Numerical Simulation in high efficiency spot welding

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Resistance spot welding, hereinafter referred to as spot welding, is one of the most important methods for metal sheet welding used in industries such as the automobile, electronics, and so on. This welding is faster than other welding process such as arc welding process, laser welding process. Since high efficiency is required in this welding, welding in a short period is required. Conventional resistance spot welding takes several hundred milliseconds to weld. Welding method in a short period less than 20 ms is developed. In order to find the optimum welding condition, 3D simulation model of spot welding in a short period was made in this research. The model based on electrical, thermal, and structural phenomena is required in this simulations. Numerical simulations were carried out by using Marc/Mentat software which had advantage of nonlinear analysis. The materials parameters were determined based on a contact domain between base metal and electrode. The validity of the 3D numerical model was verified by comparing the numerical simulations and the experimental results. The nugget size under various welding current was investigated. Since the experimental results and analytical results of this study showed almost the similar results, the validity of the proposed model was verified.

Key Words: Spot Welding, Numerical Simulation, 3D model, Nonlinear analysis, Coupled analysis

1. Introduction

In generally, the welding theology was used to join metal plates. Spot welding is one of advantage than the arc welding and a laser welding in stability of quality, cost performance and the simplicity of operation and maintenance. This is very effective and stable quality of production in the automation. The spot welding is applied in automobile, many electric appliances and so on, in which joining of thin plates were used. Since the spot welding is used in various industrial fields, high efficiency is demanded on the industry. For this purpose, it is important to reduce welding time. Pressure, the welding current and weld time are dominant parameters in spot welding. Enormous experimental results are needed to find the optimum parameters by investigating the size of nugget or the propriety of welding 1-3). In this study, the development of analytical models for a short period of spot welding was tried.

Conventional simulation has not been focused on contact surfaces. In the case of short-time welding, the contact state is important, since joule heat depends on the current density. Since the large current flows in a short time, the contact area of the surface changes due to the joule heat. The author tried to investigate contact surface 5-6). In a typical spot welding, base metal is heated and becomes soft. After electrode is completely in contact with the base metal, contact area between the base metals is melted by increasing the current. But the electrodes may not be contacted completely with the base metal, when welding time of spot welding is short. Since the current density is important in the analysis of the short time spot welding, this contact area becomes important. In this study, the authors tried to investigate the contact area between the base metal and the electrode by changing the welding parameters.

The electrical circuit, the heat conduction and the mechanical structure are considered in the simulation of spot welding. In this simulation, the thermos-electrical-mechanical coupled analysis was applied. In this analysis, nonlinear elements were used. The simulations were carried out by means of the conventional software, Marc, which was advantage of non-linear analysis 4). The simulation model of the short-time spot welding was proposed. 3D analysis was applied to the numerical simulations. The validity of the numerical models was verified between the experiment and numerical simulations.

2. Numerical Simulation

In this research, the authors employ the conventional finite element method, software MARC/Mentat, to solve the nugget generation problem. This was composed of a module system and was applied to the wide range of applications. The non-linear analysis is performed by using Marc/Mentat. Mentat is an interactive pre- and post-processor for the Marc program. It is possible to make 3D model and to display the interactive input data and analysis results on the graphical user interface. The relationship of these programs is shown in Fig1.
3. Heat - stress - electrical analysis

In the spot welding, the electrodes and the steel plates are in contact and deformed. In addition, the temperature in the contact area is changed from room temperature to the melting point. The stiffness of the metal sheets depends on the temperature. Deformed state corresponds to the plastic deformation state. In order to investigate this phenomena, the authors deal with the stress analysis, electrical analysis and heat transfer analysis, simultaneously. Moreover, the temperature dependence of the material properties were considered to treat plastic analysis. Electric - heat - stress coupled analysis was applied to solve the spot welding phenomena. Solutions were obtained with a staggered method. First, the electric analysis was applied for the node voltage. Next, the nodal temperatures were calculated based on thermal analysis. Finally, the stress analysis were applied for finding the displacement of nodal point. The heat generation $Q^e$ (joule heat) was found by electrical conduction. Heat and stress are made by a heat generated by the friction $Q^f$, heat strain load $F^T$ and the non-elastic deformation $Q^l$. Further, since the material parameters have the temperature dependency, electrical conductivity $K^E$ and mechanical rigidity $K^M$ depend on the temperature. The relationship of this coupled analysis was shown in Fig.2. The governing equations of electricity, heat and the stress are represented by the following equations.

$$K^E(T)V=I$$

$$C^H(T)\dot{T}+K^H(T)T=Q^e+Q^f+Q^l$$

$$M\ddot{u}+D\dot{u}+K^M(T,u,t)u=F+F^T$$

where the symbols mean as follows

V: Node voltage         T: Nodal temperatures
u: Nodal displacements  I: Node currents
$K^E(T)$: Electrical conductivity in consideration of the temperature dependence
$C^H(T)$: Heat capacity in consideration of the temperature dependence
$K^H(T)$: Heat conduction in consideration of the temperature dependence
$Q$: Heat flux
$Q^e$: Heat generated by electrical conduction
$Q^f$: Heat generated by the non-elastic deformation

4. Calculation algorithm in spot welding

The flow chart of numerical simulation is shown in Fig.3. The simulation was dived into two parts. One is calculation of the stiffness. The base metal comes into contact with each other by the mechanical analysis after applying force to the electrode. Second is calculation of the heat effect. The heat, the electrical and the mechanical calculations were carried out by using the coupled analysis as shown in Fig.2. First, the welding current flows through the base metals from the electrode. Joule heat was calculated. After that, the temperature distribution was calculated. The material parameters changed due to the temperature. The mechanical stiffness was calculated. The coupled analysis was repeated until the welding time has elapsed.
5. Accuracy verification of spot welding

5.1 Numerical model and analysis conditions

A model used in the analysis is shown in Fig.4. The electrode was made of chromium copper. Its shape is shown in Fig.5. Base metal size is 150mm × 50mm, its thickness is 0.6mm. 2 sheets of metal plates were superposed. There is 1mm gap between the base metal and the base metal with addition spacer of 1mm according to practical application. The spacer is represented as a rigid body without deformation. The base metals are joined together under the melting. The number of nodes in the analysis model is 34796 and the number of elements is 26440. Interval time in the analysis was 0.2ms. The temperature dependence of the material parameters of the base material was shown in Fig.6.

5.2 Numerical simulation results

In order to compare the experimental with simulation result, the surface of the metal sheet after the welding is shown in Fig.7. By using indentation, the contact area in simulation was determined. The size of indentation after current flows in the simulation is adjusted so as to fit to the experiment.

The parameters of Young modules, yield stress and so on, depend on the temperature. The latent heat is also considered in this simulation. The surface of the numerical model before and after welding are shown in Fig.8. The contact area was displayed with a color in the portion in contact with the base metal. If there is no current, the contact area was small as shown in Fig.8 (a). The size of the indentation before current flow is 2.8mm. After current flow, its size becomes 4.0mm due to the deformation. Since the temperature of the contact becomes high, the contact state was changed as shown in Fig.8 (b). The behaviors of contact area could be confirmed by adopting the parameters with the temperature dependence, as shown in Fig.8 (b). Moreover, a cross-sectional view after welding is shown in Fig.9 and the temperature distribution in the cross section view after the analysis is shown in Fig.10. In this simulation, welding current is I1 as shown in Fig.11. Table 1 is boundary conditions. The area with the temperature more than the melting point of the steel, 1541°C, to as defined as the fusion area. The nugget size in the numerical simulation is similar to the experimental result.

| Table1. Boundary conditions |
|----------------------------|
| Displacement designation   | The YZ direction of the electrode and the base metal was fixed. |
| Weighted                   | 200kgf |
| Temperature designation    | The upper part of each electrode was designated at 20 °C. |
| Current                    | I1 in Fig.11 |

Fig.4 Analysis model of spot welding

Fig.5 Electrode model

Fig.6. Temperature dependent material properties

Fig7. Base metal surface

(a) Before welding

(b) After welding

Fig.8. Electrode surface of analysis

Contact area
No contact area
6. Influence on nugget the size by the input current

The authors tried to investigate the influence on the nugget size by the input current. The fundamental simulations were carried out by using the current $I_1$ as shown Fig.11. The integral value of $I^2 \cdot t$ was calculated. The pulse width $t$ and the peak current $I_{\text{max}}$ were adjusted under the constant value of $I^2 \cdot t$

The peak current values of $I_2$, $I_3$ and $I_4$ are 20 kA, 15 kA and 8 kA, respectively. The relationship between the input current and the nugget diameter was listed on Table 2. Temperature distribution in the vicinity of the electrode is shown in Fig.12. In the current $I_4$, there is no formation of a nugget. This was confirmed by experiments. From mentioned result, it is conceivable that a nugget is formed given the high current in a short period.

![Fig9. Cross section of experiment](image)

![Fig10. Cross section of analysis](image)

![Fig12. Temperature of base metal](image)

### Table 2. Nugget sizes

|        | $I_2$ | $I_3$ | $I_4$ |
|--------|-------|-------|-------|
| Diameter of Nugget (mm) | 3.9   | 3.75  | 0     |
| Height of Nugget (mm)    | 0.92  | 0.85  | 0     |

7. Conclusions

The numerical model for the short period spot welding was developed to analysis the welding phenomena. Since the experimental results and analytical results were almost the similar, the validity of the proposed model was verified. The phenomena of the short period welding was verified. Although the integral value of the current was almost same, there is no melting area when the peak current was small. The peak current was important to make the nugget.

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