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 (called *cold working*), the grains become deformed and elongated, as shown schematically in Fig. 1.12. Deformation may be carried out by, for example, 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 (Section 16.6). 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.

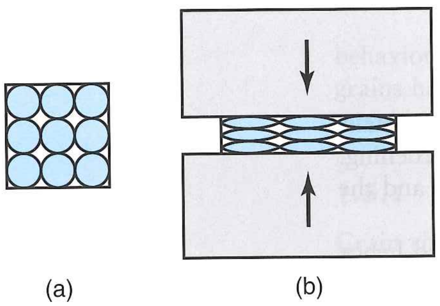

FIGURE 1.12 Plastic deformation of idealized (equiaxed) grains in a specimen subjected to compression (such as occurs in the forging or rolling of metals): (a) before deformation and (b) after deformation. Note the alignment of grain boundaries along a horizontal direction, an effect known as *preferred orientation*.

Anisotropy (Texture). Note in Fig. 1.12b 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 crack direction in Fig. 1.13, for example, that the ductility of the cold-rolled sheet in the transverse direction is lower than 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 manner that the resulting deformation imparts anisotropic magnetic properties to the sheet. This operation

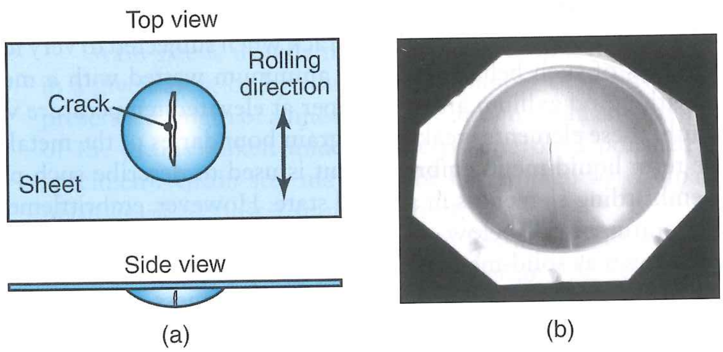

FIGURE 1.13 (a) Schematic illustration of a crack in sheet metal that has been subjected to bulging (caused, for example, by pushing a steel ball against the sheet). Note the orientation of the crack with respect to the rolling direction of the sheet; this sheet is anisotropic. (b) Aluminum sheet with a crack (vertical dark line at the center) developed in a bulge test; the rolling direction of the sheet was vertical. *Source:* Courtesy of J.S. Kallend, Illinois Institute of Technology.

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. 1.6a. When a single-crystal metal piece 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. 1.12a 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 splits easily when pulled in tension in its thickness direction.