

Chapter 13 / Types and Applications of Materials

Scanning electron micrograph showing the microstructure of a glass-ceramic material. The long acicular blades yield a material with unusual strength and toughness. 65,000 \times . (Photograph courtesy of L. R. Pinckney and G. J. Fine of Corning Incorporated.)



Why Study Types and Applications of Materials?

Engineers are often involved in materials selection decisions, which necessitates that they have some familiarity with the general characteristics of a wide variety of materials. In addition, access to data bases containing property values for a large number

of materials may be required. {For example, in Section 20.2 we discuss a materials selection process that is applied to a cylindrical shaft that is stressed in torsion.}

Learning Objectives

After careful study of this chapter you should be able to do the following:

1. Name four different types of steels and, for each, cite compositional differences, distinctive properties, and typical uses.
2. Name the four cast iron types and, for each, describe its microstructure and note its general mechanical characteristics.
3. Name seven different types of nonferrous alloys and, for each, cite its distinctive physical and mechanical characteristics; in addition, list at least three typical applications.
4. Describe the process that is used to produce glass-ceramics.
5. Name the two types of clay products and give two examples of each.
6. Cite three important requirements that normally must be met by refractory ceramics and abrasive ceramics.
7. Describe the mechanism by which cement hardens when water is added.
8. Cite the seven different polymer application types and, for each, note its general characteristics.

13.1 INTRODUCTION

Many times a materials problem is really one of selecting that material which has the right combination of characteristics for a specific application. Therefore, the persons who are involved in the decision making should have some knowledge of the available options. This extremely abbreviated presentation provides an overview of some of the types of metal alloys, ceramics, and polymeric materials, their general properties, and their limitations.

TYPES OF METAL ALLOYS

Metal alloys, by virtue of composition, are often grouped into two classes—ferrous and nonferrous. Ferrous alloys, those in which iron is the principal constituent, include steels and cast irons. These alloys and their characteristics are the first topics of discussion of this section. The nonferrous ones—all the alloys that are not iron based—are treated next.

13.2 FERROUS ALLOYS

Ferrous alloys—those of which iron is the prime constituent—are produced in larger quantities than any other metal type. They are especially important as engineering construction materials. Their widespread use is accounted for by three factors: (1) iron-containing compounds exist in abundant quantities within the earth's crust; (2) metallic iron and steel alloys may be produced using relatively economical extraction, refining, alloying, and fabrication techniques; and (3) ferrous alloys are extremely versatile, in that they may be tailored to have a wide range of mechanical and physical properties. The principal disadvantage of many ferrous alloys is their susceptibility to corrosion. These sections discuss compositions, microstructures, and properties of a number of different classes of steels and cast irons. A taxonomic classification scheme for the various ferrous alloys is presented in Figure 13.1.

STEELS

Steels are iron-carbon alloys that may contain appreciable concentrations of other alloying elements; there are thousands of alloys that have different compositions and/or heat treatments. The mechanical properties are sensitive to the content of

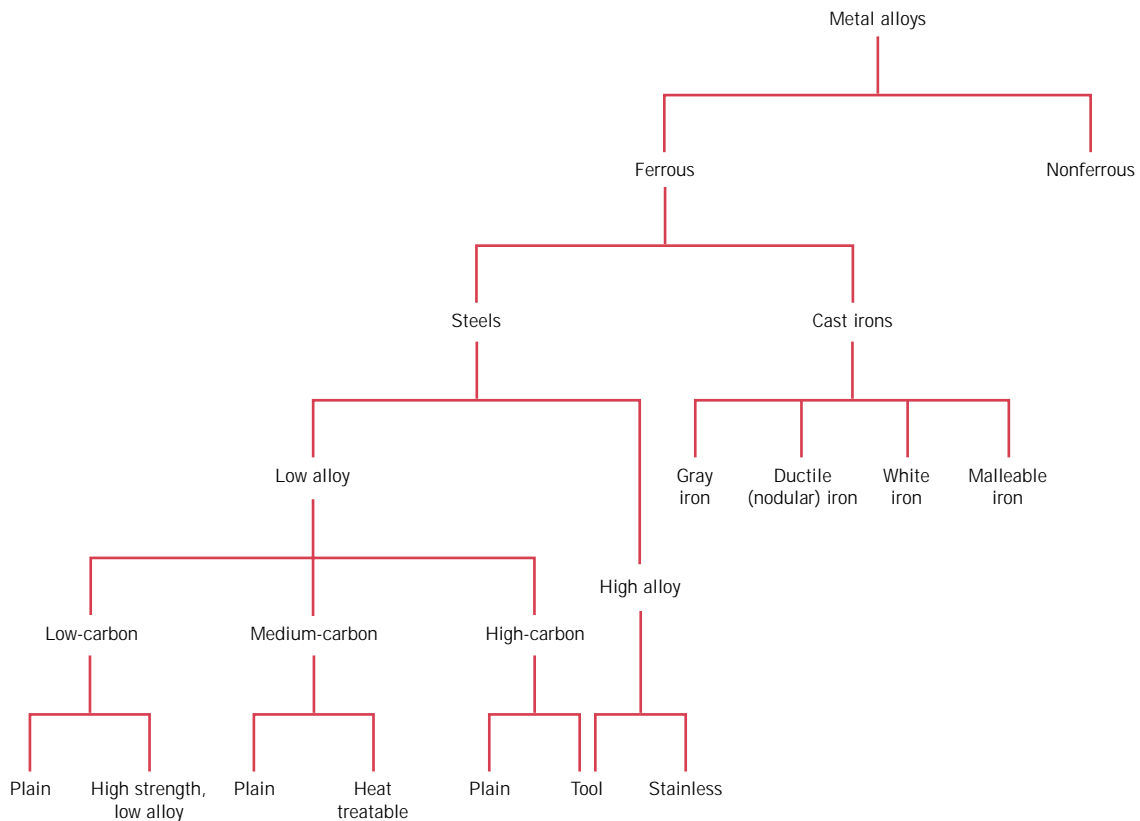


FIGURE 13.1 Classification scheme for the various ferrous alloys.

carbon, which is normally less than 1.0 wt%. Some of the more common steels are classified according to carbon concentration, namely, into low-, medium-, and high-carbon types. Subclasses also exist within each group according to the concentration of other alloying elements. **Plain carbon steels** contain only residual concentrations of impurities other than carbon and a little manganese. For **alloy steels**, more alloying elements are intentionally added in specific concentrations.

Low-Carbon Steels

Of all the different steels, those produced in the greatest quantities fall within the low-carbon classification. These generally contain less than about 0.25 wt% C and are unresponsive to heat treatments intended to form martensite; strengthening is accomplished by cold work. Microstructures consist of ferrite and pearlite constituents. As a consequence, these alloys are relatively soft and weak, but have outstanding ductility and toughness; in addition, they are machinable, weldable, and, of all steels, are the least expensive to produce. Typical applications include automobile body components, structural shapes (I-beams, channel and angle iron), and sheets that are used in pipelines, buildings, bridges, and tin cans. Tables 13.1a and 13.1b, respectively, present the compositions and mechanical properties of several plain low-carbon steels. They typically have a yield strength of 275 MPa (40,000 psi), tensile strengths between 415 and 550 MPa (60,000 and 80,000 psi), and a ductility of 25%EL.

Table 13.1a Compositions of Five Plain Low-Carbon Steels and Three High-Strength, Low-Alloy Steels

<i>Designation^a</i>		<i>Composition (wt%)^b</i>		
<i>AISI/SAE or ASTM Number</i>	<i>UNS Number</i>	<i>C</i>	<i>Mn</i>	<i>Other</i>
<i>Plain Low-Carbon Steels</i>				
1010	G10100	0.10	0.45	
1020	G10200	0.20	0.45	
A36	K02600	0.29	1.00	0.20 Cu (min)
A516 Grade 70	K02700	0.31	1.00	0.25 Si
<i>High-Strength, Low-Alloy Steels</i>				
A440	K12810	0.28	1.35	0.30 Si (max), 0.20 Cu (min)
A633 Grade E	K12002	0.22	1.35	0.30 Si, 0.08 V, 0.02 N, 0.03 Nb
A656 Grade 1	K11804	0.18	1.60	0.60 Si, 0.1 V, 0.20 Al, 0.015 N

^a The codes used by the American Iron and Steel Institute (AISI), the Society of Automotive Engineers (SAE), and the American Society for Testing and Materials (ASTM), and in the Uniform Numbering System (UNS) are explained in the text.

^b Also a maximum of 0.04 wt% P, 0.05 wt% S, and 0.30 wt% Si (unless indicated otherwise).

Source: Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), American Society for Metals, 1978, pp. 185, 407.

Table 13.1b Mechanical Characteristics of Hot-Rolled Material and Typical Applications for Various Plain Low-Carbon and High-Strength, Low-Alloy Steels

<i>AISI/SAE or ASTM Number</i>	<i>Tensile Strength [MPa (ksi)]</i>	<i>Yield Strength [MPa (ksi)]</i>	<i>Ductility [%EL in 50 mm (2 in.)]</i>	<i>Typical Applications</i>
<i>Plain Low-Carbon Steels</i>				
1010	325 (47)	180 (26)	28	Automobile panels, nails, and wire
1020	380 (55)	205 (30)	25	Pipe; structural and sheet steel
A36	400 (58)	220 (32)	23	Structural (bridges and buildings)
A516 Grade 70	485 (70)	260 (38)	21	Low-temperature pressure vessels
<i>High-Strength, Low-Alloy Steels</i>				
A440	435 (63)	290 (42)	21	Structures that are bolted or riveted
A633 Grade E	520 (75)	380 (55)	23	Structures used at low ambient temperatures
A656 Grade 1	655 (95)	552 (80)	15	Truck frames and railway cars

Another group of low-carbon alloys are the **high-strength, low-alloy (HSLA) steels**. They contain other alloying elements such as copper, vanadium, nickel, and molybdenum in combined concentrations as high as 10 wt%, and possess higher strengths than the plain low-carbon steels. Most may be strengthened by heat treatment, giving tensile strengths in excess of 480 MPa (70,000 psi); in addition, they are ductile, formable, and machinable. Several are listed in Table 13.1. In normal atmospheres, the HSLA steels are more resistant to corrosion than the plain carbon steels, which they have replaced in many applications where structural strength is critical (e.g., bridges, towers, support columns in high-rise buildings, and pressure vessels).

Medium-Carbon Steels

The medium-carbon steels have carbon concentrations between about 0.25 and 0.60 wt%. These alloys may be heat treated by austenitizing, quenching, and then tempering to improve their mechanical properties. They are most often utilized in the tempered condition, having microstructures of tempered martensite. The plain medium-carbon steels have low hardenabilities (Section 14.6) and can be successfully heat treated only in very thin sections and with very rapid quenching rates. Additions of chromium, nickel, and molybdenum improve the capacity of these alloys to be heat treated, giving rise to a variety of strength–ductility combinations. These heat-treated alloys are stronger than the low-carbon steels, but at a sacrifice of ductility and toughness. Applications include railway wheels and tracks, gears, crankshafts, and other machine parts and high-strength structural components calling for a combination of high strength, wear resistance, and toughness.

The compositions of several of these alloyed medium-carbon steels are presented in Table 13.2a. Some comment is in order regarding the designation schemes that are also included. The Society of Automotive Engineers (SAE), the American Iron and Steel Institute (AISI), and the American Society for Testing and Materials (ASTM) are responsible for the classification and specification of steels as well as other alloys. The AISI/SAE designation for these steels is a four-digit number: the first two digits indicate the alloy content; the last two, the carbon concentration. For plain carbon steels, the first two digits are 1 and 0; alloy steels are designated by other initial two-digit combinations (e.g., 13, 41, 43). The third and fourth digits represent the weight percent carbon multiplied by 100. For example, a 1060 steel is a plain carbon steel containing 0.60 wt% C.

A unified numbering system (UNS) is used for uniformly indexing both ferrous and nonferrous alloys. Each UNS number consists of a single-letter prefix followed by a five-digit number. The letter is indicative of the family of metals to which an alloy belongs. The UNS designation for these alloys begins with a G, followed by the AISI/SAE number; the fifth digit is a zero. Table 13.2b contains the mechanical characteristics and typical applications of several of these steels, which have been quenched and tempered.

High-Carbon Steels

The high-carbon steels, normally having carbon contents between 0.60 and 1.4 wt%, are the hardest, strongest, and yet least ductile of the carbon steels. They are almost always used in a hardened and tempered condition and, as such, are especially wear resistant and capable of holding a sharp cutting edge. The tool and die steels are high-carbon alloys, usually containing chromium, vanadium, tungsten, and molybdenum. These alloying elements combine with carbon to form very hard and wear-resistant

Table 13.2a AISI/SAE and UNS Designation Systems and Composition Ranges for Plain Carbon Steel and Various Low-Alloy Steels

AISI/SAE Designation ^a	UNS Designation	Composition Ranges (wt% of Alloying Elements in Addition to C) ^b			
		Ni	Cr	Mo	Other
10xx, Plain carbon	G10xx0				
11xx, Free machining	G11xx0				0.08–0.33S
12xx, Free machining	G12xx0				0.10–0.35S, 0.04–0.12P
13xx	G13xx0				1.60–1.90Mn
40xx	G40xx0			0.20–0.30	
41xx	G41xx0		0.80–1.10	0.15–0.25	
43xx	G43xx0	1.65–2.00	0.40–0.90	0.20–0.30	
46xx	G46xx0	0.70–2.00		0.15–0.30	
48xx	G48xx0	3.25–3.75		0.20–0.30	
51xx	G51xx0		0.70–1.10		
61xx	G61xx0		0.50–1.10		0.10–0.15V
86xx	G86xx0	0.40–0.70	0.40–0.60	0.15–0.25	
92xx	G92xx0				1.80–2.20Si

^a The carbon concentration, in weight percent times 100, is inserted in the place of “xx” for each specific steel.

^b Except for 13xx alloys, manganese concentration is less than 1.00 wt%.
 Except for 12xx alloys, phosphorus concentration is less than 0.35 wt%.
 Except for 11xx and 12xx alloys, sulfur concentration is less than 0.04 wt%.
 Except for 92xx alloys, silicon concentration varies between 0.15 and 0.35 wt%.

Table 13.2b Typical Applications and Mechanical Property Ranges for Oil-Quenched and Tempered Plain Carbon and Alloy Steels

AISI Number	UNS Number	Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Plain Low-Carbon Steels					
1040	G10400	605–780 (88–113)	430–585 (62–85)	33–19	Crankshafts, bolts
1080 ^a	G10800	800–1310 (116–190)	480–980 (70–142)	24–13	Chisels, hammers
1095 ^a	G10950	760–1280 (110–186)	510–830 (74–120)	26–10	Knives, hacksaw blades
Alloy Steels					
4063	G40630	786–2380 (114–345)	710–1770 (103–257)	24–4	Springs, hand tools
4340	G43400	980–1960 (142–284)	895–1570 (130–228)	21–11	Bushings, aircraft tubing
6150	G61500	815–2170 (118–315)	745–1860 (108–270)	22–7	Shafts, pistons, gears

^a Classified as high-carbon steels.

Table 13.3 Designations, Compositions, and Applications for Six Tool Steels

AISI Number	UNS Number	Composition (wt%) ^a						Typical Applications
		C	Cr	Ni	Mo	W	V	
M1	T11301	0.85	3.75	0.30 max	8.70	1.75	1.20	Drills, saws; lathe and planer tools
A2	T30102	1.00	5.15	0.30 max	1.15	—	0.35	Punches, embossing dies
D2	T30402	1.50	12	0.30 max	0.95	—	1.10 max	Cutlery, drawing dies
O1	T31501	0.95	0.50	0.30 max	—	0.50	0.30 max	Shear blades, cutting tools
S1	T41901	0.50	1.40	0.30 max	0.50 max	2.25	0.25	Pipe cutters, concrete drills
W1	T72301	1.10	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	Blacksmith tools, wood-working tools

^a The balance of the composition is iron. Manganese concentrations range between 0.10 and 1.4 wt%, depending on alloy; silicon concentrations between 0.20 and 1.2 wt% depending on alloy.

Source: Adapted from *ASM Handbook*, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

carbide compounds (e.g., Cr_2C_6 , V_4C_3 , and WC). Some tool steel compositions and their applications are listed in Table 13.3. These steels are utilized as cutting tools and dies for forming and shaping materials, as well as in knives, razors, hacksaw blades, springs, and high-strength wire.

Stainless Steels

The **stainless steels** are highly resistant to corrosion (rusting) in a variety of environments, especially the ambient atmosphere. Their predominant alloying element is chromium; a concentration of at least 11 wt% Cr is required. Corrosion resistance may also be enhanced by nickel and molybdenum additions.

Stainless steels are divided into three classes on the basis of the predominant phase constituent of the microstructure—martensitic, ferritic, or austenitic. Table 13.4 lists several stainless steels, by class, along with composition, typical mechanical properties, and applications. A wide range of mechanical properties combined with excellent resistance to corrosion make stainless steels very versatile in their applicability.

Martensitic stainless steels are capable of being heat treated in such a way that martensite is the prime microconstituent. Additions of alloying elements in significant concentrations produce dramatic alterations in the iron–iron carbide phase diagram (Figure 10.26). For austenitic stainless steels, the austenite (or γ) phase field is extended to room temperature. Ferritic stainless steels are composed of the α ferrite (BCC) phase. Austenitic and ferritic stainless steels are hardened and strengthened by cold work because they are not heat treatable. The austenitic stainless steels are the most corrosion resistant because of the high chromium contents and also the nickel additions; and they are produced in the largest quantities. Both martensitic and ferritic stainless steels are magnetic; the austenitic stainlesses are not.

Table 13.4 Designations, Compositions, Mechanical Properties, and Typical Applications for Austenitic, Ferritic, Martensitic, and Precipitation-Hardenable Stainless Steels

AISI Number	UNS Number	Composition (wt%) ^a	Condition ^b	Mechanical Properties			Typical Applications
				Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	
Ferritic							
409	S40900	0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti	Annealed	380 (55)	205 (30)	20	Automotive exhaust components, tanks for agricultural sprays
446	S44600	0.20 C, 25 Cr, 1.5 Mn	Annealed	515 (75)	275 (40)	20	Valves (high temperature), glass molds, combustion chambers
Austenitic							
304	S30400	0.08 C, 19 Cr, 9 Ni, 2.0 Mn	Annealed	515 (75)	205 (30)	40	Chemical and food processing equipment, cryogenic vessels
316L	S31603	0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction
Martensitic							
410	S41000	0.15 C, 12.5 Cr, 1.0 Mn	Annealed Q & T	485 (70) 825 (120)	275 (40) 620 (90)	20 12	Rifle barrels, cutlery, jet engine parts
440A	S44002	0.70 C, 17 Cr, 0.75 Mo, 1.0 Mn	Annealed Q & T	725 (105) 1790 (260)	415 (60) 1650 (240)	20 5	Cutlery, bearings, surgical tools
Precipitation Hardenable							
17-7PH	S17700	0.09 C, 17 Cr, 7 Ni, 1.0 Al, 1.0 Mn	Precipitation hardened	1450 (210)	1310 (190)	1–6	Springs, knives, pressure vessels

^a The balance of the composition is iron.

^b Q & T denotes quenched and tempered.

Source: Adapted from *ASM Handbook*, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

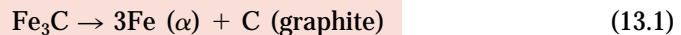
Some stainless steels are frequently used at elevated temperatures and in severe environments because they resist oxidation and maintain their mechanical integrity under such conditions; the upper temperature limit in oxidizing atmospheres is about 1000°C (1800°F). Equipment employing these steels includes gas turbines, high-temperature steam boilers, heat-treating furnaces, aircraft, missiles, and nuclear power generating units. Also included in Table 13.4 is one ultrahigh-strength stainless steel (17-7PH), which is unusually strong and corrosion

resistant. Strengthening is accomplished by precipitation-hardening heat treatments (Section 11.10).

CAST IRONS

Generically, **cast irons** are a class of ferrous alloys with carbon contents above 2.14 wt%; in practice, however, most cast irons contain between 3.0 and 4.5 wt% C and, in addition, other alloying elements. A reexamination of the iron–iron carbide phase diagram (Figure 10.26) reveals that alloys within this composition range become completely liquid at temperatures between approximately 1150 and 1300°C (2100 and 2350°F), which is considerably lower than for steels. Thus, they are easily melted and amenable to casting. Furthermore, some cast irons are very brittle, and casting is the most convenient fabrication technique.

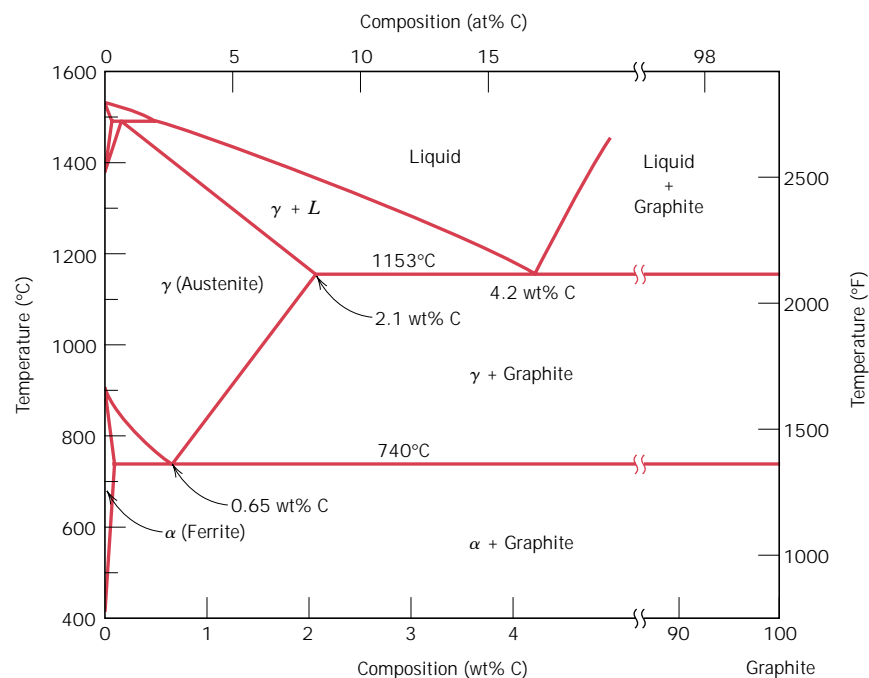
Cementite (Fe_3C) is a metastable compound, and under some circumstances it can be made to dissociate or decompose to form α ferrite and graphite, according to the reaction



Thus, the true equilibrium diagram for iron and carbon is not that presented in Figure 10.26, but rather as shown in Figure 13.2. The two diagrams are virtually identical on the iron-rich side (e.g., eutectic and eutectoid temperatures for the Fe– Fe_3C system are 1147 and 727°C, respectively, as compared to 1153 and 740°C for Fe–C); however, Figure 13.2 extends to 100 wt% carbon such that graphite is the carbon-rich phase, instead of cementite at 6.7 wt% C (Figure 10.26).

This tendency to form graphite is regulated by the composition and rate of cooling. Graphite formation is promoted by the presence of silicon in concentrations greater than about 1 wt%. Also, slower cooling rates during solidification favor graphitization (the formation of graphite). For most cast irons, the carbon exists

FIGURE 13.2 The true equilibrium iron–carbon phase diagram with graphite instead of cementite as a stable phase. (Adapted from *Binary Alloy Phase Diagrams*, T. B. Massalski, Editor-in-Chief, 1990. Reprinted by permission of ASM International, Materials Park, OH.)



as graphite, and both microstructure and mechanical behavior depend on composition and heat treatment. The most common cast iron types are gray, nodular, white, and malleable.

Gray Iron

The carbon and silicon contents of **gray cast irons** vary between 2.5 and 4.0 wt% and 1.0 and 3.0 wt%, respectively. For most of these cast irons, the graphite exists in the form of flakes (similar to corn flakes), which are normally surrounded by an α ferrite or pearlite matrix; the microstructure of a typical gray iron is shown in Figure 13.3a. Because of these graphite flakes, a fractured surface takes on a gray appearance, hence its name.

Mechanically, gray iron is comparatively weak and brittle in tension as a consequence of its microstructure; the tips of the graphite flakes are sharp and pointed, and may serve as points of stress concentration when an external tensile stress is applied. Strength and ductility are much higher under compressive loads. Typical mechanical properties and compositions of several of the common gray cast irons are listed in Table 13.5. Gray irons do have some desirable characteristics and, in fact, are utilized extensively. They are very effective in damping vibrational energy; this is represented in Figure 13.4, which compares the relative damping capacities of steel and gray iron. Base structures for machines and heavy equipment that are exposed to vibrations are frequently constructed of this material. In addition, gray irons exhibit a high resistance to wear. Furthermore, in the molten state they have a high fluidity at casting temperature, which permits casting pieces having intricate shapes; also, casting shrinkage is low. Finally, and perhaps most important, gray cast irons are among the least expensive of all metallic materials.

Gray irons having microstructures different from that shown in Figure 13.3a may be generated by adjustment of composition and/or by using an appropriate treatment. For example, lowering the silicon content or increasing the cooling rate may prevent the complete dissociation of cementite to form graphite (Equation 13.1). Under these circumstances the microstructure consists of graphite flakes embedded in a pearlite matrix. Figure 13.5 compares schematically the several cast iron microstructures obtained by varying the composition and heat treatment.

Ductile (or Nodular) Iron

Adding a small amount of magnesium and/or cerium to the gray iron before casting produces a distinctly different microstructure and set of mechanical properties. Graphite still forms, but as nodules or spherelike particles instead of flakes. The resulting alloy is called **nodular** or **ductile iron**, and a typical microstructure is shown in Figure 13.3b. The matrix phase surrounding these particles is either pearlite or ferrite, depending on heat treatment (Figure 13.5); it is normally pearlite for an as-cast piece. However, a heat treatment for several hours at about 700°C (1300°F) will yield a ferrite matrix as in this photomicrograph. Castings are stronger and much more ductile than gray iron, as a comparison of their mechanical properties in Table 13.5 shows. In fact, ductile iron has mechanical characteristics approaching those of steel. For example, ferritic ductile irons have tensile strengths ranging between 380 and 480 MPa (55,000 and 70,000 psi), and ductilities (as percent elongation) from 10 to 20%. Typical applications for this material include valves, pump bodies, crankshafts, gears, and other automotive and machine components.

White Iron and Malleable Iron

For low-silicon cast irons (containing less than 1.0 wt% Si) and rapid cooling rates, most of the carbon exists as cementite instead of graphite, as indicated in Figure

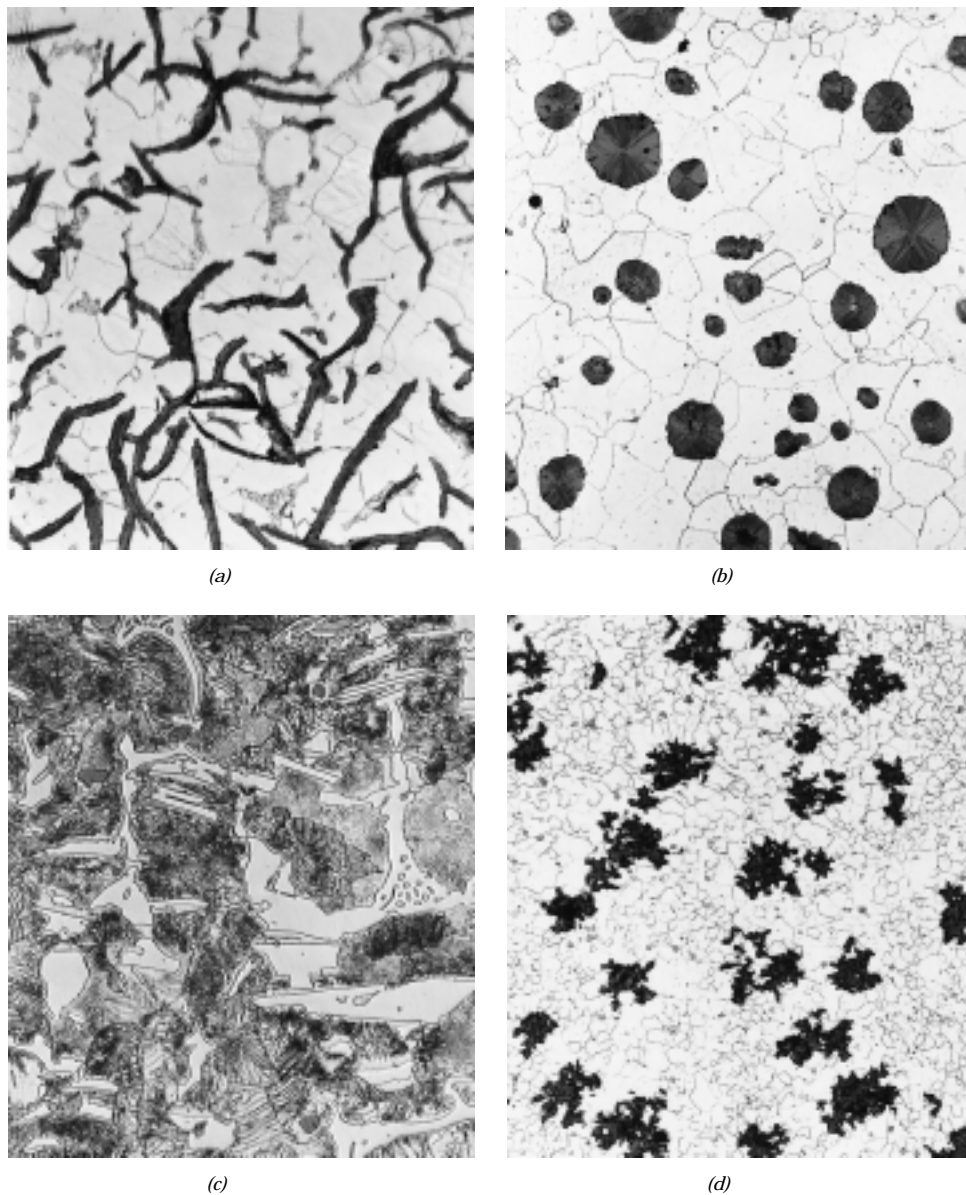


FIGURE 13.3 Optical photomicrographs of various cast irons. (a) Gray iron: the dark graphite flakes are embedded in an α -ferrite matrix. 500 \times . (Courtesy of C. H. Brady, National Bureau of Standards, Washington, DC.) (b) Nodular (ductile) iron: the dark graphite nodules are surrounded by an α -ferrite matrix. 200 \times . (Courtesy of C. H. Brady and L. C. Smith, National Bureau of Standards, Washington, DC.) (c) White iron: the light cementite regions are surrounded by pearlite, which has the ferrite–cementite layered structure. 400 \times . (Courtesy of Amcast Industrial Corporation.) (d) Malleable iron: dark graphite rosettes (temper carbon) in an α -ferrite matrix. 150 \times . (Reprinted with permission of the Iron Castings Society, Des Plaines, IL.)

Table 13.5 Designations, Minimum Mechanical Properties, Approximate Compositions, and Typical Applications for Various Gray, Nodular, and Malleable Cast Irons

Grade	UNS Number	Composition (wt%) ^a	Matrix Structure	Mechanical Properties			Typical Applications	
				Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]		
Gray Iron								
SAE G1800	F10004	3.40–3.7 C, 2.55 Si, 0.7 Mn	Ferrite + Pearlite	124 (18)	—	—	Miscellaneous soft iron castings in which strength is not a primary consideration	
SAE G2500	F10005	3.2–3.5 C, 2.20 Si, 0.8 Mn	Ferrite + Pearlite	173 (25)	—	—	Small cylinder blocks, cylinder heads, pistons, clutch plates, transmission cases	
SAE G4000	F10008	3.0–3.3 C, 2.0 Si, 0.8 Mn	Pearlite	276 (40)	—	—	Diesel engine castings, liners, cylinders, and pistons	
Ductile (Nodular) Iron								
ASTM A536 60-40-18	F32800	3.5–3.8 C, 2.0–2.8 Si, 0.05 Mg, <0.20 Ni, <0.10 Mo	Ferrite	414 (60)	276 (40)	18	Pressure-containing parts such as valve and pump bodies	
100-70-03	F34800		Pearlite	689 (100)	483 (70)	3		High-strength gears and machine components
120-90-02	F36200		Tempered martensite	827 (120)	621 (90)	2		Pinions, gears, rollers, slides
Malleable Iron								
32510	F22200	2.3–2.7 C, 1.0–1.75 Si, <0.55 Mn	Ferrite	345 (50)	224 (32)	10	General engineering service at normal and elevated temperatures	
45006	—	2.4–2.7 C, 1.25–1.55 Si, <0.55 Mn	Ferrite + Pearlite	448 (65)	310 (45)	6		

^a The balance of the composition is iron.

Source: Adapted from *ASM Handbook*, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

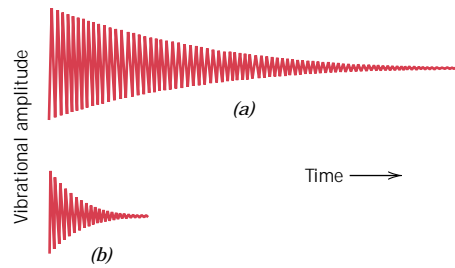
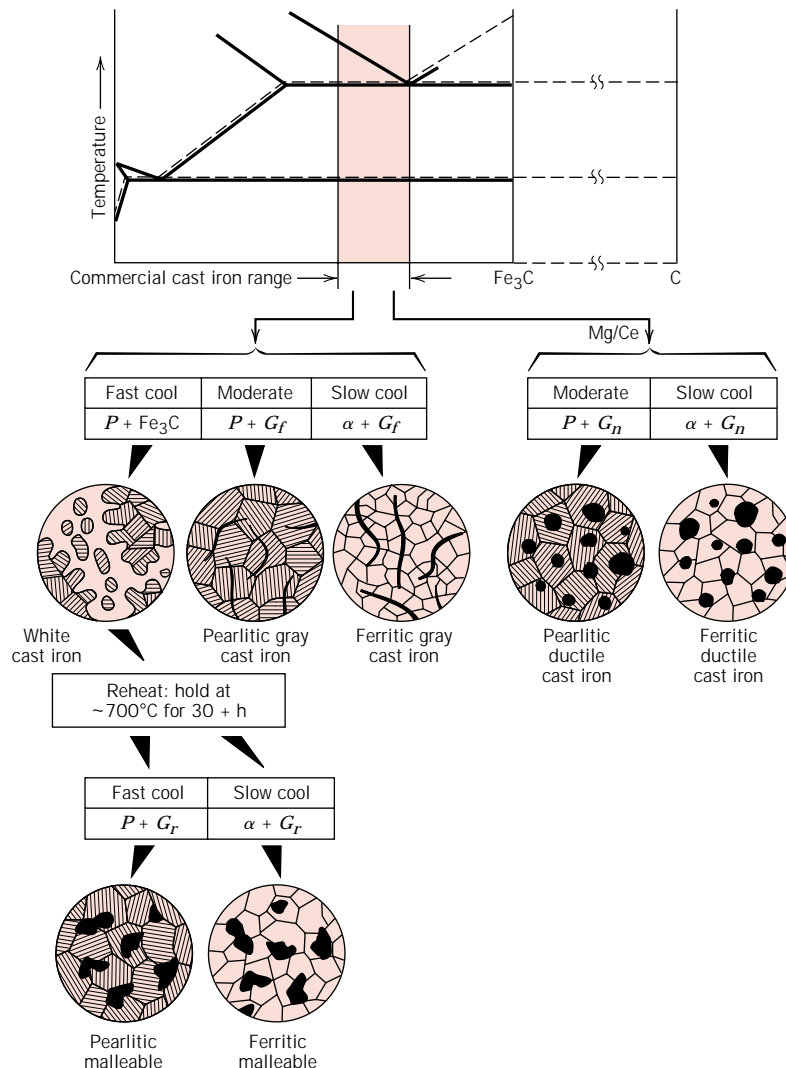


FIGURE 13.4 Comparison of the relative vibrational damping capacities of (a) steel and (b) gray cast iron. (From *Metals Engineering Quarterly*, February 1961. Copyright 1961 American Society for Metals.)

13.5. A fracture surface of this alloy has a white appearance, and thus it is termed **white cast iron**. An optical photomicrograph showing the microstructure of white iron is presented in Figure 13.3c. Thick sections may have only a surface layer of white iron that was “chilled” during the casting process; gray iron forms at interior regions, which cool more slowly. As a consequence of large amounts of the cementite

FIGURE 13.5 From the iron-carbon phase diagram, composition ranges for commercial cast irons. Also shown are microstructures that result from a variety of heat treatments. G_f , flake graphite; G_r , graphite rosettes; G_n , graphite nodules; P , pearlite; α , ferrite. (Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. 1, Structure, p. 195. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



phase, white iron is extremely hard but also very brittle, to the point of being virtually unmachinable. Its use is limited to applications that necessitate a very hard and wear-resistant surface, and without a high degree of ductility—for example, as rollers in rolling mills. Generally, white iron is used as an intermediary in the production of yet another cast iron, **malleable iron**.

Heating white iron at temperatures between 800 and 900°C (1470 and 1650°F) for a prolonged time period and in a neutral atmosphere (to prevent oxidation) causes a decomposition of the cementite, forming graphite, which exists in the form of clusters or rosettes surrounded by a ferrite or pearlite matrix, depending on cooling rate, as indicated in Figure 13.5. A photomicrograph of a ferritic malleable iron is presented in Figure 13.3*d*. The microstructure is similar to that for nodular iron (Figure 13.3*b*), which accounts for relatively high strength and appreciable ductility or malleability. Some typical mechanical characteristics are also listed in Table 13.5. Representative applications include connecting rods, transmission gears, and differential cases for the automotive industry, and also flanges, pipe fittings, and valve parts for railroad, marine, and other heavy-duty services.

13.3 NONFERROUS ALLOYS

Steel and other ferrous alloys are consumed in exceedingly large quantities because they have such a wide range of mechanical properties, may be fabricated with relative ease, and are economical to produce. However, they have some distinct limitations, chiefly: (1) a relatively high density, (2) a comparatively low electrical conductivity, and (3) an inherent susceptibility to corrosion in some common environments. Thus, for many applications it is advantageous or even necessary to utilize other alloys having more suitable property combinations. Alloy systems are classified either according to the base metal or according to some specific characteristic that a group of alloys share. This section discusses the following metal and alloy systems: copper, aluminum, magnesium, and titanium alloys, the refractory metals, the superalloys, the noble metals, and miscellaneous alloys, including those that have nickel, lead, tin, zirconium, and zinc as base metals.

On occasion, a distinction is made between cast and wrought alloys. Alloys that are so brittle that forming or shaping by appreciable deformation is not possible ordinarily are cast; these are classified as *cast alloys*. On the other hand, those that are amenable to mechanical deformation are termed **wrought alloys**.

In addition, the heat treatability of an alloy system is mentioned frequently. “Heat treatable” designates an alloy whose mechanical strength is improved by precipitation hardening or a martensitic transformation (normally the former), both of which involve specific heat-treating procedures.

COPPER AND ITS ALLOYS

Copper and copper-based alloys, possessing a desirable combination of physical properties, have been utilized in quite a variety of applications since antiquity. Unalloyed copper is so soft and ductile that it is difficult to machine; also, it has an almost unlimited capacity to be cold worked. Furthermore, it is highly resistant to corrosion in diverse environments including the ambient atmosphere, seawater, and some industrial chemicals. The mechanical and corrosion-resistance properties of copper may be improved by alloying. Most copper alloys cannot be hardened or strengthened by heat-treating procedures; consequently, cold working and/or solid-solution alloying must be utilized to improve these mechanical properties.

The most common copper alloys are the **brasses** for which zinc, as a substitutional impurity, is the predominant alloying element. As may be observed for the

copper–zinc phase diagram (Figure 10.17), the α phase is stable for concentrations up to approximately 35 wt% Zn. This phase has an FCC crystal structure, and α brasses are relatively soft, ductile, and easily cold worked. Brass alloys having a higher zinc content contain both α and β' phases at room temperature. The β' phase has an ordered BCC crystal structure and is harder and stronger than the α phase; consequently, $\alpha + \beta'$ alloys are generally hot worked.

Some of the common brasses are yellow, naval, and cartridge brass, muntz metal, and gilding metal. The compositions, properties, and typical uses of several of these alloys are listed in Table 13.6. Some of the common uses for brass alloys include costume jewelry, cartridge casings, automotive radiators, musical instruments, electronic packaging, and coins.

Table 13.6 Compositions, Mechanical Properties, and Typical Applications for Eight Copper Alloys

Alloy Name	UNS Number	Composition (wt%) ^a	Condition	Mechanical Properties			Typical Applications
				Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	
<i>Wrought Alloys</i>							
Electrolytic tough pitch	C11000	0.04 O	Annealed	220 (32)	69 (10)	45	Electrical wire, rivets, screening, gaskets, pans, nails, roofing
Beryllium copper	C17200	1.9 Be, 0.20 Co	Precipitation hardened	1140–1310 (165–190)	690–860 (100–125)	4–10	Springs, bellows, firing pins, bushings, valves, diaphragms
Cartridge brass	C26000	30 Zn	Annealed	300 (44)	75 (11)	68	Automotive radiator cores, ammunition components, lamp fixtures, flashlight shells, kickplates
			Cold-worked (H04 hard)	525 (76)	435 (63)	8	
Phosphor bronze, 5% A	C51000	5 Sn, 0.2 P	Annealed	325 (47)	130 (19)	64	Bellows, clutch disks, diaphragms, fuse clips, springs, welding rods
			Cold-worked (H04 hard)	560 (81)	515 (75)	10	
Copper-nickel, 30%	C71500	30 Ni	Annealed	380 (55)	125 (18)	36	Condenser and heat-exchanger components, saltwater piping
			Cold-worked (H02 hard)	515 (75)	485 (70)	15	
<i>Cast Alloys</i>							
Leaded yellow brass	C85400	29 Zn, 3 Pb, 1 Sn	As cast	234 (34)	83 (12)	35	Furniture hardware, radiator fittings, light fixtures, battery clamps
Tin bronze	C90500	10 Sn, 2 Zn	As cast	310 (45)	152 (22)	25	Bearings, bushings, piston rings, steam fittings, gears
Aluminum bronze	C95400	4 Fe, 11 Al	As cast	586 (85)	241 (35)	18	Bearings, gears, worms, bushings, valve seats and guards, pickling hooks

^a The balance of the composition is copper.

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The **bronzes** are alloys of copper and several other elements, including tin, aluminum, silicon, and nickel. These alloys are somewhat stronger than the brasses, yet they still have a high degree of corrosion resistance. Table 13.6 contains several of the bronze alloys, their compositions, properties, and applications. Generally they are utilized when, in addition to corrosion resistance, good tensile properties are required.

The most common precipitation hardenable copper alloys are the beryllium coppers. They possess a remarkable combination of properties: tensile strengths as high as 1400 MPa (200,000 psi), excellent electrical and corrosion properties, and wear resistance when properly lubricated; they may be cast, hot worked, or cold worked. High strengths are attained by precipitation-hardening heat treatments. These alloys are costly because of the beryllium additions, which range between 1.0 and 2.5 wt%. Applications include jet aircraft landing gear bearings and bushings, springs, and surgical and dental instruments. One of these alloys (C17200) is included in Table 13.6.

ALUMINUM AND ITS ALLOYS

Aluminum and its alloys are characterized by a relatively low density (2.7 g/cm^3 as compared to 7.9 g/cm^3 for steel), high electrical and thermal conductivities, and a resistance to corrosion in some common environments, including the ambient atmosphere. Many of these alloys are easily formed by virtue of high ductility; this is evidenced by the thin aluminum foil sheet into which the relatively pure material may be rolled. Since aluminum has an FCC crystal structure, its ductility is retained even at very low temperatures. The chief limitation of aluminum is its low melting temperature [660°C (1220°F)], which restricts the maximum temperature at which it can be used.

The mechanical strength of aluminum may be enhanced by cold work and by alloying; however, both processes tend to diminish resistance to corrosion. Principal alloying elements include copper, magnesium, silicon, manganese, and zinc. Non-heat-treatable alloys consist of a single phase, for which an increase in strength is achieved by solid solution strengthening. Others are rendered heat treatable (capable of being precipitation hardened) as a result of alloying. In several of these alloys precipitation hardening is due to the precipitation of two elements other than aluminum, to form an intermetallic compound such as MgZn_2 .

Generally, aluminum alloys are classified as either cast or wrought. Composition for both types is designated by a four-digit number that indicates the principal impurities, and in some cases, the purity level. For cast alloys, a decimal point is located between the last two digits. After these digits is a hyphen and the basic **temper designation**—a letter and possibly a one- to three-digit number, which indicates the mechanical and/or heat treatment to which the alloy has been subjected. For example, F, H, and O represent, respectively, the as-fabricated, strain-hardened, and annealed states; T3 means that the alloy was solution heat treated, cold worked, and then naturally aged (age hardened). A solution heat treatment followed by artificial aging is indicated by T6. The compositions, properties, and applications of several wrought and cast alloys are contained in Table 13.7. Some of the more common applications of aluminum alloys include aircraft structural parts, beverage cans, bus bodies, and automotive parts (engine blocks, pistons, and manifolds).

Recent attention has been given to alloys of aluminum and other low-density metals (e.g., Mg and Ti) as engineering materials for transportation, to effect reductions in fuel consumption. An important characteristic of these materials is **specific**

Table 13.7 Compositions, Mechanical Properties, and Typical Applications for Several Common Aluminum Alloys

Aluminum Association Number	UNS Number	Composition (wt%) ^a	Condition (Temper Designation)	Mechanical Properties			Typical Applications/ Characteristics
				Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	
Wrought, Nonheat-Treatable Alloys							
1100	A91100	0.12 Cu	Annealed (O)	90 (13)	35 (5)	35–45	Food/chemical handling & storage equipment, heat exchangers, light reflectors
3003	A93003	0.12 Cu, 1.2 Mn, 0.1 Zn	Annealed (O)	110 (16)	40 (6)	30–40	Cooking utensils, pressure vessels and piping
5052	A95052	2.5 Mg, 0.25 Cr	Strain hardened (H32)	230 (33)	195 (28)	12–18	Aircraft fuel & oil lines, fuel tanks, appliances, rivets, and wire
Wrought, Heat-Treatable Alloys							
2024	A92024	4.4 Cu, 1.5 Mg, 0.6 Mn	Heat treated (T4)	470 (68)	325 (47)	20	Aircraft structures, rivets, truck wheels, screw machine products
6061	A96061	1.0 Mg, 0.6 Si, 0.30 Cu, 0.20 Cr	Heat treated (T4)	240 (35)	145 (21)	22–25	Trucks, canoes, railroad cars, furniture, pipelines
7075	A97075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr	Heat treated (T6)	570 (83)	505 (73)	11	Aircraft structural parts and other highly stressed applications
Cast, Heat-Treatable Alloys							
295.0	A02950	4.5 Cu, 1.1 Si	Heat treated (T4)	221 (32)	110 (16)	8.5	Flywheel and rear-axle housings, bus and aircraft wheels, crankcases
356.0	A03560	7.0 Si, 0.3 Mg	Heat treated (T6)	228 (33)	164 (24)	3.5	Aircraft pump parts, automotive transmission cases, water-cooled cylinder blocks
Aluminum-Lithium Alloys							
2090	—	2.7 Cu, 0.25 Mg, 2.25 Li, 0.12 Zr	Heat treated, cold worked (T83)	455 (66)	455 (66)	5	Aircraft structures and cryogenic tank-age structures
8090	—	1.3 Cu, 0.95 Mg, 2.0 Li, 0.1 Zr	Heat treated, cold worked (T651)	465 (67)	360 (52)	—	Aircraft structures that must be highly damage tolerant

^a The balance of the composition is aluminum.

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strength, which is quantified by the tensile strength–specific gravity ratio. Even though an alloy of one of these metals may have a tensile strength that is inferior to a more dense material (such as steel), on a weight basis it will be able to sustain a larger load.

A generation of new aluminum-lithium alloys have been developed recently for use by the aircraft and aerospace industries. These materials have relatively low densities (between about 2.5 and 2.6 g/cm³), high specific moduli (elastic modulus–specific gravity ratios), and excellent fatigue and low-temperature toughness properties. Furthermore, some of them may be precipitation hardened. However, these materials are more costly to manufacture than the conventional aluminum alloys because special processing techniques are required as a result of lithium’s chemical reactivity.

MAGNESIUM AND ITS ALLOYS

Perhaps the most outstanding characteristic of magnesium is its density, 1.7 g/cm³, which is the lowest of all the structural metals; therefore, its alloys are used where light weight is an important consideration (e.g., in aircraft components). Magnesium has an HCP crystal structure, is relatively soft, and has a low elastic modulus: 45 GPa (6.5×10^6 psi). At room temperature magnesium and its alloys are difficult to deform; in fact, only small degrees of cold work may be imposed without annealing. Consequently, most fabrication is by casting or hot working at temperatures between 200 and 350°C (400 and 650°F). Magnesium, like aluminum, has a moderately low melting temperature [651°C (1204°F)]. Chemically, magnesium alloys are relatively unstable and especially susceptible to corrosion in marine environments. On the other hand, corrosion or oxidation resistance is reasonably good in the normal atmosphere; it is believed that this behavior is due to impurities rather than being an inherent characteristic of Mg alloys. Fine magnesium powder ignites easily when heated in air; consequently, care should be exercised when handling it in this state.

These alloys are also classified as either cast or wrought, and some of them are heat treatable. Aluminum, zinc, manganese, and some of the rare earths are the major alloying elements. A composition–temper designation scheme similar to that for aluminum alloys is also used. Table 13.8 lists several common magnesium alloys, their compositions, properties, and applications. These alloys are used in aircraft and missile applications, as well as in luggage. Furthermore, in the last several years the demand for magnesium alloys has increased dramatically in a host of different industries. For many applications, magnesium alloys have replaced engineering plastics that have comparable densities inasmuch as the magnesium materials are stiffer, more recyclable, and less costly to produce. For example, magnesium is now employed in a variety of hand-held devices (e.g., chain saws, power tools, hedge clippers), in automobiles (e.g., steering wheels and columns, seat frames, transmission cases), and in audio-video-computer-communications equipment (e.g., laptop computers, camcorders, TV sets, cellular telephones).

TITANIUM AND ITS ALLOYS

Titanium and its alloys are relatively new engineering materials that possess an extraordinary combination of properties. The pure metal has a relatively low density (4.5 g/cm³), a high melting point [1668°C (3035°F)], and an elastic modulus of 107 GPa (15.5×10^6 psi). Titanium alloys are extremely strong; room temperature tensile strengths as high as 1400 MPa (200,000 psi) are attainable, yielding remarkable specific strengths. Furthermore, the alloys are highly ductile and easily forged and machined.

Table 13.8 Compositions, Mechanical Properties, and Typical Applications for Six Common Magnesium Alloys

ASTM Number	UNS Number	Composition (wt%) ^a	Condition	Mechanical Properties			Typical Applications
				Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	
<i>Wrought Alloys</i>							
AZ31B	M11311	3.0 Al, 1.0 Zn, 0.2 Mn	As extruded	262 (38)	200 (29)	15	Structures and tubing, cathodic protection
HK31A	M13310	3.0 Th, 0.6 Zr	Strain hardened, partially annealed	255 (37)	200 (29)	9	High strength to 315°C (600°F)
ZK60A	M16600	5.5 Zn, 0.45 Zr	Artificially aged	350 (51)	285 (41)	11	Forgings of maximum strength for aircraft
<i>Cast Alloys</i>							
AZ91D	M11916	9.0 Al, 0.15 Mn, 0.7 Zn	As cast	230 (33)	150 (22)	3	Die-cast parts for automobiles, luggage, and electronic devices
AM60A	M10600	6.0 Al, 0.13 Mn	As cast	220 (32)	130 (19)	6	Automotive wheels
AS41A	M10410	4.3 Al, 1.0 Si, 0.35 Mn	As cast	210 (31)	140 (20)	6	Die castings requiring good creep resistance

^a The balance of the composition is magnesium.

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The major limitation of titanium is its chemical reactivity with other materials at elevated temperatures. This property has necessitated the development of non-conventional refining, melting, and casting techniques; consequently, titanium alloys are quite expensive. In spite of this high temperature reactivity, the corrosion resistance of titanium alloys at normal temperatures is unusually high; they are virtually immune to air, marine, and a variety of industrial environments. Table 13.9 presents several titanium alloys along with their typical properties and applications. They are commonly utilized in airplane structures, space vehicles, surgical implants, and in the petroleum and chemical industries.

THE REFRACTORY METALS

Metals that have extremely high melting temperatures are classified as the refractory metals. Included in this group are niobium (Nb), molybdenum (Mo), tungsten (W), and tantalum (Ta). Melting temperatures range between 2468°C (4474°F) for niobium and 3410°C (6170°F), the highest melting temperature of any metal, for tungsten. Interatomic bonding in these metals is extremely strong, which accounts for the melting temperatures, and, in addition, large elastic moduli and high strengths and hardnesses, at ambient as well as elevated temperatures. The applications of these metals are varied. For example, tantalum and molybdenum are alloyed with stainless steel to improve its corrosion resistance. Molybdenum alloys are utilized for extrusion dies and structural parts in space vehicles; incandescent light filaments,

Table 13.9 Compositions, Mechanical Properties, and Typical Applications for Several Common Titanium Alloys

<i>Alloy Type</i>	<i>Common Name (UNS Number)</i>	<i>Composition (wt%)</i>	<i>Condition</i>	<i>Average Mechanical Properties</i>			<i>Typical Applications</i>
				<i>Tensile Strength [MPa (ksi)]</i>	<i>Yield Strength [MPa (ksi)]</i>	<i>Ductility [%EL in 50 mm (2 in.)]</i>	
Commercially pure	Unalloyed (R50500)	99.1 Ti	Annealed	484 (70)	414 (60)	25	Jet engine shrouds, cases and airframe skins, corrosion-resistant equipment for marine and chemical processing industries
α	Ti-5Al-2.5Sn (R54520)	5 Al, 2.5 Sn, balance Ti	Annealed	826 (120)	784 (114)	16	Gas turbine engine casings and rings; chemical processing equipment requiring strength to temperatures of 480°C (900°F)
Near α	Ti-8Al-1Mo-1V (R54810)	8 Al, 1 Mo, 1 V, balance Ti	Annealed (duplex)	950 (138)	890 (129)	15	Forgings for jet engine components (compressor disks, plates, and hubs)
α - β	Ti-6Al-4V (R56400)	6 Al, 4 V, balance Ti	Annealed	947 (137)	877 (127)	14	High-strength prosthetic implants, chemical-processing equipment, airframe structural components
α - β	Ti-6Al-6V-2Sn (R56620)	6 Al, 2 Sn, 6 V, 0.75 Cu, balance Ti	Annealed	1050 (153)	985 (143)	14	Rocket engine case airframe applications and high-strength airframe structures
β	Ti-10V-2Fe-3Al	10 V, 2 Fe, 3 Al, balance Ti	Solution + aging	1223 (178)	1150 (167)	10	Best combination of high strength and toughness of any commercial titanium alloy; used for applications requiring uniformity of tensile properties at surface and center locations; high-strength airframe components

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x-ray tubes, and welding electrodes employ tungsten alloys. Tantalum is immune to chemical attack by virtually all environments at temperatures below 150°C, and is frequently used in applications requiring such a corrosion-resistant material.

THE SUPERALLOYS

The superalloys have superlative combinations of properties. Most are used in aircraft turbine components, which must withstand exposure to severely oxidizing environments and high temperatures for reasonable time periods. Mechanical integrity under these conditions is critical; in this regard, density is an important consideration because centrifugal stresses are diminished in rotating members when the density is reduced. These materials are classified according to the predominant metal in the alloy, which may be cobalt, nickel, or iron. Other alloying elements include the refractory metals (Nb, Mo, W, Ta), chromium, and titanium. In addition to turbine applications, these alloys are utilized in nuclear reactors and petrochemical equipment.

THE NOBLE METALS

The noble or precious metals are a group of eight elements that have some physical characteristics in common. They are expensive (precious) and are superior or notable (noble) in properties—i.e., characteristically soft, ductile, and oxidation resistant. The noble metals are silver, gold, platinum, palladium, rhodium, ruthenium, iridium, and osmium; the first three are most common and are used extensively in jewelry. Silver and gold may be strengthened by solid-solution alloying with copper; sterling silver is a silver–copper alloy containing approximately 7.5 wt% Cu. Alloys of both silver and gold are employed as dental restoration materials; also, some integrated circuit electrical contacts are of gold. Platinum is used for chemical laboratory equipment, as a catalyst (especially in the manufacture of gasoline), and in thermocouples to measure elevated temperatures.

MISCELLANEOUS NONFERROUS ALLOYS

The discussion above covers the vast majority of nonferrous alloys; however, a number of others are found in a variety of engineering applications, and a brief exposure of these is worthwhile.

Nickel and its alloys are highly resistant to corrosion in many environments, especially those that are basic (alkaline). Nickel is often coated or plated on some metals that are susceptible to corrosion as a protective measure. Monel, a nickel-based alloy containing approximately 65 wt% Ni and 28 wt% Cu (the balance iron), has very high strength and is extremely corrosion resistant; it is used in pumps, valves, and other components that are in contact with some acid and petroleum solutions. As already mentioned, nickel is one of the principal alloying elements in stainless steels, and one of the major constituents in the superalloys.

Lead, tin, and their alloys find some use as engineering materials. Both are mechanically soft and weak, have low melting temperatures, are quite resistant to many corrosion environments, and have recrystallization temperatures below room temperature. Many common solders are lead–tin alloys, which have low melting temperatures. Applications for lead and its alloys include x-ray shields and storage batteries. The primary use of tin is as a very thin coating on the inside of plain carbon steel cans (tin cans) that are used for food containers; this coating inhibits chemical reactions between the steel and the food products.

Unalloyed zinc also is a relatively soft metal having a low melting temperature and a subambient recrystallization temperature. Chemically, it is reactive in a num-

ber of common environments and, therefore, susceptible to corrosion. Galvanized steel is just plain carbon steel that has been coated with a thin zinc layer; the zinc preferentially corrodes and protects the steel {(Section 16.9).} Typical applications of galvanized steel are familiar (sheet metal, fences, screen, screws, etc.). Common applications of zinc alloys include padlocks, automotive parts (door handles and grilles), and office equipment.

Although zirconium is relatively abundant in the earth's crust, it was not until quite recent times that commercial refining techniques were developed. Zirconium and its alloys are ductile and have other mechanical characteristics that are comparable to those of titanium alloys and the austenitic stainless steels. However, the primary asset of these alloys is their resistance to corrosion in a host of corrosive media, including superheated water. Furthermore, zirconium is transparent to thermal neutrons, so that its alloys have been used as cladding for uranium fuel in water-cooled nuclear reactors. In terms of cost, these alloys are also often the materials of choice for heat exchangers, reactor vessels, and piping systems for the chemical-processing and nuclear industries. They are also used in incendiary ordnance and in sealing devices for vacuum tubes.



In Appendix B is tabulated a wide variety of properties (e.g., density, elastic modulus, yield and tensile strengths, electrical conductivity, coefficient of thermal expansion, etc.) for a large number of metals and alloys.

TYPES OF CERAMICS

The preceding discussions of the properties of materials have demonstrated that there is a significant disparity between the physical characteristics of metals and ceramics. Consequently, these materials are utilized in totally different kinds of applications and, in this regard, tend to complement each other, and also the polymers. Most ceramic materials fall into an application-classification scheme that includes the following groups: glasses, structural clay products, whitewares, refractories, abrasives, cements, {and the newly developed advanced ceramics.} Figure 13.6 presents a taxonomy of these several types; some discussion is devoted to each. We have also chosen to discuss the characteristics and applications of diamond and graphite in this section.

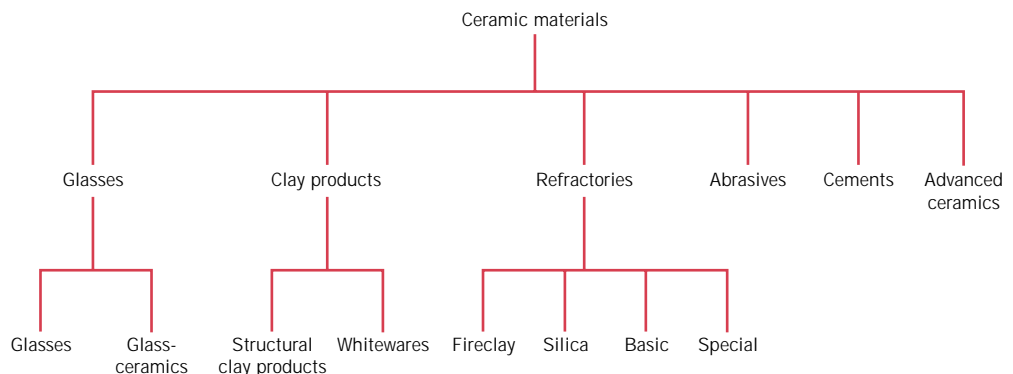


FIGURE 13.6 Classification of ceramic materials on the basis of application.

Table 13.10 Compositions and Characteristics of Some of the Common Commercial Glasses

<i>Glass Type</i>	<i>Composition (wt%)</i>						<i>Characteristics and Applications</i>
	<i>SiO₂</i>	<i>Na₂O</i>	<i>CaO</i>	<i>Al₂O₃</i>	<i>B₂O₃</i>	<i>Other</i>	
Fused silica	>99.5						High melting temperature, very low coefficient of expansion (shock resistant)
96% Silica (Vycor)	96				4		Thermally shock and chemically resistant—laboratory ware
Borosilicate (Pyrex)	81	3.5		2.5	13		Thermally shock and chemically resistant—ovenware
Container (soda-lime)	74	16	5	1		4MgO	Low melting temperature, easily worked, also durable
Fiberglass	55		16	15	10	4MgO	Easily drawn into fibers—glass-resin composites
Optical flint	54	1				37PbO, 8K ₂ O	High density and high index of refraction—optical lenses
Glass-ceramic (Pyroceram)	43.5	14		30	5.5	6.5TiO ₂ , 0.5As ₂ O ₃	Easily fabricated; strong; resists thermal shock—ovenware

13.4 GLASSES

The glasses are a familiar group of ceramics; containers, windows, lenses, and fiberglass represent typical applications. As already mentioned, they are noncrystalline silicates containing other oxides, notably CaO, Na₂O, K₂O, and Al₂O₃, which influence the glass properties. A typical soda-lime glass consists of approximately 70 wt% SiO₂, the balance being mainly Na₂O (soda) and CaO (lime). The compositions of several common glass materials are contained in Table 13.10. Possibly the two prime assets of these materials are their optical transparency and the relative ease with which they may be fabricated.

13.5 GLASS-CERAMICS

Most inorganic glasses can be made to transform from a noncrystalline state to one that is crystalline by the proper high-temperature heat treatment. This process is called **devitrification**, and the product is a fine-grained polycrystalline material which is often called a **glass-ceramic**. A nucleating agent (frequently titanium dioxide) must be added to induce the crystallization or devitrification process. Desirable characteristics of glass-ceramics include a low coefficient of thermal expansion, such that the glass-ceramic ware will not experience thermal shock; in addition, relatively high mechanical strengths and thermal conductivities are achieved. Some glass-ceramics may be made optically transparent; others are opaque. Possibly the most attractive attribute of this class of materials is the ease with which they may be fabricated; conventional glass-forming techniques may be used conveniently in the mass production of nearly pore-free ware.

Glass-ceramics are manufactured commercially under the trade names of Pyroceram, Corningware, Cercor, and Vision. The most common uses for these materials are as ovenware and tableware, primarily because of their strength, excellent resistance to thermal shock, and their high thermal conductivity. They also serve as electrical insulators and as substrates for printed circuit boards, and are utilized

for architectural cladding, and for heat exchangers and regenerators. A typical glass–ceramic is also included in Table 13.10, and the microstructure of a commercial material is shown in the chapter-opening photograph for this chapter.

13.6 CLAY PRODUCTS

One of the most widely used ceramic raw materials is clay. This inexpensive ingredient, found naturally in great abundance, often is used as mined without any upgrading of quality. Another reason for its popularity lies in the ease with which clay products may be formed; when mixed in the proper proportions, clay and water form a plastic mass that is very amenable to shaping. The formed piece is dried to remove some of the moisture, after which it is fired at an elevated temperature to improve its mechanical strength.

Most of the clay-based products fall within two broad classifications: the **structural clay products** and the **whitewares**. Structural clay products include building bricks, tiles, and sewer pipes—applications in which structural integrity is important. The whiteware ceramics become white after the high-temperature **firing**. Included in this group are porcelain, pottery, tableware, china, and plumbing fixtures (sanitary ware). In addition to clay, many of these products also contain other ingredients, each of which has some role to play in the processing and characteristics of the finished piece {(Section 14.8).}

13.7 REFRACTORIES

Another important class of ceramics that are utilized in large tonnages is the **refractory ceramics**. The salient properties of these materials include the capacity to withstand high temperatures without melting or decomposing, and the capacity to remain unreactive and inert when exposed to severe environments. In addition, the ability to provide thermal insulation is often an important consideration. Refractory materials are marketed in a variety of forms, but bricks are the most common. Typical applications include furnace linings for metal refining, glass manufacturing, metallurgical heat treatment, and power generation.

Of course, the performance of a refractory ceramic, to a large degree, depends on its composition. On this basis, there are several classifications, namely, fireclay, silica, basic, and special refractories. Compositions for a number of commercial refractories are listed in Table 13.11. For many commercial materials, the raw ingredients consist of both large (or grog) particles and fine particles, which may

Table 13.11 Compositions of Five Common Ceramic Refractory Materials

Refractory Type	Composition (wt%)						Apparent Porosity (%)	
	Al_2O_3	SiO_2	MgO	Cr_2O_3	Fe_2O_3	CaO		TiO_2
Fireclay	25–45	70–50	0–1		0–1	0–1	1–2	10–25
High-alumina fireclay	90–50	10–45	0–1		0–1	0–1	1–4	18–25
Silica	0.2	96.3	0.6			2.2		25
Periclase	1.0	3.0	90.0	0.3	3.0	2.5		22
Periclase–chrome ore	9.0	5.0	73.0	8.2	2.0	2.2		21

Source: From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2nd edition. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

have different compositions. Upon firing, the fine particles normally are involved in the formation of a bonding phase, which is responsible for the increased strength of the brick; this phase may be predominantly either glassy or crystalline. The service temperature is normally below that at which the refractory piece was fired.

Porosity is one microstructural variable that must be controlled to produce a suitable refractory brick. Strength, load-bearing capacity, and resistance to attack by corrosive materials all increase with porosity reduction. At the same time, thermal insulation characteristics and resistance to thermal shock are diminished. Of course, the optimum porosity depends on the conditions of service.

FIRECLAY REFRACTORIES (CD-ROM)

SILICA REFRACTORIES (CD-ROM)

BASIC REFRACTORIES (CD-ROM)

SPECIAL REFRACTORIES (CD-ROM)

13.8 ABRASIVES

Abrasive ceramics are used to wear, grind, or cut away other material, which necessarily is softer. Therefore, the prime requisite for this group of materials is hardness or wear resistance; in addition, a high degree of toughness is essential to ensure that the abrasive particles do not easily fracture. Furthermore, high temperatures may be produced from abrasive frictional forces, so some refractoriness is also desirable.

Diamonds, both natural and synthetic, are utilized as abrasives; however, they are relatively expensive. The more common ceramic abrasives include silicon carbide, tungsten carbide (WC), aluminum oxide (or corundum), and silica sand.

Abrasives are used in several forms—bonded to grinding wheels, as coated abrasives, and as loose grains. In the first case, the abrasive particles are bonded to a wheel by means of a glassy ceramic or an organic resin. The surface structure should contain some porosity; a continual flow of air currents or liquid coolants within the pores that surround the refractory grains will prevent excessive heating. Figure 13.7 shows the microstructure of a bonded abrasive, revealing abrasive grains, the bonding phase, and pores.

Coated abrasives are those in which an abrasive powder is coated on some type of paper or cloth material; sandpaper is probably the most familiar example. Wood, metals, ceramics, and plastics are all frequently ground and polished using this form of abrasive.

Grinding, lapping, and polishing wheels often employ loose abrasive grains that are delivered in some type of oil- or water-based vehicle. Diamonds, corundum, silicon carbide, and rouge (an iron oxide) are used in loose form over a variety of grain size ranges.

13.9 CEMENTS

Several familiar ceramic materials are classified as inorganic **cements**: cement, plaster of paris, and lime, which, as a group, are produced in extremely large quantities. The characteristic feature of these materials is that when mixed with water, they form a paste that subsequently sets and hardens. This trait is especially useful in

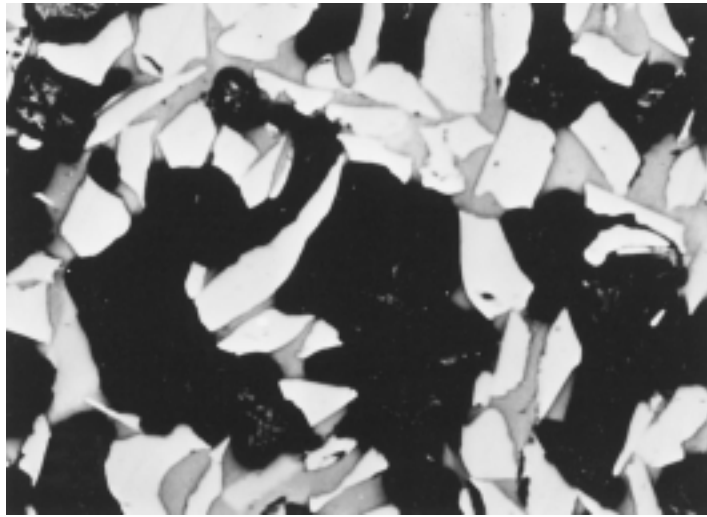
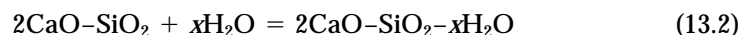


FIGURE 13.7 Photomicrograph of an aluminum oxide bonded ceramic abrasive. The light regions are the Al₂O₃ abrasive grains; the gray and dark areas are the bonding phase and porosity, respectively. 100×. (From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2nd edition, p. 568. Copyright © 1976 by John Wiley & Sons. Reprinted by permission of John Wiley & Sons, Inc.)

that solid and rigid structures having just about any shape may be expeditiously formed. Also, some of these materials act as a bonding phase that chemically binds particulate aggregates into a single cohesive structure. Under these circumstances, the role of the cement is similar to that of the glassy bonding phase that forms when clay products and some refractory bricks are fired. One important difference, however, is that the cementitious bond develops at room temperature.

Of this group of materials, portland cement is consumed in the largest tonnages. It is produced by grinding and intimately mixing clay and lime-bearing minerals in the proper proportions, and then heating the mixture to about 1400°C (2550°F) in a rotary kiln; this process, sometimes called **calcination**, produces physical and chemical changes in the raw materials. The resulting “clinker” product is then ground into a very fine powder to which is added a small amount of gypsum (CaSO₄·2H₂O) to retard the setting process. This product is portland cement. The properties of portland cement, including setting time and final strength, to a large degree depend on its composition.

Several different constituents are found in portland cement, the principal ones being tricalcium silicate (3CaO·SiO₂) and dicalcium silicate (2CaO·SiO₂). The setting and hardening of this material result from relatively complicated hydration reactions that occur between the various cement constituents and the water that is added. For example, one hydration reaction involving dicalcium silicate is as follows:



where x is variable and depends on how much water is available. These hydrated products are in the form of complex gels or crystalline substances that form the cementitious bond. Hydration reactions begin just as soon as water is added to the cement. These are first manifested as setting (i.e., the stiffening of the once-plastic

paste), which takes place soon after mixing, usually within several hours. Hardening of the mass follows as a result of further hydration, a relatively slow process that may continue for as long as several years. It should be emphasized that the process by which cement hardens is not one of drying, but rather, of hydration in which water actually participates in a chemical bonding reaction.

Portland cement is termed a hydraulic cement because its hardness develops by chemical reactions with water. It is used primarily in mortar and concrete to bind, into a cohesive mass, aggregates of inert particles (sand and/or gravel); these are considered to be composite materials {see Section 15.2.} Other cement materials, such as lime, are nonhydraulic; that is, compounds other than water (e.g., CO_2) are involved in the hardening reaction.

13.10 ADVANCED CERAMICS (CD-ROM)

13.11 DIAMOND AND GRAPHITE

DIAMOND

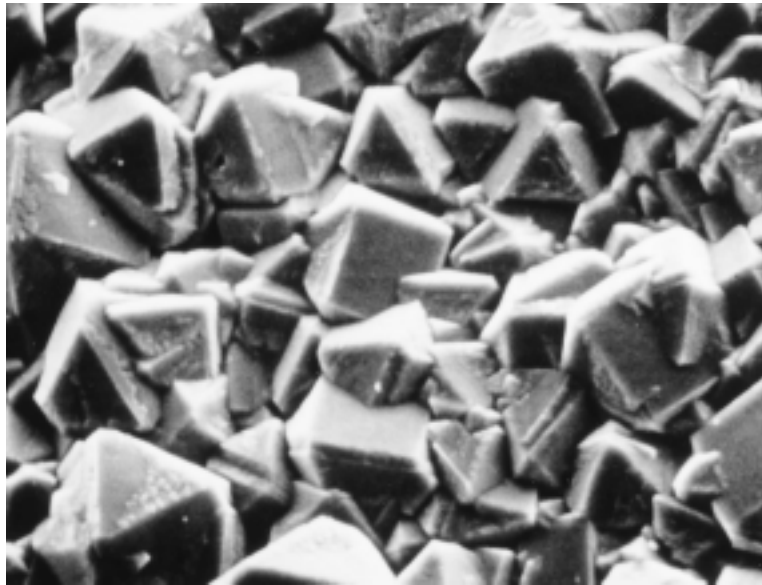
The physical properties of diamond make it an extremely attractive material. It is extremely hard (the hardest known material) and has a very low electrical conductivity; these characteristics are due to its crystal structure and the strong interatomic covalent bonds. Furthermore, it has an unusually high thermal conductivity for a nonmetallic material, is optically transparent in the visible and infrared regions of the electromagnetic spectrum, and has a high index of refraction. Relatively large diamond single crystals are used as gem stones. Industrially, diamonds are utilized to grind or cut other softer materials (Section 13.8). Techniques to produce synthetic diamonds have been developed, beginning in the mid-1950s, that have been refined to the degree that today a large proportion of the industrial-quality materials are man-made, in addition to some of those of gem quality.

Over the last several years, diamond in the form of thin films has been produced. Film growth techniques involve vapor-phase chemical reactions followed by the film deposition. Maximum film thicknesses are on the order of a millimeter. Furthermore, none of the films yet produced has the long-range crystalline regularity of natural diamond. The diamond is polycrystalline and may consist of very small and/or relatively large grains; in addition, amorphous carbon and graphite may be present. A scanning electron micrograph of the surface of a diamond thin film is shown in Figure 13.8. The mechanical, electrical, and optical properties of diamond films approach those of the bulk diamond material. These desirable properties have been and will continue to be exploited so as to create new and better products. For example, the surfaces of drills, dies, bearings, knives, and other tools have been coated with diamond films to increase surface hardness; some lenses and radomes have been made stronger while remaining transparent by the application of diamond coatings; coatings have also been applied to loudspeaker tweeters and to high-precision micrometers. Potential applications for these films include application to the surface of machine components such as gears and bearings, to optical recording heads and disks, and as substrates for semiconductor devices.

GRAPHITE

The structure of graphite is represented in Figure 3.17; in addition, the discussion of graphite in Section 3.9 noted that the electron bonding between the layers of hexagonally arranged carbon atoms is of the van der Waals type. As a consequence

FIGURE 13.8 Scanning electron micrograph of a diamond thin film in which is shown numerous multifaceted microcrystals. 1000 \times . (Photograph courtesy of the Norton Company.)



of these weak interplanar bonds, interplanar cleavage is facile, which gives rise to the excellent lubricative properties of graphite. Also, the electrical conductivity is relatively high in crystallographic directions parallel to the hexagonal sheets.

Other desirable properties of graphite include the following: high strength and good chemical stability at elevated temperatures and in nonoxidizing atmospheres, high thermal conductivity, low coefficient of thermal expansion and high resistance to thermal shock, high adsorption of gases, and good machinability. Graphite is commonly used as heating elements for electric furnaces, as electrodes for arc welding, in metallurgical crucibles, in casting molds for metal alloys and ceramics, for high-temperature refractories and insulations, in rocket nozzles, in chemical reactor vessels, for electrical contacts, brushes and resistors, as electrodes in batteries, and in air purification devices.

TYPES OF POLYMERS

There are many different polymeric materials that are familiar to us and find a wide variety of applications. These include plastics, elastomers (or rubbers), fibers, coatings, adhesives, foams, and films. Depending on its properties, a particular polymer may be used in two or more of these application categories. For example, a plastic, if crosslinked and utilized above its glass transition temperature, may make a satisfactory elastomer. Or, a fiber material may be used as a plastic if it is not drawn into filaments. This portion of the chapter includes a brief discussion of each of these types of polymer.

13.12 PLASTICS

Possibly the largest number of different polymeric materials come under the plastic classification. Polyethylene, polypropylene, polyvinyl chloride, polystyrene, and the fluorocarbons, epoxies, phenolics, and polyesters may all be classified as **plastics**.

They have a wide variety of combinations of properties. Some plastics are very rigid and brittle; others are flexible, exhibiting both elastic and plastic deformations when stressed, and sometimes experiencing considerable deformation before fracture.

Polymers falling within this classification may have any degree of crystallinity, and all molecular structures and configurations (linear, branched, isotactic, etc.) are possible. Plastic materials may be either thermoplastic or thermosetting; in fact, this is the manner in which they are usually subclassified. The trade names, characteristics, and typical applications for a number of plastics are given in Table 13.12.

Table 13.12 Trade Names, Characteristics, and Typical Applications for a Number of Plastic Materials

<i>Material Type</i>	<i>Trade Names</i>	<i>Major Application Characteristics</i>	<i>Typical Applications</i>
Thermoplastics			
Acrylonitrile-butadiene-styrene (ABS)	Abson Cyclocac Kralastic Lustran Novodur Tybrene	Outstanding strength and toughness, resistant to heat distortion; good electrical properties; flammable and soluble in some organic solvents	Refrigerator linings, lawn and garden equipment, toys, highway safety devices
Acrylics (poly-methyl methacrylate)	Acrylite Diakon Lucite Plexiglas	Outstanding light transmission and resistance to weathering; only fair mechanical properties	Lenses, transparent aircraft enclosures, drafting equipment, outdoor signs
Fluorocarbons (PTFE or TFE)	Teflon Fluon Halar Halon Hostaflon TF	Chemically inert in almost all environments, excellent electrical properties; low coefficient of friction; may be used to 260°C (500°F); relatively weak and poor cold-flow properties	Anticorrosive seals, chemical pipes and valves, bearings, antiadhesive coatings, high-temperature electronic parts
Polyamides (nylons)	Nylon Durethan Herox Nomex Ultramid Zytel	Good mechanical strength, abrasion resistance, and toughness; low coefficient of friction; absorbs water and some other liquids	Bearings, gears, cams, bushings, handles, and jacketing for wires and cables
Polycarbonates	Baylon Iupilon Lexan Makrolon Merlon Nuclon	Dimensionally stable; low water absorption; transparent; very good impact resistance and ductility; chemical resistance not outstanding	Safety helmets, lenses, light globes, base for photographic film
Polyethylene	Alathon Alkathene Ethron Fortiflex Hi-fax Petrothene Rigidex Zendel	Chemically resistant, and electrically insulating; tough and relatively low coefficient of friction; low strength and poor resistance to weathering	Flexible bottles, toys, tumblers, battery parts, ice trays, film wrapping materials

Table 13.12 (Continued)

<i>Material Type</i>	<i>Trade Names</i>	<i>Major Application Characteristics</i>	<i>Typical Applications</i>
Polypropylene	Bexphane Herculon Meraklon Moplen Poly-pro Pro-fax Propathene	Resistant to heat distortion; excellent electrical properties and fatigue strength; chemically inert; relatively inexpensive; poor resistance to UV light	Sterilizable bottles, packaging film, TV cabinets, luggage
Polystyrene	Carinex Celatron Hostyren Lustrex Styron Vestyron	Excellent electrical properties and optical clarity; good thermal and dimensional stability; relatively inexpensive	Wall tile, battery cases, toys, indoor lighting panels, appliance housings
Vinyls	Darvic Exon Geon Pee Vee Cee Pliovic Saran Tygon	Good low-cost, general-purpose materials; ordinarily rigid, but may be made flexible with plasticizers; often copolymerized; susceptible to heat distortion	Floor coverings, pipe, electrical wire insulation, garden hose, phonograph records
Polyester (PET or PETE)	Celanar Crastin Dacron Hylar Melinex Mylar Terylem	One of the toughest of plastic films; excellent fatigue and tear strength, and resistance to humidity, acids, greases, oils, and solvents	Magnetic recording tapes, clothing, automotive tire cords, beverage containers
<i>Thermosetting Polymers</i>			
Epoxies	Araldite Epikote Epon Epi-rez Lekutherm Nepoxide	Excellent combination of mechanical properties and corrosion resistance; dimensionally stable; good adhesion; relatively inexpensive; good electrical properties	Electrical moldings, sinks, adhesives, protective coatings, used with fiberglass laminates
Phenolics	Bakelite Amberol Arofen Durite Resinox	Excellent thermal stability to over 150°C (300°F); may be compounded with a large number of resins, fillers, etc.; inexpensive	Motor housings, telephones, auto distributors, electrical fixtures
Polyesters	Aropol Baygal Derakane Laguval Laminac Selectron	Excellent electrical properties and low cost; can be formulated for room- or high-temperature use; often fiber reinforced	Helmets, fiberglass boats, auto body components, chairs, fans

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Several plastics exhibit especially outstanding properties. For applications in which optical transparency is critical, polystyrene and polymethyl methacrylate are especially well suited; however, it is imperative that the material be highly amorphous or, if semicrystalline, have very small crystallites. The fluorocarbons have a low coefficient of friction and are extremely resistant to attack by a host of chemicals, even at relatively high temperatures. They are utilized as coatings on nonstick cookware, in bearings and bushings, and for high-temperature electronic components.

13.13 ELASTOMERS

The characteristics of and deformation mechanism for elastomers were treated previously (Section 8.19). The present discussion, therefore, focuses on the types of elastomeric materials.

Table 13.13 lists properties and applications of common elastomers; these properties are typical and, of course, depend on the degree of vulcanization and on whether any reinforcement is used. Natural rubber is still utilized to a large degree because it has an outstanding combination of desirable properties. However, the

Table 13.13 Tabulation of Important Characteristics and Typical Applications for Five Commercial Elastomers

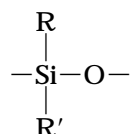
<i>Chemical Type</i>	<i>Trade (Common) Name</i>	<i>Elongation (%)</i>	<i>Useful Temperature Range [°C (°F)]</i>	<i>Major Application Characteristics</i>	<i>Typical Applications</i>
Natural polyisoprene	Natural Rubber (NR)	500–760	–60 to 120 (–75 to 250)	Excellent physical properties; good resistance to cutting, gouging, and abrasion; low heat, ozone, and oil resistance; good electrical properties	Pneumatic tires and tubes; heels and soles; gaskets
Styrene–butadiene copolymer	GRS, Buna S (SBR)	450–500	–60 to 120 (–75 to 250)	Good physical properties; excellent abrasion resistance; not oil, ozone, or weather resistant; electrical properties good, but not outstanding	Same as natural rubber
Acrylonitrile–butadiene copolymer	Buna A, Nitrile (NBR)	400–600	–50 to 150 (–60 to 300)	Excellent resistance to vegetable, animal, and petroleum oils; poor low-temperature properties; electrical properties not outstanding	Gasoline, chemical, and oil hose; seals and O-rings; heels and soles
Chloroprene	Neoprene (CR)	100–800	–50 to 105 (–60 to 225)	Excellent ozone, heat, and weathering resistance; good oil resistance; excellent flame resistance; not as good in electrical applications as natural rubber	Wire and cable; chem. tank linings; belts, hoses, seals, and gaskets
Polysiloxane	Silicone (VMQ)	100–800	–115 to 315 (–175 to 600)	Excellent resistance to high and low temperatures; low strength; excellent electrical properties	High- and low-temperature insulation; seals, diaphragms; tubing for food and medical uses

Sources: Adapted from: C. A. Harper, Editor, *Handbook of Plastics and Elastomers*. Copyright © 1975 by McGraw-Hill Book Company, reproduced with permission; and Materials Engineering's *Materials Selector*, copyright Penton/IPC.

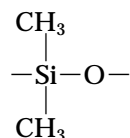
most important synthetic elastomer is SBR, which is used predominantly in automobile tires, reinforced with carbon black. NBR, which is highly resistant to degradation and swelling, is another common synthetic elastomer.

For many applications (e.g., automobile tires), the mechanical properties of even vulcanized rubbers are not satisfactory in terms of tensile strength, abrasion and tear resistance, and stiffness. These characteristics may be further improved by additives such as carbon black {(Section 15.2).}

Finally, some mention should be made of the silicone rubbers. For these materials, the backbone carbon chain is replaced by a chain that alternates silicon and oxygen atoms:



where R and R' represent side-bonded atoms such as hydrogen or groups of atoms such as CH₃. For example, polydimethylsiloxane has the mer structure



Of course, as elastomers, these materials are crosslinked.

The silicone elastomers possess a high degree of flexibility at low temperatures [to -90°C (-130°F)] and yet are stable to temperatures as high as 250°C (480°F). In addition, they are resistant to weathering and lubricating oils. A further attractive characteristic is that some silicone rubbers vulcanize at room temperature (RTV rubbers).

13.14 FIBERS

The **fiber** polymers are capable of being drawn into long filaments having at least a 100:1 length-to-diameter ratio. Most commercial fiber polymers are utilized in the textile industry, being woven or knit into cloth or fabric. In addition, the aramid fibers are employed in composite materials, {Section 15.8.} To be useful as a textile material, a fiber polymer must have a host of rather restrictive physical and chemical properties. While in use, fibers may be subjected to a variety of mechanical deformations—stretching, twisting, shearing, and abrasion. Consequently, they must have a high tensile strength (over a relatively wide temperature range) and a high modulus of elasticity, as well as abrasion resistance. These properties are governed by the chemistry of the polymer chains and also by the fiber drawing process.

The molecular weight of fiber materials should be relatively high. Also, since the tensile strength increases with degree of crystallinity, the structure and configuration of the chains should allow the production of a highly crystalline polymer; that translates into a requirement for linear and unbranched chains that are symmetrical and have regularly repeating mer units.

Convenience in washing and maintaining clothing depends primarily on the thermal properties of the fiber polymer, that is, its melting and glass transition temperatures. Furthermore, fiber polymers must exhibit chemical stability to a

rather extensive variety of environments, including acids, bases, bleaches, dry cleaning solvents, and sunlight. In addition, they must be relatively nonflammable and amenable to drying.

13.15 MISCELLANEOUS APPLICATIONS

COATINGS

Coatings are frequently applied to the surface of materials to serve one or more of the following functions: (1) to protect the item from the environment that may produce corrosive or deteriorative reactions; (2) to improve the item's appearance; and (3) to provide electrical insulation. Many of the ingredients in coating materials are polymers, the majority of which are organic in origin. These organic coatings fall into several different classifications, as follows: paint, varnish, enamel, lacquer, and shellac.

ADHESIVES

An **adhesive** is a substance used to join together the surfaces of two solid materials (termed "adherends") to produce a joint with a high shear strength. The bonding forces between the adhesive and adherend surfaces are thought to be electrostatic, similar to the secondary bonding forces between the molecular chains in thermoplastic polymers. Even though the inherent strength of the adhesive may be much less than that of the adherend materials, nevertheless, a strong joint may be produced if the adhesive layer is thin and continuous. If a good joint is formed, the adherend material may fracture or rupture before the adhesive.

Polymeric materials that fall within the classifications of thermoplastics, thermosetting resins, elastomeric compounds, and natural adhesives (animal glue, casein, starch, and rosin) may serve adhesive functions. Polymer adhesives may be used to join a large variety of material combinations: metal-metal, metal-plastic, metal-ceramic, and so on. The primary drawback is the service temperature limitation. Organic polymers maintain their mechanical integrity only at relatively low temperatures, and strength decreases rapidly with increasing temperature.

FILMS

Within relatively recent times, polymeric materials have found widespread use in the form of thin *films*. Films having thicknesses between 0.025 and 0.125 mm (0.001 and 0.005 in.) are fabricated and used extensively as bags for packaging food products and other merchandise, as textile products, and a host of other uses. Important characteristics of the materials produced and used as films include low density, a high degree of flexibility, high tensile and tear strengths, resistance to attack by moisture and other chemicals, and low permeability to some gases, especially water vapor. Some of the polymers that meet these criteria and are manufactured in film form are polyethylene, polypropylene, cellophane, and cellulose acetate.

FOAMS

Foams are plastic materials that contain a relatively high volume percent of small pores. Both thermoplastic and thermosetting materials are used as foams; these include polyurethane, rubber, polystyrene, and polyvinyl chloride. Foams are commonly used as cushions in automobiles and furniture as well as in packaging and thermal insulation. The foaming process is carried out by incorporating into the

batch of material a blowing agent that upon heating, decomposes with the liberation of a gas. Gas bubbles are generated throughout the now-fluid mass, which remain as pores upon cooling and give rise to a spongelike structure. The same effect is produced by bubbling an inert gas through a material while it is in a molten state.

13.16 ADVANCED POLYMERIC MATERIALS (CD-ROM)

SUMMARY

With regard to composition, metals and alloys are classified as either ferrous or nonferrous. Ferrous alloys (steels and cast irons) are those in which iron is the prime constituent. Most steels contain less than 1.0 wt% C, and, in addition, other alloying elements, which render them susceptible to heat treatment (and an enhancement of mechanical properties) and/or more corrosion resistant. Plain low-carbon steels and high-strength low-alloy, medium-carbon, tool, and stainless steels are the most common types.

Cast irons contain a higher carbon content, normally between 3.0 and 4.5 wt% C, and other alloying elements, notably silicon. For these materials, most of the carbon exists in graphite form rather than combined with iron as cementite. Gray, ductile (or nodular), and malleable irons are the three most widely used cast irons; the latter two are reasonably ductile.

All other alloys fall within the nonferrous category, which is further subdivided according to base metal or some distinctive characteristic that is shared by a group of alloys. The compositions, typical properties, and applications of copper, aluminum, magnesium, titanium, nickel, lead, tin, zirconium, and zinc alloys, as well as the refractory metals, the superalloys, and the noble metals were discussed.

Also discussed in this chapter were various types of ceramic materials. The familiar glass materials are noncrystalline silicates that contain other oxides; the most desirable trait of these materials is their optical transparency. Glass-ceramics are initially fabricated as a glass, then crystallized or devitrified.

Clay is the principal component of the whitewares and structural clay products. Other ingredients may be added, such as feldspar and quartz, which influence the changes that occur during firing.

The materials that are employed at elevated temperatures and often in reactive environments are the refractory ceramics; on occasion, their ability to thermally insulate is also utilized. On the basis of composition and application, the four main subdivisions are fireclay, silica, basic, and special.

The abrasive ceramics, being hard and tough, are utilized to cut, grind, and polish other softer materials. Diamond, silicon carbide, tungsten carbide, corundum, and silica sand are the most common examples. The abrasives may be employed in the form of loose grains, bonded to an abrasive wheel, or coated on paper or a fabric.

When mixed with water, inorganic cements form a paste that is capable of assuming just about any desired shape. Subsequent setting or hardening is a result of chemical reactions involving the cement particles and occurs at the ambient temperature. For hydraulic cements, of which portland cement is the most common, the chemical reaction is one of hydration.

{Many of our modern technologies utilize and will continue to utilize advanced ceramics because of their unique mechanical, chemical, electrical, magnetic, and optical properties and property combinations. Advanced materials characterization, processing, and reliability techniques need to be developed to make these materials cost effective.}

The properties and some applications for diamond and graphite were presented. Diamond is a gemstone and, because of its hardness, is used to cut and grind softer materials. Furthermore, it is now being produced and utilized in thin films. The layered structure of graphite gives rise to its excellent lubricative properties and a relatively high electrical conductivity. Graphite is also known for its high strength and chemical stability at elevated temperatures and in nonoxidizing atmospheres.

The various types and applications of polymeric materials were also discussed. Plastic materials are perhaps the most widely used group of polymers, which include the following: polyethylene, polypropylene, polyvinyl chloride, polystyrene, and the fluorocarbons, epoxies, phenolics, and polyesters.

Another polymer classification includes the elastomeric materials that may experience very large elastic deformations. Most of these materials are copolymers, whereas the silicone elastomers are really inorganic materials.

Many polymeric materials may be spun into fibers, which are used primarily in textiles. Mechanical, thermal, and chemical characteristics of these materials are especially critical.

Other miscellaneous applications that employ polymers include coatings, adhesives, films, and foams.

{This chapter concluded with discussions of three advanced polymeric materials—ultrahigh molecular weight polyethylene, liquid crystal polymers, and thermoplastic elastomers. These materials have unusual properties and are used in a host of high-technology applications.}

IMPORTANT TERMS AND CONCEPTS

Abrasive (ceramic)	Fiber	Refractory (ceramic)
Adhesive	Foam	Specific strength
Alloy steel	Glass-ceramic	Stainless steel
Brass	Gray cast iron	Structural clay product
Bronze	High-strength, low-alloy (HSLA) steel	Temper designation
Calcination	Liquid crystal polymer	Thermoplastic elastomer
Cast iron	Malleable iron	Ultrahigh molecular weight polyethylene
Cement	Nonferrous alloy	White cast iron
Devitrification	Plain carbon steel	Whiteware
Ductile (nodular) iron	Plastic	Wrought alloy

REFERENCES

- ASM Handbook*, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, ASM International, Materials Park, OH, 1990.
- ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, ASM International, Materials Park, OH, 1991.
- Billmeyer, F. W., Jr., *Textbook of Polymer Science*, 3rd edition, Wiley-Interscience, New York, 1984.

- Bowen, H. K., "Advanced Ceramics." *Scientific American*, Vol. 255, No. 4, October 1986, pp. 168–176.
- Brick, R. M., A. W. Pense, and R. B. Gordon, *Structure and Properties of Engineering Materials*, 4th edition, McGraw-Hill Book Company, New York, 1977.
- Coes, L., Jr., *Abrasives*, Springer-Verlag, New York, 1971.
- Engineered Materials Handbook*, Vol. 2, *Engineering Plastics*, ASM International, Metals Park, OH, 1988.
- Engineered Materials Handbook*, Vol. 4, *Ceramics and Glasses*, ASM International, Materials Park, OH, 1991.
- Frick, J. (Editor), *Woldman's Engineering Alloys*, 8th edition, ASM International, Materials Park, OH, 1994.
- Harper, C. A. (Editor), *Handbook of Plastics, Elastomers and Composites*, 3rd edition, McGraw-Hill Book Company, New York, 1996.
- Lea, F. M., *The Chemistry of Cement and Concrete*, Chemical Publishing Company, New York, 1971.
- Metals and Alloys in the Unified Numbering System*, 7th edition, Society of Automotive Engineers, and American Society for Testing and Materials, Warrendale, PA, 1996.
- Walton, C. F. and T. F. Opar (Editors), *Iron Castings Handbook*, Iron Castings Society, Des Plaines, IL, 1981.
- Worldwide Guide to Equivalent Irons and Steels*, 3rd edition, ASM International, Materials Park, OH, 1993.
- Worldwide Guide to Equivalent Nonferrous Metals and Alloys*, 3rd edition, ASM International, Materials Park, OH, 1996.

QUESTIONS AND PROBLEMS

Note: To solve those problems having an asterisk (*) by their numbers, consultation of supplementary topics [appearing only on the CD-ROM (and not in print)] will probably be necessary.

- 13.1** (a) List the four classifications of steels. (b) For each, briefly describe the properties and typical applications.
- 13.2** (a) Cite three reasons why ferrous alloys are used so extensively. (b) Cite three characteristics of ferrous alloys that limit their utilization.
- 13.3** Briefly explain why ferritic and austenitic stainless steels are not heat treatable.
- 13.4** What is the function of alloying elements in tool steels?
- 13.5** Compute the volume percent of graphite V_{Gr} in a 3.5 wt% C cast iron, assuming that all the carbon exists as the graphite phase. Assume densities of 7.9 and 2.3 g/cm³ for ferrite and graphite, respectively.
- 13.6** On the basis of microstructure, briefly explain why gray iron is brittle and weak in tension.
- 13.7** Compare gray and malleable cast irons with respect to (a) composition and heat treatment, (b) microstructure, and (c) mechanical characteristics.
- 13.8** It is possible to produce cast irons that consist of a martensite matrix in which graphite is embedded in either flake, nodule, or rosette form. Briefly describe the treatment necessary to produce each of these three microstructures.
- 13.9** Compare white and nodular cast irons with respect to (a) composition and heat treatment, (b) microstructure, and (c) mechanical characteristics.
- 13.10** Is it possible to produce malleable cast iron in pieces having large cross-sectional dimensions? Why or why not?
- 13.11** What is the principal difference between wrought and cast alloys?
- 13.12** What is the main difference between a brass and a bronze?
- 13.13** Why must rivets of a 2017 aluminum alloy be refrigerated before they are used?
- 13.14** Explain why, under some circumstances, it is not advisable to weld a structure that is fabricated with a 3003 aluminum alloy.

- 13.15** What is the chief difference between heat-treatable and nonheat-treatable alloys?
- 13.16** Give the distinctive features, limitations, and applications of the following alloy groups: titanium alloys, refractory metals, superalloys, and noble metals.
- 13.17** Cite the two desirable characteristics of glasses.
- 13.18** (a) What is devitrification?
(b) Cite two properties that may be improved by devitrification and two that may be impaired.
- 13.19*** Briefly explain why glass-ceramics are generally not transparent. You may want to consult Chapter 19.
- 13.20** For refractory ceramic materials, cite three characteristics that improve with and two characteristics that are adversely affected by increasing porosity.
- 13.21*** Find the maximum temperature to which the following two magnesia-alumina refractory materials may be heated before a liquid phase will appear.
(a) A spinel-bonded alumina material of composition 95 wt% Al_2O_3 -5 wt% MgO.
(b) A magnesia-alumina spinel of composition 65 wt% Al_2O_3 -35 wt% MgO. Consult Figure 10.22.
- 13.22*** Upon consideration of the SiO_2 - Al_2O_3 phase diagram, Figure 10.24, for each pair of the following list of compositions, which would you judge to be the more desirable refractory? Justify your choices.
(a) 20 wt% Al_2O_3 -80 wt% SiO_2 and 25 wt% Al_2O_3 -75 wt% SiO_2 .
(b) 70 wt% Al_2O_3 -30 wt% SiO_2 and 80 wt% Al_2O_3 -20 wt% SiO_2 .
- 13.23*** Compute the mass fractions of liquid in the following refractory materials at 1600°C (2910°F):
(a) 6 wt% Al_2O_3 -94 wt% SiO_2 .
(b) 10 wt% Al_2O_3 -90 wt% SiO_2 .
(c) 30 wt% Al_2O_3 -70 wt% SiO_2 .
(d) 80 wt% Al_2O_3 -20 wt% SiO_2 .
- 13.24*** (a) For the SiO_2 - Al_2O_3 system, what is the maximum temperature that is possible without the formation of a liquid phase? At what composition or over what range of compositions will this maximum temperature be achieved?
(b) For the MgO- Al_2O_3 system, what is the maximum temperature that is possible without the formation of a liquid phase? At what composition or over what range of compositions will this maximum temperature be achieved?
- 13.25** Compare the manner in which the aggregate particles become bonded together in clay-based mixtures during firing and in cements during setting.
- 13.26** Explain why it is important to grind cement into a fine powder.
- 13.27** During the winter months, the temperature in some parts of Alaska may go as low as -55°C (-65°F). Of the elastomers natural isoprene, styrene-butadiene, acrylonitrile-butadiene, chloroprene, and polysiloxane, which would be suitable for automobile tires under these conditions? Why?
- 13.28** Briefly explain the difference in molecular chemistry between silicone polymers and other polymeric materials.
- 13.29** Silicone polymers may be prepared to exist as liquids at room temperature. Cite differences in molecular structure between them and the silicone elastomers.
- 13.30** List two important characteristics for polymers that are to be used in fiber applications.
- 13.31** Cite five important characteristics for polymers that are to be used in thin-film applications.

Design Problems

- 13.D1** Of the following alloys, pick the one(s) that may be strengthened by heat treatment, cold work, or both: R50500 titanium, AZ31B magnesium, 6061 aluminum, C51000 phosphor bronze, lead, 6150 steel, 304 stainless steel, and C17200 beryllium copper.
- 13.D2** A structural member 100 mm (4 in.) long must be able to support a load of 50,000 N (11,250 lb_f) without experiencing any plastic

deformation. Given the following data for brass, steel, aluminum, and titanium, rank them from least to greatest weight in accordance with these criteria.

<i>Alloy</i>	<i>Yield Strength MPa (ksi)</i>	<i>Density (g/cm³)</i>
Brass	415 (60)	8.5
Steel	860 (125)	7.9
Aluminum	310 (45)	2.7
Titanium	550 (80)	4.5

13.D3 Discuss whether it would be advisable to hot work or cold work the following metals and alloys on the basis of melting temperature, oxidation resistance, yield strength, and degree of brittleness: tin, tungsten, aluminum alloys, magnesium alloys, and a 4140 steel.

13.D4 Below is a list of metals and alloys:

Plain carbon steel	Magnesium
Brass	Zinc
Gray cast iron	Tool steel
Platinum	Aluminum
Stainless steel	Tungsten
Titanium alloy	

Select from this list the one metal or alloy that is best suited for each of the following applications, and cite at least one reason for your choice:

- (a) The base for a milling machine.
- (b) The walls of a steam boiler.
- (c) High-speed aircraft.
- (d) Drill bit.
- (e) Cryogenic (i.e., very low temperature) container.
- (f) As a pyrotechnic (i.e., in flares and fireworks).

(g) High-temperature furnace elements to be used in oxidizing atmospheres.

13.D5 (a) List at least three important characteristics required of metal alloys that are used for coins. (b) Write an essay in which you cite which metal alloys are employed in the coinage of your country, and then provide the rationale for their use.

13.D6 Some of our modern kitchen cookware is made of ceramic materials.

(a) List at least three important characteristics required of a material to be used for this application.

(b) Make a comparison of three ceramic materials as to their relative properties, and, in addition, to cost.

(c) On the basis of this comparison, select that material most suitable for the cookware.

13.D7 (a) List several advantages and disadvantages of using transparent polymeric materials for eyeglass lenses.

(b) Cite four properties (in addition to being transparent) that are important for this application.

(c) Note three polymers that may be candidates for eyeglass lenses, and then tabulate values of the properties noted in part b for these three materials.

13.D8 Write an essay on polymeric materials that are used in the packaging of food products and drinks. Include a list of the general requisite characteristics of materials that are used for these applications. Now cite a specific material that is utilized for each of three different container types and the rationale for each choice.