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Workpiece property effects on nugget microstructure determined by heat transfer and solidification rate during resistance spot welding

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ABSTRACT

This study theoretically investigates workpiece property effects on nugget microstructure determined by temperature gradient and solidification rate during resistance spot welding. Dimensionless properties include Curie temperature, thermal conductivity and specific heat ratios between solid and liquid, equilibrium partition coefficient, and electrical and thermal conductivity ratios between electrode and workpiece. Based on a previous realistic transport model, the computed results show that a lower morphology parameter due to smaller heat flux and higher solidification rate in radial direction near the faying surface than that in axial direction near the axisymmetric axis is responsible for equiaxed grains usually observed in the central region. Morphological parameters decrease as the liquid-to-solid specific heat ratio and equilibrium partition coefficient increase, and Curie temperature decreases. Cooling rates responsible for the primary and secondary dendrite arm spacings, however, are uncertain. Other property parameters exhibit definite and uncertain effects on cooling rate and morphology parameter, respectively. The effects of workpiece properties on weld microstructures are revealed.

1. Introduction

Resistance spot welding has been widely used in joining thin and small-sized workpieces in automobile, aerospace, medical, electronics packaging and manufacturing fields [1–7]. In resistance spot welding, two metal sheets are compressed between two water-cooled copper electrodes. Current is supplied to the sheets via the two electrodes to create high joule heating at the faying surface. A molten nugget initiates and grows until current flow is terminated. The joint is completed via solidification due to cooling through electrodes [8–12]. Weld quality depends on microstructure of the nugget affected by thermal processes and cooling rates [13–16].

Qualities and structures of the weld nugget have been well-known to be dependent of the heating and melting processes [17–20]. Short time for welding of any material obviously reduces the extent of the heat-affected zone, increases the rate of cooling, and enhances the hardening of the weld, tendency to form shrinkage cracks and porosity [21]. Microstructures of the weld nugget also depend on the cooling and solidification processes [17–19]. Since the cooling rate is the highest in the direction of electrode, the directions of columnar grains are roughly perpendicular to the welded sheet metal [20,21]. Gould and Chang [20] also observed that in resistance spot welding of low carbon steels the solidification structure ranged from cellular at the fusion zone, heat affected zone boundary, to cellular dendritic at the faying surface, as a consequence of constitutional supercoiling [19,22,23]. The finest cell/dendrite spacing was near the fusion zone-heat affected zone interface, and the coarsest spacings were at the weld centerline. Wang et al. [21] summarized that the nugget microstructure of most metals, such as steel, Mo, Ni, Ti alloy and Cu alloy, is a columnar dendritic structure and that of a few metals (i.e. Al alloy) is columnar grains around periphery and equiaxed grains in the centre, as shown in Fig. 1. The nugget of Mg alloy only consists of an equiaxed dendritic structure in the absence of columnar dendritic grains. Xu et al. [24] also observed that some pores occurred on the edges and large pores were in the center of weld nugget in refractory alloy 50Mo–50Re (wt%) sheets. The periphery of the molten pool was solidified first, because the cooling rate of this area was higher than that of the interior. The solidified periphery, therefore, confined further solidification inside. High gas pressure in the molten pool pushes the metal liquid to be solidified to the periphery. A big pore is finally formed in the center of the pool.

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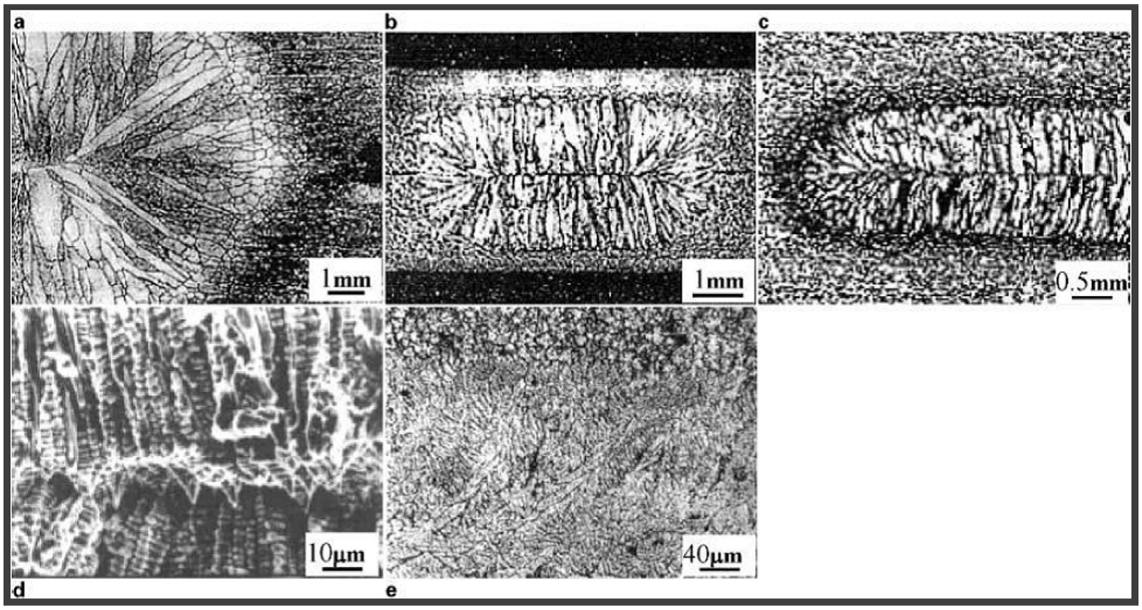

Fig. 1. Typical microstructures of resistance spot welds of joints of (a) stainless steel (Cr17), (b)Ti alloy (TA7), (c) Cu alloy (H62), and nuggets of (d) steel (65Mn), and (e) Al alloy (Ly12CZ) [21].

Systematically speaking, microstructures can be interpreted and determined by the cooling rate (G_TV) and the morphology parameter (G_T/V) [19,22,23], where G_T and V are the liquid temperature gradient at the solidification front and solidification rate, respectively. As the morphological parameter G_T/V decreases, microstructures and morphologies of the solidification front vary from the planar, columnar, columnar dendrite and equiaxed dendrite. This is the reason why columnar dendrites and equiaxed grains occur near the top fusion boundary and center of the nugget, respectively. On the other hand, smaller spacings of the primary and secondary dendrite arms due to the higher product of temperature gradient and solidification rate, namely, the cooling rate, take place near the top fusion boundary. Gould and Chang [20] applied an one-dimensional simple thermal model [25] to predict and compare the measured primary dendrite spacings during resistance spot welding. It was found that the primary dendrite spacings linearly decreases with increasing the cooling rate. Wang et al. [21], however, showed that the primary dendrite spacings were related to G_T^2V , whereas the secondary dendrite arm spacings were directly related to cooling rate during resistance spot welding.

The effects of thermal properties of different alloys on nugget growth, heat transfer and cooling rates during resistance spot welding were numerically studied by Feng et al. [25]. They proposed an axisymmetric finite element model to find that the onset time for nugget formation of Mg and Al alloys was about the same, which was less than that of mild steel. The heat loss rate of magnesium alloy from the weld region was smaller than that of aluminum alloy and greater than that of mild steel. Wang et al. [21] therefore concluded that thermal gradient of Al alloy is greater than that of Mg alloy during resistance spot welding. At the beginning of the solidification, temperature gradients of both materials increased with distance from the centre of weld and reached the maximum at the fusion boundary. The change of the temperature gradient with distance is nonlinear for Mg alloy. The increased latent heat of fusion during solidification raises the temperature and temperature gradient near the solidification front. In view of high thermal conductivity, temperature gradient in the molten region is nearly small and constant in Mg alloy, promoting the formation of fine equiaxed grains in the entire liquid and eliminating columnar grains. On the other hand, Al alloy exhibited columnar grains around periphery and equiaxed grains in the center.

Wei et al. [26] found that the nugget formation can be delayed and heat transfer is reduced by increasing the solid-to-liquid thermal conductivity ratio and liquid-to-solid specific heat ratio. Decreases in solid-to-liquid thermal conductivity ratio and liquid-to-solid specific heat ratio enhance heat transfer in both the radial and axial directions. The molten nugget solidifies rapidly within a few cycles after the moment welding current turns off. Melting rate increases whereas solidification rate decreases by reducing solid-to-liquid thermal conductivity ratio and liquid-to-solid specific heat ratio. Ho et al. [27] also showed that nugget formation is delayed by increasing radius, equilibrium partition coefficient of the workpiece, and electrode-to-workpiece electrical conductivity and thermal conductivity ratios. In all cases, the nugget growth and solidification are greater, whereas the heat transfer rate is lower in the radial direction than those in the axial direction. A critical and general study of nugget microstructure related to solidification rate and temperature gradient, however, has not been presented. This is the aim of this study.

In this work, heat transfer or temperature gradient along the liquidus line, and solidification rate responsible for microstructure of weld nugget affected by different properties of workpiece during resistance spot welding are theoretically and quantitatively investigated. This study uses the self-developed general computer code from previous work [28], accounting for transient magneto-fluid mechanics, heat and species transport, and temperature-dependent bulk resistance in workpiece, and film and constriction resistances at contact interfaces. Microstructures of weld nuggets in the resistance spot welding of different alloys therefore can be revealed and controlled.

2. System model

Resistance spot welding, as illustrated in Fig. 2, is in a cylindrical coordinate system with the origin at the intersection of the axisymmetric axis and lower electrode-workpiece surface. The electrode contains a coolant hole. The imposed welding current is AC. Instead of dealing with specific materials, this study provides a