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A mesoscale solidification simulation of fusion welding in aluminum–magnesium–silicon alloys

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Abstract

A 3-D granular model has been developed to simulate solidification during fusion welding of Al alloys. The model simulates the gradual development of the weld mushy zone composed of both continuous liquid films and solidifying grains by coupling thermal fields based on the Rosenthal equation, a modified Voronoi tessellation to provide grain structure at the mesoscale, and the evolution of solid fraction within a grain based on the Scheil equation. The shape and geometry of the columnar and equiaxed grains within the weld pool has been characterized from experiments, and therefore the model can be used to link the solidification behaviour of individual grains to the macroscopic properties of the weld. The gradual formation of microscale liquid channels lying along the grain boundaries within the mushy zone is investigated and the role of welding parameters, including amperage and welding speed, on transitions in the semisolid microstructure is explored. The study reveals that the ability of the microscale liquid channels to feed molten metal into the solidifying areas is not uniform through the weld, and is strongly affected by grain size since smaller grains hinder the feeding ability of the mushy zone.

Keywords: Solidification; Welding; Modelling; Microstructure; Mesoscale

1. Introduction

During fusion welding of Al alloys, restraining forces may arise due to component geometry, clamping configuration and thermal contraction, and lead to tensile stresses along the fusion line. If not properly controlled, the result of these stresses is a solidification defect known as hot cracking [1] that significantly lowers weldability. A hot crack forms and grows behind the weld pool, within the two-phase mushy zone, rupturing liquid films that are present at grain boundaries [2]. In addition to tensile stresses, the formation of a hot crack during welding is strongly linked to the grain morphology. The initiated microcracks within the mushy zone will only survive if the microstructure configuration does not allow for liquid feeding to heal the hot crack [3]. Knowledge of the transient microstructure of the semisolid weld pool not only gives insight into hot crack survival, but also contributes to an understanding of other transient phenomena within the mushy zone, including molten metal flow characteristics and defect formation.

The high-temperature condition in welding and the very short lifetime of the semisolid weld pool restrict the application of experimental methods for investigating the transient microstructure of the weld. Instead, numerical techniques are most often used [2]. In the past few years, four major complementary techniques have been developed to model solidification on the scale of the microstructure: front tracking, phase-field, cellular automaton (CA), and granular or discrete-based methods. The first two techniques work rather well to reproduce most phenomena

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associated with microstructure evolution, but as the mesh size must remain small, the simulation is limited to modelling only a few grains due to computational cost. In welding, these techniques have been implemented to study the solidification morphology of grains [4], and also the columnar-to-equiaxed transition (CET) phenomenon [5]. In contrast, the CA method has had much success in modelling solidification structure. For welding, this technique has been used to model the competitive growth process between columnar and equiaxed grains, and also to predict the weld microstructure in two dimensions [6]. The CA method has also recently been applied to model hot cracking in welding [7], showing that the sites susceptible to hot cracking are normally located along columnar grain boundaries. However, this technique does not lend itself to investigating microstructure transitions since the solid and liquid phases are not explicitly defined. Knowledge of such transitions is a key factor for reducing hot cracking susceptibility.

The so-called granular model of solidification [8–13] is a recently developed numerical technique in which an assembly of discrete elements is used to simulate equiaxed-globular solidification. The main advantage of this technique is its use of discrete elements, which allows for the simulation of large and non-isothermal mushy zones, as well as inclusion of stochastic effects and solid–liquid interactions [3,11,12]. In this model, grains are approximated by polyhedra based on the Voronoi diagram of a random set of nuclei, resulting in irregular grain arrangements. Solidification is then carried out [12] by advancing the grain edges towards the border along a linear segment connecting the nuclei with a Voronoi vertex. Vernède et al. [3,8,11] first developed a comprehensive model of this type based on an original idea of Mathier et al. [13] to simulate in two dimensions the solidification sequence and grain percolation of an Al–Cu binary alloy. The authors were able to link the behaviour of the grain network to the macroscopic properties of the semisolid material. Later, Phillion et al. [12] extended this approach to a three-dimensional (3-D) domain, and showed that the extension to three dimensions allows for concurrent continuity of both the liquid and solid phases. Such a concurrent continuity is a key factor for semisolid defect formation. Granular-type models have also been used by Sistaninia et al. [9,10], Phillion et al. [14] and Zaragoci et al. [15] to investigate semisolid deformation and crystal rearrangement.

Although the previous granular models of solidification have provided much insight into the stochastic microstructure variability, structure transitions from a continuous liquid to coherent solid, and also grain percolation, the basic assumptions of equiaxed-globular microstructure and uniform cooling rates do not apply in complex casting processes such as die-casting and welding where the solidification kinetics are highly complex. In the case of welding, the fast variable cooling rates containing strong nonlinear thermal gradients must be taken into account, along with spatial variations in grain morphology that depend on process parameters. In this study, a mesoscale model is presented that simulates in three dimensions the transient two-phase microstructure of the semisolid weld pool during tungsten inert gas welding of an industrial aluminum–magnesium–silicon alloy, AA6061. The microstructure is modelled based on a granular approach, while reproducing a weld domain that is large enough to relate the microstructure and stochastic effects to macroscopic properties. In the first part of this work, a mesoscale model of solidification during welding is developed. Results from welding experiments that are used as input to link the final as-solidified microstructure of the weld pool with processing conditions are also given. Then, mesoscale observations of the solidification sequence during welding are analyzed. Finally, mushy zone morphology maps calculated from the model as a function of process parameters are discussed.

2. Model description

2.1. Simulation domain

2.1.1. Size and geometry of the RVE

The model domain for investigating microstructure evolution during fusion welding of Al alloys is illustrated in Fig. 1. Due to symmetry, only one-half of the weld is included in the actual simulation. This 3-D representative volume element (RVE) can be described through both its macroscopic and microscopic characteristics.

At the macroscale, the simulation domain must encompass the entire cross-section of the weld zone in order to be considered an RVE, and therefore its size is determined from the depth of penetration and width of the weld assuming a parabolic cross-sectional fusion zone. A small amount of base metal is also included in order to create a cuboid domain. The white dashed cube in Fig. 1 indicates

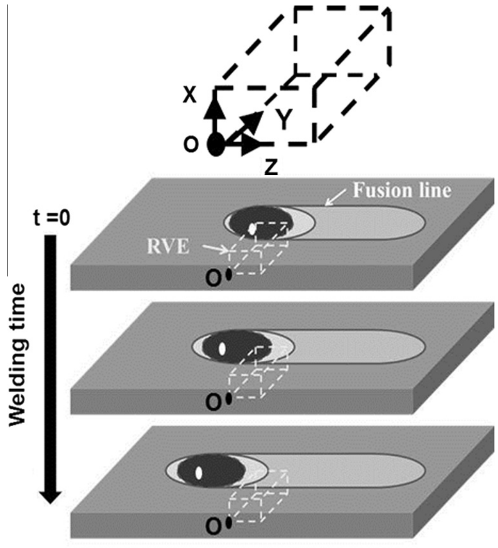

Fig. 1. The base geometry and relative position of the RVE at various welding times.