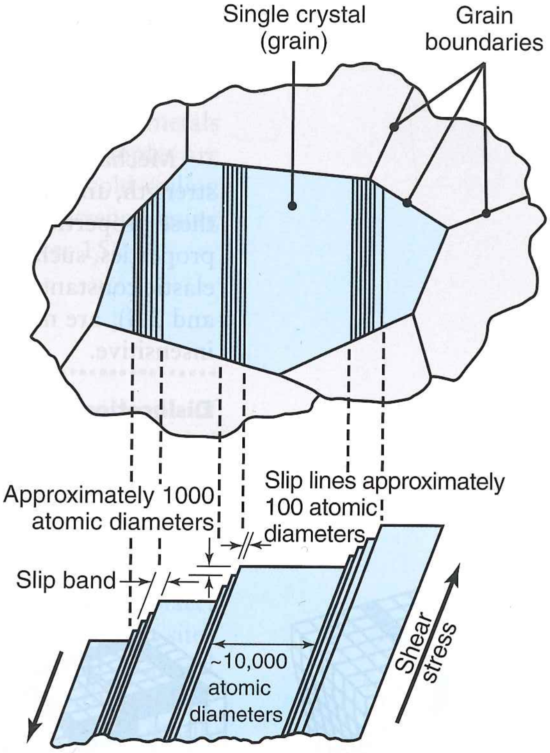

FIGURE 1.7 Schematic illustration of slip lines and slip bands in a single crystal (grain) subjected to a shear stress. A slip band consists of a number of slip planes. The crystal at the center of the upper illustration is an individual grain surrounded by several other grains.

1.4.1 Imperfections in the Crystal Structure of Metals

The actual strength of metals is approximately one to two orders of magnitude lower than the strength levels obtained from theoretical calculations. This discrepancy is explained in terms of **defects** and **imperfections** in the crystal structure. Unlike in idealized models described earlier, actual metal

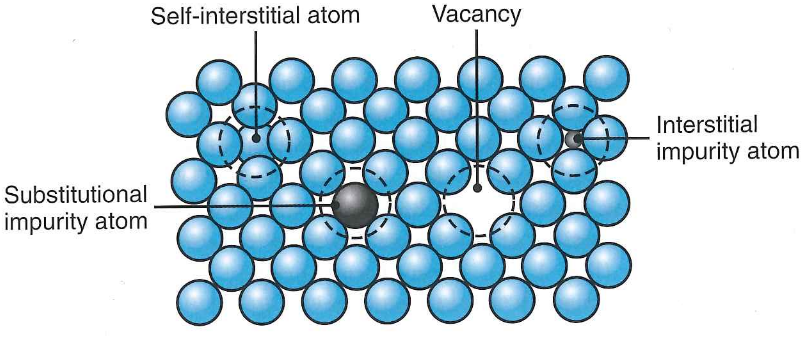

FIGURE 1.8 Schematic illustration of types of defects in a single-crystal lattice: self-interstitial, vacancy, interstitial, and substitutional.

crystals contain a large number of defects and imperfections, which generally are categorized as:

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. 1.8).
2. *Linear*, or *one-dimensional, defects*, called **dislocations** (Fig. 1.9).
3. *Planar*, or *two-dimensional, imperfections*, such as **grain boundaries** and **phase boundaries** (Section 1.5).
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 the presence of 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, such as modulus of elasticity and modulus of rigidity (Sections 2.2.1 and 2.4), 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. 1.10) requires much lower 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.

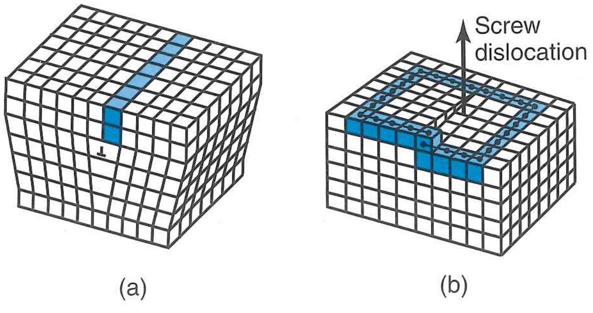

FIGURE 1.9 Types of dislocations in a single crystal: (a) edge dislocation and (b) screw dislocation.

There are two types of dislocations: **edge** and **screw** (Fig. 1.9). 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 moving a large carpet on a floor by first forming a hump at one end and moving the hump gradually to the other end. (Recall that 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, like the threads on a screw or bolt.

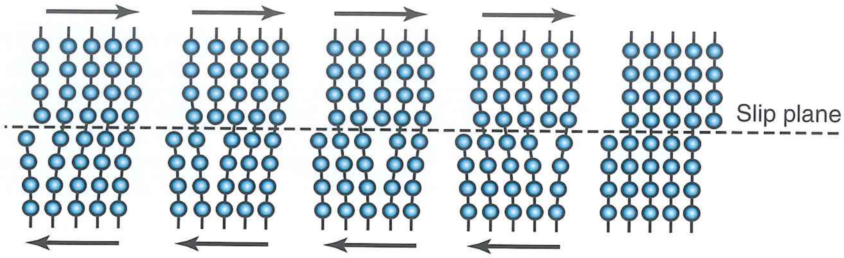

FIGURE 1.10 Movement of an edge dislocation across the crystal lattice under a shear stress. Dislocations help explain why the actual strength of metals is much lower than that predicted by theory.

1.5 Grains and Grain Boundaries

When a mass of molten metal begins to solidify, crystals form independently of each other at various locations within the liquid mass, and thus have random and unrelated orientations (Fig. 1.11). Each of these crystals eventually 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 (a) the number of different sites at which individual crystals begin to form (note that there are seven in Fig. 1.11a) and (b) 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 crystal growth rate is high (as 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.

Note in Fig. 1.11d that the growing grains eventually interfere with and impinge upon one another; the interfaces that separate the 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

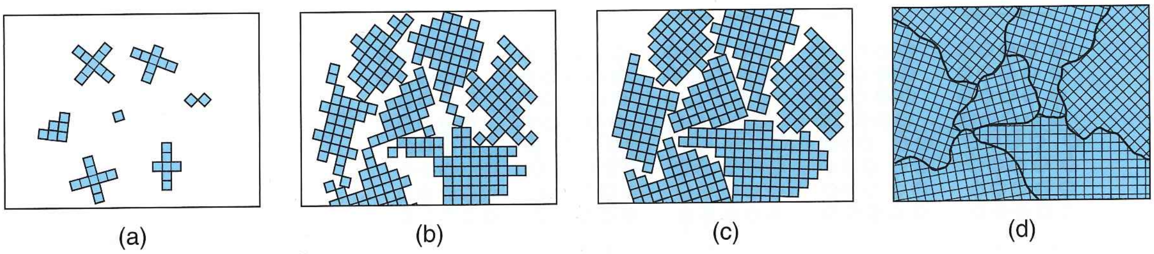

FIGURE 1.11 Schematic illustration of the stages during the solidification of molten metal; each small square represents a unit cell. (a) Nucleation of crystals at random sites in the molten metal; note that the crystallographic orientation of each site is different. (b) and (c) Growth of crystals as solidification continues. (d) Solidified metal, showing individual grains and grain boundaries; note the different angles at which neighboring grains meet each other.

behavior of a single crystal or a single grain is anisotropic. Thus, because its many grains have random crystallographic orientations, the behavior of a polycrystalline metal is essentially **isotropic**; that is, its properties do not vary with direction.

1.5.2 Influence of Grain Boundaries

Grain boundaries have an important influence on the strength and ductility of metals; they interfere with dislocation movement and thus also influence strain hardening. The magnitude of these effects depends on temperature, deformation rate, and the type and amount of impurities present along grain boundaries.

Because the atoms along the grain boundaries are more disordered and hence packed less efficiently, 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; thus, they can be more easily removed or chemically bonded to another atom. As a result, for example, the surface of a metal piece becomes rougher when etched or is subjected to corrosive environments (see also *end grains in forging*, in Section 4.11).

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 (deformation under stress over time, usually at elevated temperatures) involves *grain-boundary sliding* (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 with liquid gallium and (b) copper at elevated temperature wetted with lead or bismuth; these 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.**

Another embrittlement phenomenon, called **hot shortness,** is caused by local melting of a constituent or of an impurity along 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 (a) antimony in copper, (b) leaded steels (Section 21.7.1), and (c) leaded brass. To avoid hot shortness, the metal is usually worked at a lower temperature to prevent softening and melting along the grain boundaries. **Temper embrittlement** in alloy steels is another form of embrittlement, caused by segregation (movement) of impurities to the grain boundaries (Section 4.11).