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Finite Element Analysis for Transient Thermal Characteristics of Resistance Spot Welding Process with Three Sheets Assemblies

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Abstract

This project built a two dimensional finite element (FE) model for resistance spot welding (RSW) process of Mild steel with three sheets assemblies instead of conventional two sheets stack ups on practical aspect of industry applications. The thermal-electrical coupling method was implemented to investigate transient thermal characteristics during resistance spot welding history with commercial software code, namely ANSYS. Temperature dependency electrical and thermal material properties, phase change as well as convection boundary condition were taken into consideration throughout the coupling procedure. The temperature distribution changes of three sheets assemblies were obtained and transient thermal characteristics were analyzed during RSW thermal-electrical coupled history. Moreover, nugget formation was particularly viewed and discussed under appropriate welding contact condition and other experimental physical parameters.

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Keywords: finite element (FE) model; resistant spot welding (RSW); mild steel; three sheets assemblies; thermal-electrical coupling method; transient thermal characteristics; nugget formation;

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1. Introduction

Resistance spot welding (RSW) is a very effective method to join two or more metal workpieces together with heat produced by current flow through work parts and electrodes pressure. It is widely used in automotive industry since thousands of spot welds are applied in the auto body. RSW is a fast but complicated process since electrical, thermal and mechanical fields are interrelated and interact on each other. Considering the influence parameters for RSW quality, these factors would be taken into considerations such as maximum voltage, contact resistance or thermal expansion and so on during the forming of welding nugget [1]. Numerous researches conducted the finite element method (FEM) to study the transient thermal-electrical coupled resistance spot welding process since it is a feasible approach for investigating RSW thermal history and predicting weld nugget formation, which is beneficial for spot welding process optimization and spot welds quality improvement [1-20]. C.L.TSAI in [1] theoretically analyzed the real-time systematic control approach of RSW process with two sheets assembly in detail, and three joint types which are good fitup, poor fitup and current shunting affecting the contact area of workpiece-workpiece are considered. Moreover, temperature changes through the thickness of workpiece during RSW process and predicted nugget growth as well as thermal response are analyzed in [1]. In [5], finite element method for the mechanical features of RSW process is conducted with two sheets assembly and both temperature dependant and plastic behavior of material properties are taken into consideration. More factors like primary circuit are taken into account for determining the weld strength and nugget diameter to quality estimation in [8].

However, most RSW process studies are limited to two sheet assemblies and less research is paid attention to multiple sheets assembled spot welds in RSW process. However, three or more sheets stack up spot welds represents high frequency in vehicle manufacturing and other engineering fields. Therefore, in this project, FE simulation of RSW process for three sheets assemblies is conducted and transient thermal characteristics of resistance spot welding process are investigated with commercial software code ANSYS. In this study, temperature dependency material property, phase change as well as convection boundary condition were taken into consideration throughout the coupling procedure.

2. Introduction

2.1. Theoretical methodology

In this project, the simulation is achieved based on electrical-thermal field analysis. In the theoretical investigation, not only contact resistivity, thermal conductivity, but also specific heat and phase change are taken into consideration for three sheets assemblies in RSW process. The theoretical basis is the same as two sheets assembly in RSW process. The transient temperature result calculated in heating and holding stage is regarded as the initial temperature condition when computing the result in cooling stage. In fact, electrode force is also considered in the project but ignored in this paper. The heat generated by electrodes current in a certain period can be calculated by (1) shown as below:

\[ Q = I^2 R t \]  \hspace{1cm}  (1)

Where \( Q \) is the heat, \( I \) is the electrical current, \( R \) is the electrical resistivity, \( t \) is time.

The temperature generated by heat flow can be calculated by (2) represented below when (1) is obtained:

\[ \frac{\partial T}{\partial t} = \rho c \nabla \cdot \mathbf{v} + \frac{Q}{\rho c} \]  \hspace{1cm}  (2)
Where, \( \rho \) is density, \( T \) is temperature, \( c \) is heat capacity, and the thermal diffusivity is indicated by \( \alpha \), shown in (3):

\[
\alpha = \frac{\lambda}{\rho c}
\]

(3)

Where, \( \lambda \) is thermal diffusivity.

\( \nabla \) is Laplace operator explained in (4) which reveals the gradient of temperature for objects:

\[
\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}
\]

(4)

2.2. FE Model and Mesh

The two dimensional symmetrical theoretical simulation model with regard to spot welding process is illustrated in Fig.1. There are three sheets of workpieces and each sheet has 25.5mm radius and 1.64mm thickness since the specimen dimension provided in this project is obtained from experiments in [13]. The outer radius of electrode is 8mm and the radius of bottom surface contacting with workpiece is 2.9mm. Enose type electrode is offered and the angle is 20°.

Fig. 1. The dimension of simulation model
This finite element simulation is investigated with software code ANSYS and the mesh of RSW model are illustrated in Fig.2. It can be seen clearly that the center area of workpieces are meshed in fine size since an explicit observation for nugget formation during the simulation process is necessary. Therefore, 0.1mm mesh size with mapped shape is employed for center region of workpieces and electrode region adjacent to sheets. For other domains including the rest parts of workpieces and electrodes, 0.5mm mesh size is applied because of both accuracy and efficiency consideration.

Fig. 2. The mesh of FE model
2.3. Element types

Element type Plane 67 which has both thermal and electrical calculation capability is specifically used in thermal-electrical field of RSW analysis. Moreover, in order to have good insights of thermal history approaching to realistic spot welding conditions, contact elements are employed between workpieces faying surfaces. The contacts are assumed as no sliding modes and the surface roughness is very small and continuous, therefore, all contacts are considered as surface-surface contacts. Contact element type 171 and Target element 169 are used as a pair to define contact property and degrees of freedom in thermal-electrical field.

2.4. Material properties and Loads

Mild steel is one of the most readily weldable materials for RSW process and it is provided as the spot welded sheets material in this project. Copper which has high thermal conductivity performance is selected for electrodes. Time dependency nonlinear thermal and electrical material properties as well as convection coefficient rate for water and air are all researched from literature and paper [3-7]. Furthermore, the latent heat is taken into consideration since there is phase change in RSW process. For welding conditions, all parameter values were derived from experiment procedure, which are: 4223N (950lbs.) weld force, 12 cycle (0.24s) weld time, 5 cycles (0.1s) hold time. The initial weld current was 10.5kA. The water in cooling stage is 12 centigrade. The loading is applied sequentially according to industrial RSW process represented as Fig.3.

![Fig. 3. The RSW processing sequence for loads](image)

3. Results and Discussion

Temperature distributions during the whole welding history are demonstrated from Fig.4 to Fig.7. From finite element simulation, the temperature distribution changes of three sheets assemblies were obtained and transient thermal characteristics were analyzed in the entire RSW process. Moreover, nugget formation was particularly viewed and studied. Comparing it with conventional two sheets assembly in RSW process, due to one more increased sheet which has the same thickness of the other two sheets, the highest temperature distributed is basically symmetrical to the center of middle sheet, which differs from that of two sheets assembly during the whole thermal history in RSW process.

When current is applied, the temperature increases fast and the highest temperature distributed at the two faying surfaces between workpiece-workpiece, instead of center region of entire sheets and keeps the same temperature distribution phenomenon before current is off in the RSW process of three sheets assembly. The typical temperature distribution in thermal history is represented in Fig.4. The dominant effect for this is because of large contact resistance at those regions, when introduces a great amount of heating to faying surfaces at the beginning. Meanwhile, the resistivity in the center domain of entire
workpieces is small at first which generates less heat and thus induces relatively lower temperature in the center.

Fig. 4. Temperature distribution at the beginning of nugget form; T=0.17s.

The temperature continues to rise with the current kept on. As soon as the highest temperature went up over 1500 centigrade which is above the melting point, the nugget begin to form which can be seen in Fig.4 as well. After heating, these areas in RSW process which melt, fused and resolidified could be formed as welded nugget [14].

The temperature reaches to its peak before current is cutoff, and the temperature distribution map at the highest temperature point is illustrated in Fig.5. It indicates that the highest temperature keeps at the faying surfaces between workpiece-workpiece but expands inward, which is to say, the temperature for the center domain of entire sheets gradually increased. The main reason is not only because of center resistivity changes in a rising trend, but also affected by heat conductance and energy flow. Ultimately, the nugget is completely formed at this moment before current went off.
The molten region begins to cool down when cold water is applied. The convection is intensive since the temperature differences between specimen and water is large. The typical temperature distribution in cooling step is illustrated in Fig.6. It is seen that the temperature decrease rate is not uniform over the section surface. The welding zone inside has a lower cooling speed than outside because the middle sheet is further away from electrodes comparing with other two sheets, therefore, the middle region has low convection and the temperature in the center of entire sheets gradually appears a relative high temperature degree.
The temperature distribution at the end of RSW process is shown in Fig. 7. The temperature is redistributed at the end of processing and the temperature mapped in the center region likes an elliptical shape which is much affected by convection coefficient and cooling rate as discussed before. Furthermore, the microstructure of nugget becomes coarser than parent metal and residual stress is generated after the coupled processing [14]. The electrodes near sheet metal wear more quickly because of high temperature environment.

Fig. 7. Temperature distribution at the end of RSW process; T=0.8s.
Compared RSW simulation results with experimental RSW process history captured by advance cameras provided in [15], the images convincingly verified the effectiveness of FE simulation results for transient thermal characteristics in resistance spot welding process with three sheets assemblies.

4. Conclusion

In this study, a two dimensional finite element (FE) model for resistance spot welding (RSW) process of Mild steel with three sheets assemblies is set up. The transient thermal characteristics during resistance spot welding history with three sheets assemblies are investigated in thermal-electrical field with nonlinear finite element method. All results are discussed under the conditions that temperature dependent material properties, phase change, and convection boundary condition are taken into consideration. From temperature distributions analysis during the welding process, it is concluded that the highest temperature begins at two faying surfaces between workpiece-workpiece symmetric to the center of entire sheets because of contact resistance and equal sheet thickness which differs from temperature distribution of two sheets assembly. The temperature expanded inward during heating and holding stages due to resistivity and heat conduction. In the cooling stage, however, the temperature decreased faster at the faying surfaces than that decreased in the middle sheet because of different thermal expansion and convection rate. The nugget begins to form at the melting point and solidifies as an ellipse at the end of process due to heat conduction and thermal convection. The material property of nugget is ultimately changed in the coupled field of RSW process.

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