Estimation of lobe curve with material strength in resistance projection welding

Sangun Ha, Siva Prasad Murugan, Karuppasamy Pandian Marimuthu, Yeongdo Park, Hyungyil Lee

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 on, 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 RPWF 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

\[ \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \]  

(1)

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

\[ \int_V \frac{\partial^2 \phi}{\partial x^2} \sigma_x \frac{\partial \phi}{\partial x} dV = \int_S \delta \phi J dS \]  

(2)

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

\[ \int_V \frac{\partial^2 \phi}{\partial x^2} \sigma_x \frac{\partial \phi}{\partial x} dV = \int_{\partial S_p} \delta \phi J dS + \int_{\partial S_i} \delta \phi J dS \]  

(3)

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

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

(4)

where \( k \) refers to thermal conductivity, \( \rho \) 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

\[ \int_V \rho \delta T \frac{\partial T}{\partial t} dV + \int_V \frac{\partial \dot{Q}}{\partial x} \frac{\partial T}{\partial x} dV = \int_V \frac{\partial \dot{Q}}{\partial y} \frac{\partial T}{\partial y} dV + \int_V \frac{\partial \dot{Q}}{\partial z} \frac{\partial T}{\partial z} dV + \int_S \delta T \dot{q} dS \]  

(5)

where Joule heat \( \dot{q} \) represents the heat generated inside the volume, \( q \) is the heat flux per unit area, and \( k \) 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:

\[ \int_V \rho \delta T \frac{\partial T}{\partial t} dV + \int_V \frac{\partial \dot{Q}}{\partial x} \frac{\partial T}{\partial x} dV = \int_V \frac{\partial \dot{Q}}{\partial y} \frac{\partial T}{\partial y} dV + \int_V \frac{\partial \dot{Q}}{\partial z} \frac{\partial T}{\partial z} dV + \int_{S_p} \delta T \dot{q} dS + \int_{S_i} \delta T (q_v + q_r + q_e) dS \]  

(6)

where \( q_v \) is a factor for energy conversion from electricity to heat, \( q_r \) is heat conduction, \( q_i \) is heat radiation, and \( q_e \) 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
is above the melting temperature of the base material, is considered as a nugget without considering the actual weld-joining in the melting region.

A factor for determining the nugget size under current flow is the heat generation by contact resistance between the upper and lower specimen. The actual plate surface comprises numerous micro-asperities, and contact resistance is caused by partial contact between the micro-asperities rather than the apparent entire surface. It is difficult to predict contact resistance as it changes due to various factors during the actual welding process. For modeling of contact resistance, the equation proposed by Tsai et al. (1991) is used, which expresses contact resistance as a function of yield strength with temperature as

$$ R_c(T) = R_c(20^\circ C) \frac{\sigma_y(T)}{\sigma_y(20^\circ C)} $$

where $R_c$ refers to contact resistance, $\sigma_y$ is yield strength, and $T$ is temperature. According to Eq. (7), contact resistance is the greatest at the initial time of current flow period and decreases gradually as the temperature increases.

2.4. Sequence of RPW

The resistance projection welding is performed in order of squeeze, ramp, welding and holding as outlined in Fig. 3; each stage is measured with a unit of cycle (1 cycle = 1 / 60 s). Squeeze stage is the interval between application of electrode force and initiation of current flow. The initial contact area due to the projection collapse is determined in the interval, and initial contact area affects the current density at the initial stage of the current flow. Squeeze time is necessary for the electrode force to reach the target value. Ramp stage represents the time required for the current to reach the target value which is usually less than 16 ms. During ramping stage, nugget forms with a size proportional to the welding time for a given welding current because the heat generation increases with welding time. If the welding time is too long, the molten region grows, which results in welding problems such as surface flash and expulsion. During the holding stage, the electrode force is applied without current flow to solidify the molten part. A solidified weld nugget is formed with less shrinkage cavity during this stage. Electrode heating occurs owing to heat transfer from the molten part to the electrode when the holding time is longer than the appropriate value. Aslanlar (2006) noted that a longer holding time is required for welding of galvanized carbon steel compared with other materials.

2.5. FE modeling

RPW is a complex welding method due to triply-coupled electrical-thermal-mechanical behavior, in addition, thermal and mechanical properties of weld material change in real time. A flow chart for analyzing the RPW process is described step by steps as shown in Fig. 4. The RPW FE model consists of about 2000 8-node Q3D8 elements (Abaqus, 2014), and refined elements are placed near the projection region of large deformation (Fig. 5). Lee (2015) considered the residual stress within the projection after projection stamping process. The FE model of Lee (2015) is improved to reduce the convergence problems caused by large deformation of projection. The temperature ranges for material properties (specific heat, thermal conductivity, electrical conductivity, flow stress, etc.) are then subdivided to get the reliable FE results. Finally, the RPW FE model is reconstructed based on experimental setup. The model comprises an electrode pair, 1.4 mm projected specimen, and 1.4 mm flat specimen. To maximize the efficiency of analyses than prior axisymmetric model of Sun (2001), only $10^6$ in the circumferential direction based on x-y planar symmetric condition FE model is developed using *ncopy (Abaqus, 2014). The boundary conditions about x-y plane are applied to prevent unreal deformation. In the opposite plane, displacements within the plane only allowed with the ratio of x- and z-axis displacements set using *equation (Abaqus, 2014). The symmetry plane is used to apply symmetry boundary conditions.

To consider heat loss, internal area of the electrode is set to have forced convection via cooling water; whereas external area of the electrode and specimen are exposed to air to have natural convection and radiation condition (Fig. 6). Based on the study of Lee (2015) and Abaqus documentation (Abaqus, 2014), ambient temperature, Boltzmann constant, emissivity, natural convection coefficient, cooling water temperature, and forced convection coefficient are given as 25 $^\circ$C, 5.669 $\times$ 10$^{-8}$ J/(s $^\circ$C $^2$ K$^4$), 0.4, 15 $\times$ 10$^{-8}$ W/(mm$^2$ $^\circ$C), 20 $^\circ$C, and 300 $\times$ 10$^{-6}$ W/(mm$^2$ $^\circ$C), respectively. Accurate convection coefficients and emissivity are difficult to obtain from the experimental setup.
The energy conversion factor ($\eta_v$) is set to 1 by assuming all electrical energy is converted to heat energy. If $\eta_v$ is less than unity, all electrical energy cannot be converted to heat energy; this reduces heat generation at the projection. As a result, small $\eta_v$ leads to the maximum temperature decrease. DP780 steel is used as a weld material in the simulation and its physical properties at high temperature are obtained by performing high-temperature tensile tests at various temperatures (20, 200, 400, 600 and 800 °C). Considering the deformation due to high temperature during the welding process, a dome-type electrode made of a Cu-Cr alloy is used (Lu et al., 2006; Mu et al., 2008). Flow strength, thermal/electrical conductivity, specific heat, and coefficient of thermal expansion are set according to Batra et al. (2001) and Zhigang et al. (2006), and the thermal, electrical, mechanical, and physical properties of the electrode and specimen at various temperatures are presented in Tables 1 and 2. In the tables, $C_p$ refers to specific heat, $\rho_e$ is resistivity, $E$ is Young’s modulus, $\sigma_o$ is yield strength, $\nu$ is Poisson’s ratio and $\rho$ is density. Based on the data obtained from the high temperature tensile test, the flow strength can be regressed by using the Swift equation as

$$\sigma_t = K (\varepsilon_o + \varepsilon_t)^n$$

where $\sigma_t$ refers to true stress, $K$ is strength coefficient, $\varepsilon_o$ is yield strain, $\varepsilon_t$ is true strain, and $n$ is strain hardening exponent. The lobe curve is then estimated based on the analysis results of strength coefficient $K/K_{base} = 0.75, 1.00, 1.25$. Obtained values of $K$ and $n$ at different temperatures (20, 100, 400, 600, 700 and 1000 °C) are listed in Table 3.

During the welding simulation, the electrode force and current are applied to the upper electrode top, while all displacements at the bottom of the lower electrode are fixed. The electrode force linearly increases up to the maximum during the squeeze stage and then maintains at the maximum until the holding stage. After the squeeze stage, current flows until the end of welding stage. Therefore, welding analyses are performed by considering the two stamping steps and four welding stages. Bi et al. (2016) analyzed the shunting effect which means that some current flows through already formed nuggets. However, the shunting effect is not considered in this study as welding behavior of a single projection is analyzed here.

### Table 1

<table>
<thead>
<tr>
<th>temperature (°C)</th>
<th>$C_p$ [J / (kg K)]</th>
<th>$k$ [W / (m K)]</th>
<th>$\rho_e$ (Ωm × 10⁻⁸)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-Cr electrode</td>
<td>DP780 steel</td>
<td>Cu-Cr electrode</td>
<td>DP780 steel</td>
</tr>
<tr>
<td>20</td>
<td>398</td>
<td>480</td>
<td>291</td>
</tr>
<tr>
<td>200</td>
<td>418</td>
<td>533</td>
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<tr>
<td>600</td>
<td>456</td>
<td>800</td>
<td>316</td>
</tr>
<tr>
<td>800</td>
<td>479</td>
<td>810</td>
<td>360</td>
</tr>
</tbody>
</table>
2.6. RPW experiments

The RPW experiments were conducted with projection heights of 0.7, 0.9 and 1.1 mm in a cold rolled dual phase (DP-780 MPa) steel of thickness 1.4 mm. The dimensions of the experimental specimen are illustrated in Fig. 7. The chemical composition of DP780 steel is listed in Table 4. Prior to the experiment, impurities on the specimen surface were removed by using acetone as the impurities can affect the resistivity. The specimen with a processed projection was placed on a flat specimen in such a way that the projection side faced downwards as shown in Fig. 7. Both ends of the specimen were fixed, and the upper electrode was set to have complete contact with the upper specimen. All the experiments were conducted at room temperature (18°C) and a dome-type Cu-Cr electrode with a tip diameter of 6 mm was employed. A C-type welding gun integrated with a MFDC power source was used in the experiments and Table 5 lists the experimental conditions. The cross-section of nugget was obtained by cutting through the center of the nugget and then polished to measure the nugget size. Intergranular corrosion was induced by using a 5% Nital etching reagent (95 ml ethanol + 5 ml nitric acid) to make easier observation of nugget.

3. Results and discussion

Since the nugget size is influenced by the electrode force, current, welding time, projection height and initial contact area, an acceptable weld domain can be presented by using the lobe curves. The nugget size is used as a reference for plotting the lobe curves. Therefore, the expression of lobe curve should consider all the welding variables that affect the nugget size. Here, Taguchi method (Peace, 1992) is used to identify the welding variables, which affect nugget size. Based the results of 81 sets of analyses with five welding variables (electrode force, current, welding time, material strength and projection height), the lobe curve is estimated. It is difficult to estimate the nugget size owing to the complexity of the RPW process such as projection collapse and conversion of the electrical energy to heat energy in real time. To predict the nugget size and temperature distribution, RPW is analyzed in detail by using RPW FE model. Fig. 8 shows the dynamic welding process including projection and nugget formation in chronological order. Melting initiates in the form of small ring on the projection because of high current density. As the welding time increases, the melting grows towards the center of the weld.

3.1. Initial contact resistance

The initial contact resistances (ICR) of the DP780 steel with various projection height, electrode force and welding current are plotted as shown in Fig. 9. ICR increases with the projection height; this increases heat generation at the initial current flow. Whereas, ICR decreases with increasing current and electrode force. As the welding current increases, the material becomes soft because of the rapid increment in temperature. When the electrode force increases, severe deformation causes drop in ICR. After stamping process, the residual stress distribution in cross-sectioned projection are shown in Fig. 10 for different projection height of 0.7, 0.9 and 1.1 mm. The tensile and compressive residual stresses are formed on the outside and inside of the projection, respectively. As the projection height increases, residual stress within the projection increases and the initial contact radius between the
projection and specimen decreases. High ICR due to residual stress within the projection and the small initial contact radius results in higher heat generation and hence the nugget size increases. The residual stress for projection height 1.1 mm is higher than those for 0.7 and 0.9 mm projections, however, the neck-down causes decrease in cross-sectional area of 1.1 mm projection. As a result, projection collapses easily, and heat generation reduces. Hence, the projection height should be included as an additional welding variable along with the three major welding variables for the estimation of the lobe curve.

Nugget diameter over contact diameter is hardly affected by the projection height as the contact area and heat generation are inversely proportional to each other.

3.2. Validation of FE model

RPW is a complex triply-coupled electrical-thermal-mechanical
process, therefore the reliability of analysis results should be validated before and after the projection collapse time. To validate the FE model of RPW, the size and shape of nugget are compared between the experimental and numerical analyses for a wide range of welding conditions (projection height, electrode force, current and welding time) as listed in Table 6. Here, \( h \) refers to the projection height, \( d_n |_{\text{FEA}} \) and \( d_n |_{\text{Exp}} \) refer to the nugget size obtained through FE analyses and experiments, respectively. The welding conditions before and after the projection collapse time, and comparison between experiments and analyses are presented in the Appendix A. For the validation of FE model, three levels of major variables except projection height (two levels) are considered. In Table 6, the region marked with ‘×’ refers to the condition at which the nugget is not formed and ‘–’ refers to the condition at which the analysis is not converged. Welding problems such as shrinkage cavity and spatter in the experiments are marked as ‘–’. The average error for the nugget size between the experiments and FE analyses is less than 10%. The nugget and corona bond shapes acquired through FE analyses are comparable to that of the experiments (Fig. 11). At the corona bond, which is not a melted part, the materials are joined at high temperature to form a solid state joint due to heat and pressure. Based on the above results, it is judged that the developed FE model in the present study reflects real phenomena. Thus, the predicted lobe curves based on the FE analyses are highly reliable.

High electrical conductivity accelerates current flow, which also limits the nugget growth due to low heat generation. To check the effect of inaccurate input data, the 20% greater values than those of actual specific heat, thermal and electrical conductivities of DP780 steel were inputted, which resulted in a long oval nugget shape as shown Fig. 12. Note again that the nugget grows in the vertical direction towards the electrodes with original accurate values of specific heat, thermal conductivity and electrical conductivity as shown Fig. 11.

### Table 6

Comparison of nugget size from FE analyses and experiments.

| \( h \) (mm) | \( f_c \) (kN) | \( I \) (kA) | \( t \) (ms) | \( d_n |_{\text{FEA}} \) (mm) | \( d_n |_{\text{Exp}} \) (mm) | gap (%) |
|-------|-------|-------|-------|----------------|----------------|-------|
| 0.7   | 2.0   | 5     | 17    | 2.42           | 2.14           | 13.1  |
| 0.7   | 2.0   | 5     | 83    | 3.92           | 4.00           | 2.00  |
| 0.7   | 2.0   | 7     | 33    | 2.54           | 2.49           | 2.01  |
| 0.7   | 3.0   | 5     | 17    | ×              | ×              | 9.30  |
| 0.7   | 3.0   | 5     | 83    | 3.90           | 4.30           | 9.30  |
| 0.7   | 3.0   | 7     | 166   | –              | –              | –     |
| 0.7   | 4.5   | 5     | 83    | 3.50           | 3.60           | 2.78  |
| 0.7   | 4.5   | 7     | 17    | 3.15           | 2.97           | 6.06  |
| 0.9   | 3.0   | 5     | 17    | ×              | ×              | –     |
| 0.9   | 3.0   | 5     | 83    | 4.18           | 4.00           | 4.50  |
| 0.9   | 4.5   | 5     | 17    | ×              | ×              | –     |
| 0.9   | 4.5   | 5     | 83    | 4.30           | 4.18           | 2.87  |
| 0.9   | 4.5   | 7     | 166   | 4.68           | 4.40           | 6.36  |
| 0.9   | 4.5   | 10    | 50    | 5.00           | 4.20           | 19.1  |
| 0.9   | 4.5   | 10    | 83    | –              | –              | –     |

**Fig. 11.** Comparison of experimental nugget region with those from FE analysis (\( h = 0.7 \) mm, \( f_c = 3 \) kN, \( I = 5 \) kA, \( t = 5 \) cycles).

**Fig. 12.** Nugget shape under the condition of 20% greater specific heat and thermal and electrical conductivities values of DP780 steel (\( h = 0.7 \) mm, \( f_c = 3 \) kN, \( I = 5 \) kA, \( t = 5 \) cycles) ; effects of inaccurate input data on RPW process.

#### 3.3. Welding behavior with material strength

For DP780 steel with projection height of 0.9 mm, the strength coefficient \( K / K_{\text{base}} = 0.75, 1.00, 1.25 \) are used to investigate residual stress state within the projection, and the flow stress variation with the strength coefficient ratio and temperature are shown in Fig. 13. After the stamping process, Table 7 lists the contact diameter ratio and Fig. 14 shows the residual stress distribution in the specimen. As the strength coefficient increases, residual stress within the projection increases. The high strength coefficient induces high flow stress, thus resistance against projection deformation is larger under the same electrode force. This decreases the contact area under the applied electrode force as shown in Table 7. The small contact area increases the heat generation, consequently the lobe curve moves to a lower current region than that of mild steel.

#### 3.4. Estimation of lobe curve

The acceptable weld domain i.e. welding current-electrode force plane or welding current-welding time plane of RPW process can be identified from the lobe curve by maintaining all the other variables as constant. Unlike RSW, the projection height should be considered to predict the lobe curve of RPW, because projection height significantly affects nugget formation. The major difference between RPW and RSW is the projection collapse, which affects the initiation and growth of the weld nugget. The electrode force is an influential factor in RPW (Sun, 2000), the welding time is therefore fixed at 20 ms rather than fixing the electrode force while predicting the lobe curve with material strength. The electrode force affects projection collapse, and nugget forms within a short welding time compared to RSW.

A multivariate statistics method i.e. Taguchi method is used to determine major welding variables (Appendix B in Supplementary material). The lobe curves are then estimated by using the four main variables such as projection height, current, electrode force and welding time. Joining quality is affected by various factors such as nugget size, porosity and microstructure in molten zone are not considered in the developed FE model whereas the effect of nugget size on joining quality is focused.

To predict the lobe curve with material strength, FE analyses are performed by using a combination of 81 variables (electrode force \( f_c = 2, 3 \) and 4.5 kN, current \( I = 5, 7 \) and 10 kA, \( t = 20 \) ms, strength coefficients ratio \( K / K_{\text{base}} = 0.75, 1.00 \) and 1.25, and projection height \( h = 0.7, 0.9 \) and 1.1 mm) and with the mechanical properties of DP780 steel. Regression equations of the maximum temperature in the welding region and the nugget diameter are then derived for predicting the lobe curve as...
The values of the constants in Eqs. (9) & (10) are presented in Table 8. The average regression error decreased about 7% compared to the previous method.

Table 7
Contact diameter ratio $d_c / d_{c, \text{base}}$ with electrode force $f_e$.

<table>
<thead>
<tr>
<th>$K / K_{\text{base}}$</th>
<th>$d_c / d_{c, \text{base}}$</th>
<th>$f_e = 2, \text{kN}$</th>
<th>$f_e = 3, \text{kN}$</th>
<th>$f_e = 4.5, \text{kN}$</th>
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<td>1.00</td>
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</tbody>
</table>

Fig. 13. Stress-strain curve according to various temperature and material strength of $K/K_{\text{base}} = \text{(a) 0.75, (b) 1.00, (c) 1.25.}$

Fig. 14. $\sigma_{eq}/\sigma_{\text{max}}$ at steps 2 for $K/K_{\text{base}}$ (a) 0.75, (b) 1.00, (c) 1.25.
with the equation considering only the linear terms of $f_e$ and $I$. According to Browne et al. (1995), expulsion occurs when the nugget diameter is greater than the contact radius at the faying interface.

The lobe curves obtained for various projection heights ($h$) and strength coefficients ($K$) at $t = 20$ ms using Eqs. (9) & (10) are shown in Fig. 15. The domain between the upper and lower limits of the curve is the region from which nugget starts to form before the occurrence of expulsion, and gray regions represent the acceptable welding domains. As shown in Fig. 15, the acceptable weld domain moves to a lower current and higher electrode force region as the material strength increases, which implies that actual high strength steel (HSS) has a lobe curve in a lower current region and requires higher electrode force compared with mild steel (Keeler and Kimchi, 2014). Since the strength coefficients of HSS are higher than that of mild steel, the resistance against projection deformation increases under the same electrode force. The high current density is induced in the projection due to the reduction in the contact area caused by higher residual stress within projection after projection forming process. As a result, the acceptable weld domain moves towards a lower current and higher electrode force region with increasing $K/K_{base}$ from 0.75 to 1.25, as shown in Fig. 15 from (a) to (c).

As the projection height increases from 0.7 to 0.9 mm, the acceptable weld domain moves to a lower current region owing to the high ICR (Fig. 9) and small initial contact area. On the other hand, when $h$ increases from 0.9 to 1.1 mm, the cross-sectional area of projection decreases due to occurrence of neck-down for height $h \geq 1.1$ mm (Fig. 10). This leads to easier projection collapse and increase in contact area between the projection and the specimen. In this case, the heat generation is dropped than that of $h = 0.7$, 0.9 mm and the acceptable weld domain moves towards a higher current region as shown in Fig. 15. The lobe curves for various welding times also can be predicted in this way.

### 4. Conclusions

To identify the movement of the acceptable weld domain between the conventional steels and the high strength steels in resistance projection welding, the lobe curves were estimated with material strength considering the main welding variable such as projection height, current, electrode force and welding time. The analyses results are summarized as follows:

1. With increasing projection height and material strength, nugget size increases for a constant welding current due to the increasing initial contact resistance and decreasing contact area.

2. When the projection height was increased, (i) the initial contact diameter between the projection and the specimen was decreased, whereas (ii) the residual stress and hence the initial contact resistance were increased and (iii) heat generation was increased. However, an early projection collapse occurred for projection height $h = 1.1$ mm or greater due to neck-down of the projection; as a

### Table 8

<table>
<thead>
<tr>
<th>constant</th>
<th>$c_0$</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$c_4$</th>
<th>$c_5$</th>
<th>$c_6$</th>
<th>$c_7$</th>
<th>$c_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq. (9)</td>
<td>0.8900</td>
<td>0.5700</td>
<td>-0.1300</td>
<td>0.0100</td>
<td>-0.6500</td>
<td>0.1000</td>
<td>-0.0008</td>
<td>0.0750</td>
<td>0.0002</td>
</tr>
<tr>
<td>Eq. (10)</td>
<td>0.2000</td>
<td>0.6800</td>
<td>-0.0560</td>
<td>0.0110</td>
<td>-0.7400</td>
<td>0.1460</td>
<td>-0.0178</td>
<td>-0.0570</td>
<td>-0.0070</td>
</tr>
</tbody>
</table>

Fig. 15. Estimated lobe curves with welding variables ($I$, $f_e$, $h$) at $t = 20$ ms for $K/K_{base} = $ (a) 0.75, (b) 1.00, (c) 1.25 (d) combined.
result, heat generation was reduced.

(3) With a 20% increase in the value of specific heat, thermal conductivity and electrical conductivity, a long oval shaped nugget was formed and grew in parallel direction to the specimen rather than in the vertical direction towards the electrodes. Thus accurate input data are crucial in RPW FE analysis.

(4) As the average error for nugget size between the experiments and FEA is less than 10% for a wide range of welding conditions, the predicted lobe curve for the given DP780 steel are highly reliable.

(5) The relocation of lobe curves in Fig. 15 demonstrates that the acceptable set of welding variables depends on material strength, which should be considered in the RPW of emerging new ultra-high strength steels.

Acknowledgments

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Appendix A. Comparison of simulation and experimental results

To validate the FE model, the nugget size and shape are compared between the experiments and FE analyses (Fig. A1). Comparison is performed with three levels of major welding variables except projection height (two levels). The average nugget size in Table 6, which is measured three times in each condition, is used. From Fig. A1, projection collapse time is considered around 17 ms under the electrode force from 2 to 4.5 kN. The nugget size, shape and projection collapse time are almost the same between the experiments and FE analyses. Therefore, the developed FE model is reliable for all welding time, and the estimated lobe curve from FE analyses is judged to be valid.

Experiment results show that there is a limitation to adjust the welding spot on the top of projection without any error. It leads the irregular left and right spaces of the projection after the welding time, and nugget is not formed into a completely elliptical shape at earlier welding time. For the specific welding condition in Table 6 in which nugget is not formed, we can obtain the same results as the regression equation.

Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jmatprotec.2018.07.037.

Fig. A1. Comparison of nugget regions of experiment (left) and FE analysis (right) for (a) \( h = 0.7 \text{ mm}, f_e = 2 \text{ kN}, I = 5 \text{ kA}, t = 17 \text{ ms} \) (b) \( h = 0.7, f_e = 4.5, I = 7, t = 17 \) (c) \( h = 0.9, f_e = 4.5, I = 10, t = 50 \).
References


