The Microstructural Characterization of Semi-Solid Slurries

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INTRODUCTION

Conventional solidification of foundry alloys including Al-Si takes place with the dendritic formation of the primary α-Al phase in the eutectic matrix. The alloy composition, temperature gradient within the melt, convection, and rate of heat extraction and the resulting constitutional supercooling are the most effective parameters on the morphology of the primary α-Al phase. Variation of any of these factors during solidification should alter the as-cast structure. For instance, the introduction of agitation (forced convection) into the solidifying melt changes the distribution of chemical composition. This could remove constitutional supercooling and promote dendrite-to-equiaxed transformation (the breakdown and globularization of the α-Al phase). The degeneration of the α-Al phase creates some opportunities that are of commercial interest.

The advantages of semi-solid metal (SSM) processing and available technologies have been discussed in the past by other researchers, including the authors. There is no doubt of the great potential of SSM. However, the lack of industrial interest in the 1980s and 1990s stemmed mainly from the high cost of billet preparation and the issue of recycling the returned and scraped parts. Those problems were solved with the application of new materials and alloying systems as well as the introduction of more cost-effective rheocasting techniques. The techniques involve the preparation of SSM slurry from the liquid phase and directly transferring it into a die or mold for component shaping.

In order to generate a semi-solid structure, the alloy system plays a key role where the co-existence of liquid and solid within a temperature range is the prerequisite for the slurry preparation. The mechanics and mechanisms of the primary particles’ evolution (dendrite-to-equiaxed transformation) is the next concern since the formation of globule morphology is expected to enhance die filling and improve mechanical properties of as-cast parts. The ideal microstructure for an SSM slurry is individual fine spherical solid particles uniformly distributed within a liquid matrix. The solid fraction should be considered carefully, since a low-fraction solid may lead to handling and mold-filling problems due to insufficient viscosity and turbulence. High-fraction solids, however, may have die-filling troubles or increase the cost of machinery.

According to the described requirements, characterization of semi-solid material is necessary to confirm, modify, and obtain an optimum structure for the SSM component-shaping process. This knowledge not only gives an idea about the material, but also could lead to better understanding of rheological behavior.
and eventually improve the mechanical properties of cast pieces.

**STRUCTURAL ANALYSIS**

In order to be able to accurately characterize SSM microstructure, it is necessary to understand the features and complexity of the resulting solidified structures and be able to differentiate between the observed two-dimensional (2-D) structures and the actual three-dimensional (3-D) morphologies.

Normally after initial visual inspection, the microstructure of the solidified alloy is observed on the plane of polish using optical microscopy. The 2-D analysis may not give a complete picture of the structure and sometimes could lead to invalid conclusions. This is particularly true for cases where, in spite of a well-distributed primary phase in the 2-D state, the inter-connectivity of isolated primary particles from underneath has resulted in misleading conclusions, especially on viscosity.

In the literature, different techniques are described that reveal the true morphological evolution of the primary phase, including reconstruction of 3-D images by serial sectioning, x-ray microtomography, and finding the crystallographic orientation relationships. Serial sectioning is based on the successive grinding and polishing of the sample and capturing the consequent images. The major difficulties are calibration of the sectioning distance and also the working frame. These shortcomings are overcome by automatic polishing procedures and drilling guides and controlling holes perpendicular to the polished section. The morphology of primary particles together with their possible interconnectivity are characterized based on the position and shape of each feature along these serial sections. The final 3-D image is constructed with the aid of computer software.

Another technique, developed by Suery and his co-researchers, is x-ray micro-tomography (e.g., Reference 6). The system is based on the x-ray beam passing across the sample and consequently capturing the transmitted image by a charge-coupled-device camera. The sample is placed on a high precision rotating table. The final stage is the same as in the serial sectioning method which is retrieving a 3-D image of the sample. In this method, the contrast between the phases is directly related to the atomic number difference between various phases (Figure 1).

The more recent technique is the investigation of the microstructure by electron-backscatter diffraction. This technique is based on the crystallographic analysis of the surface texture, where primary particles with different crystallographic orientations appear in distinct colors. It is a quantitative technique to reveal the grain size, grain boundary, grain orientation and texture, and phase identification.

**Structural Complexities in SSM Alloys**

Polarized light microscopy and image analysis can be used to render a more reliable characterization of microstructural features in SSM cast parts where certain complexities may generate misleading results. In addition to microcopy-based routes, there are rheological tests as potential production-line quality checks to differentiate between globular and dendritic structures, as explained later in this article.

**Dendritic and Non-Dendritic Distinction**

Occasionally, solidification conditions may lead to dendritic growth in all or portions of the semi-solid billet. For example, the area most prone to dendritic solidification is near the mold wall. As a result, the final polished microstructure may show dendrites’ main trunks and their branches. Also, in some segments, isolated individual globules could be observed which are not real globules. As depicted schematically in Figure 2, the way dendrites intersect the polished surface may generate numbers of pseudo-individual and isolated particles. This is shown in Figure 3 for a metallographically prepared sample.

The conventional bright-field micrograph in Figure 3 confirms the inadequate nature of analysis carried out on 2-D sections. The dendrite secondary branches in this alloy will be treated as individual and isolated particles if processed by an image-analyzing system. This leads to erroneous interpretation of quantitative metallography results and...