10.5 Heat Transfer

The heat transfer during the complete cycle (from pouring, to solidification, and to cooling to room temperature) is another important consideration in metal casting. Heat flow at different locations in the system is a complex phenomenon and depends on several factors relating to the material cast, the mold, and process parameters. For instance, in casting thin sections, the metal flow rates must be high enough to avoid premature chilling and solidification. On the other hand, the flow rate must not be so high as to cause excessive turbulence—with its detrimental effects on the casting process.

A typical temperature distribution at the mold liquid–metal interface is shown in Fig. 10.10. Heat from the liquid metal is given off through the mold wall and to the surrounding air. The temperature drop at the air–mold and mold–metal interfaces is caused by the presence of boundary layers and imperfect contact at these interfaces. The shape of the curve depends on the thermal properties of the molten metal and the mold.

10.5.1 Solidification Time

During the early stages of solidification, a thin skin begins to form at the relatively cool mold walls, and as time passes, the thickness of the skin increases (Fig. 10.11). With flat mold walls, the thickness is proportional to the square root of time; thus, doubling the time will make the skin $\sqrt{2} = 1.41$ times or 41% thicker.

The **solidification time** is a function of the volume of a casting and its surface area (*Chvorinov's rule*):

$$\text{Solidification time} = C\left(\frac{\text{Volume}}{\text{Surface area}}\right)^n, \qquad (10.7)$$

where C is a constant that reflects (a) the mold material, (b) the metal properties (including latent heat), and (c) the temperature. The parameter n has a value between 1.5 and 2, but usually is taken as 2. Thus, a large solid sphere will solidify and cool to ambient temperature at a much slower rate than will a smaller solid sphere. The reason for this is that the volume of a sphere is proportional to the cube of its diameter, whereas the surface area is proportional to the square of its diameter.

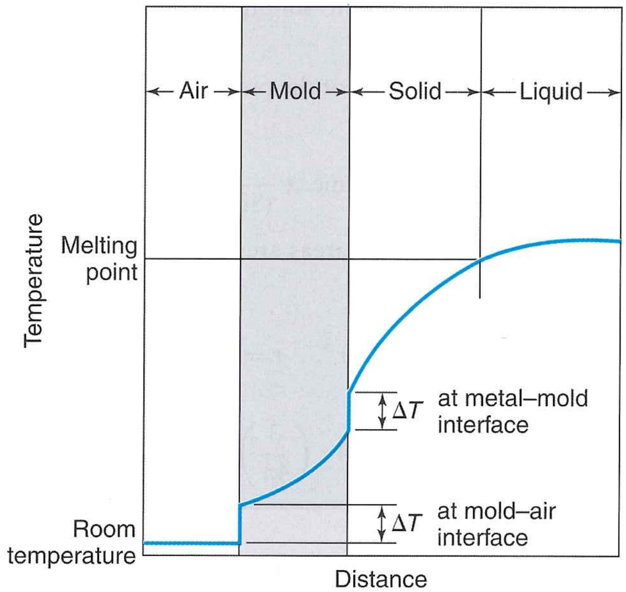

FIGURE 10.10 Temperature distribution at the interface of the mold wall and the liquid metal during the solidification of metals in casting.

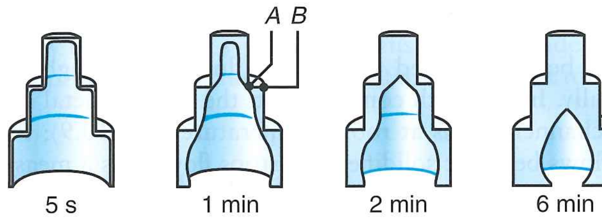

FIGURE 10.11 Solidified skin on a steel casting. The remaining molten metal is poured out at the times indicated in the figure. Hollow ornamental and decorative objects are made by a process called *slush casting*, which is based on this principle. *Source:* After H.F. Taylor, J. Wulff, and M.C. Flemings.

Similarly, it can be shown that molten metal in a cube-shaped mold will solidify faster than in a spherical mold of the same volume (see Example 10.1).

The effects of mold geometry and elapsed time on skin thickness and shape are shown in Fig. 10.11. As illustrated, the unsolidified molten metal has been poured from the mold at time intervals ranging from 5 s to 6 min. Note that (as expected) the skin thickness increases with elapsed time, and that the skin is thinner at internal angles (location *A* in the figure) than at external angles (location *B*). The latter condition is caused by slower cooling at internal angles than at external angles.

EXAMPLE 10.1 Solidification Times for Various Shapes

Given: Three metal pieces being cast have the same volume, but different shapes: One is a sphere, one a cube, and the other a cylinder with its height equal to its diameter. Assume that $n = 2$.

Find: Which piece will solidify the fastest, and which one the slowest?

Solution: The volume of the piece is taken as unity. Thus from Eq. (10.7),

$$\text{Solidification time} \propto \frac{1}{(\text{Surface area})^2}.$$

The respective surface areas are:

Sphere:

$$V = \left(\frac{4}{3}\right)\pi r^3, \quad r = \left(\frac{3}{4\pi}\right)^{1/3},$$

$$A = 4\pi r^2 = 4\pi\left(\frac{3}{4\pi}\right)^{2/3} = 4.84.$$

Cube:

$$V = a^3, \quad a = 1, \quad \text{and} \quad A = 6a^2 = 6.$$

Cylinder:

$$V = \pi r^2 h = 2\pi r^3, \quad r = \left(\frac{1}{2\pi}\right)^{1/3},$$

$$A = 2\pi r^2 + 2\pi r h$$

$$= 6\pi r^2 = 6\pi\left(\frac{1}{2\pi}\right)^{2/3} = 5.54.$$

The respective solidification times are

$$t_{\text{sphere}} = 0.043C, \quad t_{\text{cube}} = 0.028C,$$

$$t_{\text{cylinder}} = 0.033C.$$

Hence, the cube-shaped piece will solidify the fastest, and the spherical piece will solidify the slowest.

10.5.2 Shrinkage

Because of their thermal expansion characteristics, metals usually shrink (contract) during solidification and while cooling to room temperature. *Shrinkage*, which causes dimensional changes and sometimes warping and cracking, is the result of the following three sequential events:

1. Contraction of the molten metal as it cools prior to its solidification
2. Contraction of the metal during phase change from liquid to solid
3. Contraction of the solidified metal (the casting) as its temperature drops to ambient temperature

The largest shrinkage occurs during the phase change of the material from liquid to solid, but this can be reduced or eliminated through the use of risers or pressure-feeding of molten metal. The amount of contraction during the solidification of various metals is shown in Table 10.1; note that some metals (such as gray cast iron) expand. The reason is that graphite has a relatively high specific volume, and when it precipitates as graphite flakes during solidification of the gray cast iron, it causes a net expansion of the metal. Shrinkage, especially that due to thermal contraction, is further discussed in Section 12.2.1 in connection with design considerations in casting.

TABLE 10.1

Volumetric Solidification Contraction or Expansion for Various Cast Metals

Contraction (%)		Expansion (%)	
Aluminum	7.1	Bismuth	3.3
Zinc	6.5	Silicon	2.9
Al–4.5% Cu	6.3	Gray iron	2.5
Gold	5.5		
White iron	4–5.5		
Copper	4.9		
Brass (70–30)	4.5		
Magnesium	4.2		
90% Cu–10% Al	4		
Carbon steels	2.5–4		
Al–12% Si	3.8		
Lead	3.2		