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Effects of cone angle of truncated electrode on heat and mass transfer in resistance spot welding

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ABSTRACT

Truncated electrodes with different cone angle are widely used in vehicle body assembly. However, the effect of the cone angle on welding process still keeps unclear. In this paper, a multi-physics finite element model, which considered the coupling of electric field, magnetic field, fluid flow and heat transfer, was used to study the effect of the cone angle variation on resistance spot welding. Four kinds of cone angles, including 15°, 30°, 45°, and 60°, were studied systematically. Research results showed that the cone angle variation affects not only weld quality but also electrode life. Specifically, the lower cone angle, the more severe current density singularity at the tip edge, the stronger electromagnetic stirring in the molten nugget, and thus the stronger fluid flow and more uniform temperature field in the weld nugget, which would produce a positive effect on the weld quality. At the same time, the low cone angles would enhance the cooling ability of the electrode for the increased mass and present lower electrode temperature, and thus have a better electrode life, which was also verified with electrode wear experiments. However, the low cone angle electrodes would produce smaller nuggets and consume more coppers. Moreover, for the small cone angle electrode, a larger welding current has to be applied to compensate the heat dissipated by the electrodes due to their excellent cooling capability. As a result, considering the effects of the electrode cone angle on electrode life, weld quality and production cost, the 30° and 45° cone angle would be recommended in vehicle body production.

1. Introduction

Resistance spot welding (RSW) technology is widely used to assemble sheet metal structures, especially in automotive industry. A typical all-steel car body is generally assembled through 4000–6000 spot welds. During RSW, not only electricity, but also copper electrodes are consumed. The functions of the copper electrode in RSW include applying force to clamp the workpieces, conveying conduction current into the workpieces and facilitating post-weld cooling of the weld. In order to produce an acceptable nugget size in a very short time, the applied conduction current flowing through the electrodes and workpieces must be high enough, thus the electrode is heated up quickly during RSW. Meanwhile, in order to provide a good conductive path along the electrodes and the workpieces, a large force must be exerted through the electrodes, which would lead to a large internal stress within the electrode. Thus, during RSW, the copper electrodes bear both high temperature and large stress. In RSW, the electrodes are in direct contact with the high-temperature metal surrounding the liquid nugget. The repeated thermal and mechanical actions will aggravate the electrode wear, especially in welding thin gage sheet metals, aluminums or galvanized steels [1–4]. For a car body assembly line of 300,000 annual production capacities, it generally consumes 600,000 copper electrodes per year, which worth over 350,000 USD. Manufacturers have been seeking for methods to slow down the electrode wear and reduce the frequency of electrode replacement so as to lower the manufacturing cost and improve production efficiency.

Electrode geometry is a key factor influencing electrode wear. Lots of experimental and numerical studies have investigated the effects of electrode internal geometry [5–9]. The external geometry of the electrodes also demonstrates significant effects on electrode wear and weld nugget formation [10–13]. As shown in Fig. 1, there are six different types of external geometry designs for RSW [14], of which, types A, B and E are general design, Type D is adopted when a weld has to be made near an upturned flange or corner, and types C and F are designed for improved weld surface quality. Among the general designs, type A is able to support weld sizes larger than $4\sqrt{t}$ (t represents the thickness of the thinnest sheet in the combination) when a properly sized electrode end surface is utilized, type B will typically result in more indentation due to

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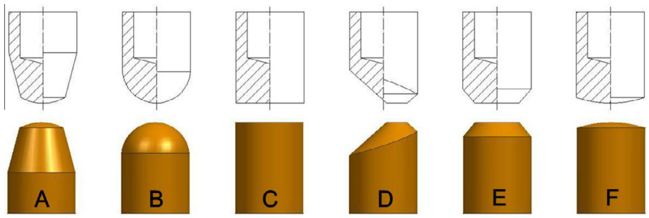

Fig. 1. Typical RSW electrode geometric shapes. Type A represents "Pointed", Type B "Dome", Type C "Flat", Type D "Offset", Type E "Truncated", and Type F "Radius".

its spherical shape and is not able to support very large weld sizes, and type E, e.g. the truncated design, are typically recommended due to its low contact tip wear rate and easy to electrode dressing. So far, a number of studies [2,6,10,12,15] have been done based on the truncated electrodes. However, for the truncated electrodes, the cone angle's effects on the weld nugget formation and electrode wear are still unclear.

Because the electrode cone angle affects the geometry singularity between the electrode and sheet metal, its variation would directly affect the current density distribution in the electrode and workpieces, and eventually affect the electrode life and nugget formation. Furthermore, in RSW process, a large magnetic field is induced by the welding current. Moreover, the current and magnetic field interact with each other to form a magnetic force field in the nugget, which will stir the molten metal and mix the hot and relatively cold regions in the nugget, and as a result will affect the temperature distribution in the weld joint and the final nugget's shape and size. For different cone angle, the current density field will interact with its induced magnetic field to produce different magnetic force field, which would surely produce different magneto-hydro-dynamics (MHD) behaviors in the nugget, and thus affect the nugget formation and temperature field in the electrodes.

Since the invisibility and high temperature of the weld nugget, it is hard to directly measure the MHD behaviors during RSW. Since 1996, Wei [16] for the first time proposed a 2D finite difference (FD) model considering the coupling of electric, magnetic, thermal and fluid flow fields in RSW process, and systematically investigated the effect of electric current, workpiece property, magnetic property, phase change and electric contact resistance on MHD behaviors in RSW with truncated electrodes [17–21]. Following up his work, Khan [22,23] proposed a 3D FD model and a Abaqus based FE model to study the effect of gravity on fluid flow during RSW in 2000. Since 2007, Li [24–27] proposed a multi-physics finite element (FE) model to systematically study the fluid flow and heat transfer patterns under the induced magnetic field, and the effect of welding current magnitude and welding current input mode (e.g. AC mode and RMS mode) on transient evolutions of MHD behaviors in RSW with truncated electrodes. However, all these researches did not systematically consider the effect of the cone angle variation on MHD behaviors in the weld nugget, especially on the temperature field in the electrodes.

In this study, a multi-physics FE model, which considers the magneto-hydrodynamics (MHD) behavior in the weld nugget, will be used to investigate the effect of the cone angle of truncated electrodes on RSW process. Based on the numerical simulations, electrode wear rate of different cone angles was discussed and validated with experiments too.

2. Numerical model

In view of the interaction between the electrodes and workpieces in RSW, both the electrodes and workpieces were modeled in this paper. For the typical RSW process, the electric conduction and heat and mass transports are axisymmetric around the axisymmetric axes of electrodes. Therefore, they can be described with an axisymmetric model, as shown in Fig. 2(a) and (b). However, according to electromagnetic theories, the magnetic field induced by the axisymmetric electric field is physically normal to the electric field, e.g. the axisymmetric plane shown in Fig. 2(a) and (b). Therefore, the magnetic field in RSW cannot be modeled with an axisymmetric model. Thus, a 1/4 3D wedge-shaped model was used for the magnetic analysis in view of the symmetry feature of the magnetic field. As shown in Fig. 2(c), both finite air layer and infinite air layer are used in the magnetic model. In theory, a very thick finite air layer could be included to model the decay of the magnetic field, however, this would substantially increase the model size and thus greatly reduce the calculation efficiency. As a result, a single layer of infinite far field element (e.g. Infin111 in ANSYS), were used to model the far field decay of the magnetic field so as to get a better results [28]. As shown in Fig. 2, the cone angle can be parametrically changed while the electrode length, outer radius and tip radius maintain constant. In this study, four kinds of cone angle, e.g. 15°, 30°, 45° and 60° were modeled and compared to study its effect on RSW process.

In order to further reduce the complexity of the coupled multi-physics process, the molten metal in the nugget was assumed as incompressible, viscous, laminar, and Newtonian fluid [24]; the effect of gravity on fluid flow was ignored [22,23]; and the electromagnetic field was viewed as quasi-stable for low electric current frequency [29,30]. Based on the above assumptions, the MHD equations to describe the multi-physics behaviors in RSW process, which consists of continuity equation, momentum equation, energy equation and Maxwell electromagnetic equation, could be given respectively as follows:

$$\nabla \cdot \vec{V} = 0; \tag{1}$$

$$\rho\left(\frac{\partial V_i}{\partial t} + \vec{V}\cdot\nabla V_i\right) = (\vec{J}\times\vec{B})_i + \frac{\partial}{\partial x_j}\left[-\delta_{ij}P + \mu_e\left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i}\right)\right], \quad (i,j = x,y);$$

$$\rho C_M\left(\frac{\partial T}{\partial t} + \vec{V}\cdot\nabla T\right) = \nabla\cdot(k\nabla T) + S_h; \tag{3}$$

$$\left.\begin{array}{l} \nabla\times\vec{E} = 0 \\ \nabla\times\vec{H} = \vec{J} \\ \nabla\cdot\vec{B} = 0 \\ \nabla\cdot\vec{J} = 0 \\ \vec{J} = \sigma\vec{E} \\ \vec{B} = \mu_r\mu_0\vec{H} \\ \vec{B} = \nabla\times\vec{A} \end{array}\right\}. \tag{4}$$

where, $\vec{E}$ is the electric field intensity vector, $\vec{B}$ the magnetic flux density vector, $\vec{H}$ the magnetic field intensity vector, $\vec{J}$ the current

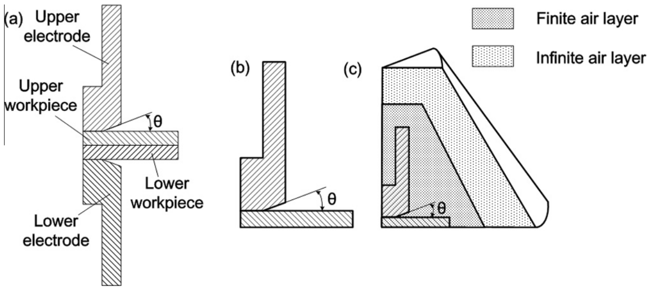

Fig. 2. Multi-physics model of RSW. (a) 1/2 axisymmetric electric model; (b) 1/4 fluid dynamics model; (c) 1/4 3D wedge-shaped magnetic model, the wedge angle is 10°. θ represents the cone angle.