Effect of Electrode Radius on Expulsion in Two Pulsed Spot Welding*

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Since spot welding is quick in production and stable in quality, the joining of thin materials in automobiles and electrical products. The nugget in the joint part took place due to the joule effect of high current. Therefore, the current density at the contact between the base material and the electrode becomes high and weld expulsion is generated in welding for high tensile strength steels with high current during a short time. The authors introduced a numerical model of resistance spot welding and analyzed this phenomenon. In the numerical model, the temperature characteristics of the material were considered. The contact state between the electrode and the base material and that between the base materials depend on the yield stress of the material and the pressure at the contact part. Moreover, the contact resistance depends on the radius of the electrode. The contact resistance was confirmed by performing simulation when the radius of the electrode was changed. The relationship between the electrode radius and the temperature distribution was investigated. The welding condition of two pulsed welding current are induced analyzing its relationship.

Key Words: Spot welding, Simulation, Electrode shape, Contact resistance, High strength steel, Expulsion

1. Introduction

Resistance spot welding is stable in quality, easy to weld, and excellent in productivity. Therefore, it is often used in automobiles and electrical products that use a lot of sheet plates. The joining principle is that nugget is formed by Joule heating. In addition, recently, high tensile strength steel and advanced high tensile strength steel have been used as materials for the body of an automobile in order to make the body lighter and stronger in order to improve fuel efficiency1)-3).

In spot welding of high tensile steel with short time and high current, expulsion is generated at the contact part between base metal and electrode. It is reported that expulsion is likely to occur when welding is performed with high welding current4). Since the occurrence of expulsion leads to a decrease in the quality and strength of welds, the selection of appropriate welding conditions without expulsion is one of the major challenges. Various reports have been made on the mechanism and welding conditions without expulsion5)-9). In addition, numerical simulation is an effective method for understanding the phenomenon of resistance spot welding, and there are many studies on the analysis of resistance spot welding using numerical simulation4),10)-14). In resistance welding, welding parameters such as current waveform, pressure and shape of the electrode affect the welding result. It is thought that expulsion is likely to occur because the current density at the contact part between the electrode and the base material increases.

In other words, it is considered that the contact resistance between the electrode and the base material has a large influence. Contact condition between the electrode and the matrix depends on the shape of the electrode. Therefore, in this paper, a numerical model of resistance spot welding in which the tip shapes of the electrodes are R 25, R 60, R 100 and R 200, respectively, is introduced, and numerical simulation of the welding phenomenon is performed. The material properties in the numerical model with temperature characteristics were used in the simulation. The contact state between the electrode and the base material and between the base materials depends on the yield stress of the material and the pressure at the contact part. When the temperature between the electrode and the base material becomes close to the melting point after the current has been applied, the welding current is turned off to prevent expulsion. After the surface temperature of the base material is sufficiently cooled by the water-cooled electrode, the current is increased again to form nuggets. According to the proposed method, two pulse current waveforms are used. After comparing the simulation results with the experimental welding results, the authors confirmed the validity of the numerical model. Then, the relationship between the current density and the molten state of the base material was examined while changing the electrode shape.

2. Numerical model of spot welding

In the resistance spot welding, after electrodes contact with base material, these are deformed, and the temperature changes from room temperature to the melting point. Therefore, rigidity decrease and the contact and deformation states change and plastically deform. Since they are nonlinear analyses, the authors apply the
finite element method here. The authors used Marc/Mentat for nonlinear analysis as its software. Thus, coupled electrical, thermal, and structural analyses were performed. First, load is applied to the electrodes and the process of contact between the base materials is determined by structural analysis. Next, the voltage generated in each part of the material by the welding current is obtained by electrical analysis, and heat generation due to Joule heat at each node is obtained. Thermal conduction analysis was performed to determine the temperature of each node. Furthermore, structural analysis was performed using the temperature dependence of the temperature and material properties. By repeating this, the authors analyzed the resistance welding phenomenon. According to the softening state of the electrode material and the base material, the condition of the contact surface changes\(^{(15)}\).

The relationship between current and voltage, based on Ohm’s law, as follows:

\[
\varepsilon(T, x, y, z) V = I
\]

where \(V\) is the node voltage and \(\varepsilon(T, x, y, z)\) is electrically conductive considering temperature dependence.

According to Eq.(1), the voltage of each node is found. The Joule heating \(Q^F\) is determined from the current and electrical conductivity, and the temperature is calculated to apply the following heat conduction equation.

\[
C^T(T) \frac{dT}{dt} + K^T(T) T = Q^E + Q^I + Q^F
\]

where, \(T\) is nodal temperature, \(C^T(T)\) is heat capacity considering temperature dependence, the temperature state of the base material is thermoelectric, \(K^T(T)\) is heat conduction considering temperature dependence, \(Q^E\) is heat generation due to inelastic deformation, and \(Q^I\) is heat generation due to friction.

The temperature of each node determines the material value with temperature dependence such as Young’s modulus, and the displacement \(u\) and stress of each node are determined using the following equation of structural analysis.

\[
M \frac{d^2u}{dt^2} + D \frac{du}{dt} + K^M(T, u, t) u = F + F^T
\]

where, \(M\) is mass, \(D\) is attenuation, \(K^M(T, u, t)\) is synthesis matrix considering temperature, deformation and time dependence, and \(F\) is externally applied force. \(F^T\) is thermal strain force.

Since the phenomenon in the resistance welding occurs at the base material and the electrode, the welding phenomenon becomes axisymmetric around the center of the base material and the electrode. Considering this and the reduction of the calculation cost, the authors simulated using a two-dimensional axisymmetric model. Fig. 1 shows the finite element mesh of the two-dimensional axis object model used in the simulation. At the same time as a force is applied to the base metal part directly under the electrode, a temperature rise occurs, resulting in a nonlinear phenomenon. Therefore, adaptive mesh was used to set the mesh finely during calculation to improve calculation accuracy. The boundary conditions are shown in Fig. 1 (b) and Table 1. Specifically, welding current was uniformly applied to the upper surface of the upper electrode. Moreover, in order to clarify the path of current flow, the voltage of the lower electrode is set to 0V.

The force was applied to the upper electrode, and in order to perform a coupled analysis, the electrode force was set to a desired applied force by linearly increasing the applied force for 0.1 s before energization, as in the experiment. The position corresponding to the water-cooled part of the electrode was set at 20 °C. Generally, the experiment is performed at room temperature, so that the ambient temperature was set to 20 °C in this numerical model\(^{(11)}\). The melting point of the base material was set at 1535 °C, and the melting part was set at or above this temperature. To compare with the experiment, the authors used the same current waveform as the experiment in Fig. 2. Since the material properties have temperature dependent, the temperature dependent material properties were used in the numerical analysis as shown in Fig. 3\(^{(16)}\).

The electrical resistivity is obtained by approximating the value in the Mentat database by the equation of Babu et al\(^{(15, 16)}\). Contact resistance exists between the electrode and the base material, and between the base materials. In the numerical analysis, the contact resistance was determined according to the method proposed by Babu et al. so as to be dependent on temperature and pressure (yield stress)\(^{(15)}\). Here, the contact condition is set so that the contact state is changed to the adhesive state when the material reaches the melting point, and at the same time, the contact resistance is set to 0.

### Table 1 Boundary condition

| potential | Below the lower electrode is fixed at 0V |
|-----------|----------------------------------------|
| temperature | Electrode cooling part and ambient temperature 20 °C |
| contact condition | When the melting point is reached. contact = adhesion, contact resistance is 0 |
| energizing condition | Energized from the upper part of the upper electrode |
| pressure | 400kgf |

![Fig.1 Finite element model](image-url)
3. Simulation results and discussion

In order to confirm the validity of the numerical model, experiments and simulations were performed under the welding conditions shown in Table 2 using the tip shape of the electrode of R 100. A comparison of the nugget diameter corresponding to the melted part is shown in Fig. 4. The experimental results are in good agreement with the welding condition $D$, which is the reference condition, and a deviation occurs before and after the welding condition $D$. The correlation coefficient is 0.86 as shown in Fig. 4. The experimental nugget diameter and the simulated nugget diameter are positively correlated.

\[
\text{Nugget Diameter (experiment)} = 0.7316 \times \text{Nugget Diameter (simulation)} + 1.5944
\]

Instead of the electrode shapes R 25, R 60, R 100 and R 200, simulations were performed using the welding current waveforms shown in Fig. 2. Among the current waveforms of the two pulses, the first waveform is set so that the melting temperature region between the electrode and the base material is not enlarged due to Joule heating. Then, when the temperature of the contact part between the electrode and the base material decreases, the second waveform is energized to make the nugget grow. Since the energization time of the first waveform is as short as 10 ms or less, the temperature rise in the base material is considered to be caused not by heat conduction from Joule heat at the contact surface but by Joule heating due to the resistivity of the material. Temperature distribution at the end of energization is shown in Fig. 5. Here, the gray part indicates the nugget. The nugget was formed in any electrode shapes. However, when the electrode of R 25 is used, it is considered that the temperature of the contact part between the electrode and the base material becomes equal to or higher than the melting point when the first waveform is energized, and the electrode is melted. Fig. 6 shows the change in the contact area between the electrode and base metal from the start of energization to the end of energization. Fig. 7 shows a change in the current density at the electrode contact part obtained by dividing the value of the energizing current by the contact area during energization of the first waveform. Assuming that the resistance of the material is constant, the amount of heat generated by Joule heat increases with increasing current density. Therefore, the generation of expulsion just under the electrode is related to the current density. As shown in Figs. 6 and 7, the contact area at the start of energization is due to applied force. According to the curvature radius of the tip becomes the smaller the contact area becomes small. Further, since the current density becomes higher as the radius of curvature is smaller (small area of contact), the contact part is more likely to generate heat. Therefore, in the case of the electrode R 25 having a small radius of curvature, as the welding process progresses, the electrode thermal expansion coefficient affects the electrode, and the contact area gradually increases. At the end of weld, the contact area shows the same value regardless of the electrode shape.

In order to suppress the heat generation just under the electrode, the peak value in the first current waveform was lowered from 12.5 kA to 6 kA, and the electrode shape of R 25 was simulated. During

| Table 2 Welding condition |
|---------------------------|
| Condition | A | B | C | D |
| Current (mA) | 40kA, 20ms | 10kA, 60ms | 1kA, 50ms | 25kA, 15ms |
| Pressure (kN) | 600kN | 400kN | 400kN | 600kN |

The correlation coefficient is 0.86 as shown in Fig. 4. The experimental nugget diameter and the simulated nugget diameter are positively correlated.
the first waveform energization, the current value was low and the temperature rise of the base material was suppressed, so that no melting was observed at the contact part between the electrode and the base material. However, during the second waveform energization, melting was observed between the electrode and the base material. Fig. 8 shows the electrical resistivity of the base material at the beginning of the second waveform energization. If the current of the first waveform is 6kA at R25 electrode, there is no temperature difference between the center of the nugget and the electrode-base material contact part. Therefore, there is no difference in the temperature-dependent electrical resistivity of the base material as shown in Fig. 8. Heat was generated not from the contact part between the base materials but from the contact part between the electrode and the base material with a higher current density. On the other hand, when the radius of curvature becomes large, the temperature difference between the center of the nugget and the contact part becomes big at the end of the first current waveform. According to the temperature differences, the difference of resistivity becomes big as shown in Fig. 8. In this case, the heat is generated from the contact part between the base materials.

The nugget diameter after energization obtained by the simulation of each electrode shape model is shown in Fig. 9. The figure shows that there was no significant difference in the nugget diameter finally obtained even when the curvature radius of the tip shape was different. This is thought to be because the nugget diameter is determined by the amount of heat input to the base materials by Joule heating of the current. Since no significant difference was found in the final nugget diameter due to the difference in the first waveform, the heat input of the second waveform is considered to be dominant in the nugget diameter. Therefore, the difference of the curvature radius of the electrode tip does not greatly affect the size of the nugget diameter finally obtained. However, it is considered that the smaller the radius of curvature is, the more likely surface dust is generated, because current density at the base material surface is greatly affected.
4. Conclusions

In this paper, the authors simulated the effect of the shape of the electrode tip on the occurrence of surface expulsion using a numerical model. Conclusions are as follows.

1) The smaller the radius of curvature at the tip of the electrode, the smaller the contact area at the start of energization, the higher the current density, and the easier it is to generate heat.

2) If the radius of curvature is small, since the temperature of the contact part is high, it is affected by the thermal expansion coefficient as the welding process progresses, and the contact area expands.

3) If the radius of curvature is large, since it already has a certain contact area at the start of energization, heat generation is suppressed compared with the case of the radius of curvature (small), and the contact radius is hardly affected by the coefficient of thermal expansion, and almost does not change during the welding process.

4) The first waveform of the two pulses is intended to cause a temperature difference between the contact part between the sheet plates and the electrode-base material contact part, and if the current value of the first waveform is lowered, expulsion is easily generated in the second waveform.

5) The curvature radius of the electrode tip does not affect the final nugget diameter, and the contact area at the end of welding and the heat input of the second waveform are dominant.

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