An Article from the June 2003 *JOM*: A Hypertext-Enhanced Article

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Exploring traditional, innovative, and revolutionary issues in the minerals, metals, and materials fields.

Overview: Welding

Welding: Solidification and Microstructure

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Parameters that control the solidification of castings also control the solidification and microstructure of welds. However, various physical processes that occur due to the interaction of the heat source with the metal during welding add a new dimension to the understanding of the weld pool solidification. Conventional theories of solidification over a broad range of conditions can be extended to understand weld pool solidification. In certain cases, because of rapid cooling rate effects, it is not unusual to observe nonequilibrium microstructures. Recent developments in the application of computational thermodynamics and kinetic models, studies on single-crystal welds, and advanced in-situ characterization techniques have led to a better understanding of weld solidification and microstructures.

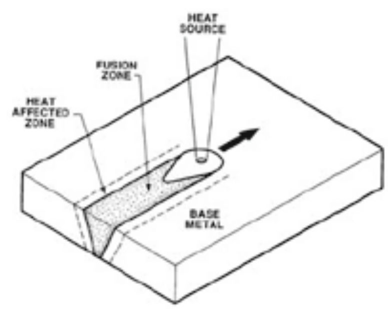

Figure 1. A schematic diagram showing the interaction between the heat source and the base metal. Three distinct regions in the weldment are the fusion zone, the heat-affected zone, and the base metal.

INTRODUCTION

In welding, as the heat source interacts with the material, the severity of thermal excursions experienced by the material varies from region to region, resulting in three distinct regions in the weldment (Figure 1). These are the fusion zone (FZ), also known as the weld metal, the heat-affected zone (HAZ), and the unaffected base metal (BM). The FZ experiences melting and solidification, and its microstructural characteristics are the focus of this

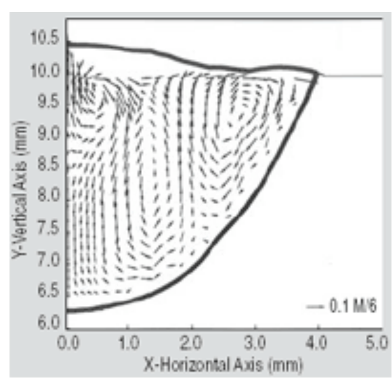

Figure 2. The calculated fluid-flow pattern in a stainless-steel stationary arc weld pool 25 s after

MICROSTRUCTURE

Unlike in casting, during welding, where the molten pool is moved through the material, the growth rate and temperature gradient vary considerably across the weld pool. Geometrical analyses have been developed that relate welding speed to the actual growth rates of the solid at various locations in the weld pool.[1,2,27]

Along the fusion line the growth rate is low while the temperature gradient is steepest. As the weld centerline is approached, the growth rate increases while the temperature gradient decreases. Consequently, the microstructure that develops varies noticeably from the edge to the centerline of the weld. Most of these microstructural features can be interpreted by considering classical theories of nucleation and growth.

In welds, weld pool solidification often occurs without a nucleation barrier. Therefore, no significant undercooling of the liquid is required for nucleation of the solid. Solidification occurs spontaneously by epitaxial growth on the partially melted grains. This is the case during autogenous welding. In certain welds, where filler metals are used, inoculants and other grain-refining techniques are used in much the same way as they are in casting practices. In addition, dynamic methods for promoting nucleation such as weld-pool stirring and arc oscillation have been used to refine the weld metal solidification structure.[2] Although the mechanisms of nucleation in weld metal are reasonably well understood, not much attention is given to modeling this phenomenon. Often, weld solidification models assume epitaxial growth and for most of the cases the assumption seems to be appropriate. However, to describe the effects of inoculants, arc oscillations, and weld pool stirring, heat and mass transfer models[18,24,25] have to be coupled with either probabilistic models such as cellular automata[31–33] or deterministic models using the fundamental equations of nucleation as described elsewhere.[34]

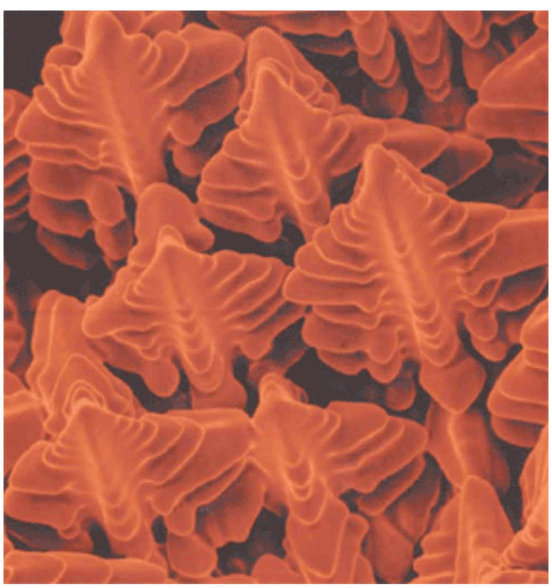

Figure 3. A scanning-electron micrograph showing the development of dendrites in a nickel-based superalloy single-crystal weld.

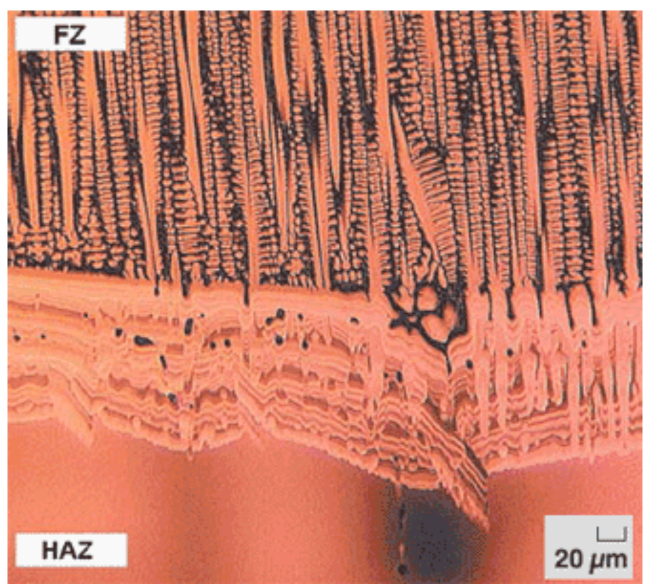

Figure 4. An optical micrograph shows the change in dendrite morphology from cellular to dendritic as the growth velocity increases toward the center of spot weld (from bottom to top) after the spot weld arc is extinguished.

During growth of the solid in the weld pool, the shape of the solid-liquid interface controls the development of microstructural features. The nature and the stability of the solid-liquid interface is mostly determined by the thermal and constitutional conditions (constitutional supercooling) that exist in the