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MODELING OF RESISTANCE SPOT WELDING USING FEM

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ABSTRACT

The resistance spot welding process is significant for joining materials in the automotive industry because it offers high speed and can be easily automated. Recently, there has been a demand in the automotive industry to reduce vehicle weight to improve fuel efficiency. Aluminium alloys are considered a viable alternative for auto-body materials to meet this requirement. It not only helps enhance fuel efficiency but also addresses the issue of vehicle corrosion. However, joining aluminium through resistance spot welding presents serious challenges compared to steel. One significant difficulty arises from the faster deterioration of electrodes. Aluminium alloys possess high electrical and thermal conductivity, significant shrinkage during solidification, and a natural oxide coating. These features make the spot welding process for aluminium alloys notably distinct. When exposed to high temperatures, aluminium undergoes a chemical reaction with the copper alloy found in the electrode material. This results in the unpredictable removal of material from the electrode surfaces, causing wear and significantly reducing the lifespan of the electrode during spot welding of aluminium alloys. This decrease in electrode tip longevity poses a significant drawback in weldability, as the durability of the electrode tip significantly affects its suitability for automotive applications.

Due to the rapid nature of the process, obtaining crucial information, such as the transient distribution of current density and temperature through experimental methods, becomes challenging. Therefore, this study aims to develop an integrated computer simulation model using the finite element method to analyze the resistance spot welding process of aluminium alloys. Multiple calculations were performed considering different welding currents, weld times, electrode forces, and various surface conditions of the aluminium sheets. The simulation considers the nonlinear, temperature-dependent, thermo-physical properties of the materials. Interestingly, it was observed that in most cases, the nugget diameter is formed within a short time frame of 0.02 to 0.04 seconds, and further application of welding current primarily increases the heating of the electrode face. Moreover, the aluminium sheets' initial surface condition significantly influences the nugget's formation. Several other conclusions have been drawn as a result of this study.

Keywords: *Simulation modelling, resistance welding, spot welding process*

1. Introduction

The resistance spot welding process is the most significant joining process in the automobile industry due to its high speed and suitability for automation. Thus, the industry's demand closely influences any new development of this welding process. The need to reduce vehicle weight, improve fuel economy, and reduce exhaust emission has increased the use of lightweight materials such as aluminium alloys. However, many technical issues must be solved before aluminium use becomes commonplace in high-volume production. Unlike resistance spot welding of steel, joining aluminium through the same process has met with severe difficulties. Aluminium is an excellent electrical conductor with a bulk resistivity of one-third that of steel. Joule heating is proportional to resistance for a given current. It is understandable that a significant increase in welding current will be required to join aluminium, compared to an equivalent gauge of steel sheet. Further, aluminium has a high thermal conductivity and the localized heat generated by the welding current will be will be conducted away rapidly. It is therefore necessary to use short weld times. Aluminium alloys posses a surface oxide layer that varies depending on the prior thermal and mechanical processing. The oxide has a high resistivity band high melting point, around three times greater than pure aluminium. Therefore, spot welding of aluminium alloys has become an important research area in the last couple of years both in the academic as well as industrial research laboratories.

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The electrical resistance spot welding process for joining two materials at their common interface is a complicated interaction of electrical, thermal, mechanical, metallurgical and surface phenomena. In this process, electrodes press against two or more steel sheets and a high amperage current is passed through the sheet-electrode system. Because of the electrical contact resistance, heat will be generated at electrode/workpiece interfaces and faying surface. The heat at the faying face melts the workpieces to form a nugget. To prevent melting at the electrode/workpiece interface, water is circulated in the cooling chamber of the electrode.

The current carrying zone in the sheet is determined by the region over which electrodes touch the sheet. This, in turn, depends on the electrode force and consequent plastic flow at the sheet-electrode interface. The complete phenomenon is, thus, an electro-thermal problem which is also influenced by plastic flow in the sheet. Coupled with this are various types of nonlinearities present in the system. For example, thermal conductivity and bulk electrical resistivity vary with the temperature. Besides, the interface resistance along sheet–sheet interface and sheet–electrode interface varies with various parameters in a very uncertain manner. Hence, a finite element code for simulating the spot welding process, which includes all those features mentioned above, is developed in the present work for modelling the resistance spot welding process of aluminium alloys.

2. Previous Investigations

Since the physics of the process is so complicated, it is quite understandable that very little was published in the open literature on finite element modelling which covers these many aspects. In 1984, Nied [3] reported a two-dimensional simulation model for analyzing uncoated steel's resistance spot welding process using the commercial FEM package ANSYS. A coupled thermo-electrical and thermo-mechanical analysis has been tried. However, the contact resistance along the sheet-to-sheet and sheet-to-electrode interfaces was neglected. Gould [4] reported a one-dimensional numerical model to calculate weld nugget development during spot welding of uncoated steel. However, the one-dimensional model failed to account for the radial heat loss into the surrounding sheet. Cho [5] reported a two-dimensional, finite difference method-based heat transfer model for the resistance spot welding process. It has been concluded from the publications cited above that the resistance spot weldability of aluminium alloys is not yet fully explored. However, there is now tremendous demand for these materials in the automobile industry. This work aims to develop a finite element-based numerical model consisting of a nonlinear thermomechanical coupling to provide a more realistic simulation of aluminium alloys' resistance spot welding process.

3. Modelling Design

3.1 Geometric Modeling

Considering a typical arrangement for resistance spot welding of two pieces of aluminium sheets, the geometric representation of two identical electrodes simplifies the geometry of two – dimensional axisymmetric model. Fig. 1 shows the finite element mesh structure used for the modelling purpose. The mesh structure consists of 358 nodes and 297 elements. The element mesh size at the end of the electrode and the workpiece is sufficiently refined to account for thermal gradients in that region. A coarser mesh is considered in the upper region of the electrode, where the gradients are shallower because of heat conduction to the water–cooling channel. Only one quadrant of the complete geometry has been analyzed, considering the axial symmetry of the sheet-electrode system in the spot welding process.

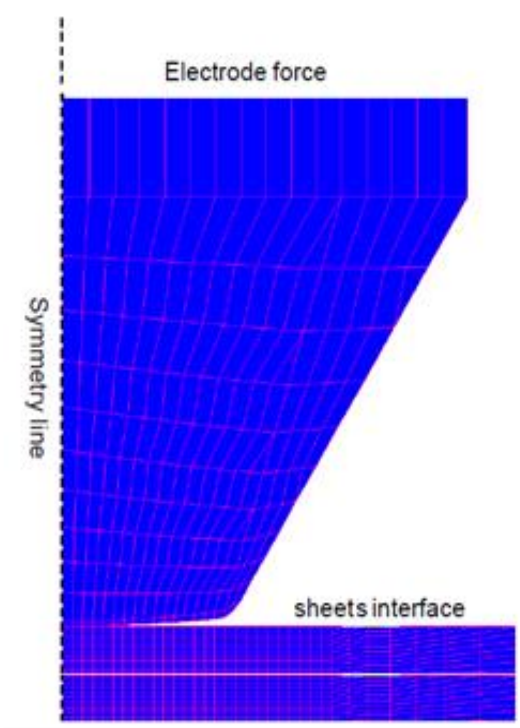

Fig. 1 Finite Element Model for equal sheet thickness

3.2 Heat Transfer Analysis

Heat transfer in the resistance spot welding process involves convective heat transfer and heat conduction in the bulk of the sheet-electrode system. The transient heat flow in the resistance spot welding process has been modelled as a case of the axisymmetric heat conduction problem.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial T}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial z}\left(rK\frac{\partial T}{\partial z}\right)+\dot{Q}=sc\frac{\partial T}{\partial t} \quad (1)$$

where s, c and K are density, specific heat and thermal conductivity, respectively. All the material properties are considered to be temperature-dependent. The term $\dot{Q}$ refers to the rate of internal heat generation per unit volume.

3.3 Electrical Field Analysis

The current density distribution in the sheet-electrode geometry (in two-dimensional cylindrical coordinate system) can be represented by the following relationship,

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{1}{\rho}\frac{\partial \mathbf{J}}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial z}\left(r\frac{1}{\rho}\frac{\partial \mathbf{J}}{\partial z}\right)=0 \quad (2)$$

where ρ is the electrical resistivity and **J** is the current density vector. The electrical resistivity is considered temperature dependent in the present work.

3.4 Internal Heat Generation

The following relationship calculates the internal heat generation at every point in the sheet-electrode geometry,

$$\dot{Q}=\rho J^2 \quad (3)$$

3.5 Internal Heat Generation

The finite element discretization of the complete sheet-electrode geometry has been carried out using a four-noded ring-type isoparametric, solid element with a rectangular cross-section. Within an element, temperature (T) can be expressed as,

$$\{T\}=[N_i \;\ldots..\; N_l]\{T^e\} \quad (4)$$

where N_i, …. N_l are the shape functions (based on nodal coordinates of the element) of the element. The transient heat conduction equation (eq.1) is first discretized, and the discretized equation can be stated as,

$$[H]\{T\}+[S]\frac{\partial}{\partial t}+\{F\}=0 \quad (5)$$

where $[H]$ is the thermal conductivity matrix, $[S]$ is the thermal capacity matrix and $\{F\}$ is the load vector due to internal heat generation. Equation (6) is further discretized in the time domain following Galerkin's Principle. The solution of electrical analysis represents the elemental current density distribution throughout the sheet-electrode geometry. These results are then used to calculate the internal heat generation in each element. Subsequently, the heat transfer equation is solved to obtain the nodal temperature distribution in the complete geometry. The total weld time has been divided into several small time steps. The electrical field analysis is carried out within each time step first to obtain the elemental current density. The heat transfer analysis is done next, considering the internal heat generation.

4. Results and Discussions

A Simulation model was developed, and extensive numerical calculations were carried out to find the nugget diameter, penetration, etc., for resistance spot welding of aluminium alloy sheets using the FEM Software ANSYS. Fig. 1 shows the geometry used for the modelling purpose. Only one quadrant of the complete geometry has been analyzed, considering the axial symmetry of the sheet-electrode system in the spot welding process.

The sheet thickness used for the present analysis is 0.8mm, and the temperature-dependent material properties for aluminium and copper electrode are shown in Fig.2 – 5.

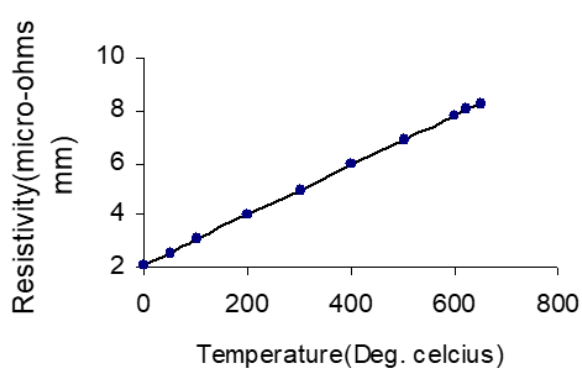

Fig. 2 Temperature-dependent resistivity of copper

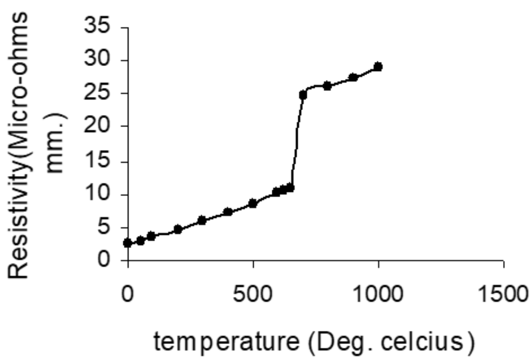

Fig. 3 Temperature-dependent resistivity heat of aluminium

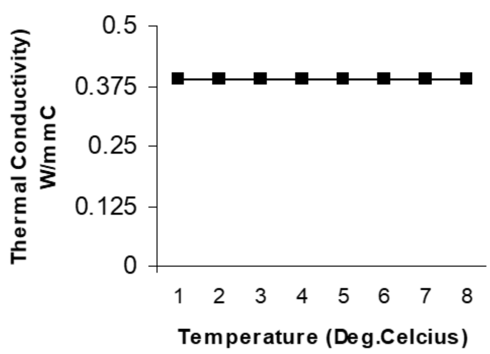

Fig. 4 Temperature-dependent thermal conductivity of copper

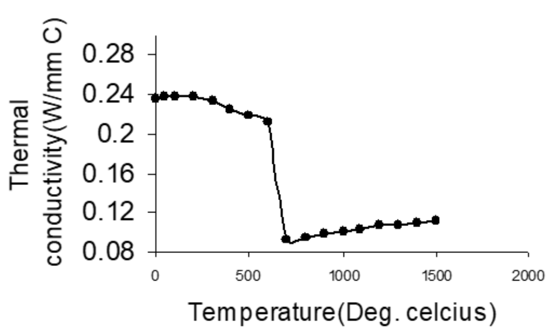

Fig. 5 Temperature-dependent thermal conductivity of aluminium

The sample temperature distributions in the sheet-electrode system for welding current of 45 KA at different instant times are shown in Fig.6. It can be observed that the temperature isotherms are more concentrated along the faying surface, and the maximum temperature occurs along the sheet-to-sheet contact zone only. The time histories of the highest temperature experienced by the sheet-electrode system at two different welding currents (35 KA and 45 KA) are plotted in Fig.7. The development of nugget diameter with time for two different weld currents (40 KA & 45 KA) for the same material is shown by the Fig.-8. The nugget development process is observed to be complete within 0.06 sec, and with further increase in time, no more radial growth occurs. It has been observed in Fig.9 that within 0.02 sec., the maximum temperature generated is above the liquidus temperature of the sheet and with further increase in time, there is no more rise in maximum temperature. This occurs presumably as the faying surface resistance decreases and heat generation becomes more heavily dependent on bulk resistivity further due to the higher conductivity of aluminium alloy heat dissipation becomes more with longer weld time. It has been shown in Fig.9 that the current density is not uniform throughout the sheet-electrode geometry and hence hosts the electrical field analysis's importance in the resistance spot welding process.

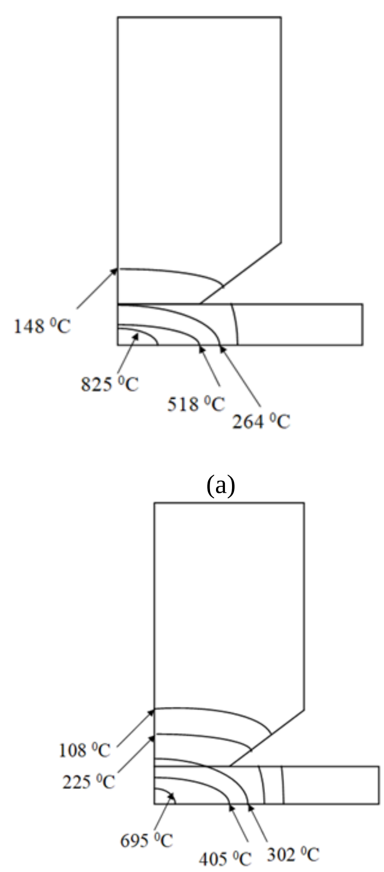

Fig. 6 Temperature Distribution as Resistive heating progress, (a) after 0.2 sec, (b) after 0.8 sec

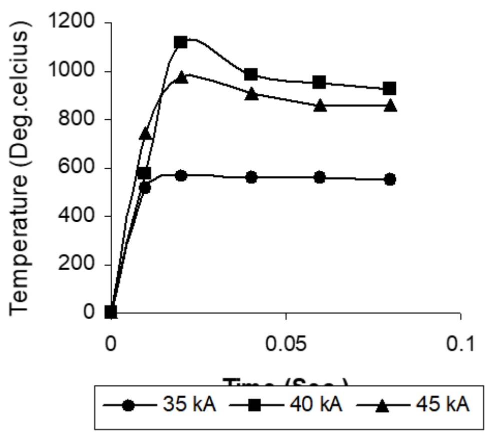

Fig. 7 Maximum temperature generated at different instant of time (sec)

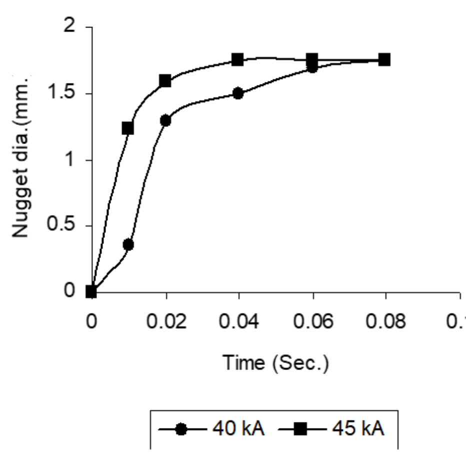

Fig.8 Nugget development at different instants of time (sec.)

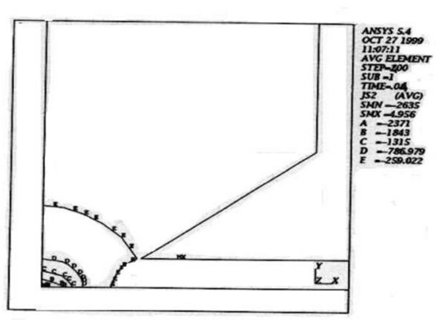

Fig. 9 Current Density Distribution as Resistive Heating Progress

(For sheet thickness 0.8 mm and current I = 45 kA)

5. Conclusion

A comprehensive simulation model using FEM to analyze the resistance spot welding process has been developed. It has been observed that the finite element modelling of the resistance spot welding process can provide good simulation if the model includes the electro-thermal mechanical interaction and suitable temperature–dependent material properties. The results presented herein indicate another alternative: a realistic analytic model. The developed finite element model can calculate most of the resistance spot welding responses in terms of nugget diameter, penetration depth, the extent of heat affected zone, heating and cooling rate, electrode face heating, etc. Finally, this FEM model will help optimize process parameter combinations in any industrial application of the resistance spot welding process. The authors also intend to perform real-time experiments to validate the theoretical results with in-house experimental data since such data are scarcely available in the literature.

References

1. *K. I. Johnson, "Aluminium in vehicle bodies," Metal Construction & British Welding Journal, vol. 8, no. 9, pp. 392-395, 1976.*

2. *E. Ostgard, "Spot welding of aluminium as delivered," Metal Construction, vol. 12, no. 2, pp. 78-86, 1980.*

3. *H. A. Nied, "The finite element modeling of the resistance spot welding process," Welding Journal, vol. 63, no. 4, pp. 123-132, 1984.*

4. *J. E. Gould, "An examination of nugget development during spot welding using both experimental and analytical techniques," Welding Journal, vol. 66, no. 1, pp. 1-10, 1987.*

5. *H. S. Cho, "Study of the thermal behavior in resistance spot welding," Welding Journal, vol. 68, no. 6, pp. 236-244, 1989.*

6. *D. J. Brown, "Computer simulation of resistance spot welding in aluminium," Welding Journal, vol. 74, no. 10, pp. 339-344, 1995.*

7. *D. J. Brown, "Computer simulation of resistance spot welding in aluminium," Welding Journal, vol. 74, no. 12, pp. 417-422, 1995.*

8. *H. Murakawa, H. Kimura, and Y. Ueda, "Weldability analysis of spot welding on aluminium using FEM," Transaction of JWRI, vol. 24, pp. 101-111, 1995.*

9. *A. De, L. Dorn, and A. V. Gohil, "Numerical Modeling of Resistance spot welding of aluminium alloys," Proc. International Conf. on Advances in Welding and Cutting Technology, Eds. The Indian Institute of Welding, 2001.*