6

Metals

Chapter Contents

Part II covers the four types of engineering materials: (1) metals, (2) ceramics, (3) polymers, and (4) composites. Metals are the most important engineering materials and the topic of this chapter. A *metal* is a category of materials generally characterized by properties of ductility, malleability, luster, and high electrical and thermal conductivity. The category includes both metallic elements and their alloys. Metals have properties that satisfy a wide variety of design requirements. The manufacturing processes by which they are shaped into products have been developed and refined over many years; indeed, some of the processes date from ancient times (Historical Note 1.2). In addition, the properties of metals can be enhanced through heat treatment, covered in Chapter 26.

The technological and commercial importance of metals derives from the following general properties possessed by virtually all of the common metals:

➢ *High stiffness and strength*. Metals can be alloyed for high rigidity, strength, and hardness; thus, they are used to provide the structural framework for most engineered products.

➢ *Toughness*. Metals have the capacity to absorb energy better than other classes of materials.

➢ *Good electrical conductivity*. Metals are conductors because of their metallic bonding that permits the free movement of electrons as charge carriers.

➢ *Good thermal conductivity*. Metallic bonding also explains why metals generally conduct heat better than ceramics or polymers.

In addition, certain metals have specific properties that make them attractive for specialized applications. Many common metals are available at relatively low cost per unit weight and are often the material of choice simply because of their low cost.

Metals are converted into parts and products using a variety of manufacturing processes. The starting form of the metal differs, depending on the process. The major categories are (1) *cast metal*, in which the initial form is a casting; (2) *wrought metal*, in which the metal has been worked or can be worked (e.g., rolled or otherwise formed) after casting; better mechanical properties are generally associated with wrought metals compared with cast metals; and (3) *powdered metal*, in which the metal is purchased in the form of very small powders for conversion into parts using powder metallurgy techniques. Most metals are available in all three forms. The discussion in this chapter focuses on categories (1) and (2), which are of greatest commercial and engineering interest. Powder metallurgy techniques are examined in Chapter 15.

Metals are classified into two major groups: (1) *ferrous*—those based on iron; and (2) *nonferrous*—all other metals. The ferrous group can be further subdivided into steels and cast irons. Most of the discussion in the present chapter is organized around this classification, but first the general topic of alloys and phase diagrams is introduced.

6.   Alloys and Phase Diagrams

Although some metals are important as pure elements (e.g., gold, silver, copper), most engineering applications require the improved properties obtained by alloying. Through alloying, it is possible to enhance strength, hardness, and other properties compared with pure metals. This section defines and classifies alloys; it then discusses phase diagrams which indicate the phases of an alloy system as a function of compo- sition and temperature.

6.1.1   *ALLOYS*

An alloy is a metal composed of two or more elements, at least one of which is metal- lic. The two main categories of alloys are (1) solid solutions and (2) intermediate phases.

Solid Solutions   A solid solution is an alloy in which one element is dissolved in another to form a single-phase structure. The term *phase* describes any homogeneous mass of material, such as a metal in which the grains all have the same crystal lattice structure. In a solid solution, the solvent or base element is metallic, and the dissolved element can be either metallic or nonmetallic. Solid solutions come in two forms, shown in Figure 6.1. The first is a *substitutional solid solution*, in which atoms of the solvent element are replaced in its unit cell by the dissolved element. Brass is an example, in which zinc is dissolved in copper. To make the substitution, several rules must be satisfied ([3], [6], [7]): (1) the atomic radii of the two elements must be simi- lar, usually within 15%; (2) their lattice types must be the same; (3) if the elements have different valences, the lower valence metal is more likely to be the solvent; and (4) if the elements have high chemical affinity for each other, they are less likely to form a solid solution and more likely to form a compound.

FIGURE 6.1 Two forms of solid solutions: (a) substitutional solid solution, and (b) interstitial solid solution.

(a)   (b)
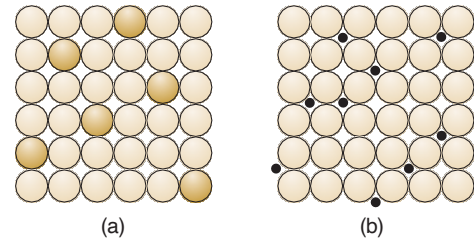
The second type of solid solution is an ***interstitial solid solution***, in which atoms of the dissolving element fit into the vacant spaces between base metal atoms in the lattice structure. It follows that the atoms fitting into these interstices must be small compared with those of the solvent metal. The most important example of this second type is carbon dissolved in iron to form steel.

In both forms of solid solution, the alloy structure is generally stronger and harder than either of the component elements.

Intermediate Phases   There are usually limits to the solubility of one element in another. When the amount of the dissolving element in the alloy exceeds the solid solubility limit of the base metal, a second phase forms in the alloy. The term ***intermediate phase*** is used to describe it because its chemical composition is intermediate between the two pure elements. Its crystalline structure is also different from those of the pure metals. Depending on composition, and recognizing that many alloys consist of more than two elements, these intermediate phases can be of several types, including (1) metallic compounds consisting of a metal and nonmetal such as Fe_3C; and (2) intermetallic compounds—two metals that form a compound, such as Mg_2Pb. The composition of the alloy is often such that the intermediate phase is mixed with the primary solid solution to form a two-phase structure, one phase dispersed throughout the second. These two-phase alloys are important because they can be formulated and heat-treated for significantly higher strength than solid solutions.

6.1.2 *PHASE DIAGRAMS*

As the term is used in this text, a phase diagram is a graphical means of representing the phases of a metal alloy system as a function of composition and temperature. Discussion of the diagram will be limited to alloy systems consisting of two elements at atmospheric pressures. This type of diagram is called a ***binary phase diagram***. Other forms of phase diagrams are discussed in texts on materials science, such as [6].

The Copper–Nickel Alloy System   The best way to introduce the phase diagram is by example. Figure 6.2 presents one of the simplest cases, the Cu–Ni alloy system. Composition is plotted on the horizontal axis and temperature on the vertical axis. Thus, any point in the diagram indicates the overall composition and the phase or phases present at the given temperature. Pure copper melts at 1083°C (1981°F), and pure nickel at 1455°C (2651°F). Alloy compositions between these extremes exhibit gradual melting that commences at the solidus and concludes at the liquidus as temperature is increased.

The copper–nickel system is a solid solution alloy throughout its entire range of compositions. Anywhere in the region below the solidus line, the alloy is a solid
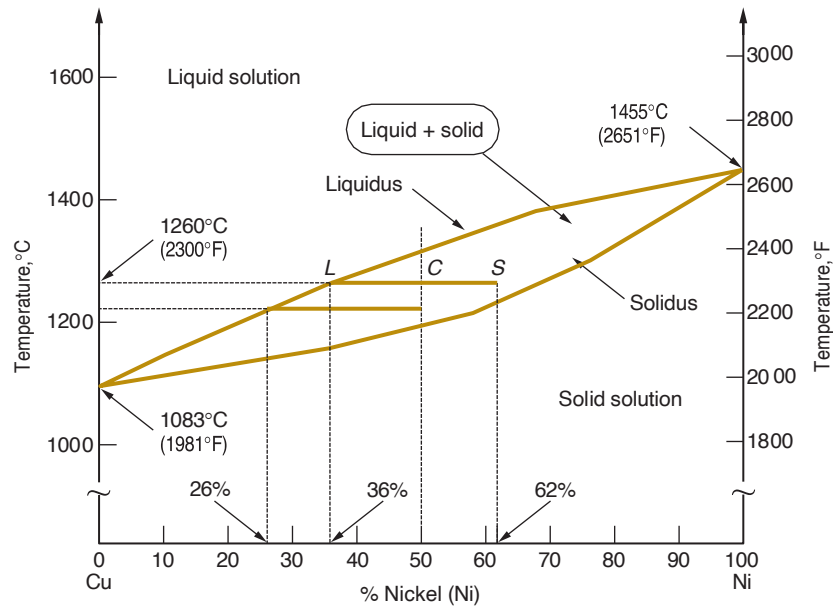
FIGURE 6.2 Phase diagram for the copper–nickel alloy system.

solution; there are no intermediate solid phases in this system. However, there is a mixture of phases in the region bounded by the solidus and liquidus. Recall from Section 4.1.3 that the solidus is the temperature at which the solid metal begins to melt as temperature is increased, and the liquidus is the temperature at which melting is completed. It can now be seen in the phase diagram that these temperatures vary with composition. Between the solidus and liquidus, the metal is a solid–liquid mix.

Determining Chemical Compositions of Phases   Although the overall composition of the alloy is given by its position along the horizontal axis, the compositions of the liquid and solid phases are not the same. It is possible to determine these compositions from the phase diagram by drawing a horizontal line at the temperature of interest. The points of intersection between the horizontal line and the solidus and liquidus indicate the compositions of the solid and liquid phases present, respectively. Simply construct the vertical projections from the intersection points to the *x*-axis and read the corresponding compositions.

Example 6.1 Determining compositions from the phase diagram	Analyze the compositions of the liquid and solid phases present in the copper-nickel system at an aggregate composition of 50% nickel and a temperature of 1260°C (2300°F). **Solution:** A horizontal line is drawn at the given temperature level as shown in Figure 6.2. The line intersects the solidus at a composition of 62% nickel, thus indicating the composition of the solid phase. The intersection with the liquidus occurs at a composition of 36% Ni, corresponding to the analysis of the liquid phase.

As the temperature of the 50–50 Cu–Ni alloy is reduced, the solidus line is reached at about 1221°C (2230°F). Applying the same procedure used in the example, the composition of the solid metal is 50% nickel, and the composition of the last remaining liquid to freeze is about 26% nickel. How is it, the reader might ask, that the last ounce of molten metal has a composition so different from the solid metal into which it freezes? The answer is that the phase diagram assumes equilibrium conditions are allowed to prevail. In fact, the binary phase diagram is sometimes called an equilibrium diagram because of this assumption. What it means is that enough time is permitted for the solid metal to gradually change its composition by diffusion to achieve the composition indicated by the intersection point along the liquidus. In practice, when an alloy freezes (e.g., a casting), *segregation* occurs in the solid mass because of nonequilibrium conditions. The first liquid to solidify has a composition that is rich in the metal element with the higher melting point. Then as additional metal solidifies, its composition is different from that of the first metal to freeze. As the nucleation sites grow into a solid mass, compositions are distributed within the mass, depending on the temperature and time in the process at which freezing occurred. The overall composition is the average of the distribution.

Determining Amounts of Each Phase   The amounts of each phase present at a given temperature can also be determined from the phase diagram. This is done by the *inverse lever rule*: (1) using the same horizontal line as before that indicates the overall composition at a given temperature, measure the distances between the aggregate composition and the intersection points with the liquidus and solidus, identifying the distances as *CL* and *CS*, respectively (refer back to Figure 6.2); (2) the proportion of liquid phase present is given by

$$L \text{ phase proportion} = \frac{CS}{(CS + CL)} \tag{6.1}$$

(3) the proportion of solid phase present is given by

$$S \text{ phase proportion} = \frac{CL}{(CS + CL)} \tag{6.2}$$

Example 6.2 Determining proportions of each phase	Determine the proportions of liquid and solid phases for the 50% nickel composition of the copper–nickel system at the temperature of 1260°C (2300°F). **Solution:** Using the same horizontal line in Figure 6.2 as in previous Example 6.1, the distances *CS* and *CL* are measured as 10 mm and 12 mm, respectively. Thus the proportion of the liquid phase is 10/22 = 0.45 (45%), and the proportion of solid phase is 12/22 = 0.55 (55%).

The proportions given by Eqs. (6.1) and (6.2) are by weight, same as the phase diagram percentages. Note that the proportions are based on the distance on the opposite side of the phase of interest; hence the name inverse lever rule. One can see the logic in this by taking the extreme case when, say, *CS* = 0; at that point, the proportion of the liquid phase is zero because the solidus has been reached and the alloy is therefore completely solidified.

The methods for determining chemical compositions of phases and the amounts of each phase are applicable to the solid region of the phase diagram as well as the liquidus–solidus region. Wherever there are regions in the phase diagram in which two phases are present, these methods can be used. When only one phase is present (in Figure 6.2, this is the entire solid region), the composition of the phase is its aggregate composition under equilibrium conditions; and the inverse lever rule does not apply because there is only one phase.

The Tin–Lead Alloy System A more complicated phase diagram is the Sn–Pb system, shown in Figure 6.3. Tin–lead alloys have traditionally been used as solders for making electrical and mechanical connections (Section 30.2).[1] The phase diagram exhibits several features not included in the previous Cu–Ni system. One feature is the presence of two solid phases, alpha (*a*) and beta (*b*). The *a* phase is a solid solution of tin in lead at the left side of the diagram, and the *b* phase is a solid solution of lead in tin that occurs only at elevated temperatures around 200°C (375°F) at the right side of the diagram. Between these solid solutions lies a mixture of the two solid phases, *a* + *b*.

Another feature of interest in the tin–lead system is how melting differs for different compositions. Pure tin melts at 232°C (449°F), and pure lead melts at 327°C (621°F). Alloys of these elements melt at lower temperatures. The diagram shows two liquidus lines that begin at the melting points of the pure metals and meet at a composition of 61.9% Sn. This is the eutectic composition for the tin–lead system. In general, a *eutectic alloy* is a particular composition in an alloy system for which the solidus and liquidus are at the same temperature. The correspond- ing *eutectic temperature*, the melting point of the eutectic composition, is 183°C (362°F) in the present case. The eutectic temperature is always the lowest melt- ing point for an alloy system (eutectic is derived from the Greek word *eutektos*, meaning easily melted).
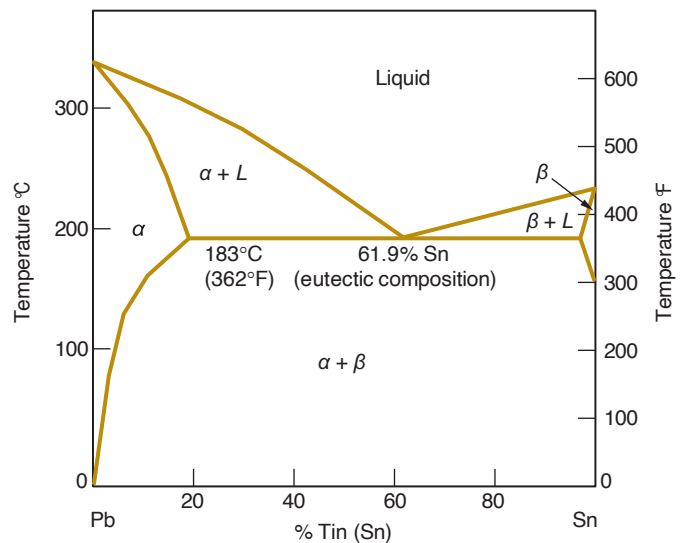

FIGURE 6.3 Phase diagram for the tin–lead alloy system.

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[1]Because lead is a poisonous substance, alternative alloying elements have been substituted for lead in many commercial solders. These are called lead-free solders.

TABLE • 6.1 Basic data on the metallic elements: (a) iron.

Symbol:	Fe
Atomic number:	26
Specific gravity:	7.87
Crystal structure:	BCC
Melting temperature:	1539°C (2802°F)
Elastic modulus:	209,000 MPa (30 X 10^6 lb/in^2)
Principal ore:	**Hematite** (Fe_2O_3)
Alloying elements:	Carbon; also chromium, manganese, nickel, molybdenum, vanadium, and silicon.
Typical applications:	Construction, machinery, automotive, railway tracks and equipment.

Compiled from [6], [11], [12], and other references.

Methods for determining the chemical analysis of the phases and the proportions of phases present can be readily applied to the Sn–Pb system just as it was used in the Cu–Ni system. In fact, these methods are applicable in any region containing two phases, including two solid phases. Most alloy systems are characterized by the existence of multiple solid phases and eutectic compositions, and so the phase diagrams of these systems are often similar to the tin–lead diagram. Of course, many alloy systems are considerably more complex, for example, the iron-carbon system, considered next.

6.2 Ferrous Metals

The ferrous metals are based on iron, one of the oldest metals known to humans (Historical Note 6.1). The properties and other data relating to iron are listed in Table 6.1(a). The ferrous metals of engineering importance are alloys of iron and carbon. These alloys divide into two major groups: steel and cast iron. Together, they constitute approximately 85% of the metal tonnage in the United States [6]. The discussion of ferrous metals begins with the iron–carbon phase diagram.

Historical Note 6.1   *Iron and steel*

Iron was discovered sometime during the Bronze Age. It was probably uncovered from ashes of fires built near iron ore deposits. Use of the metal grew, finally surpassing bronze in importance. The Iron Age is usually dated from about 1200 B.C.E, although artifacts made of iron have been found in the Great Pyramid of Giza in Egypt, which dates to 2900 B.C.E. Iron-smelting furnaces have been discovered in Israel dating to 1300 B.C.E. Iron chariots, swords, and tools were made in ancient Assyria (northern Iraq) around 1000 B.C.E. The Romans inherited ironworking from their provinces, mainly Greece, and they developed the technology to new heights, spreading it throughout Europe. The ancient civilizations learned that iron was harder than bronze and that it took a sharper, stronger edge.

During the Middle Ages in Europe, the invention of the cannon created the first real demand for iron; only then did it finally exceed copper and bronze in usage. Also, the cast iron stove, the appliance of the seventeenth and eighteenth centuries, significantly increased demand for iron (Historical Note 11.3).

In the nineteenth century, industries such as railroads, shipbuilding, construction, machinery, and the military created a dramatic growth in the demand for iron and steel in Europe and America. Although large quantities of (crude) **pig iron** could be produced by **blast furnaces**, the subsequent processes

for producing wrought iron and steel were slow. The necessity to improve productivity of these vital metals was the "mother of invention." Henry Bessemer developed the process of blowing air up through the molten iron that led to the **Bessemer converter** (patented in 1856). Pierre and Emile Martin in France built the first **open hearth furnace** in 1864. These methods permitted up to 15 tons of steel to be produced in a single batch (heat), a substantial increase from previous methods.

In the United States, expansion of the railroads after the Civil War created a huge demand for steel. In the 1880s and 1890s, steel beams were first used in significant quantities in construction. Skyscrapers came to rely on these steel frames.

When electricity became available in abundance in the late 1800s, this energy source was used for steelmaking. The first commercial **electric furnace** for production of steel was operated in France in 1899. By 1920, this had become the principal process for making alloy steels.

The use of pure oxygen in steelmaking was initiated just before World War II in several European countries and the United States. Work in Austria after the war culminated in the development of the **basic oxygen furnace** (BOF). This has become the leading modern technology for producing steel, surpassing the open hearth method around 1970. The Bessemer converter had been surpassed by the open hearth method around 1920 and ceased to be a commercial steelmaking process in 1971.

6.2.1 THE IRON–CARBON PHASE DIAGRAM

The iron–carbon phase diagram is shown in Figure 6.4. Pure iron melts at 1539°C (2802°F). During the rise in temperature from ambient, it undergoes several solid phase transformations as indicated in the diagram. Starting at room temperature the phase is alpha (a), also called **ferrite**. At 912°C (1674°F), ferrite transforms to gamma (g), called **austenite**. This, in turn, transforms at 1394°C (2541°F) to delta (d), which remains until melting occurs. The three phases are distinct; alpha and delta have BCC lattice structures (Section 2.3.1), and between them, gamma is FCC.
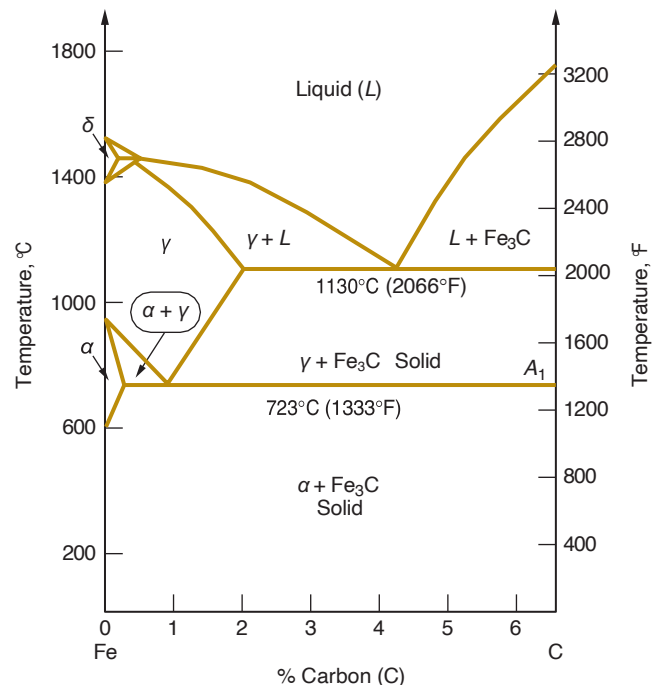

FIGURE 6.4 Phase diagram for iron–carbon system, up to about 6% carbon.

Iron as a commercial product is available at various levels of purity. ***Electrolytic iron*** is the most pure, at about 99.99%, for research and other purposes where the pure metal is required. ***Ingot iron***, containing about 0.1% impurities (including about 0.01% carbon), is used in applications in which high ductility or corrosion resistance are needed. ***Wrought iron*** contains about 3% slag but very little carbon, and is easily shaped in hot forming operations such as forging.

Solubility limits of carbon in iron are low in the ferrite phase—only about 0.022% at 723°C (1333°F). Austenite can dissolve up to about 2.1% carbon at a temperature of 1130°C (2066°F). This difference in solubility between alpha and gamma leads to opportunities for strengthening by heat treatment, but leave that for Chapter 26. Even without heat treatment, the strength of iron increases dramatically as carbon content increases, and the metal is called steel. More precisely, ***steel*** is defined as an iron–carbon alloy containing from 0.02% to 2.11% carbon.[2] Of course, steels can also contain other alloying elements as well.

The diagram indicates a eutectic composition at 4.3% carbon. There is a similar feature in the solid region of the diagram at 0.77% carbon and 723°C (1333°F). This is called the ***eutectoid composition***. Steels below this carbon level are known as ***hypoeutectoid steels***, and above this carbon level, from 0.77% to 2.1%, they are called ***hypereutectoid steels***.

In addition to the phases mentioned, one other phase is prominent in the iron–carbon alloy system. This is Fe_3C, also known as ***cementite***, an intermediate phase. It is a metallic compound of iron and carbon that is hard and brittle. At room temperature under equilibrium conditions, iron–carbon alloys form a two-phase system at carbon levels even slightly above zero. The carbon content in steel ranges between these very low levels and about 2.1% C. Above 2.1% C, up to about 4% or 5%, the alloy is defined as ***cast iron***.

6.2.2   *IRON AND STEEL PRODUCTION*

Coverage of iron and steel production begins with the iron ores and other raw materials required. Iron-making is then discussed, in which iron is reduced from the ores, and steelmaking, in which the iron is refined to obtain the desired purity and composition (alloying) of steel. The casting processes accomplished at the steel mill are then considered.

Iron Ores and Other Raw Materials   The principal ore used in the production of iron and steel is ***hematite*** (Fe_2O_3). Other iron ores include ***magnetite*** (Fe_3O_4), ***siderite*** ($FeCO_3$), and ***limonite*** (Fe_2O_3-$x$$H_2O$, in which x is typically around 1.5). Iron ores contain from 50% to around 70% iron, depending on grade (hematite is almost 70% iron). In addition, scrap iron and steel are widely used today as raw materials in iron- and steelmaking.

Other raw materials needed to reduce iron from the ores are coke and limestone. ***Coke*** is a high carbon fuel produced by heating bituminous coal in a limited oxygen atmosphere for several hours, followed by water spraying in special quenching towers. Coke serves two functions in the reduction process: (1) it is a fuel that

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[2] This is the conventional definition of steel, but exceptions exist. A recently developed steel for sheet metal forming, called ***interstitial-free steel***, has a carbon content of only 0.005%. It is discussed in Section 6.2.3.

supplies heat for the chemical reactions; and (2) it produces carbon monoxide (CO) to reduce the iron ore. **Limestone** is a rock containing high proportions of calcium carbonate ($CaCO_3$). The limestone is used in the process as a flux to react with and remove impurities in the molten iron as slag.

Iron-making   To produce iron, a charge of ore, coke, and limestone are dropped into the top of a blast furnace. A **blast furnace** is a refractory-lined chamber with a diameter of about 9 to 11 m (30–35 ft) at its widest and a height of 40 m (125 ft), in which hot gases are forced into the lower part of the chamber at high rates to accom- plish combustion and reduction of the iron. A typical blast furnace and some of its technical details are illustrated in Figures 6.5 and 6.6. The charge slowly descends from the top of the furnace toward the base and is heated to temperatures around 1650°C (3000°F). Burning of the coke is accomplished by the hot gases (CO, H_2, CO_2, H_2O, N_2, O_2, and fuels) as they pass upward through the layers of charge material. The carbon monoxide is supplied as hot gas, and it is also formed from combustion of coke. The CO gas has a reducing effect on the iron ore; the reaction (simplified) can be written as follows (using hematite as the starting ore):
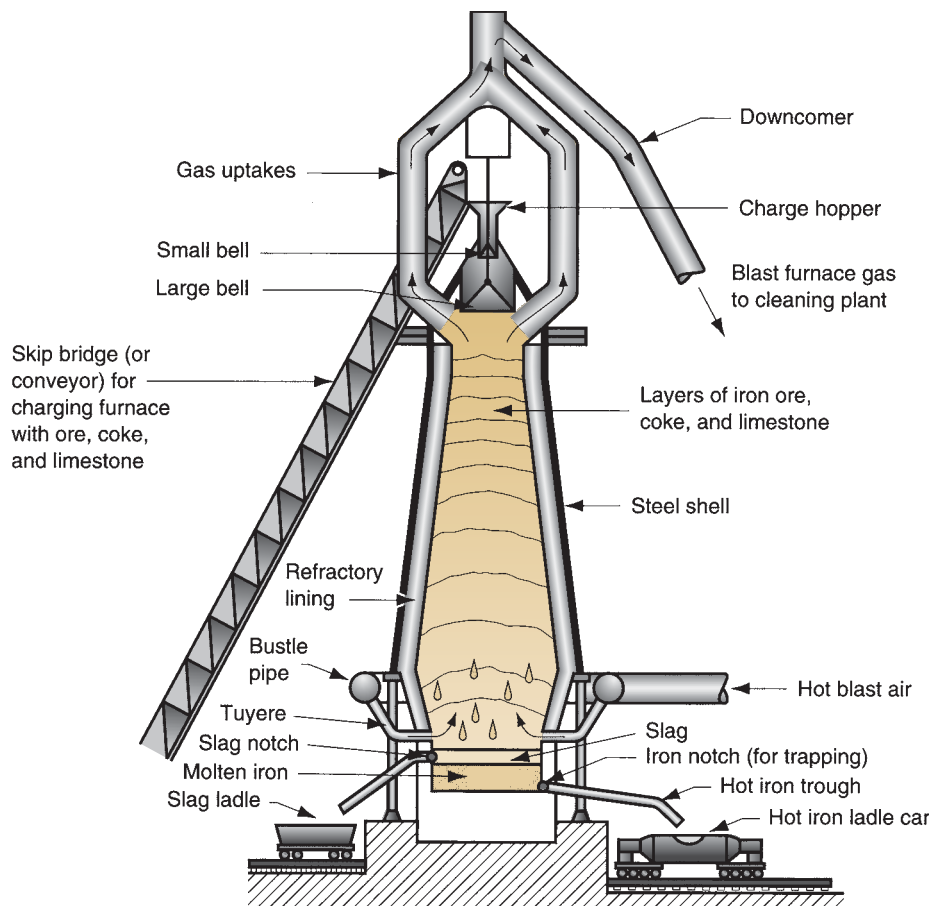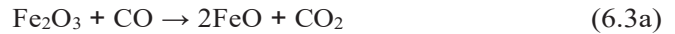
$$Fe_2O_3 + CO \rightarrow 2FeO + CO_2 \tag{6.3a}$$

FIGURE 6.5 Cross section of ironmaking blast furnace showing major components.

Iron ore, coke, and limestone

Gas to cleaning and reheating

Typical temperature profile

200°C (400°F)

800°C (1500°F)

Direction of motion of charge material

1100°C (2000°F)

Direction of motion of hot gases

1400°C (2500°F)

1650°C (3000°F)

Hot blast air

Slag

Molten pig iron

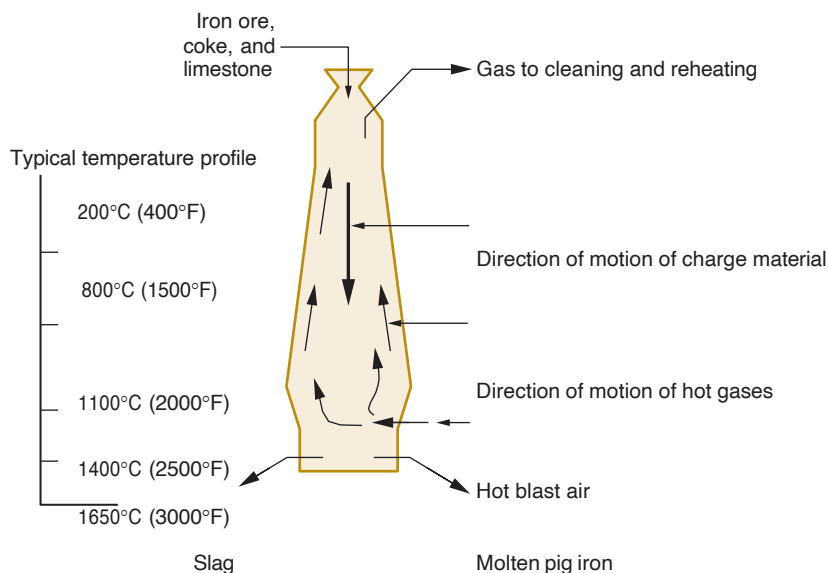**FIGURE 6.6**
Schematic diagram indicating details of the blast furnace operation.

Carbon dioxide reacts with coke to form more carbon monoxide:

$$CO_2 + C\,(coke) \rightarrow 2CO \qquad (6.3b)$$

which then accomplishes the final reduction of FeO to iron:

$$FeO + CO \rightarrow Fe + CO_2 \qquad (6.3c)$$

The molten iron drips downward, collecting at the base of the blast furnace. This is periodically tapped into hot iron ladle cars for transfer to subsequent steelmaking operations.

The role played by limestone can be summarized as follows. First the limestone is reduced to lime (CaO) by heating, as follows:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (6.4)$$

The lime combines with impurities such as silica (SiO_2), sulfur (S), and alumina (Al_2O_3) in reactions that produce a molten slag that floats on top of the iron.

It is instructive to note that approximately 7 tons of raw materials are required to produce 1 ton of iron. The ingredients are proportioned about as follows: 2.0 tons of iron ore, 1.0 ton of coke, 0.5 ton of limestone, and (here's the amazing statistic) 3.5 tons of gases. A significant proportion of the byproducts are recycled.

The iron tapped from the base of the blast furnace (called ***pig iron***) contains more than 4% C, plus other impurities: 0.3–1.3% Si, 0.5–2.0% Mn, 0.1–1.0% P, and 0.02–0.08% S [11]. Further refinement of the metal is required for both cast iron and steel. A furnace called a ***cupola*** (Section 11.4.1) is commonly used for converting pig iron into gray cast iron. For steel, compositions must be more closely controlled and impurities brought to much lower levels.

Steelmaking   Since the mid–1800s, a number of processes have been developed for refining pig iron into steel. Today, the two most important processes are the basic oxygen furnace (BOF) and the electric furnace. Both are used to produce carbon and alloy steels.
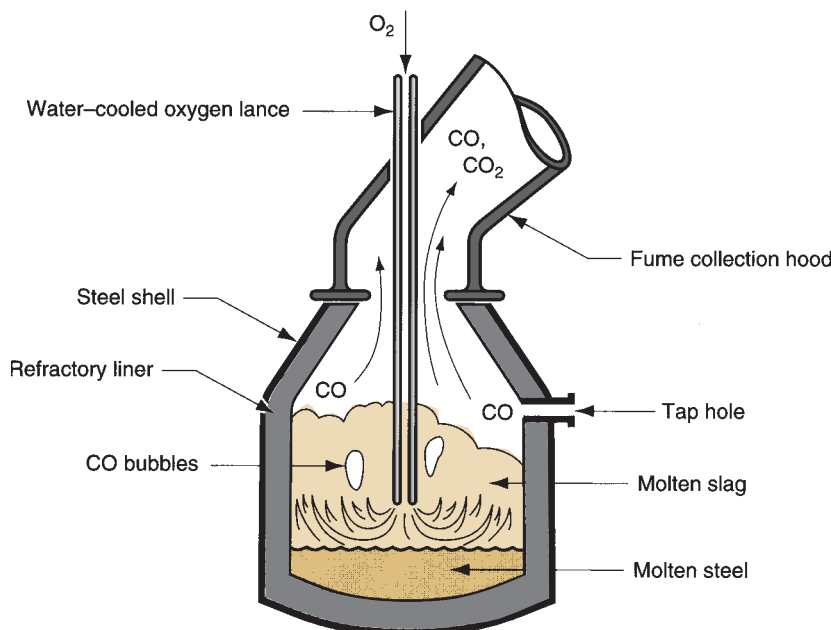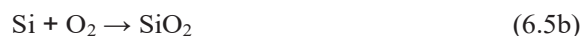
FIGURE 6.7 Basic oxygen furnace showing BOF vessel during processing of a heat.

The ***basic oxygen furnace*** accounts for about 70% of U.S. steel production. The BOF is an adaptation of the Bessemer converter. Whereas the Bessemer process used air blown up through the molten pig iron to burn off impurities, the basic oxygen process uses pure oxygen. A diagram of the conventional BOF during the middle of a heat is illustrated in Figure 6.7. The typical BOF vessel is about 5 m (16 ft) inside diameter and can process 150 to 200 tons in a heat.

The BOF steelmaking sequence is shown in Figure 6.8. Integrated steel mills transfer the molten pig iron from the blast furnace to the BOF in railway cars called hot-iron ladle cars. In modern practice, steel scrap is added to the pig iron, accounting for about 30% of a typical BOF charge. Lime (CaO) is also added. After charging, the lance is inserted into the vessel so that its tip is about 1.5 m (5 ft) above the surface of the molten iron. Pure O_2 is blown at high velocity through the lance, causing combustion and heating at the surface of the molten pool. Carbon dissolved in the iron and other impurities such as silicon, manganese, and phosphorus are oxidized. The reactions are

$$2C + O_2 \rightarrow 2CO \text{ (CO}_2 \text{ is also produced)} \tag{6.5a}$$

$$Si + O_2 \rightarrow SiO_2 \tag{6.5b}$$

$$2Mn + O_2 \rightarrow 2MnO \tag{6.5c}$$

$$4P + 5O_2 \rightarrow 2P_2O_5 \tag{6.5d}$$

The CO and CO_2 gases produced in the first reaction escape through the mouth of the BOF vessel and are collected by the fume hood; the products of the other three reactions are removed as slag, using the lime as a fluxing agent. The C content in the iron decreases almost linearly with time during the process, thus permit- ting fairly predictable control over carbon levels in the steel. After refining to the
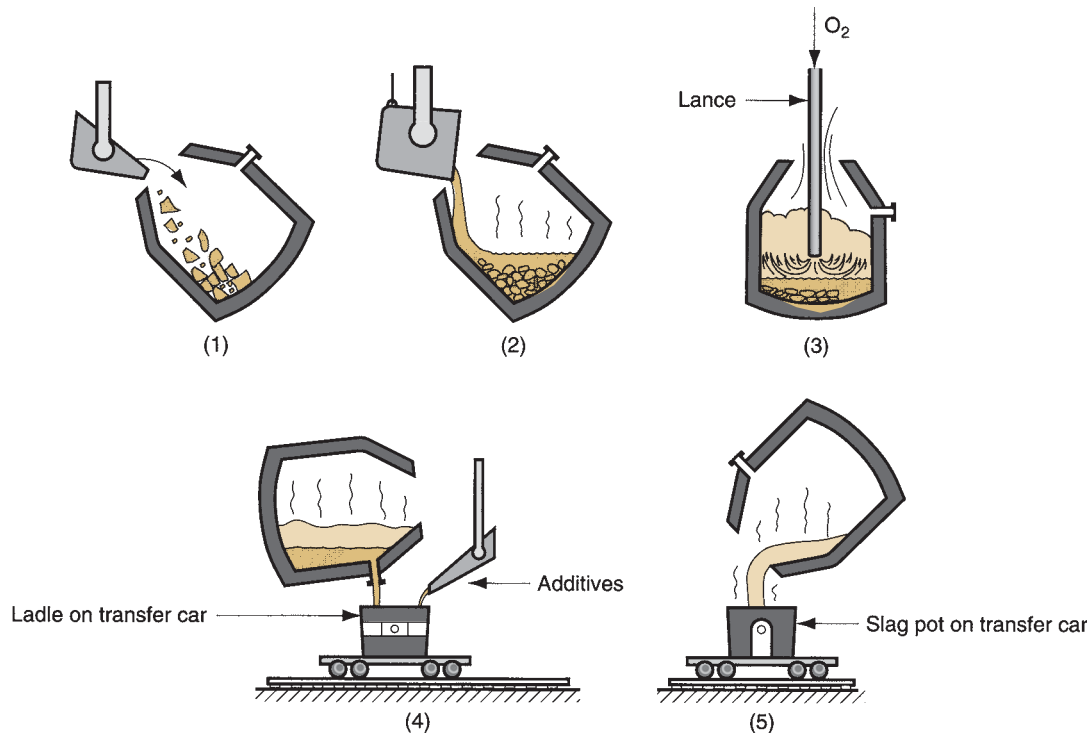
FIGURE 6.8 BOF sequence during processing cycle: (1) charging of scrap and (2) pig iron; (3) blowing (Figure 6.7); (4) tapping the molten steel; and (5) pouring off the slag.

desired level, the molten steel is tapped; alloying ingredients and other additives are poured into the heat; then the slag is poured. A 200-ton heat of steel can be processed in about 20 min, although the entire cycle time (tap-to-tap time) takes about 45 min.

Recent advances in the technology of the basic oxygen process include the use of nozzles in the bottom of the vessel through which oxygen is injected into the molten iron. This allows better mixing than the conventional BOF lance, resulting in shorter processing times (a reduction of about 3 min), lower carbon contents, and higher yields.

The *electric arc furnace* accounts for about 30% of U.S. steel production. Although pig iron was originally used as the charge in this type of furnace, scrap iron and scrap steel are the primary raw materials today. Electric arc furnaces are available in several designs; the direct arc type shown in Figure 6.9 is currently the most economical type. These furnaces have removable roofs for charging from above; tapping is accomplished by tilting the entire furnace. Scrap iron and steel selected for their compositions, together with alloying ingredients and limestone (flux), are charged into the furnace and heated by an electric arc that flows between large electrodes and the charge metal. Complete melting requires about 2 hours; tap-to-tap time is 4 hours. Capacities of electric furnaces commonly range between 25 and 100 tons per heat. Electric arc furnaces are noted for better quality steel but higher cost per ton, compared with the BOF. The electric arc furnace is generally associated with production of alloy steels, tool steels, and stainless steels.
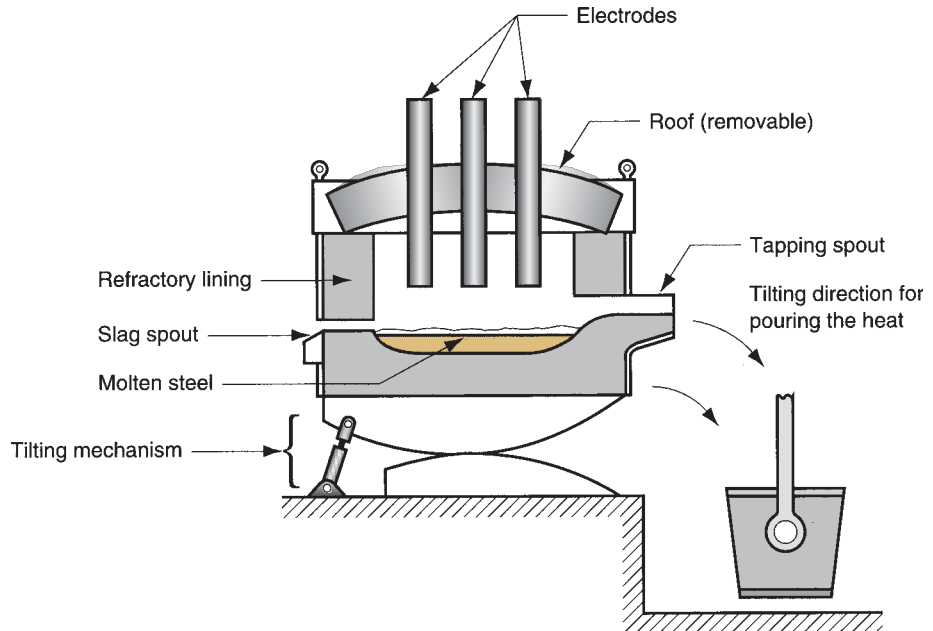
FIGURE 6.9 Electric arc furnace for steelmaking.

Casting of Ingots   Steels produced by BOF or electric furnace are solidified for subsequent processing either as cast ingots or by continuous casting. Steel *ingots* are large discrete castings weighing from less than 1 ton up to around 300 tons (the weight of an entire heat). Ingot molds are made of high carbon iron and are tapered at the top or bottom for removal of the solid casting. A *big-end-down mold* is illustrated in Figure 6.10. The cross section may be square, rectangular, or round, and the perimeter is usually corrugated to increase surface area for faster cooling. The mold is placed on a platform called a *stool*; after solidification the mold is lifted, leaving the casting on the stool.

The solidification process for ingots as well as other castings is described in Chapter 10 on casting fundamentals. Because ingots are such large castings, the time required for solidification and the associated shrinkage are significant. Porosity caused by the reaction of carbon and oxygen to form CO during cooling and solidification is a problem that must be addressed in ingot casting. These gases are liberated from the molten steel because of their reduced solubility with decreasing temperature. Cast steels are often treated to limit or prevent CO gas evolution
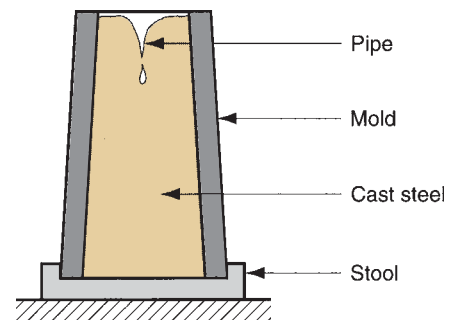
FIGURE 6.10 A big-end-down ingot mold typical of type used in steelmaking.

during solidification. The treatment involves adding elements such as Si and Al that react with the oxygen dissolved in the molten steel, so it is not available for CO reaction. The structure of the solid steel is thus free of pores and other defects caused by gas formation.

Continuous Casting   Continuous casting is widely applied in aluminum and copper production, but its most noteworthy application is in steelmaking. The process is replacing ingot casting because it dramatically increases productivity. Ingot casting is a discrete process. Because the molds are relatively large, solidification time is significant. For a large steel ingot, it may take 10 to 12 hours for the casting to solidify. The use of continuous casting reduces solidification time by an order of magnitude.

The continuous casting process, also called *strand casting*, is illustrated in Figure 6.11. Molten steel is poured from a ladle into a temporary container called a *tundish*, which dispenses the metal to one or more continuous casting molds. The steel begins to solidify at the outer regions as it travels down through the water-cooled mold. Water sprays accelerate the cooling process. While still hot and plastic, the metal is bent from vertical to horizontal orientation. It is then cut into sections or fed continuously into a rolling mill (Section 18.1) in which it is formed into plate or sheet stock or other cross sections.

FIGURE 6.11
Continuous casting; steel is poured into tundish and distributed to a water-cooled continuous casting mold; it solidifies as it travels down through the mold. Thickness of slab is exaggerated for clarity.

6.2.3 *STEELS*

As defined earlier, ***Steel*** is an alloy of iron that contains carbon ranging by weight between 0.02% and 2.11% (most steels range between 0.05% and 1.1% C). It often includes other alloying ingredient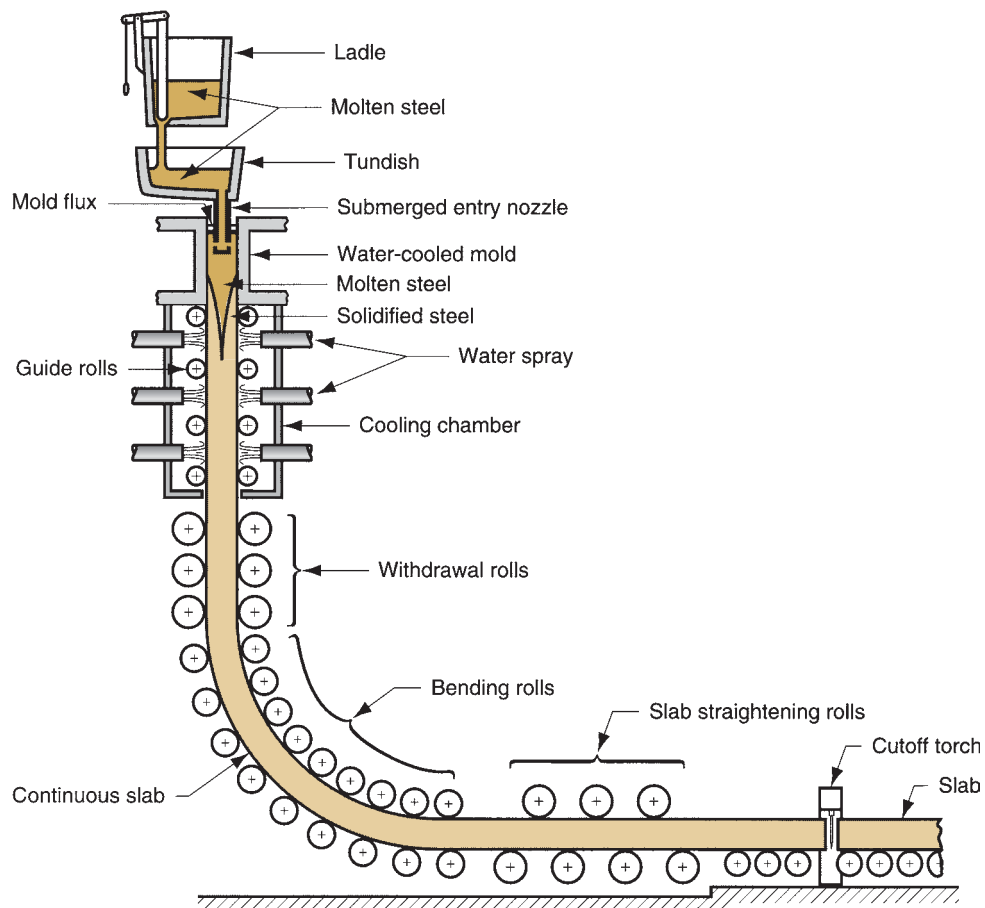s, such as manganese, chromium, nickel, and/or molybdenum; but it is the carbon content that turns iron into steel. Hundreds of compositions of steel are available commercially. For purposes of organization here, the vast majority of commercially important steels can be grouped into the following categories: (1) plain carbon steels, (2) low alloy steels, (3) stainless steels, (4) tool steels, and (5) specialty steels.

Plain Carbon Steels   These steels contain carbon as the principal alloying element, with only small amounts of other elements (about 0.4% manganese plus lesser amounts of silicon, phosphorus, and sulfur). The strength of plain carbon steels increases with carbon content. A typical plot of the relationship is illustrated in Figure 6.12. As seen in the phase diagram for iron and carbon (Figure 6.4), steel at room temperature is a mixture of ferrite (*a*) and cementite (Fe_3C). The cementite particles distributed throughout the ferrite act as obstacles to the movement of dislocations during slip (Section 2.3.3); more carbon leads to more barriers, and more barriers mean stronger and harder steel.

According to a designation scheme developed by the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE), plain carbon steels are specified by a four-digit number system: 10XX, where 10 indicates that the steel is plain carbon, and XX indicates the percent of carbon in hundredths of percentage points. For example, 1020 steel contains 0.20% C. The plain carbon steels are typically classified into three groups according to their carbon content:

1. ***Low carbon steels*** contain less than 0.20% C and are by far the most widely used steels. Typical applications are automobile sheet-metal parts, plate steel for fabrication, and railroad rails. These steels are relatively easy to form, which accounts for their popularity where high strength is not required. Steel castings usually fall into this carbon range, also.
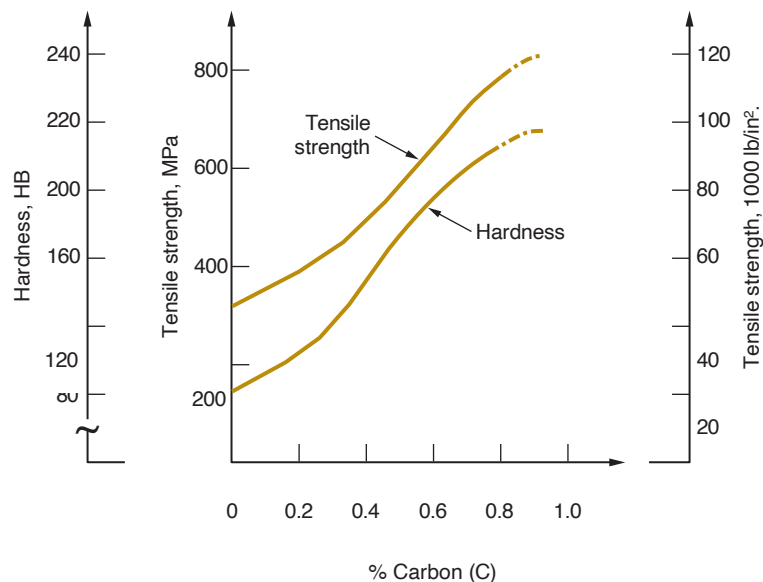

FIGURE 6.12 Tensile strength and hardness as a function of carbon content in plain carbon steel (hot-rolled, unheat-treated).

2. **Medium carbon steels** range in carbon between 0.20% and 0.50% and are specified for applications requiring higher strength than the low-C steels. Applications include machinery components and engine parts such as crankshafts and connecting rods.

3. **High carbon steels** contain carbon in amounts greater than 0.50%. They are specified for still higher strength applications and where stiffness and hardness are needed. Springs, cutting tools and blades, and wear-resistant parts are examples.

Increasing carbon content strengthens and hardens the steel, but its ductility is reduced. Also, high carbon steels can be heat treated to form martensite, making the steel very hard and strong (Section 26.2).

Low Alloy Steels Low alloy steels are iron–carbon alloys that contain additional alloying elements in amounts totaling less than about 5% by weight. Owing to these additions, low alloy steels have mechanical properties that are superior to those of the plain carbon steels for given applications. Superior properties usually mean higher strength, hardness, hot hardness, wear resistance, toughness, and more desirable combinations of these properties. Heat treatment is often required to achieve these improved properties.

Common alloying elements added to steel are chromium, manganese, molybdenum, nickel, and vanadium, sometimes individually but usually in combinations. These elements typically form solid solutions with iron and metallic compounds with carbon (carbides), assuming sufficient carbon is present to support a reaction. The effects of the principal alloying ingredients can be summarized as follows:

➢ **Chromium** (Cr) improves strength, hardness, wear resistance, and hot hardness. It is one of the most effective alloying ingredients for increasing hardenability (Section 26.2.3). In significant proportions, Cr improves corrosion resistance.

➢ **Manganese** (Mn) improves the strength and hardness of steel. When the steel is heat treated, hardenability is improved with increased manganese. Because of these benefits, manganese is a widely used alloying ingredient in steel.

➢ **Molybdenum** (Mo) increases toughness and hot hardness. It also improves hardenability and forms carbides for wear resistance.

➢ **Nickel** (Ni) improves strength and toughness. It increases hardenability but not as much as some of the other alloying elements in steel. In significant amounts it improves corrosion resistance and is the other major ingredient (besides chromium) in certain types of stainless steel.

➢ **Vanadium** (V) inhibits grain growth during elevated temperature processing and heat treatment, which enhances strength and toughness of steel. It also forms carbides that increase wear resistance.

The AISI-SAE designations of many of the low alloy steels are presented in Table 6.2, which indicates nominal chemical analysis. As before, carbon content is specified by XX in 1/100% of carbon. For completeness, plain carbon steels (10XX) are included. To obtain an idea of the properties possessed by some of these steels, Table 6.3 lists the treatment to which the steel is subjected for strengthening and its strength and ductility.

TABLE • 6.2 AISI-SAE designations of steels.

Code	Name of Steel	Nominal Chemical Analysis, %							
		Cr	Mn	Mo	Ni	V	P	S	Si
10XX	Plain carbon		0.4				0.04	0.05	
11XX	Resulfurized		0.9				0.01	0.12	0.01
12XX	Resulfurized, rephosphorized		0.9				0.10	0.22	0.01
13XX	Manganese		1.7				0.04	0.04	0.3
20XX	Nickel steels		0.5		0.6		0.04	0.04	0.2
31XX	Nickel–chrome	0.6			1.2		0.04	0.04	0.3
40XX	Molybdenum		0.8	0.25			0.04	0.04	0.2
41XX	Chrome–molybdenum	1.0	0.8	0.2			0.04	0.04	0.3
43XX	Ni–Cr–Mo	0.8	0.7	0.25	1.8		0.04	0.04	0.2
46XX	Nickel–molybdenum		0.6	0.25	1.8		0.04	0.04	0.3
47XX	Ni–Cr–Mo	0.4	0.6	0.2	1.0		0.04	0.04	0.3
48XX	Nickel–molybdenum		0.6	0.25	3.5		0.04	0.04	0.3
50XX	Chromium	0.5	0.4				0.04	0.04	0.3
52XX	Chromium	1.4	0.4				0.02	0.02	0.3
61XX	Cr–Vanadium	0.8	0.8			0.1	0.04	0.04	0.3
81XX	Ni–Cr–Mo	0.4	0.8	0.1	0.3		0.04	0.04	0.3
86XX	Ni–Cr–Mo	0.5	0.8	0.2	0.5		0.04	0.04	0.3
88XX	Ni–Cr–Mo	0.5	0.8	0.35	0.5		0.04	0.04	0.3
92XX	Silicon–Manganese		0.8				0.04	0.04	2.0
93XX	Ni–Cr–Mo	1.2	0.6	0.1	3.2		0.02	0.02	0.3
98XX	Ni–Cr–Mo	0.8	0.8	0.25	1.0		0.04	0.04	0.3

Source: [11].

Low alloy steels are not easily welded, especially at medium and high carbon levels. Since the 1960s, research has been directed at developing low carbon, low alloy steels that have better strength-to-weight ratios than plain carbon steels but are more weldable than low alloy steels. The products developed out of these efforts are called ***high-strength low-alloy*** (HSLA) steels. They generally have low carbon contents (in the range 0.10% to 0.30% C) plus relatively small amounts of alloying ingredients (usually only about 3% total of elements such as Mn, Cu, Ni, and Cr). HSLA steels are hot-rolled under controlled conditions designed to provide improved strength compared with plain C steels, yet with no sacrifice in formability or weldability. Strengthening is by solid solution alloying; heat treatment is not feasible because of low carbon content. Table 6.3 lists one HSLA steel, together with properties (chemistry is: 0.12 C, 0.60 Mn, 1.1 Ni, 1.1 Cr, 0.35 Mo, and 0.4 Si).

Stainless Steels   Stainless steels are a group of highly alloyed steels designed to provide high corrosion resistance. The principal alloying element in stainless steel is chromium, usually above 15%. The chromium in the alloy forms a thin, impervious oxide film in an oxidizing atmosphere, which protects the surface from corrosion. Nickel is another alloying ingredient used in certain stainless steels to increase corrosion protection. Carbon is used to strengthen and harden the metal; however,

TABLE • 6.3 Treatments and mechanical properties of selected steels.

Code	Treatment[a]	Tensile Strength		Elongation, %
		MPa	**lb/in²**	
1010	HR	304	44,000	47
1010	CD	366	53,000	12
1020	HR	380	55,000	28
1020	CD	421	61,000	15
1040	HR	517	75,000	20
1040	CD	587	85,000	10
1055	HT	897	130,000	16
1315	None	545	79,000	34
2030	None	566	82,000	32
3130	HT	697	101,000	28
4130	HT	890	129,000	17
4140	HT	918	133,000	16
4340	HT	1279	185,000	12
4815	HT	635	92,000	27
9260	HT	994	144,000	18
HSLA	None	586	85,000	20

Compiled from [6], [11], and other sources.
[a]HR = hot-rolled; CD = cold-drawn; HT = heat treatment involving heating and quenching, followed by tempering to produce tempered martensite (Section 26.2).

increasing the carbon content has the effect of reducing corrosion protection because chromium carbide forms to reduce the amount of free Cr available in the alloy.

In addition to corrosion resistance, stainless steels are noted for their combination of strength and ductility. Although these properties are desirable in many applications, they generally make these alloys difficult to work in manufacturing. Also, stainless steels are significantly more expensive than plain C or low alloy steels.

Stainless steels are traditionally divided into three groups, named for the predominant phase present in the alloy at ambient temperature:

1. *Austenitic stainless* steels have a typical composition of around 18% Cr and 8% Ni and are the most corrosion resistant of the three groups. Owing to this composition, they are sometimes identified as 18-8 stainless. They are nonmagnetic and very ductile; but they show significant work hardening. The nickel has the effect of enlarging the austenite region in the iron–carbon phase diagram, making it stable at room temperature. Austenitic stainless steels are used to fabricate chemical and food processing equipment, as well as machinery parts requiring high corrosion resistance.

2. *Ferritic stainless* steels have around 15% to 20% chromium, low carbon, and no nickel. This provides a ferrite phase at room temperature. Ferritic stain- less steels are magnetic and are less ductile and corrosion resistant than the austenitics. Parts made of ferritic stainless range from kitchen utensils to jet engine components.

TABLE • 6.4 Compositions and mechanical properties of selected stainless steels.

| Type | Chemical Analysis, % | | | | | | Tensile Strength | | |
	Fe	Cr	Ni	C	Mn	Other[a]	MPa	lb/in²	Elongation, %
Austenitic									
301	73	17	7	0.15	2		620	90,000	40
302	71	18	8	0.15	2		515	75,000	40
304	69	19	9	0.08	2		515	75,000	40
309	61	23	13	0.20	2		515	75,000	40
316	65	17	12	0.08	2	2.5 Mo	515	75,000	40
Ferritic									
405	85	13	—	0.08	1		415	60,000	20
430	81	17	—	0.12	1		415	60,000	20
Martensitic									
403	86	12	—	0.15	1		485	70,000	20
403[b]	86	12	—	0.15	1		825	120,000	12
416	85	13	—	0.15	1		485	70,000	20
416[b]	85	13	—	0.15	1		965	140,000	10
440	81	17	—	0.65	1		725	105,000	20
440[b]	81	17	—	0.65	1		1790	260,000	5

Compiled from [11].
[a]All of the grades in the table contain about 1% (or less) Si plus small amounts (well below 1%) of phosphorus, sulfur, and other elements such as aluminum.
[b]Heat treated.

3. *Martensitic stainless* steels have a higher carbon content than ferritic stainlesses, thus permitting them to be strengthened by heat treatment (Section 26.2). They have as much as 18% Cr but no Ni. They are strong, hard, and fatigue resistant, but not generally as corrosion resistant as the other two groups. Typical products include cutlery and surgical instruments.

Most stainless steels are designated by a three-digit AISI numbering scheme. The first digit indicates the general type, and the last two digits give the specific grade within the type. Table 6.4 lists the common stainless steels with typical compositions and mechanical properties. The traditional stainless steels were developed in the early 1900s. Since then, several additional high alloy steels have been developed that have good corrosion resistance and other desirable properties. These are also classi- fied as stainless steels. Continuing the list:

4. *Precipitation hardening stainless* steels, which have a typical composition of 17% Cr and 7% Ni, with additional small amounts of alloying elements such as aluminum, copper, titanium, and molybdenum. Their distinguishing feature among stainlesses is that they can be strengthened by precipitation hardening (Section 26.3). Strength and corrosion resistance are maintained at elevated temperatures, which suits these alloys to aerospace applications.

5. *Duplex stainless* steels possess a structure that is a mixture of austenite and ferrite in roughly equal amounts. Their corrosion resistance is similar to the austenitic grades, and they show improved resistance to stress-corrosion crack- ing. Applications include heat exchangers, pumps, and wastewater treatment plants.

TABLE • 6.5 Tool steels by AISI prefix identification, with examples of composition and typical hardness values.

AISI	Example	Chemical Analysis, %[a]							Hardness, HRC
		C	**Cr**	**Mn**	**Mo**	**Ni**	**V**	**W**	
T	T1	0.7	4.0				1.0	18.0	65
M	M2	0.8	4.0		5.0		2.0	6.0	65
H	H11	0.4	5.0		1.5		0.4		55
D	D1	1.0	12.0		1.0				60
A	A2	1.0	5.0		1.0				60
O	O1	0.9	0.5	1.0				0.5	61
W	W1	1.0							63
S	S1	0.5	1.5					2.5	50
P	P20	0.4	1.7		0.4				40[b]
L	L6	0.7	0.8		0.2	1.5			45[b]

[a]Percent composition rounded to nearest tenth.
[b]Hardness estimated.

Tool Steels   Tool steels are a class of (usually) highly alloyed steels designed for use as industrial cutting tools, dies, and molds. To perform in these applications, they must possess high strength, hardness, hot hardness, wear resistance, and toughness under impact. To obtain these properties, tool steels are heat treated. Principal reasons for the high levels of alloying elements are (1) improved hardenability, (2) reduced distortion during heat treatment, (3) hot hardness, (4) formation of hard metallic carbides for abrasion resistance, and (5) enhanced toughness.

The tool steels divide into major types, according to application and composition. The AISI uses a classification scheme that includes a prefix letter to identify the tool steel. In the following list of tool steel types, the prefix is indicated, and some typical compositions are presented in Table 6.5:

T, M ***High-speed steels*** (Section 22.2.1) are used as cutting tools in machining operations (Chapter 21). They are formulated for high wear resistance and hot hardness. The original high-speed steels (HSS) were developed around 1900. They permitted dramatic increases in cutting speed compared to previously used tools; hence their name. The two AISI designations indicate the principal alloying element: T for tungsten and M for molybdenum.

H ***Hot-working tool steels*** are intended for hot-working dies in forging, extrusion, and die-casting.

D ***Cold-work tool steels*** are die steels used for cold working operations such as sheet metal pressworking, cold extrusion, and certain forging operations. The designation D stands for die. Closely related AISI designations are A and O. A and O stand for air- and oil-hardening. They all provide good wear resistance and low distortion.

W ***Water-hardening tool steels*** have high carbon with little or no other alloying elements. They can only be hardened by fast quenching in water. They are widely used because of low cost, but they are limited to low temperature applications. Cold heading dies are a typical application.

S   **Shock-resistant tool steels** are intended for use in applications where high toughness is required, as in many sheet metal shearing, punching, and bending operations.

P   **Mold steels** are used to make molds for molding plastics and rubber.

L   **Low-alloy tool steels** are generally reserved for special applications.

Tool steels are not the only tool materials. Plain carbon, low alloy, and stainless steels are used for many tool and die applications. Cast irons and certain nonferrous alloys are also suitable for certain tooling applications. In addition, several ceramic materials (e.g., Al_2O_3) are used as high-speed cutting inserts, abrasives, and other tools.

Specialty Steels   To complete this survey, several specialty steels not included in the previous coverage are mentioned. One of the reasons why these steels are special is that they possess unique processing characteristics.

Maraging steels are low carbon alloys containing high amounts of nickel (15%–25%) and lesser proportions of cobalt, molybdenum, and titanium. Chromium is also sometimes added for corrosion resistance. Maraging steels are strength- ened by precipitation hardening (Section 26.3), but in the unhardened condition, they are quite processable by forming and/or machining. They can also be readily welded. Heat treatment results in very high strength together with good toughness. Tensile strengths of 2000 MPa (290,000 lb/in^2) and 10% elongation are not unusual. Applications include parts for missiles, machinery, dies, and other situations where these properties are required and justify the high cost of the alloy.

Free-machining steels are carbon steels formulated to improve machinability (Section 23.1). Alloying elements include sulfur, lead, tin, bismuth, selenium, tellu- rium, and/or phosphorus. Lead is less-frequently used today because of environmen- tal and health concerns. Added in small amounts, these elements act to lubricate the cutting operation, reduce friction, and break up chips for easier disposal. Although more expensive than non-free-machining steels, they often pay for themselves in higher production rates and longer tool lives.

Because of their good ductility, low-carbon sheet steels are widely used in sheet metal forming operations. Further improvements in formability have been achieved using a new class of sheet steel product called **interstitial-free steels**. These steels have extremely low carbon levels (0.005% C), which result from the use of alloying elements such as niobium and titanium that combine with carbon and leave the steel virtually free of interstitial atoms. The result is excellent ductility, even greater than low-C steels. Applications include deep-drawing operations in the automotive industry.

6.2.4 *CAST IRONS*

Cast iron is an iron alloy containing from 2.1% to about 4% carbon and from 1% to 3% silicon. Its composition makes it highly suitable as a casting metal. In fact, the tonnage of cast iron castings is several times that of all other cast metal parts combined (excluding cast ingots made during steelmaking which are subsequently rolled into bars, plates, and similar stock). The overall tonnage of cast iron is second only to steel among metals.

FIGURE 6.13 Carbon and silicon compositions for cast irons, with comparison to steels (most steels have relatively low silicon contents—cast steels have the higher Si content). Ductile iron is formed by special melting and pouring treatment of gray cast iron, and malleable iron is formed by heat treatment of white cast iron.
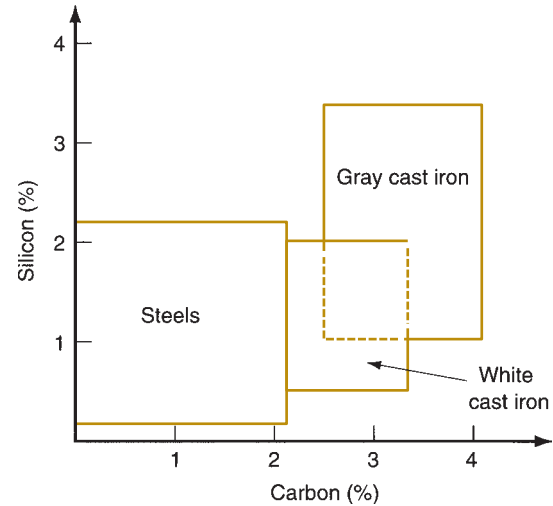
There are several types of cast iron, the most important being gray cast iron. Other types include ductile iron, white cast iron, malleable iron, and various alloy cast irons. Typical chemical compositions of gray and white cast irons are shown in Figure 6.13, indicating their relationship with cast steel. Ductile and malleable irons possess chemistries similar to the gray and white cast irons, respectively, but result from special treatments to be described in the following. Table 6.6 presents a listing of chemistries for the principal types together with mechanical properties.

TABLE • 6.6 Compositions and mechanical properties of selected cast irons.

Type	Typical Composition, %					Tensile Strength		
	Fe	C	Si	Mn	Other[a]	MPa	lb/in^2	Elongation, %
Gray cast irons								
ASTM Class 20	93.0	3.5	2.5	0.65		138	20,000	0.6
ASTM Class 30	93.6	3.2	2.1	0.75		207	30,000	0.6
ASTM Class 40	93.8	3.1	1.9	0.85		276	40,000	0.6
ASTM Class 50	93.5	3.0	1.6	1.0	0.67 Mo	345	50,000	0.6
Ductile irons								
ASTM A395	94.4	3.0	2.5			414	60,000	18
ASTM A476	93.8	3.0	3.0			552	80,000	3
White cast iron								
Low-C	92.5	2.5	1.3	0.4	1.5Ni, 1Cr, 0.5Mo	276	40,000	0
Malleable irons								
Ferritic	95.3	2.6	1.4	0.4		345	50,000	10
Pearlitic	95.1	2.4	1.4	0.8		414	60,000	10

Compiled from [11]. Cast irons are identified by various systems. This table is an attempt to indicate the particular cast iron grade using the most common identification for each type.
[a]Cast irons also contain phosphorus and sulfur usually totaling less than 0.3%.

Gray Cast Iron Gray cast iron accounts for the largest tonnage among the cast irons. It has a composition in the range 2.5% to 4% carbon and 1% to 3% sili- con. This chemistry results in the formation of graphite (carbon) flakes distributed throughout the cast product upon solidification. The structure causes the surface of the metal to have a gray color when fractured; hence the name gray cast iron. The dispersion of graphite flakes accounts for two attractive properties: (1) good vibra- tion damping, which is desirable in engines and other machinery; and (2) internal lubricating qualities, which makes the cast metal machinable.

The strength of gray cast iron spans a significant range. The American Society for Testing of Materials (ASTM) uses a classification method for gray cast iron that is intended to provide a minimum tensile strength (*TS*) specification for the various classes: Class 20 gray cast iron has a *TS* of 20,000 lb/in^2, Class 30 has a *TS* of 30,000 lb/in^2, and so forth, up to around 70,000 lb/in^2 (see Table 6.6 for equiva- lent *TS* in metric units). The compressive strength of gray cast iron is significantly greater than its tensile strength. Properties of the casting can be controlled to some extent by heat treatment. Ductility of gray cast iron is very low; it is a relatively brit- tle material. Products made from gray cast iron include automotive engine blocks and heads, motor housings, and machine tool bases.

Ductile Iron This is an iron with the composition of gray iron in which the mol- ten metal is chemically treated before pouring to cause the formation of graphite spheroids rather than flakes. This results in a stronger and more ductile iron, hence its name. Applications include machinery components requiring high strength and good wear resistance.

White Cast Iron This cast iron has less carbon and silicon than gray cast iron. It is formed by more rapid cooling of the molten metal after pouring, thus causing the carbon to remain chemically combined with iron in the form of cementite (Fe_3C), rather than precipitating out of solution in the form of flakes. When fractured, the surface has a white crystalline appearance that gives the iron its name. Owing to the cementite, white cast iron is hard and brittle, and its wear resistance is excellent. Strength is good, with *TS* of 276 MPa (40,000 lb/in^2) being typical. These properties make white cast iron suitable for applications in which wear resistance is required. Railway brake shoes are an example.

Malleable Iron When castings of white cast iron are heat treated to separate the carbon out of solution and form graphite aggregates, the resulting metal is called malleable iron. The new microstructure can possess substantial ductility (up to 20% elongation)—a significant difference from the metal out of which it was transformed. Typical products made of malleable cast iron include pipe fittings and flanges, certain machine components, and railroad equipment parts.

Alloy Cast Irons Cast irons can be alloyed for special properties and applica- tions. These alloy cast irons are classified as follows: (1) heat-treatable types that can be hardened by martensite formation; (2) corrosion-resistant types, whose alloying elements include nickel and chromium; and (3) heat-resistant types containing high proportions of nickel for hot hardness and resistance to high temperature oxidation.

6.3 Nonferrous Metals

The nonferrous metals include metal elements and alloys not based on iron. The most important engineering metals in the nonferrous group are aluminum, copper, magnesium, nickel, titanium, and zinc, and their alloys.

Although the nonferrous metals as a group cannot match the strength of the steels, certain nonferrous alloys have corrosion resistance and/or strength-to-weight ratios that make them competitive with steels in moderate-to-high stress applications. In addition, many of the nonferrous metals have properties other than mechanical that make them ideal for applications in which steel would be quite unsuitable. For example, copper has one of the lowest electrical resistivities among metals and is widely used for electrical wire. Aluminum is an excellent thermal conductor, and its applications include heat exchangers and cooking pans. It is also one of the most readily formed metals, and is valued for that reason also. Zinc has a relatively low melting point, so zinc is widely used in die casting opera- tions. The common nonferrous metals have their own combination of properties that make them attractive in a variety of applications. The following nine sections cover the nonferrous metals that are the most commercially and technologically important.

6.3.1 *ALUMINUM AND ITS ALLOYS*

Aluminum and magnesium are light metals, and they are often specified in engineering applications for this feature. Both elements are abundant on Earth, aluminum on land and magnesium in the sea, although neither is easily extracted from their natural states.

Properties and other data on aluminum are listed in Table 6.1(b). Among the major metals, it is a relative newcomer, dating only to the late 1800s (Historical Note 6.2). The coverage in this section includes (1) a brief description of how alumi- num is produced and (2) a discussion of the properties and the designation system for the metal and its alloys.

TABLE • 6.1 (continued): (b) Aluminum.

Symbol:	Al
Atomic number:	13
Specific gravity:	2.7
Crystal structure:	FCC
Melting temperature:	660°C (1220°F)
Elastic modulus:	69,000 MPa (10×10^6 lb/in^2)
Principal ore:	Bauxite (impure mix of Al_2O_3 and $Al(OH)_3$)
Alloying elements:	Copper, magnesium, manganese, silicon, and zinc
Typical applications:	Containers (aluminum cans), wrapping foil, electrical conductors, pots and pans, parts for construction, aerospace, automotive, and other uses in which light weight is important

Aluminum Production The principal aluminum ore is **bauxite**, which consists largely of hydrated aluminum oxide (Al_2O_3-H_2O) and other oxides. Extraction of the aluminum from bauxite can be summarized in three steps: (1) washing and crushing the ore into fine powders; (2) the Bayer process, in which the bauxite is converted to pure alumina (Al_2O_3); and (3) electrolysis, in which the alumina is separated into aluminum and oxygen gas (O_2). The **Bayer process**, named after the German chemist who developed it, involves solution of bauxite powders in aqueous caustic soda ($NaOH$) under pressure, followed by precipitation of pure Al_2O_3 from solution. Alumina is commercially important in its own right as an engineering ceramic (Chapter 7).

Electrolysis to separate Al_2O_3 into its constituent elements requires dissolving the precipitate in a molten bath of cryolite (Na_3AlF_6) and subjecting the solution to direct current between the plates of an electrolytic furnace. The electrolyte dissociates to form aluminum at the cathode and oxygen gas at the anode.

Properties and Designation Scheme Aluminum has high electrical and thermal conductivity, and its resistance to corrosion is excellent because of the formation of a hard, thin oxide surface film. It is a very ductile metal and is noted for its formability. Pure aluminum is relatively low in strength, but it can be alloyed and heat treated to compete with some steels, especially when weight is an important consideration.

The designation system for aluminum alloys is a four-digit code number. The system has two parts, one for wrought aluminums and the other for cast aluminums. The difference is that a decimal point is used after the third digit for cast aluminums. The designations are presented in Table 6.7(a).

Because properties of aluminum alloys are so influenced by work hardening and heat treatment, the temper (strengthening treatment, if any) must be designated in addition to the composition code. The principal temper designations are presented in Table 6.7(b). This designation is attached to the preceding four-digit number, separated from it by a hyphen, to indicate the treatment or absence thereof; for

TABLE • 6.7(a) Designations of wrought and cast aluminum alloys.

Alloy Group	Wrought Code	Cast Code
Aluminum, 99.0% or higher purity	1XXX	1XX.X
Aluminum alloys, by major element(s):		
Copper	2XXX	2XX.X
Manganese	3XXX	
Silicon + copper and/or magnesium		3XX.X
Silicon	4XXX	4XX.X
Magnesium	5XXX	5XX.X
Magnesium and silicon	6XXX	
Zinc	7XXX	7XX.X
Tin		8XX.X
Other	8XXX	9XX.X

TABLE • 6.7(b) Temper designations for aluminum alloys.

Temper	Description
F	As fabricated—no special treatment.
H	Strain hardened (wrought aluminums). H is followed by two digits, the first indicating a heat treatment, if any; and the second indicating the degree of work hardening remaining; for example:
	H1X No heat treatment after strain hardening, and X = 1 to 9, indicating degree of work hardening.
	H2X Partially annealed, and X = degree of work hardening remaining in product.
	H3X Stabilized, and X = degree of work hardening remaining. *Stabilized* means heating to slightly above service temperature anticipated.
O	Annealed to relieve strain hardening and improve ductility; reduces strength to lowest level.
T	Thermal treatment to produce stable tempers other than F, H, or O. It is followed by a digit to indicate specific treatments; for example:
	T1 = cooled from elevated temperature, naturally aged.
	T2 = cooled from elevated temperature, cold worked, naturally aged.
	T3 = solution heat treated, cold worked, naturally aged.
	T4 = solution heat treated and naturally aged.
	T5 = cooled from elevated temperature, artificially aged.
	T6 = solution heat treated and artificially aged.
	T7 = solution heat treated and overaged or stabilized.
	T8 = solution heat treated, cold worked, artificially aged.
	T9 = solution heat treated, artificially aged, and cold worked.
	T10 = cooled from elevated temperature, cold worked, and artificially aged.
W	Solution heat treatment, applied to alloys that age harden in service; it is an unstable temper.

example, 2024-T3. Of course, temper treatments that specify strain hardening do not apply to the cast alloys. Some examples of the remarkable differences in the mechanical properties of aluminum alloys that result from the different treatments are presented in Table 6.8.

TABLE • 6.8 Compositions and mechanical properties of selected aluminum alloys.

Code	Typical Composition, %ᵃ						Temper	Tensile Strength		Elongation
	Al	Cu	Fe	Mg	Mn	Si		MPa	lb/in²	
1050	99.5		0.4			0.3	O	76	11,000	39
							H18	159	23,000	7
1100	99.0		0.6			0.3	O	90	13,000	40
							H18	165	24,000	10
2024	93.5	4.4	0.5	1.5	0.6	0.5	O	185	27,000	20
							T3	485	70,000	18
3004	96.5	0.3	0.7	1.0	1.2	0.3	O	180	26,000	22
							H36	260	38,000	7
4043	93.5	0.3	0.8			5.2	O	130	19,000	25
							H18	285	41,000	1
5050	96.9	0.2	0.7	1.4	0.1	0.4	O	125	18,000	18
							H38	200	29,000	3
6063	98.5		0.3	0.7		0.4	O	90	13,000	25
							T4	172	25,000	20

Compiled from [12].

ᵃIn addition to elements listed, alloy may contain trace amounts of other elements such as copper, magnesium, manganese, vanadium, and zinc.

6.3.2 *MAGNESIUM AND ITS ALLOYS*

Magnesium (Mg) is the lightest of the structural metals. Its specific gravity and other basic data are presented in Table 6.1(c). Magnesium and its alloys are avail- able in both wrought and cast forms. It is relatively easy to machine. However, in all processing of magnesium, small particles of the metal (such as small metal cutting chips) oxidize rapidly, and care must be taken to avoid fire hazards.

Magnesium Production Sea water contains about 0.13% $MgCl_2$, and this is the source of most commercially produced magnesium. To extract Mg, a batch of sea water is mixed with milk of lime—calcium hydroxide ($Ca(OH)_2$). The resulting reaction pre- cipitates magnesium hydroxide ($Mg(OH)_2$) that settles and is removed as a slurry.

TABLE • 6.1 (continued): (c) Magnesium.

Symbol:	Mg
Atomic number:	12
Specific gravity:	1.74
Crystal structure:	HCP
Melting temperature:	650°C (1202°F)
Elastic modulus:	48,000 MPa (7 X 10⁶ lb/in²)
Extracted from:	$MgCl_2$ in sea water by electrolysis
Alloying elements:	See Table 6.9
Typical applications:	Aerospace, missiles, bicycles, chain saw housings, luggage, and other applications where light weight is a primary requirement.

TABLE • 6.9 Code letters used to identify alloying elements in magnesium alloys.

A	Aluminum (Al)
E	Rare earth metals
H	Thorium (Th)
K	Zirconium (Zr)
M	Manganese (Mn)
P	Lead (Pb)
Q	Silver (Ag)
S	Silicon (Si)
T	Tin (Sn)
Z	Zinc (Zn)

The slurry is then filtered to increase $Mg(OH)_2$ content and then mixed with hydrochloric acid (HCl), which reacts with the hydroxide to form concentrated $MgCl_2$—much more concentrated than the original sea water. Electrolysis is used to decompose the salt into magnesium (Mg) and chlorine gas (Cl_2). The magnesium is then cast into ingots for subsequent processing. The chlorine is recycled to form more $MgCl_2$.

Properties and Designation Scheme   As a pure metal, magnesium is relatively soft and lacks sufficient strength for most engineering applications. However, it can be alloyed and heat treated to achieve strengths comparable to aluminum alloys. In particular, its strength-to-weight ratio is an advantage in aircraft and missile components.

The designation scheme for magnesium alloys uses a three-to-five-character alphanumeric code. The first two characters are letters that identify the principal alloying elements (up to two elements can be specified in the code, in order of decreasing percentages, or alphabetically if equal percentages). These code letters are listed in Table 6.9. The letters are followed by a two-digit number that indicates, respectively, the amounts of the two alloying ingredients to the nearest percent. Finally, the last symbol is a letter that indicates some variation in composition, or simply the chronological order in which it was standardized for commercial availability. Magnesium alloys also require specification of a temper, and the same basic scheme presented in Table 6.7(b) for aluminum is used for magnesium alloys.

Some examples of magnesium alloys, illustrating the designation scheme and indicating tensile strength and ductility of these alloys, are presented in Table 6.10.

TABLE • 6.10 Compositions and mechanical properties of selected magnesium alloys.

Code	Typical Composition, %						Process	Tensile Strength		Elongation
	Mg	Al	Mn	Si	Zn	Other		MPa	lb/in²	
AZ10A	98.0	1.3	0.2	0.1	0.4		Wrought	240	35,000	10
AZ80A	91.0	8.5			0.5		Forged	330	48,000	11
HM31A	95.8		1.2			3.0 Th	Wrought	283	41,000	10
ZK21A	97.1				2.3	6 Zr	Wrought	260	38,000	4
AM60	92.8	6.0	0.1	0.5	0.2	0.3 Cu	Cast	220	32,000	6
AZ63A	91.0	6.0			3.0		Cast	200	29,000	6

Compiled from [12].

TABLE • 6.1 (continued): (d) Copper.

Symbol:	Cu
Atomic number:	29
Specific gravity:	8.96
Crystal structure:	FCC
Melting temperature:	1083°C (1981°F)
Elastic modulus:	110,000 MPa (16 X 10^6 lb/in^2)
Ore extracted from:	Several: e.g., chalcopyrite ($CuFeS_2$).
Alloying elements:	Tin (bronze), zinc (brass), aluminum, silicon, nickel, and beryllium.
Typical applications:	Electrical conductors and components, ammunition (brass), pots and pans, jewelry, plumbing, marine applications, heat exchangers, springs (Be-Cu).

6.3.3   COPPER AND ITS ALLOYS

Copper (Cu) is one of the oldest metals known (Historical Note 6.3). Basic data on the element copper are presented in Table 6.1(d).

Historical Note 6.3   *Copper*

Copper was one of the first metals used by human cultures (gold was the other). Discovery of the metal was probably around 6000 B.C.E. At that time, copper was found in the free metallic state. Ancient peoples fashioned implements and weapons out of it by hitting the metal (cold forging). Pounding copper made it harder (strain hardening); this and its attractive reddish color made it valuable in early civilizations.

Around 4000 B.C.E., it was discovered that copper could be melted and cast into useful shapes. It was later found that copper mixed with tin could be more readily cast and worked than the pure metal. This led to the widespread use of bronze and the subsequent naming of the Bronze Age, dated from about 2000 B.C.E. to the time of Christ.

To the ancient Romans, the island of Cyprus was almost the only source of copper. They called the metal *aes cyprium* (ore of Cyprus). This was shortened to *Cyprium* and subsequently renamed *Cuprium*. From this derives the chemical symbol Cu.

Copper Production In ancient times, copper was available in nature as a free element. Today these natural deposits are more difficult to find, and copper is now extracted from ores that are mostly sulfides, such as *chalcopyrite* ($CuFeS_2$). The ore is crushed (Section 16.1.1), concentrated by flotation, and then *smelted* (melted or fused, often with an associated chemical reaction to separate a metal from its ore). The resulting copper is called *blister copper*, which is between 98% and 99% pure. Electrolysis is used to obtain higher purity levels suitable for commercial use.

Properties and Designation Scheme Pure copper has a distinctive reddish- pink color, but its most distinguishing engineering property is its low electrical resistivity— one of the lowest of all elements. Because of this property, and its rela- tive abundance in nature, commercially pure copper is widely used as an electrical conductor. (The conductivity of copper decreases significantly as alloying elements are added.) Cu is also an excellent thermal conductor. Copper is one of the noble

TABLE • 6.11 Compositions and mechanical properties of selected copper alloys.

Code	Typical Composition, %					Tensile Strength		Elongation, %
	Cu	Be	Ni	Sn	Zn	MPa	lb/in²	
C10100	99.99					235	34,000	45
C11000	99.95					220	32,000	45
C17000	98.0	1.7	a			500	70,000	45
C24000	80.0				20.0	290	42,000	52
C26000	70.0				30.0	300	44,000	68
C52100	92.0			8.0		380	55,000	70
C71500	70.0		30.0			380	55,000	45
C71500[b]	70.0		30.0			580	84,000	3

Compiled from [12].
[a]Small amounts of Ni and Fe + 0.3 Co.
[b]Heat treated for high strength.

metals (gold and silver are also noble metals), so it is corrosion resistant. All of these properties combine to make copper one of the most important metals.

On the downside, the strength and hardness of copper are relatively low, especially when weight is taken into account. Accordingly, to improve strength (as well as for other reasons), copper is frequently alloyed. *Bronze* is an alloy of copper and tin (typically about 90% Cu and 10% Sn), still widely used today despite its ancient ancestry. Additional bronze alloys have been developed, based on other elements than tin; these include aluminum bronzes, and silicon bronzes. *Brass* is another familiar copper alloy, composed of copper and zinc (typically around 65% Cu and 35% Zn). The highest strength alloy of copper is beryllium-copper (only about 2% Be). It can be heat treated to tensile strengths of 1035 MPa (150,000 lb/in²). Be-Cu alloys are used for springs.

The designation of copper alloys is based on the Unified Numbering System for Metals and Alloys (UNS), which uses a five-digit number preceded by the letter C (C for copper). The alloys are processed in wrought and cast forms, and the designation system includes both. Some copper alloys with compositions and mechanical properties are presented in Table 6.11.

6.3.4 NICKEL AND ITS ALLOYS

Nickel (Ni) is similar to iron in many respects. It is magnetic, and its modulus of elasticity is virtually the same as that of iron and steel. However, it is much more corrosion resistant, and the high temperature properties of its alloys are generally superior. Because of its corrosion-resistant characteristics, it is widely used as an alloying element in steel, such as stainless steel, and as a plating metal on other metals such as plain carbon steel.

Nickel Production   The most important ore of nickel is *pentlandite* ($(Ni, Fe)_9S_8$). To extract the nickel, the ore is first crushed and ground with water. Flotation techniques are used to separate the sulfides from other minerals mixed with the ore. The nickel sulfide is then heated to burn off some of the sulfur, followed by smelting to remove iron and silicon. Further refinement is accomplished in a Bessemer-style converter

TABLE • 6.1 (continued): (e) Nickel.

Symbol:	Ni
Atomic number:	28
Specific gravity:	8.90
Crystal structure:	FCC
Melting temperature:	1453°C (2647°F)
Elastic Modulus:	209,000 MPa (30 $\times$ 10^6 lb/in^2)
Ore extracted from:	Pentlandite ((Fe, Ni)$_9$S$_8$)
Alloying elements:	Copper, chromium, iron, aluminum.
Typical applications:	Stainless steel alloying ingredient, plating metal for steel, applications requiring high temperature and corrosion resistance.

to yield high-concentration nickel sulfide (NiS). Electrolysis is then used to recover high-purity nickel from the compound. Ores of nickel are sometimes mixed with cop- per ores, and the recovery technique described here also yields copper in these cases.

Nickel Alloys Alloys of nickel are commercially important in their own right and are noted for corrosion resistance and high temperature performance. Composition, tensile strength, and ductility of some of the nickel alloys are given in Table 6.12. In addition, a number of superalloys are based on nickel (Section 6.4).

6.3.5   *TITANIUM AND ITS ALLOYS*

Titanium (Ti) is fairly abundant in nature, constituting about 1% of Earth's crust (aluminum, the most abundant, is about 8%). The density of Ti is between alumi- num and iron. Data for Ti are presented in Table 6.1(f). Its importance has grown in recent decades due to its aerospace applications where its light weight and good strength-to-weight ratio are exploited.

Titanium Production The principal ores of titanium are *rutile*, which is 98 to 99% TiO$_2$, and *ilmenite*, which is a combination of FeO and TiO$_2$. Rutile is preferred

TABLE • 6.12 Compositions and mechanical properties of selected nickel alloys.

	Typical Composition, %							Tensile Strength		Elongation, %
Code	Ni	Cr	Cu	Fe	Mn	Si	Other	MPa	lb/in^2	
270	99.9		a	a				345	50,000	50
200	99.0		0.2	0.3	0.2	0.2	C, S	462	67,000	47
400	66.8		30.0	2.5	0.2	0.5	C	550	80,000	40
600	74.0	16.0	0.5	8.0	1.0	0.5		655	95,000	40
230	52.8	22.0		3.0	0.4	0.4	b	860	125,000	47

Compiled from [12].
[a]Trace amounts.
[b]Other alloying ingredients in Grade 230: 5% Co, 2% Mo, 14% W, 0.3% Al, 0.1% C.

TABLE • 6.1 (continued): (f) Titanium.

Symbol:	Ti
Atomic number:	22
Specific gravity:	4.51
Crystal structure:	HCP
Melting temperature:	1668°C (3034°F)
Elastic modulus:	117,000 MPa (17×10^6 lb/in^2)
Ores extracted from:	Rutile (TiO_2) and Ilmenite ($FeTiO_3$)
Alloying elements:	Aluminum, tin, vanadium, copper, and magnesium.
Typical applications:	Jet engine components, other aerospace applications, prosthetic implants.

as an ore because of its higher Ti content. In recovery of the metal from its ores, the TiO_2 is converted to titanium tetrachloride ($TiCl_4$) by reacting the compound with chlorine gas. This is followed by a sequence of distillation steps to remove impurities. The highly concentrated $TiCl_4$ is then reduced to metallic titanium by reaction with magnesium; this is known as the ***Kroll process***. Sodium can also be used as a reducing agent. In either case, an inert atmosphere must be maintained to prevent O_2, N_2, or H_2 from contaminating the Ti, owing to its chemical affinity for these gases. The resulting metal is used to cast ingots of titanium and its alloys.

Properties of Titanium   Ti's coefficient of thermal expansion is relatively low among metals. It is stiffer and stronger than aluminum, and it retains good strength at elevated temperatures. Pure titanium is reactive, which presents problems in processing, especially in the molten state. However, at room temperature it forms a thin adherent oxide coating (TiO_2) that provides excellent corrosion resistance.

These properties give rise to two principal application areas for titanium: (1) in the commercially pure state, Ti is used for corrosion resistant components, such as marine components and prosthetic implants; and (2) titanium alloys are used as high-strength components in temperatures ranging from ambient to above 550°C (1000°F), especially where its excellent strength-to-weight ratio is exploited. These latter applications include aircraft and missile components. Some of the alloying elements used with titanium include aluminum, manganese, tin, and vanadium. Some compositions and mechanical properties for several alloys are presented in Table 6.13.

TABLE • 6.13 Compositions and mechanical properties of selected titanium alloys.

	Typical Composition, %						Tensile Strength		
Code[a]	Ti	Al	Cu	Fe	V	Other	MPa	lb/in^2	Elongation, %
R50250	99.8			0.2			240	35,000	24
R56400	89.6	6.0		0.3	4.0	[b]	1000	145,000	12
R54810	90.0	8.0			1.0	1 Mo,[b]	985	143,000	15
R56620	84.3	6.0	0.8	0.8	6.0	2 Sn,[b]	1030	150,000	14

Compiled from [1] and [12].
[a]United Numbering System (UNS).
[b]Traces of C, H, O.

TABLE • 6.1 (continued): (g) zinc.

Symbol:	Zn
Atomic number:	30
Specific gravity:	7.13
Crystal structure:	HCP
Melting temperature:	419°C (786°F)
Elastic modulus:	90,000 MPa (13 X 10^6 lb/in²)[a]
Ore extracted from:	Sphalerite (ZnS)
Alloying elements:	Aluminum, magnesium, copper
Typical applications:	Galvanized steel and iron, die castings, alloying element in brass

[a]Zinc creeps, which makes it difficult to measure modulus of elasticity; some tables of properties omit E for zinc for this reason.

6.3.6 *ZINC AND ITS ALLOYS*

Table 6.1(g) lists basic data on zinc. Its low melting point makes it attractive as a casting metal. It also provides corrosion protection when coated onto steel or iron; *galvanized steel* is steel that has been coated with zinc.

Production of Zinc   Zinc blende or *sphalerite* is the principal ore of zinc; it contains zinc sulfide (ZnS). Other important ores include *smithsonite*, which is zinc carbonate ($ZnCO_3$), and *hemimorphate*, which is hydrous zinc silicate ($Zn_4Si_2O_7OH$-H_2O).

Sphalerite must be concentrated (*beneficiated*, as it is called) because of the small fraction of zinc sulfide present in the ore. This is accomplished by first crushing the ore, then grinding with water in a ball mill (Section 16.1.1) to create a slurry. In the presence of a frothing agent, the slurry is agitated so that the mineral particles float to the top and can be skimmed off (separated from the lower grade minerals). The concentrated zinc sulfide is then roasted at around 1260°C (2300°F), so that zinc oxide (ZnO) is formed from the reaction.

There are various thermochemical processes for recovering zinc from this oxide, all of which reduce zinc oxide by means of carbon. The carbon combines with oxygen in ZnO to form CO and/or CO_2, thus freeing Zn in the form of vapor that is condensed to yield the desired metal.

An electrolytic process is also widely used, accounting for about half the world's production of zinc. This process also begins with the preparation of ZnO, which is mixed with dilute sulfuric acid (H_2SO_4), followed by electrolysis to separate the resulting zinc sulfate ($ZnSO_4$) solution to yield the pure metal.

Zinc Alloys and Applications   Several alloys of zinc are listed in Table 6.14, with data on composition, tensile strength, and applications. Zinc alloys are widely used in die casting to mass produce components for the automotive and appliance industries. Another major application of zinc is in galvanized steel. As the name suggests, a galvanic cell is created in galvanized steel (Zn is the anode and steel is the cathode) that protects the steel from corrosive attack. A third important use of zinc is in brass. As previously indicated in the discussion of copper, this alloy

TABLE • 6.14 Compositions, tensile strength, and applications of selected zinc alloys.

Code	Typical Composition, %					Tensile Strength		Application
	Zn	**Al**	**Cu**	**Mg**	**Fe**	**MPa**	**lb/in²**	
Z33520	95.6	4.0	0.25	0.04	0.1	283	41,000	Die casting
Z35540	93.4	4.0	2.5	0.04	0.1	359	52,000	Die casting
Z35635	91.0	8.0	1.0	0.02	0.06	374	54,000	Foundry alloy
Z35840	70.9	27.0	2.0	0.02	0.07	425	62,000	Foundry alloy
Z45330	98.9		1.0	0.01		227	33,000	Rolled alloy

Compiled from [12].
[a]UNS - Unified Numbering System for metals.

consists of copper and zinc, in the ratio of about 2/3 Cu to 1/3 Zn. Finally, readers may be interested to know that the U.S. one-cent coin is mostly zinc. The penny is coined out of zinc and then electroplated with copper, so that the final propor- tions are 97.5% Zn and 2.5% Cu. It costs the U.S. Mint about 1.5 cents to produce each penny.

6.3.7 *LEAD AND TIN*

Lead (Pb) and tin (Sn) are often considered together because of their low melting temperatures, and because they are used in soldering alloys to make electrical con- nections. The phase diagram for the tin–lead alloy system is depicted in Figure 6.3. Basic data for lead and tin are presented in Table 6.1(h).

Lead is a dense metal with a low melting point; other properties include low strength, low hardness (the word "soft" is appropriate), high ductility, and good cor- rosion resistance. In addition to its use in solder, applications of lead and its alloys include ammunition, type metals, x-ray shielding, storage batteries, bearings, and vibration damping. It has also been widely used in chemicals and paints. Principal alloying elements with lead are tin and antimony.

TABLE • 6.1 (continued): (h) lead and tin.

	Lead	Tin
Symbol:	Pb	Sn
Atomic number:	82	50
Specific gravity:	11.35	7.30
Crystal structure:	FCC	HCP
Melting temperature:	327°C (621°F)	232°C (449°F)
Modulus of elasticity:	21,000 MPa (3×10^6 lb/in²)	42,000 MPa (6×10^6 lb/in²)
Ore from which extracted:	Galena (PbS)	Cassiterite (SnO_2)
Typical alloying elements:	Tin, antimony	Lead, copper
Typical applications:	See text	Bronze, solder, tin cans

TABLE • 6.1 (continued): (i) refractory metals.

	Molybdenum	Tungsten
Symbol:	Mo	W
Atomic number:	42	74
Specific gravity:	10.2	19.3
Crystal structure:	BCC	BCC
Melting point:	2619°C (4730°F)	3400°C (6150°F)
Elastic modulus:	324,000 MPa (47 X 10^6 lb/in^2)	407,000 MPa (59 X 10^6 lb/in^3)
Principal ores:	Molybdenite (MoS_2)	Scheelite ($CaWO_4$), Wolframite ($(Fe,Mn)WO_4$)
Alloying elements:	See text	[a]
Applications:	See text	Light filaments, rocket engine parts, WC tools.

[a]Tungsten is used as a pure metal and as an alloying ingredient, but few alloys are based on W.

Tin has an even lower melting point than lead; other properties include low strength, low hardness, and good ductility. The earliest use of tin was in bronze, the alloy consisting of copper and tin developed around 3000 B.C. in Mesopotamia and Egypt. Bronze is still an important commercial alloy (although its relative importance has declined during 5000 years). Other uses of tin include tin-coated sheet steel containers ("tin cans") for storing food and, of course, solder metal.

6.3.8 *REFRACTORY METALS*

The refractory metals are metals capable of enduring high temperatures. The most important metals in this group are molybdenum and tungsten; see Table 6.1(i). Other refractory metals are columbium (Cb) and tantalum (Ta). In general, these metals and their alloys are capable of maintaining high strength and hardness at elevated temperatures.

Molybdenum has a high melting point and is relatively dense, stiff, and strong. It is used both as a pure metal (99.9$^+$% Mo) and as an alloy. The principal alloy is TZM, which contains small amounts of titanium and zirconium (less than 1% total). Mo and its alloys possess good high temperature strength, and this accounts for many of its applications, which include heat shields, heating elements, elec- trodes for resistance welding, dies for high temperature work (e.g., die casting molds), and parts for rocket and jet engines. In addition to these applications, molybdenum is also widely used as an alloying ingredient in other metals, such as steels and superalloys.

Tungsten (W) has the highest melting point among metals and is one of the densest. It is also the stiffest and hardest of all pure metals. Its most familiar application is filament wire in incandescent light bulbs. Applications of tungsten are typically characterized by high operating temperatures, such as parts for rocket and jet engines and electrodes for arc welding. W is also widely used as an element in tool steels, heat resistant alloys, and tungsten carbide (Section 7.3.2).

TABLE • 6.1 (continued): (j) the precious metals

	Gold	**Platinum**	**Silver**
Symbol:	Au	Pt	Ag
Atomic number:	79	78	47
Specific gravity:	19.3	21.5	10.5
Crystal structure:	FCC	FCC	FCC
Melting temperature:	1063°C (1945°F)	1769°C (3216°F)	961°C (1762°F)
Principal ores:	a	a	a
Applications:	See text	See text	See text

[a]All three precious metals are mined from deposits in which the pure metal is mixed with other ores and metals. Silver is also mined from the ore *Argentite* (Ag_2S).

A major disadvantage of both Mo and W is their propensity to oxidize at high temperatures, above about 600°C (1000°F), thus detracting from their high temperature properties. To overcome this deficiency, either protective coatings must be used on these metals in high temperature applications or the metal parts must operate in a vacuum. For example, the tungsten filament must be energized in a vacuum inside the glass light bulb.

6.3.9   *PRECIOUS METALS*

The precious metals, also called the ***noble metals*** because they are chemically inactive, include silver, gold, and platinum. They are attractive metals, available in limited supply, and have been used throughout civilized history for coinage and to underwrite paper currency. They are also widely used in jewelry and similar applications that exploit their high value. As a group, these precious metals possess high density, good ductility, high electrical conductivity, and good corrosion resistance; see Table 6.1(j).

Silver (Ag) is less expensive per unit weight than gold or platinum. Nevertheless, its attractive "silvery" luster makes it a highly valued metal in coins, jewelry, and tableware (which even assumes the name of the metal: "silverware"). It is also used for fillings in dental work. Silver has the highest electrical conductivity of any metal, which makes it useful for contacts in electronics applications. Finally, it should be mentioned that light-sensitive silver chloride and other silver halides are the basis for photography.

Gold (Au) is one of the heaviest metals; it is soft and easily formed, and possesses a distinctive yellow color that adds to its value. In addition to currency and jewelry, its applications include electrical contacts (owing to its good electrical conductivity and corrosion resistance), dental work, and plating onto other metals for decorative purposes.

Platinum (Pt) is also used in jewelry and is in fact more expensive than gold. It is the most important of six precious metals known as the platinum group metals, which consists of Ruthenium (Ru), Rhodium (Rh), Palladium (Pd), Osmium (Os), and Iridium (Ir), in addition to Pt. They are clustered in a rectangle in the

periodic table (Figure 2.1). Osmium, Iridium, and Platinum are all denser than gold (Ir is the densest material known, at 22.65 g/cm^3). Because the platinum group metals are all scarce and very expensive, their applications are generally limited to situations in which only small amounts are needed and their unique properties are required (e.g., high melting temperatures, corrosion resistance, and catalytic characteristics). The applications include thermocouples, electrical contacts, spark plugs, corrosion resistant devices, and catalytic pollution control equipment for automobiles.

6.4 Superalloys

Superalloys constitute a category that straddles the ferrous and nonferrous metals. Some of them are based on iron, whereas others are based on nickel and cobalt. In fact, many of the superalloys contain substantial amounts of three or more met- als, rather than consisting of one base metal plus alloying elements. Although the tonnage of these metals is not significant compared with most of the other metals discussed in this chapter, they are nevertheless commercially important because they are very expensive; and they are technologically important because of what they can do.

The *superalloys* are a group of high-performance alloys designed to meet very demanding requirements for strength and resistance to surface degradation (corro- sion and oxidation) at high service temperatures. Conventional room temperature strength is usually not the important criterion for these metals, and most of them possess room temperature strength properties that are good but not outstanding. Their high temperature performance is what distinguishes them; tensile strength, hot hardness, creep resistance, and corrosion resistance at very elevated tempera- tures are the mechanical properties of interest. Operating temperatures are often in the vicinity of 1100°C (2000°F). These metals are widely used in gas turbines— jet and rocket engines, steam turbines, and nuclear power plants—systems in which operating efficiency increases with higher temperatures.

The superalloys are usually divided into three groups, according to their principal constituent: iron, nickel, or cobalt:

➢ *Iron-based alloys* have iron as the main ingredient, although in some cases the iron is less than 50% of the total composition.

➢ *Nickel-based alloys* generally have better high temperature strength than alloy steels. Nickel is the base metal. The principal alloying elements are chromium and cobalt; lesser elements include aluminum, titanium, molybdenum, niobium (Nb), and iron. Some familiar names in this group include Inconel, Hastelloy, and Rene 41.

➢ *Cobalt-based alloys* consist of cobalt (around 40%) and chromium (perhaps 20%) as their main components. Other alloying elements include nickel, molyb- denum, and tungsten.

In virtually all of the superalloys, including those based on iron, strengthening is accomplished by precipitation hardening. The iron-based superalloys do not use martensite formation for strengthening. Typical compositions and strength prop- erties at room temperature and elevated temperature for some of the alloys are presented in Table 6.15.

TABLE • 6.15 Some typical superalloy compositions together with strength properties at room temperature and elevated temperature.

Superalloy	Chemical Analysis, %[a]							Tensile Strength at Room Temperature		Tensile Strength at 870°C (1600°F)	
	Fe	Ni	Co	Cr	Mo	W	Other[b]	MPa	lb/in^2	MPa	lb/in^2
Iron-based											
Incoloy 802	46	32		21			<2	690	100,000	195	28,000
Haynes 556	29	20	20	22	3		6	815	118,000	330	48,000
Nickel-based											
Incoloy 807	25	40	8	21		5	1	655	95,000	220	32,000
Inconel 718	18	53		19	3		6	1435	208,000	340	49,000
Rene 41		55	11	19	1		5	1420	206,000	620	90,000
Hastelloy S	1	67		16	15		1	845	130,000	340	50,000
Nimonic 75	3	76		20			<2	745	108,000	150	22,000
Cobalt-based											
Stellite 6B	3	3	53	30	2	5	4	1010	146,000	385	56,000
Haynes 188	3	22	39	22		14		960	139,000	420	61,000
L-605		10	53	20		15	2	1005	146,000	325	47,000

Compiled from [11] and [12].

[a]Compositions to nearest percent.

[b]Other elements include carbon, niobium, titanium, tungsten, manganese, and silicon.