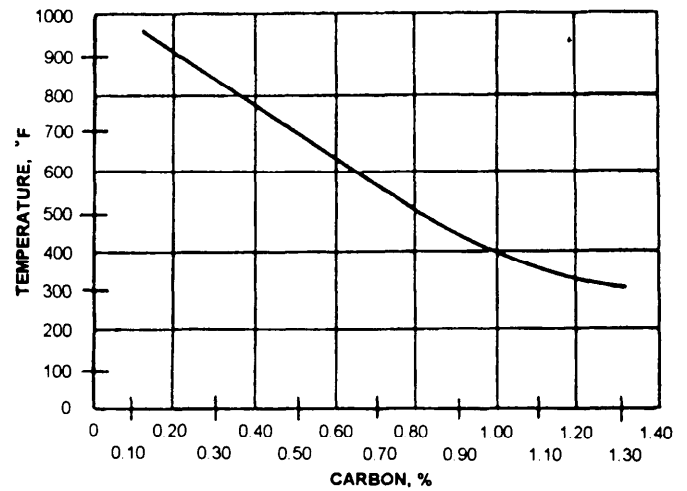


Figure 15-17.—Influence of carbon on the start of martensite (M_s) transformation of high-purity, iron-carbon alloys.

of critical importance. Somewhat slower rates of cooling above and below this temperature range can be tolerated and a completely hardened steel (one that is completely martensite) can be obtained if the cooling through the temperature interval at the nose of the S-curve is sufficiently fast. In practice, however, steels are usually cooled rapidly from the quenching temperature to relatively low temperatures (20° to 250°F) and then tempered immediately to prevent cracking.

Although the discussions of the decomposition of austenite have been limited to a steel of eutectoid composition, other steels behave in a similar manner, at different temperatures and times of reaction. In hypoeutectoid steels, free ferrite plus pearlite are formed if transformation begins above the temperature range at the nose of the S-curve. The amount of free ferrite decreases as the temperature of transforming approaches the nose of the curve. In hypereutectoid steels, free ferrite plus pearlite are formed if transformation occurs above the nose. The time for the start of the transformation at the nose increases as the carbon increases up to the eutectoid composition, and then decreases with further increase in carbon. That is, the nose is shifted to the right on the time axis (fig. 15-15) as the carbon is increased to 0.8 percent and back to the left with further increases in carbon content.

The temperature of formation of bainite is not appreciably affected by carbon content, but the time for its formation increases with the carbon.

Both the M_s and the M_f temperatures are lowered significantly by increasing carbon content, as shown for M_s in figure 15-17. The M_f temperatures of the plain-carbon steels have not been adequately determined.

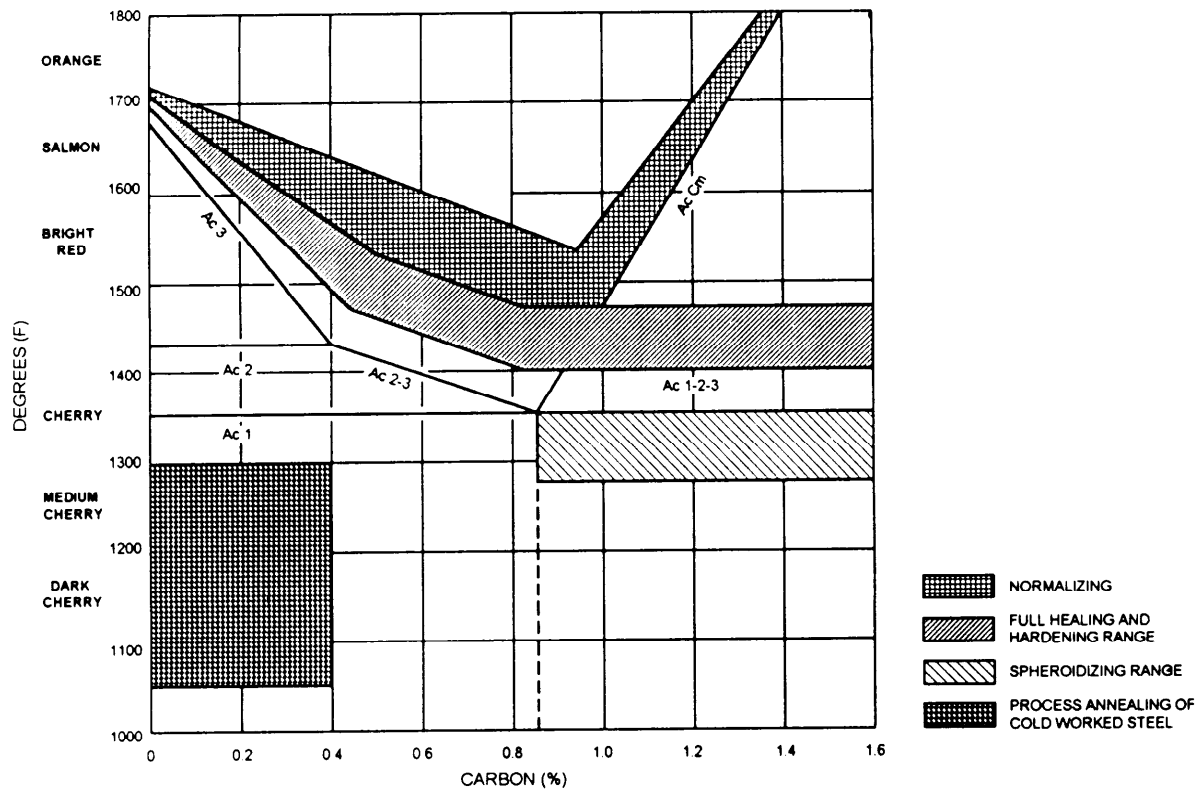


Figure 15-18.—Heat treatment temperature ranges.

Available information indicates that the M_f of high-carbon steels is actually below room temperature. Slight amounts of austenite are frequently retained in quenched steels, especially in the higher carbon grades, even when they are cooled to room temperature.

HEAT-TREATING FERROUS METALS

The heat-treating processes most commonly used for ferrous metals are hardening, tempering, annealing, normalizing, spheroidizing, and case hardening. Annealing is the only one of these processes that is also used for nonferrous metals. Some nonferrous metals (including some aluminum alloys and some magnesium alloys) can be hardened by a process generally referred to as precipitation heat treatment. Precipitation hardening is discussed in the section of this chapter on nonferrous metals. Figure 15-18 shows the heat treatment temperature ranges. You should refer to this figure as you study the following information on hardening, normalizing, and spheroidizing temperatures.

HARDENING

Many tools and pieces of equipment must be hardened before they are used. Cutting tools, chisels,

twist drills, and other tools must be hardened so they can retain their cutting edges. Surfaces of roller bearings, parallel blocks, and armor plate must be hardened to prevent wear and penetration. Hardening is used to increase tensile strength as well as to increase hardness. Since hardening increases the brittleness of the material, most alloys are tempered after being hardened.

Steels are hardened by being heated to a temperature just above the upper transformation temperature, soaked long enough to ensure a completely austenitic structure, and then cooled rapidly. This result is either fine-grained pearlite, bainite, or martensite. If maximum hardness is to be developed, the austenite must be transformed to martensite. Martensite is extremely hard and strong, has great resistance, and has practically no machinability.

Carbon steels are usually quenched in brine or water to ensure rapid cooling. The production of martensite throughout a plain-carbon steel is extremely difficult, requiring that the steel be cooled to below 1,000°F in less than 1 second and that the remainder of the cooling be quite rapid. If more than 1 second is taken for the first part of the cooling (to below 1,000°F), some of the austenite will transform into fine pearlite. Pearlite varies

in hardness, but it is much softer than martensite. If the purpose of the hardening is to develop something less than maximum hardness, the first part of the cooling (to below 1,000°F) must still be accomplished within 1 second; then the remainder of the cooling must be done at a somewhat slower rate.

The rate of quenching alloy steels depends upon the composition of the material. In general, a slower quench is used for hardening alloy steels than is used for hardening plain-carbon steels.

Various quenching mediums are used to produce the desired end results. The more common quenching mediums are oil, water, and brine. When water or brine is used, the temperature of the bath must not rise above 80°F. Generally, 70°F is the best temperature for these quenching mediums. Above 80°F, water loses thermal conductivity.

The plain-carbon steels are generally quenched in water or brine; brine is preferred because it has less tendency to cause steam pockets to form. Steam pockets may cause soft spots or uneven stresses. These steels require a very active agitation or shaking action when quenched. The agitation removes the steam bubbles from the surface of the metal. When the quenched material reaches about 200° to 250°F, or a temperature low enough to dry the material thoroughly without too much sizzle, it can be removed from the water and tempered immediately.

The alloy steels, with the exception of the high-alloy, air-hardening steels, are generally oil quenched. The oil bath should be maintained at a temperature of 120° to 150°F. (This is just below the M_f line of most low-alloy steels.) At this temperature the heat-treating oils have a lower viscosity, and therefore, a better and more uniform cooling effect. The warm oil also results in a more moderate cooling rate, which lessens the chance of residual stresses and cracking.

Although steels must be heated and soaked so the structure becomes completely austenitic, you should take care to see that they are not overheated and that they are not held too long at temperature. Using too high a temperature or too long a soaking period allows a coarse grain structure to develop.

TEMPERING

After hardening, most alloys are tempered to reduce brittleness and to relieve some of the high internal stresses developed during hardening. Tempering

always follows, rather than precedes, the hardening process. Tempering is occasionally done after materials have been normalized, but its major use is after hardening.

In some alloy steels tempering may increase hardness when tempered to certain temperature ranges. In most other materials, however, tempering causes an unavoidable loss of some hardness. The amount of hardness removed by tempering depends upon the tempering temperature; the higher the temperature, the softer the material will be.

Tempering is always done at temperatures below the lower transformation point. In this respect, tempering differs from hardening, annealing, and normalizing, which all involve heating the material to temperatures above the upper transformation point.

The temperatures used for tempering are selected on the basis of the properties required in the final product. For example, permanent magnets are tempered at 121°F because they must retain considerable strength and hardness. Case-hardened objects are also tempered at relatively low temperatures (212° to 400°F) because the surface of such objects must remain hard. Many cutting tools are tempered at 430°F or below so they will retain hardness. Battering tools must have great impact resistance and must be able to cut or penetrate metal; therefore, battering tools are tempered between 450° and 600°F even though the higher temperatures mean some sacrifice of hardness to produce impact resistance. Springs are tempered between 600° and 900°F because the property of elasticity is more important in a spring than the property of hardness. Tools made of high-speed steels are tempered at 1,050° to 1,100°F. Note, however, that with high-speed tools the high tempering temperature increases, rather than decreases, hardness. This increase in hardness occurs because high-speed steels retain austenite during quenching; when the hardened steel is tempered, the austenite changes to martensite.

Since tempering uses temperatures below the lower transformation point, the rate of cooling generally has no effect upon the structure of the material. However, some nickel-chromium steels and a few other special steels become brittle if they are heated to the tempering temperature and then allowed to cool slowly. These steels, which are often called temper brittle or blue brittle steels, must be quenched rapidly from the tempering temperature to prevent brittleness. In general, however, steels are cooled

slowly from the tempering temperature by cooling in still air.

Tempering is usually done before the material has completely cooled from the hardening process. The holding time at temperature varies according to the thickness of the material, but the minimum time is about 1 hour. If the part is more than an inch thick, the holding time should be increased by about 1 hour for each additional inch of thickness.

ANNEALING

ANNEALING is a term used to describe any heat-treatment process that is used for the primary purpose of softening the metal. Two types of annealing processes are commonly used. FULL ANNEALING is done to soften the metal and make it more ductile, and to relieve internal stresses caused by previous treatment such as casting, cold working, or hot working. The operation known as PROCESS ANNEALING or STRESS RELIEF ANNEALING is done to soften the metal somewhat, although not as much as by full annealing, and to relieve internal stresses.

In general, full annealing requires higher temperatures, longer soaking time, and slower cooling than process annealing. In the full annealing of steels, the steel is heated to a temperature that is 25° to 50°F above the upper transformation point. In the process annealing of steels, lower temperatures are generally used. The rate of cooling used for annealing varies greatly, depending upon the metal being annealed and the degree of softening required.

NORMALIZING

The form of heat treatment known as NORMALIZING is used only for ferrous metals. Normalizing is sometimes used as a preliminary step before full annealing. The chief purposes of normalizing are (1) to relieve internal stresses caused by forging, bending, machining, or other working, or by uneven cooling; and (2) to give a uniform predictable grain structure. Steel that has been normalized is soft and ductile enough for many purposes, but it is harder than steel that has been fully annealed. Normalizing is sometimes followed by tempering, particularly in the case of certain steels that tend to become brittle when normalized.

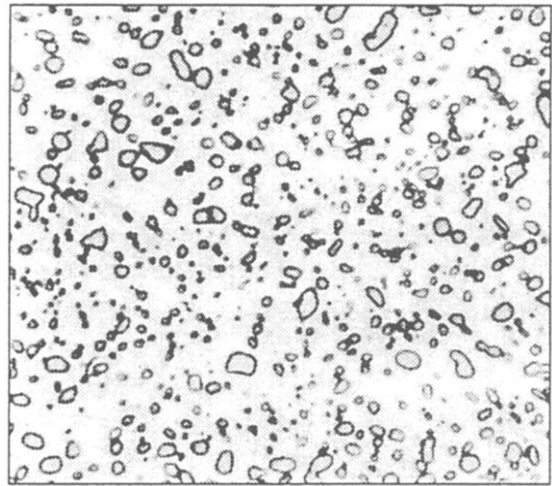


Figure 15-19.—Microscopic structure called spherodite magnified 1,000 times.

In normalizing, the steel is heated to a temperature above the upper transformation point and is cooled in still air.

SPHEROIDIZING

SPHEROIDIZING is a term used to describe any heating and cooling process that produces a rounded or globular form of iron carbide in the steel. This globular or spheroidal form of iron carbide is developed when fine pearlite is heated to a temperature just below the lower transformation point of the steel, held at this temperature for a long time, and then cooled very slowly. Temperatures, holding time, cooling rates, and other details of the process vary, depending upon the carbon content of the steel and the extent of spheroidizing that is required. In general, the object of spheroidizing is to improve machinability. Spheroidizing is sometimes regarded as being a special annealing process. The typical globular form of spheroidized steel is illustrated in cross section in figure 15-19.

AUSTEMPERING

AUSTEMPERING is a hardening treatment of metals that involves quenching the metal in a bath of molten salt maintained above the start of the martensite temperature and holding it until transformation is complete. The product formed is called bainite; a tough, hard structure.

There are two distinct advantages of austempering—(1) the high degree of freedom it provides

from distortion and quenching cracks, and (2) normal tempering is not required after the process.

MARTEMPERING

MARTEMPERING is the quenching from the normal austenitizing temperature in a molten salt bath maintained at approximately the start of the martensite temperature. The part is held at this temperature long enough to allow equalization of temperature throughout the piece, but not long enough to allow any transformation to take place. The material being heat-treated is then removed from the hot bath and allowed to air cool through the martensite temperature range, followed by tempering to obtain the desired mechanical properties. This two-step cooling process has the same advantage as austempering—freedom from distortion and quenching cracks.

CASE HARDENING

CASE HARDENING is a process by which a steel can be given a hard, wear-resistant surface while retaining a softer but tougher interior than would be possible if the whole piece were hardened. Steels may be case hardened by carburizing, cyaniding, nitriding, and various other processes.

CARBURIZING is a term applied to several case-hardening processes in which carbon is introduced into the surface layer of the steel. The steel is heated in contact with a substance that has a high carbon content; it is held at a temperature above the upper transformation temperature for a suitable length of time and is then quenched rapidly to produce a hardened outer layer or “case” over a softer, tougher core. As a rough indication, a carburized depth of about 0.030 to 0.050 inch can be obtained in about 4 hours at 1,700°F, depending upon the type of carburizing agent, which may be a solid, liquid, or gas.

Sometimes the steel to be carburized is packed in a substance such as charcoal and is then heated in a furnace. The length of time the piece is left in the furnace determines the depth to which the carbon will be absorbed. For many pieces the procedure is to carburize the material, allow it to cool slowly, reheat it, and then harden it by quenching. Small pieces are sometimes dumped into the quenching medium as soon as they are removed from the carburizing furnace.

Other methods of carburizing use gases or liquids that have a high carbon content. Although these methods also use the principle of increasing the carbon content to harden the outer shell or case of the steel, they use different equipment and different procedures.

CYANIDING can be used to obtain a hard superficial case on low-carbon steels. The process involves the introduction of both carbon and nitrogen into the surface layers of the steel. Steels to be cyanided normally are heated in a molten bath of cyanide-carbonate-chloride salts and then quenched in brine, water, or mineral oil. The temperature of operation is generally within the range of 1,550° to 1,600°F. The depth of the case is a function of time, temperature, and composition of the cyanide bath. The time of immersion is quite short as compared with carburizing, usually varying from 15 minutes to 2 hours. The maximum case depth is rarely more than about 0.020 inch and the average depth is considerably less.

NITRIDING is still another method by which a case or skin of hardened steel can be produced. The piece to be case hardened is put into a furnace and heated to between 950° and 1,200°F and, at the same time, is exposed to ammonia gas. The heat of the furnace causes the ammonia to break down into nitrogen and hydrogen. Some of the nitrogen combines with the elements in the steel to form chemical compounds called nitrides in the outer layer of the steel. These nitrides give the surface its hard, wear-resistant qualities.

CARBON TOOL STEELS

The carbon content of plain-carbon steels ranges from about 0.20 to 1.13 percent. To heat-treat these steels, heat them uniformly to 1,450° to 1,550°F, using the lower end of the temperature range for the higher carbon content. Use brine or water as the quenching medium, and agitate the part vigorously to prevent the accumulation of bubbles on the surface of the metal. Do not remove these steels from the quench until they have reached a temperature of less than 200° to 250°F. To prevent cracking, do not allow the steel to cool below 125°F and follow the cooling immediately with tempering. Tools made from these steels do not have to withstand severe usage or high cutting speeds. Some examples are wrenches, hammers, pliers, knives, simple dies, and low-speed cutting tools.

Table 15-4.—Heat-Treating Temperatures and Quenching Medium for Standard SAE Steels

SAE NO.	NORMALIZING TEMP. (°F)	HARDENING TEMP. (°F)	QUENCH	TEMPERING TEMP. (°F)
1020	1650-1700	1600-1650	water	200
1030	1650-1700	1600-1650	water	200
1040	1600-1650	1500-1550	water	200
1050	1600-1650	1500-1550	water	200*
1060	1550-1600	1450-1550	water or oil	200*#
1070	1550-1600	1450-1550	water or oil	200*#
1080	1550-1600	1450-1500	water or oil	200*#
1090	1550-1600	1450-1500	water or oil	200*#
1345	1600-1700	1450-1500	oil	200*
2345	1600-1700	1450-1500	oil	200#
3140	1600-1650	1455-1550	oil	200"
4130	1600-1650	1550-1600	water	200*
4140	1600-1650	1525-1575	oil	200*
4340	1600-1650	1475-1525	oil	200*
4060	1550-1600	1500-1550	oil	200*
5140	1600-1650	1500-1550	oil	200*
5210	1550-1600	1425-1475	water	200*
6150	1600-1650	1550-1600	oil	200*
8630	1600-1650	1550-1600	water	200*
8640	1600-1650	1525-1575	oil	200*

*Temper immediately after quenching. Lower temperatures will result in a harder final product.
 #Use water for maximum hardness. Use oil for toughness and for intricate shapes.
 Note: Temperature of water quench is 70°F.
 Temperature of oil quench is 120-150°F.

Table 15-4 will assist you in choosing the proper quenching medium and temperatures for the standard SAE steels.

ALLOY TOOL STEELS

The number of alloy tool steels is too great to include them all in this text, so we will deal with the type most important to you. You, as a Machinery Repairman, are concerned primarily with the manufacture of taps, dies, reamers, hobs, and form tools. An

all-around tool steel for this purpose is type 01. This steel is listed under QQT-570 and is available in the standard stock system in various shapes and sizes. Type 01 is suitable for all applications except where a high-speed steel is required. It heat treats well and is readily machinable in the spheroidized condition. Type 01 stock replaces the 46S40 class C-5.

Type 01 should be preheated slowly to 1,200°F, then transferred to an oven at 1,450°F and soaked at heat for about 20 minutes per inch of cross section, and then

quenched in warm oil (120° to 140°F). Do not remove the material from the oil bath until you can hold the work comfortably in your hand. This procedure should result in a minimum hardness of 65 Rc. Temper to the desired hardness.

HEAT-TREATING NONFERROUS METALS

The information in this section deals primarily with the heat-treating of nonferrous alloys. For specific information on a particular composition, consult the *Metals Handbook*, published by the American Society for Metals, or any handbook that deals with heat-treating nonferrous metals.

You can anneal most nonferrous metals by heating them uniformly within a certain temperature range, soaking them within this temperature range, and then cooling them back to room temperature. In most cases, the annealing temperature for most nonferrous metals is the temperature at which recrystallization takes place. For example, aluminum recrystallizes at a temperature of 300°F and copper recrystallizes at 390°F.

The rate at which the metal may be cooled from the annealing temperature depends upon the type of metal. If the metal is pure, or nearly so, or if it remains a solid solution without precipitation when cooled, any method of cooling is usually satisfactory. If, on the other hand, the constituents precipitate during or after cooling, furnace cooling may be necessary for complete annealing to occur.

There are two types of heat treatment of nonferrous alloys—the solution treatment and the precipitation treatment. Some alloys require both treatments. Others require only the solution treatment.

The solution treatment consists of heating the alloy to the temperature at which the principal constituents go into solid solution, soaking the alloy at this temperature to produce a uniform structure, then cooling it at a rate fast enough to retain the solid solution at room temperature. You should remain aware that different alloys have different solution temperatures.

After a nonferrous alloy has been solution treated, it is in a form of supersaturated solid solution. For the alloy to attain maximum hardness and strength, excess hardening constituents that are soluble at room temperature must precipitate from the solid solution. After the precipitation is complete and the alloy has reached its full hardness and strength, it is said to be AGE HARDENED. Alloys that do not precipitate at

room temperature are given the precipitation treatment called artificial aging. Precipitation from aging or artificial aging usually causes an increase in hardness strength and a decrease in ductility.

The following definitions will aid you in understanding some of the terminology used in heat-treating nonferrous alloys:

- Homogenizing—a mill process that uses high temperature for prolonged periods to eliminate or decrease segregation in castings that are to be hot- or cold-worked. This process is usually used for copper alloys.

- Stress equalizing—a low temperature heat treatment used to balance stress in cold-worked material with decreasing mechanical strength properties induced by the cold-working. Nickel and nickel alloys may be subjected to this heat treatment, depending on their chemical composition, the fabrication requirements, and the intended usage of the parts made from the metals.

HEAT-TREATING PROBLEMS

No matter how carefully you follow instructions for heat-treating, you may occasionally find yourself with a job that just will not turn out right. To some extent you can avoid this problem by knowing in advance something about the many problems encountered in heat-treating metals and alloys. The most common heat-treating problems include (1) design problems, (2) cracking, (3) warping, (4) soft spots, (5) size changes, and (6) spalling, and (7) blistering.

DESIGN PROBLEMS

Although you are not usually in a position to do much, if anything, about the design of a piece to be heat treated, you should have some knowledge of the effects of design upon heat treatment. Unsatisfactory performance of tools and structural parts is often the result of poor design rather than poor materials, poor fabrication, or incorrect heat treatment. Errors in design cannot be corrected by heat treatment, but you can minimize the problems of heat-treating a poorly designed piece if you know how to compensate for design errors when heat-treating the piece.

When a piece of metal is removed from the heat-treating furnace, its temperature is uniform throughout. Whether or not this piece will cool uniformly depends largely upon the design. Uniform cooling is, of course, a slightly inaccurate term; no piece of metal can cool

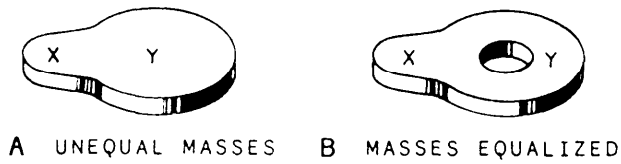


Figure 15-20.—Design of a cam. A. Unequal masses not satisfactory for heat treatment. B. Equalized masses satisfactory for heat treatment.

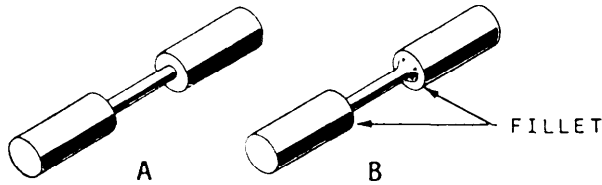


Figure 15-21.—A. Part with unequal masses and sharp corners. B. Use of fillet design to reduce danger of cracking during heat treatment.

with perfect uniformity, since some parts of it must always cool before others. In a well-designed piece, however, the cooling is as uniform as possible for a piece of that particular composition and size.

For example, consider the cooling of a cube of steel. The surfaces of the cube will cool evenly except at the edges and at the corners. At each edge there are two surfaces that dissipate heat at the same time, and at each corner there are three surfaces. Consequently, the corners cool more rapidly than the edges, and the edges cool more rapidly than the surface areas that are not at the edges or corners. If the rate of cooling is extremely rapid, the difference in cooling rate between corners, edges, and other surface areas could be sufficient to cause cracking.

Unequal masses in a single piece are likely to cause trouble when the piece is heat-treated. View A of figure 15-20 shows a cam that might very well become distorted or cracked during heat treatment because the mass of area X is smaller than the mass of area Y. View B of figure 15-20 shows how the masses of the two areas may be equalized, while still keeping the required shape of the cam. The design shown in view B would not be as likely to distort or crack during heat treatment.

The piece shown in view A of figure 15-21 has two design features that would make heat treatment difficult. First, it has unequal masses; and second, it has sharp junctions where the smaller mass joins the larger end portions. A better design for heat treatment is shown

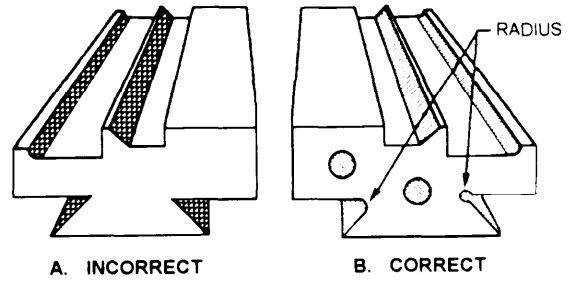


Figure 15-22.—Two designs for undercutting a form tool. A. Poor design. B. Correct design.

in view B of figure 15-21. Although the piece must necessarily have unbalanced masses, the use of a fillet (indicated by an arrow in figure 15-21, view B) at each junction of the smaller and the larger masses would tend to reduce the danger of the piece cracking from heat treatment.

Figure 15-22 shows two designs for undercutting form tools. The design shown in view A does not lend itself to heat treatment because of the combination of heavy and light sections and because of the sharp corners. The design shown in view B corrects both of these errors. The corners have been rounded where possible, and holes have been drilled through the two heaviest sections to make the masses more nearly balanced.

In general, parts that are designed with sharp corners or unequal masses are extremely difficult to heat-treat. When the design cannot be improved, you will have to determine the best way to heat-treat the part to reduce the chances of cracking or distortion.

Even with a poorly designed part, there are two ways in which you can usually reduce the problems of heat-treating. First, you can select the method of cooling that will be safest while still producing the required properties in the metal. For example, flush quenching of some areas might help to solve the problem. And second, you can shield the danger spots by packing them with fire-resistant cloth and sheet steel or other materials to reduce the rate of heating and the rate of cooling in the areas that would otherwise tend to distort or crack. Shielding materials for steel are usually fastened in place with soft iron wire; the wire must have a very low carbon content so it will not become hard and brittle and fall off during the heat treatment. Holes near an outside edge or between an edge and an interior opening are usually packed with asbestos rope.

CRACKING

Cracking during heat treatment may be caused by heating the material unevenly, by heating it to too high a temperature, by soaking it for too long a time, or by quenching it so it cools unevenly. Some steels are given extra preheats to minimize the danger of cracking from uneven heating. Steel that has been overheated or soaked should be allowed to cool in air to room temperature, and then it should be heated to the correct temperature. However, metals and alloys that have been severely overheated cannot be salvaged; they are actually burned, and no amount of subsequent heat treatment can restore them to their original condition.

Uneven cooling is a major cause of cracking, particularly in some steels. Factors that contribute to uneven cooling are poor design, the presence of scale or other material on the surface of the metal, and the presence of gas pockets in various recesses of the part. Scale should usually be removed before the material is quenched. Gas pockets in recesses of the part can be avoided by circulation or agitation of the quenching medium.

Tool steels that have been deformed or worked while cold tend to crack during hardening unless they are fully annealed before the hardening treatment is started. These steels must also be tempered immediately after they are hardened.

WARPING

Any change of shape in the form of a twist or a bend is known as warping. Poor design, uneven heating through the lower temperature range, and uneven cooling are common causes of warping. Preheating tends to minimize the danger of warping from uneven heating. Annealing parts before hardening them will sometimes prevent warping. This is particularly true of parts that are rough machined on one side and smooth ground on the other. Air-hardening steels tends to warp them if they are not protected from drafts while being cooled.

SOFT SPOTS

Soft spots in a hardened piece can usually be traced to the use of the wrong quenching medium, the use of incorrect quenching procedures, the presence of scale on some parts of the surface, or the use of the wrong kind of tongs for handling the material. Soft spots in case-hardened steels are usually caused by packing the pieces so they touch each other.

Soft spots will result when plain water is used as a quenching medium, if the vapor stage of the quench is not broken up. In this stage, air bubbles or air pockets form on the surface of the metal and retard the cooling rate wherever they touch the metal.

SIZE CHANGES

Some permanent change in dimensions may occur during heat treatment. In some cases this change of size is unavoidable. In others it is merely the result of incorrect heat treatment.

Oil-hardened and air-hardened steels tend to shrink during hardening. This size change is normal and cannot be prevented. However, it must be allowed for in the design of any part that must be precisely dimensioned. These steels tend to shrink excessively, more than the normal amount, if they are not heated sufficiently for hardening. They tend to increase in size if they are overheated. Very close control of temperature is necessary for successful heat treatment of these steels.

When metal scales, some of the surface metal is lost. Thus, scaling causes a decrease in size. Scaling can usually be prevented by controlling the furnace atmosphere. If furnaces with controlled atmospheres are not available, a fuels source such as a small block of wood or a small amount of charcoal can be placed in the furnace chamber. This will reduce the oxygen in an electric furnace to about 3%.

Nitrided steels increase in dimension during the nitriding process. This increase in size cannot be prevented, but parts to be nitrided should be machined slightly undersized to allow for the increase.

Steel that has been cold-drawn may undergo a permanent increase in size when it is heated, because cold-drawing leaves the metal highly stressed. The size increase in cold-drawn steel can be avoided by annealing the steel before machining the part to size.

Excessive shrinkage occurs whenever there is a great difference in the cooling rates of the outer and the inner portions of the metal being heat-treated. The flush quenching method should be used to prevent shrinkage of the metal being heat-treated.

SPALLING

Spalling is the surface cracking or flaking of steel. The cracks are usually very shallow, but in severe cases fairly large sections of the surface may peel away.

In carburized steel, spalling is caused by an undesired carbide network which forms of grain boundaries. To prevent in carburized steel, quench the parts immediately upon removing them from the carburized medium if the grains have not increased in size. If there has been an increase in grain size, reheat the metal to its critical temperature of the core and the case. Improper use of grinding wheels and insufficient use of coolant to keep the surface of the metal cool at all times will also cause spalling.

BLISTERING

Special care must be taken in heat-treating wrought aluminum alloy to prevent blistering. Blistering is caused by overheating and, in some cases, oversoaking. Overheated hardenable aluminum alloys are rendered useless because the eutectic constituent has melted.

HARDNESS TEST

A number of tests are used to measure the physical properties of metals and to determine whether a metal meets specification requirements. Some of the more common tests are hardness tests, tensile strength tests, shear strength tests, bend tests, fatigue tests, and compression tests. Of primary importance to a Machinery Repairman after heat-treating metal is the hardness test.

Most metals possess some degree of hardness—that is, the ability to resist penetration by another material. Many tests for hardness are used; the simplest is the file hardness test, which will be discussed later in this chapter. While fair estimates of hardness can be made by an experienced worker, more consistent quantitative measurements are obtained with standard hardness testing equipment.

Hardness may be measured by many types of instruments. The most common are the Rockwell and Brinell hardness testers. Other hardness tests include the Vickers, Eberbach, Monotron, Tukon, and Scleroscope. Since there are many tests and the hardness numbers derived are not equivalent, the hardness numbers must be designated according to the test and the scale used in the test. Comparison charts for the various hardness numbers can be found in the current edition of the *Machinery's Handbook*. Since you are more likely to have access to a Rockwell tester than any other, we will discuss this method.

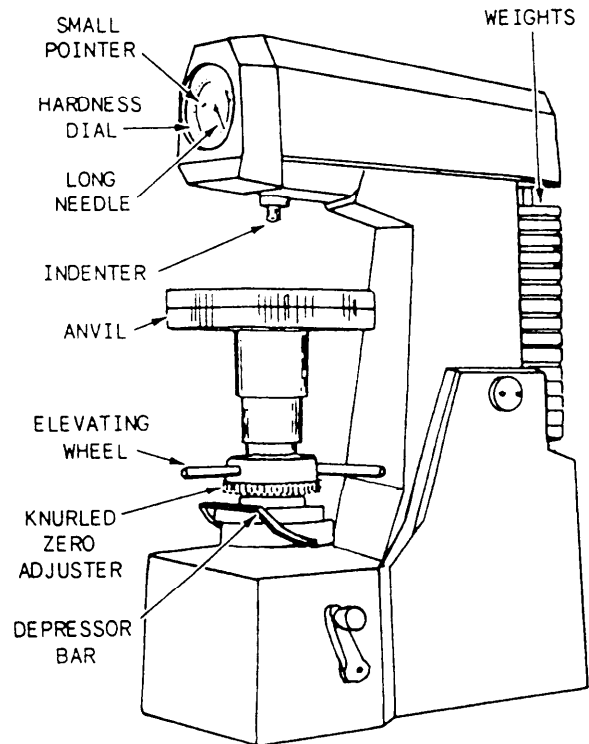


Figure 15-23.—Standard Rockwell hardness testing machine.

ROCKWELL HARDNESS TEST

Of all the hardness tests, the Rockwell is the one most frequently used. The basic principle of the Rockwell test (like that of the Brinell, Vickers, Eberbach, Tukron, and Monotron tests) is that a hard material will penetrate a softer one. This test operates on the principle of measuring the indentation, in a test piece of metal, made by a ball or cone of a specified size that is being forced against the test piece of metal with specified pressure. In the Rockwell tester, shown in figure 15-23, the hardness number is obtained by measuring the depression made by a hardened steel ball (indenter) or a spheroconical diamond penetrator of a given size under a given pressure.

With the normal Rockwell tester shown, the 120° spheroconical penetrator is used in conjunction with a 150-kilogram (kg) weight to make impressions in hard metals. The hardness number obtained is designated Rockwell C (Rc). For softer metals, the penetrator is a 1/16-inch steel ball used in conjunction with a 100-kg weight. A hardness number obtained under these conditions is designated Rockwell B (Rb).

Figure 15-24 illustrates the principle of indenter hardness tests. Although the conical penetrator is shown, the principle is the same for a ball penetrator.

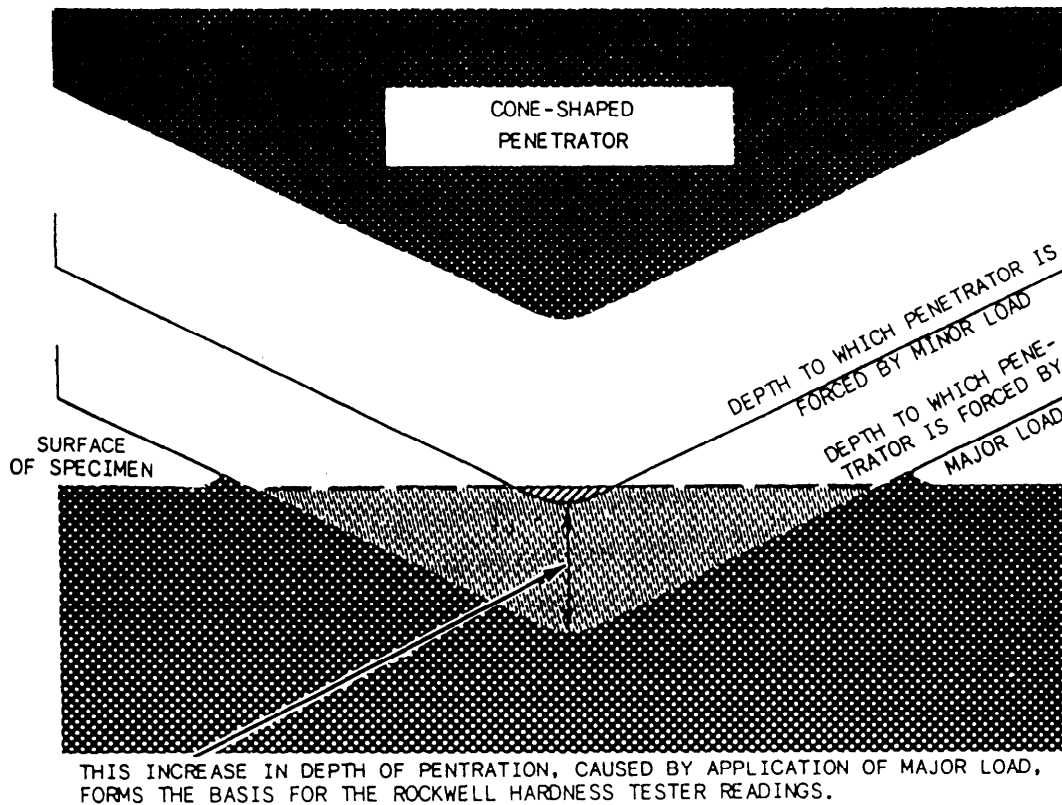


Figure 15-24.—Principle of the Rockwell hardness test.

(The geometry of the indentations will, of course, differ slightly.)

With the Rockwell tester, a deadweight, acting through a series of levers, is used to press the ball or cone into the surface of the metal to be tested. Then, the depth of penetration is measured. The softer the metal being tested, the deeper the penetration will be under a given load. The average depth of penetration on samples of very soft steel is only about 0.008 inch. The hardness is indicated on a dial, calibrated in the Rockwell B and the Rockwell C hardness scales. The harder the metal, the higher the Rockwell number will be. Ferrous metals are usually tested with the spheroconical penetrator, with hardness numbers being read from the Rockwell C scale. The steel ball is used for nonferrous metals, and the results are read on the B scale.

With most indenter-type hardness tests, the metal being tested must be sufficiently thick to avoid bulging or marking the opposite side. The specimen thickness should be at least 10 times the depth of penetration. It is also essential that the surface of the specimen be flat and clean. When hardness tests are necessary on thin material, a superficial Rockwell tester should be used.

The Rockwell superficial tester differs from the normal Rockwell tester in the amount of load applied to perform the test and in the kind of scale used to interpret the results. While the major loads on the normal tester are 100 and 150 kg, the major loads on the superficial tester are 15, 30, and 45 kg. One division on the dial gauge of the normal tester represents a vertical displacement of the indenter of 0.002 millimeter (mm). One division of the dial gauge of the superficial tester represents a vertical displacement of the indenter of 0.001 mm. Hardness scales for the Rockwell superficial tester are the N and T scales. The N scale is used for materials that, if they were thicker, would usually be tested with the normal tester using the C scale. The T scale is comparable to the B scale used with the normal tester. In other respects, the normal and superficial Rockwell testers are much alike.

Once you have prepared your sample for testing, refer to your testers operator manual for step-by-step operating instructions.

FILE HARDNESS TEST

The simplest method of testing a material's hardness is the file hardness test. This test cannot be

used to make positive identification of metals, but it can be used to get a general idea of the type of metal being tested and to compare the hardness of various metals on hand. Thus, when identification of metals by other means is not possible, you can use a file to determine the relative hardness of various metals. The results of such a test may enable you to select a metal suitable for the job being performed.

The file hardness test is simple to perform. You may hold the metal being tested in your hand and rested on a bench or put it in a vise. Grasp the file with your index finger extended along the file and apply the file slowly but firmly to the surface being tested.

If the material is cut by the file with extreme ease and tends to clog the spaces between the file teeth, it is VERY SOFT. If the material offers some resistance to

the cutting action of the file and tends to clog the file teeth, it is SOFT. If the material offers considerable resistance to the file but can be filed by repeated effort, it is HARD and may or may not have been treated. If the material can be removed only by extreme effort and in small quantities by the file teeth, it is VERY HARD and has probably been heat treated. If the file slides over the material and the file teeth are dulled, the material is EXTREMELY HARD and has been heat-treated.

The file test is not a scientific method. It should not be used when positive identification of metal is necessary or when an accurate measurement of hardness is required. Tests already described should be used for positive identification of metals. Special machines, such as the Rockwell and Brinell testers, should be used when it is necessary to determine accurately the hardness of the material.