CHAPTER 12

POROSITY

Movies from experiments and simulations of porosity formation during solidification can be found at: http://solidification.org/Movies/porosity.html

12.1 INTRODUCTION

One of the most important types of defects that can form in cast products is porosity. There are many types of porosity (see for example the book by Campbell [1]), but the most severe is microporosity, the subject of this chapter. For convenience, we will use the terms porosity and microporosity interchangeably. Microporosity has a strong negative effect on mechanical properties, especially on ductility and fatigue life, because internal pores act as local stress concentrators and crack initiation sites.

**Key Concept 12.1: Types of microporosity**

There are two main causes of microporosity in castings:

- *Shrinkage porosity*, due to the volume change upon solidification combined with restricted feeding of liquid to the final solidification region, and
- *Gas porosity*, due to the “condensation” of dissolved gases in the melt upon freezing, as a result of the difference in solubility of such gases in the liquid and solid phases.

The two types of porosity manifest themselves in different ways: where they form in the mushy zone, their morphologies and the extent to which they interconnect are quite distinct. This chapter is devoted to the understanding and control of both types of porosity.

Figure 12.1(a) shows a micrograph of an Al-10wt%Cu alloy that was allowed to remain in an atmosphere of N₂-10%H₂ for an extended period of time, causing it to become saturated with hydrogen. Figure 12.1(b) shows
shrinkage porosity in an Al-4.5wt%Cu alloy. Although both alloys exhibit microporosity, the morphology of the pores is clearly different. As one can see in Fig. 12.1(a), the pore formed at an early stage of solidification, perhaps even in the liquid phase, due to the melt being saturated with hydrogen. The pore appears as a nearly spherical hole about 300µm in diameter, with dendrites growing around it, thus indicating that the pore existed prior to the development of the dendritic network. The pore is initiated by the presence of excess dissolved hydrogen in the melt, caused by the rejection of hydrogen by the solid. This is a typical case of “gas porosity”. In contrast, Fig. 12.1(b) shows several very fine pores (in black), which appear in the interstices between the primary dendrites (in gray). The Al-Al₂Cu eutectic appears as white in this image, obtained using X-ray tomography. This is typical of “shrinkage porosity”. Since the melt does not contain much dissolved gas in this case, the initial solidification occurs without the formation of bubbles as in Fig. 12.1(a). Due to its low copper content, the eutectic in this alloy forms at very high volume fraction of the primary phase (around 90%). The secondary phase, Al₂Cu, is much denser than the primary aluminum, which necessitates a significant amount of fluid flow through the dendritic network to compensate for the solidification shrinkage. Since feeding through densely packed dendrite arms is made difficult, shrinkage porosity appears as fine holes, typically a few tens of microns in size, but usually interconnected in a complex extended network, as described further below.

The formation of porosity in solidifying alloys can now be visualized in-situ using X-ray radiography or X-ray tomography. Lee and Hunt [12] were the first to apply this technique to visualize the formation of porosity in Al-Cu alloys, using a micro-focus X-ray source. They were able to observe the evolution of the pore density and the mean pore radius, even though the limited resolution available at that time (about 25µm) and the beam intensity were fairly limiting factors. The availability of X-ray synchrotron
radiation improved the situation dramatically. A resolution below 1 \( \mu \text{m} \) can be attained in several synchrotron facilities, and the beam intensity is high enough to allow in-situ X-ray tomography.

Figures 12.2 and 12.3 show time sequences obtained using such techniques, illustrating well the difference between gas and shrinkage porosity. The first set of images corresponds to the directional solidification of a 200 \( \mu \text{m} \)-thick Al-30wt\%Cu alloy contained between two quartz plates. X-rays penetrated the specimen during growth, and their absorption was proportional to the atomic number of the elements. Thus, regions of low Cu concentration appear white and regions with high concentration appear dark. In this experiment, columnar dendrites grew downward at an angle of about 30\(^\circ\) from the vertical thermal gradient. The liquid became enriched in Cu as solidification proceeded, and thus appears darker near the dendrite roots in comparison to the region ahead of the dendrite tips. The interdendritic eutectic front can be seen as a thin, nearly horizontal line at approximately mid-height of the images. Because the solidification interval is only about 10 K, the liquid can flow very easily in between the dendrites. Thus, shrinkage porosity is unlikely to form in this alloy and the small pores observed in these images are believed to be gas porosity.

Let us focus our attention on the pore located to the left in the images. At the onset of this sequence, a small pore nucleates and is trapped within the dendrite arms (small white spherical bubble). In fact, the origin of this bubble can be traced to earlier frames, revealing it to be an elongated air bubble at the surface of the mold, probably in a tiny groove, that was present prior to the start of solidification. As the dendrite front approached the air bubble, some liquid, probably induced by the density difference, caused the bubble to escape from the groove and become a spherical bubble trapped among the dendrites. It then moved toward the eutectic front in Fig. 12.2(b) under the influence of buoyancy forces. As the eutectic front passed around the pore, it became more ellipsoidal (Fig. 12.2c). The smaller pore seen in the top right corner in this sequence followed a
similar evolution. We can thus conclude that gas porosity forms early in the mushy zone, is associated with a certain gas precipitation (in this case the gas was already present) and is nearly spherical because it grows in a fairly open dendritic network.

In contrast to gas porosity, shrinkage porosity forms deep in the mushy zone in fairly large solidification interval alloys. It is induced primarily by the difficulty to provide the shrinkage flow required by the final solidification of a solid phase that is denser than the interdendritic liquid, e.g., the Al\(_2\)Cu phase in Al-Cu alloys. Figure 12.3 illustrates the formation of shrinkage porosity in an Al-10wt\%Cu alloy through a sequence of micrographs obtained by X-ray tomography. In this case, the specimen was about 1 mm in diameter and 2 to 3 mm long. The liquid was self-contained by its oxide skin during heating in an air-blowing furnace. It was then solidified by air cooling, while simultaneously being examined by X-ray tomography. Figure 12.3 shows a longitudinal section of the reconstructed 3-D microstructure. As the specimen cools, one first observes the formation of equiaxed dendrites (Fig. 12.3a). Note that the contrast is opposite to that of the radiographs shown in Fig. 12.2, i.e., the dendrites are darker than the Cu-rich liquid. Some very fine porosity (black region) is already present at the early stages of cooling, probably associated with the presence of entrained oxides. Notice that the surface of the specimen has already deformed inward as a result of solidification shrinkage and thermal contraction of both the liquid and solid phases, producing a sharp cusp on the left, in a region where the dendrites are widely spaced, and a smooth S-shape in the upper right corner. The fraction of primary phase increases with time, and the lighter colored liquid is close to the eutectic composition at the time of Fig. 12.3(b). A pore with a size on the order of the secondary dendrite arm spacing subsequently can be seen to have nucleated in the upper left part of the specimen. The image in Fig. 12.3(c) suggests that new pores formed as the solidification of the eutectic phase
was completed. A 3-D reconstruction of the porosity, obtained using x-ray microtomography, is shown in Fig. 12.4. One can see clearly that this was actually a single pore with a very complex shape, resulting from growth in the tortuous space left between the solid dendrites. This is a typical feature of shrinkage porosity.

**Key Concept 12.2: Governing equations for microporosity**

Although shrinkage and gas microporosity have quite different morphologies and appear at quite different stages of solidification, they both involve the nucleation and growth of pores. The main contribution for gas porosity is the evolution of dissolved gases, whereas that of shrinkage porosity is the failure to feed solidification shrinkage. Nevertheless, both can be described using the same set of governing equations to determine the pressure drop in the mushy zone associated with liquid feeding and segregation/precipitation of dissolved gases.

Models for the two cases are developed in Sects. 12.3 and 12.4–12.5, respectively. Before doing so, we first extend the average mass balance equation derived in Sect. 4.2 to the case where a compressible phase is present. Section 12.6 addresses the issue of boundary conditions to apply to the problem of liquid feeding, and Sect. 12.7 presents a few applications of the theory and models presented in this chapter.
12.2 GOVERNING EQUATIONS

Consider a fixed representative volume element (RVE) of the mushy zone within which the liquid, various solid phases and pores coexist. The average mass conservation equation for such a volume element, derived in Chap. 4, is

$$\frac{\partial \langle \rho \rangle}{\partial t} + \nabla \cdot (\langle \rho \rangle \mathbf{v}) = 0 \quad (12.1)$$

where the density $\langle \rho \rangle$ is averaged over the various phases

$$\langle \rho \rangle = \rho_\ell g_\ell + \rho_p g_p + \sum_{\nu} \rho_\nu g_\nu = \rho_\ell g_\ell + \rho_p g_p + \langle \rho \rangle_s g_s \quad (12.2)$$

The subscript $p$ refers to the pore, and $\langle \rho \rangle_s$ is the density averaged over the $N$ solid phases. Neglecting the density of the gaseous phase, and introducing the pore-free average density $\langle \rho_0 \rangle_i = (\rho_\ell g_\ell + \langle \rho \rangle_s g_s)/(g_\ell + g_s)$, the average density can be expressed as

$$\langle \rho \rangle = \langle \rho_0 \rangle_i (1 - g_p) \approx \langle \rho_0 \rangle - \rho_\ell g_p \quad (12.3)$$

since $g_p + g_s + g_\ell = 1$. Following the same procedure, the average mass flow $\langle \rho \mathbf{v} \rangle$ is given by

$$\langle \rho \mathbf{v} \rangle = \rho_\ell g_\ell \langle \mathbf{v} \rangle_\ell + \langle \rho \rangle_s g_s \langle \mathbf{v} \rangle_s \quad (12.4)$$

We have neglected the mass transport associated with the gaseous phase, and assumed that all of the solid phases have the same average velocity $\langle \mathbf{v} \rangle_s$ at the scale of the RVE. Inserting Eqs. (12.3) and (12.4) into Eq. (12.1) yields

$$\frac{\partial \langle \rho_0 \rangle_i}{\partial t} - \rho_\ell \frac{\partial g_p}{\partial t} + \nabla \cdot (\rho_\ell g_\ell \langle \mathbf{v} \rangle_\ell) + \nabla \cdot (\langle \rho \rangle_s g_s \langle \mathbf{v} \rangle_s) = 0 \quad (12.5)$$

The term $g_p \partial \rho_\ell / \partial t$ has been neglected in Eq. (12.5) since it is much smaller than the others. The leading term, $\partial \langle \rho_0 \rangle / \partial t$, represents the change in density due to the combined effects of solidification shrinkage and thermal contraction of the solid and liquid phases. This change in density must be compensated by three phenomena: void growth in the liquid (second term), inward flow of the interdendritic liquid (third term) or compression of the solid phase (fourth term). If the solid phase is under a tensile load, arising for instance from external constraints, void growth and interdendritic flow must produce additional compensating volumes, which can lead to hot tears, as discussed in Chap. 13. Three cases are illustrated in Fig. 12.5: the compensation of shrinkage by interdendritic flow in (a), void formation in (b) and the additional effect of tensile strains in (c).

We focus on porosity for the remainder of this chapter, ignoring strains in the solid for now, to be taken up again in Chap. 13. This simplifies the mass conservation equation.
Key Concept 12.3: Mass conservation equation for microporosity

Considering a fixed solid, the mass conservation equation governing fluid flow and microporosity formation becomes:

$$\frac{\partial \langle \rho_0 \rangle}{\partial t} - \rho_\ell \frac{\partial g_p}{\partial t} + \nabla \cdot (\rho_\ell g_\ell \langle \mathbf{v} \rangle_\ell) = 0$$  \hspace{1cm} (12.6)

where $\langle \rho_0 \rangle$ is the pore-free average density of the solid and liquid phases, $g_p$ is the volume fraction of pores and the last term represents liquid feeding. There are two unknown fields in this equation: the pore fraction $g_p(x,t)$ and the velocity field $\langle \mathbf{v} \rangle_\ell(x,t)$. An additional (state) equation will be required to find a solution. As we will show later, this equation relates the pore fraction and the local pressure in the liquid, considering the various gaseous and volatile elements contained in the alloy.

We treat first the case of fluid flow in the mushy zone without pore formation, thus allowing to find the pressure drop in the mushy zone due to solidification shrinkage, and then return to consider pore formation.