Technical paper

Estimation of the weldability of single-sided resistance spot welding

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A single-sided spot welding technique is investigated by numerical analysis using a commercial CAE package to estimate the weldability. The reliability of the method is verified by the welding experiment performed under conditions similar to those of a real product. Several conditions are analyzed to find an optimal condition set, including the boundary condition for the ground location and the electrical contact resistance. The resulting Lobe curve with respect to welding time and current is obtained. The weldability of the single-sided spot welding specimen is estimated through the tensile strength test. A certain level of tensile strength can be obtained at the range of welding variables for the optimal nugget sizes, which supports the reliability of the single-sided RSW.

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1. Introduction

Resistance spot welding (RSW) has been widely employed in sheet metal fabrications for several decades because it is a simple and cost-effective joining method [1–4]. However, the use of two electrodes limits the machine’s own adaptability for RSW of an automotive body assembly. For example, a large C-type gun for a weld on the autobody floor hinders access to the weld spots; hydroforming tubes have no weld flanges, and welding is often limited to single-side accessibility [5–7].

A new RSW was introduced to overcome the drawback of traditional RSW [8]. This welding system was designed to create a weld using single-side access with low electrode force. Using the system, spot welds were made using only single-sided access with or without a backing plate. It is expected that the practical use of this method may be successful, but the basic characteristics of the welding method are not well understood. It is well known that a numerical method such as finite element analysis has been used to obtain detailed information about a welding procedure such as spot welding [9–12]. Recently, a numerical analysis of single-sided RSW for hydroformed tubes was reported to explain the effects of welding parameters on a nugget [13]. It may be possible to numerically model the spot welding of hydroformed tubes because the current path can be captured in finite tube geometry. However, numerical analysis of single-sided RSW welding is questionable when the dimension of the real chassis of an autobody is large compared with the nugget or electrode geometry because the numerical model requires a considerable number of meshes and computing time.

In this paper, we extend a conventional FEM model for RSW with two-sided electrodes to a model for a single-sided electrode. A feasible numerical analysis of the single-sided RSW for a real chassis structure is proposed. Weldability lobe curves are also determined in terms of welding time, current, and electrode force. Several unique performances on single-sided RSW are also described. Experimental verification is performed using a specimen cut from a manufactured chassis.

2. Numerical analysis model for RSW with a single-sided electrode

2.1. Fundamentals of numerical analysis

FEM analysis has been performed using a customized RSW package called SORPAS [14,15], which accurately estimates the behavior of RSW and can determine the conditions of RSW. The whole numerical scheme is described in Ref. [16], a brief summary is below.

The resistance welding in SORPAS is simulated with four numerical models: an electrical, a thermal, a metallurgical and a mechanical model. In electrical model, the distribution of the voltage and the current as well as the heat generation in materials and electrodes is calculated by using the governing equation for the electrical potential \( \Phi \) field such as

\[
\frac{\partial}{\partial x} \left( \sigma_x \frac{\partial \Phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \sigma_y \frac{\partial \Phi}{\partial y} \right) = 0
\]

\( 1 \)
where $\sigma_x$ and $\sigma_y$ are the electric conductivities in $x$ and $y$ coordinates. The boundary conditions can be established in potential or potential gradient on boundaries. The thermal and metallurgical models calculate the heat transfer and the temperature distribution, and the phase transformation and the material properties dependent on temperature. The transient heat transfer equation with internal heat source mainly due to electrical Joule heating is stated as

$$\frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \dot{Q} = \rho C \frac{\partial T}{\partial t}$$  \hspace{1cm} (2)$$

where $k_x$ and $k_y$ are the thermal conductivities in $x$ and $y$ coordinates, $\rho$ is the mass density and $C$ is the heat capacity. The boundary conditions for the heat transfer analysis can be prescribed in temperature only, thermally insulated boundary condition, or a convective heat transfer one. The mechanical analysis calculates the deformation and geometry of materials, the stress and strain distribution and the contact areas in interfaces. The analysis considering plastic deformation may use a governing equation of the functional of the potential energy as

$$\pi = \int_{\Omega} \tilde{s} : \tilde{\varepsilon} \, dV - \int_{\partial\Omega} F_t \, dS$$  \hspace{1cm} (3)$$

where the potential energy of the bulk deformation and surface energy term due to external load or velocity of the material are calculated. The mechanical boundary conditions can be stated in a form of velocity with known movement or force with known forces. The material properties for this analysis can be obtained from [17].

The contact resistance at the interfaces is calculated according to Wannheim and Bay's friction theory [18] for the real contact areas, known as

$$\rho_{\text{contact}} = 3 \left( \frac{\sigma_{\text{soft}}}{\sigma_n} \right) \left( \frac{\rho_1 + \rho_2}{2} + \gamma \rho_{\text{contaminants}} \right)$$  \hspace{1cm} (4)$$

where $\sigma_{\text{soft}}$ is the flow stress of the softer of the two metals in contact, $\sigma_n$ is the contact normal pressure at the interface, $\rho_1, 2$ are the resistivities (with subscripts 1 and 2 indicating the two base metals in contact, respectively), $\rho_{\text{contaminants}}$ is the surface contaminant resistivity due to oxides, oil, water vapor, and dirt, and $\gamma$ is a factor introduced to adjust and verify the contact resistance. Later the effect of a factor of $\gamma$ on the simulation results is explained.

A strong coupling between each analysis in RSW can influence the dynamic behaviors of the materials and the processes. In SORFAS program, four different analysis models are interrelated and influenced each other: mechanical, thermal, electrical, and metallurgical models. The mechanical model calculates the deformation and the stress and strain in the materials which properties are a function of temperature. Through the thermal model, the heat transfer is calculated and the temperature field is obtained but requires the heat generation source from the electrical model and the deformed geometry from the mechanical model. The electrical model calculates the current distribution and the heat generation source but needs the temperature field to determine the materials' properties and the deformed geometry from the mechanical model. The metallurgical model calculates the phase transformation and the material properties dependent on temperature. In order to make efficient simulations, a simultaneous coupling is made for electrical, thermal and metallurgical models, whereas the mechanical model is coupled stepwise with the others. All the models are strongly interrelated to each other and they are all influenced by the dynamic behaviors of the materials, the interfaces, the machines and the processes.

Since SORPAS is basically optimized for RSW with a double-sided electrode machine with upper and lower electrodes, several numerical techniques are required to incorporate the model of single-sided RSW. Fig. 1 shows a possible current path of a two-sided electrode model (a) and a single-sided electrode model (b). In the two-sided electrode model, the current travels a shorter distance from the upper electrode to the lower one since the path has minimum electrical resistance. Thus, it is possible to simulate RSW for a model with a limited dimension without considering the full dimension of the model. On the other hand, the single-sided electrode model generates a current path between an electrode and the ground that is far distant from the electrode and which varies according to the shape of the weldment. Thus, the shape of a weldment is a key element in single-sided RSW. Thus, in order to properly simulate RSW, the weldments should be the same shape. However, since it is impossible to consider a full-scale model in RSW simulation, an approximated model is sought to appropriately simulate the single-sided RSW.

In SORPAS software, two possible models, block and axisymmetric, can be established, as shown in Fig. 2. In the block model, the grounds are attached at the left and right sides, limiting the current path to the left and right directions. In the axisymmetric model, the ground under the weldment is circular so that the current can flow in all directions. This is a merit of single-sided RSW. Thus, we conclude that the axisymmetric model is suitable for single-sided RSW.

The single-sided RSW forms various current paths according to the real shape of the weldment. Thus, it is difficult to obtain the same current density distribution as in the real case by using a limited analysis model which does not consider the full scale of the welding system. In order to obtain a current density distribution close to that of the real case, we have attempted to find an approximate ground connection. Fig. 3 shows two of several ground connections. The ground is connected to the lower weldment in Fig. 3(a) and is connected to both the lower and upper weldments in Fig. 3(b). Note that we use the ground connection of Fig. 3(a) for the experimental setup. Applying FEM analysis, the resulting current distributions of the two connections in Fig. 3(a) and (b) are obtained and are shown in Fig. 4(a) and (b), respectively. While the current density distribution for the ground connection
Fig. 3. Two different ground connections for RSW with single-sided welding and the corresponding current density distributions: (a) the first boundary condition, (b) the second boundary condition.

of Fig. 3(b) is distributed in both the upper and lower weldments, the current density of Fig. 3(a) concentrates in the lower weldment. This is because the FEM result of deformation for the ground connection of Fig. 3(a) shows a separation at the end of the weldment. Thus, most of the current passes through the contact region from the upper weldment to the lower one, leading to the concentration of current density in the lower weldment. This induces a significant difference in heat generation between the upper and lower weldments, which can hinder welding. In the production of a welding system, contact between weldments can occur at locations other than between the electrode and the weldments. This is why the ground connection in Fig. 3(b) is appropriate for single-sided RSW.

Since the electrical contact resistance Eq. (4) has been optimized for the two-sided electrode model that has symmetric pressure distribution between electrodes, the contact resistance should be changed for the single-sided RSW model. In addition, the applied force of the electrode in the single-sided model decreases to about 1/10 of the force of the two-sided model. Thus, this force variation increases the electrical contact resistance between weldments. In this software, the contact resistance can be changed by adjusting $\gamma$. The effect of contact resistance is investigated in the section on verification.

3. Verification of numerical method

In order to verify numerical simulation with experimental results, welding was carried out with a medium frequency direct current (MFDC) welding machine controller. A
single-sided welding gun with a pneumatic cylinder was used to apply the electrode force. The gun was designed for a maximum electrode force of 150 kgf with twin piston rods. A truncated dome-type electrode tip was used with an outer diameter of 16 mm and tip-end diameter of 6 mm. Various tip-end shapes were tested to generate a sound fusion area between faying surfaces of the sheets. Two kinds of materials were welded with the same material of two-sheet combination. One was a low-carbon steel called SPCC with a thickness of 0.7 mm and tensile strength of 270 MPa. The other was a high strength, low-alloy steel called SPRC with a thickness of 1.2 mm and tensile strength of 340 MPa.

The variation in nugget geometry from the numerical results has been compared with that of the experiment results. As stated in the previous section, there is great possibility in obtaining various current distributions according to the real geometry of weldments, affecting the welding quality in the single-sided RSW. Thus, it is important to perform welding experiments under the same geometry of mass-production. This is different from the double-sided RSW that can identify the weldability, alone with the standardized welding specimen. Because of this fact, a section from a mass-produced body was used in this research. Fig. 4 shows the mass-produced section for the experiment and the individual welding specimen from the mass-produced section.

If the difference between the large mass-produced body and the small size of nugget in the single-sided RSW is considered, the geometry of the numerical analysis model should differ from that of the experiment model since it is very difficult to make a FEM model for a large size of mass-produced body in the single-sided RSW. However, we can obtain a certain level of similarity in the approximated nugget size through the application of the previously presented methodology.

We have mentioned the ground connections located at both the upper and lower weldments. This connection method is contrived from the idea that the location of the ground connection affects the current density distribution of the weldment, which could be a substantial factor in optimizing the current distribution. According to the ground connection methods suggested in the numerical model, the formations of the nugget geometry are shown in Fig. 5. For the ground connections of Fig. 3(a) and (b), the nugget geometries of Fig. 5(a) and (b) are obtained, respectively. Each ground connection provides isosceles trapezoidal nugget formation, but the lower angles of the trapezoidal nugget for the cases of Fig. 5(a) and (b) are acute and obtuse, respectively. Through the nugget geometry obtained from the experiment
Fig. 7. Variation of the nugget geometry according to the relative distance between the upper and lower electrodes and the factor of electrical contact resistance.

that is shown in Fig. 5(c), we confirmed that the nugget formation of Fig. 5(b) is more appropriate and the ground connection of Fig. 3(b) is the appropriate one, as we anticipated in the modeling.

Another interesting result is that the nugget sizes differ according to the relative distance between the upper and lower grounds. Note that we only consider the case in which the upper ground is always situated on the right side of the lower ground. Fig. 6 shows the nugget size variations according to the two ground connections. These results indicate that, when the relative distance increases, the slope of nugget size variation in the direction of weldment thickness decreases. For the comparison of the nugget size obtained from the experiment, the optimal distance between the upper and lower grounds is chosen, as well as the electrical contact resistance.

The adjustment of electrical contact resistance to single-sided RSW is performed using the factor γ. Since the applied force of the electrode in the single-sided model is smaller than that of the two-sided model, the electrical contact resistance for the single-sided model is greater than that of the two-sided model. We find that when we change the factor γ from 0.5 to 9.0, the corresponding nugget size in the single-sided model increases according to γ.

The optimal welding conditions for the numerical analysis were chosen by selecting the relative distance between the upper and lower electrodes and the factor of electrical contact resistance and comparing the nugget size and the angle of nugget geometry with the experimental results. Fig. 7 shows the nugget size variation according to the relative distance between the upper and lower electrodes and the factor of electrical contact resistance. Based on the results, the distance between the upper and lower electrodes was set at 1.2 mm, and the factor of electrical contact resistance was 9.0.

4. Results and discussion

4.1. Comparison of experimental results

The simulation results for the variations of current and time are compared with the experimental results by applying the boundary conditions to the numerical model. Fig. 8 compares the nugget shape results between the experimental and simulation results according to current and welding time. Although the nugget shapes and sizes are similar to each other, the simulation does not reproduce the exact shape or size of the nugget. However, it allows the possibility of a proper boundary condition so that the selection of boundary conditions may require careful consideration at the initial stage of the selection. The results of the nugget indicate that we must determine the nugget shape using the simulation results.

4.2. Effect of the electrode geometry

In the two-sided RSW, two types of electrodes, round or flat tipped, are generally used. These electrode geometries induce

Fig. 8. Comparison of nugget shape between the experiment and simulation according to current (kA) and time (s).
different contact pressure distributions at the faying surface and the bulk region of a weldment, thus affecting current density distribution and nugget geometry. In particular, the two-sided electrodes generate sufficient contact between weldments. However, single-sided RSW uses just one electrode on one side, so the applied force does not produce a good contact between weldments. Thus, single-sided RSW depends on electrode shape.

The limitation of single-sided RSW is that there is no support on the opposite side of the applied force, inducing insufficient contact at the faying surface. Thus, single-sided RSW requires a higher contact pressure at the weld interface. The magnitude of contact pressure is higher for the round tip electrode than for the flat tip electrode. Furthermore, the contact pressure for the round electrode is more or less concentrated at the center of the faying surface, unlike that for the flat electrode. Fig. 9 shows the thermal distribution and nugget shape according to electrode type. For the flat electrode, a separation of the weldment at the center of the faying surface is seen, producing an incomplete nugget in the process of spot welding. On the other hand, the round electrode produces a dense nugget in the same welding conditions. The round electrode is recommended for single-sided RSW. We used a round electrode with a radius of 40 mm.

4.3. Estimation of Lobe curve

The range of optimized variables has been estimated. The criterion for the optimal nugget is generally that \((X_{\text{max}} + Y_{\text{max}})/2\) is greater than \(4\sqrt{t_{\text{mm}}/3}\), where \(X_{\text{max}}, Y_{\text{max}}\) are the largest dimensions of the nugget in the X and Y directions, respectively, and \(t_{\text{mm}}\) is the minimum thickness of the weldment [19]. This criterion is based on the nugget shape in the two-sided electrode RSW that generates symmetric nugget geometry. However, since the nugget shape of single-sided RSW is asymmetric, the optimal nugget criterion cannot be followed in the one-sided electrode model. Thus, we need to modify the criterion of optimum nugget geometry of a one-sided electrode model considering an asymmetric characteristic by replacing \(X_{\text{max}}\) with \(X_{\text{cen}}\), which is defined as the nugget size at the contact interface between two weldments. Adopting the new criterion, proper sizes of the nugget are estimated and shown in the green region of Fig. 9. The red region presents the expulsion region, which increases by 40% of the optimized nugget size.

4.4. Measurement of tensile strength

In order to estimate the weldability of the single-sided RSW specimen, tensile strength is measured by the tension test. Table 1 shows the tensile strength of the welding specimen according to the welding time and current. The specimens can be divided into three groups by changing welding time under a constant welding current. The tensile strength of these sets shows a possibility of the proportional relationship between tensile strength and welding time. Another division of specimen can be obtained by changing welding current under the same welding time. These groups also show a possibility of the proportional relationship between tensile strength and welding current.

The tensile strength recommended by the automotive industry is greater than 200 kgf [5]. The tensile strength test result indicates that most combinations are satisfied with this criterion, assuring the reliability of the single-sided RSW. Furthermore, the tensile strength above 360 kgf can be obtained at the range of welding variables for the optimal nugget sizes obtained in Fig. 10. This is another result that supports the reliability of the welding method and the merit of the single-sided RSW.

Although a consistent outcome for the tensile strength can be obtained, the test shows that the geometry of breakage and the deformation of specimen in the upper and lower plate are irregular. Fig. 11 shows the deformation of nugget weld after the tension test, representing that the breakage or facture of nugget can be seen in both front and back sides of the specimen. Since the nugget geometry in single side RSW is not symmetric in the upper and lower plate and the size of nugget of one plate is larger than the other, we expect that a regular pattern of breakage or deformation of specimen could occur. However, the breakage of nugget occurs

<table>
<thead>
<tr>
<th>Current (kA)</th>
<th>Time (s)</th>
<th>Tensile strength (kgf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.6</td>
<td>0.10</td>
<td>321</td>
</tr>
<tr>
<td>6.6</td>
<td>0.15</td>
<td>351</td>
</tr>
<tr>
<td>6.6</td>
<td>0.20</td>
<td>381</td>
</tr>
<tr>
<td>7.2</td>
<td>0.10</td>
<td>353</td>
</tr>
<tr>
<td>7.2</td>
<td>0.15</td>
<td>397</td>
</tr>
<tr>
<td>7.2</td>
<td>0.20</td>
<td>426</td>
</tr>
<tr>
<td>7.8</td>
<td>0.10</td>
<td>369</td>
</tr>
<tr>
<td>7.8</td>
<td>0.15</td>
<td>424</td>
</tr>
<tr>
<td>8.4</td>
<td>0.10</td>
<td>398</td>
</tr>
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at both the upper and lower plate. This issue is important when the robustness of the weld structure including the fracture of weld is considered. This breakage phenomenon is not understood yet, thus it is necessary for a careful fracture analysis of single-sided RSW specimen to be performed.

5. Conclusions

A welding technique single-sided RSW is investigated by numerical analysis using a commercial CAE package to estimate the weldability. The reliability of this welding method is verified through the experiment performed under conditions similar to a real production, showing an asymmetrical nugget which contrasts with two-sided RSW. Several conditions are analyzed to find an optimal condition set, including the boundary condition for the ground location and the electrical contact resistance. The resulting Lobe curve with respect to welding time and current is obtained. Through the tensile strength test, the weldability of the single-sided RSW specimen is estimated. A certain level of tensile strength (360 kgf) can be obtained at the range of welding variables for the optimal nugget sizes. This is another result that supports the reliability of the single-sided RSW.

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References


