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The Nature of Surface Cracking in Direct Chill Cast Aluminum Alloy Ingots

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The vertical direct chill (DC) semicontinuous casting process has been the mainstay of the aluminum industry for the production of billets and ingots since the late 1930s due largely to its robust nature and relative simplicity. Unfortunately, the process can produce distortions in the ingot and cracks can form[1,2,3] owing to the nonuniform, high rate of heat removal imparted by the direct contact of the bottom block or water with the partially solidified ingot. The surface crack is one type of crack that increases the cost and reduces the yield of the DC casting process. This article is concerned with the nature of the surface cracking in large cross-section ingots produced using the DC casting process.

In the DC casting process, molten metal flows into a short, rectangular, water-cooled mold, which is initially closed by a plug (called a starter or bottom block) on a movable ram. The metal freezes against the bottom block and forms a shell on the mold surface. The ram is then steadily withdrawn, pulling the shell with it. As the shell exits the bottom of the mold, cold water is sprayed directly on it for cooling. In this manner, a cast ingot of a desired length is produced.

Figure 1 shows one quarter of a horizontal cross section of a 3004 alloy ingot with overall dimensions of 0.7 × 1.85 × 7.6 m (28 × 73 × 300 in.). The composition of aluminum 3004 alloy is given in Table I. The section was obtained approximately 0.15 m (6 in.) from the bottom of the ingot. Small surface cracks occur near the middle and quarter point of the long side of the ingot. The locations of the surface cracks are marked A and B. Research[4–7] has been carried out to control the formation of surface cracks, but the nature of the crack formation is unclear. During DC casting, the ingot surface is in direct contact with either a metal mold or cooling water. This often leads to expectations that the surface crack could be a cold crack,[7] *i.e.*, one that occurs below the solidus temperature of the alloy, rather than a hot tear, *i.e.*, one that occurs above the solidus temperature.

It is difficult to believe that the stresses or strains generated during DC casting due to the uneven shrinkage of the ingot can produce cracks in solid aluminum, which is highly ductile at elevated temperatures. In order to clarify the nature of the surface crack, *i.e.*, whether it was a cold crack or a hot tear, we examined cracks on samples taken directly from the surface of a DC cast ingot. The microstructure around the crack was examined. The samples were then fractured along the crack and scanning electron microscopy (SEM) images of the crack surface were obtained.

The middle photograph in Figure 2 shows the entire crack, indicating that it is approximately 50 to 80 mm deep. The top micrograph in Figure 2 shows the crack and the microstructure near the surface of the ingot. The bottom micrograph in Figure 2 shows the tip of the crack and the microstructure near the tip. The aluminum alloy grains are equiaxed throughout the ingot due to the addition of a grain refiner. If we track the crack from the ingot surface all the way to its tip, we see that the crack is formed along grain

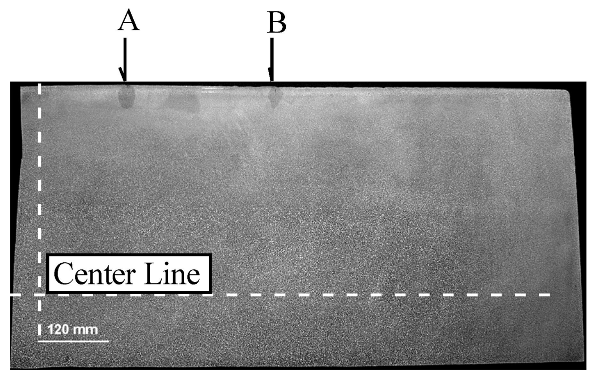

Fig. 1—One quarter of a horizontal cross section of a DC cast aluminum 3004 alloy ingot. Surface crack locations are indicated by A and B.

Table I. Nominal Composition (in Weight Percent) of 3004 Alloy

Mg	Mn	Si	Fe	Cu	Zn	Al
1.0	1.25	0.3	0.7	0.2	0.25	balance

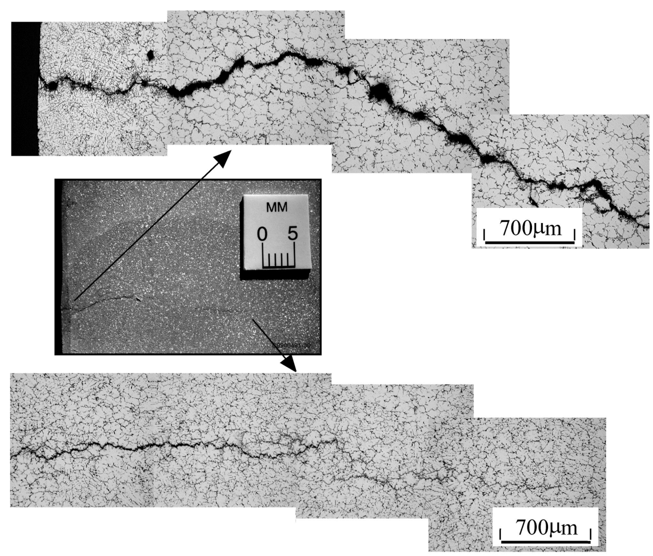

Fig. 2—A surface crack, shown in the middle of the figure with enlarged views at the top and bottom indicating the surrounding microstructure. Note that the crack lies between dendrites or along grain boundaries.

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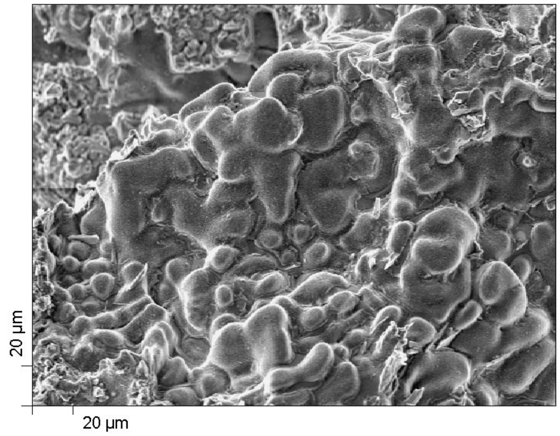

Fig. 3—Scanning electron microscopy image of the crack surface. Dendrites are clearly visible on the fracture surface.

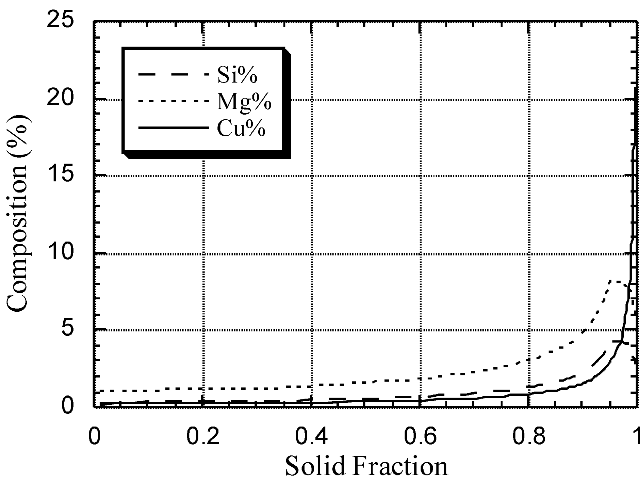

Fig. 4—Calculated concentrations of solute elements in the interdendritic liquid during solidification of aluminum 3004 alloy. Copper, silicon, and magnesium segregate in the last liquid to solidify.

boundaries. No transgranular cracking was observed. At the tip of the crack, small secondary cracks invisible to the naked eye are evident. These secondary cracks are discontinuous but are also formed along grain boundaries.

If we fracture the sample along the crack, we can observe the morphology of the crack surface using SEM. As shown in Figure 3, dendrites are clearly visible on the fracture surface. This is evidence that the crack is due to hot tearing. If the fracture occurred at temperatures below the solidus temperature of the alloy, the fracture would likely be transgranular. The dendritic morphology of the fracture surface is usually an indication that the fracture occurred near the end of solidification when some liquid is present in the interdendritic region, but is not sufficient to fill or heal the crack.

Figure 4 shows the segregation of solute elements during the solidification of aluminum 3004 alloy calculated using the thermodynamic simulation software THERMO-CALC*[8] and a commercially available aluminum database.[9] The segregation was calculated assuming nonequilibrium Scheil conditions commonly prevalent during solidification (*i.e.*, no diffusion of solute in the solid, complete mixing of solute in the liquid, and local equilibrium at the solid-liquid interface). In the literature, the Scheil condition has been widely shown to be appropriate for modeling the solidification of aluminum alloys.

*THERMOCALC is a trademark of Thermocalc Software, Stockholm, Sweden SE-113 47.

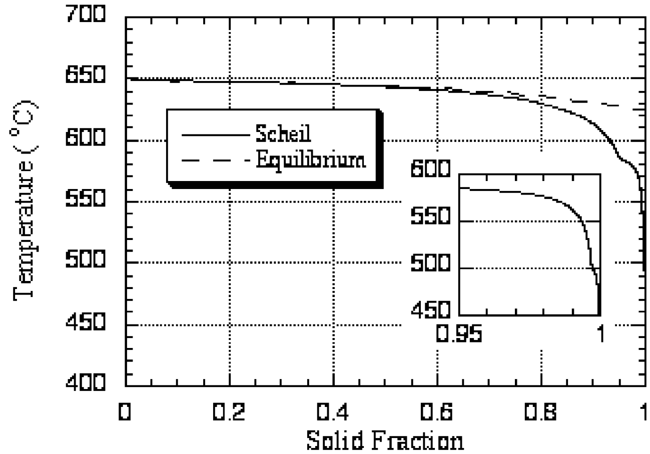

Fig. 5—Relationship between temperature and solid mole fraction calculated for the solidification of aluminum 3004 alloy. The solidus temperature for nonequilibrium solidification (Scheil type) is much lower than that under equilibrium conditions.

As shown in Figure 4, magnesium, silicon and copper tend to segregate in the last regions to solidify. The concentration of magnesium in the liquid increases from 1 to about 8 pct when the solid fraction reaches 0.9. The silicon concentration increases from 0.3 to more than 4 pct in the last region to freeze. The copper concentration increases from 0.2 to more than 20 pct until Al_7Cu_2Fe forms. The segregation of copper, silicon, and magnesium significantly decreases the solidus temperature in the last region to solidify. These regions are usually dendrite or grain boundaries where hot tearing is expected to occur. As shown in Figures 2 and 3, the surface crack occurs along dendrite or grain boundaries.

Figure 5 shows plots of the fraction solid *vs* temperature for aluminum 3004 alloy. The top curve was calculated assuming equilibrium conditions, *i.e.*, the lever rule, while the bottom curve was calculated assuming nonequilibrium Scheil conditions. A comparison of the two curves in Figure 5 indicates a significant difference in the calculated solidus temperature for equilibrium and the normal nonequilibrium Scheil-type solidification of aluminum 3004 alloy. Whereas the equilibrium phase diagram would predict a solidus temperature of 624 °C, the actual solidus temperature is likely significantly lower. In fact, it could be as low as 450 °C, the eutectic temperature of binary aluminum-magnesium alloys.

The metallographic evidence of the crack pattern, the SEM image of the fracture surface, and an analysis of the solidification behavior of aluminum 3004 alloy permit us to establish a phenomenological model of surface cracks in DC cast ingots: (a) segregation during solidification significantly lowers the solidus temperature of the alloy; (b) the lowered solidus temperature permits interdendritic liquid to persist for longer times during casting, in particular when the solid fraction is close to one; (c) the preceding conditions make it more likely that interdendritic liquid will be present when the surface of the ingot experiences tensile stress; and

(d) the presence of interdendritic liquid embrittles the alloy and promotes hot tearing.

The preceding analysis suggests that the surface cracks that occur during DC casting of aluminum alloys are hot tears that form above the solidus temperature, rather than cold cracks that form below the solidus temperature. Consequently, the prediction of surface cracking during DC ingot casting requires an analysis of the stress state during casting as well as the local solidification conditions, in particular, the effect of microstructure, segregation, and interdendritic liquid.

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