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# CHAPTER 7

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# SOLID MATERIALS

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<b>7.1</b>	<b>STRUCTURE OF SOLIDS / 7.1</b>
<b>7.2</b>	<b>ATOMIC BONDING FORCES / 7.2</b>
<b>7.3</b>	<b>ATOMIC STRUCTURES / 7.4</b>
<b>7.4</b>	<b>CRYSTAL IMPERFECTIONS / 7.11</b>
<b>7.5</b>	<b>SLIP IN CRYSTALLINE SOLIDS / 7.15</b>
<b>7.6</b>	<b>MECHANICAL STRENGTH / 7.17</b>
<b>7.7</b>	<b>MECHANICAL PROPERTIES AND TESTS / 7.20</b>
<b>7.8</b>	<b>HARDNESS / 7.21</b>
<b>7.9</b>	<b>THE TENSILE TEST / 7.25</b>
<b>7.10</b>	<b>TENSILE PROPERTIES / 7.32</b>
<b>7.11</b>	<b>STRENGTH, STRESS, AND STRAIN RELATIONS / 7.36</b>
<b>7.12</b>	<b>IMPACT STRENGTH / 7.42</b>
<b>7.13</b>	<b>CREEP STRENGTH / 7.43</b>
<b>7.14</b>	<b>MECHANICAL-PROPERTY DATA / 7.46</b>
<b>7.15</b>	<b>NUMBERING SYSTEMS / 7.51</b>
	<b>REFERENCES / 7.55</b>

This chapter summarizes the structure of solids, including atomic bonding forces, atomic structures, crystal imperfections, slip, and mechanical strength. The section on mechanical properties and tests discusses all the hardness tests and includes a detailed explanation of the tensile test and tensile properties. The section on strength, stress, and strain relations includes many new relationships that have been developed during the past two decades and are not found in other handbooks. The mechanical property data presented in this section are in a new format that is well suited for use in computer-aided-engineering (CAE) applications.

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## **7.1 STRUCTURE OF SOLIDS**

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A study of the mechanical properties of materials must begin with an understanding of the structure of solid materials. In this context, *structure* refers to the atomistic and crystalline patterns of which the solid material is composed. The definitions of the mechanical properties given in the following sections are on the basis of the crystalline structure of material. For example, *strength* (and *hardness*) is defined as the ability of the material to resist slip along its crystallographic planes. Thus, in order to increase the strength of a material, something must be done to it which will make

slip more difficult to initiate. The following sections will explain the manner in which the various thermal and mechanical processes affect the structure of a material, which in turn determines the mechanical properties. The next section presents a brief review of atomic structure.

## 7.2 ATOMIC BONDING FORCES

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The smallest particles that must be considered in the preceding context are atoms. The manner in which atoms are arranged in a solid material determines the material's crystal structure. The crystal structure and the type of interatomic bonding forces determine the strength and ductility of the material.

The simple model of an atom is a dense *nucleus*, consisting of *protons* and *neutrons*, surrounded by discrete numbers of planetary *electrons* orbiting in shells at specific distances from the nucleus. Each proton has a positive electric charge of unity (1+). The number of protons in the nucleus determines the nuclear charge of the atom and is called the *atomic number*. The neutrons have no charge, but they do have mass. The *atomic weight* of an atom is the sum of the number of protons and neutrons. The electrons have negligible mass and a negative charge of unity (1-). The number of electrons in a given type of atom is also equal to the atomic number of that element. The maximum number of electrons in any shell is  $2n^2$ , where  $n$  is the *quantum number* of the shell. Thus the maximum number of electrons that can be present in the first (innermost) shell is 2, and 8 is the maximum in the second shell. However, no more than 8 electrons are ever present in the outermost shell of an atom. The *valence* of an element is either the number of electrons in its outermost shell or the number of electrons necessary to fill that shell, whichever number is lower.

The interatomic bonding forces are determined by the valence, or outer-shell, electrons. There are four types of atomic bonding forces that hold the atoms of a solid material in their relatively fixed positions. The three strongest (*ionic*, *covalent*, and *metallic*) types of bond are referred to as *primary*; the fourth (*molecular*) is referred to as a *secondary* type of bond.

### 7.2.1 Ionic Bonds

From the preceding brief description of atomic structure, it is evident that the uncombined atom is electrically neutral—the number of protons (+ charges) in the nucleus exactly equals the number of electrons (– charges). When atoms combine, only the valence electrons are involved and not the nuclei. When a metal combines with a nonmetal, each metal atom “loses” its valence electrons and thus acquires a positive charge that is equal to the number of electrons so lost. Likewise each non-metallic atom “gains” a number of electrons equal to its valence and acquires an equal negative charge. While in this state, the positively charged metallic atom and the negatively charged nonmetallic atom are called *ions*.

Like-charged particles repel each other and oppositely charged particles attract each other with an electric force called the *Coulomb force*. When a material is maintained in the solid state by the mutual attraction of positively and negatively charged ions, the interatomic bonding force is called *ionic*.

The Coulomb forces attracting oppositely charged ions are very large. Therefore, ionic-bonded solids exhibit very high strength and relatively low melting tempera-

tures. However, they exhibit very low ductility under normal conditions because the interatomic bonds must be broken in order for the atoms to slide past each other. This is one of the most important distinctions between ionic (or covalent) bonding and metallic bonding and is discussed later.

### 7.2.2 Covalent Bonds

*Covalent bonds* are those in which the atoms reach a stable configuration (filled outer shell) by *sharing* valence electrons. Unlike ionic bonds, which are nondirectional, covalent bonds act between specific pairs of atoms and thus form molecules. Covalent bonds are most prevalent in gas molecules. Covalent bonding also results in the formation of very large molecules which are present as solids rather than as liquids and gases. Diamond, silicon, and silicon carbide are examples of such covalent-bonded solids. They are characterized by high strength and melting temperature and low ductility. The atoms in the diamond structure are arranged on two interpenetrating face-centered cubic lattices. The entire crystal is composed of only one molecule, and in order to fracture the crystal, the strong covalent interatomic bonds must be broken.

### 7.2.3 Metallic Bonds

Of the three primary bonding forces, the metallic bond is by far the most important for an understanding of the mechanical properties of the materials with which the practicing engineer is concerned. The *metallic bond* is a special type of covalent bond wherein the positively charged nuclei of the metal atoms are attracted by electrostatic forces to the valence electrons that surround them. Unlike the common covalent bond, which is directional, i.e., between a pair of atoms, the metallic bond is nondirectional, and each nucleus attracts as many valence electrons as possible. This leads to a dense packing of the atoms, and thus the most common crystal structures of the metals are the close-packed ones: face- and body-centered cubic and hexagonal close-packed structures.

The reason that metal atoms have their own unique type of bonding force is the looseness with which their valence electrons are held in the outer shell. This is evident from the fact that the ionization potential of metal atoms is one-half to two-thirds that of nonmetal atoms. The mean radius of the valence electrons in a free (isolated) metal atom is larger than the interatomic distance of that metal in the solid crystalline state. This means that the valence electrons are closer to a nucleus in the solid metal than they are in a free atom, and thus their potential energy is lower in the solid.

Since the valence electrons are not localized between a pair of positive ions, they are free to move through the solid. Thus the structure of the solid metal is a close-packed arrangement of positive ion "cores" (the nucleus plus the nonvalence electrons) that is permeated by an electron "gas" or "cloud." This ability of the valence electrons to move freely through the solid explains the high thermal and electrical conductivities of metals. Also, the fact that the valence electrons are nondirectional (not shared by only two atoms) explains the relatively low strength and high ductility of elemental metals, since the positive ions can move relative to one another without breaking any primary bonds. This mechanism is referred to as *slip* and is discussed in more detail in a following section on crystal structures.

### 7.2.4 Molecular or van der Waals Bonds

In addition to the three strong primary bonds discussed above, there are also several much weaker (and therefore called *secondary*) bonds which provide the interatomic attractive forces that hold some types of atoms together in a solid material. These forces are referred to as either *secondary* bonds, *molecular* bonds, or *van der Waals* bonds. These bonds are due to residual electrostatic fields between neutral molecules whose charge distribution is not uniform.

Covalently bonded atoms frequently form molecules that behave as electric or magnetic *dipoles*. Although the molecule itself is electrically neutral, there is an electrical imbalance within the molecule. That is, the center of the positive charge and the center of the negative charge do not coincide, and it is this dipole that creates molecular bonding.

## 7.3 ATOMIC STRUCTURES

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Whereas the electrical properties of a material depend on the internal structure of the atoms, the mechanical properties depend on the types of structures that groups of atoms form. In this context, *atomic structures* refer to the structures that are built by particular arrangements of atoms, not to the internal structure of individual atoms. All solid materials can be classified on the basis of atomic structure into three groups: amorphous, molecular, or crystalline (in order of increasing importance to mechanical properties). Knowledge of the atomic structure of solids makes it possible to understand why a given material has its unique properties and thus to be able to specify the type of material and the condition it should be in to achieve optimum mechanical properties.

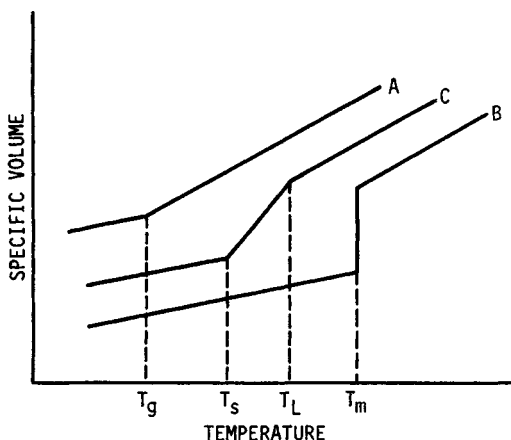
### 7.3.1 Amorphous Solids

*Amorphous* materials are those whose structure has no repetitive arrangement of the atoms of which it is comprised. In a sense, they have no "structure." Although gases and liquids are amorphous materials, the only important amorphous solids are the glasses, and they are frequently considered simply as supercooled liquids.

Glass behaves as a typical liquid at high temperatures. The atoms are very mobile and do not vibrate in a fixed location in space. A given mass of hot glass, like any liquid, takes the shape of the container in which it is placed.

As a hot glass cools, its atoms vibrate at lower amplitudes and come closer together, resulting in an overall thermal contraction or decrease in specific volume. This decrease in specific volume of a liquid as temperature decreases is approximately linear and occurs with all liquids, including liquid metals. This is illustrated in Fig. 7.1.

When any unalloyed liquid metal (a pure metallic element) or chemical compound is cooled to its freezing (or melting) temperature  $T_m$ , the atoms come much closer together and become relatively immobile with respect to one another. They form a crystalline structure with very efficient packing, and thus there is a very marked decrease in specific volume at this temperature, as shown in Fig. 7.1. When an alloyed liquid metal freezes to form a solid solution, the transition from liquid to solid takes place in the range of temperatures between the liquidus and the solidus. Further cooling of both solid metals results in a further decrease in specific volume, also linear but of lower slope than in the liquid state.



**FIGURE 7.1** Specific volume versus temperature. (A) Glass with a transition temperature  $T_g$ ; (B) a crystal that melts at a fixed temperature  $T_m$ , such as a pure element or a compound; (C) a crystal that melts over a range of temperature, such as a solid-solution alloy with  $T_L$  the liquidus temperature and  $T_s$  the solidus temperature.

When hot liquid glass is cooled to some temperature  $T_g$ , called the *glass transition temperature*, there is an abrupt change in the slope of the specific volume versus temperature curve. Unlike crystalline solids, the glass shows no marked decrease in specific volume at this temperature. Below  $T_g$ , glass behaves as a typical solid.

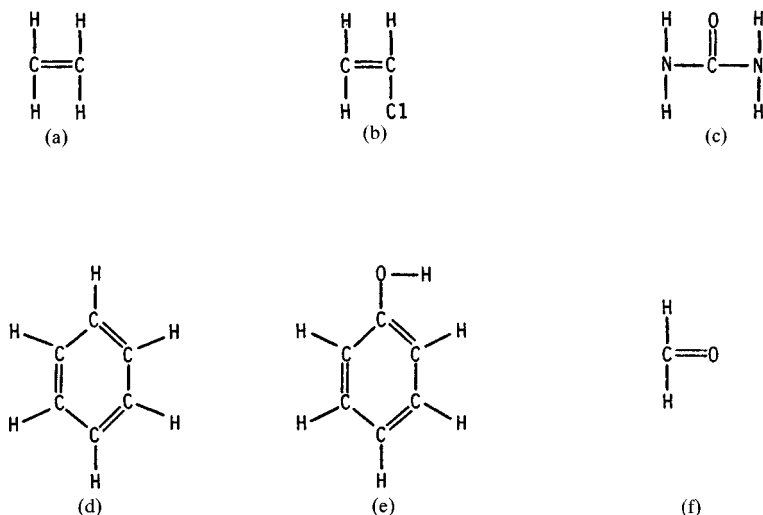
### 7.3.2 Molecular Solids

A *molecule* is a group of atoms that are held together by strong ionic or covalent bonds. A *molecular solid* is a structure made up of molecules that are attracted to each other by weak van der Waals forces. The two most common types of molecular solids are silicates and polymers. The silicates have ionic intramolecular bonds, and the polymers have covalent ones. Since it is the latter materials that are more important in terms of mechanical properties, they will be discussed in more detail.

Polymers are organic compounds of carbon, hydrogen, and oxygen to which other elements such as chlorine or fluorine may be added. They cover a wide range of structural arrangements, with resulting variations in properties. Large molecules are constructed from a repeating pattern of small structural units. The hydrocarbons have repeating structural units of carbon and hydrogen atoms.

Figure 7.2 shows some of the more common monomers or unsaturated molecules that are used in the building of macromolecules. The simplest monomer is ethylene ( $C_2H_4$ ); it is shown in Fig. 7.2a. It is the base of the group of hydrocarbons called *olefins*. The olefins have the chemical formula  $C_nH_{2n}$ . The benzene molecule, shown in Fig. 7.2d, is another important building unit. Because of the shape of the molecule, it is described as a ring molecule or compound. The benzene group is also called the *aromatic* hydrocarbons.

Figure 7.3 illustrates the addition polymerization of the ethylene monomer. The double bonds of ethylene are broken in the presence of a catalyst such as boron tri-

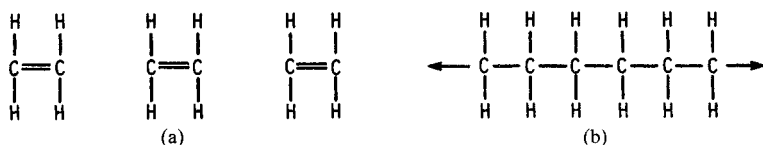


**FIGURE 7.2** Monomers: Small unsaturated (double-bonded) molecules that are building units for large polymer molecules. (a) Ethylene; (b) vinyl chloride; (c) urea; (d) benzene; (e) phenol; (f) formaldehyde.

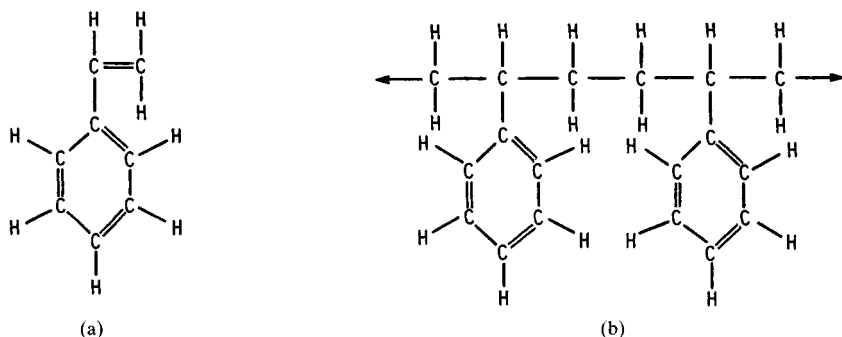
fluoride. The vinyl chloride monomer, as shown in Fig. 7.2b, is similar to ethylene except that one of the hydrogen atoms is replaced with a chlorine atom. The polymerization of this monomer results in polyvinyl chloride. These macromolecules resemble, more or less, smooth strings or chains, as can be seen from their structural arrangement.

Some macromolecules resemble rough chains—that is, chains with many short side arms branching from them. Polystyrene, which is a very important industrial polymer, is of this type. The styrene monomer is made from the benzene ring ( $C_6H_6$ ) with one of the hydrogen atoms replaced with a  $CH=CH_2$  molecule, as shown in Fig. 7.4a. Polymerization then occurs by breaking the double bond in the  $CH=CH_2$  group with the help of a peroxide catalyst and joining two of them together, as shown in Fig. 7.4b.

The polymers just described are *thermoplastic*; they melt or soften when they are heated. This is due to the fact that the individual macromolecules are stable and the linkages to other macromolecules are loose (since they are attracted to each



**FIGURE 7.3** Addition polymerization. (a) Three individual monomers of ethylene; (b) a portion of a polyethylene molecule formed when each double bond of the monomers is broken by a catalyst to form two single bonds and join the individual molecules together.



**FIGURE 7.4** (a) Styrene structure; (b) polystyrene structure. The polymerization takes place in the presence of a peroxide catalyst.

other by weak van der Waals forces). Some polymers are *thermosetting*; they do not soften when they are heated, but retain their “set” or shape until charred. This is due to the fact that the individual macromolecules unite with each other and form many cross-linkages. Bakelite (phenol formaldehyde) is such a polymer. Figure 7.5 shows how each formaldehyde monomer joins two phenol monomers together, under suitable heat and pressure, to form a macromolecule. This is a condensation type of polymerization because one water molecule is formed from the oxygen atom of each formaldehyde molecule and a hydrogen atom from each of the two phenol molecules.

### 7.3.3 Mechanical Properties of Molecular Structures

The mechanical properties of polymers are determined by the types of forces acting between the molecules. The polymers are amorphous with random chain orientations while in the liquid state. This structure can be retained when the polymer is cooled rapidly to the solid state. In this condition, the polymer is quite *isotropic*. However, with slow cooling or plastic deformation, such as stretching or extruding, the molecules can become aligned. That is, the long axes of the chains of all the molecules tend to be parallel. A material in this condition is said to be “oriented” or “crystalline,” the degree of orientation being a measure of the crystallinity. When the molecular chains of a polymer have this type of directionality, the mechanical properties are also directional and the polymer is *anisotropic*. The strength of an aligned polymeric material is stronger along the axis of the chains and much lower in the perpendicular directions. This is due to the fact that only weak van der Waals forces hold the individual, aligned macromolecules together, whereas the atoms along the axes of the chains are held together by strong and covalent bonds. The intermolecular strength of linear polymers can be increased by the addition of polar (dipole) groups along the length of the chain. The most frequently used polar groups are chlorine, fluorine, hydroxyl, and carboxyl.

The thermosetting (cross-linked) types of polymers have all the macromolecules connected together in three directions with strong covalent bonds. Consequently, these polymers are stronger than thermoplastic ones, and they are also more isotropic.

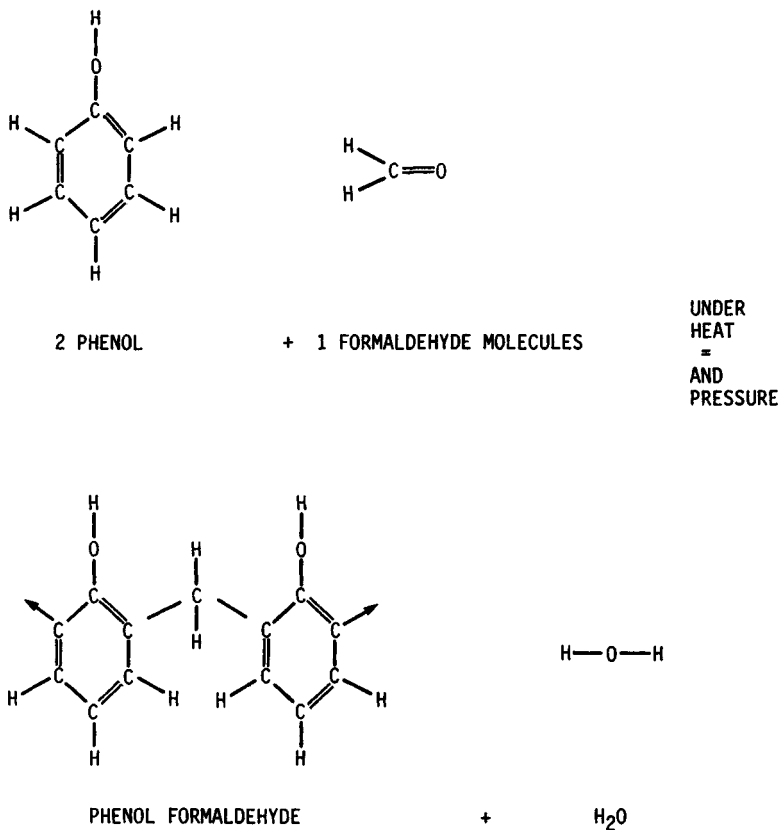


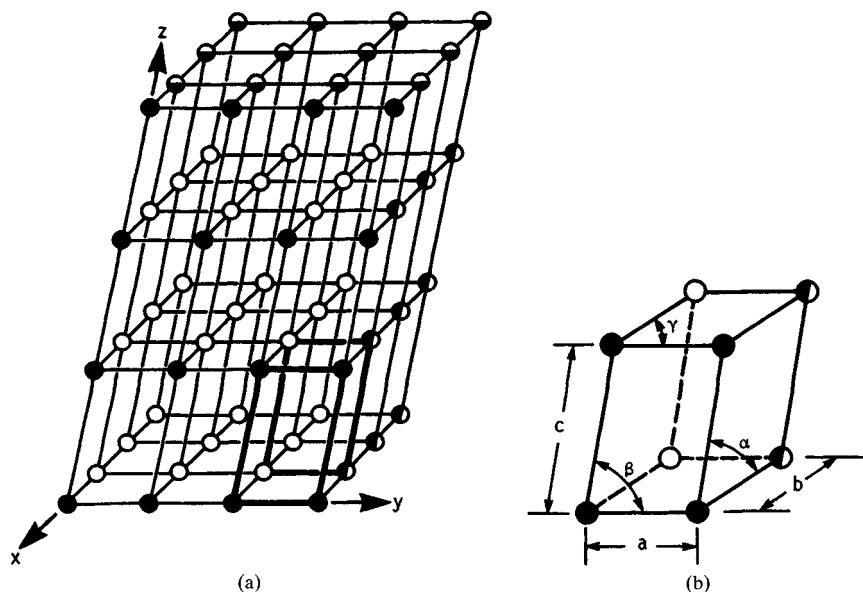
FIGURE 7.5 Condensation polymerization of phenol and formaldehyde into bakelite.

### 7.3.4 Crystalline Solids

Crystalline solids are by far the most frequently used ones on the basis of mechanical properties or load-carrying capacity. Moreover, of all the crystalline solids, metals are the most important. A *crystal* (or crystalline solid) is an orderly array of atoms having a repeating linear pattern in three dimensions. The atoms are represented as spheres of radius  $r$ . A *space lattice* is the three-dimensional network of straight lines that connects the centers of the atoms along three axes. The intersections of the lines are *lattice points*, and they designate the locations of the atoms. Although the atoms vibrate about their centers, they occupy the fixed positions of the lattice points. Figure 7.6 is a sketch of a space lattice, with the circles representing the centers of the atoms. A space lattice has two important characteristics: (1) the space-lattice network divides space into equal-sized prisms whose faces contact one another in such a way that no void spaces are present, and (2) every lattice point of a space lattice has identical surroundings.

The individual prisms that make up a space lattice are called *unit cells*. Thus a unit cell is the smallest group of atoms which, when repeated in all three directions, make up the space lattice, as illustrated by the dark-lined parallelepiped in Fig. 7.6.





**FIGURE 7.6** A space lattice. (a) A unit cell is marked by the heavy lines. Black circles are on the front face; horizontal shading on the top face; vertical shading on the right side face; hidden circles are white. (b) An isolated unit cell showing dimensions  $a$ ,  $b$ , and  $c$  and angles  $\alpha$ ,  $\beta$ , and  $\gamma$ .

Only 14 different space lattices and 7 different systems of axes are possible. Most of the metals belong to three of the space-lattice types: face-centered cubic, body-centered cubic, and hexagonal close-packed. They are listed in Table 7.1, along with four metals that have a rhombohedral and two that have orthorhombic structures.

**TABLE 7.1** Lattice Structure of Metal Crystals

Face-centered cubic	Body-centered cubic	Hexagonal close-packed	Rhombohedral	Orthorhombic
Ag	Cb	Be	As	Ga
Al	$\alpha$ -Cr	Cd	Bi	U
Au	Cs	$\alpha$ -Co	Hg	
Ce	$\alpha$ -Fe	$\beta$ -Cr	Sb	
$\beta$ -Co	$\delta$ -Fe	Hf		
Cu	K	Mg		
$\gamma$ -Fe	Li	Os		
Ir	Mo	Ru		
Ni	Na	Se		
Pb	Ta	Te		
Pd	V	Ti		
Pt	W	Tl		
Rh		Y		
Sc		Zn		
Th		Zr		
$\beta$ -Ti				

The crystalline structure is not restricted to metallic bonding; ionic and covalent bonding are also common. Metallic-bonded crystals are very ductile because their valence electrons are not associated with specific pairs of ions.

### 7.3.5 Face-Centered Cubic

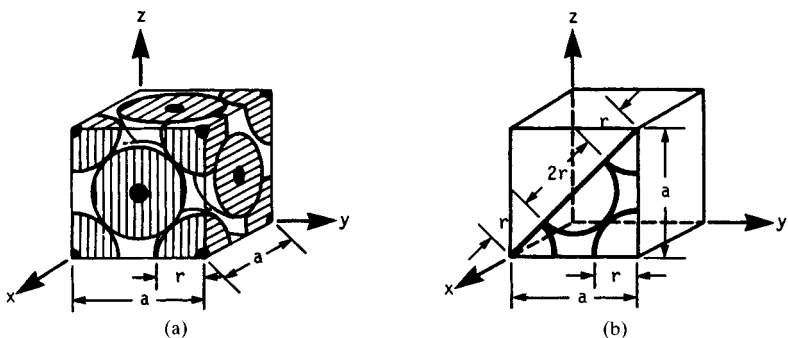
Most of the common metals (see Table 7.1) have face-centered cubic structures. Figure 7.7 shows the arrangement of the atoms, represented by spheres, in the face-centered cubic (FCC) structure as well as that fraction or portion of each atom associated with an individual unit cell. Each atom in the FCC structure has 12 contacting atoms. The number of contacting atoms (or nearest neighbors) is called the *coordination number*.

The FCC structure is referred to as a dense or closely packed structure. A quantitative measure of how efficiently the atoms are packed in a structure is the *atomic packing factor* (APF), which is the ratio of the volume of the atoms in a cell to the total volume of the unit cell. The APF for the FCC structure is 0.74. This means that 26 percent of the FCC unit cell is "void" space.

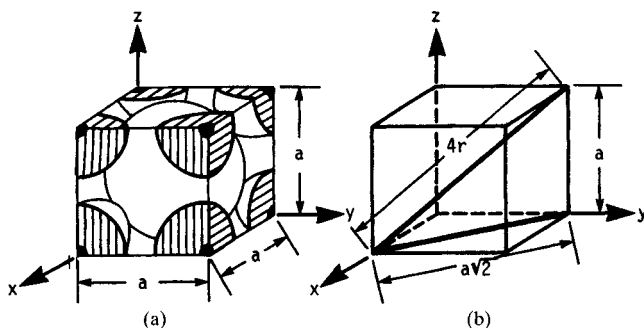
### 7.3.6 Body-Centered Cubic

Many of the stronger metals (Cr, Fe, Mo, W) have body-centered cubic (BCC) lattice structures, whereas the softer, more ductile metals (Ag, Al, Au, Cu, Ni) have the FCC structure (see Table 7.1). Figure 7.8 shows the arrangement of atoms in the BCC structure. There are two atoms per unit cell: one in the center (body center) and  $\frac{1}{8}$  in each of the eight corners. As can be seen in Fig. 7.8, each atom is contacted by eight other atoms, and so its coordination number is 8. The atomic packing factor for the BCC structure is 0.68, which is a little lower than that for the FCC structure.

The *Miller indices* are used to designate specific crystallographic planes with respect to the axes of the unit cell. They do not fix the position in terms of distance from the origin; thus, parallel planes have the same designation. The Miller indices are determined from the three intercepts that the plane makes with the three axes of the crystal. Actually it is the reciprocal of the distances between the intercepts with



**FIGURE 7.7** Unit cell of face-centered cubic structure. (a) The unit cell has 8 corners with  $\frac{1}{8}$  atom at each plus 6 faces with  $\frac{1}{2}$  atom, for a total of 4 atoms per unit cell; (b) one half of the front face showing the relationship between the lattice parameter  $a$  and the atomic radius  $r$ .



**FIGURE 7.8** Unit cell of body-centered cubic structure. (a) The unit cell has  $\frac{1}{8}$  atom at each of 8 corners and 1 atom at the geometric center of the cell, for a total of 2 atoms; (b) the relationship of the lattice parameter  $a$  and atomic radius  $r$ .

the axis and the origin measured in terms of multiples or fractions of the unit cell lengths  $a$ ,  $b$ , and  $c$  used in the determination. The final steps in specifying the Miller indices are to reduce the three reciprocals to the lowest integers having the same ratio and then to enclose them in parentheses. As is true with direction indices, the sequence of integers relates to the distances along the  $x$ ,  $y$ , and  $z$  axes, respectively. The following examples should make this procedure clear.

Figure 7.9a identifies the front face of the crystal with the Miller indices (100). This notation is arrived at as follows: The front face intercepts the  $x$  axis at one  $a$  distance, and it does not intercept the  $y$  and  $z$  axes (or it intercepts at zero  $b$  and zero  $c$  units). If the side lengths are dropped, the intercepts are 1, 0, and 0. The reciprocals of these are also 1, 0, and 0. Since these are already the smallest integers, the Miller indices are specified by enclosing them in parentheses: (100). The commas are not included because they are simply part of the sentence structure.

Figure 7.9b shows the (110) plane that is parallel to the  $z$  axis and is a face diagonal on the top and bottom faces of the unit cell. This plane intercepts the  $x$  axis at one  $a$  distance, the  $y$  axis at one  $b$  distance, and the  $z$  axis at zero  $c$  distance. The intercepts are 1, 1, and 0, and so are the reciprocals. Since these are the smallest integers, the Miller indices are specified as (110).

Figure 7.9d shows the crystallographic plane that intercepts the  $x$  axis at  $\frac{1}{2}a$ , the  $y$  axis at one  $b$ , and the  $z$  axis at one  $c$ . The reciprocals are therefore 2, 1, and 1, and so this plane is identified as the (211) plane.

Parentheses are used, as in the preceding examples, to specify a single plane or a family of parallel planes. Thus (100) represents all the planes that are parallel to the  $yz$  axes and intercept the lattice structure at one  $a$ , two  $a$ , three  $a$ , etc. distances. Wavy brackets, or braces, are used to designate all planes in a crystal that are equivalent. For example, the six face planes of a unit cell such as that in Fig. 7.9a are (100), (010), (001), ( $\bar{1}00$ ), ( $0\bar{1}0$ ), and ( $00\bar{1}$ ). The notation {100} includes all these six planes.

## 7.4 CRYSTAL IMPERFECTIONS

The previous discussions on crystal structure assumed a perfect lattice; that is, an atom occupied each and every lattice point, and the distances between equivalent

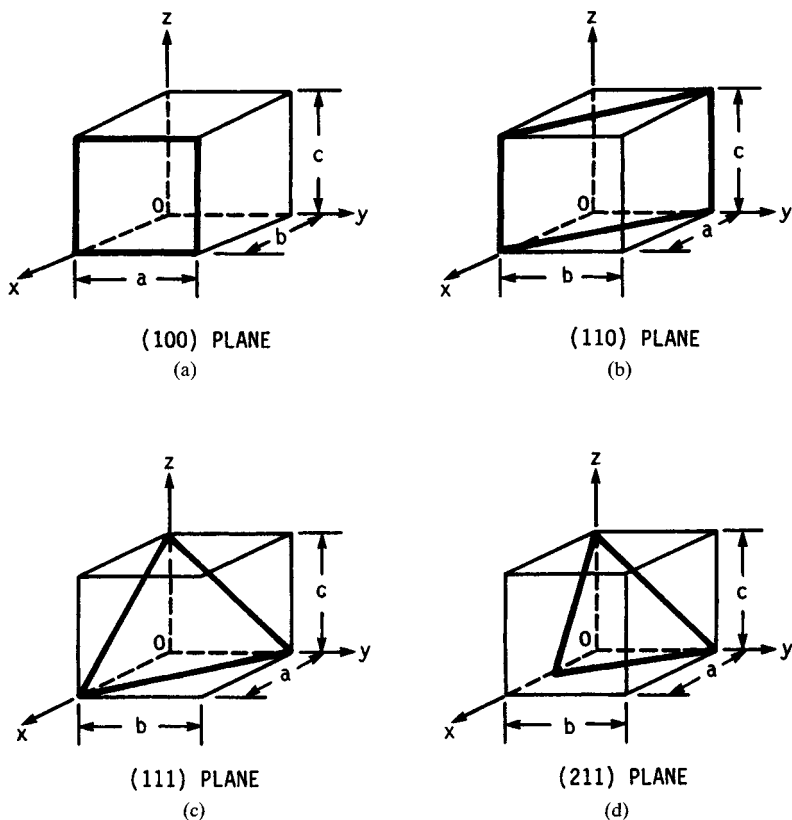


FIGURE 7.9 Miller indices for some crystallographic planes.

lattice points were all exactly the same. In the early 1900s it was found that real crystals did not have perfect properties. Notable among these properties was a mechanical strength much lower than crystals should have. As early as 1928 Prandtl suggested that slip (plastic deformation) in a crystal and the strength of a crystal are related to the presence of linear imperfections within the crystal. This type of imperfection is now called a *dislocation*. At the present time, the terms *imperfection* and *defect* refer to a deviation from a perfectly ordered lattice structure.

Lattice imperfections are classified into three types: *point defects*, where the imperfection is localized about a single lattice point and involves only a few atoms; *line defects*, where the imperfection lies along a line of finite length involving a row (line) or many atoms; and *planar defects* or *boundaries*, where the imperfections involve entire planes or atoms such as the interface between adjacent crystals.

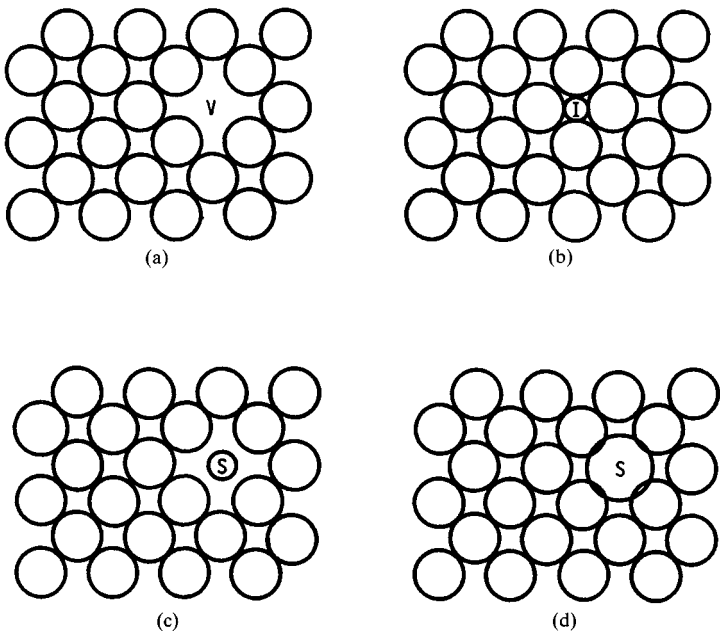
#### 7.4.1 Point Defects

Point defects are caused by (1) the absence of an atom from a lattice point, (2) the presence of an extra atom (usually a small foreign one) in the "void" spaces of the lat-

tice, (3) the presence of a foreign atom at one of the lattice sites, or (4) atoms that are displaced from their normal positions in the array. Figure 7.10 illustrates these defects.

The first type of point defect, the absence of an atom from a lattice point, is called a *vacancy*. Figure 7.10a shows a vacancy on the (100) planes of an FCC lattice. The sketch was not made to be a true representation in order to make the defect more apparent. In reality, the atoms that are near neighbors to the vacant site would be displaced from their normal positions in the array toward centers closer to the vacancy. Thus the lattice lines joining the centers of the atoms are not straight in the vicinity of the vacancy. In three dimensions this means that the crystallographic planes are warped inward near a vacancy. Individual vacancies can cluster together to form larger voids. Vacancies have no effect on the metallurgical control of the mechanical properties discussed in later sections. However, they do affect properties such as conductivity and diffusivity.

The second type of point defect, the presence of an extra atom at the interstices of the lattice, is known as an *interstitial defect*. This type of defect in the lattice structure is the basis for the strengthening mechanism known as *interstitial alloying*, where the solute atom fits in the interstices of the solvent lattice, and it accounts for the high strength in fully hardened (heat-treated) steel. Commercially pure iron (ferrite with a BCC structure) has a yield strength of 70 to 140 MPa. However, with 0.8 percent carbon dissolved interstitially in the iron and stress relieved after heat treating, it has a yield strength of 2400 to 2800 MPa. No other metal has such high room-temperature strength, and no other strengthening mechanism has a greater effect than the interstitial alloying of carbon in iron. The details of these strengthening mechanisms are discussed later.



**FIGURE 7.10** Some common point defects. (a) Vacancy; (b) interstitial atom I; (c) substitution of a smaller atom S; (d) substitution of a larger atom S.

Figure 7.10*b* shows an interstitial atom I in the solvent matrix. However, it does not lie in the plane of the solvent lattice but lies either above or below the sketched plane. Also, the foreign atom is always larger than the “void” space it occupies, and so it necessarily forces the surrounding solvent atoms out of their normal array. Therefore, the crystallographic planes are warped outward in the vicinity of an interstitial defect.

The third type of point defect, the presence of a foreign atom at one of the lattice points, is referred to as a *substitutional defect*. When an alloy is made by adding solute atoms that replace (substitute for) solvent atoms in the lattice structure, it is called a *substitutional alloy*. This type is the most common one in the metal system. Figure 7.10*c* and *d* shows the substitution of a smaller and a larger atom S at one of the lattice points. Unlike the interstitial atom, the substitutional one is in the plane of the solvent matrix. The crystallographic planes are also warped in the vicinity of the substitutional defect, inward for the smaller atom and outward for the larger atom. The distortion of the crystallographic planes is very important to an understanding of control of the strength of materials, which is presented later.

The fourth type of point defect, atoms that are displaced from their normal position, occurs in several forms. The atoms in the “contacting” planes of two adjoining crystals are not in their normal positions as a result of the crystals having solidified from the liquid without being in perfect registry with each other. This is considered to be a *grain boundary defect*, which has a significant effect on the strength of all polycrystalline materials.

Two additional types of atom displacement defects occur in ionic crystals that are not present in metallic-bonded crystals. A vacancy in an ionic crystal that is associated with a displaced pair, one cation and one anion, is called a *Schottky defect*. A *Frenkel defect* occurs when a small cation moves from a lattice point, leaving a vacancy, and occupies an interstitial site.

## 7.4.2 Line Defects or Dislocations

Examinations of crystals under the electron microscope have shown interruptions in the periodicity of the lattice structure in certain directions. In a two-dimensional representation these interruptions appear as lines; hence the name *line defects*. It is believed that a perfect crystal of a metal such as pure iron should have a strength of 1 or 2 million pounds force per square inch, whereas in reality such perfect crystals have a yield strength of only a few thousand. The reason given for the three orders of magnitude difference between the postulated and actual strength of metal crystals is the presence of these line defects.

The two most common line defects are edge dislocation and screw dislocation. An *edge dislocation* is the line defect that results from the presence of an extra plane of atoms in one portion of a crystal compared to the adjacent part. Actually, it is the edge of this extra plane of atoms and runs from one end of the crystal to the other. When looking at the crystalline plane that is perpendicular to the dislocation line, the imperfection appears as an extra row of atoms in a part of the crystal.

An edge dislocation is customarily represented by a symbol in which the vertical leg designates the extra plane of atoms. When the vertical leg is above the horizontal leg, the dislocation is considered positive. When the extra plane of atoms is in the bottom portion of the crystal, the vertical leg is placed below the horizontal one and the dislocation is said to be negative. The part of the crystal containing the extra plane of atoms is in compression, whereas that portion on the other side of the dislocation line is in tension. Since one dislocation line runs completely across a crystal, it deforms the lattice structure to a greater extent than does one point defect.

A *screw dislocation* is a crystal defect in which the lattice points lie on a spiral or helical surface that revolves around a center line that is called the *dislocation line*. A screw dislocation terminates at a crystal surface. Shear stresses are set up in the lattice surrounding a screw dislocation as a result of the distortion in atomic array that the defect causes.

The *Burgers vector* is the distance, measured in multiples of the lattice parameter, that is needed to close a straight-sided loop around a dislocation when going the same number of lattice distances in all four directions. It is the term used to define the size of a dislocation and is designated by the letter *b*. A characteristic of an edge dislocation is that it lies perpendicular to its Burgers vector, whereas a screw dislocation lies parallel to its Burgers vector.

### 7.4.3 Planar Defects

There are several types of planar (or surface) defects that occur from a change in the orientation of crystallographic planes across a surface boundary. The most important planar defect is the *grain boundary*, which is the imperfect plane surface that separates two crystals of different orientation in a polycrystalline solid. Grain boundaries originate when the last few remaining atoms of a liquid freeze onto the meeting faces of two adjacent crystals that have grown from the melt or, similarly, when two adjacent crystals that grow by recrystallization meet each other.

The material in the grain boundary is at a higher energy level than the material near the center of the grain because of the increased elastic strain energy of the atoms that are forced from their normal (lowest-energy) sites in a perfect lattice. This higher energy level and lattice distortion cause the grain boundary material to be stronger, have a higher diffusion rate, and serve as a more favorable site for the nucleation of second phases than the interior materials.

Another important planar defect is the *twin boundary*, which is the plane that separates two portions of a single crystal having slightly different orientations. The two twins are mirror images of each other. The distortion of the twinned lattice is low in comparison to that at a grain boundary. Twins which form in most FCC metal crystals, especially the copper- and nickel-base alloys, during freezing from the melt or recrystallization are called *annealing twins*. Twins which form in some metals during cold work (plastic deformation) are called *mechanical twins*.

A third planar defect is the *low-angle grain boundary* or *low-angle tilt boundary*, where the angular misalignment of the two grains is very small, on the order of a few degrees. In a sense it is a very undistorted grain boundary. The angular mismatch of the crystal planes is due to a row of dislocations piled above each other.

A *stacking fault* is a planar defect that occurs when one crystalline plane is stacked out of its normal sequence in the lattice array. The lattice on both sides of the defect is normal. For example, the normal FCC stacking of planes may be interrupted by one layer of a hexagonal close-packed (HCP) plane, since both are close-packed structures with atomic packing factors of 0.74. Such stacking faults can occur during the formation of a crystal or by plastic deformation.

## 7.5 SLIP IN CRYSTALLINE SOLIDS

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*Slip* can be defined as the massive sliding movement of one large body of atoms with respect to the remaining body of atoms of the crystal along crystallographic planes. Slip can also be considered as an avalanche of dislocations along one plane that pile

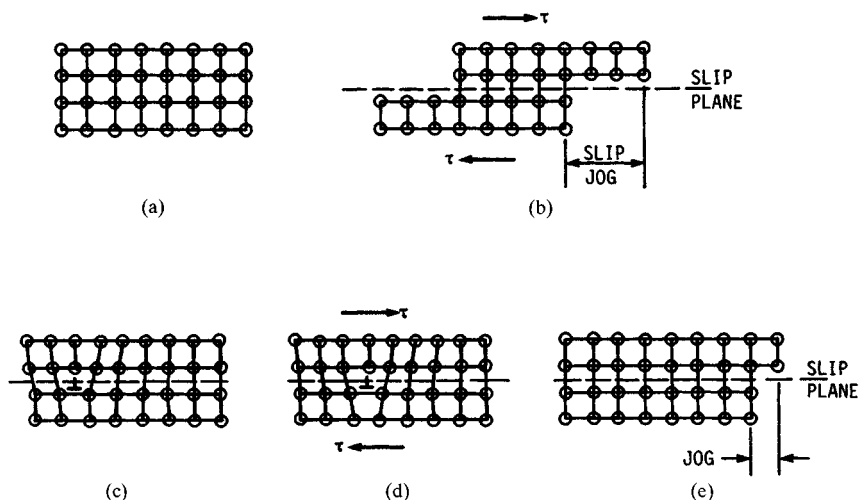
up at grain boundaries or inclusions. The planes along which slip occurs are called *slip planes*. Slip occurs only with relatively high stresses, greater than the yield strength, and it causes plastic deformation.

When a crystalline solid or a single crystal is subjected to low loads, the atoms move slightly from their normal lattice sites and return to their proper positions when the load is removed. The displacements of the individual atoms are very small during elastic deformation. They are submicroscopic, a fraction of an atomic distance. Although there are some dislocation movements, they are few in number, involve very short distances, and are reversible.

Slip, however, is microscopic in size and causes plastic (permanent) deformation that is macroscopic. Figure 7.11 contains several two-dimensional lattice arrays which, in a simplified manner, illustrate the mechanism by means of which slip takes place. A typical perfect cubic lattice is shown in Fig. 7.11a, which is a small part of a single crystal. If sufficiently large shear stresses  $\tau$  are placed on the crystal, all the atoms above the labeled slip plane move to the right simultaneously with respect to the atoms below the slip plane, as shown in Fig. 7.11b. The lattice is still a perfect cubic structure; only the outline or exterior shape of the single crystal has changed. It is believed, on the basis of the theories of elasticity, that the shear stress must be equal to the value of  $G/2\pi$ , where  $G$  is the shear modulus of elasticity. Young's modulus of elasticity  $E$ , Poisson's ratio  $\nu$ , and  $G$  are related to one another by the equation

$$G = \frac{E}{2(1 + \nu)} \quad (7.1)$$

For iron,  $E = 30$  Mpsi and  $\nu = 0.30$ , and so  $G = 11.5$  Mpsi. Therefore, the so-called theoretical shear strength for slip to occur in iron is



**FIGURE 7.11** Two-dimensional sketch of the slip mechanism. (a) A perfect crystal; (b) idealized slip in a perfect crystal; (c) part of a crystal with one edge dislocation; (d) movement of dislocation subject to shear stress; (e) jog produced in the crystal face by dislocation motion.



$$\tau = \frac{G}{2\pi} = \frac{11.5}{2\pi} = 1.83 \text{ Mpsi}$$

However, slip occurs in iron crystals with shear stresses of only 4 to 5 kpsi, which is more than two orders of magnitude smaller. The “theoretical” shear strength of the other pure metals is also 400 to 500 times larger than the actual shear strength. The commonly accepted explanation of why the actual shear stress is so much lower than the theoretical value is that slip does not occur by the simultaneous movement of all the atoms along the slip plane; rather, it occurs by the movement of individual rows (the dislocation row or plane) of atoms. Thus it is the movement of dislocations along the slip plane to the grain boundary that causes the actual shear stress for plastic deformation to be so low. Figure 7.11c, d, and e illustrates the movement of a dislocation that results in slip.

In real crystals of metals, slip terminates at the grain boundaries or the free-surface faces and causes substantial jogs or steps, much larger than shown in Fig. 7.11. Experimental study of the spacings of the slip planes and the sizes of the jog have been made on some of the common metals. The spacing of the parallel planes along which slip occurs varies randomly, with an average distance between slip planes of about 2000 atom diameters. The length of the step or jog at the surface of the grain is approximately 200 to 700 atom diameters.

The atomic displacements associated with slip, unlike those of the initial movements of dislocations, are irreversible in that the slip jog remains when the shear stresses are removed. That is, slip causes a permanent change in shape, or *plastic deformation*, as it is called.

The evidence of slip is seen on metallurgically prepared samples as slip lines when examined under a microscope. The slip lines are the intersection of the crystallographic planes along which slip occurred with the etched surface of the specimen. Slip results in a narrow band on either side of the slip plane within which the lattice structure is severely distorted. These slip lines do not appear on the face of a specimen that is metallurgically polished after slip occurs; they appear only after etching with a suitable chemical reagent that dissolves the metal being studied. The slip lines become visible for the same reason that grain boundaries are visible after etching: The internal energy of the material within the distorted area is considerably higher than that of the material within the rest of the crystal. The metal in the higher energy level dissolves into the reagent much more rapidly than the rest of the crystal, leaving a narrow groove where the severely distorted band intersects the surface. Slip lines can also be seen on specimens that are polished prior to being plastically deformed and that have not been etched.

## 7.6 MECHANICAL STRENGTH

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Although the specific mechanical properties of real materials are discussed in detail in the material that follows, it is very appropriate at this time to relate the concepts of the strengthening mechanisms to the previously described crystalline structures. Mechanical properties can best be studied on the basis of three precepts which encompass all the strengthening mechanisms. These three principles are stated here because they involve the distortion of the lattice structure that has just been discussed.

### 7.6.1 Principles of Mechanical Strength

*Strength* can be defined as a material's ability to resist slip. Thus it follows that the first principle of mechanical strength is this: *A material is strengthened when slip is made more difficult to initiate.* Therefore, to make a material stronger, it must be given a treatment that retards the avalanche of dislocations or, in other words, "pegs" the slip planes.

The second principle of mechanical strength is this: *Slip is retarded by inducing mechanical strains, or distortions, in the lattice structure of the material.* These distortions were discussed previously as lattice imperfections or defects. Thus it is a paradox that the source of strength in real polycrystalline materials is "crystal imperfections" or "crystal defects."

The third principle of mechanical strength is this: *There are four methods to induce mechanical strains or lattice distortions in a material, namely, decreasing the grain size, low-temperature plastic deformation (cold work), single-phase alloying, and multiple-phase alloying.*

### 7.6.2 Grain Size

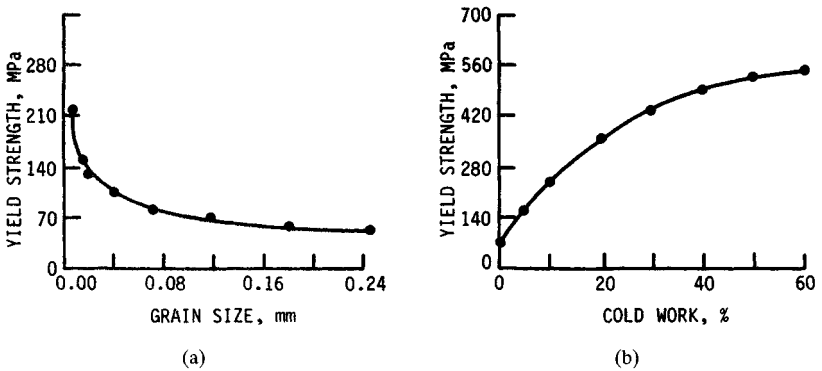
Local distortion of the lattice structure at the grain boundaries induces substantial strain energy in those regions. This distortion impedes slip, or causes the dislocations to pile up, and consequently, the grain-boundary material is stronger than the material at the central portions of the crystal. This is true for most metals at room temperature. However, as additional energy is added to a polycrystalline material by raising the temperature, the grain-boundary material softens (and also melts) sooner or at a lower temperature than the bulk of the grain. At some temperature, called the *equicohesive temperature*, the strengths at these two regions are equal. Above the equicohesive temperature, the grain-boundary material is the weaker of the two. This explains why materials that are used at elevated temperatures have higher creep strengths when their grains are coarse rather than fine.

The surface-area-to-volume ratio of a sphere is inversely proportional to its diameter. Therefore, as the diameter of a sphere decreases, its ratio of surface area to volume increases. This means that for a given weight or volume of a polycrystalline solid, the total grain-boundary surface increases as the grain size decreases. Since the grain-boundary material is stronger than the interior material, the strength also varies inversely with the grain size. Also, since the surface area of a sphere is proportional to the square of its diameter, it can be assumed as a first approximation that the yield strength is proportional to the reciprocal of the square of the grain diameter.

Figure 7.12a shows how the 0.2 percent offset yield strength of 70Cu-30Zn brass varies with grain size. In this case, the yield strength increases by a factor of 4 with a grain diameter ratio of 24. The strengths of some materials, such as aluminum or steel, are not so greatly affected by grain size alone.

### 7.6.3 Cold Work

Cold work is a more significant strengthening mechanism than decreasing the grain size for most metals. When a crystalline material is plastically deformed, there is an avalanche of dislocations (called *slip*) that terminates at the grain boundaries. It is a mass movement of a body of atoms along a crystallographic plane. This movement in a polycrystalline material distorts both the grain boundaries and the crystalline planes in the grain so that slip occurs in the adjacent grains as well. Actually, a por-



**FIGURE 7.12** Yield strength versus grain size (a) and percent cold work (b) for 70Cu-30Zn brass.

tion of one grain intrudes into the space that was previously occupied by another grain, with a resulting distortion of the lattice in both grains.

Figure 7.12b illustrates the effect of cold work on the yield strength of 70Cu-30Zn brass. With only 10 percent cold work, the yield strength is raised by a factor of 3.5, and 60 percent cold work increases the strength nearly 8 times. In general, 10 percent cold work more than doubles the yield strength of most metals.

#### 7.6.4 Single-Phase Alloying

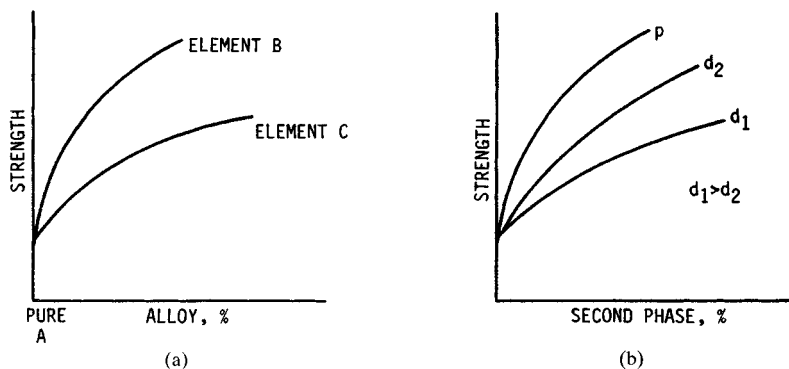
Alloying (single- and multiple-phase) is the most important of the methods available to control or manipulate the mechanical properties of materials. The greatest increase in strength known today occurs when iron having a yield strength of 10 to 20 kpsi (70 to 140 MPa) is alloyed with less than 1.0 percent carbon to form a single phase (martensite) that has a yield strength of nearly 435 kpsi (3000 MPa).

The lattice is distorted and dislocation movement is impeded when foreign (solute) atoms are added to the lattice structure of a pure material. Figure 7.10b through d illustrates this condition, which was discussed previously under the heading "Point Defects." Vacancy defects, as shown in Fig. 7.10a, are not a practical strengthening method. The reason single-phase alloying has such a great effect on strength is that the entire lattice network is distorted, and uniformly, whereas in the other mechanism, there are regions in each crystal that are severely distorted and other regions that are hardly distorted at all.

Figure 7.13a shows the effect on the strength of the material of adding a foreign element B or C to the lattice structure of element A. From this figure it is clear that not all elements have the same strengthening effect. In general, the further the ratio of diameters of solute to solvent atoms is from unity, the greater will be the strengthening effect. However, the further this ratio is from unity, as previously explained, the less soluble the two atoms are in each other's lattice.

#### 7.6.5 Multiple-Phase Alloying

This mechanism is sometimes referred to as *fine-particle strengthening*. In a sense, multiple-phase alloying is a combination of single-phase alloying and grain-boundary



**FIGURE 7.13** The effect of alloying on strength. (a) Single-phase alloying; atomic diameter ratio  $B/A > C/A$ ; (b) multiple-phase alloying;  $p$  is a nonspherical-shaped particle;  $d$  is the spherical particle diameter.

strengthening. That is, some of the added element goes into solution in the solvent lattice and thus has a strengthening effect; the remainder of the added element forms a second phase (either another solid solution or a compound) that is present as small grains or crystals.

Multiple-phase alloys can be made in three different ways. One method is by *annealing*. In this case, the alloy is heated to a one-phase region where the second element is completely soluble in the first. On slow cooling, the second phase precipitates as a massive network in the grain-boundary regions of the solvent matrix. This is the least beneficial form of alloying. The second method is similar except that the alloy is rapidly cooled from the high one-phase region so that a supersaturated solid phase occurs at room temperature. This material is then reheated to a relatively low temperature so that the second phase precipitates throughout the entire crystal as extremely fine particles rather than concentrating at the grain boundaries. This is the common *precipitation-hardening procedure*. The third method is to add a compound, in the form of small particles, that is insoluble in the parent material. Thus the two phases must be mixed in powder form and then sintered. This method is called *dispersion hardening*. At the present time there are only about a half dozen dispersion-hardenable alloys in commercial use. The most notable ones are  $\text{Al}_2\text{O}_3$  particles in aluminum (called SAP, for sintered aluminum power) and  $\text{ThO}$  in nickel.

## 7.7 MECHANICAL PROPERTIES AND TESTS

Most mechanical properties are structure-sensitive; that is, they are affected by changes in either the lattice structure or the microstructure. However, modulus of elasticity is one property that is structure-insensitive. For example, ductility and toughness of any material (regardless of whether it is a pure element such as copper, a simple alloy such as AISI 1080 steel, or a complex alloy such as a cobalt-base superalloy) vary with grain size, amount of cold work if any, or the microstructure if heat-treated. The modulus of elasticity of any material is the same regardless of grain size, amount of cold work, or microstructure.

Mechanical properties are discussed individually in the sections that follow. Several new quantitative relationships for the properties are presented here which make it possible to understand the mechanical properties to a depth that is not possible by means of the conventional tabular listings, where the properties of each material are listed separately.

## 7.8 HARDNESS

Hardness is used more frequently than any other of the mechanical properties by the design engineer to specify the final condition of a structural part. This is due in part to the fact that hardness tests are the least expensive in time and money to conduct. The test can be performed on a finished part without the need to machine a special test specimen. In other words, a hardness test may be a nondestructive test in that it can be performed on the actual part without affecting its service function.

Hardness is frequently defined as a measure of the ability of a material to resist plastic deformation or penetration by an indenter having a spherical or conical end. At the present time, hardness is more a technological property of a material than it is a scientific or engineering property. In a sense, hardness tests are practical shop tests rather than basic scientific tests. All the hardness scales in use today give relative values rather than absolute ones. Even though some hardness scales, such as the Brinell, have units of stress ( $\text{kg/mm}^2$ ) associated with them, they are not absolute scales because a given piece of material (such as a 2-in cube of brass) will have significantly different Brinell hardness numbers depending on whether a 500-kg or a 3000-kg load is applied to the indenter.

### 7.8.1 Rockwell Hardness

The *Rockwell hardnesses* are hardness numbers obtained by an indentation type of test based on the depth of the indentation due to an increment of load. The Rockwell scales are by far the most frequently used hardness scales in industry even though they are completely relative. The reasons for their large acceptance are the simplicity of the testing apparatus, the short time necessary to obtain a reading, and the ease with which reproducible readings can be obtained, the last of these being due in part to the fact that the testing machine has a "direct-reading" dial; that is, a needle points directly to the actual hardness value without the need for referring to a conversion table or chart, as is true with the Brinell, Vickers, or Knoop hardnesses. Table 7.2 lists the most common Rockwell hardness scales.

**TABLE 7.2** Rockwell Hardness Scales

	Scale								
	A	B	C	D	E	F	G	H	K
Indenter Load, kg	1 60	2 100	1 150	1 100	3 100	2 60	2 150	3 60	3 150