undercooling and recalescence is usually very small and can be observed in cooling curves only by very careful measurements. If effective heterogeneous nuclei are present in the liquid, solidification begins at the freezing temperature [Figure 9-8 (b)]. The latent heat keeps the remaining liquid at the freezing temperature until all of the liquid has solidified and no more heat can be evolved. Growth under these conditions is planar. The **total solidification time** of the casting is the time required to remove both the specific heat of the liquid and the latent heat of fusion. Measured from the time of pouring until solidification is complete, this time is given by Chvorinov's rule. The **local solidification time** is the time required to remove only the latent heat of fusion at a particular location in the casting; it is measured from when solidification begins until solidification is completed. The local solidification times (and the total solidification times) for liquids solidified via undercooled and inoculated liquids will be slightly different. We often use the terms "melting temperature" and "freezing temperature" while discussing solidification. It would be more accurate to use the term "melting temperature" to describe when a solid turn completely into a liquid. For pure metals and compounds, this happens at a fixed temperature (assuming fixed pressure) and without superheating. "Freezing temperature" or "freezing point" can be defined as the temperature at which solidification of a material is complete.

Cast Structure

In manufacturing components by casting, molten metals are often poured into molds and permitted to solidify. The mold produces a finished shape, known as a *casting*. In other cases, the mold produces a simple shape called an **ingot**. An ingot usually requires extensive plastic deformation before a finished product is created. A *macrostructure* sometimes referred to as the **ingot structure**, consists of as many as three regions (Figure 9-9). (Recall that in Chapter 2 we used the term "macrostructure" to describe the structure of a material at a macroscopic scale. Hence, the term "ingot structure" may be more appropriate.)

Chill Zone

The **chill zone** is a narrow band of randomly oriented grains at the surface of the casting. The metal at the mold wall is the first to cool to the freezing temperature. The mold wall also provides many surfaces at which heterogeneous nucleation takes place.

Columnar Zone

The **columnar zone** contains elongated grains oriented in a particular crystallographic direction. As heat is removed from the casting by the mold material, the grains in the chill zone grow in the direction opposite to that of the heat
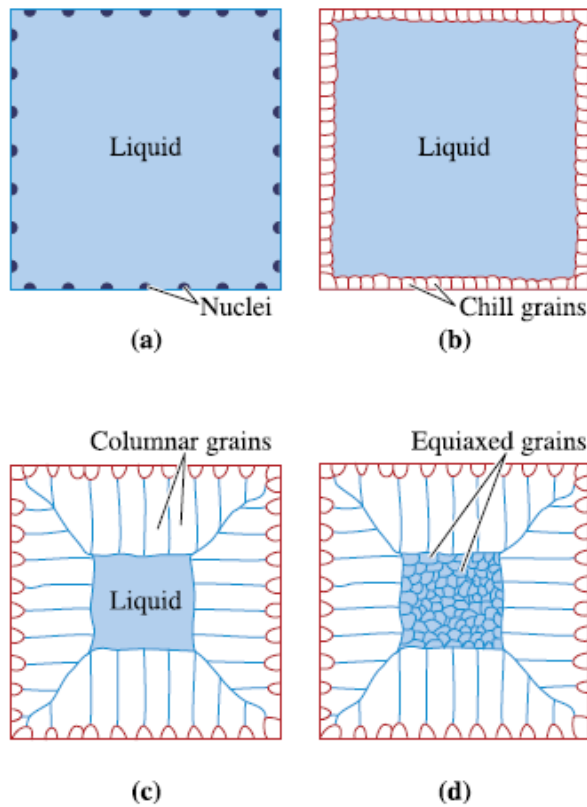
Figure 9-9
Development of the ingot structure of a casting during solidification: (a) nucleation begins, (b) the chill zone forms, (c) preferred growth produces the columnar zone, and (d) additional nucleation creates the equiaxed zone.

flow, or from the coldest toward the hottest areas of the casting. This tendency usually means that the grains grow perpendicular to the mold wall. Grains grow fastest in certain crystallographic directions. In metals with a cubic crystal structure, grains in the chill zone that have 100 direction perpendicular to the mold wall grow faster than other less favorably oriented grains (Figure 9-10). Eventually, the grains in the columnar zone have 100 directions that are parallel to one another, giving the columnar zone anisotropic properties. This formation of the columnar zone is
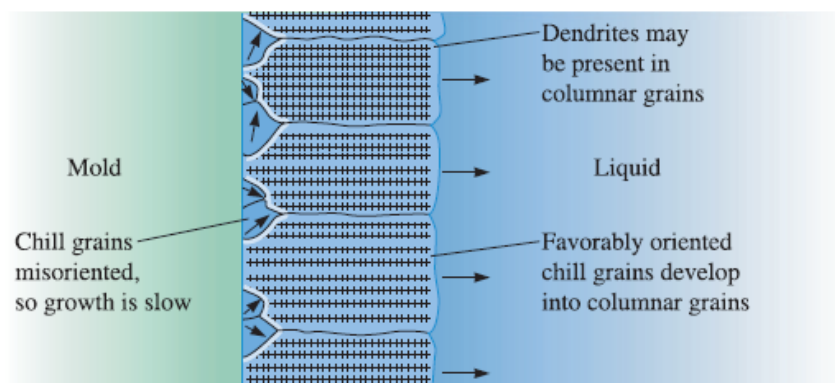

Figure 9-10   Competitive growth of the grains in the chill zone results in only those grains with favorable orientations developing into columnar grains.

influenced primarily by growth—rather than nucleation—phenomena. The grains may be composed of many dendrites if the liquid is originally undercooled. The solidification may proceed by planar growth of the columnar grains if no undercooling occurs.

Equiaxed Zone

Although the solid may continue to grow in a columnar manner until all of the liquid has solidified, an equiaxed zone frequently forms in the center of the casting or ingot. The **equiaxed zone** contains new, randomly oriented grains, often caused by a low pouring temperature, alloying elements, or grain refining or inoculating agents. Small grains or dendrites in the chill zone may also be torn off by strong convection currents that are set up as the casting begins to freeze. These also provide heterogeneous nucleation sites for what ultimately become equiaxed grains. These grains grow as relatively round, or equiaxed, grains with a random orientation, and they stop the growth of the columnar grains. The formation of the equiaxed zone is a nucleation-controlled process and causes that portion of the casting to display isotropic behavior.

By understanding the factors that influence solidification in different regions, it is possible to produce castings that first form a "skin" of a chill zone and then dendrites. Metals and alloys that show this macrostructure are known as **skin-forming alloys**. We also can control the solidification such that no skin or advancing dendritic arrays of grains are seen; columnar to equiaxed switchover is almost at the mold walls. The result is a casting with a macrostructure consisting predominantly of equiaxed grains. Metals and alloys that solidify in this fashion are known as **mushy-forming alloys** since the cast material seems like a mush of solid grains floating in a liquid melt. Many aluminum and magnesium alloys show this type of solidification. Often, we encourage an all-equiaxed structure and thus create a casting with isotropic properties by effective grain refinement or inoculation.

In a later section, we will examine one case (turbine blades) where we control solidification to encourage all columnar grains and hence anisotropic behavior. Cast ingot structure and microstructure are important particularly for components that are directly cast into a final shape. In many situations though, as discussed in Section 9-1, metals and alloys are first cast into ingots, and the ingots are subsequently subjected to thermomechanical processing (e.g., rolling, forging etc.). During these steps, the cast macrostructure is broken down and a new microstructure will emerge, depending upon the thermomechanical process used (Chapter 8).

Solidification Defects

Although there are many defects that potentially can be introduced during solidification, shrinkage and porosity deserve special mention. If a casting contains pores (small holes), the cast component can fail catastrophically when used for load-bearing applications (e.g., turbine blades).

Shrinkage

Almost all materials are denser in the solid state than in the liquid state. During solidification, the material contracts, or shrinks, as much as 7% (Table 9-2). Often, the bulk of the **shrinkage** occurs as **cavities**, if solidification begins at all surfaces of the casting, or *pipes*, if one surface solidifies more slowly than the others (Figure 9-11). The presence of such pipes can pose problems. For example, if in the production of zinc ingots a shrinkage pipe remains, water vapor can condense in it. This water can lead to an explosion if the ingot gets introduced in a furnace in which zinc is being remelted for such applications as hot-dip galvanizing.

TABLE 9-2 ■ *Shrinkage during solidification for selected materials*

Material	Shrinkage (%)
Al	7.0
Cu	5.1
Mg	4.0
Zn	3.7
Fe	3.4
Pb	2.7
Ga	+3.2 (expansion)
H_2O	+8.3 (expansion)
Low-carbon steel	2.5–3.0
High-carbon steel	4.0
White Cast Iron	4.0–5.5
Gray Cast Iron	+1.9 (expansion)

Note: Some data from DeGarmo, E. P., Black, J. T., and Koshe, R. A. *Materials and Processes in Manufacturing*, Prentice Hall, 1997.
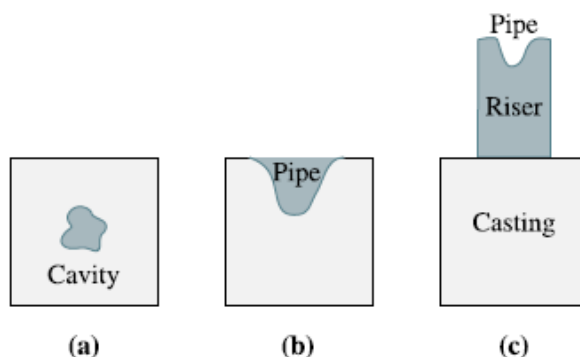

Figure 9-11
Several types of macroshrinkage can occur, including cavities and pipes. Risers can be used to help compensate for shrinkage.

(a) (b) (c)

A common technique for controlling **cavity** and **pipe shrinkage** is to place a **riser**, or an extra reservoir of metal, adjacent and connected to the casting. As the casting solidifies and shrinks, liquid metal flows from the riser into the casting to fill the shrinkage void. We need only to ensure that the riser solidifies after the casting and that there is an internal liquid channel that connects the liquid in the riser to the last liquid to solidify in the casting. Chvorinov's rule can be used to help design the size of the riser. The following example illustrates how risers can be designed to compensate for shrinkage.

Example 9-6 *Design of a Riser for a Casting*

Design a cylindrical riser, with a height equal to twice its diameter, that will compensate for shrinkage in a 2 cm * 8 cm* 16 cm, casting (Figure 9-12).
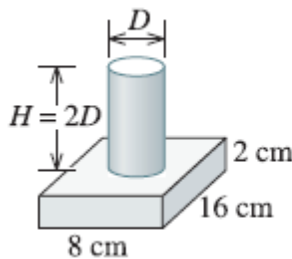

Figure 9-12
The geometry of the casting and riser (for Example 9-6).

SOLUTION

We know that the riser must freeze after the casting. To be conservative, we typically require that the riser take 25% longer to solidify than the casting. Therefore,

$$t_r = 1.25t_c \text{ or } B\left(\frac{V}{A}\right)_r^2 = 1.25\ B\left(\frac{V}{A}\right)_c^2$$

The subscripts r and c stand for riser and casting, respectively. The mold constant B is the same for both casting and riser, so

$$\left(\frac{V}{A}\right)_r = \sqrt{1.25}\left(\frac{V}{A}\right)_c$$

The volume of the casting is
$V_c = (2 \text{ cm}) (8 \text{ cm}) (16 \text{ cm}) = 256 \text{ cm}^3$
The area of the riser adjoined to the casting must be subtracted from the total surface area of the casting in order to calculate the surface area of the casting in contact with the mold:

$$A_c = (2)(2 \text{ cm})(8 \text{ cm}) + (2)(2 \text{ cm})(16 \text{ cm}) + (2)(8 \text{ cm})(16 \text{ cm}) - \frac{\pi D^2}{4} = 352 \text{ cm}^2 - \frac{\pi D^2}{4}$$

where D is the diameter of the cylindrical riser. We can write equations for the volume and area of the cylindrical riser, noting that the cylinder height $H = 2D$:

$$V_r = \frac{\pi D^2}{4} H = \frac{\pi D^2}{4} (2D) = \frac{\pi D^3}{2}$$

$$A_r = \frac{\pi D^2}{4} + \pi D H = \frac{\pi D^2}{4} + \pi D (2D) = \frac{9}{4} \pi D^2$$

where again we have not included the area of the riser adjoined to the casting in the area calculation. The volume to area ratio of the riser is given by

$$\left(\frac{V}{A}\right)_r = \frac{(\pi D^3/2)}{(9\pi D^2/4)} = \frac{2}{9} D$$

and must be greater than that of the casting according to

$$\left(\frac{V}{A}\right)_r = \frac{2}{9} D > \sqrt{1.25} \left(\frac{V}{A}\right)_c$$

Substituting,

$$\frac{2}{9} D > \sqrt{1.25} \left(\frac{256 \text{ cm}^3}{352 \text{ cm}^2 - \pi D^2/4}\right)$$

Solving for the smallest diameter for the riser:

$$D = 3.78 \text{ cm}$$

Although the volume of the riser is less than that of the casting, the riser solidifies more slowly because of its compact shape
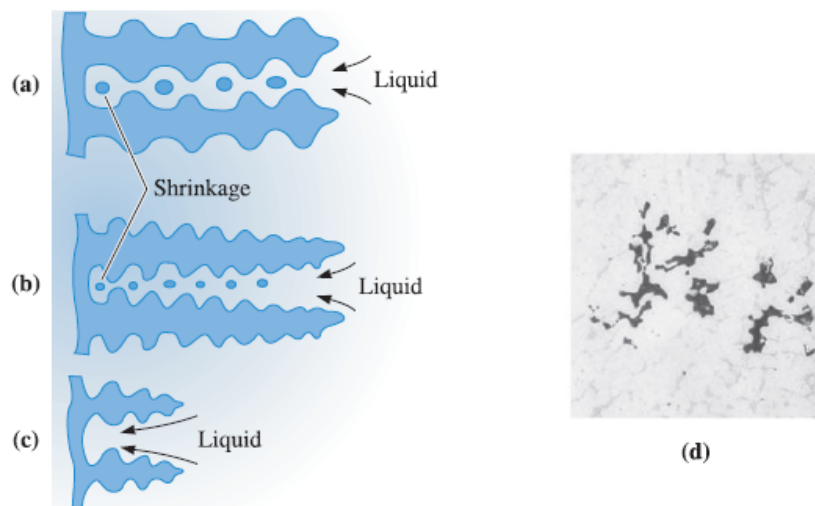

Figure 9-13 (a) Shrinkage can occur between the dendrite arms. (b) Small secondary dendrite arm spacings result in smaller, more evenly distributed shrinkage porosity. (c) Short primary arms can help avoid shrinkage. (d) Interdendritic shrinkage in an aluminum alloy is shown (× 80). (*Reprinted courtesy of Don Askeland.*)

Interdendritic Shrinkage

This consists of small shrinkage pores between dendrites (Figure 9-13). This defect, also called **microshrinkage** or **shrinkage porosity**, is difficult to prevent by the use of risers. Fast cooling rates may reduce problems with **interdendritic shrinkage**; the dendrites may be shorter, permitting liquid to flow through the dendritic network to the solidifying solid interface. In addition, any shrinkage that remains may be finer and more uniformly distributed.

Gas Porosity

Many metals dissolve a large quantity of gas when they are molten. Aluminum, for example, dissolves hydrogen. When the aluminum solidifies, however, the solid metal retains in its crystal structure only a small fraction of the hydrogen since the solubility of the solid is remarkably lower than that of the liquid (Figure 9-14). The excess hydrogen that cannot be incorporated in the solid metal or alloy crystal structure forms bubbles that may be trapped in the solid metal, producing **gas porosity**. The amount of gas that can be dissolved in molten metal is given by **Sievert's law**:

$$\text{Percent of gas} = K\sqrt{p_{gas}} \qquad (9\text{-}7)$$

where p_{gas} is the partial pressure of the gas in contact with the metal and K is a constant which, for a particular metal-gas system, increases with increasing temperature. We can minimize gas porosity in castings by keeping the liquid temperature low, by adding materials to the liquid to combine with the gas and form a solid, or by ensuring that the partial pressure of the gas remains low. The latter may be achieved by placing the molten metal in a vacuum chamber or bubbling an inert gas through the metal. Because p_{gas} is low in the vacuum, the gas leaves the metal, enters the vacuum, and is
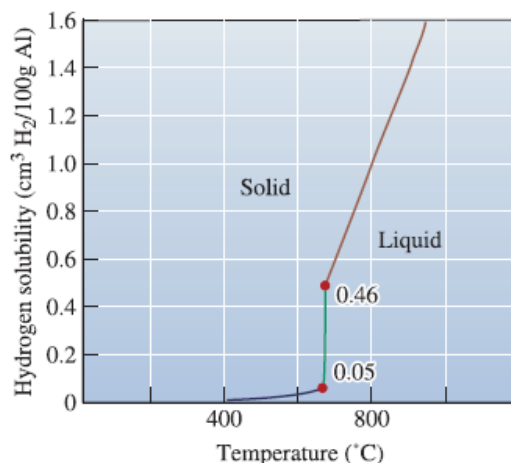

Figure 9-14
The solubility of hydrogen gas in aluminum when the partial pressure of $H_2 = 1$ atm.

carried away. **Gas flushing** is a process in which bubbles of a gas, inert or reactive, are injected into a molten metal to remove undesirable elements from molten metals and alloys. For example, hydrogen in aluminum can be removed using nitrogen or chlorine. The following example illustrates how a degassing process can be designed.