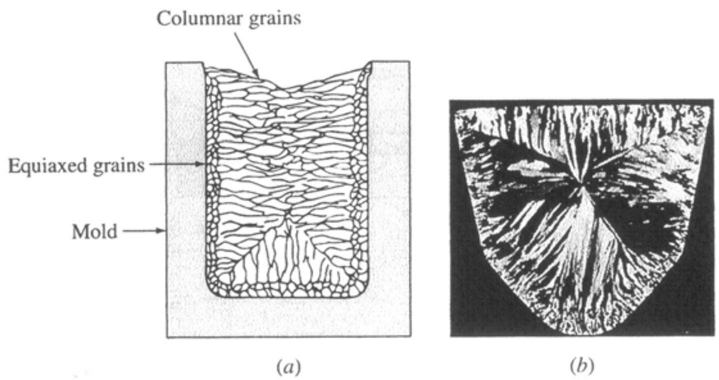


Figure 4.7
(*a*) Schematic drawing of a solidified metal grain structure produced by using a cold mold. (*b*) Transverse section through an ingot of aluminum alloy 1100 (99.0% Al) cast by the Properzi method (a wheel and belt method). Note the consistency with which columnar grains have grown perpendicular to each mold face.
(After "Metals Handbook," vol. 8, 8th ed., American Society for Metals, 1973, p. 164.)

Columnar grains are long, thin, coarse grains created when a metal solidifies rather slowly in the presence of a steep temperature gradient. Relatively few nuclei are available when columnar grains are produced. Equiaxed and columnar grains are shown in Fig. 4.7. Note that in Fig. 4.7*b* the columnar grains have grown perpendicular to the mold faces since large thermal gradients were present in those directions.

4.1.3 Grain Structure of Industrial Castings

In industry, metals and alloys are cast into various shapes. If the metal is to be further fabricated after casting, large castings of simple shapes are produced first and then fabricated further into semifinished products. For example, in the aluminum industry, common shapes for further fabrication are sheet ingots (Fig. 4.1), which have rectangular cross sections, and extrusion[4] ingots, which have circular cross sections. For some applications, the molten metal is cast into essentially its final shape as, for example, an automobile piston (see Fig. 6.3).

The large aluminum alloy sheet ingot in Fig. 4.1 was cast by a direct-chill semicontinuous casting process. In this casting method the molten metal is cast into a

[4]*Extrusion* is the process of converting a metal ingot into lengths of uniform cross section by forcing solid plastic metal through a die or orifice of the desired cross-sectional outline.

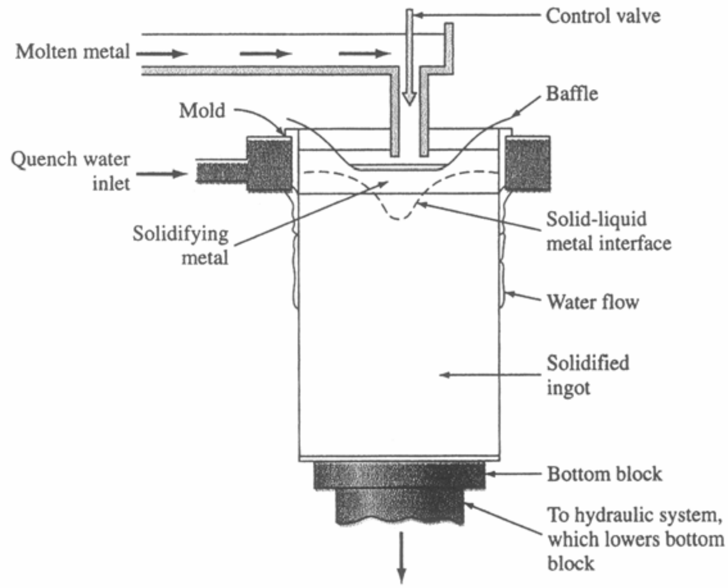


Figure 4.8
Schematic of an aluminum alloy ingot being cast in a direct-chill semicontinuous casting unit.

mold with a movable bottom block that is slowly lowered after the mold is filled (Fig. 4.8). The mold is water-cooled by a water box, and water is also sprayed down the sides of the solidified surface of the ingot. In this way large ingots about 15 ft long can be cast continuously, as shown in Fig. 4.1. In the steel industry about 60 percent of the metal is cast into stationary molds, with the remaining 40 percent being continuously cast, as shown in Fig. 4.9.

To produce cast ingots with a fine grain size, grain refiners are usually added to the liquid metal before casting. For aluminum alloys, small amounts of grainrefining elements such as titanium, boron, or zirconium are included in the liquid metal just before the casting operation so that a fine dispersion of heterogeneous nuclei will be available during solidification. Figure 4.10 shows the effect of using a grain refiner while casting 6-in.-diameter aluminum extrusion ingots. The ingot section cast without the grain refiner has large columnar grains (Fig. 4.10*a*), and the section cast with the grain refiner has a fine, equiaxed grain structure (Fig. 4.10*b*).

4.2 SOLIDIFICATION OF SINGLE CRYSTALS

Almost all engineering crystalline materials are composed of many crystals and are therefore **polycrystalline.** However, there are a few that consist of only one crystal and are therefore *single crystals.* For example, high-temperature creepresistant gas

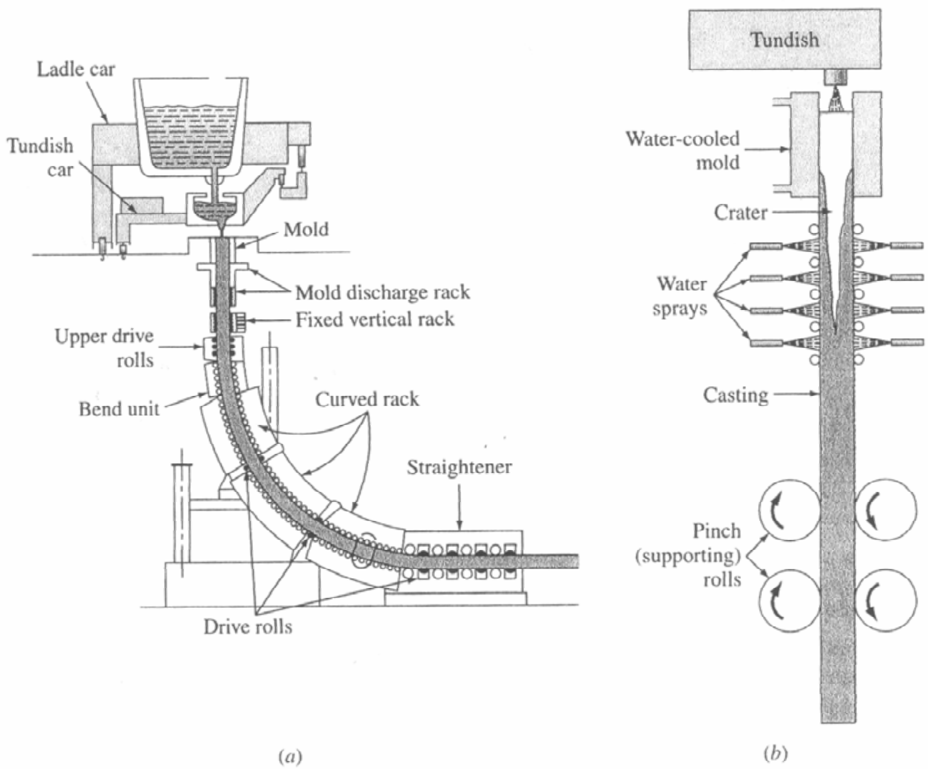
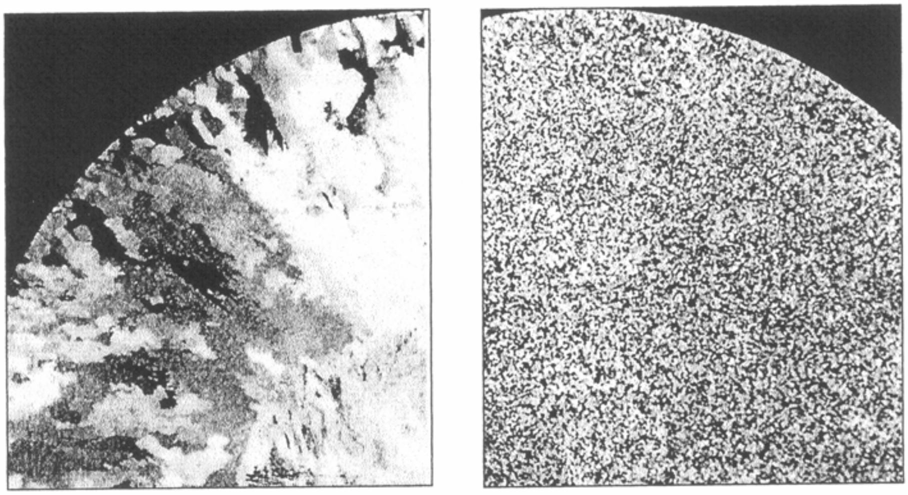


Figure 4.9
Continuous casting of steel ingots. (*a*) General setup and (*b*) close-up of the mold arrangement.
(*After "Making, Shaping, and Treating of Steel," 10th ed., Association of Iron and Steel Engineers, 1985.*)

turbine blades are sometimes made of single crystals, as shown in Fig. 4.11*c*. Single-crystal turbine blades are more creep resistant at high temperatures than the same blades made with an equiaxed grain structure (Fig. 4.11*a*) or a columnar grain structure (Fig. 4.11*b*) because at high temperatures above about half the absolute melting temperature of a metal the grain boundaries become weaker than the grain bodies.

In growing single crystals, solidification must take place around a single nucleus so that no other crystals are nucleated and grow. To accomplish this, the interface temperature between the solid and liquid must be slightly lower than the melting point of the solid, and the liquid temperature must increase beyond the interface. To achieve this temperature gradient, the latent heat of solidification[5] must be conducted through the solidifying solid crystal. The growth rate of the crystal must be slow so

The latent heat of solidification is the thermal energy released when a metal solidifies.



(*a*) (*b*)

Figure 4.10
Parts of transverse sections through two 6-in-diameter ingots of alloy 6063 (Al–0.7% Mg–0.4% Si) that were direct-chill semicontinuous cast. (*a*) Ingot section was cast without the addition of a grain refiner; note columnar grains and colonies of featherlike crystals near the center of the section. (*b*) Ingot section was cast with the addition of a grain refiner and shows a fine, equiaxed grain structure. (Tucker's reagent; actual size.)
(*After "Metals Handbook," vol. 8, 8th ed., American Society for Metals, 1973, p. 164.*)

that the temperature at the liquid-solid interface is slightly below the melting point of the solidifying solid. Figure 4.12*a* illustrates how single-crystal turbine blades can be cast, and Fig. 4.12*b* and *c* show how competitive grain growth is reduced to a single grain by using a "pigtail" selector.

Another example of an industrial use of single crystals is the silicon single crystals that are sliced into wafers for solid-state electronic integrated circuit chips (see Fig. 13.1). Single crystals are necessary for this application since grain boundaries would disrupt the flow of electrons in devices made from semiconductor silicon. In industry, single crystals of silicon 8 to 12 in. (20 to 25 cm) in diameter have been grown for semiconducting device applications. One of the commonly used techniques to produce high-quality (minimization of defects) silicon single crystals is the Czochralski method. In this process high-purity polycrystalline silicon is first melted in a nonreactive crucible and held at a temperature just above the melting point. A high-quality seed crystal of silicon of the desired orientation is lowered into the melt while it is rotated. Part of the surface of the seed crystal is melted in the liquid to remove the outer strained region and to produce a surface for the liquid to solidify on. The seed crystal continues to rotate and is slowly raised from the melt. As it is raised from the melt, silicon

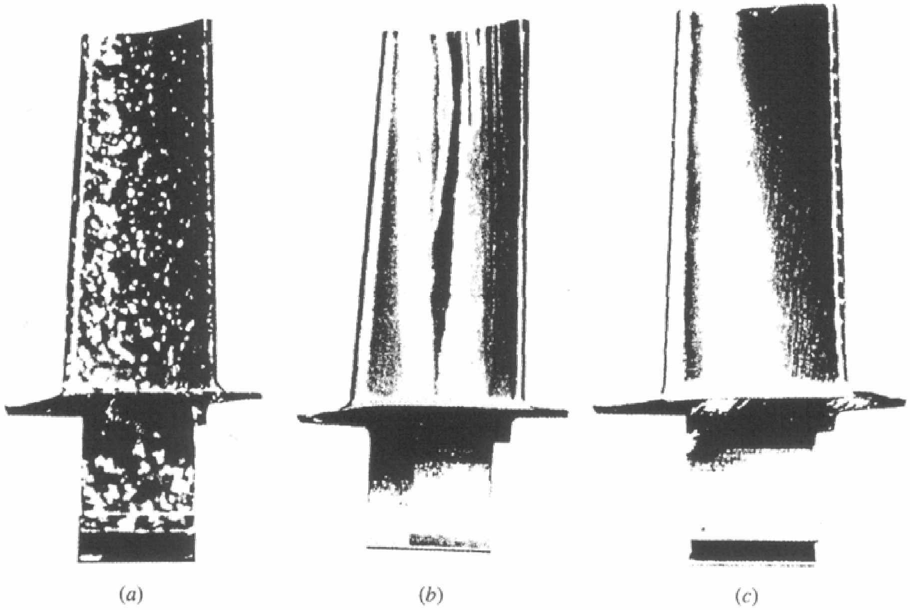


Figure 4.11
Different grain structures of gas turbine airfoil blades: (*a*) Polycrystal equiaxed, (*b*) polycrystal columnar, and (*c*) single crystal.
(*Courtesy of Pratt and Whitney Co.*)

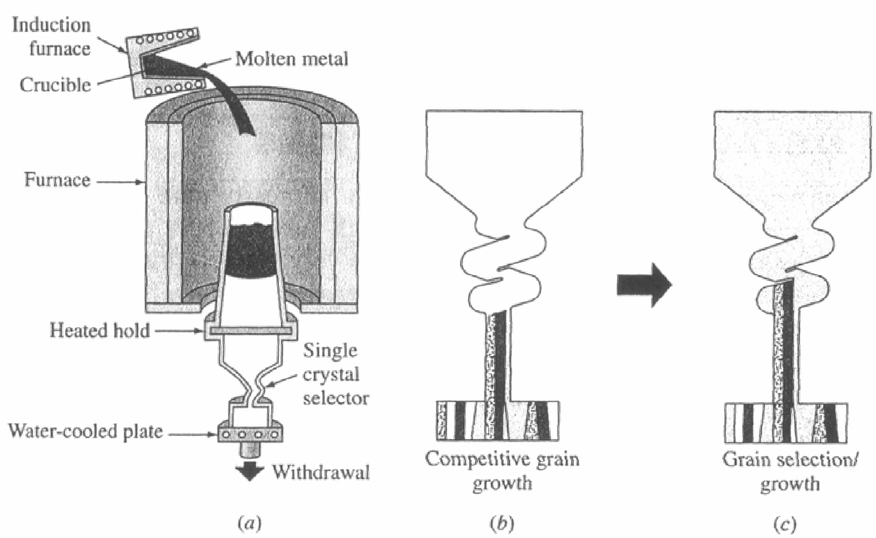


Figure 4.12
(*a*) A process schematic for producing a single-crystal gas turbine airfoil. (*b*) Starter section of casting for producing a single-crystal airfoil showing competitive growth during solidification below the single-crystal selector ("pigtail"). (*c*) Same as (*b*) but showing the survival of only one grain during solidification through the single-crystal selector.
(*After Pratt and Whitney Co.*)

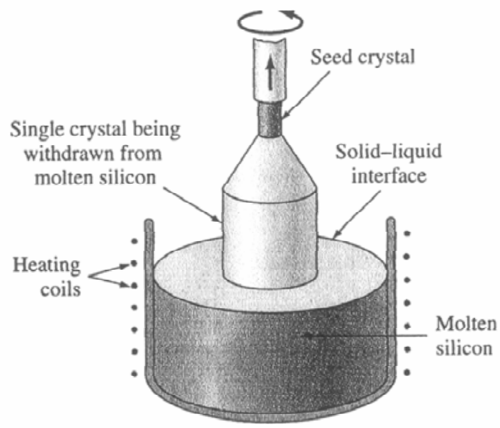


Figure 4.13
Formation of single crystal of silicon by the Czochralski process.

from the liquid in the crucible adheres and grows on the seed crystal, producing a much larger diameter single crystal of silicon (Fig. 4.13). With this process large single-crystal silicon ingots up to about 12 in. (≅30 cm) in diameter can and have been made.

4.3 METALLIC SOLID SOLUTIONS

Although very few metals are used in the pure or nearly pure state, a few are used in the nearly pure form. For example, high-purity copper of 99.99 percent purity is used for electronic wires because of its very high electrical conductivity. High-purity aluminum (99.99% Al) (called *superpure aluminum*) is used for decorative purposes because it can be finished with a very bright metallic surface. However, most engineering metals are combined with other metals or nonmetals to provide increased strength, higher corrosion resistance, or other desired properties.

A *metal alloy,* or simply an **alloy,** is a mixture of two or more metals or a metal (metals) and a nonmetal (nonmetals). Alloys can have structures that are relatively simple, such as that of cartridge brass, which is essentially a binary alloy (two metals) of 70% Cu and 30% Zn. On the other hand, alloys can be extremely complex, such as the nickel-base superalloy Inconel 718 used for jet engine parts, which has about 10 elements in its nominal composition.

The simplest type of alloy is that of the solid solution. A **solid solution** is a *solid* that consists of two or more elements atomically dispersed in a single-phase structure. In general there are two types of solid solutions: *substitutional* and *interstitial.*