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Investigation on Weld Nugget and HAZ Development of Resistance Spot Welding using SYSWELD's Customized Electrode Meshing and Experimental Verification

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Abstract: This study investigates the development of weld nugget and Heat Affected Zone (HAZ) in Resistance Spot Welding (RSW) using numerical simulation approach and experimental process. The finite element modeling technique known as SYSWELD was utilized for the simulation process. In the simulation process, a two dimensional axis-symmetric finite element model using customized electrode meshing modeling was chosen to develop the thermal-mechanical-electrical characteristic of the spot weld. The model was developed for welding of two and three sheets of 1 mm thick low carbon steel by flat-faced copper electrodes. The RSW simulation parameters such as force, weld current, weld time and the temperature distribution of the welded sheets and electrodes used were taken into consideration throughout the study. For the experimental verification, an actual welding by RSW with similar welding parameter was carried out. The formation of spot weld nugget and HAZ, based on the common welding parameter for simulation and experiment were compared and discussed. It was found that the theoretical radius of weld nugget and HAZ developed by finite element method are accurately correlated with the results of the experiment.

Key words: Resistance spot welding, finite element method, SYSWELD, VISUAL MESH, customized electrode meshing

INTRODUCTION

Resistance Spot Welding (RSW) is widely used in many industrial sectors such as the automotive industry. The welding process is efficient, inexpensive and easy to understand and learn. The operational cost is generally low, as no shielding gas or filler metal is required.

This process involves strong interactions between electrical, thermal, metallurgical and mechanical phenomena, which are shown in Fig. 1 (Feulvarch *et al.*, 2004). Electrokinetics and heat transfer are coupled via the power dissipation through Joule effect and the temperature dependency of electrical properties. The three interaction types between thermal and metallurgical analysis are: (1) metallurgical transformations directly depending on the thermal history of the part, (2) metallurgical transformations accompanied by latent heat effects which modify temperature distribution and (3) phase-dependent thermal properties.

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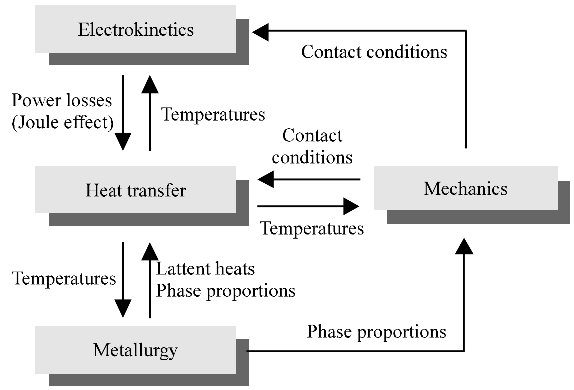

Fig. 1: Coupling between electrokinetics, heat transfer, metallurgy and mechanics

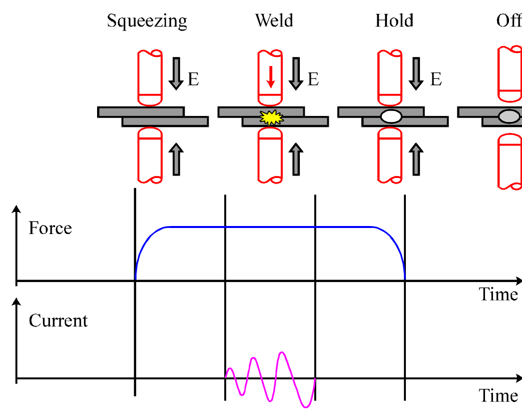

Fig. 2: The sequence of the RSW process

The interactions between thermal and mechanical analysis are due to thermal expansion effects, the temperature dependency of material behavior and contact conditions between electrodes and the steel sheets and between the sheets themselves. Metallurgy is involved in the mechanical analysis through the volume change resulting from metallurgical transformations and a special mechanical behavior due to the multi-phase aspect of the material and particularly the transformation induced plasticity.

In principle, RSW utilizes Joule heating (I^2R) to produce a molten nugget at the contacting surface of the workpieces. The RSW process fundamentally consists of four stages which are squeeze cycle, weld cycle, hold cycle and off cycle. The sequence of the process is shown in Fig. 2. Squeeze cycle is a time during which the upper electrode is brought in contact with the sheets to be welded and force is exerted at the welding region. While the weld cycle is a time during which current is turned on and resistance to current flow at the sheet interface producing a nugget. The hold cycle is a time during which the current is turned off and the fully grown nugget is allowed to cool slowly and solidify under constant pressure. The off cycle is final time during which the electrode is raised from the welded sheets.

Force is applied before, during and after the application of electric current, to maintain the electrical connectivity and to provide the pressure necessary for defect free spot welds

(Feng *et al.*, 1998). Between the electrodes, the highest electrical resistance occurred at the interface of sheet metal. During welding, the surge of high current generates heat, temperature rises to plastic and molten state. During the holding or forging stage, the molten pool consolidates to a spot weld nugget (Sampaio *et al.*, 2008).

The increased adoption of electronics has also made resistance spot welding parameters easier to measure and control with simulation software and precise weld controllers. By using scientific theories and numerical method, the engineering problems can be simulated on a computer. The solutions of the practical problems can be obtained virtually by computations and without having to perform the real engineering process (Zhang, 2003). Hence, the use of software to simulate the weld parameters and to predict the results before the weld is performed will provide better understanding of the welding process.

The followings are some works that had been carried out on the modeling and simulation of a spot welding process.

- Khan *et al.* (1999) had used ABAQUS code to develop an axis-symmetric finite element model employing coupled thermal-electrical-mechanical analysis
- Researchers had studied the numerical simulation of resistance spot welding process using finite element method, SYSWELD. In their studies, a 2-D axis-symmetrical finite element models incorporating electrical-thermal and thermal-mechanical coupling procedures were developed for the resistance spot welding process simulation. They used the curved-face electrode for the simulation and made comparison of the nugget formation with the experimental study
- Mei *et al.* (2006) used in their research finite element analyzing tool ANSYS to simulate the coupling problem at different stages during the welding cycles in order to determine and predict the welding quality at different input parameters. Their aim was to obtain optimum settings of current, time and pressure of the spot welding process for different materials to produce the desired weld quality

In the other study by Hamedi and Pashazadeh (2008), the finite element code of ANSYS was used to model a 2-D axis-symmetry to simulate the thermo-electro-mechanical coupling of RSW process. They had simulated the development of weld nugget during process and effect of process parameters on nugget formation by considering the temperature-dependent on the material properties, thermal contact conductivity and also electrical contact conductivity.

There are several software available dealing with simulation of RSW such as SORPAS, LUSAS, ANSYS, NASTRAN and SYSWELD. In this study, a two dimensional axis-symmetric finite element using customized electrode meshing modeling in SYSWELD 2009 was used to develop and simulate the thermal-mechanical-electrical coupling of the spot welding process. Since the quality of spot weld is effectively influenced by process parameters, the key to improve the spot weld quality is to determine the optimum process parameters. A customized electrode meshing was created in VISUAL MESH software and then exported to SYSWELD for the numerical simulation of the spot welding process. The simulation model consists of a flat-faced electrode on two to three sheets of carbon steel sheet-metal with equal thicknesses of 1.0 mm simultaneously the actual resistance spot welding on the similar design and welding parameter was carried out in order to compare and validate the results from the simulation process.

SIMULATION AND EXPERIMENTAL INVESTIGATION

Basic Principle

According to the axis-symmetric and two dimensional problems with full coupling between the electrical and thermal phenomena, the coupling system governing equations are

$$\rho\frac{\partial H}{\partial t} - (\lambda.\text{gradT}) - \text{gradV}.\sigma.\text{gradV} - Q = 0 \tag{1}$$

$$\text{div}(\sigma.\text{gradV}) = 0 \tag{2}$$

where, T is the temperature and V is the scalar electrical potential, respectively. The ρ, λ and σ represent the density, the thermal conductivity and the electrical conductivity of the media with respect to temperature dependency characteristic. H is the enthalpy with temperature dependency and Q is internal heat generation. The current flow in an electrical conductance generates Joule heating effect, the internal heat dissipation is represented in term of grad.σ. gradV.

Meshing Strategy Using SYSWELD's Customized Meshing

SYSWELD offers two different methods for solving the RSW problem which are predefined method and customized meshing method. In the predefined method, a standard electrode form is selected and SYSWELD generates the meshing automatically, after all parameters are defined such as curvature, radius of electrode and height internal radius as shown in Fig. 3a.

Using the customized electrode meshing, any type electrode geometries can be meshed and simulated. Using the customized electrode meshing, electrode geometries were created in VISUAL MESH (Fig. 3b). Before the customized electrodes meshing are exported to SYSWELD, the skin elements have to be created in order to define the boundary conditions that will be used in the simulation. The element groups of the skin have to be defined according to Fig. 3c. The characteristic of the curves are as follows (SYSWELD User Guide, 2007):

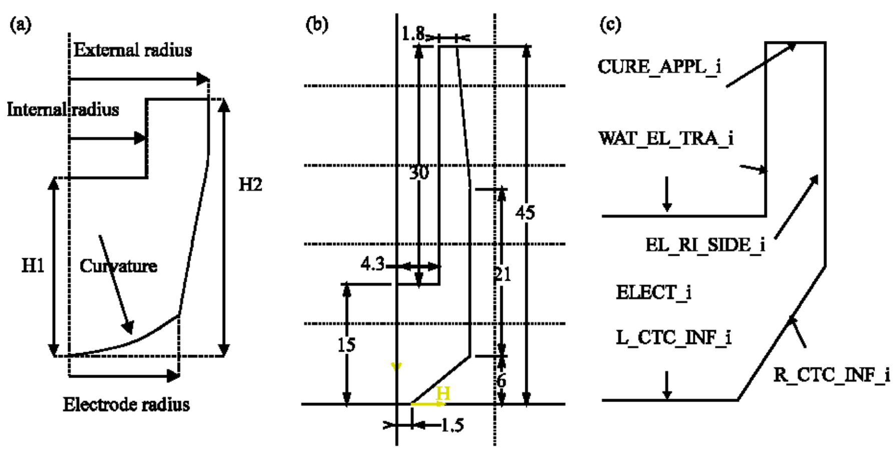

Fig. 3: Designations of curves for (a) predefined, (b) real electrode dimension in mm and (c) group of skin elements

- WAT_EL_TRA_i contains elements where thermal transfer between electrode and water is modeled
- CURE_ APPL_i contains elements where current density and pressure are applied
- EL_RI_SIDE_i contains elements where thermal transfer between electrode and air is modeled
- R_CTC_INF_i contains elements where thermal transfer between electrode and air is modeled. They are sliding contact elements between electrode and sheets too
- L_CTC_INF_i contains elements where thermal transfer between electrode and sheets is modeled. They are sliding or sticking (it depends on the pressure application) contact elements between electrode and sheets too
- ELECT_i contains 2D elements where electro-thermo-metallurgical and mechanical properties are affected

After completion of the electrode meshing process and the defining of the boundary conditions of the skin element, as shown in Fig. 4, the files now ready to be exported to the SYSWELD as *DATA*.ASC file in a new working directory file.

Experimental Process Procedures

The material used in this research is low carbon steel sheet-metal, with a thickness of 1.0 mm. The experiment involved joining of two and three sheets layer of sheet-metal. In this study the electrode size, squeezing force, squeezing cycle and welding time were constant throughout the study. The parameters vary only on weld current used and number of sheet layers, as shown in Table 1.

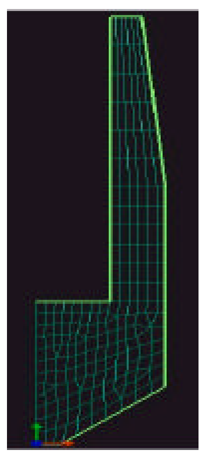

Fig. 4: Meshing strategy of electrode using visual mesh

Table 1: Experimental process parameters

	Parameter (s)				
No. of layers	Weld current (kA)	Electrode radius (mm)	Squeezing force (N)	Squeezing time (cycle)	Welding time (cycle)
2 layers (1.0+1.0 mm)	5.0	1.5	1,500	25	5
3 layers (1.0+1.0+1.0 mm)	6.0				
	7.0				

RESULTS

The development of weld nugget using FEM simulation approach is shown in Fig. 5. In this simulation, weld current of 5.0 kA was applied during weld cycles for two layers. For three layers, weld current applied were 6.0 kA and 7.0 kA. Figure 5a shows that the nugget development starts at 0.12 sec. The development is rapid until it reaches the maximum value of 1.55 mm at 0.17 sec. After that, the weld nugget does not develop anymore and the value of the radius will be constant. From Fig. 5b, for three layers using 6.0 kA weld current, nugget development starts at 0.12 sec and maximum radius of weld nugget is 1.94 mm at 0.19 sec, while for the 7.0 kA weld current, nugget development starts at a bit earlier time of 0.11 sec and reaches the maximum value of weld nugget of 2.29 mm at 0.19 sec. Figure 6 shows the radius of HAZ for two layers and three layers, respectively. From Fig. 6a, it shows that the maximum radius of the HAZ is 2.05 mm at 0.18 sec. Figure 6b shows that, for 6.0 kA weld current, the maximum radius of HAZ is 2.29 mm at 0.17 s while for the 7.0 kA weld current, the maximum radius of HAZ is 2.44 mm at 0.19 sec.

The experimental process results of RSW are presented in form of macrographs. From the macrographs, the diameter of the weld nugget and HAZ can be measured. Figure 7-9, show the macrograph for the two layers (I = 5.0 kA) and three layers (I = 6.0 kA and 7.0 kA) respectively. Table 2 shows the comparison between experimental and simulation results.

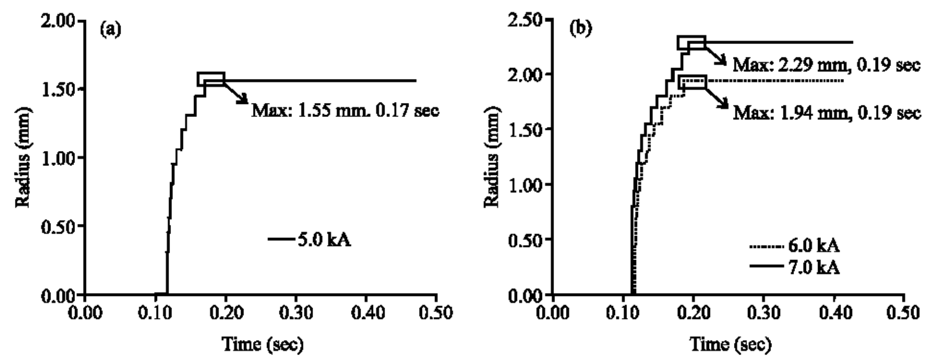

Fig. 5: Graph of molten zone radius for (a) 2 layers using 5.0 kA weld current and (b) 3 layers using 6.0 and7.0 kA weld current

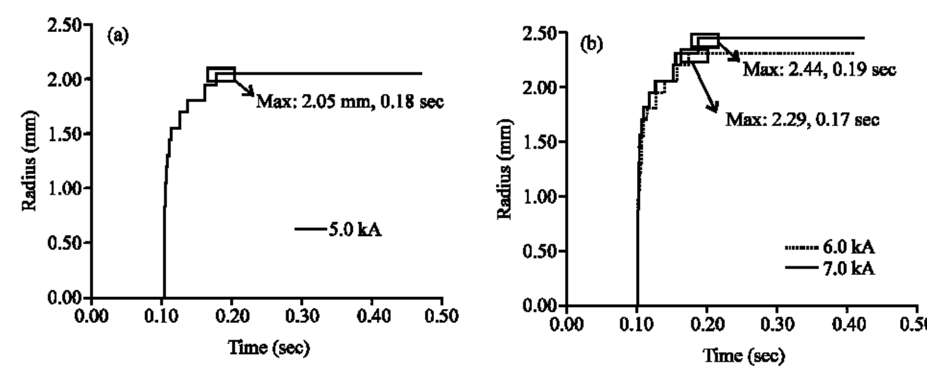

Fig. 6: Graph of HAZ radius for (a) two layers using 5.0 kA weld current and (b) three layers using 6.0 and 7.0 kA weld current

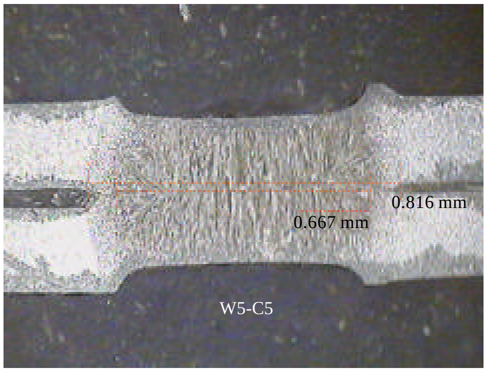

Fig. 7: The macrograph for two sheet layers using 5.0 kA weld current (dimension measured with 5X magnification)

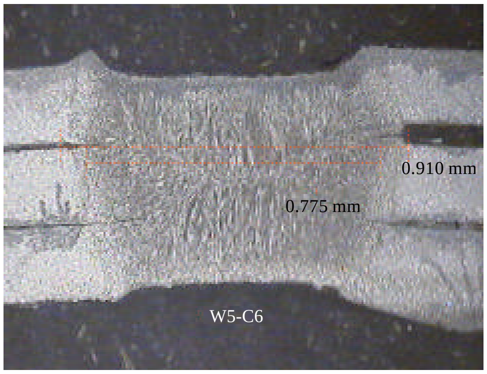

Fig. 8: The macrograph for three sheet layers using 6.0 kA weld current (dimension measured with 5X magnification)

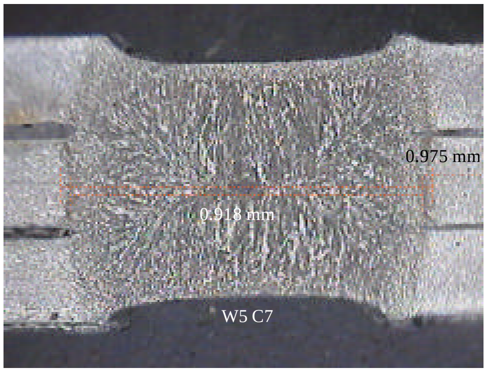

Fig. 9: The macrograph for three sheet layers using 7.0 kA weld current (dimension measured with 5X magnification)

Table 2: Simulation and experimental results for radius of weld nugget and HAZ

		Simulation result		Experimental result	
No. of layers	Weld current (kA)	Radius of weld nugget (mm)	Radius of HAZ (mm)	Radius of weld nugget (mm)	Radius of HAZ (mm)
2 layers (1.0+1.0 mm)	5.0	1.55	2.05	1.67	2.04
3 layers (1.0+1.0+1.0 mm)	6.0	1.94	2.29	1.93	2.26
	7.0	2.29	2.44	2.28	2.44

DISCUSSION

Table 2 shows that the radius of weld nugget and HAZ obtained by simulation are in compatible with experimental results. The result indicates that the weld nugget radius is proportional to increase in welding current, in both simulation and experimental process of the resistance spot welding. According to Hamedi and Pashazadeh (2008), at constant welding time, an increase of welding current affects the rise in nugget temperature.

From the experimental investigation on welding of three sheet layers, the radius of weld nugget with welding current of 7.0 kA has shown further increment as compared to that obtained with 6.0 kA welding current. The radius of weld nugget increased from 1.94 to 2.29 mm. Welding current is the most dominant factor that affects the nugget area, such that increasing the welding current simultaneously increases the nugget area (Darwis and Al-Dekhial, 1999). As the radius of weld nugget increases, the radius of heat affected zone also increases proportionally. From the simulation results produced by SYSWELD, it is shown that the nugget size increased with the weld current. In the Joule heating formula, the welding current has the greatest effect on the generation of heat at faying surface (Hamid *et al*., 2010). Therefore, higher weld current generates more heat and forms a bigger weld nugget.

The results obtained from this study validate the use of simulation using SYSWELD for the prediction of nugget sizes development. Hence simulation process using SYSWELD is an effective method for predicting the optimum welding parameters and the weld nugget formation in resistance spot welding. According to Feulvarch *et al.* (2004), the results of the finite element analysis present a correct correlation with experiments in terms of HAZ size as well as nugget shape.

CONCLUSION

A simulation using SYSWELD and experimental process on two and three sheet layers of low carbon steel having similar thicknesses had been studied. In this study, it was found that a two dimensional axis-symmetric finite element model could be developed using customized electrode meshing to model the thermo-mechanical-electrical coupling of the RSW based on the actual electrode dimension.

From the study, it can be concluded that the result of finite element method presents a theoretically accurate correlation with that of experiments in terms of radius of weld nugget as well as HAZ developed. The simulation process was seen effective in welding of both two and three layers of sheet-metal.

The simulation approach of the RSW provides better understanding of the effects of welding parameters on the nugget formation. It provides the precise analysis, cost and time saving in welding process. From the study it was found that the rate of weld nugget growth is mostly influenced by welding current.

It is recommended that this study to be continued with other parameters such as electrode size, materials, weld time, squeezing time and force. It is also recommended that various types of electrode meshing shall be investigated to determine their effect on nugget development and formation.

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