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Electrode geometry effects on microstructure determined by heat transfer and solidification rate during resistance spot welding

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ABSTRACT

The present work theoretically and quantitatively investigates the geometrical effects of the electrode containing a coolant hole on heat transfer or temperature gradient, and solidification rate responsible for microstructure of the nugget during resistance spot welding. Resistance spot welding has been widely used in joining thin and small-sized workpieces in automobile, aerospace, and different manufacturing fields. This model adopted from previous work realistically accounts for transient magneto-fluid mechanics, heat and species transport, and bulk resistance in workpiece and electrode, and film and constriction resistances at contact interfaces. The computed results show the geometrical effects of the electrode containing a coolant hole on heat fluxes, and nugget growth and solidification rates in different directions. In view of the smaller heat flux and higher solidification rate in radial direction than those in axial direction, equiaxed grains due to a lower morphology parameter are usually observed in the central region of the weld nugget. Morphological parameter in both directions decreases or equiaxed grains readily occur, for example, if the face radius and truncated length of the electrode increase. Fine spacings of the primary and secondary dendrite arms resulting from enhanced cooling rate can be achieved by maintaining the coolant hole close to the electrode face. Different microstructures of the weld nugget therefore can be controlled via designing the shapes of the electrode containing coolant hole.

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. The electrodes thus apply force to clamp the workpieces, provide electric current through the workpieces, and post-weld cooling of the weld nugget [4,8–13]. It is therefore critical to find that geometrical effects of electrodes containing a coolant hole, leading to different thermal processes and cooling rates, on microstructure of weld nugget.

Thermal processes in workpieces are responsible for different solidification microstructures of the resistance spot welding nugget in different materials [14–16]. Wang et al. [17] showed that the microstructure of the nugget in resistance spot welding of most metals, for example, steel, Mo, Ni, Ti alloy and Cu alloy is single columnar dendritic structure and that of a few metals, Al alloy, is columnar grains around the periphery and equiaxed grains in the centre. The nugget of Mg alloy only consists of an equiaxed dendritic structure while columnar dendritic grains are not found. Microstructures are determined by the cooling rate (GR) and the morphology parameter (G/R) [18–21], where G and R are, respectively, the liquid temperature gradient at the solidification front and solidification rate. As the morphological parameter G/R decreases, microstructures and morphologies of the solidification front were observed to vary from the planar, columnar, columnar dendrite to equiaxed dendrite. The columnar grains grew in the direction of the heat flow during cooling. Based on their previous heat conduction model computation [22], Wang et al. [17] stated that thermal gradient of Al alloy is greater than that of Mg alloy during resistance spot welding. At the beginning of the solidification, it was found that the temperature gradient increased with increasing distance to the centre of weld and the maximum at the boundary of the weld for both two materials. The change of the temperature gradient with distance is nonlinear for Mg alloy.

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Nomenclature

C	liquid-to-solid specific heat ratio, defined in Eq. (7)
Bi_E, Bi_{oEs}	Biot numbers, $Bi_E \equiv \tilde{h}_E\tilde{r}_o/\tilde{k}_s$, $Bi_{oEs} \equiv \tilde{h}_{oEs}\tilde{r}_o/\tilde{k}_E$
Bi_{oET}, Bi_w	$Bi_{oET} \equiv \tilde{h}_{oET}\tilde{r}_o/\tilde{k}_E$, $Bi_w \equiv \tilde{h}_w\tilde{r}_o/\tilde{k}_E$
Da	Darcy number, defined in Eq. (7)
E_f	effective thickness of heat source due to thermal contact resistance = $\tilde{\varepsilon}_f/\tilde{r}_o$
E^*	dimensionless electrical static contact resistance = $\tilde{\sigma}_{liq}\tilde{R}_0\tilde{r}_o$
f	mass fraction of liquid or solid
F_0	dimensionless parameter, defined in Eq. (7)
f^α	solute mass fraction = $\tilde{f}^\alpha/\tilde{f}^\alpha_{m,0}$
$\tilde{f}^\alpha_{m,0}$	initial solute content
g	volume fraction or gravitational acceleration
Gr	Grashof number, defined in Eq. (7)
h	enthalpy = $\tilde{h}/h_f$
H	magnetic field intensity in θ direction, $H = \tilde{H}\pi\tilde{r}_o/I$
H_v	hardness
h_f	fusion latent heat at eutectic point, J/kg
h_ℓ	RCT + $R(1 - C)$ T_e + 1
h_s	RT
I, j	welding current, amp, electric current density, $j = \tilde{j}\pi\tilde{r}_o^2/I$
K	$g_sk_s + g_\ell$
k_E	thermal conductivity ratio = $\tilde{k}_E/\tilde{k}_s$
k_s	thermal conductivity ratio = $\tilde{k}_s/\tilde{k}_\ell$
k_p	equilibrium partition coefficient
K_0	permeability constant, m^2
L	distance between electrodes
L_1, L_2, L_3, L_4	length, as illustrated in Fig. 1
Lo	dimensionless parameter, defined in Eq. (7)
M	$-(dr_c/d\zeta + \xi dN/d\zeta)/N$
N	$r_s(\zeta) - r_c(\zeta)$
n	total number of contact spots
n_1	number of contact spots in the first control volume near axisymmetric axis
Pr	Prandtl number, defined in Eq. (7)
Pr_m	magnetic Prandtl number, defined in Eq. (7)
R	$\tilde{c}_s\tilde{T}_0/h_f$, solidification rate or electrical resistance
R_E	$\tilde{c}_E\tilde{T}_0/h_f$
r_o	electrode radius, as illustrated in Fig. 1
$\tilde{R}_0$	electrical contact resistance at faying surface at T_0
s	film thickness
Sc	Schmidt number, defined in Eq. (7)
T	temperature = $\tilde{T}/\tilde{T}_0$
T_e	eutectic temperature
u, v	axial and radial velocity, $u = \tilde{u}\tilde{r}_o/\tilde{\alpha}_\ell$, $v = \tilde{v}\tilde{r}_o/\tilde{\alpha}_\ell$
$\mathbf{V}$	velocity vector
W	electrode force

Greek letters

$\tilde{\alpha}_\ell$	liquid thermal diffusivity
β_s, β_T	solutal and thermal expansion coefficient
δ	nugget thickness
$\tilde{\eta}_\ell$	liquid magnetic diffusivity = $1/\tilde{\sigma}_\ell\mu_0\mu_{r\ell}$
η_E	$\tilde{\eta}_E/\tilde{\eta}_\ell$, where $\tilde{\eta}_E = 1/\tilde{\sigma}_E\mu_0\mu_{rE}$
θ_0	temperature ratio, defined in Eq. (7)
μ_0, μ_r	free and relative magnetic permeability, $\mu_r = g_\ell + g_s\mu_{rs}/\mu_{r\ell}$
ε_f	effective thickness of heat source due to thermal contact resistance, m
ρ	density = $\tilde{\rho}/\tilde{\rho}_\ell$
σ	electrical conductivity, $\sigma = \tilde{\sigma}/\tilde{\sigma}_l = g_s\sigma_s + g_\ell$
Σ	dimensionless parameter, defined in Eq. (7)
τ	time = $t\tilde{\alpha}_\ell/\tilde{r}_o^2$

Superscripts

α	solute
$\sim$	dimensional quantity

Subscripts

c	coolant or contact surface
E	electrode
f	film
ℓ, liq	liquid and liquidus
m	mixture
o	electrode outer radius
s, sol	solid and solidus
0	ambient

The increased latent heat of fusion during solidification raises the temperature and temperature gradient near the solidification front. In view of high thermal conductivity of liquid Mg alloy, 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 centre.

Thermal processes also influence microstructures characterized by the sizes and spacings of the primary and secondary dendrite arms of the solidification front. The higher the product of temperature gradient and solidification rate, the smaller the spacings of the primary and secondary dendrite arms are. Gould and Chang [23] applied a developed one-dimensional simple thermal model [24] to successfully 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. [17], however, showed that the primary dendrite spacings were related to G^2R, whereas the secondary dendrite arm spacings were directly related to cooling rate during resistance spot welding. Porosity in the nugget is also strongly affected by cooling rate during resistance spot welding [25]. The periphery of the molten pool was solidified first, because the cooling rate of this area was higher than that of the inside. 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. Martensite formation and hardness in steels are also consequences of an increase in cooling rate [26,27].

The effects of electrode geometry affect thermal processes in not only the electrode, but also the workpiece [28–31] during resistance spot welding. The nugget width is of the same magnitude of diameter of the electrode face [32]. Since concentrated electric current density unavoidably occurs near the face edge, a lower cone angle gives rise to stronger electromagnetic stirring fluid flow in the weld nugget [8,30], and melting through the surface [8]. A decrease in electrode cooling due to the coolant hole results in an early onset, fast growth of the weld nugget, regardless of the geometries of the electrode and coolant hole [31]. An increase in electrode face radius also decreases nugget growth rate. Quantitative results for heat transfer and nugget growth rats are essentially required.

In this work, heat transfer or temperature gradient along the solidification front and solidification rates affected by different geometries of the electrode during resistance spot welding are theoretically and quantitatively investigated. Temperature gradient