Solidification of Metals

Class-6/5th SEM

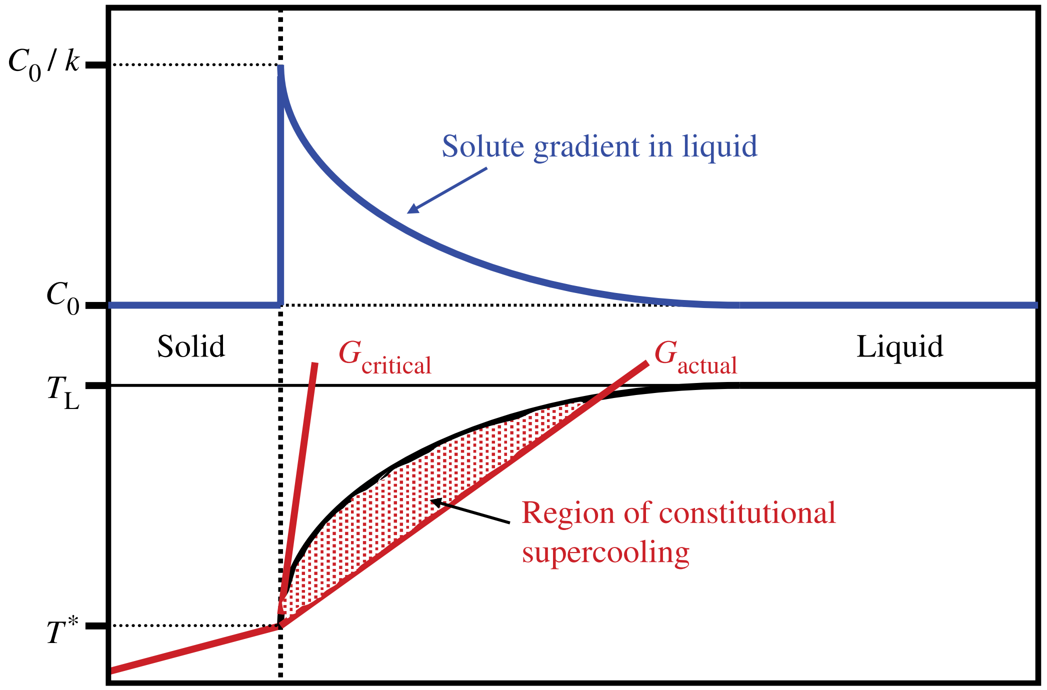

FIGURE 2.13 Simplified schematic of the constitutional supercooling theory for the case of $k < 1$.

when the temperature gradient (G_L) is very steep. In fusion welds, this condition is only satisfied at the fusion boundary, as discussed later in this chapter.

Sections 2.3.2 and 2.3.3 summarize the macroscopic and microscopic aspects of weld solidification and are not intended to be a comprehensive review of these topics. For more detailed coverage of weld solidification, the reader is referred to review papers by Davies and Garland [9], David and Vitek [10], and Katayama [11, 12].

2.3.2 Macroscopic Aspects of Weld Solidification

Solidification of welds occurs under nonequilibrium conditions and must be studied from both a macroscopic and microscopic viewpoint. Macroscopic solidification will be considered at both the trailing edge of the weld pool and along solidification grain boundaries (SGBs). From a solute redistribution standpoint, the macroscopic approach considers the solidification front as a plane front even though microscopically this front is usually cellular or dendritic. The macroscopic shape of the weld pool will be shown to be strongly influenced by welding conditions, particularly heat flow, heat input, and travel speed.

Microscopic solidification will be used to describe the formation and solute redistribution of solidification subgrains, such as cells and dendrites. Solidification parameters k, G_L, R, and $G{\cdot}R$ affect the nature of microscopic solidification and segregation.

As noted previously and illustrated in Figure 2.8, nucleation in fusion welds is dominated by epitaxial growth from the surrounding base metal. The thermodynamic driving force required for epitaxial nucleation is very low, and essentially, no undercooling is required for nucleation to occur. The newly formed grains maintain the same crystallographic orientation as the base metal grains from which they nucleate. As a result, grain boundaries are continuous across the fusion boundary.

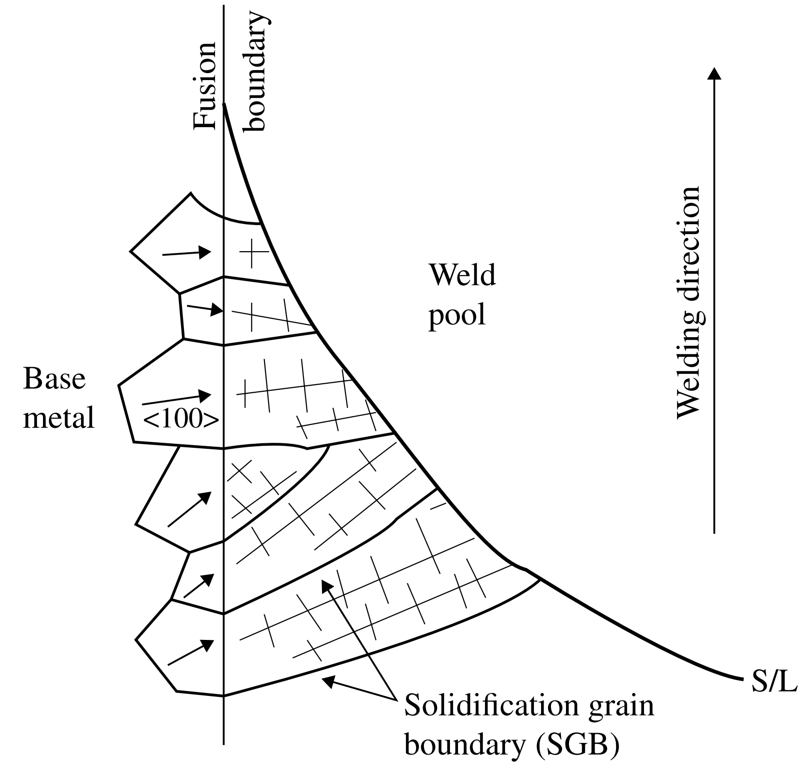

FIGURE 2.14 Illustration of epitaxial nucleation and competitive growth (From Ref. [16]. © AWS).

In fcc and bcc metals, which constitute the bulk of the engineering alloys that are commonly welded, solidification occurs preferentially along the cube edge, or <100> directions. These are sometimes called “easy growth” directions because solidification is most efficient in these orthogonal directions. This growth direction is maintained as long as the solidifying grain remains in contact with the S–L interface or until it is grown out of existence by adjacent weld metal grains that are more favorably oriented. This latter phenomenon is called “competitive” growth. The boundaries between these grains are defined as SGBs. The concepts of epitaxial nucleation and competitive growth are illustrated in Figure 2.14.

Occasionally, nonepitaxial nucleation and growth may occur in the fusion zone. The introduction of heterogeneous nuclei directly into the weld pool may cause nucleation to occur in advance of the S–L interface. For example, the addition of titanium oxide powder into titanium and aluminum welds has been shown to promote nucleation and grain refinement [13, 14].

In some systems, heterogeneous nuclei may actually form in the liquid ahead of the advancing interface. This is most likely to occur along the weld centerline where the temperature gradient is shallow and these nuclei cannot be swept into hotter regions of the weld pool. Nonepitaxial nucleation has also been observed along the fusion boundary in some systems. For example, in lithium-bearing aluminum alloys, small equiaxed grains have been observed at the fusion boundary that nucleate from $Al(Li, Zr)_3$ particles from the base metal [15].

Nonepitaxial nucleation has also been identified in systems where the base metal and weld metal have different crystal structures. For example, when austenitic stainless steel or Ni-base alloys (fcc) are deposited onto a ferritic steel (bcc), there is no evidence

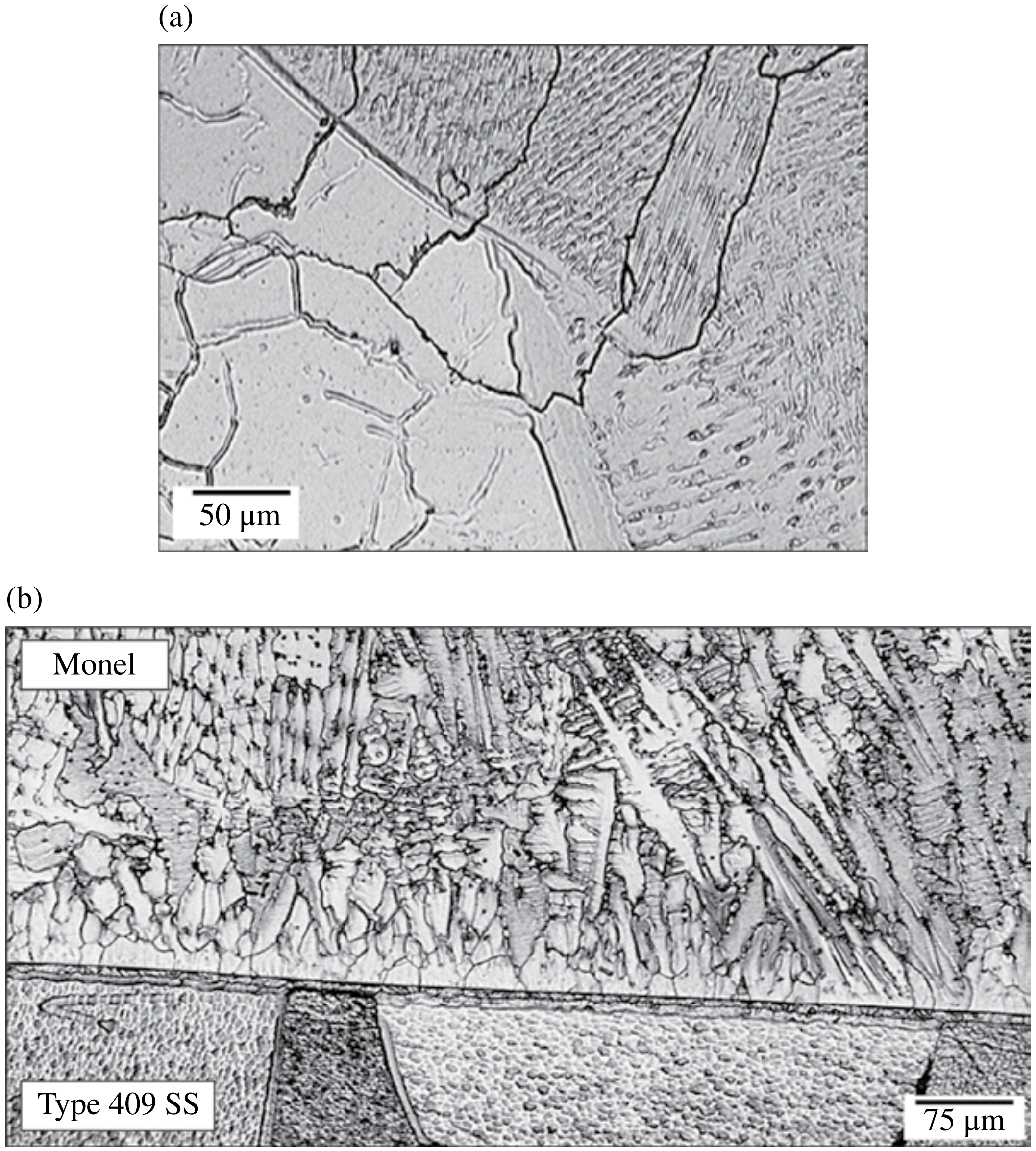

FIGURE 2.15 Examples of (a) epitaxial nucleation in austenitic stainless steel and (b) non-epitaxial nucleation of fcc weld metal (Monel) deposited on bcc base metal (Type 409 SS).

of epitaxy at the fusion boundary. The bcc substrate effectively acts as a "mold wall," and nucleation of fcc crystals occurs heterogeneously [16, 17]. Examples of epitaxial and nonepitaxial nucleation at the fusion boundary are provided in Figure 2.15.

Because of epitaxial nucleation and growth, grains will solidify along easy growth directions at the trailing edge of the weld pool. Base metal grains in polycrystalline metals are normally randomly oriented, and the resulting fusion zone grains will adopt the same degree of misorientation. Growth is most favorable along the heat flow direction or, conversely, perpendicular to the temperature isotherms at the S–L interface. These isotherms run roughly parallel to the S–L interface. Grains are most favored whose growth direction is most nearly perpendicular to the S–L interface.

The macroscopic weld pool shape is determined by a combination of material physical properties, process parameters, and heat flow conditions. Two general types of pool shape, teardrop and elliptical, are normally encountered as illustrated in Figure 2.16 [1]. Elliptical pools are usually associated with high heat input, low travel speeds, and 3-D heat flow conditions. Materials with high thermal conductivity, such as aluminum and copper, form elliptical weld pools over a wide range of conditions.

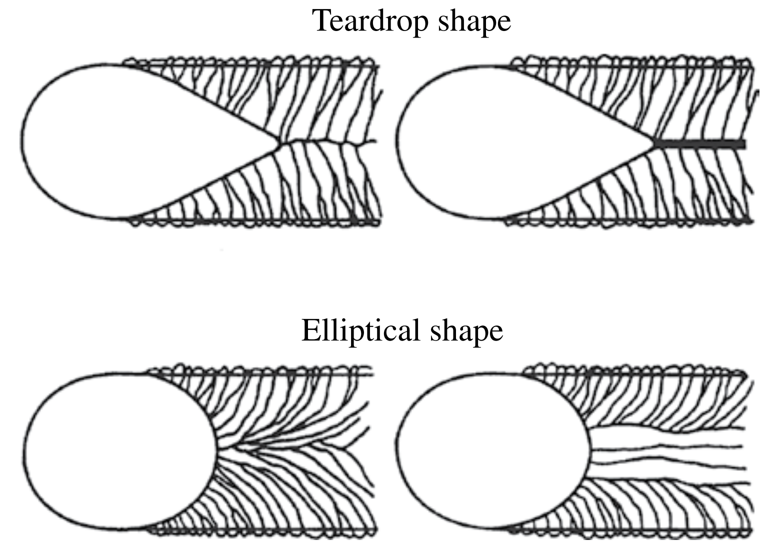

FIGURE 2.16 Illustration of the elliptical and teardrop-shaped weld pools (From Ref. [18]. © Wiley).

Teardrop pool shapes are most favored when travel speeds are rapid, thermal conductivity is low, and heat flow is 2-D. For example, austenitic stainless steels and nickel-base alloys often exhibit teardrop shape pools when welded in thin-sheet form at high travel speeds. This shape is generally to be avoided in high-restraint conditions, since centerline cracking can be a problem.

Fluid flow in the weld is affected by a number of forces including buoyancy, electromagnetic, and surface tension. Surface tension-induced fluid flow may dominate these other forces in some cases, often resulting in significant heat-to-heat variations in weld pool shape and penetration characteristics. This behavior is shown in Figure 2.17.

In systems where surface tension decreases as temperature increases, the hot fluid under the arc flows along the surface to the periphery of the weld and causes melting at the weld edge, or toe. If the surface temperature gradient is positive, a strong downward flow occurs and melting is most efficient at the root of the weld. The latter case provides the best weld penetration.

Small changes in composition can promote large changes in penetration due to the so-called "Marangoni" effect [18]. For example, reducing sulfur content in stainless steels from 0.010 to 0.003 wt% can result in a 50% reduction in weld penetration. Other elements, including oxygen, titanium, and aluminum, may have similar effects.

2.3.2.1 Effect of Travel Speed and Temperature Gradient Weld pool shape is usually controlled by adjusting the weld travel speed. At high travel speeds in materials with low thermal conductivity, heat extraction from the weld becomes more difficult and the pool tends to elongate. This results in a gradual evolution from an oval, or elliptical, shape to a teardrop, as illustrated in Figure 2.18. In the elliptical pool, the angular relation of the velocity vector and principal heat flow direction at the S–L interface relative to the fusion boundary gradually changes from perpendicular to parallel upon moving toward the centerline. This results in considerable competitive growth along the solidification front.

The growth rate at the fusion boundary is extremely low relative to the weld centerline and approaches zero at the point that epitaxial nucleation and solidification begin at the fusion boundary. As noted previously, this low growth rate (in addition to higher temperature gradients in the liquid) can support planar solidification at the fusion boundary. As R increases, the planar front breaks down and cellular and dendritic growth modes dominate.

These shifts in solidification mode are illustrated schematically in Figure 2.20 from Easterling [2]. In actuality, most of the fusion zone solidifies in the same mode, usually cellular or cellular dendritic. In materials that solidify as fcc (austenite), such as austenitic stainless steels and Ni-base alloys, it is common to see evidence of planar growth at the fusion boundary, as shown in Figure 2.21a. The remainder of the fusion zone normally solidifies in a cellular/cellular dendritic mode, as shown in Figure 2.21b. Equiaxed dendritic solidification is rarely observed, except in the terminal weld crater as shown by the cross section and SEM micrograph in Figure 2.22.

2.3.3 Microscopic Aspects of Weld Solidification

On a microscopic scale, the fusion zone consists of a solidification microstructure exhibiting various types of interfaces or boundaries. It is important to understand the nature of boundaries in the fusion zone, since many of the defects associated with this region, both during fabrication and service, are associated with these boundaries. At least three different boundary types can be observed metallographically, as shown schematically in Figure 2.23.

Solidification subgrain boundaries (SSGBs) are the finest resolvable boundaries in the microstructure. These result from the formation of cells and dendrites during the solidification process. These boundaries form under microscopic solidification conditions and solute redistribution according to the boundary conditions described later in this section. Crystallographic misorientation across these boundaries is small, that is, they represent low-angle boundaries.

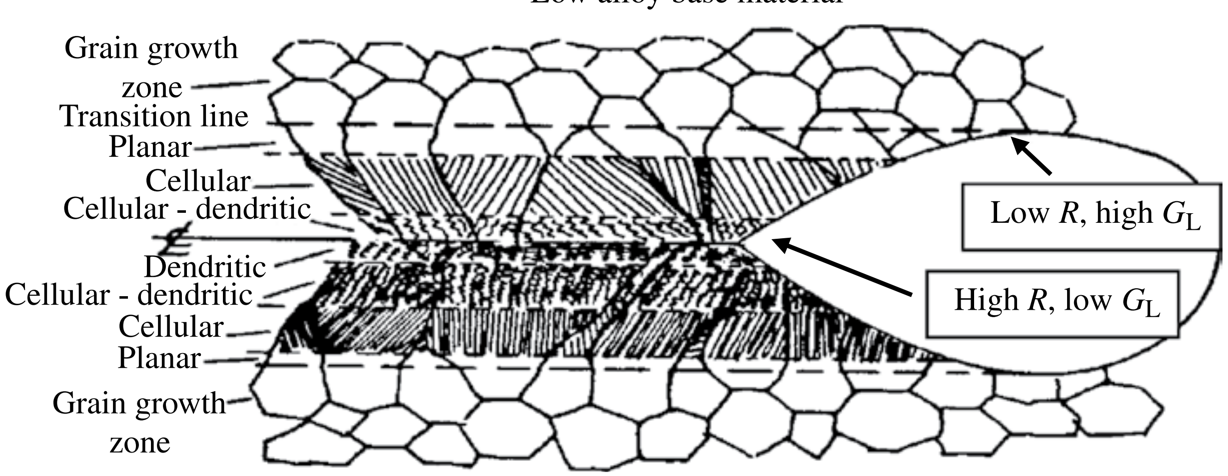

FIGURE 2.20 Change in solidification growth mode as a function of location in the weld (From Ref. [2]. © Wiley).

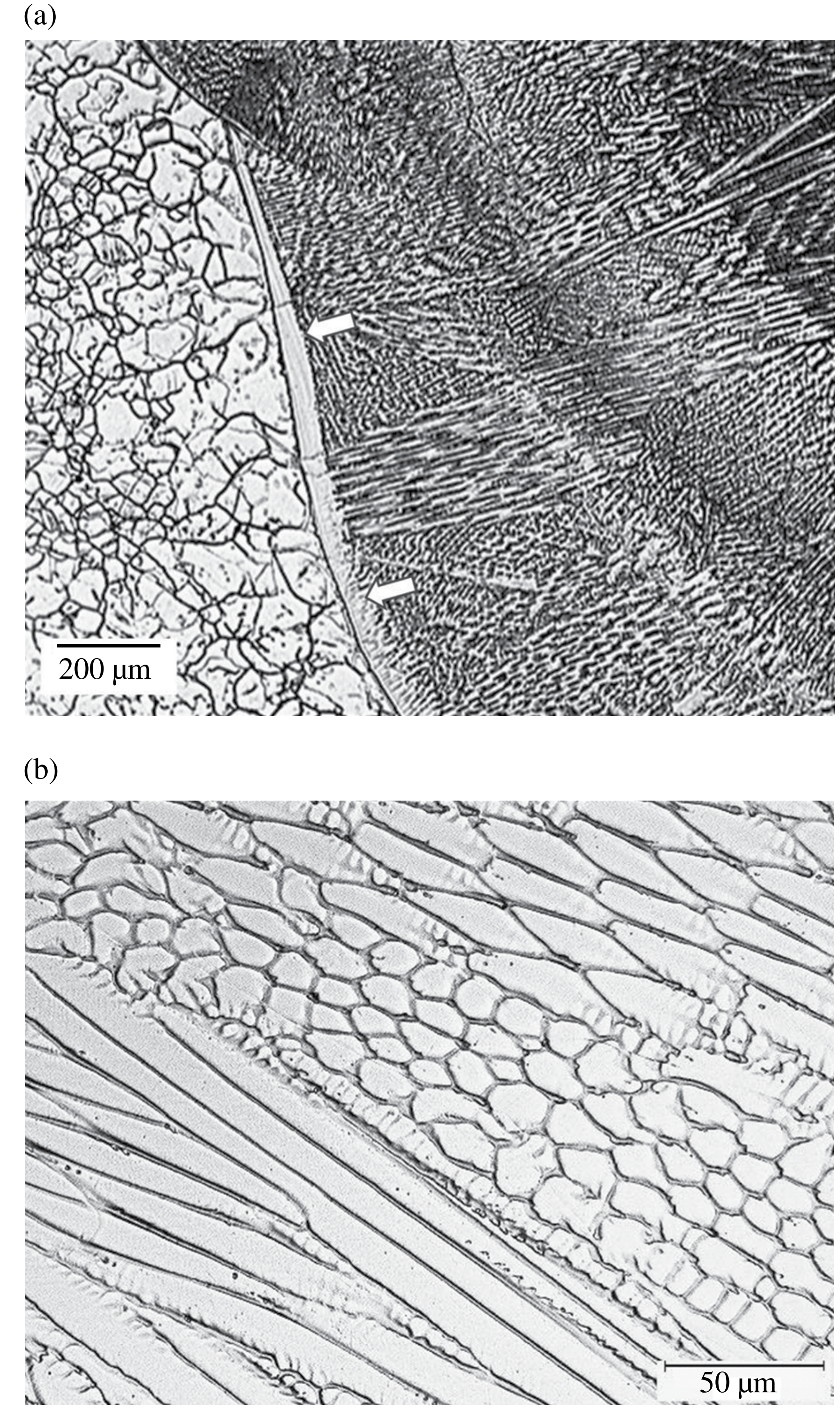

FIGURE 2.21 Examples of planar (a) and cellular dendritic (b) growth modes.

Solidification grain boundaries (SGBs) arise from the intersection of packets of subgrains, resulting in a crystallographic misorientation across the boundary. Solute and impurity segregation to these boundaries during solidification is defined under the macroscopic solute redistribution conditions described in Section 2.3.4.1.

Migrated grain boundaries (MGBs) represent true crystallographic grain boundaries in the fusion zone. These boundaries maintain the misorientation of the parent SGBs that they migrated from following solidification.