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Numerical Simulation on Nugget Formation and Evolution in Spot Welding of Aluminum Alloy*

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Abstract: With the squeeze of electrode tips, the oxide film on aluminum (Al) alloy surface is broken and numbers of micro-gaps are formed randomly. The micro-gaps act as conducting spots at the beginning of welding, so the contact resistance is extremely high and unstable in spot welding of Al alloy. In this paper, a new contact resistance model is adopted to simulate the nugget forming process. This model describes the random distribution characteristic of conducting spots. The simulation results indicate that, within the first 5 ms of welding current (AC, 50 Hz), the temperature distribution at the workpieces interface is seriously irregular. In addition, the nugget does not nucleate from the weld center and grow continuously, however, it nucleates randomly from several points almost instantaneously and then merges into an entity quickly. Experimental results agreed with the numerical simulation.

Keywords: aluminum alloy; spot welding; nugget; oxide film; contact resistance

Aluminum (Al) alloy has excellent properties, e.g., high specific strength, excellent corrosion resistance, and low recycle cost. In recent years, Al alloy has been applied to automotive bodies to reduce fuel consumption while maintaining the vehicle acceleration performance. Resistance spot welding is a traditional process for assembly lines in mass production industries such as automotive manufactures[1-3]. Generally, the surface of Al alloy is covered with a compacted oxide film, so the contact resistance is extremely high and unstable. Compared with mild steel, the contact resistance of Al alloy is unstable during spot welding. As a result, the weldability of Al alloy is worse than that of mild steel, and the nugget forming process shows a different characteristic.

In the present work, the nugget forming process in spot welding of Al alloy was studied by numerical simulation and experiment.

1 Electric contact characteristic in spot welding of Al alloy

In spot welding, due to the existence of resistance which includes workpiece bulk resistance and contact resistance, the welding current generates enough heat to melt the weld area. Compared with mild steel, the bulk resistance of Al alloy is much lower, meanwhile the effect of contact resistance on thermal generation becomes more obvious. The value and distribution of contact resistance are key factors to nugget formation in spot welding of Al alloy.

With the squeeze of electrode tips, the oxide film on Al alloy surface is broken randomly. Based on the microcosmic electric contact theory, when current goes through a faying surface, electrons only pass conducting spots, where the oxide film has been broken and pure metal-to-metal contact is formed. Near to these conducting spots, current lines are crooked and shrunk, which generates additional resistance, i.e., shrink resistance. On the other hand, at some conducting spots, electrons should meet with the conductible film (such as the adsorption film), which induces another kind of additional resistance, i.e., film resistance. Shrink resistance and film resistance compose contact resistance. During spot welding process, the contact resistance of Al alloy is much higher and more irregular than that of mild steel or galvanized steel. So the current field at the interface is irregular seriously.

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Current will pass through the initial conducting spots and generate heat at these spots, which also makes the temperature distribution on contact surfaces irregular. This kind of electric contact characteristic in spot welding of Al alloy has important effect on the nugget forming process, especially in the initial melting period.

2 Simulation of nugget formation

Because the nugget formation is instantaneous and invisible, numerical simulation is a useful method to study it. How to deal with contact resistance is a critical issue for the numerical simulation of spot welding. The most popular method is to deal with contact resistance by a certain empirical formula[4,5]. As we know, contact resistance depends on some certain factors, such as material hardness, temperature, and surface roughness. There are several empirical formulas to calculate contact resistance. It is difficult to define the values of some coefficients for Al alloy due to the absence of test data. The other method is based on the assumption that the faying surface contact resistance varies with temperature linearly between room temperature and the melting point of workpieces. At room temperature, contact resistance is static which is easily measured experimentally, and at the melting point, contact resistance is zero[6,7]. Although this method is practical, the assumption is not precise enough. Another method is to measure the actual contact resistance under different welding conditions and apply these disperse data directly to the numerical simulation program. Of course, this method is expensive and the data are not universal[8].

All the above methods describe the contact resistance only by a single number (the value of contact resistance). They cannot depict the random distribution and discontinuous characteristic of conducting spots at the interface. When using these methods, simulation results cannot reveal the random distribution characteristic at the interface caused by the broken oxide film.

In this paper a new model of contact resistance is adopted to depict the discontinuous and randomly distributed characteristic of conducting spots[9]. Based on the microcosmic contact characteristic between two rough surfaces, this model can describe the nonlinear relationship between contact resistance and temperature and electrode force. Therefore, contact resistance and its distribution can be obtained once temperature and electrode force are given. More information about this model and the coupling among mechanical, electrical and thermal parameters are described in Ref.[8].

There are two governing equations in the thermal process simulation of spot welding.

The electric potential obeys Laplace equation:

$$\frac{\partial}{\partial x}\left(\frac{1}{\sigma}\frac{\partial \psi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\sigma}\frac{\partial \psi}{\partial y}\right)=0 \quad (1)$$

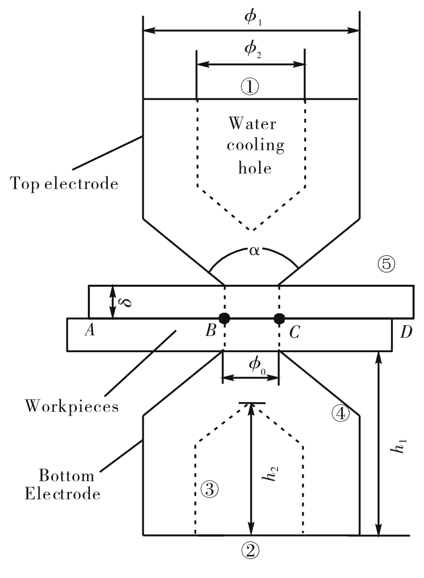
where σ is the resistivity of material; and ψ the electric potential distribution function.

The thermal process is a transient heat transfer problem with inside heat source, which obeys the following equation:

$$\frac{\partial T}{\partial t}=\frac{k}{\rho c_{\mathrm{p}}}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{q_{\mathrm{v}}}{\rho c_{\mathrm{p}}} \quad (2)$$

where T is transient temperature of mass, ℃; t time; k coefficient of thermal conductance, W/(m·℃); ρ density, kg/m^3; c_{p} specific heat at constant pressure, J/(kg·℃); and q_{v} density of inside heat source, W/m^3.

Because the electrodes and nugget are axisymmetrical, it is reasonable to select a cross section including the main axial as simulation area. So the simulation is a two-dimensional problem and Fig.1 shows the dimensions of the calculation model. The geometric model was meshed by ANSYS 5.6 FEM software.



ϕ_1—Outside diameter of electrode (20 mm);
ϕ_2—Inside diameter of electrode (12 mm);
α— Electrode tip angle (90°);
h_2— Depth of water cooling hole (27.5 mm);
h_1— Height of electrode (34 mm);
δ—Thickness of workpieces (0.7 mm);
ϕ_0—Tip diameter (4.5 mm).

Fig.1 Schematic diagram of geometrical model

The boundary conditions of the electric potential problem are as follows: Boundary ① and ② are the electric current input-output boundary and all nodes on Boundary ② are defined as zero volt (the first kind boundary condition). At the faying surface of two workpieces, *AB* and *CD* belong to insulating area and *BC* with length ϕ_0 is the real conducting section. All the other boundaries are free.

The boundary conditions of the thermal problem are as follows: The temperatures on Boundary ① and ② are defined as a constant, 20 ℃. Both of the inside walls of the water cooling holes are water cooling boundary (Boundary ③). The temperature of cooling water is room temperature (20 ℃), the heat exchange coefficient is α_{H2O} (its value is 3 800 $W\cdot m^{-2}\cdot K^{-1}$ in this paper). There are convection and radiation on all of the outside surfaces which are atmosphere cooling boundaries and the surface heat exchange coefficient is α_w (Boundary ④ and ⑤) which is shown in Tab.1.

Tab.1 Surface heat exchange coefficient α_w at different temperatures

T/℃	α_w /($W\cdot m^{-2}\cdot K^{-1}$)
20	0
100	11.30
200	13.59
300	20.47
400	26.42
500	33.79
600	42.83

The welding current is 20 kA (AC, 50 Hz), welding time is 4 cycles, electrode force is 2.5 kN. The electrode material is Cr-Zr-Cu alloy and workpieces are LF2 Al alloy. Some of the physical property parameters of the electrode and workpieces are given in Tab.2, where λ is coefficient of thermal conductance, *C* is specific heat.

Tab.2 Physical property parameters of materials

Material	λ / ($W\cdot m^{-1}\cdot K^{-1}$)	C / ($J\cdot kg^{-1}\cdot K^{-1}$)	ρ / ($kg\cdot mm^{-3}$)	σ / ($\mu\Omega\cdot mm$)
Electrode	330	385+0.098 8T	8.89×10^{-3}	21.7+0.043T
Workpieces	154.9−0.042T	921+0.42T	2.68×10^{-3}	49.3+0.1T

Note: the unit of temperature T is K in Tab.2.

3 Results and discussion

The simulation results are shown in Fig.2, which reveals the evolution of the temperature field with welding time. The temperature field is irregular at the initial several milliseconds. At some conducting spots, temperature increases quickly and the maximum temperature is higher than the melting point of material. However, the temperature far from these conducting spots is still very low. This nonuniform heating phenomenon keeps no more than 5 ms according to the simulation results. Within the first 5 ms of welding current, e.g., a quarter of the first welding pulse, the temperature distribution is inclined to be uniform.

From Fig.2(a)—(f), in spot welding of Al alloy, the nugget does not nucleate from the weld center of the contact area and grow continuously[4], however, it nucleates randomly from several conducting spots and extends quickly, at last it merges into an entity. This nucleation process is different from that of mild steel sheet. It can be seen from Fig.2(e) and Fig.2(f) that the nugget expansion in horizontal direction has been finished within 5 ms at the beginning of welding current. The nugget expands mainly in the vertical direction during the rest welding time.

The characteristics of such a nucleation process indicate that the initial nucleation energy is mainly generated at the interfaces. After the nugget formation, because contact resistance and its heat disappear, the energy for the nugget to grow is mainly generated by bulk resistance. Meantime, the nugget expansion mainly appears in the thickness direction.

To verify the simulation results, weld experiments were done under the same welding conditions. The welding time is 1 cycle, 2 cycles, 3 cycles and 4 cycles AC 50 Hz, respectively. Fig.3 shows the comparison between simulation and experimental results of the nugget size. As shown in Fig.3, there is generally good agreement between simulation and experimental results.

In experiments, a low and single cycle welding current was used to simulate the initial nucleation behavior. The welding conditions are the same as simulation except that welding current is only 15 kA and 1 cycle. Under the welding current, the initial melting sections cannot extend enough to converge to a whole nugget, so this experiment could behave the initial melting characteristic under common welding condition. Fig.4 shows the initial nucleation condition at workpieces interface after welding. The initial melting appears from several points randomly, rather than from the center of contact area, which is consistent with simulation results in this paper.

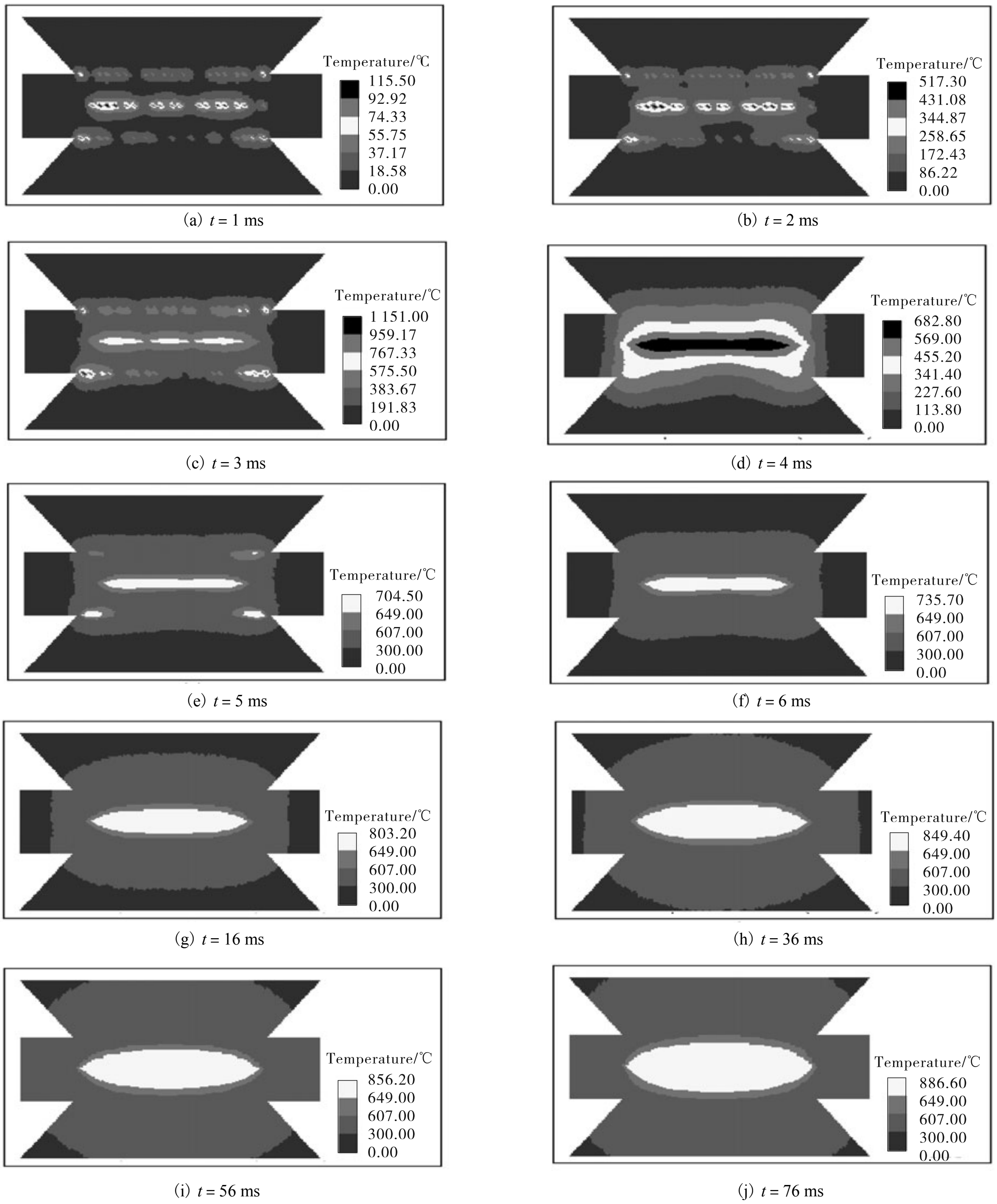


Fig.2 Temperature distribution in spot welding of Al alloy

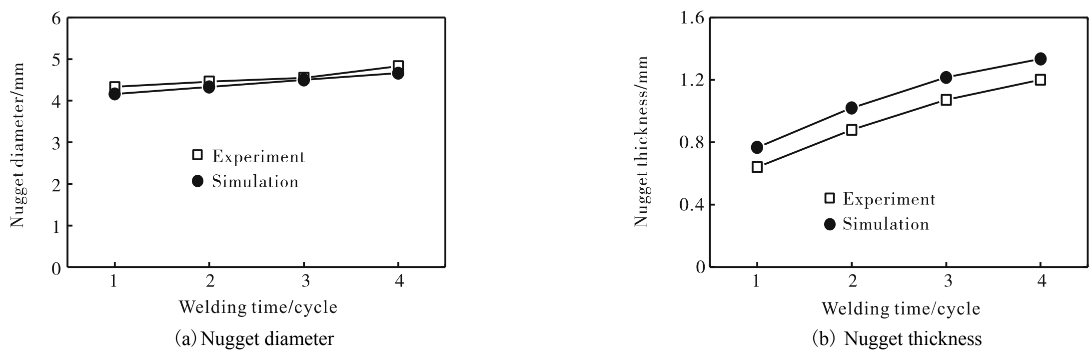


Fig.3 Comparison of the nugget size between simulation and experimental results

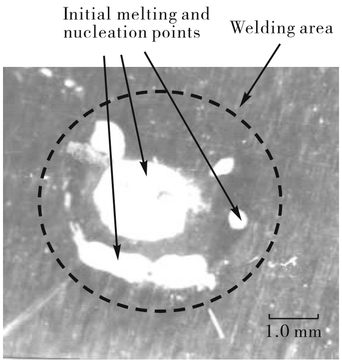


Fig.4 Random nucleation phenomena in spot welding of Al alloy

4 Conclusions

(1) At the beginning of welding current, the temperature field at the interfaces is very irregular. At some conducting spots, the temperature is higher than the melting point. However, the temperature far from these spots is still very low. This nonuniform heating phenomenon keeps only several milliseconds.

(2) In spot welding of Al alloy, the nugget does not nucleate from the center of contact area and grow continuously, but it nucleates randomly from several conducting spots and extends quickly.

(3) In spot welding of Al alloy, the energy for initial nucleation is mainly generated from the heat of contact resistance. At the beginning, the nugget diameter extends very quickly, which has been almost finished within the first 5 ms.

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