Finite Element Simulation of the Process of Aluminum Alloy Resistance Spot Welding

Li Baoqing, Shan Ping, Lian Jinrui, Hu Shengsun, Cheng Fangjie
Tianjin University, Tianjin, P.R.C

Abstract

In this paper, an axis-symmetric finite element analysis (FEA) model for the resistance spot welding (RSW) of aluminum alloys is developed using the FEA software ANSYS. It accounts for the interactions of mechanical, electrical and thermal phenomena. The coupled analysis is accomplished through the cycles of contact analysis and electrical-thermal analysis. In order to perform the coupled mechanical-electrical-thermal analysis, the relationship for contact electrical resistivity as a function of contact pressure and temperature is proposed, and the phase change due to melting is also accounted for. At the same time, temperature-dependent variable material properties are used to the simulation. In addition, the coupled analysis also includes the effect of distortion on the electrical-thermal analysis.

Introduction

Resistance spot welding (RSW) is a complicated process, including interactions of electrical, thermal, mechanical and metallurgical phenomena. Fig.1.(a) is a simplified representation of the process, showing some of the essential features. In the RSW process, two metal sheets are compressed between a pair of water-cooled electrodes with applied force. Current is supplied to the sheet via the two electrodes to create a concentrated heating at the faying interface (the actual contact face between workpieces). The heat is constrained about the weld centerline by the water-chilled electrodes and the relatively high contact resistance at the faying interface.

The entire process, from the squeeze to cool down, is divided into three stages, as shown in Fig.1.(b). Firstly, during the squeeze cycle, the electrode force is applied and held. The current is switched at time-x, held for several complete cycles and switched off at time-y. The pressure is held until time-z, and the weld is cooling on during this period. Finally, the electrode force is released and the repeat cycle of operation is started again.

Figure 1 - The Structure And Sequence Of RSW
The interest in volume production of aluminum vehicles has been growing rapidly in the last two decades. Aluminum has a number of advantages for vehicles' applications when compared to steel, particular with regard to reducing fuel consumption and the consequent reduction of CO₂. The density of aluminum is one-third that of steel. Reducing in mass of body-in-white up to 50% can be achieved while equaling or exceeding the strength and stiffness of compared steel bodies (Ref.1). Overall vehicles mass could be reduced by at least by 10% and that would reduce fuel consumption by a similar amount (Ref.2). Smaller and more efficient power units could also be fitted to reduce fuel consumption with no loss of vehicle performance and a reduction in the amount of fuel burned. In addition, aluminum has a low secondary energy cost. The energy to re-melt aluminum is approximately to 5% of that required to produce new aluminum and similar material properties can be maintained by recycled aluminum (Ref.1). Further, aluminum and its alloys have good inherent corrosion resistance and need little additional surface protection, unlike steel, which must be galvanized.

More recently, automobiles’ interest in aluminum is growing rapidly in Europe and North America. Because RSW is the key technique in the volume production of automobile, to produce automobiles in volume, the problems of RSW for aluminum must be solved. Now, there are two problems in the process of aluminum RSW, one is the fast wear of electrode, the other is the weld quality. The study about the mechanism of aluminum RSW process is the basis to solve these problems. Some scholars simulated the process of aluminum RSW using FEA, and showed the temperature, electricity and stress and strain fields during the RSW process, which supplied a powerful tool to understand the RSW process. But, the RSW is a very complicated process, involving contact, contact electric resistance, mechanical-electrical-thermal couple, non-linear material properties and other complicated factors. The most of existing models accounted for some of above factors, and made many assumptions to some complicated factors as follows. Contact area between work-pieces was often assumed to be that of electrode tip. Contact pressure distribution on contact areas was assumed to be uniformly and have no effect on the contact electrical resistance, the effect of distortion on the electrical-thermal analysis was often ignored, and the relationship of contact electrical resistance was also over simple (Ref 3~10).

In this paper, the coupled electrical-thermal FEA model and mechanical- thermal FEA model are proposed to simulate the process of RSW for aluminum. The contact and mechanical analysis is accomplished through the latter model, the electrical-thermal analysis is completed through the former. And these two analyses are coupled every load step (about 0.5ms). These analyses are accomplished through the secondary development on the base of the commercial computer software, ANSYS™ Version 5.6.2.

### Governing Equation

The governing equations for the coupled thermal-mechanical and electrical-thermal problems during the RSW of aluminum alloys can be written as

\[ h \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q \]  
\[ \nabla \cdot J = 0 \]  
\[ \nabla \cdot \sigma + F = 0 \]

Where \( T, K, h, \sigma, F, J \) and \( t \) are temperature, thermal conductivity, enthalpy, heat generation, stress, body force, electric current density and time, respectively.

Equation 1 is the energy-governing equation that includes the phase change due to melting. The enthalpy algorithm is used to solve the phase change process. The phase change occurs between the solidus and liquidus temperatures of alloys. The last term of equation 1 is a combination of heat generation due to contact resistance at the faying surface and the W-E interface (the contact face between electrode and workpiece) and Joule heating due to of work-piece and electrodes. The flow of electric current is described by equation 2 allowing computation of the current density distribution. The mechanical deformation, contact pressure distribution and contact area are simulated by equation 3. The heat generation can be estimated by the coupled thermal-mechanical and thermal- electrical modeling. The thermal-mechanical model was used to solve the contact pressure distribution, contact area and deformation according to the
electrode force and the temperature field from the thermal-electrical analysis. The fully coupled thermal-electrical modeling was used to solve the nugget development and temperature history. And the coordinates of nodes in the model, contact resistivity and contact area are updated every load step. It is noted that the contact resistance works by a layer of solid elements with very thin thickness.

Contact Resistance

The contact resistance is the sum of a low-resistance metallic contact and a high-resistance film. The surface film may be composed of compounds besides oxide, and it may be conducting, semi-conducting or insulting, depending upon the thickness of the film. The magnitude of the contact resistance varies over a wide range of values, depending on the load and surface conditions.

In general, the contact resistance decreases with an increase in pressure and temperature. In fact, the contact pressure distributions on the three contact surfaces are all uneven. The contact degree and the fragmentation of the film are directly relative to the contact pressure. So, the contact electric resistivity of different locations is different on the contact area. But, many papers ignored this problem, and accounted for the relationship for contact resistance as a function of temperature only. According the experimental results, the following relationship for contact resistivity on the contact surfaces are assumed.

$$\rho_c = \rho_0 \frac{k_1 \cdot e^{-k_2 \cdot (T+T_0)} + k_3 \cdot \frac{(T - T_0)}{(T_f - T_0)}}{p^\alpha}$$

(4)

Where, $\rho_c$, $T$, $T_0$, $P$ are contact electric resistivity, temperature, room temperature and contact pressure. $\rho_0$, $k_1$, $k_2$, $k_3$ and $\alpha$ are constants, to different contact surfaces and surface condition, they are different.

Analysis Results & Discussion

The boundary conditions and loads are shown in Fig.2. The materials of electrode and work-pieces are copper and 5052 aluminum alloy respectively in the simulation. The computational simulation results of the current models are shown in Fig.3-11.
Fig. 2 shows the change of contact radius between work-pieces with time. During the welding, contact radius is not constant, and changes greatly in the first half cycle. When the geometry parameters of electrode, force and the depth of workpiece are determinate, the contact radius depends on the performances of materials and the temperature field. However, the temperature field and the resistance to distortion vary rapidly in the first cycle. The influences of factors are very complicated. Thermal expansion on the faying surface makes contact area decrease, but at the same time, the decrease of distortion resistance makes contact area increase. It is a synthesis effect resulting from many factors. In the second half cycle, the liquid nugget has formed, and the faying surface is plastic. With the electrode force, plastic expansion occurs on the faying surface, and the contact radius increases with time.

Fig. 3 - Contact Radius At Different Time
Contact pressure distributions on the W-E interface and faying surface are shown in Fig.4 and Fig.5. It varies greatly in the first cycle, but is rather uniform in the second cycle. Contact pressure distribution bears a close relationship with temperature. On one hand, great thermal expansion often means greater force to some degree, and the thermal expansion is proportional to the temperature. On the other hand, the resistance for distortion decreases with the increase of temperature and also makes contact pressure decline. Fig.6 and Fig.7 illustrate the temperature history on the W-E surface and the faying surface respectively. From the equation 4, the higher temperature means lower electric resistivity, and as described above, also often means greater pressure, which also leads to the lower electric resistivity. As we all know, electric resistivity is inversely proportional to the current density. Fig.8 and Fig.9 show the current density history on the W-E interface and the faying surface respectively. In the start of welding, the contact pressure on the faying surface is not uniform, and there is a peak-value point. The contact resistivity in the area near this point is lower than that in other areas, so the current density in this area is higher and the temperature rises rapidly. The increase of temperature makes the contact resistivity decrease greatly, and lead to the increase of temperature further. When the temperature exceeds the melting point, the local liquid nugget occurs as illustrated in Fig.7, and it is liquid annulus. As the annulus occurs, the contact resistance in this area disappears. So, the current density is getting much greater. As the temperature rises, the heat also spreads toward other areas, then the annulus becomes much larger. In the melting annulus, contact resistance doesn’t exists, but in the both sides of it, contact resistance still exits. It results that the current “lines” in the area with contact resistance curve to the melting annulus, which leads to the concentration of current density at the edges of the melting annulus. So, the two peaks of current density form on the faying surface as shown in Fig.9. At about 7ms, the melting annulus becomes the elliptical nugget. At this time, the concentration of current density occurs only at the outside edge of liquid nugget.
Figure 5 - Contact Pressure On The Faying Surface

Figure 6 - Temperature On The W-E Surface

Figure 7 - Temperature On The Faying Surface
On the W-E interface, the contact pressure bears a close relationship with the development of the melting annulus in work-pieces. In the area corresponding to the melting annulus, there is greater contact pressure distribution because of the thermal expansion. The increase of contact pressure makes contact resistivity decrease, and lead to greater current density as illustrated in Fig.8. In addition, there is also the concentration of current density at the edge of electrode tip because of the constraint of the geometry. The peak point of temperature on the W-E interface moves from the edge of electrode to the axis gradually as shown in Fig.6. It is the results of the thermal conduction of melting annulus and the change of contact pressure on the W-E interface.

Fig.10 shows the temperature field and weld nugget at the end of welding, and Fig.11 shows the voltage contours at time of 2.5 ms. Numerical simulation results show the radius of liquid nugget doesn’t increase obviously after the first cycle, and the depth of liquid nugget increases with time. The fast wear of electrode has much to do with the temperature on the W-E interface. In the process of welding, the temperature on the W-E interface increases with time, which is harm to the wear of electrode. And, because the strength of weld is mainly associated with the radius of weld nugget, so a long time of welding is not helpful to the weld quality and the wear of electrode. So, the numerical simulation program may be used to optimize the
welding specification for producing qualified welds and reducing the wear of electrode and consumption of electric energy. The relevant results will be published in later articles.

**Figure 10 - Temperature Contours At Time 0.04s**

**Figure 11 - Voltage Contours At Time 0.025s**

**Conclusion**

In this paper, an incrementally coupled finite element analysis procedure is presented with a reference specific to the electrical-thermal-mechanical phenomena associated with the aluminum RSW process. Unlike most of the previous efforts in this subject area, which don’t include the coupled effect or only consider the electrical-thermal analysis, this study takes into account the contact area change, the deformation history effect of work-pieces and the influences of temperature and contact pressure on contact resistance.
The electrical-thermal analysis and thermal-mechanical analysis are accomplished using the electrical-thermal model and thermal-mechanical model respectively, these two analyses are coupled every load step (about 0.5 ms). Contact electric resistivity and the node coordinates are updated according the results of thermal-mechanical analysis every load step.

This paper studies the change process of contact pressure, contact area size, temperature and current density on contact surfaces, and made the process mechanisms of aluminum for RSW clear. It supplies the tools to solve the problems of aluminum for RSW.

Acknowledgements

Acknowledgments are due to the National Science Foundation for financial support. And special thanks are extended to Jiao. Lixin & Cai. Peng of China ANSYS Office for help numerical simulation.

References