

The Structure of Metals

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EXAMPLE:

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- This chapter introduces the subject of the crystalline structure of metals and explains why it is important in determining their properties and behavior.
- It begins with a review of the types of atomic bonds and explains the importance of ionic, covalent, and metallic bonds.
- Metal structures and the arrangement of atoms within the structure are then examined, and the types of imperfections in the crystal structure and their effects are presented.
- Recognizing that even a small metal pin contains thousands of crystals, or grains, the effects of grains and grain boundaries are examined, followed by a discussion of strain hardening and anisotropy of metals.
- All of these topics are examined within the framework of their relevance to manufacturing processes.

1.1 Introduction

Why are some metals hard and others soft? Why are some metals brittle, while others are ductile and thus can be shaped easily without fracture? Why is it that some metals can withstand high temperatures, while others cannot? Why is it that a sheet metal may behave differently when stretched in one direction versus another?

These and numerous other questions can be answered by studying the atomic structure of metals—that is, the arrangement of the atoms within the metals—because atomic structure greatly influences the properties and behavior of those metals. This knowledge then guides us in controlling and predicting the behavior and performance of metals in various manufacturing processes. Understanding the structure of metals also allows us to predict and evaluate their properties, thus allowing us to make appropriate selections for specific applications under various conditions. In addition to atomic structure, several other factors influence the properties and behavior of metals. Among these are the composition of the metal, impurities and vacancies in the atomic structure, grain size, grain boundaries, environment, size and surface condition of the metal, and the methods by which metals are made into products.

The topics described in this chapter and their sequence are outlined in Fig. 1.1. The structure and general properties of materials other than metals are described in

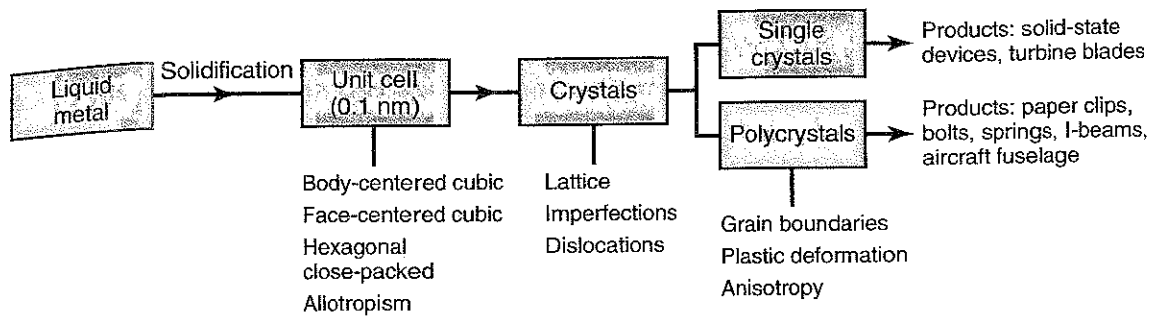


FIGURE 1.1 An outline of the topics described in Chapter 1.

Chapter 7 (on polymers), Chapter 8 (ceramics and glasses), and Chapter 9 (composite materials). The structure of metal alloys, the control of their structure, and heat-treatment processes are described in Chapter 4.

1.2 Types of Atomic Bonds

All matter is made up of atoms containing a nucleus of *protons* and *neutrons* and surrounding clouds, or orbits, of *electrons*. In recent decades, a large number of sub-atomic particles have been identified, with additional complexities in the nucleus. For the purposes of this textbook, however, the planetary model of a nucleus orbited by electrons is sufficient.

The number of protons in the nucleus determines whether an atom will be metallic, nonmetallic, or semimetallic. An atom with a balanced charge has the same number of electrons as protons; when there are too many or too few electrons, the atom is called an **ion**. An excess of electrons results in a negatively charged atom, referred to as an **anion**, while too few electrons results in a positively charged atom, called a **cation**. The number of electrons in the outermost orbit of an atom determines the chemical affinity of that atom for other atoms.

Atoms can transfer or share electrons; in doing so, multiple atoms combine to form **molecules**. Molecules are held together by attractive forces called **bonds** through electron interaction. The basic types of atomic attraction associated with electron transfer, called **primary** or **strong bonds**, are as follows:

- **Ionic bonds.** When one or more electrons from an outer orbit are transferred from one material to another, a strong attractive force develops between the two ions. An example is that of sodium (Na) and chlorine (Cl) in common table salt; such salt consists of Na^+ and Cl^- ions (hence the term *ionic bond*), which are strongly attracted to each other. Also, the attraction is between all adjacent ions, allowing crystalline structures to be formed, as discussed in Section 1.3. Molecules with ionic bonds generally have poor ductility and low thermal and electrical conductivity.
- **Covalent bonds.** In a covalent bond, the electrons in outer orbits are shared by atoms to form molecules. The number of electrons shared is reflected by terms such as “single bond,” “double bond,” etc. Polymers consist of large molecules that are covalently bonded together; water (H_2O) and nitrogen gas (N_2) are additional common examples of molecules formed from covalent bonds. Solids formed

by covalent bonding typically have low electrical conductivity and can have high hardness. (Diamond, a form of covalently bonded carbon, is an example.)

- **Metallic bonds.** Metals have relatively few electrons in their outer orbits; thus, they cannot complete the outer shell of other self-mated atoms. Instead, metals and alloys form *metallic bonds*, whereby the available electrons are shared by all atoms in contact. The resultant electron cloud provides attractive forces to hold the atoms together and results in generally high thermal and electrical conductivity.

In addition to the strong attractive forces associated with electrons, weak or secondary attractions occur between molecules. Also referred to as *van der Waals forces*, these forces arise from the attraction of opposite charges without electron transfer. As an example, water molecules consist of one oxygen and two smaller hydrogen atoms, located around 104° from each other. Although each molecule has a balanced, or neutral, charge, there are more hydrogen atoms on one side of the molecule (i.e., it is a *dipole*), so that the molecule develops a weak attraction to nearby oxygen atoms on that side.

1.3 The Crystal Structure of Metals

When metals solidify from a molten state, the atoms arrange themselves into various orderly configurations, called *crystals*; this atomic arrangement is called *crystal structure* or *crystalline structure*. The smallest group of atoms showing the characteristic *lattice structure* of a particular metal is known as a *unit cell*. It is the building block of a crystal, and a single crystal can have many unit cells.

The following are the three basic atomic arrangements in metals:

1. **Body-centered cubic (bcc);** examples: alpha iron, chromium, molybdenum, tantalum, tungsten, and vanadium.
2. **Face-centered cubic (fcc);** examples: gamma iron, aluminum, copper, nickel, lead, silver, gold, and platinum.
3. **Hexagonal close-packed (hcp);** examples: beryllium, cadmium, cobalt, magnesium, alpha titanium, zinc, and zirconium.

These structures are represented by the illustrations given in Figs. 1.2 through 1.4; each sphere represents an atom. The distance between the atoms in these crystal structures is on the order of 0.1 nm. The models shown in the figure are known as *hard-ball* or *hard-sphere* models; they can be likened to tennis balls arranged in various configurations in a box.

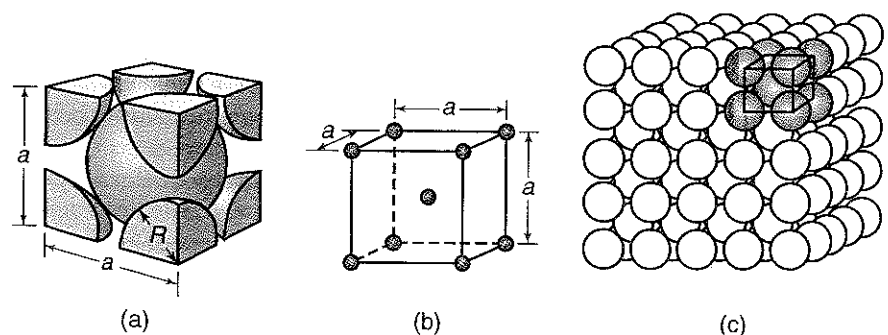


FIGURE 1.2 The body-centered cubic (bcc) crystal structure: (a) hard-ball model; (b) unit cell; and (c) single crystal with many unit cells.

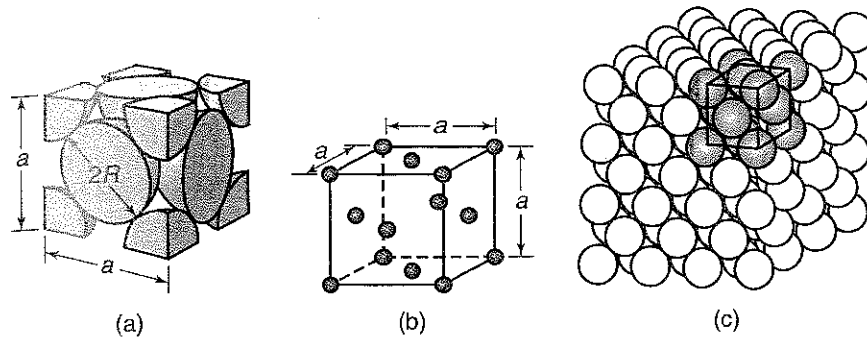


FIGURE 1.3 The face-centered cubic (fcc) crystal structure: (a) hard-ball model; (b) unit cell; and (c) single crystal with many unit cells.

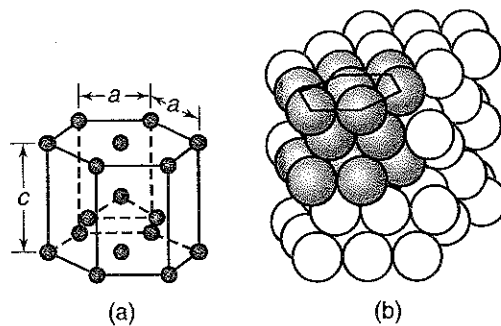


FIGURE 1.4 The hexagonal close-packed (hcp) crystal structure: (a) unit cell; and (b) single crystal with many unit cells.

In the three structures illustrated, the hcp crystals have the most densely packed configurations, followed by fcc and then bcc. In the hcp structure, the top and bottom planes are called **basal planes**. All three arrangements can be modified by adding atoms of some other metal or metals, known as **alloying**, often to improve various properties of the metal. Crystal structure plays a major role in determining the properties of a particular metal.

The reason that metals form different crystal structures is to *minimize* the energy required to fill space. Tungsten, for example, forms a bcc structure because that structure involves less energy than other structures do; likewise, aluminum forms an fcc structure. At different temperatures, however, the same metal may form different structures, because of a lower energy requirement. For example, as described in Chapter 4, iron forms a bcc structure (alpha iron) below 912°C and above 1394°C, but it forms an fcc structure (gamma iron) between 912°C and 1394°C.

The appearance of more than one type of crystal structure is known as **allotropism** or **polymorphism** (meaning “many shapes”). Because the properties and behavior of a metal depend greatly on its crystal structure, allotropism is an important factor in heat treatment of metals, as well as in metalworking and welding operations, described in Parts III and V, respectively. Single crystals of metals are now produced as ingots in sizes on the order of 1 m long and up to 300 mm in diameter, with applications such as turbine blades and semiconductors (see Sections 11.15 and 34.3). However, most metals used in manufacturing are polycrystalline, as described in Section 1.5.

1.4 Deformation and Strength of Single Crystals

When a single crystal is subjected to an external force, it first undergoes **elastic deformation**; that is, it returns to its original shape when the force is removed. A simple analogy to this type of behavior is a helical spring that stretches when loaded and returns to its original shape when the load is removed. If the force on the crystal structure is increased sufficiently, the crystal undergoes **plastic deformation** or **permanent deformation**; that is, it does *not* return to its original shape when the force is removed.

There are two basic mechanisms by which plastic deformation takes place in crystal structures. One is the slipping of one plane of atoms over an adjacent plane (called the **slip plane**) under a **shear stress** (Fig. 1.5a). Note that this behavior is much like the sliding of playing cards against each other. *Shear stress* is defined as the ratio of the applied shearing force to the cross-sectional area being sheared.

Just as it takes a certain magnitude of force to slide playing cards against each other, a single crystal requires a certain amount of shear stress (called **critical shear stress**) to undergo permanent deformation. Thus, there must be a shear stress of sufficient magnitude within a crystal for plastic deformation to occur; otherwise the deformation remains elastic.

The shear stress required to cause slip in single crystals is directly proportional to the ratio b/a in Fig. 1.5a, where a is the spacing of the atomic planes and b is inversely proportional to the atomic density in the atomic plane. As b/a decreases, the shear stress required to cause slip decreases. Thus, slip in a single crystal takes place along planes of *maximum atomic density*; in other words, slip takes place in closely packed planes and in closely packed directions.

Because the b/a ratio varies for different directions within the crystal, a single crystal exhibits different properties when tested in different directions; this property is called **anisotropy**. A simple example of anisotropy is the behavior of woven cloth, which stretches differently when pulled in different directions. Another example is

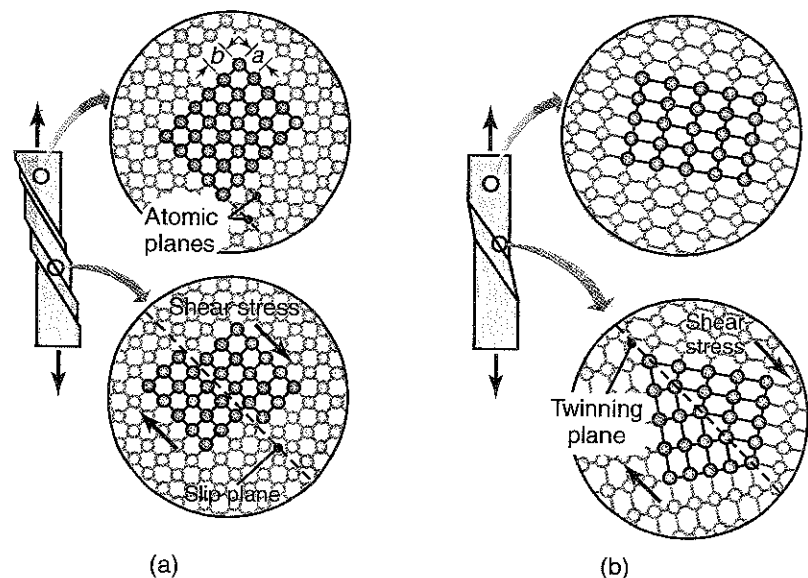


FIGURE 1.5 Permanent deformation of a single crystal under a tensile load. The highlighted grid of atoms emphasizes the motion that occurs within the lattice. (a) Deformation by slip. The b/a ratio influences the magnitude of the shear stress required to cause slip. (b) Deformation by twinning, involving the generation of a “twin” around a line of symmetry subjected to shear. Note that the tensile load results in a shear stress in the plane illustrated.

the behavior of plywood, which is much stronger in the planar direction than along its thickness direction. Note, for example, how plywood splits easily when a thick nail is driven through its thickness.

The second and less common mechanism of plastic deformation in crystals is **twinning**, in which a portion of the crystal forms a mirror image of itself across the *plane of twinning* (Fig. 1.5b). Twins form abruptly and are the cause of the creaking sound (“tin cry”) that occurs when a tin or zinc rod is bent at room temperature. Twinning usually occurs in hcp metals.

Slip Systems. The combination of a slip plane and its direction of slip is known as a *slip system*. In general, metals with 5 or more slip systems are ductile, whereas those with fewer than 5 slip systems are not.

1. In **body-centered cubic** crystals, there are 48 possible slip systems. Therefore, the probability is high that an externally applied shear stress will operate on one of these systems and cause slip. Because of the relatively high b/a ratio in this crystal, however, the required shear stress is high. Metals with bcc structures generally have good strength and moderate ductility, but can have high ductility at elevated temperatures.
2. In **face-centered cubic** crystals, there are 12 slip systems. The probability of slip is moderate, and the shear stress required is low because of the relatively low b/a ratio. These metals generally have moderate strength and good ductility.
3. The **hexagonal close-packed** crystal has 3 slip systems and therefore has a low probability of slip; however, more slip systems become active at elevated temperatures. Metals with hcp structures are generally brittle at room temperature.

Note in Fig. 1.5a that the portions of the single crystal that have slipped have rotated from their original angular position toward the direction of the tensile force; note also that slip has taken place only along certain planes. It can be seen from electron microscopy that what appears to be a single slip plane is actually a **slip band** consisting of a number of slip planes (Fig. 1.6).

1.4.1 Imperfections in the Crystal Structure of Metals

The actual strength of metals is found to be approximately one to two orders of magnitude lower than the strength levels obtained from theoretical calculations based on molecular dynamics. This discrepancy is explained in terms of **defects and imperfections** in the crystal structure. Unlike in idealized models, actual metal crystals contain a large number of defects and imperfections, which generally are categorized as follows:

1. *Point defects*, such as a **vacancy** (missing atom), an **interstitial atom** (extra atom in the lattice), or an **impurity** (foreign atom that has replaced the atom of the pure metal) (Fig. 1.7);
2. *Linear, or one-dimensional, defects*, called **dislocations** (Fig. 1.8);
3. *Planar, or two-dimensional, imperfections*, such as **grain boundaries** and **phase boundaries** (see Section 1.5);

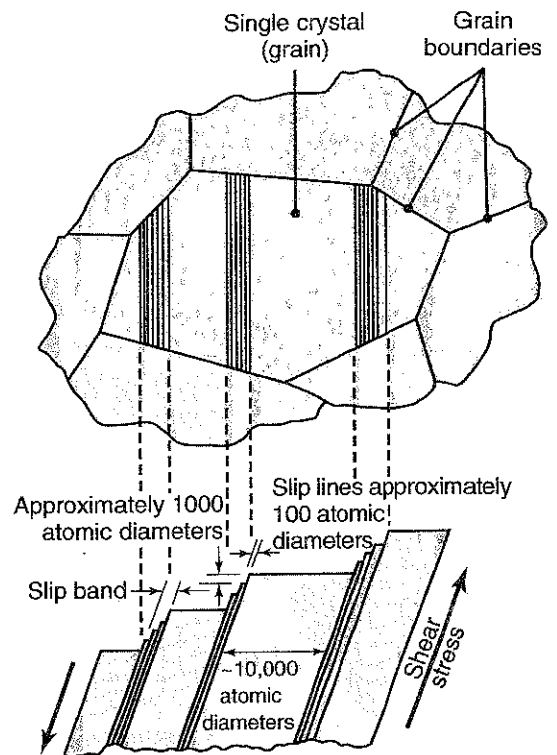


FIGURE 1.6 Schematic illustration of slip lines and slip bands in a single crystal (grain) subjected to a shear stress. A slip band consists of a number of slip planes. The crystal at the center of the upper illustration is an individual grain surrounded by several other grains.

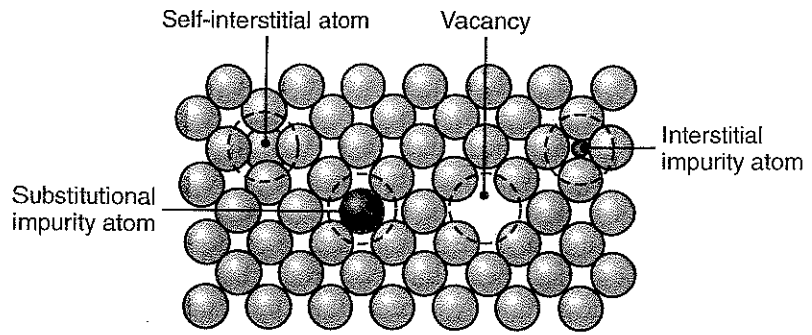


FIGURE 1.7 Schematic illustration of types of defects in a single-crystal lattice: self-interstitial, vacancy, interstitial, and substitutional.

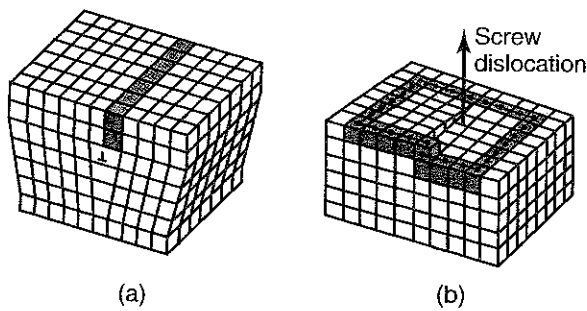


FIGURE 1.8 Types of dislocations in a single crystal: (a) edge dislocation; and (b) screw dislocation.

4. *Volume, or bulk, imperfections*, such as voids, inclusions (nonmetallic elements such as oxides, sulfides, and silicates), other phases, or cracks.

Mechanical and electrical properties of metals, such as yield stress, fracture strength, and electrical conductivity, are adversely affected by defects; these properties are known as **structure sensitive**. By contrast, physical and chemical properties, such as melting point, specific heat, coefficient of thermal expansion, and elastic constants (e.g., modulus of elasticity and modulus of rigidity), are not sensitive to these defects; these properties are known as **structure insensitive**.

Dislocations. First observed in the 1930s, *dislocations* are defects in the orderly arrangement of a metal's atomic structure. Because a slip plane containing a dislocation (Fig. 1.9) requires less shear stress to allow slip than does a plane in a perfect lattice, dislocations are the most significant defects that explain the discrepancy between the actual and theoretical strengths of metals.

There are two types of dislocations: edge and screw (Fig. 1.8). An analogy to the movement of an edge dislocation is the progress of an earthworm, which moves forward by means of a hump that starts at the tail and moves toward the head. Another analogy is the movement of a large carpet on the floor by first forming a hump at one end and moving the hump gradually to the other end. The force required to move a carpet in this way is much lower than that required to slide the whole carpet along the floor. Screw dislocations are so named because the atomic planes form a spiral ramp.

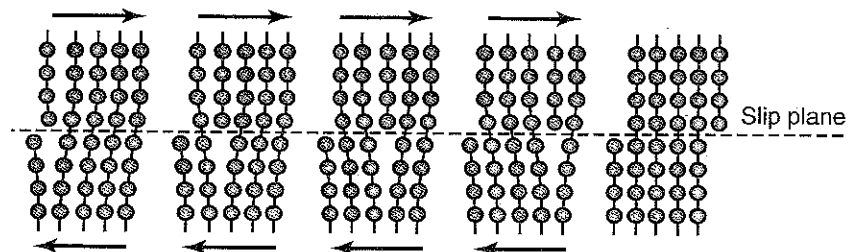


FIGURE 1.9 Movement of an edge dislocation across the crystal lattice under a shear stress. Dislocations help explain why the actual strength of metals is much lower than that predicted by theory.

1.4.2 Work Hardening (Strain Hardening)

Although the presence of a dislocation lowers the shear stress required to cause slip, dislocations can:

1. Become entangled and interfere with each other, and
2. Be impeded by barriers, such as grain boundaries, impurities, and inclusions in the material.

The increased shear stress required to overcome entanglements and impediments results in an increase in the overall strength and the hardness of the metal and is known as **work hardening** or **strain hardening**. The greater the deformation, the greater is the number of entanglements and hence the higher the increase in the metal's strength. Work hardening is used extensively for strengthening in metal-working processes at ambient temperatures. Typical examples are producing sheet metal for automobile bodies and aircraft fuselages by cold rolling (Chapter 13), producing the head of a bolt by forging (Chapter 14), and strengthening wire by reducing its cross section by drawing it through a die (Chapter 15).

1.5 Grains and Grain Boundaries

When a mass of molten metal begins to solidify, crystals begin to form independently of each other at various locations within the liquid mass; they have random and unrelated orientations (Fig. 1.10). Each of these crystals then grows into a crystalline structure, or *grain*. Each grain consists of either a single crystal (for pure metals) or a polycrystalline aggregate (for alloys).

The number and size of the grains developed in a unit volume of the metal depends on the *rate* at which nucleation (the initial stage of crystal formation) takes place. The *median size* of the grains developed depends on the number of different sites at which individual crystals begin to form (note that there are seven in Fig. 1.10a) and the rate at which these crystals grow. If the nucleation rate is high, the number of grains in a unit volume of metal will be large, and thus grain size will be small. Conversely, if the rate of growth of the crystals is high (compared with their nucleation rate), there will be fewer grains per unit volume, and thus grain size will be larger. Generally, rapid cooling produces smaller grains, whereas slow cooling produces larger grains.

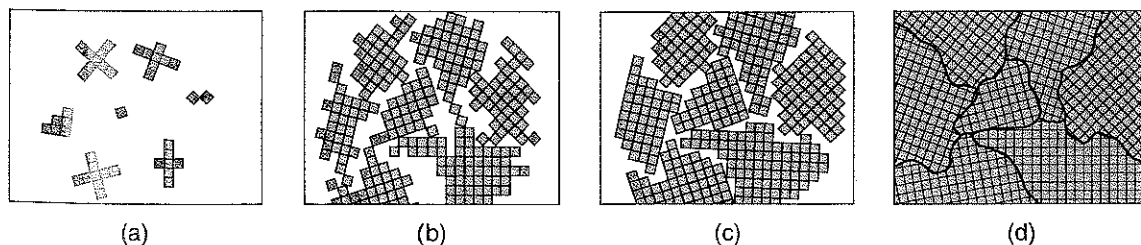


FIGURE 1.10 Schematic illustration of the stages during the solidification of molten metal; each small square represents a unit cell. (a) Nucleation of crystals at random sites in the molten metal; note that the crystallographic orientation of each site is different. (b) and (c) Growth of crystals as solidification continues. (d) Solidified metal, showing individual grains and grain boundaries; note the different angles at which neighboring grains meet each other.

Note in Fig. 1.10d that the growing grains eventually interfere with and impinge upon one another. The surfaces that separate these individual grains are called **grain boundaries**. Note also that the crystallographic orientation changes abruptly from one grain to the next across the grain boundaries. (Recall, from Section 1.4, that the behavior of a single crystal or a single grain is anisotropic.) Thus, because its many grains have random crystallographic orientations, the behavior of a piece of polycrystalline metal is essentially **isotropic**; that is, its properties do not vary with the direction of testing.

1.5.1 Grain Size

Grain size has a major influence on the mechanical properties of metals. At room temperature, for example, a large grain size is generally associated with low strength, low hardness, and low ductility. Grains can be so large as to be visible with the naked eye; zinc grains on the surface of galvanized sheet steels are an example. Large grains also cause a rough surface appearance after the material has been plastically deformed, particularly in the stretching of sheet metals (see **orange peel**, Section 1.7).

Grain size is usually measured by counting the number of grains in a given area, or by counting the number of grains that intersect a length of a line randomly drawn on an enlarged photograph of the grains (taken under a microscope on a polished and etched specimen). Grain size may also be determined by comparing such a photograph against a standard chart.

The ASTM (American Society for Testing and Materials) grain size number, n , is related to the number of grains, N , per square inch at a magnification of $100 \times$ (equal to 0.0645 mm^2 of actual area) by the formula

$$N = 2^{n-1}. \quad (1.1)$$

Because grains are typically extremely small, many grains can occupy a piece of metal (Table 1.1). Grain sizes between 5 and 8 are generally considered fine grained.

TABLE 1.1

Grain Sizes		
ASTM No.	Grains/mm ²	Grains/mm ³
-3	1	0.7
-2	2	2
-1	4	5.6
0	8	16
1	16	45
2	32	128
3	64	360
4	128	1,020
5	256	2,900
6	512	8,200
7	1,024	23,000
8	2,048	65,000
9	4,096	185,000
10	8,200	520,000
11	16,400	1,500,000
12	32,800	4,200,000

A grain size of 7 is generally acceptable for sheet metals for making car bodies, appliances, and kitchen utensils (Chapter 16).

EXAMPLE 1.1 Number of Grains in the Ball of a Ballpoint Pen

Assume that the ball of a ballpoint pen is 1 mm in diameter and has an ASTM grain size of 10. Calculate the number of grains in the ball.

Solution A metal with an ASTM grain size of 10 has 520,000 grains per mm^3 . (See Table 1.1.) The volume of the 1-mm-diameter ball is

$$V = \frac{4\pi r^3}{3} = \frac{4\pi(0.5 \text{ mm})^3}{3} = 0.5236 \text{ mm}^3.$$

The total number of grains is calculated by multiplying the volume by the grains per mm^3 , or

$$\begin{aligned} \text{No. grains} &= (0.5236 \text{ mm}^3) (520,000 \text{ grains/mm}^3) \\ &= 272,300 \end{aligned}$$

1.5.2 Influence of Grain Boundaries

Grain boundaries have an important influence on the strength and ductility of metals, and because they interfere with the movement of dislocations, grain boundaries also influence strain hardening. These effects depend on temperature, deformation rate, and the type and amount of impurities present *along* the grain boundaries.

Because the atoms along the grain boundaries are packed less efficiently and are more disordered, grain boundaries are more reactive than the grains themselves. As a result, the boundaries have lower energy than the atoms in the orderly lattice within the grains, and thus they can be more easily removed or chemically bonded to another atom. For example, a metal surface becomes rougher when etched or subjected to corrosive environments. (See also *end grains in forging*, in Section 14.5).

At elevated temperatures, and in metals whose properties depend on the rate at which they are deformed, plastic deformation also takes place by means of *grain-boundary sliding*. The creep mechanism (elongation under stress over time, usually at elevated temperatures) results from grain-boundary sliding (see Section 2.8).

Grain-boundary embrittlement. When exposed to certain low-melting-point metals, a normally ductile and strong metal can crack when subjected to very low external stresses. Examples of such behavior are (a) aluminum wetted with a mercury–zinc amalgam or liquid gallium, and (b) copper at elevated temperature wetted with lead or bismuth. These added elements weaken the grain boundaries of the metal by *embrittlement*. The term **liquid-metal embrittlement** is used to describe such phenomena, because the embrittling element is in a liquid state. However, embrittlement can also occur at temperatures well below the melting point of the embrittling element, a phenomenon known as **solid-metal embrittlement**.

Hot shortness is caused by local melting of a constituent or of an impurity in the grain boundary at a temperature below the melting point of the metal itself. When subjected to plastic deformation at elevated temperatures (*hot working*), a piece of metal crumbles along its grain boundaries; examples are antimony in copper, leaded steels (Section 21.7.1), and leaded brass. To avoid hot shortness, the metal is usually worked at a lower temperature in order to prevent softening and melting along the grain boundaries. Another form of embrittlement is **temper embrittlement** in alloy steels, which is caused by segregation (movement) of impurities to the grain boundaries (Section 4.11).

1.6 Plastic Deformation of Polycrystalline Metals

When a polycrystalline metal with uniform *equiaxed grains* (grains having equal dimensions in all directions) is subjected to plastic deformation at room temperature (a process known as *cold working*), the grains become deformed and elongated, as shown schematically in Fig. 1.11. Deformation may be carried out, for example, by compressing the metal piece, as is done in a forging operation to make a turbine disk (Chapter 14) or by subjecting it to tension, as is done in stretch forming of sheet metal to make an automobile body (Chapter 16). The deformation within each grain takes place by the mechanisms described in Section 1.4 for a single crystal.

During plastic deformation, the grain boundaries remain intact and mass continuity is maintained. The deformed metal exhibits higher strength, because of the entanglement of dislocations with grain boundaries and with each other. The increase in strength depends on the degree of deformation (*strain*) to which the metal is subjected; the higher the deformation, the stronger the metal becomes. The strength is higher for metals with smaller grains, because they have a larger grain-boundary surface area per unit volume of metal and hence more entanglement of dislocations.

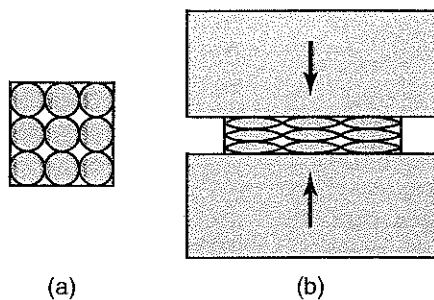


FIGURE 1.11 Plastic deformation of idealized (equiaxed) grains in a specimen subjected to compression (such as occurs in the forging or rolling of metals): (a) before deformation; and (b) after deformation. Note the alignment of grain boundaries along a horizontal direction; this effect is known as *preferred orientation*.

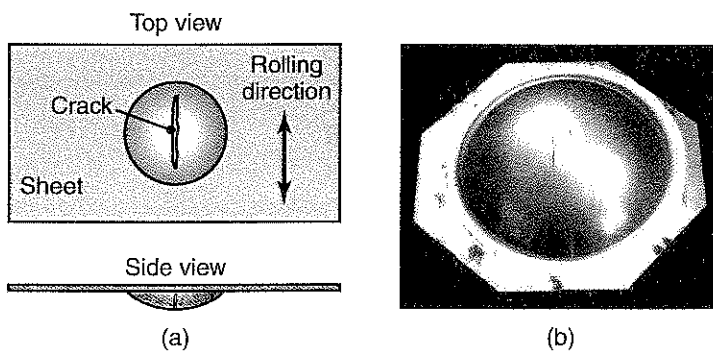


FIGURE 1.12 (a) Schematic illustration of a crack in sheet metal that has been subjected to bulging (caused, for example, by pushing a steel ball against the sheet). Note the orientation of the crack with respect to the rolling direction of the sheet; this sheet is anisotropic. (b) Aluminum sheet with a crack (vertical dark line at the center) developed in a bulge test; the rolling direction of the sheet was vertical. *Courtesy: J.S. Kallend, Illinois Institute of Technology.*

Anisotropy (Texture). Note in Fig. 1.11b that, as a result of plastic deformation, the grains have elongated in one direction and contracted in the other. Consequently, this piece of metal has become *anisotropic*, and thus its properties in the vertical direction are different from those in the horizontal direction. The degree of anisotropy depends on the temperature at which deformation takes place and on how uniformly the metal is deformed. Note from the direction of the crack in Fig. 1.12, for example, that the ductility of the cold-rolled sheet in the transverse direction is lower than that in its rolling direction. (See also Section 16.5.)

Anisotropy influences both mechanical and physical properties of metals, described in Chapter 3. For example, sheet steel for electrical transformers is rolled in such a way that the resulting deformation imparts anisotropic magnetic properties to the sheet. This operation reduces magnetic-hysteresis losses and thus improves the efficiency of transformers. (See also *amorphous alloys*, Section 6.14.) There are two general types of anisotropy in metals: *preferred orientation* and *mechanical fibering*.

Preferred Orientation. Also called *crystallographic anisotropy*, *preferred orientation* can be best described by referring to Fig. 1.5a. When a single-crystal piece of metal is subjected to tension, the sliding blocks rotate toward the direction of the tensile force; as a result, slip planes and slip bands tend to align themselves with the general direction of deformation. Similarly, for a polycrystalline metal, with grains in random orientations, all slip directions tend to align themselves with

the direction of the tensile force. By contrast, slip planes under compression tend to align themselves in a direction perpendicular to the direction of the compressive force.

Mechanical Fibering. This is a type of anisotropy that results from the alignment of inclusions (*stringers*), impurities, and voids in the metal during deformation. Note that if the spherical grains in Fig. 1.11a were coated with impurities, these impurities would align themselves in a generally horizontal direction after deformation. Because impurities weaken the grain boundaries, this piece of metal will now be weaker and less ductile when tested in the vertical direction. As an analogy, consider plywood, which is strong in tension along its planar direction, but peels off (splits) easily when pulled in tension in its thickness direction.

1.7 Recovery, Recrystallization, and Grain Growth

We have seen that plastic deformation at room temperature causes distortion of the grains and grain boundaries (leading to anisotropic behavior), a general increase in strength, and a decrease in ductility. These effects can be reversed, and the properties of the metal can be brought back to their original levels, by heating the metal to a specific temperature range for a given period of time—a process called **annealing** (described in detail in Section 4.11). Three events take place consecutively during the heating process:

1. **Recovery.** During *recovery*, which occurs at a certain temperature range below the **recrystallization temperature** of the metal (described next), the stresses in the highly deformed regions of the metal piece are relieved. Subgrain boundaries begin to form (a process called **polygonization**), with no significant change in mechanical properties such as hardness and strength (Fig. 1.13).
2. **Recrystallization.** This is the process in which, within a certain temperature range, new equiaxed and strain-free grains are formed, replacing the older grains. The temperature required for recrystallization ranges approximately between $0.3T_m$ and $0.5T_m$, where T_m is the melting point of the metal on the absolute scale.

Generally, the recrystallization temperature is defined as the temperature at which complete recrystallization occurs within approximately one hour. Recrystallization decreases the density of dislocations, lowers the strength, and raises the ductility of the metal (Fig. 1.13). Lead, tin, cadmium, and zinc recrystallize at about room temperature; consequently, they do not work harden when cold worked.

The recrystallization temperature depends on the degree of prior cold work (work hardening): The more the cold work, the lower the temperature required for recrystallization. The reason is that, as the amount of cold work increases, the number of dislocations and the amount of energy stored in dislocations (**stored energy**) also increase. This energy supplies some of the work required for recrystallization.

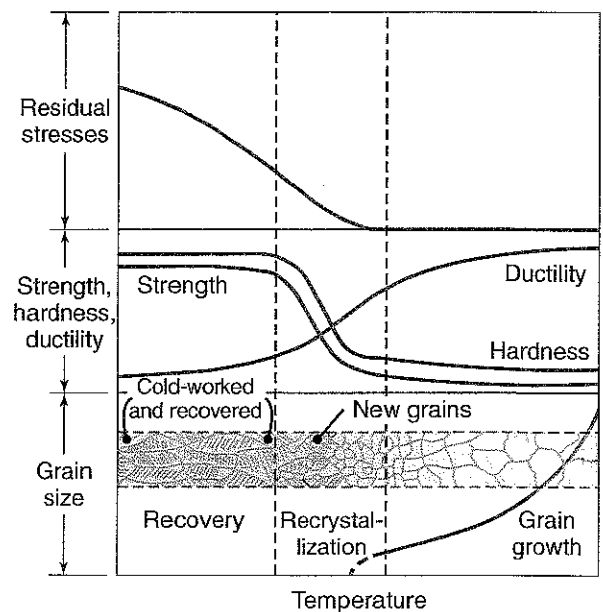


FIGURE 1.13 Schematic illustration of the effects of recovery, recrystallization, and grain growth on mechanical properties and on the shape and size of grains. Note the formation of small new grains during recrystallization. *Source:* After G. Sachs.

Recrystallization is also a function of time, because it involves **diffusion**—the movement and exchange of atoms across grain boundaries.

The effects on recrystallization of temperature, time, and plastic deformation by cold working are as follows:

- a. For a constant amount of deformation by cold working, the time required for recrystallization decreases with increasing temperature;
 - b. The more the prior cold work, the lower the temperature required for recrystallization;
 - c. The higher the amount of deformation, the smaller the grain size becomes during recrystallization; this effect is a commonly used method of converting a coarse-grained structure to one having a finer grain, and thus one with improved properties;
 - d. Some anisotropy due to preferred orientation usually persists after recrystallization; to restore isotropy, a temperature higher than that required for recrystallization may be necessary.
3. **Grain growth.** If the temperature of the metal is raised further, the grains begin to grow, and their size may eventually exceed the original grain size; called *grain growth*, this phenomenon adversely affects mechanical properties (Fig. 1.13). Large grains also produce a rough surface appearance on sheet metals, called **orange peel**, when they are stretched to form a part, or on the surfaces of a piece of metal when subjected to bulk deformation, such as compression in forging (Chapter 14).

1.8 Cold, Warm, and Hot Working

Cold working refers to plastic deformation that is usually, but not necessarily, carried out at room temperature. When deformation occurs above the recrystallization temperature, it is called **hot working**. “Cold” and “hot” are relative terms, as can be seen from the fact that deforming lead at room temperature is a hot-working process, because the recrystallization temperature of lead is about room temperature. As the name implies, **warm working** is carried out at intermediate temperatures; thus, warm working is a compromise between cold and hot working. The important technological differences in products that are processed by cold, warm, and hot working are described in Part III.

The temperature ranges for these three categories of plastic deformation are given in Table 1.2 in terms of a ratio, T/T_m , where T is the working temperature and T_m is the melting point of the metal, both on the absolute scale. Although it is a dimensionless quantity, this ratio is known as the **homologous temperature**.

TABLE 1.2

Homologous Temperature Ranges for Various Processes	
Process	T/T_m
Cold working	<0.3
Warm working	0.3 to 0.5
Hot working	>0.6

SUMMARY

- There are three basic crystal structures in metals: body-centered cubic (bcc), face-centered cubic (fcc), and hexagonal close-packed (hcp). Grains made of these crystals typically contain various defects and imperfections, such as dislocations, vacancies, impurities, inclusions, and grain boundaries. Polycrystalline metals consist of many crystals, or grains, in random orientations.
- Plastic deformation in metals takes place by a slip mechanism. Although the theoretical shear stress required to cause slip is very high, actual stresses are much lower because of the presence of dislocations (edge or screw type). Dislocations become entangled with one another or are impeded by barriers such as grain boundaries, impurities, and inclusions. As a result, the shear stress required to cause further slip is increased; consequently, the overall strength and hardness of the metal is also increased (through work hardening or strain hardening).
- Grain size has a significant effect on the strength of metals: The smaller the size, the stronger is the metal, and the larger the size, the more ductile is the metal.
- Grain boundaries have a major influence on the behavior of metals. Boundaries can undergo embrittlement, severely reducing ductility at elevated temperatures (hot shortness); they are also responsible for the creep phenomenon, which is due to grain boundary sliding.
- Metals may be plastically deformed at room, warm, or high temperatures, their behavior and workability depending largely on whether deformation takes place below or above the recrystallization temperature of the metal. Deformation at room temperature (cold working) results in higher strength, but reduced ductility; generally, it also causes anisotropy (preferred orientation or mechanical fibering), whereby the properties are different in different directions.
- The effects of cold working can be reversed by annealing the metal: heating it in a certain temperature range for a given period of time, thereby allowing the successive processes of recovery, recrystallization, and grain growth to take place.

KEY TERMS

Allotropism	Grain boundaries	Orange peel	Slip system
Anisotropy	Grain growth	Plastic deformation	Strain hardening
Basal plane	Grain size	Polycrystals	Structure-insensitive
Body-centered cubic	Hexagonal close-packed	Polygonization	Structure-sensitive
Cold working	Homologous temperature	Polymorphism	Texture
Covalent bond	Hot shortness	Preferred orientation	Twinning
Creep	Hot working	Primary bond	Unit cell
Crystals	Imperfections	Recovery	Vacancy
Dislocations	Ionic bond	Recrystallization	van der Waals force
Elastic deformation	Lattice structure	Secondary bond	Warm working
Embrittlement	Mechanical fibering	Shear stress	Work hardening
Face-centered cubic	Metallic bond	Slip band	
Grains	Nucleation	Slip plane	