Research Programs

Evolution of the Eutectic Microstructure During Solidification of Hypoeutectic Aluminum-Silicon Alloys

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Foundry alloys are usually alloyed close to the eutectic composition due to the small freezing range, good castability and desirable properties obtained. The most important aluminum foundry alloys are based on the Al-Si system, especially the hypoeutectic alloys with compositions ranging from 7 to 11 wt. % silicon. Solidification of these alloys is characterized by four events: (1) a short nucleation event, followed by (2) growth of the dendrites until they impinge on one another, (3) growth and coarsening of the dendrite arms, and finally (4) eutectic precipitation. Though the initial steps are fairly well understood, the precipitation of the eutectic is not well understood. In hypoeutectic Al-Si alloys, the eutectic precipitates at the end of the solidification "journey", after the primary dendrites have been formed. Thus the eutectic can nucleate either on the primary dendrites, within the inter-dendritic liquid by heterogeneous nucleants, or on the mold walls.

The main objective of this research project is to understand the mechanism and the sequence of events that lead to the formation of the eutectic microstructure in aluminum silicon hypoeutectic casting alloys. Understanding the mechanism of eutectic formation is essential to analyzing resistance to melt flow. Melt flow influences feeding efficiency, which, in turn influences shrinkage, porosity formation, and segregation.

Mechanism of Evolution of Eutectic Phases in Unmodified Hypoeutectic Al-Si Alloys

During solidification, the primary aluminum phase forms as dendrites at the liquidus temperature of the alloy. This is followed by the evolution of a secondary β-(Al,Si,Fe) phase at some temperature between the liquidus temperature and the eutectic temperature of the alloy depending on the concentration of Fe in the alloy. At the eutectic temperature, and at an undercooling of 0.4°C-0.8°C, eutectic silicon (Si_{eut}) nucleates on the secondary β-(Al,Si,Fe) phase in the solute field ahead of the growing aluminum dendrites. Once nucleated, the eutectic silicon grows as flakes into the eutectic liquid. The liquid surrounding the eutectic silicon flakes become enriched with aluminum as it is being depleted of silicon; consequently, eutectic aluminum (Al_{eut}) nucleates and grows on the edges and tips of the eutectic silicon flakes. Finally, the aluminum dendrites stop growing upon impingement with the growing eutectic aluminum grains. A representative TEM microstructure to substantiate the proposed mechanism is shown in Figure 1.

Mechanism of Evolution of Eutectic Phases in Sr Modified Hypoeutectic Al-Si Alloys

Strontium is in solid solution in the melt and its concentration in the eutectic liquid within the interdendritic regions reaches relatively high levels at the end of solidification of the mushy zone. Strontium in solution changes the rheological characteristics (specifically, it increases viscosity) of the eutectic liquid ahead of the β-Al dendrites. The interface characteristics between the eutectic liquid and the solids in the melt are so altered by the presence of strontium that the wetting angle between the eutectic liquid and the solid...
substrates (the $\beta$-(Al,Si,Fe) particles) on which the eutectic phases nucleate is increased. Hence, the eutectic phases do not nucleate on the solid substrates at the eutectic temperature and significant undercooling of the melt occurs. Meanwhile, the $\alpha$-Al dendrites continue to grow rendering the eutectic liquid ahead of them super saturated with silicon. The eutectic liquid now acts as a highly undercooled hypereutectic alloy and the silicon super saturation in the liquid reduces the liquid's viscosity and the liquid/$\beta$-(Al,Si,Fe) interface wetting angle so that primary (blocky) silicon particles instantaneously nucleate ahead of the dendrites forming a boundary between the $\alpha$-Al dendrites and the liquid. The liquid can no longer penetrate through the chain of blocky silicon particles (interface effect) to further the growth of the $\alpha$-Al dendrites. This triggers an instantaneous nucleation of numerous Al grains in the supercooled liquid. The eutectic silicon instantly nucleates and grows between the arrays of Al grains. This forces silicon to acquire a 'fibrous tree-like' morphology rather than a 'flaky plate-like' morphology. In unmodified alloys, silicon nucleates before the eutectic Al nucleates and this result in a free growth of silicon into the eutectic liquid resulting in its typical plate-like morphology. In modified alloys, on the other hand, the growth of $\alpha$-Al dendrites is halted resulting in large number of equiaxed eutectic Al grains nucleating before the nucleation of the eutectic silicon and hence silicon is forced to grow in between the Al grains as a fibrous coral morphology. Figure 2 shows the viscosity vs. temperature curves for unmodified and Sr modified Al-Si alloys. Figure 3 and 4 show representative microstructures of Sr modified Al-Si alloys to substantiate the proposed mechanism.

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Figure 1 Summary of TEM analysis of an Al-7wt.%Si alloy solidified at 200°C/min. A schematic of the TEM image is shown to highlight the Al dendrite, eutectic Al grains and eutectic Si flakes. The schematic is a 1:1 scale representation of the TEM micrograph. Crystallographic relations were observed between various eutectic Al and eutectic Si and are shown in the image. One such crystallographic relationship is shown from a set of diffraction patterns obtained from eutectic Al, interface between eutectic Al and Si, and eutectic Si marked A, B and C, respectively. The other crystallographic relationships observed between eutectic Al and Si were obtained from location marked 1 through 7 in the schematic and listed as Area 1 through Area 7, respectively in the image. Each location is marked with a circle in the schematic for better visualization.
Figure 2: Viscosity (η) vs. Temperature (T) for unmodified and Sr modified Al-12.7wt.% Si alloys. The Sr modified alloy is more viscous and hence, has a higher surface tension value.

Figures 3 and 4 show representative microstructures of Sr modified Al-Si alloys to substantiate the proposed mechanism.

Figure 3: Typical microstructures of Sr modified Al-7wt.%Si alloy solidified at 200°C/min. (a) Ga ion beam image showing one α-Al dendrite and the adjoining eutectic phases in an air cooled sample. (b) TEM image showing one α-Al dendrite and adjoining eutectic phases in another air cooled sample. Both images show a fine equiaxed eutectic Al grains along with a refined eutectic Si morphology.
Figure 4: TEM micrographs of various Sr modified Al-7wt.%Si alloy samples. (a) Bright field image showing the boundary between $\alpha$-Al dendrite and eutectic region. (b) is a centered dark field image of $\alpha$-Al dendrite showing the distinct boundary between the $\alpha$-Al dendrite and the eutectic region. (c) and (d) are high magnification bright field images of the chain of blocky Si particles nucleated at the boundary between $\alpha$-Al dendrite and the eutectic region. Also seen in all four images are the fine equiaxed eutectic Al grains.