2

NATURE OF MATERIALS

To a large extent, the behavior of materials is dictated by the structure and bonding of the atoms that are the building blocks for all matter. Knowledge of the bonding and structure of materials at the molecular level allows us to understand their behavior. The chapter presents a broad overview of concepts essential to our understanding of these behaviors. The chapter reviews the basic types of bonds and then, based on the type of bond, classifies materials as metallic, ceramic, or amorphous. The general nature of each of these classes of materials is presented.

2.1 Basic Materials Concepts

Atoms are the basic building blocks of all materials. For the purpose of this text, atoms will be considered to consist of three subatomic particles: *protons, neutrons,* and *electrons.* The protons and neutrons are at the center of the atom, while the electrons travel about the nucleus in paths or shells. The *atomic number* is the number of protons in the nucleus of the atom. The *atomic mass* of an atom is the number of protons plus the number of neutrons in the center of the atom. An *element* is an atom or group of atoms with the same atomic number. *Isotopes* are elements with different numbers of neutrons in the nucleus.

2.1.1 Electron Configuration

The behavior of an atom's electrons controls, to a large extent, the characteristics of an element. An electrically neutral (or complete) atom has equal numbers of electrons and protons. However, an atom may either release or attract electrons to reach a more stable configuration. Electrons travel around the nucleus in orbital paths, or orbits, around the nucleus. The distance between electrons and the nucleus is not fixed; it is better described as a random variable with a distribution, as shown in Figure 2.1.

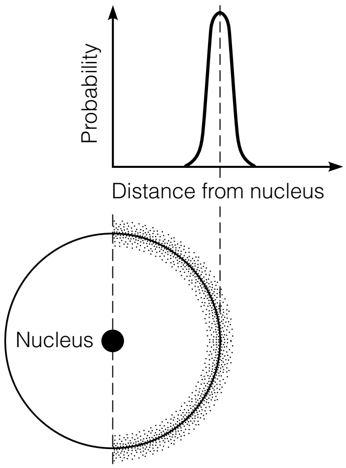

FIGURE 2.1 Orbital path of model electrons.

Each orbital path, or *shell,* can hold only a fixed number of electrons. The maximum number of electrons in a shell is equal to $2n^2$, where n is the principal quantum number of the shell. The orbital path of electrons is defined by four parameters: the principal quantum number or shell designation, the subshell designation, the number of energy states of the subshell, and the spin of the electron. Table 2.1 lists the number of electrons that can be in each shell and subshell.

The energy level of an electron depends on its shell and subshell location, as shown in Figure 2.2 (Callister 2003). Electrons always try to fill the lowest energy location first. As shown in Figure 2.2, for a given subshell, the larger the principal quantum number, the higher is the energy level

TABLE 2.1 Number of Available Electron States in Some of the Electron Shells and Subshells

Principal Quantum Number	Shell Designation	Subshell	Number of States	Number of Electrons	
				per subshell	per shell
1	K	s	1	2	2
2	L	s	1	2	8
		p	3	6	
3	M	s	1	2	18
		p	3	6	
		d	5	10	
4	N	s	1	2	32
		p	3	6	
		d	5	10	
		f	7	14	

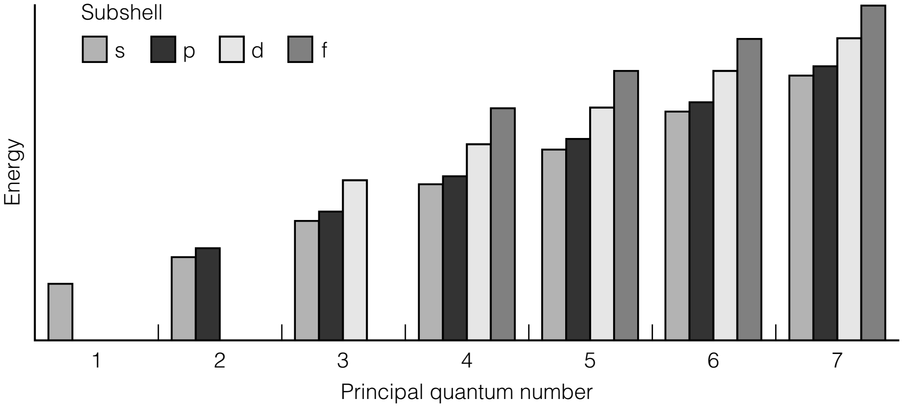

FIGURE 2.2 Energy levels of electrons in different shells and subshels.

(e.g., the energy of subshell 1s is less than subshell 2s). Within a shell, the energy level increases with the subshell location: Subshell f is a higher energy state than subshell d, and so on. There is an energy overlap between the shells: Subshell 4s is at a lower energy state than subshell 3d. The electron configuration, or structure of an atom, describes the manner in which the electrons are located in the shells and subshells. The convention for listing the location of shells in the atom is to list the quantum number, followed by the subshell designation, followed by the number of electrons in the subshell raised to a superscript. This sequence is repeated for each subshell that contains electrons. Table 2.2 provides some examples.

TABLE 2.2 Sample Electron Configurations

Element	Atomic Number	Electron Configuration
Hydrogen	1	$1s^1$
Helium	2	$1s^2$
Carbon	6	$1s^2 2s^2 2p^2$
Neon	10	$1s^2 2s^2 2p^6$
Sodium	11	$1s^2 2s^2 2p^6 3s^1$
Aluminum	13	$1s^2 2s^2 2p^6 3s^2 3p^1$
Silicon	14	$1s^2 2s^2 2p^6 3s^2 3p^2$
Sulfur	16	$1s^2 2s^2 2p^6 3s^2 3p^4$
Argon	18	$1s^2 2s^2 2p^6 3s^2 3p^6$
Calcium	20	$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2$
Chromium	24	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^5 4s^1$
Iron	26	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^6 4s^2$
Copper	29	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^1$

The electrons in the outermost filled shell are the *valence electrons.* These are the electrons that participate in the formation of primary bonds between atoms. The eight electrons needed to fill the s and p subshells are particularly important. If these subshells are completely filled, the atoms are very stable and virtually nonreactive, as is the case for the noble gases neon and argon. In many cases atoms will release, attract, or share electrons to complete these subshells and reach a stable configuration. Calcium and chromium are examples of atoms with electrons that fill the 4s subshell, while the 3d subshell is incomplete or empty, as would be expected from Figure 2.2. Copper demonstrates that there are exceptions to the energy rule. One would expect copper to have two electrons in the 4s subshell, leaving nine electrons for the 3d subshell. However, it has ten electrons in the 3d subshell and only one in the 4s subshell. A similar disparity exists for chromium. Note that iron has two electrons in the 4s subshell; thus, it has two electrons more than it needs for a stable configuration. These two electrons are readily released to form iron molecules. Aluminum is also an exception, since it has an excess of three electrons.

2.1.2 Bonding

As two atoms are brought together, both attractive and repulsive forces develop. The effects of these forces are additive, as shown in Figure 2.3, such that once the atoms are close enough to interact, they will reach a point at which the attractive and repulsive forces are balanced and an equilibrium is reached. Energy is required either to bring the atoms closer together

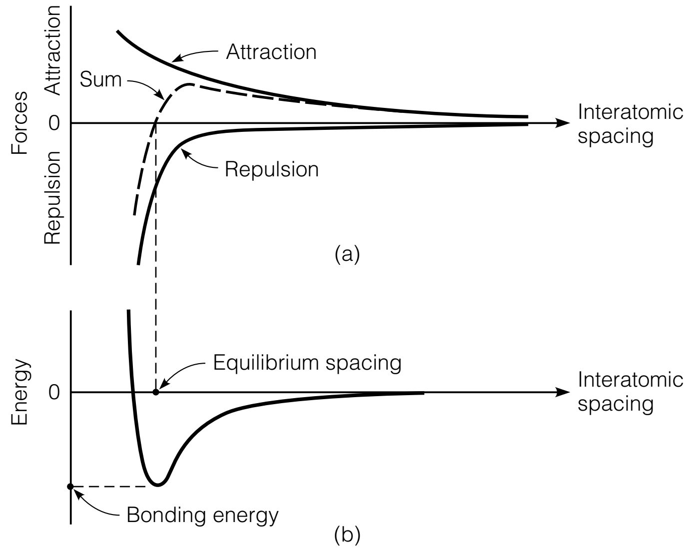

FIGURE 2.3 Attractive and repulsive (a) forces, and (b) energies between atoms. (© Pearson Education, Inc. Used by permission.)

(*compression*) or to separate them (*tension*). The distance at which the net force is zero corresponds to the minimum energy level and is called the *equilibrium spacing.* The minimum energy is represented by a negative sign. The largest negative value is defined as the bonding energy. The bonding energy can be computed from equations for the attractive and repulsive forces. Based on the strength of the bonds, the theoretical strength of a material can be estimated. However, this theoretical strength grossly overestimates the actual strength due to flaws in the molecular structure (Van Vlack 1964, 1989).

The bonding energy depends on the molecular mechanism holding the atoms together. There are two basic categories of bonds: primary and secondary. *Primary bonds* form when atoms interact to change the number of electrons in their outer shells so as to achieve a stable and nonreactive electron structure similar to that of a noble gas. *Secondary bonds* are formed when the physical arrangement of the atoms in the molecule results in an imbalanced electric charge; one side is positive and the other is negative. The molecules are then bonded together through electrostatic force.

Primary Bonds Three types of primary bonds are defined, based on the manner in which the valence electrons interact with other atoms:

1. *ionic bonds*—transfer of electrons from one elemental atom to another (Figure 2.4)
2. *covalent bonds*—sharing of electrons between specific atoms (Figure 2.5)
3. *metallic bonds*—mass sharing of electrons among several atoms (Figure 2.6)

Ionic bonds are the result of one atom releasing electrons to other atoms that accept the electrons. Each of the elements reaches a stable electron configuration of the outer s and p subshells. All of the atoms are ions, since they have an electrical charge. When an atom releases an electron, the atom becomes positively charged; the atom receiving the electron becomes negatively

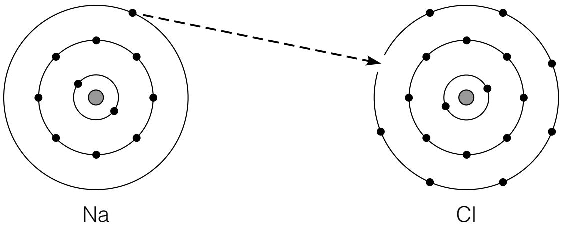

FIGURE 2.4 Ionic bonding. (© Pearson Education, Inc. Used by permission.)

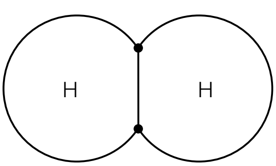

FIGURE 2.5 Covalent bonding. (© Pearson Education, Inc. Used by permission.)

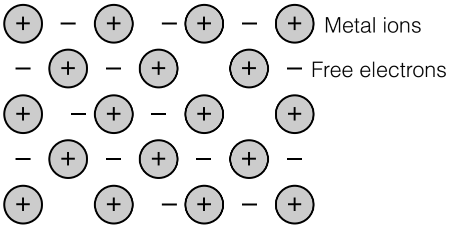

FIGURE 2.6 Metallic bonding. (© Pearson Education, Inc. Used by permission.)

charged. An ion with a positive charge is a *cation* and one with a negative charge is an *anion.* The ionic bond results from the electrostatic attraction of the negatively and positively charged atoms. Since these bonds are based on the transfer of electrons, they have no directional nature.

Covalent bonds occur when two similar atoms *share* electrons in the outer subshell. The atomic orbitals of the atoms overlap and an electron in each atom can exchange with an electron in its partner atom. If the shared electron is considered to be attached to either of the atoms, that atom would have the s and p subshells filled and would therefore be a stable atom. Since the orbital paths of the atoms must overlap for the covalent bond to form, these bonds are highly directional. In materials such as diamond, the covalent bonds are very strong. However, the carbon chain structure of polymers is also formed by covalent bonds and these elements display a wide range of bond energy. The number of bonds that form depends on the number of valence electrons. An atom with N electrons in the valence shell can bond with only $8N$ neighbors by sharing electrons with them. When the number of electrons N equals 7, the atoms join in pairs. When N equals 6, as in sulfur, long chains can form since the atom can bond with two neighbors. When N equals 5, a layered structure can be developed. If there are 4 valence electrons, three-dimensional covalent bonds can result (e.g., the structure of carbon in diamonds) (Jastrzebski 1987). The calcium-silicate chain in portland cement concrete is based on covalent bonds.

Most interatomic bonds are partially ionic and partially covalent, and few compounds have pure covalent or ionic bonds. In general, the degree of either type of bonding depends on the relative positions of the elements in the periodic table. The wider the separation, the more ionic bonds form. Since the electrons in ionic and covalent bonds are fixed to specific atoms, these materials have good thermal and electrical insulation properties.

Metallic bonds are the result of the metallic atoms having loosely held electrons in the outer s subshell. When similar metallic atoms interact, the outer electrons are released and are free to float between the atoms. Thus, the atoms are ions that are electrically balanced by the free electrons. In other words, the free electrons disassociate themselves from the original atom and do not get attached to another atom. Metallic bonds are not directional, and the spacing of the ions depends on the physical characteristics of the atoms. The atoms tend to pack together to give simple, high density structures, like marbles shaken down in a box. The easy movement

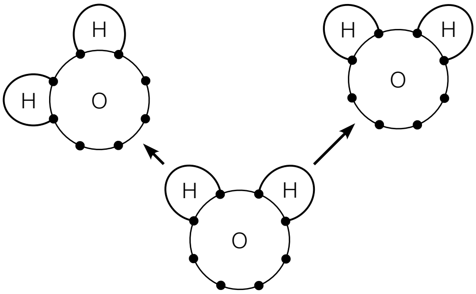

FIGURE 2.7 Secondary bond: hydrogen bridge. (© Pearson Education, Inc. Used by permission.)

of the electrons leads to the high electrical and thermal conductivity of metals.

Secondary Bonds Secondary bonds are much weaker than primary bonds, but they are important in the formation of links between polymer materials. These bonds result from a dipole attraction between uncharged atoms. As the electrons move about the nucleus, at any instant the charge is distributed in a nonsymmetrical manner relative to the nucleus. Thus, at any instant one side of the atom has a negative charge and the other side of the atom has a positive charge. Secondary bonds result from electrostatic attraction of the dipoles of the atoms. These dipole interactions occur between induced dipoles or polar molecules that have permanent dipoles; both types of interactions are classified as *van der Waals forces*. Hydrogen, however, has only one proton and one electron; thus, it tends to form a polar molecule when bonded with other atoms. The electrostatic bond formed due to the hydrogen bond is generally stronger than van der Waals forces, so the hydrogen bond, shown in Figure 2.7, is a special form of the secondary bond.

2.1.3 Material Classification by Bond Type

Based on the predominant type of bond a material's atoms may form, materials are generally classified as metal, inorganic solids, and organic solids. These materials have predominantly metallic, covalent and ionic, and covalent bonds, respectively. Solids with each of these types of bonds have distinctly different characteristics. Metals and inorganic solids generally have a *crystalline* structure, a repeated pattern or arrangement of the atoms. On the other hand, organic solids usually have a random molecular structure. The following are the predominant materials used in civil engineering in each category:

- Metallic
    - steel
    - iron
    - aluminum
- Inorganic solids
    - portland cement concrete
    - bricks and cinder blocks

  - glass
  - aggregates (rock products)
- Organic solids
  - asphalt
  - plastics
  - wood

2.2 Metallic Materials

The chemical definition of a metal is an element with one, two, or three valence electrons. These elements bond into a mass with metallic bonds. Due to the nature of metallic bonds, metals have a very regular and well-defined structure. Since the metallic bonds are nondirectional, the atoms are free to pack into a dense configuration. The regular three-dimensional geometric pattern of the atoms in a metal is called a *unit cell*. Repeated coalescing of unit cells forms a space lattice of the material. However, in a mass of material, a perfect structure can be achieved only through carefully controlled conditions. Generally, metallic solids are formed by cooling a mass of molten material. As the material cools, the atoms are vibrating. This can cause one atom to occupy the space of two atoms, generating a defect in the lattice structure. In addition, during the cooling process crystals grow simultaneously from several nuclei. As the material continues to cool, these crystals grow together with a boundary forming between the grains. This produces flaws or slip planes in the structure that have an important influence on the behavior and characteristics of the material. In addition, rarely are pure elemental metals used for engineering applications. Even highly refined materials contain impurities that were not removed in the refining process. In addition, most metals do not have desirable properties in a pure state. For example, iron and aluminum used for structural applications have alloying elements that impart special characteristics to the metal. As a result, understanding the nature of metals at the molecular level requires an examination of the primary structure of the metal, the effect of cooling rates, and the impact of impurities and alloying elements.

2.2.1 Lattice Structure

As metals cool from the molten phase, the atoms are arranged into definite structures dependent on the size of the atom and the valence electrons. Certain characteristics are apparent in the three-dimensional array of points formed by the intersection of the parallel lines shown in Figure 2.8. In this configuration, the arrangement of neighboring points about any specific point is identical with the arrangement around any other internal point. This property can be described mathematically by three unit vectors, **a**, **b**,

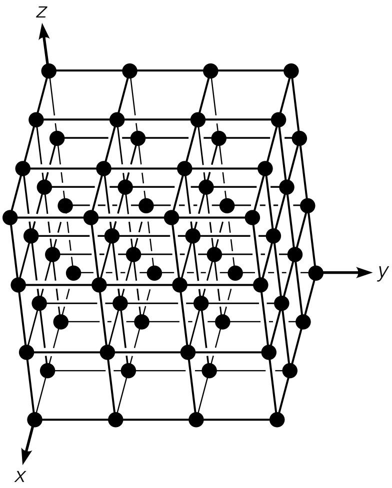

FIGURE 2.8 Parallelogram structure for crystal lattices. (© Pearson Education, Inc. Used by permission.)

and **c**. The location of any point, $\mathbf{r}'$, relative to a reference point, can be defined in terms of an integer number of vector movements:

$$\mathbf{r}' = \mathbf{r} + n_1\mathbf{a} + n_2\mathbf{b} + n_3\mathbf{c} \tag{2.1}$$

A continuous repetition of Equation 2.1, using incremental integers for n_1, n_2, and n_3 will result in the parallelogram shown in Figure 2.8, where **r** is the position vector of the origin relative to the reference point. It should be noted that the angles between the axes need not be 90 degrees. Such a network of lines is called a *space lattice.* There are 14 possible space lattices in three dimensions that can be described by vectors **a**, **b**, and **c**. However, the space lattices of common engineering metals can be described by two cubic structures and one hexagonal structure, as shown in Figure 2.9.

A simple cubic lattice structure has one atom on each corner of a cube that has axes at 90 degrees and equal vector lengths. However, this is not a common structure, although it does exist in some metals. There are two important variations on the cubic structure: the *face center cubic* and the *body center cubic.* The face center cubic (FCC) structure has an atom at each corner of the cube plus an atom on each of the faces, as shown in Figure 2.9(a). The body center cubic (BCC) structure has one atom on each of the corners plus one in the center of the cube, as shown in Figure 2.9(b).

The third common metal lattice structure is the *hexagonal close pack* (HCP). As shown in Figure 2.9(c), the HCP has top and bottom layers, with atoms at each of the corners of the hexagon and one atom in the center of the top and bottom planes; in addition, there are three atoms in a center plane. The atoms in the center plane are equidistant from all neighboring atoms. See Table 2.3 for the crystal structures and the atomic radii of some metals.

Two of the important characteristics of the crystalline structure are the coordination number and the atomic packing factor. The *coordination number* is the number of "nearest neighbors." The coordination number is 12 for FCC

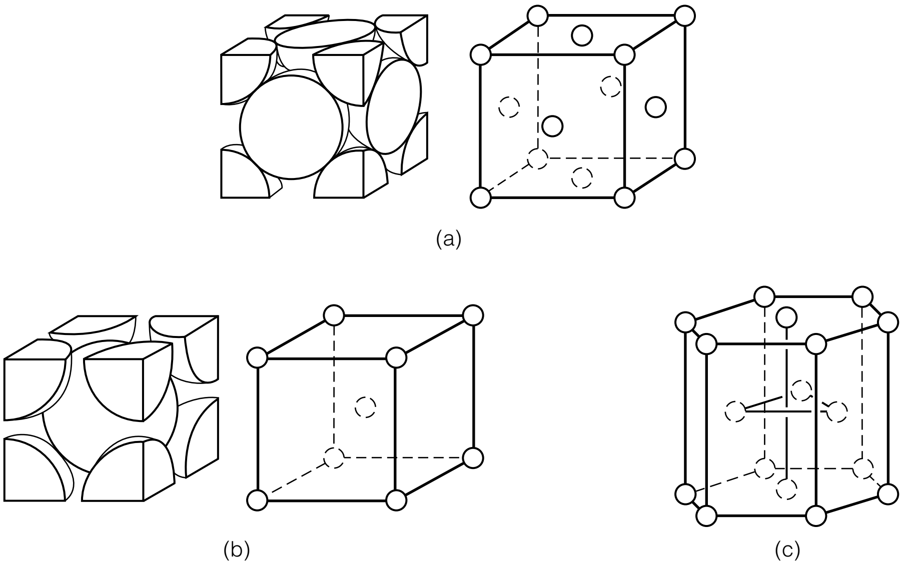

FIGURE 2.9 Common lattice structures for metals: (a) face center cubic (FCC) (b) body center cubic (BCC), and (c) hexagonal close pack (HCP).

TABLE 2.3 Lattice Structure of Metals

Metal (nm)	Crystal Structure	Atomic Radius (nm)	Metal	Crystal Structure	Atomic Radius
Aluminum	FCC	0.1413	Molybdenum	BCC	0.1363
Cadmium	HCP	0.1490	Nickel	FCC	0.1246
Chromium	BCC	0.1249	Platinum	FCC	0.1387
Cobalt	HCP	0.1253	Silver	FCC	0.1445
Copper	FCC	0.1278	Tantalum	BCC	0.1430
Gold	FCC	0.1442	Titanium	HCP	0.1445
Iron	BCC	0.1241	Tungsten	BCC	0.1371
Lead	FCC	0.1750	Zinc	HCP	0.1332

and HCP structures and 8 for BCC structures. This can be confirmed by examination of Figure 2.9. The *atomic packing factor* (APF) is the fraction of the volume of the unit cell that is occupied by the atoms of the structure:

$$\text{APF} = \frac{\text{volume of atoms in the unit cell}}{\text{total unit volume of the cell}} \tag{2.2}$$

In order to compute the atomic packing factor, the *equivalent number of atoms* associated with each unit cell must be determined, along with the atomic radius of the atoms, which are given in Table 2.3. The equivalent number of atoms associated with a cell is the number of atoms in a large block of material divided by the number of unit cells in the block. However, by properly considering the fraction of atoms in Figure 2.9, we can count the number of "whole" atoms in each unit cell. The FCC structure has eight corner atoms, each of which is shared with seven other unit cells; thus, all the corner atoms contribute one atom to the atom count for the unit cell. The face atoms are shared only with one other unit cell so that each of the face atoms contributes one-half atom. Since there are six faces, the face atoms add 3 atoms to the count. Adding the face and corner atoms yields a total of four atoms. The BCC structure has the equivalent of only two atoms. The HCP structure has an equivalent of 6 atoms. Each of the 12 corner atoms is shared between six unit cells, the face atoms are shared between two unit cells, and the three atoms on the center planes are not shared with any other unit cells, so $12/6 + 2/2 + 3 = 6$.

The volume of the atoms in the unit cell can then be computed as the volume of one atom times the number of equivalent atoms. The volume of a sphere is $V = (4/3)\pi r^3$, where r is the radius. The volume of the unit cell can be determined by knowing the radius of the atoms and the fact that the atoms are in contact with each other.

Sample Problem 2.1

Show that the atomic packing factor for the FCC lattice structure (Fig. SP2.1) is 0.74.

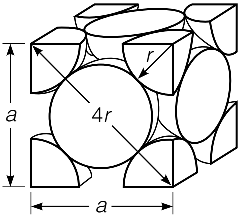

FIGURE SP2.1

Solution

$$\text{Number of equivalent whole atoms in each unit cell} = 4$$

$$\text{Volume of the sphere} = \left(\frac{4}{3}\right)\pi r^3$$

$$\text{Volume of atoms in the unit cell} = 4 \times \left(\frac{4}{3}\right)\pi r^3 = \left(\frac{16}{3}\right)\pi r^3$$

By inspection, the diagonal of the face of an FCC unit cell $= 4r$

Length of each side of unit cell $= 2\sqrt{2}r$

Volume of unit cell $= \left(2\sqrt{2}r\right)^3$

$$\text{APF} = \frac{\text{volume of atoms in the unit cell}}{\text{total unit volume of the cell}} = \frac{\left(\frac{16}{3}\right)\pi r^3}{\left(2\sqrt{2}r\right)^3} = 0.74$$

Similar geometric considerations allow for the calculation of the atomic packing factor for the BCC and HCP structures as 0.68 and 0.74, respectively.

The density of a metal is a function of the type of lattice structure and can be determined from

$$r = \frac{nA}{V_c N_A} \tag{2.3}$$

where

r = density of the material
n = number of equivalent atoms in the unit cell
A = atomic mass of the element (grams/mole)
V_C = volume of the unit cell
N_A = Avogadro's number (6.023×10^{23} atoms/mole)

Sample Problem 2.2

Calculate the radius of the aluminum atom, given that aluminum has an FCC crystal structure, a density of 2.70 Mg/m^3, and an atomic mass of 26.98 g/mole. Note that the APF for the FCC lattice structure is 0.74.

Solution

$$r = \frac{nA}{V_c N_A}$$

For an FCC lattice structure, $n = 4$, so

$$V_c = \frac{4 \times 26.98}{2.70 \times 10^6 \times 6.023 \times 10^{23}} = 6.636 \times 10^{-29}\ \text{m}^3$$

$$\text{APF} = 0.74 = \frac{4 \times \left(\frac{4}{3}\right)\pi r^3}{6.636 \times 10^{-29}}$$

$$r^3 = 0.293 \times 10^{-29}$$

$$r = 0.143 \times 10^{-9}\text{ m} = 0.143\text{ nm}$$

Knowledge of the type of lattice structure is important when determining the mechanical behavior of a metal. Under elastic behavior, the bonds of the atoms are stretched, but when the load is removed, the atoms return to their original position. On the other hand, plastic deformation, by definition, is a permanent distortion of the materials; therefore, plastic deformation must be associated with a change in the atomic arrangement of the metal. Plastic deformation is the result of planes of atoms slipping over each other due to the action of shear stress. Naturally, the slip will occur on the planes that are the most susceptible to distortion. Since the basic bonding mechanism of the various metals is similar, differences in the theoretical strength of a material are attributed to the differences in the number and orientation of the slip planes that result from the different lattice structures.

2.2.2 Lattice Defects

Even under special circumstances, it is very difficult to grow perfect crystalline structures. Generally, pure crystalline structures are limited to 1 micron in diameter. These pure materials have a strength and modulus of elasticity approaching the maximum theoretical values based on the bonding characteristics. However, the strength and deformation of all practical materials are limited by defects. There are several causes for the development of defects in the crystal structure. These can be classified as follows:

1. point defects or missing atoms
2. line defects or rows of missing atoms, commonly called an *edge dislocation*
3. area defects or grain boundaries
4. volume defects or cavities in the material

In the case of point defects, single atoms can be missing in the lattice structure because the atoms are vibrating as they transition from liquid to solid. As a result, one atom may vibrate in the area where two atoms should be in the lattice. Vacancies have little effect on the properties of the material.

In considering the differences between manufactured and theoretical material behavior, an understanding of line defects becomes important. A typical line defect is shown in Figure 2.10, where a line of missing atoms extends back into the illustration (Van Vlack 1989; Guy and Hren 1974). The atoms above the dislocation are in compression and those below the

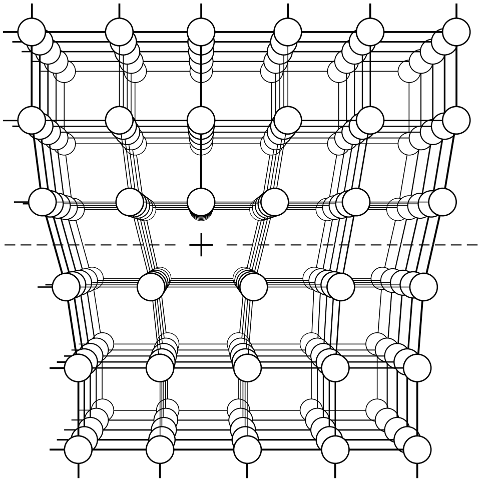

FIGURE 2.10 Atomic packing at a line defect. (© Pearson Education, Inc. Used by permission.)

dislocation are in tension. As a result, the atoms are not at their natural spacing, so the bonds of these atoms are not at the point of minimum energy, as shown in Figure 2.2. Thus, when a shear stress is applied to this location, there will be a tendency for the atoms to slip in a progressive manner from position (a) to (b) to (c), as shown in Figure 2.11 (Flinn and Trojan 1986; Budinski 1996).

Volume defects are flaws in the manufactured material; they will not be discussed further. Area defects are discussed next.

2.2.3 Grain Structure

The structure of metals has been described in terms of the unit cell or the repeated crystalline structure. However, equally important to the behavior of

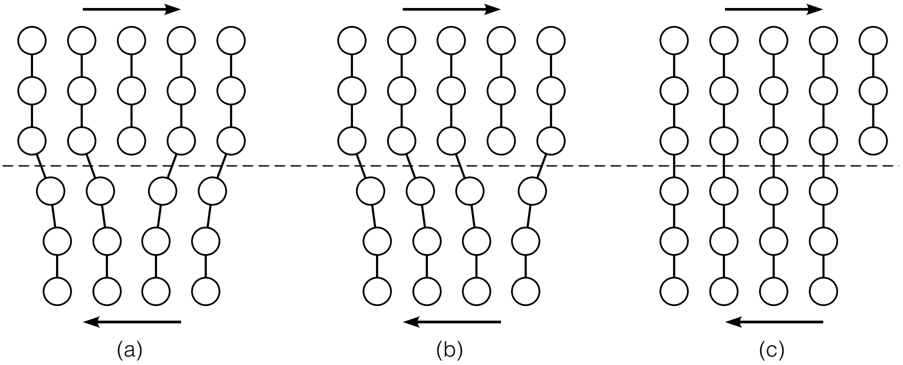
(a) (b) (c)

FIGURE 2.11 Plastic deformation involving movement of atoms along a slip plane.

the material is the size and arrangement of the grains in the material. The grain structure (microscopic structure) of the material should be distinguished from the atomic structure. Figure 2.12, for example, is an optical photomicrograph of a low-carbon steel. This photomicrograph was obtained using a scanning electron microscope with a magnification of 500 times. Note that this microscopic scale is much different than the atomic scale of Figure 2.9, which has a magnification in the order of 10,000,000 times.

In metals manufacturing, the material is heated to a liquid, impurities are removed from the stock material, and alloying agents are added. An *alloy* is simply the addition of a second element to a metal. As the material cools from the liquid state, crystals form. Under normal cooling conditions, multiple nuclei will form, producing multiple crystals. As these crystals grow, they will eventually contact each other, forming boundaries. For a given material, the size of the grains depends primarily on the rate of cooling. Under rapid cooling, multiple nuclei are formed, resulting in small grains with extensive boundaries.

There are four types of grain boundaries: coherent, coherent strain, semicoherent, and incoherent, as shown in Figure 2.13. At the coherent

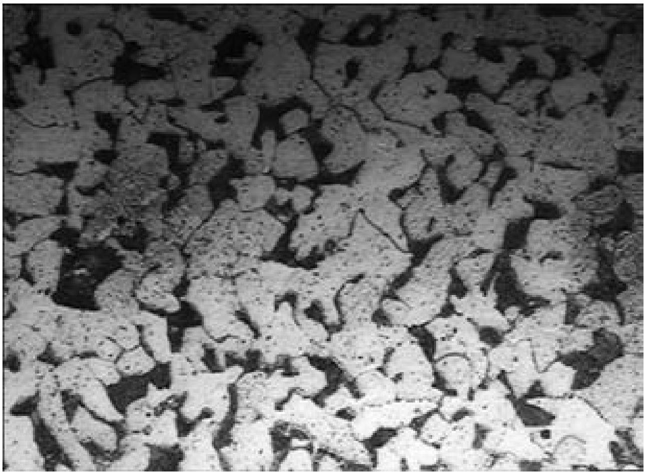

FIGURE 2.12 Optical photomicrograph of low-carbon steel (magnification: 500x).

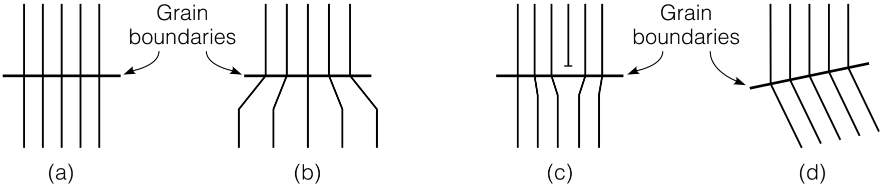

FIGURE 2.13 Types of grain boundaries: (a) coherent, (b) coherent strain, (c) semi-coherent, and (d) incoherent.

boundary, the lattices of the two grains align perfectly, and, in essence, there is no physical boundary. Coherent strain boundaries have a different spacing of atoms on each side of the boundary, which may be the effect of an alloying agent. As with the line dislocation, there will be a strain in the atoms on each side of the boundary due to the difference in the spacing of the atoms. The semicoherent boundary has a different number of atoms on each side of the boundary; therefore, not all of the boundaries can match up. Again, this is similar to line dislocation, with strain occurring on each side of the boundary. The incoherent boundary has a different orientation of the crystals on each side of the boundary; thus, the atoms do not match up in a natural manner.

Grain boundaries have an important effect on the behavior of a material. Although the bonds across the grain boundary do not have the strength of the pure crystal structure, the grain boundaries are at a higher energy state than the atoms away from the grain boundary. As a result, when slip occurs along one of the slip planes in the crystal, it is blocked from crossing the grain boundary, and can be diverted to run along the grain boundary. This increases the length of the slip path, thus requiring more energy to deform or fracture the material. Therefore, reducing grain size increases the strength of a material.

The grain structure of metals is affected by plastic strains. Fabrication methods frequently involve plastic straining to produce a desired shape (e.g., wire is produced by forcing a metal through successively smaller dies to reduce the dimension of the metal from the shape produced in the mill to the desired wire diameter.)

Heat treatments are used to refine grain structure. There are two basic heat treatment methods: *annealing* and *hardening*. Both processes involve heating the material to a point at which the existing grain boundaries will break down and re-form upon cooling. The differences between the processes include the temperature to which the material is heated, the amount of time it is held at the elevated temperature, and the rate of cooling. In hardening, rapid cooling is achieved by immersing the material in a liquid. In annealing, the material is slowly cooled. The slowest rate of cooling is achieved by leaving the material in the furnace and gradually reducing the temperature. This is an expensive process, since it ties up the furnace. More commonly, the material is cooled in air. Heat treatments of steel and aluminum are discussed in Chapters 3 and 4.

The grain size is affected by the rate of cooling. Rapid cooling limits the time available for grain growth, resulting in small grains, whereas slow cooling results in large grains.

2.2.4 Alloys

The engineering characteristics of most metallic elements make them unsuitable for use in a pure form. In most cases, the properties of the materials can be significantly improved with the addition of alloying agents. An alloying agent is simply a chemical that is compounded or in solution in the crystalline structure of a metal. Steel, composed primarily of iron and carbon, is perhaps the most common alloy. The way the alloying agent fits into the crystalline structure is extremely important. The alloying atoms can either fit into the voids between the atoms (*interstitial* atoms) or can replace the atoms in the lattice structure (*substitutional* atoms).

Because metals have a close pack structure, the radius of the interstitial atom must be less than 0.6 of the radius of the host element (Derucher et. al. 1994). Also, the solubility limit of interstitial atoms—less than 6%—is relatively low. Interstitial atoms can be larger than the size of the void in the lattice structure, but this will result in a strain of the structure and, therefore, will limit solubility.

If the characteristics of two metal elements are sufficiently similar, the metals can have complete miscibility; that is, there is no solubility limit. The atoms of the elements are completely interchangeable. The similarity criteria are defined by the Hume–Rothery rules (Shackelford 1996). Under these rules, the elements must have the following characteristics:

1. less than 15% difference in the atomic radius
2. the same crystal structure
3. similar electronegatives (the ability of the atom to attract an electron)
4. the same valence

Violation of any of the Hume–Rothery rules reduces the solubility of the atoms. Atoms that are either too large or too small will result in a strain of the lattice structure.

The arrangement of the alloy atoms in the structure can be either random or ordered. In a random arrangement, there is no pattern to the placement of the alloy atoms. An ordered arrangement can develop if the alloy element has a preference for a certain location in the lattice structure. For example, in a gold–copper alloy, an FCC structure, the copper preferably occupies the face positions and the gold preferably occupies the corner positions.

Frequently, more than one alloying agent is used to modify the characteristics of a metal. Steel is a good example of a multiple element alloy. By definition, steel contains iron with carbon; however, steel frequently includes other alloying elements such as chromium, copper, nickel, phosphorous, etc.

2.2.5 Phase Diagrams

To produce alloys metals, the components are heated to a molten state, mixed, and then cooled. The temperature at which the material transitions between a liquid and a solid is a function of the percentages of the components. The liquid and solid states of a material are called *phases*, and a phase diagram displays the relationship between the percentages of the elements and the transition temperatures.

Soluble Materials The simplest type of phase diagram is for two elements that are completely soluble in both the liquid and solid phases. Solid solutions occur when the elements in the alloys remain dispersed throughout the matrix of the material in the solid state. A two-element or *binary* phase diagram is shown in Figure 2.14(a) for two completely soluble elements. In this diagram, temperature is plotted on the vertical axis and the percent weight of each element is plotted on the horizontal axis. In this case, the top axis is used for element A and the bottom axis is used for element B. The percentage of element B increases linearly across the axis, while the percentage of element A starts at 100% on the left and decreases to 0% on the right. Since this is a binary phase diagram, the sum of the percentage of elements A and B must equal 100%. In Figure 2.14(a), there are three areas. The areas at the top and bottom of the diagram have a single phase of liquid and solid material, respectively. Between the two single-phase areas, there is a two-phase area where the material is both liquid and solid. The line between the liquid and two-phase areas is the *liquidus*, and the line between the two-phase area and the solid area is the *solidus*. For a given composition of elements A and B, the liquidus defines the temperature at which, upon cooling, the first solid crystals form. The solidus defines the temperature at which all material has crystallized. It should be noted that, for a pure element, the transition between liquid and solid occurs at a single temperature. This is indicated on the phase diagram by the convergence of the liquidus and solidus on the left and right sides of Figure 2.14(a), where there is pure element A and B, respectively.

A specific composition of elements at a specific temperature is defined as the *state point*, as shown in Figure 2.14(b). If the state point is above the liquidus, all the material is liquid and composition of the liquid is the same as the total composition of the material. Similarly, if the state point is below the solidus, all the material is solid and the composition of the solid is the same as for the material. In the two-phase region between the liquidus and the solidus, the percent of material that is in either the liquid or solid phase varies with the temperature. In addition, the composition of the liquid and solid phases in this region changes with temperature. The compositions of the liquid and solid can be determined directly from the phase diagram by using the lever rule. First a *tie line* is established by connecting the liquidus and solidus with a horizontal line that passes through the state point, as shown on Figure 2.14(b). A vertical projection from the intersection of the tie line and the liquidus defines the composition of the liquid phase. A vertical projection from the intersection of the tie line and the solidus defines the composition of the solid phase. For the example in Figure 2.14(b), the alloy is composed of 50% material A and 50% material B. For the defined state point, 79% of the liquid material is element A and 21% is element B, and 31% of the solid phase material is element A and 69% of the solid material is element B. In addition, the percent of the material in the liquid and solid phases can be determined from the phase diagram. From mass balance, the total material must equal the sum of the masses of the components; that is,

$$m_t = m_l + m_s \tag{2.4}$$

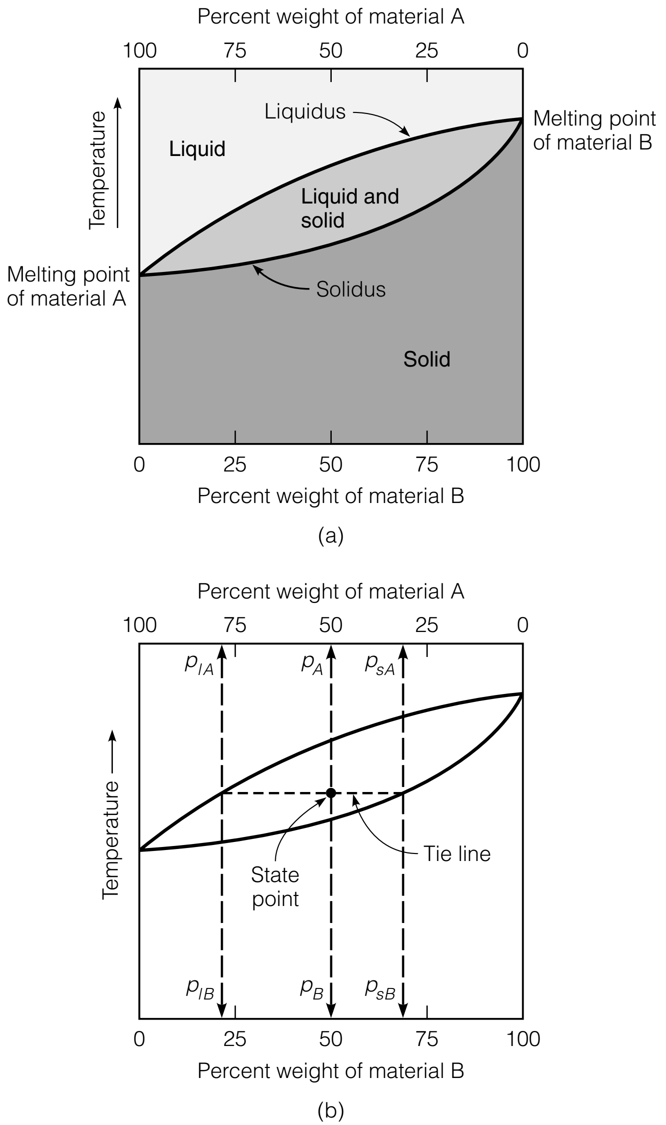

FIGURE 2.14 Binary phase diagram, two soluble elements.

where

m_t = mass of total material
m_l = mass of the total material that is in the liquid phase
m_s = mass of the total material that is in the solid phase

This mass balance also applies to each of the component materials; that is,

$$p_B m_t = p_{\mathrm{lB}} m_l + p_{\mathrm{sB}} m_s \tag{2.5}$$

where

p_{lB} = percent of the liquid phase that is composed of material B
p_{sB} = percent of the solid phase that is composed of material B
p_B = percent of the material that is component B

From these two equations, the amount of material in the liquid and solid phase can be derived as

$$\begin{aligned}
p_B m_t &= p_{\mathrm{lB}} m_l + p_{\mathrm{sB}}(m_t - m_l) \\
p_B m_t &= p_{\mathrm{lB}} m_l + p_{\mathrm{sB}} m_t - p_{\mathrm{sB}} m_l \\
p_B m_t - p_{\mathrm{sB}} m_t &= p_{\mathrm{lB}} m_l - p_{\mathrm{sB}} m_l \\
m_l &= \frac{(p_B - p_{\mathrm{sB}})}{(p_{\mathrm{lB}} - p_{\mathrm{sB}})} m_t \\
m_s &= m_t - m_l \qquad (2.6)
\end{aligned}$$

Sample Problem 2.3

Considering an alloy of the two soluble components A and B described by a phase diagram similar to that shown in Figure 2.14, determine the masses of the alloy that are in the liquid and solid phases at a given temperature if the total mass of the alloy is 100 grams, component B represents 40% of the alloy, 20% of the liquid is component B, and 70% of solid is component B.

Solution

$m_t = 100$ g
$p_B = 40\%$
$p_{\mathrm{lB}} = 20\%$
$p_{\mathrm{sB}} = 70\%$

From Equations 2.4 and 2.5,

$$\begin{aligned}
m_l + m_s &= 100 \\
20m_l + 70m_s &= 40 \times 100
\end{aligned}$$

Solving the two equations simultaneously, we get

m_l = mass of the alloy that is in the liquid phase = 60 g
m_s = mass of the alloy that is in the solid phase = 40 g

The same answer can also be obtained using Equation 2.6.

Insoluble Materials The discussion thus far has dealt with two completely soluble materials. It is equally important to understand the phase diagram for immiscible materials, that is, for components that are so dissimilar that their solubility in each other is nearly negligible in the solid phase. Figure 2.15 shows the phase diagram for this situation. The intersections of the liquidus with the right and left axes are the melting points for each of the components. As the materials are blended together, the liquidus forms a V shape. The point of the V defines the combination of the components that will change from liquid to solid without the formation of two phases. This point defines the eutectic temperature and the eutectic composition for the components. The solidus is horizontal and passes through the eutectic temperature. There are two areas on the graph with two phases. The area to the left of the eutectic composition will have solid component A, and the liquid phase will be a mixture of the A and B components (vice versa for the area to the right of the eutectic composition).

The sudden phase transformation at the eutectic temperature means that the grains do not have time to grow as the material cools. Thus, the eutectic material will have a fine grain structure.

As the material cools at a temperature other than the eutectic temperature, one of the components becomes solid as the temperature drops below the liquidus. As a result, the amount of this component in the liquid continuously decreases as the material cools in the two-phase area. In fact, the composition of the liquid will follow the liquidus as the temperature decreases. When the eutectic temperature is reached, the remainder of the liquid becomes solid and has a fine grain structure. Starting with a composition of 80% B and 20% A, as in Figure 2.15, when the temperature is lowered to *T*, the liquid will contain 55% B and 45% A. The amount of each component in the liquid and solid phases can be determined by mass balance (Equations 2.4 and 2.5). At *T*, this will yield 44.4% liquid and 55.6% solid; all of the solid will be component B. Similarly, the composition of the solid at the eutectic temperature can be computed to be 66.7% solid B and 33.3% eutectic mixture. Since these materials are insoluble in the solid state, the

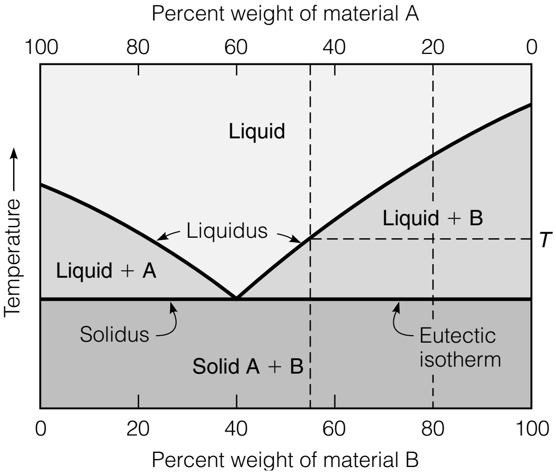

FIGURE 2.15 Binary phase diagram, insoluble solids.

eutectic mixture is composed of an intimate mixture of fine crystals of A and B, usually in a plate-like structure.

Partially Soluble Materials In between purely soluble and insoluble materials are the materials that are partially soluble. In other words, there is a solubility limit between the components of A and B. If the percent of component B is less than or equal to the solubility limit, on cooling all of the B atoms will be in solution with the A component. If the percent of the B component is above the solubility limit, the atoms in excess of the amount that will go into solution will form separate grains of the component B. The result is shown on the phase diagram in Figure 2.16. Note that the only difference between this phase diagram and the one shown in Figure 2.15 is the presence of the solid solution regions on each side of the graph. The composition analysis of the two-phase region is the same as that described for Figure 2.15.

Eutectoid Reaction Up to now, the phase diagram has been used to describe the transition between liquid and solid phases of materials. However, the lattice structure of some elements (e.g., iron) is a function of the temperature of the solid. As a result of the lattice transformation, the microstructure of the solid material changes as a function of temperature, as shown by the phase diagram in Figure 2.17. When this occurs, a eutectoid reaction occurs on the phase diagram; it has characteristics similar to the eutectic reaction, but is for a lattice structure transformation of the material rather than for a liquid–solid transformation. The rules for the analysis of the components of the material are the same as those discussed for the eutectic material. As with the phase transformation at the eutectic temperature, the transformation of the lattice structure at the eutectoid temperature will result in fine-grained materials.

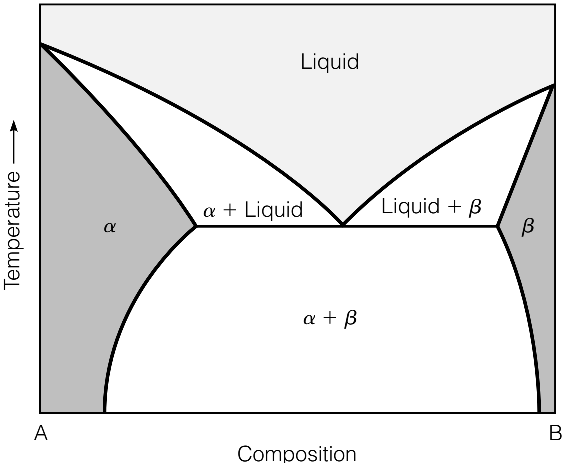

FIGURE 2.16 Binary phase diagram, partially soluble material.

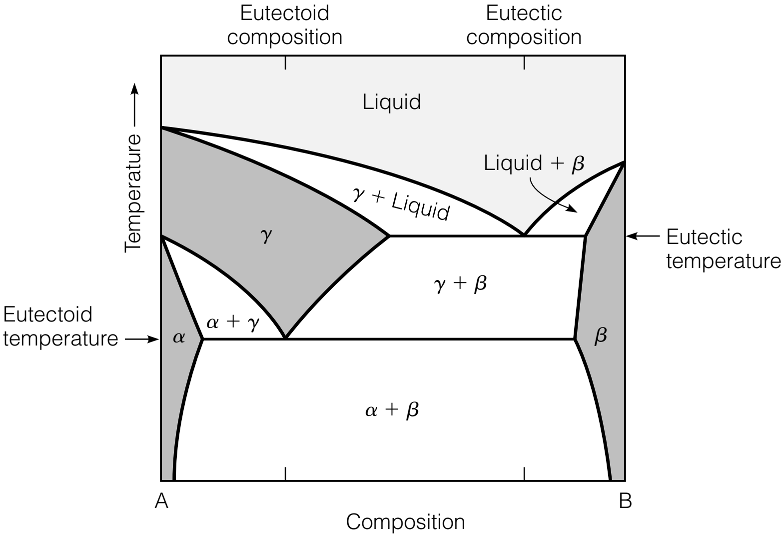

FIGURE 2.17 Phase diagram for a eutectoid reaction.

2.2.6 Combined Effects

The topics of lattice structure, grain size, heat treatments, and alloying are closely interrelated. The behavior of a metal is dictated by the combination of each of these factors. Clearly, the properties of a metal depend on the elemental make up, the refining and production process, and the types and extent of alloys used in the metal. These topics are too complex for detailed treatment in this text. A practicing engineer in this area must devote considerable study to material characteristics and the impact of alloying and heat treatments. Due to the importance of steel in civil engineering, the phase diagram and heat treatment of steel will be presented in Chapter 3.

2.3 Inorganic Solids

Inorganic solids include all materials composed of nonmetallic elements or a combination of metallic and nonmetallic elements. This class of materials is sometimes referred to as ceramic materials. By definition, ceramic elements have five, six, and seven valence electrons. Ceramic materials are formed by a combination of ionic and covalent bonds. In the generic sense, ceramics encompass a broad range of materials, including glass, pottery, inorganic cements, and various oxides. Fired clay products, including bricks and pottery, are some of the oldest ceramic products made by humans. In terms of tonnage, portland cement concrete is the most widely used manufactured material. In the 1980s, the search for highly durable products with unique strength and thermal properties initiated the rapid development of advanced ceramics, such as zirconias, aluminum oxides, silicon carbides, and silicon nitrates. These materials have high strength, stiffness, and wear resistance, and are corrosion resistant. The high-performance or engineered ceramics have found many applications in machine and tool design. Although the availability of high-performance ceramics has grown rapidly, the civil and construction engineering applications of these materials have been generally limited due to the cost of the sophisticated ceramics and their lack of fracture toughness that is needed for structural design.

Five classes of ceramic materials have been defined (Ashby and Jones 1986):

1. glasses—based on silica
2. vitreous ceramics—clay products used for pottery, bricks, etc.
3. high-performance ceramics—highly refined inorganic solids used for specialty applications in which properties, not available from other materials, compensate for the high cost
4. cement and concrete—a multiphase material widely used in civil engineering applications
5. rocks and minerals

Ceramics can also be classified by the predominant type of their atomic bonding. Materials composed of a combination of nonmetallic and metallic elements have predominantly ionic bonds. Materials composed of two nonmetals have predominantly covalent bonds. The type of bond dictates the crystal structure of the compound. As with metals, inorganic solids have a well-defined, although more complicated, unit cell structure. This structure is repeated for the formation of the crystals.

In a simple ionic compound, the nonmetallic element will form either a face centered cubic or hexagonal close pack structure, as shown in Figure 2.18. Octahedral holes fit in the middle of the octahedron that is formed by connecting all the face atoms of the FCC unit cell. Tetrahedral holes are in the middle of the tetrahedron formed by connecting a corner atom with the adjacent face atoms. In the FCC structure, there is one octahedral hole and six tetrahedral holes. The number of atoms and the way

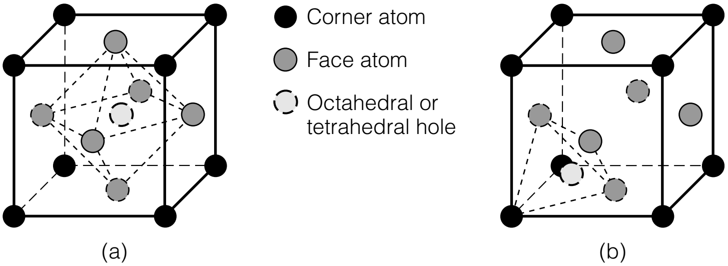

FIGURE 2.18 Lattice structure for simple ionic bonded ceramic materials: (a) octahedral hole and (b) tetrahedral hole.

they fit into the holes in the close pack structure is determined by the number of valence electrons in the metallic and nonmetallic elements. The atoms pack to maximize density, with the constraint that like ions are not nearest neighbors (Ashby and Jones 1986).

Simple covalent bonds form materials that are highly durable and strong. Diamond is the preeminent example of an elemental high-strength material. Diamond is widely used in industrial applications needing wear resistance, such as cutting tools. However, the most important of the predominately covalent bond materials used by civil engineers are the silicate compounds of portland cement concrete. Silicon atoms link with four oxygen atoms to form a stable tetrahedron (Figure 2.19) that is the basic building block for all silicates. When combined with metal oxides, MO, with a ratio of $MOSiO_2$ of 2 or greater, the resulting silicate is made up of separate SiO_4 monomers linked by the MO molecules. Figure 2.20 shows the calcium silicate crystal structure. The primary reaction compounds of portland cement are tricalcium silicates and dicalcium silicates. Each of these have two or more metal oxides, CaO, per silicate molecule. An ionic bond forms between the metal oxide and the silicate.

Ceramics have only about one-fiftieth the fracture toughness of metals. Due to the nature of the ionic and covalent bonds, ceramic compounds tend to fracture in a brittle manner rather than to have plastic deformation, as is the case for metals. Like metals, ceramic compounds form distinct grains as a result of multiple nuclei forming multiple crystals during the production of the compound. In addition, due to the production process, ceramic materials tend to have internal cracks and flaws. Stress concentrations occur at the cracks, flaws, and grain boundaries, all of which lower the strength and toughness of the material. As a result, ceramic materials lack tensile strength and must be reinforced when they are used for structural applications.

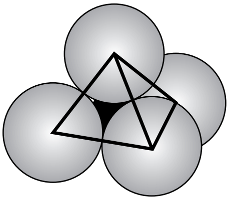

FIGURE 2.19 Silicate tetrahedron.

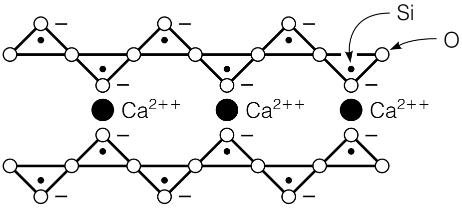

FIGURE 2.20 Simple inorganic solid structure (calcium silicate).

Glasses are a special type of inorganic solids; they do not develop a crystalline structure. Commercial glasses are based on silica. In glass, the silica tetrahedrons link at the corners, resulting in a random or amorphous structure. Glass can be made of pure silica; it has a high softening point and low thermal expansion. However, due to the high softening point, pure silica glass is hard to form. Metal oxides are added to reduce the cross-linking of the silicates, improving the ability to form the glass into the desired shape. Although glass has an amorphous structure, it is a very stable compound at atmospheric temperatures. It does not flow despite the often cited example of glass windows in European churches.

2.4 Organic Solids

All organic solids are composed of long molecules of covalent bonded carbon atoms. These molecules are chains of carbon and hydrogen combined with various radical components. The radical component can be a hydrogen atom, another hydrocarbon, or another element. These long molecules are bound together by secondary bonds; in many cases the molecules are also cross-linked with covalent bonds. There are a wide range of organic solids used in engineering. These can be classified as follows (Ashby and Jones 1986):

1. *Thermoplastics* are characterized by linear carbon chains that are not cross-linked; at low temperatures secondary bonds adhere the chains. Upon heating, the secondary bonds melt and the thermoplastics become a viscous material. Asphalt is a natural thermoplastic. It is obtained primarily by refining petroleum. In addition, there are many manufactured thermoplastics that have broad engineering applications. These include polyethylene, polypropylene, polytetrafluroethylene, polystyrene, and polyvinyl chloride. Polyethylene and polypropylene are used in tubing, bottles, and electrical insulation. Polytetrafluroethylene is commonly known as Teflon. In addition to cookware applications, Teflon is widely used for bearings and seals due to its very low friction and good adhesion characteristics. (Polytetrafluroethylene is a carbon–fluorine chain.) Polystyrene is used for molded objects. It is foamed with carbon dioxide to make packing materials and thermal insulation. Polyvinyl chloride is used for low-pressure waterlines.
2. *Thermosets* are characteristically made of a resin and a hardener that chemically react to harden. In the formation of the solid, the carbon chains are cross-linked to form stable compounds that do not soften upon heating. The three generic types of thermosets are epoxy, polyester, and phenol–formaldehyde. Epoxies are used as glues and as the matrix material in plastic composites. Polyester is a fibrous material used in the reinforcing phase of fiberglass. Phenol–formaldehydes are brittle plastics such as bakelite and formica.

3. *Elastomers or rubbers* are characterized as linear polymers with limited cross-linking. At atmospheric temperatures the secondary bonds have melted. The cross-linking enables the material to return to its original shape when unloaded. Three forms of elastomers are polyisoprene (natural rubber), polybutadiene (synthetic rubber), and polychloroprene (Neoprene).
4. *Natural materials* are characterized as being grown in all plant matter. The primary material of interest is wood, which is composed of cellulose, lignin, and protein.

Other than the natural polymers, the balance of the organic solids are produced from refining and processing crude oil. In general, these products are classified as plastics. The properties of these materials are highly variable. Mechanical properties depend on the length of the polymer chains, the extent of cross-linking, and the type of radical compound. All of these factors can be controlled and altered in the production process to alter the material properties.

2.4.1 Polymer Development, Structure, and Cross-Linking

The physical structure of the polymer chain grossly affects the mechanical response of plastics. The word polymer literally means multiple “mer” units. The mer is a base molecule that can be linked together to form the polymers. Figure 2.21 shows the structure of a simple ethylene molecule and the development of a polymer. The square boxes are carbon atoms and the open circles are hydrogen. Forming the polymer requires breaking the double bond, activating the monomer, and allowing it to link to others to form a long chain. The end of the chain either links to other chains or a terminator molecule, such as OH. Chains with useful mechanical properties require at least 500 monomers. The number of monomers in the chain defines the degree of polymerization; commercial polymers have a degree of polymerization of 10^3 to 10^5.

The complexity of the linear chain polymer is increased by replacing hydrogen atoms with side groups or radicals, as shown in Figure 2.21. The radicals or side groups can be aligned on one side of the chain (*isotactic*), symmetrically on alternate sides of the chain (*sindiotactic*), or in a random fashion (*atactic)*. The radicals can range from simple to complex molecules. For example, polyvinyl chloride has a Cl radical, polypropylene has a CH_3 radical, and polystyrene has C_6H_5. The ability of the polymer chains to stack together is determined by the arrangement of the side chains. The simple chains can fold together into an orderly arrangement, whereas the complex side groups prevent stacking, leading to the amorphous nature of these materials.

More complex linear polymers are formed when two of the hydrogen atoms are replaced by different radicals. Polymethylmethacrylate, (Plexiglas), has the radicals CH_3 and $COOCH_3$. As the complexity of the radicals and the

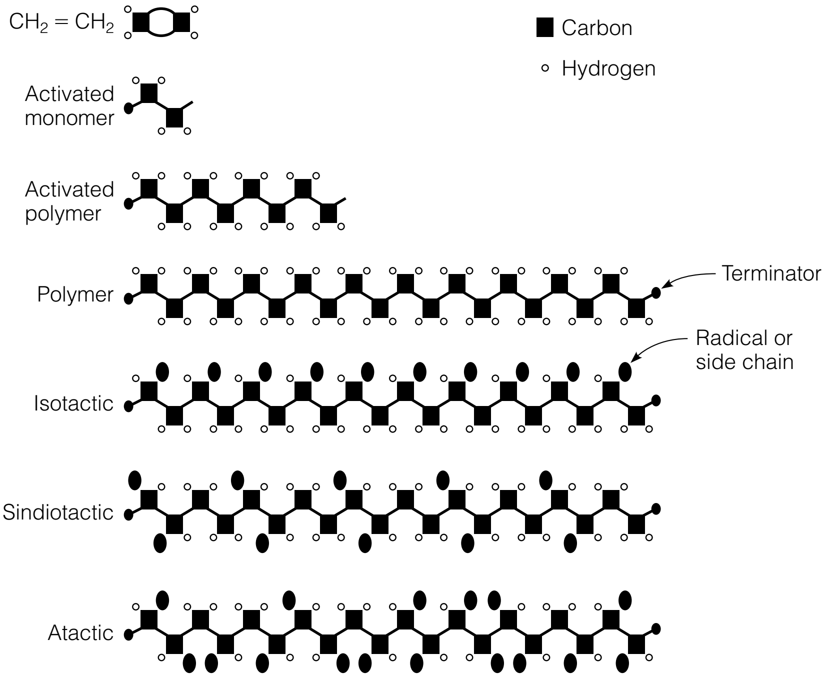

FIGURE 2.21 Polymer structures.

substitution for hydrogen increase, it becomes more difficult to form regular patterns.

In thermoplastics, formed from linear polymers, the structure of the molecules is a blend of amorphous and crystal structure. When there are few side groups, an ordered structure is produced [Figure 2.22(a)]. As the number of side groups increases, the structure becomes increasingly random and cross-links develop. These structures are shown in Figure 2.22(b). Thermosets are formed from polyfunctional monomers. They are formed in a condensation reaction; in essence, the reaction bonds two chains together. Since the chains are formed from polyfunctional crystals, they have an amorphous structure with extensive cross-linking. Elastomers are formed with linear chains that have a limited number of cross-links.

2.4.2 Melting and Glass Transition Temperature

The reaction of polymers to temperature depends on the degree to which the material has crystallized. Highly ordered polymers have a fairly well-defined transition between elastic and viscous behavior. As the percent of crystallization decreases, the melting point is not well defined. However, the point at which these polymers transition to a glass phase is well defined. At elevated temperatures, the motion of the molecules forces a

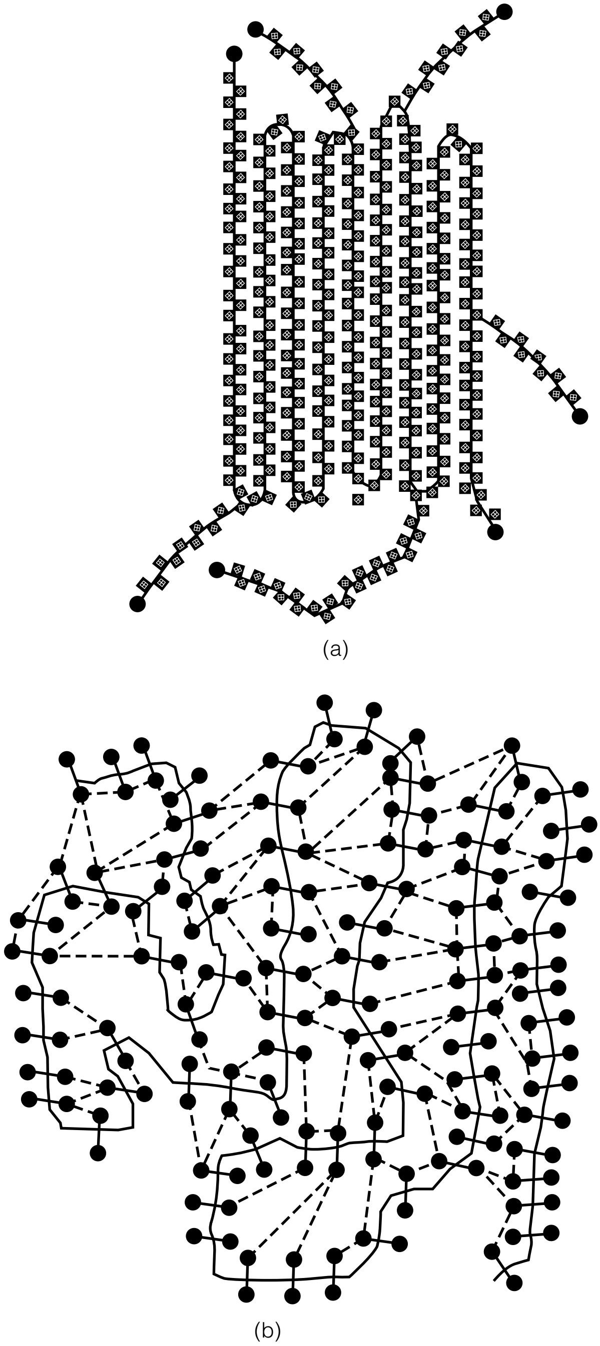

FIGURE 2.22 Polymer chain structures: (a) ordered structure of linear polymer and (b) cross linked structure of linear polygon.

separation between them, resulting in a volume that is greater than required for tightly packed, motionless molecules. This excess volume is termed the *free volume*. As the material cools, the motion of the molecules is reduced and the viscosity increases. At a sufficiently low temperature, the molecules are no longer free to rearrange; thus, their position is fixed and the free volume becomes zero. This is the glass transition temperature. Below this temperature, the secondary bonds bind the material into an amorphous solid; above this temperature, the material behaves in an elastic manner. Figure 2.23 illustrates the concept of melting and glass transition temperatures, T_m and T_g. The glass transition temperature of Plexiglass is 100°C; at room temperature it is a brittle solid. Above T_g, it becomes leathery and then rubbery. T_g for natural rubber is −70°C; it is flexible at all atmospheric temperatures. However, when frozen, say in liquid nitrogen, it becomes a brittle solid.

2.4.3 Mechanical Properties

The mechanical behavior of polymers is directly related to the degree of orientation of the molecules and the amount of cross-linking by covalent bonds. The modulus of a polymer is the average of the stiffness of the bonds.

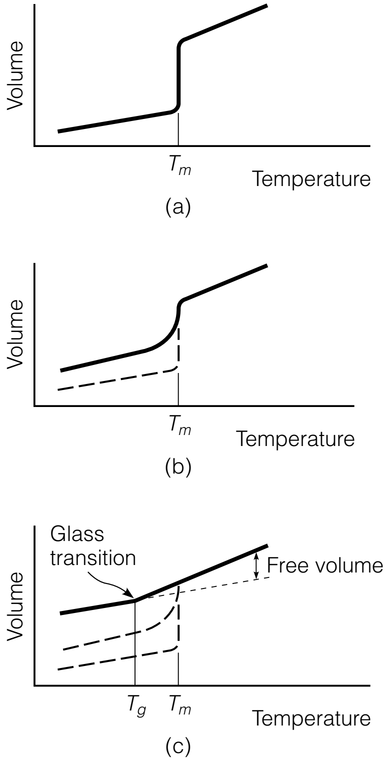

FIGURE 2.23 Melting point and glass transition temperatures: (a) perfect crystallization, (b) imperfect crystallization, and (c) glass formation.

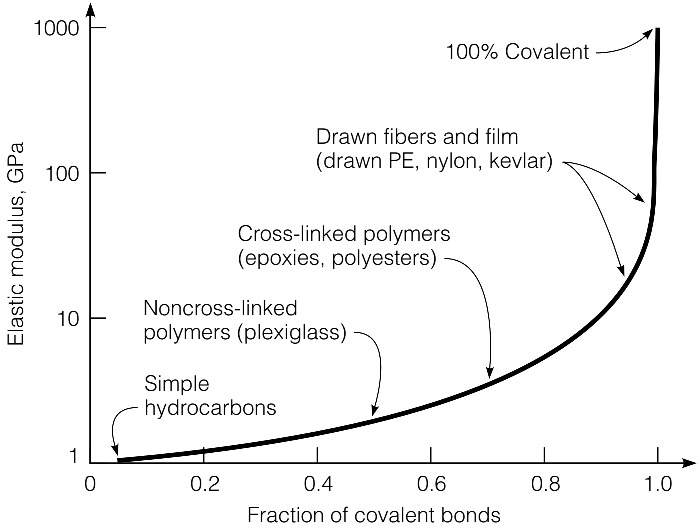

FIGURE 2.24 Modulus of polymers.

The modulus can be estimated from volume fractions of the covalent bonding as (Ashby and Jones 1986)

$$\varepsilon = f\frac{\sigma}{E_1} + (1 - f)\frac{\sigma}{E_2} \tag{2.7}$$

where

ε = strain of the material
σ = stress of the material
f = fraction of covalent bonds
E_1 = stiffness of covalent bonds, about 1000 GPa for diamond
E_2 = stiffness of secondary bonds, about 1 GPa for paraffin wax

Based on Equation 2.7, the expected modulus of various polymers can be computed for temperatures less than the glass transition temperature, as shown in Figure 2.24.

SUMMARY

The behavior of materials important to engineering is directly related to their microscopic and macroscopic structure. Although our understanding of these materials is imperfect at this time, much of the their behavior can be attributed to the bonding and arrangement of the materials at the atomic level. This chapter provides only a broad overview of the subject. For more information, consult references with more in-depth treatments of these subjects.

QUESTIONS AND PROBLEMS

2.1 Define elastic and plastic behaviors at the micro and macro levels.

2.2 Describe the parts of an atom. Define proton, electron, atomic number, and atomic mass.

2.3 What are the valence electrons and why are they important?

2.4 Describe the order in which electrons fill the shells and subshells.

2.5 Describe the different types of bonds.

2.6 Why do atoms maintain specific separations?

2.7 Materials are generally classified into three categories based on the predominant types of bond. What are these three categories and what are the predominant types of bond in each category? For each category, provide two examples of common materials used by civil engineers.

2.8 What is the atomic packing factor? What information do you need to compute it?

2.9 Describe FCC, BCC, and HCP lattice structures.

2.10 Show for the face-center cubic crystal structure that the unit cell edge length a and the atomic radius r are related through $a = 2\sqrt{2}r$

2.11 Referring to the BCC lattice structure shown in Figure P2.11

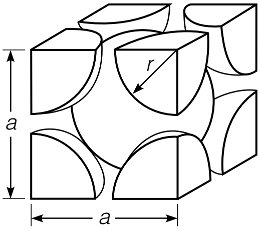

FIGURE P2.11

a. Determine the number of equivalent whole atoms in the unit cell.

b. Calculate the relation between a and r.

c. Calculate the atomic packing factor of the BCC lattice structure if the volume of the sphere is $4/3\pi r^3$.

2.12 Calculate the volume of the unit cell of iron in cubic meters, given that iron has a body-center cubic crystal structure and an atomic radius of 0.124 nm.

2.13 If aluminum has an FCC crystal structure and an atomic radius of 0.143 nm, calculate the volume of its unit cell in cubic meters.

2.14 Using the information available in Table 2.3, calculate the volume of the unit cell of copper in cubic meters.

2.15 Calculate the density of iron, given that it has a BCC crystal structure, an atomic radius of 0.124 nm, and an atomic mass of 55.9 g/mole.

2.16 Calculate the density of aluminum, given that it has an FCC crystal structure, an atomic radius of 0.143 nm, and an atomic mass of 26.98 g/mole.

2.17 Calculate the radius of the copper atom, given that copper has an FCC crystal structure, a density of 8.89 g/cm^3, and an atomic mass of 63.55 g/mole.

2.18 What are the classes of defects in crystal structures?

2.19 Why do grains form in crystal structures?

2.20 Explain the slipping of atoms and the effect on material deformation.

2.21 Sketch a phase diagram for two soluble components.

2.22 What is the eutectic composition and why is it important?

2.23 Considering an alloy of the two soluble components A and B described by a phase diagram similar to that shown in Figure 2.14, determine the masses of the alloy that are in the liquid and solid phases at a given temperature if the total mass of the alloy is 100 grams, component B represents 65% of the alloy, 30% of the liquid is component B, and 80% of solid is component B.

2.24 Considering an alloy of the two soluble components A and B described by a phase diagram similar to that shown in Figure 2.14, determine the masses of the alloy that are in the liquid and solid phases at a given temperature if the total mass of the alloy is 100 grams, component B represents 45% of the alloy, 17% of the liquid is component B, and 65% of solid is component B.

2.25 Figure P2.25 shows a portion of the H_2O–NaCl phase diagram.

a. Using the diagram, briefly explain how spreading salt on ice causes the ice to melt. Show numerical examples in your discussion.

b. At a salt composition of 10%, what is the temperature at which ice will start melting?

c. What is the eutectic temperature of the ice and salt combination?

2.26 What are the five classes of ceramic materials?

2.27 What are the four types of organic solids used in engineering applications? Define each one and give examples.

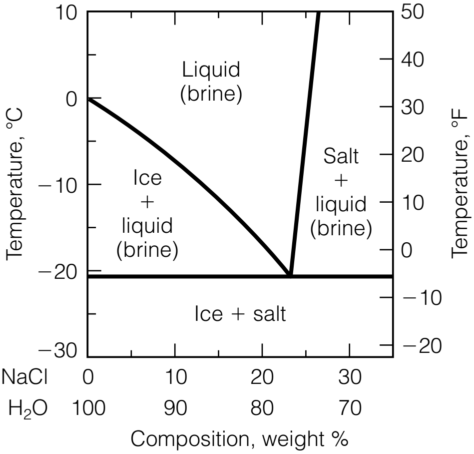

FIGURE P2.25

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