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Estimation of lobe curve with material strength in resistance projection welding

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ABSTRACT

This study aims at estimating lobe curve in resistance projection welding (RPW) according to material strength. A three-dimensional (3D) fully coupled electrical-thermal-mechanical finite element (FE) model was developed by considering temperature-dependent material properties and projection forming process. Residual stress within the projection after stamping process, which affects the initial contact resistance, increases as projection height and material strength increase. For DP780 steel, an average error of nugget size between welding experiments and FE analyses is less than 10 %. A method for estimating lobe curves with material strength including welding parameters such as electrode force, current, welding time and projection height is proposed based on systematic FE analyses. Lobe curve moves towards a lower current region as the material strength increases.

1. Introduction

Resistance welding is classified into resistance spot welding (RSW) and resistance projection welding (RPW) depending on the existence of a projection. In RPW, projection forms at welding position on a plate, where current is concentrated to induce local heat generation. This concentrated current on the small projected contact area generates nuggets with lower electrode force and current when compared with those of RSW. As a result, better weld appearance can be obtained by performing welding process under low electrode force.

The quality of RPW depends on various welding variables such as electrode force, current, and welding time during welding process. Low current provide insufficient heating in weld part and results in insufficient nugget size, while high current results in defective welding such as surface flash and expulsion. Low electrode force generates expulsion as the small projection collapse leads to concentrated heat generation, while a high electrode force induce insufficient heat generation. Therefore, to analyze welding mechanism of RPW, Cunningham and Begeman (1965) investigated welding behavior by using high-speed photography. Harris and Riley (1961) conducted RPW experiment to determine the suitable values of welding variables including projection shape, electrode force, current, welding time and plate thickness, and proposed an optimal projection shape with plate thickness. RPW is a complicated process as electricity, heat and stress involve simultaneously at the projection; earlier researches were mainly performed by using experimental methods. However, as nugget forms in a few milliseconds, there are limitations to study the nugget growth by experimental method only.

To simulate the RPW process, Sun (2000) constructed a two-dimensional (2D) axisymmetric finite element (FE) model including the H&R-shape projection of Harris and Riley (1961). Accordingly, projection collapse and nugget forming processes were analyzed in chronological order. Sun (2001) analyzed the projection deformation with various projection heights and the subsequent nugget growth process. Although, the previous RPW studies were focused on the nugget formation process according to each welding condition, those are limited to specific materials and focused on a simple comparison of simulation and experimental results. It is because the prediction of welding behavior is extremely difficult due to the involvement of various factors such as electricity, heat, mechanical deformation, metallurgical elements, and residual stresses around projection after the forming process. Moreover, there are limited literatures about RPW FE modeling of projection forming process and subsequent welding despite residual stresses due to projection forming process that affects welding behavior. With the aid of enhanced numerical techniques, it is possible to understand the quantitative phenomena that affects welding performance.

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Constructing RSW model considering temperature-dependent properties of materials in ANSYS, Moshayedi and Sattari-Far (2012) discovered that current has the greatest effect on the nugget size than welding time. Later then, Moshayedi and Sattari-Far (2014) analyzed the generation of welding residual stress with current and welding time in RSW. Bi et al. (2016) examined the shunting effect between two plates with different thicknesses. While RSW simulations have been continuously conducted, few studies were conducted on RPW. One of reasons is the difficulty of numerical convergence from the large geometry change of projection during current flow. In addition, the solution for the convergence problem has not been addressed well.

With the limitations of previous studies in mind, we aim at estimating the lobe curve with material strength considering residual stress after projection forming process, and the acceptable weld domain can be identified from the lobe curve. An *x-z* planar symmetric RPW FE model is first developed from the prior axisymmetric 2D FE model using *contact controls and *stabilize code (Abaqus, 2014) to solve the convergence problem. The FE model is then validated by comparing the numerical nugget sizes with those from experiments under the conditions of three levels of main welding variables and two levels of projection height. The upper/lower limits of the lobe curve are predicted as functions of five welding variables − electrode force, current, welding time, projection height, and material strength − for the conditions that cause expulsion/non-melting. Based on the suggested approach, a lobe curve for any weld material can be predicted, and thereby significantly reducing time and cost required for analyzing welding behavior.

2. Resistance projection welding

2.1. Theory of electrical-thermal-mechanical analysis

To simultaneously investigate the temperature distribution, nugget size and residual stress, a triply-coupled electrical-thermal-mechanical RPW FE model is developed in three-dimensional (3D) by considering only 10 ° in the circumferential direction for efficient analysis based on *x–z* planar symmetric condition. By assuming that there are no the magnetic field effects and no current source inside the conductor, a governing equation of 3D electrical analysis can be presented as

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \tag{1}$$

where electrical potential φ is a function of x, y, z-coordinates and time. Eq. (1) is rewritten according to the equation in Abaqus (2014) as follows

$$\int_V \frac{\partial \delta \phi}{\partial \mathbf{x}} \boldsymbol{\sigma}^E \frac{\partial \phi}{\partial \mathbf{x}} dV = \int_S \delta \phi J \, dS \tag{2}$$

where J refers to current density, $\boldsymbol{\sigma}^E$ refers to electrical conductivity matrix, $\mathbf{x}$ refers to position vector, and S refers to the surface. The body surface S can be divided into S_p, where the boundary conditions are given, and S_i, which can interact with the surfaces of other bodies. Eq. (2) is then expressed as

$$\int_V \frac{\partial \delta \phi}{\partial \mathbf{x}} \boldsymbol{\sigma}^E \frac{\partial \phi}{\partial \mathbf{x}} dV = \int_{S_p} \delta \phi J \, dS + \int_{S_i} \delta \phi J \, dS \tag{3}$$

By considering heat generation by current, and heat transfer by convection and radiation, a governing equation for thermal analysis is given as follows

$$k(T)\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \dot{Q} = \rho(T) C_p(T)\left(\frac{\partial T}{\partial t}\right) \tag{4}$$

where k refers to thermal conductivity, ρ is density, $\dot{Q}$ is the internal heat generation rate per unit volume, U is the internal energy, and T and t refer to temperature and time, respectively. Eq. (4) is altered by using the classical Galerkin method as

$$\int_V \rho \dot{U} \delta T \, dV + \int_V \frac{\partial \delta T}{\partial \mathbf{x}} \mathbf{k} \frac{\partial T}{\partial \mathbf{x}} dV = \int_V \delta T r \, dV + \int_S \delta T q \, dS \tag{5}$$

where Joule heat r represents the heat generated inside the volume, q is the heat flux per unit area, and $\mathbf{k}$ is the thermal conductivity matrix, which is the derivative of the net flux vector with respect to the nodal temperature vector. Hence, it includes the effect of temperature-dependent flux conditions such as film and radiation. The volume can be divided into a region that has its own heat source and a heated region due to Joule heat, and again the entire surface S can be divided into S_p and S_i. Eq. (5) is rewritten as follows:

$$\int_V \rho \dot{U} \delta T \, dV + \int_V \frac{\partial \delta T}{\partial \mathbf{x}} \mathbf{k} \frac{\partial T}{\partial \mathbf{x}} dV = \int_V \delta T r \, dV + \int_V \delta T \eta_v P_{ec} \, dV + \int_{S_p} \delta T q \, dS + \int_{S_i} \delta T \left(q_c + q_r + q_{ec}\right) dS \tag{6}$$

where η_v is a factor for energy conversion from electricity to heat, q_c is heat conduction, q_r is heat radiation, and q_{ec} is the amount of heat energy converted from electricity.

2.2. Modeling of projection forming process

In RPW, the stamping process produces the projection, which shape is determined by the punch and die. At the end of the stamping process, residual stresses are distributed within the projection. The configurations of H & R projection (Harris and Riley, 1961) is used for punch and die (Fig. 1) during the stamping process. To analyze residual stress within the projection, a FE model for stamping process comprises forming tools (punch, die, holder) and sheet specimen. The forming tools are modeled with about 200 R3D4 rigid elements as they are far more rigid than the specimen. Fig. 2 shows an integrated FE model of 1 / 36 (10 °) in the circumferential direction. The stamping analysis for producing the projection by punch is performed in step 1, in which punch is moved in the *y*-direction corresponding to the projection height while the die and holder are fixed in all *x*, *y*, and *z*-axes. The punch is unloaded in step 2. As a result, the projection springs back due to elastic recovery. Followed by, welding analyses are then performed with the specimen obtained through the stamping process (steps 1 & 2).

2.3. Faying interface modeling

There are three contact regions in the developed FE model: (i) between upper electrode and specimen, (ii) between upper and lower specimens, and (iii) between lower electrode and specimen. An accurate contact condition is required to obtain a reliable solution because temperature distribution is determined by the contact properties such as contact resistance, friction coefficient and thermal conductivity in the contact part. Sun (2001) used *contact pair in Abaqus for surface contact conditions; the same is also used in this study. The contact friction coefficient is set to 0.3 through comparisons of the nugget size between the experiments and simulation using the trial and error method. To solve the convergence problem due to complicated contact conditions, the *stabilize code is included. Area, where the temperature

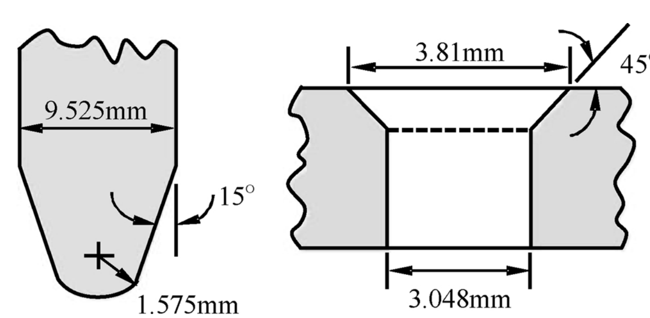

Fig. 1. Configurations of H & R punch and die.