FEM Simulation of Spot Welding Process (report IV) †

- Characteristics of Electrode Displacement and Nugget Formation -

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Abstract

The real time measurement of the electrode displacement during spot welding is very important to control the spot welding process in order to get a sound weld. In this report, the electrode displacement and nugget formation during spot welding were investigated numerically by means of the finite element method. Important parameters characterizing the relationship between electrode displacement and nugget formation were introduced based on experiment and numerical analysis. The effects of welding current, squeezing force and plate thickness on the electrode displacement and nugget formation were clarified. Through the present study, the following conclusions were drawn: (1) The time when the electrode displacement reaches the maximum value is closely related to the timing of nugget formation and it is influenced by the welding current, the squeezing force and the plate thickness, (2) The formation of a sound spot weld with nugget size between $4\sqrt{t}$ *and* $5\sqrt{t}$ *can be detected by monitoring the time when the electrode displacement at the top reaches the maximum value.*

KEY WORDS: (Spot Welding) (Nugget Formation) (Electrode Displacement) (FEM)(Experiment)

1. Introduction

It has been reported that the displacement between electrodes is a very important parameter to control the spot welding process in order to get a sound weld[1, 2]. The electrode displacement can be divided into two parts. One is the thermal expansion of both the plates and the electrodes. Another is the mechanical deformation of the plates under the thermal cycle with the application of squeezing force. Though the magnitude of the electrode displacement is quite small, its real time monitoring became possible due to the new developments in the spot welding system. The monitored data shows that the electrode displacement and its time rate are closely related to the nugget formation process[3, 4].

The spot welding process involves the electric field problem, the heat conduction problem and the thermal elastic-plastic deformation problem. The numerical simulation method is widely used to investigate the physical and mechanical phenomenon occurring during the spot welding process. The electric and thermal fields during the spot welding process are precisely simulated by a number of researches. The basic simulation of the spot welding is the thermal simulation. The computed temperature distribution can be used to predict the nugget formation and its size. However, the simulation of elastic-plastic deformation during spot welding is very complex and delicate because it involves the contact problem. In addition to the contact, the important factors influential to the elastic-plastic deformation are thermal properties of materials at the elevated temperature. Especially in the liquid state, these are not clearly known.

After the nugget formation, it grows and deforms in the liquid state. But the molten nugget can not deform freely because of the restraint by the surrounding solids. Though the problem involves both the solid and the liquid phases, the finite element codes employing the solid model are widely used and it has been recognized that the FEM is a versatile tool to study the thermal and mechanical phenomena in spot welding[5, 6].

In order to solve the complex coupled problem in a strict manner, simultaneous solutions of the electric, the thermal and the mechanical fields are necessary. In

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addition to these, the change of contact states between electrode/plate and plate/plate, as well as the expulsion must be considered. The authors developed a FEM code in which the electric, the thermal and the mechanical problems are sequentially solved in each small time step. It has been applied to various spot welding problems. The weldability for the spot welding of aluminum alloy is investigated using the FEM[7]. The effect of the initial gap and the electrode shape on the nugget formation and the occurrence of expulsion were investigated[8,9]. Further, a method to control the welding current based on the electrode displacement was proposed in order to get large enough nugget without expulsion[10].

In this report, the possibility of detecting the full growth of the nugget based on the electrode displacement is examined. For this purpose, the relation between the electrode displacement and the nugget formation is closely examined using the FEM and experiment. From the results obtained through serial computations and experiments, the parameters characterizing the relationship between electrode displacement and nugget formation are proposed. Further, the effects of the welding current, the squeezing force and the plate thickness on the parameter are discussed in detail.

2. Method of Analysis

2.1 Computing procedure and FEM model

A finite element code for simulating the spot welding process used in this report is developed by the authors. A spring-type interface element is introduced to simulate the contact states between the electrode/plate interface and the plate/plate interface. When the reaction force acting on the spring is compressive the corresponding part of the interface is judged to be in-contact. If the interface is in-contact, the stiffness of the spring is set large enough to be considered as a rigid link. When the reaction force becomes tensile, the contact state is judged to be out-of-contact and the stiffness of the spring is set to be zero to cut the link. The transition from out-of-contact to in-contact is judged based on the relative distance between nodes.

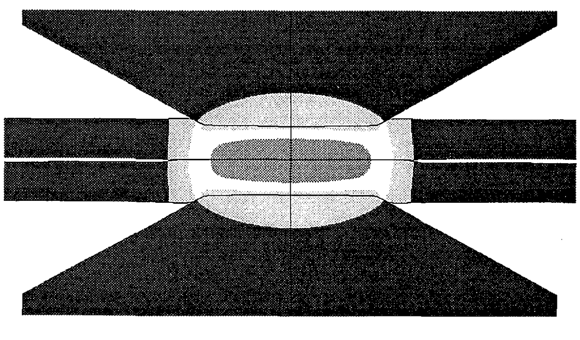

Fig.1 Temperature distribution profile during spot welding simulated by finite element code

The forms of spot welding joints largely depend on the types of the structures. The full numerical analysis of the joints should be three-dimensional problems.

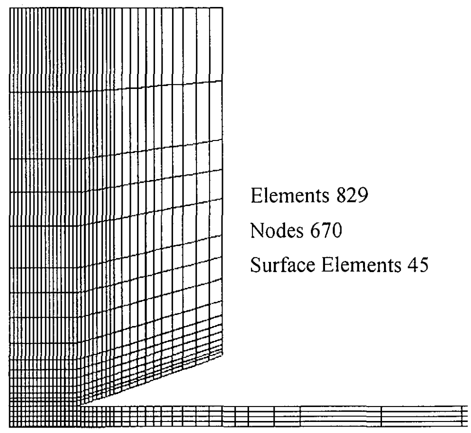

Fig.2 Finite element mesh used in simulations with 829 elements and 670 nodes

Table 1 Physical Properties of materials

Item	Unit	Mild Steel	Copper
Heat Conductivity	J/cm.s.K	Eq.1	0.22
Specific Heat	J/g.K	Eq.2	0.022
Electric Resistivity	μΩ.cm	Eq.3	2.026
Specific Density	g/cm^3	7.7	8.9

Eq. 1:

$$K = -1.99*10^{-8}T^2 - 5.98*10^{-6}T + 299 \quad (20^\circ C \le T < 400^\circ C)$$
$$K = -1.79*10^{-8}T^2 - 2.39*10^{-6}T + 282 \quad (400^\circ C \le T < 800^\circ C)$$
$$K = 0.0156 \quad (800^\circ C \le T < 1530^\circ C)$$
$$K = 8.907*T - 1.34726 \quad (1530^\circ C \le T < 1600^\circ C)$$
$$K = 0.078 \quad (1600^\circ C \le T)$$

Eq. 2:

$$C = 7.34*10^{-8}T^2 - 1.83*10^{-5}T - 0.0257 \quad (20^\circ C \le T < 400^\circ C)$$
$$C = 4.43*10^{-8}T^2 - 0.0271 \quad (400^\circ C \le T < 600^\circ C)$$
$$C = 1.67*10^{-4}T - 0.0572 \quad (600^\circ C \le T < 750^\circ C)$$
$$C = 0.2912 - 2.975*10^{-4}T \quad (750^\circ C \le T < 850^\circ C)$$
$$C = 0.0383 \quad (850^\circ C < T)$$

Eq. 3

$$\rho = 8.56*10^{-5}T^2 - 4.9*10^{-2}T - 15.4 \quad (20^\circ C \le T < 800^\circ C)$$
$$\rho = 2.875*10^{-2}(T - 800) - 109.4 \quad (800^\circ C \le T < 1200^\circ C)$$
$$\rho = 120 \quad (1200^\circ C \le T < 1530^\circ C)$$
$$\rho = 120 - 40(T - 1530) \quad (1530^\circ C \le T < 1560^\circ C)$$
$$\rho = 240 \quad (1560^\circ C \le T)$$

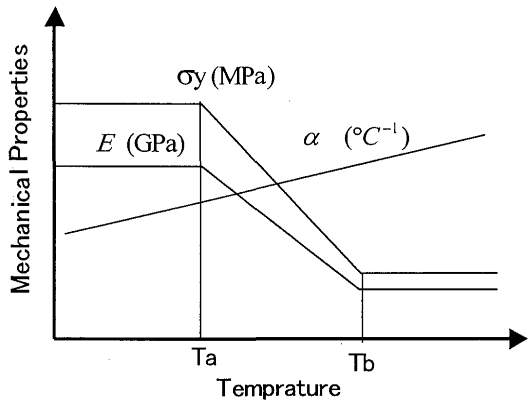

Fig.3 Mechanical Property scheme of Materials

Table 2 Mechanical Properties

	Mild steel	Copper
T_a (°C)	400	400
T_b (°C)	1100	800
$(\sigma_y)_a$ MPa	270	200
$(\sigma_y)_b$ MPa	10	10
E_a GPa	210	120
E_b GPa	0.3	0.2
α 1/°C	Eq.1	Eq.2
Eq. 1: $\alpha = 11.7*10^{-6} + 6.0*10^{-8}T$		

However, the problem is simplified as an axisymmetric problem in this report. The model of the spot weld joint is shown in **Fig.1** with the typical temperature distribution computed by the finite element code. Because of the symmetry, only one quarter of the model is divided into FEM mesh as shown **Fig.2** with 670 nodes and 829 elements including 45 surface elements. The material constants dependent on the temperature are listed in **Table 1**. The profile of mechanical properties are shown in **Fig.3** and corresponding parameters are listed in **Table 2**.

2.2 Comparison with experiment

To clarify the relation between the electrode displacement and the nugget formation, a series of experiments were conducted for specimens with different plate thicknesses, welding currents and squeezing forces. The details of the experiments will be reported elsewhere. Two typical examples are cited for the comparison with the computation by FEM. **Figures 4** and **5** show the history of electrode displacement at its top. The measured and the computed results are compared in these figures. The welding conditions and the plate thickness are shown in the figures.

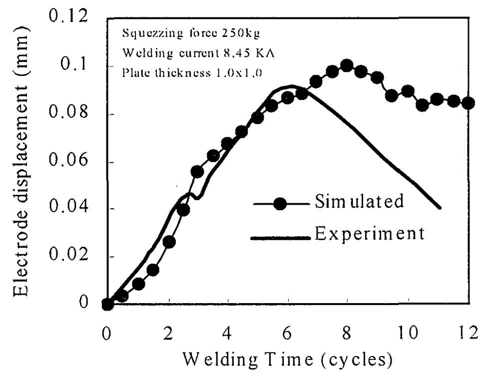

Fig.4 Comparison of simulated and experimental electrode displacement for welding current 8.45kA, squeezing

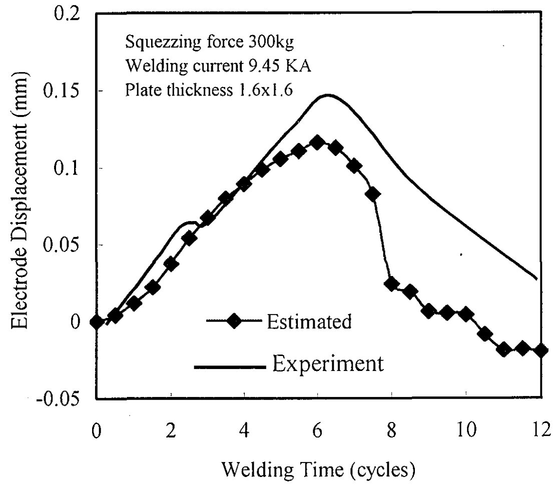

Fig.5 Comparison of simulated and experimental electrode displacement for welding current 9.45kA, squeezing force 3kN and plate thickness 1.6x1.6mm

As seen from these figures, the maximum values appear in both measured and computed electrode displacement curves. Though some differences are observed between the experiment and the computation after the peak, their agreement up to the peak is fairly good. These figures indicate that the electrode displacement may provide important information on the nugget formation. In order to examine closely the relation between the electrode displacement and the nugget formation, serial FEM simulations were conducted. In the serial simulation, the plate thickness is assumed to be 1.0, 1.2 and 1.6mm. The welding current is 8, 9, 10 and 11 kA. The squeezing force is 1.5, 2.0, 2.5 and 3.0 kN.

3. Results and Discussion

3.1 Characteristic Parameters

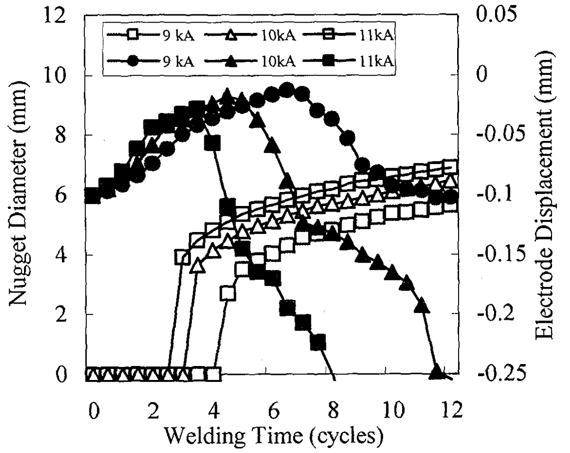

Fig.6 Development of electrode displacement and nugget formation in deferent currents for thickness 1.0mm and squeezing force 3 kN

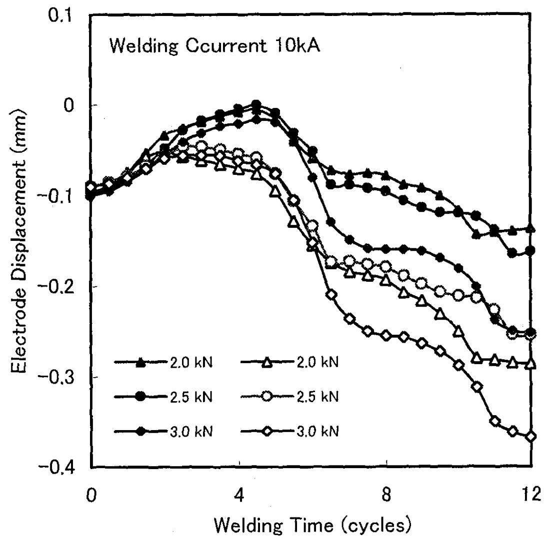

Fig.7 Influence of squeezing forces on the development of electrode displacement at top and tip for welding current 10kA and thickness 1.0mm

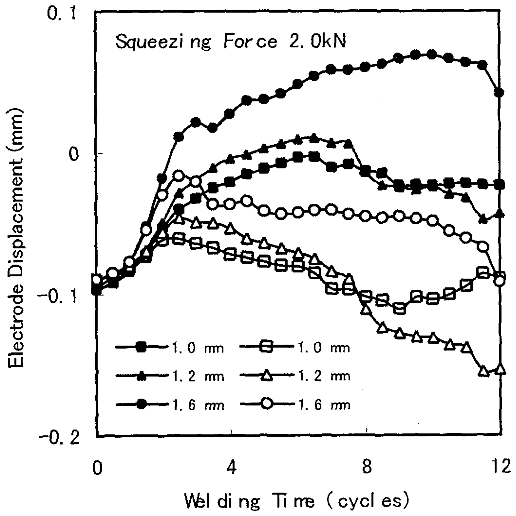

Fig.8 Influence of plate thickness on the development of electrode displacement at top and tip for welding current 10kA and squeezing force 2kN

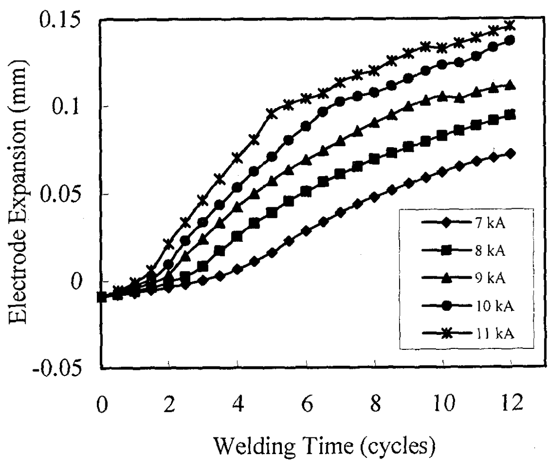

Fig.9 Effect of welding currents on electrode expansion in squeezing force 2.5kN and plate thickness 1.0mm

Figure 6 shows the effect of welding current on the displacement at the top of the electrode and nugget formation. The squeezing force and plate thickness are assumed as 3 kN and 1.0 mm, respectively. The computed results for cases with different welding current, namely 9 kA, 10 kA and 11 kA are plotted in the figure. It can be seen from the figure that the peak is observed in the curve for the electrode displacement. The peak appears earlier when the welding current is large. Similarly, the formation of the nugget starts earlier when the welding current is large.

The effects of the squeezing force on the electrode displacements are shown in **Fig. 7**. The case in which the welding current is 10 kA and the plate thickness is 1.0mm is taken as an example. In the figure, the lines with solid marks show the displacement at the top of the electrode and those with open marks show the displacement at the tip of the electrode. Within the cases examined here, the influence of the squeezing force is small before the electrode displacement at its top reaches the maximum value. Thus, the time for the peak value of the displacement does not change with the squeezing force. Its influence becomes significant after the maximum displacement is reached. The electrode displacement shifts in the compressive side when the squeezing force is large.

The effects of the plate thickness on the electrode displacements are shown in **Fig. 8**. The case in which the welding current is 10 kA and the squeezing force is 2.0 kN is taken as an example. It can be seen from the figure that the electrode displacement at the tip reaches the maximum before that of the top does. The time

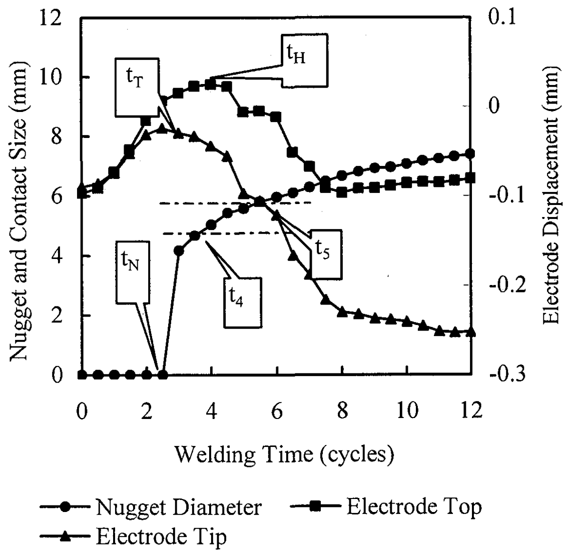

Fig.10 The typical development of electrode displacement and nugget formation, and parameter definitions.

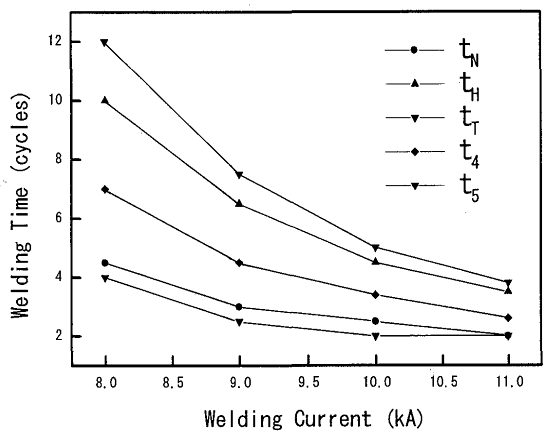

Fig.11 Influence of welding current on the parameters representing the features of electrode displacement and nugget formation

associated with the maximum value of the displacement at the electrode tip changes little with the plate thickness. While that for the displacement at the electrode top becomes larger with the increase of plate thickness. It should be noticed that the difference between the displacements at electrode top and electrode tip represents the thermal expansion of the electrode itself. **Figure 9** shows an example of the thermal expansion of the electrode. The difference between the electrode displacement at the top and the tip is plotted for cases in which the welding current is 7, 8, 9, 10 and 11 kA, respectively. The squeezing force and the plate thickness are assumed to be 2.5 kN and 1.0 mm. As it is see from the figure, the electrode expands smoothly with time and its expansion is large when the welding current is large.

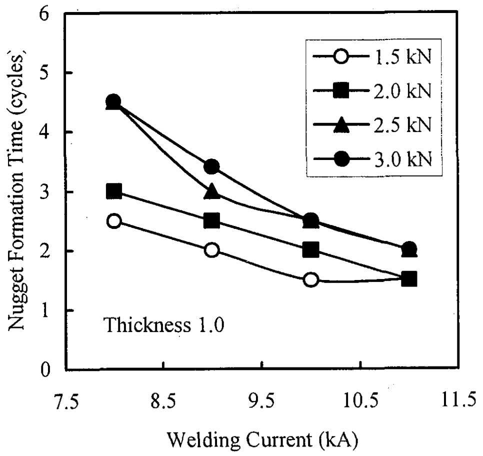

Fig.12 Influence of welding current on nugget formation with different squeezing forces and a plate thickness of 1.0mm

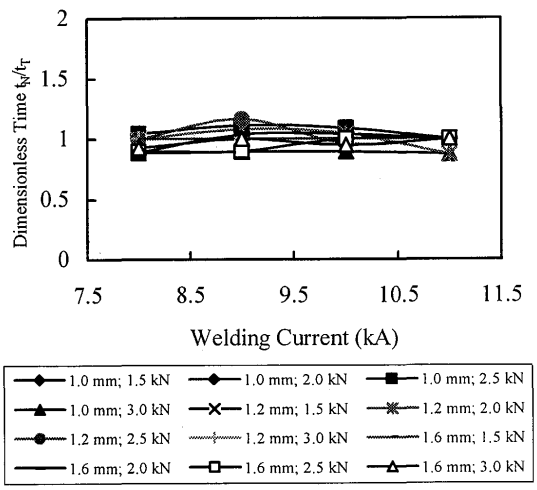

Fig.13 Influence of welding current on dimensionless nugget formation time t_N/t_T for different squeezing forces and plate thickness

As has been shown, the electrode displacement and the nugget formation are closely related. It is very important to clarify their relations using parameters which characterize the time history of the electrode displacement and the nugget growth. For this purpose, five time parameters, namely t_H, t_T, t_N, t_4 and t_5 shown in **Fig.10** are introduced. The parameter t_H is the time associated with the maximum value of the electrode displacement at the top. Similarly, the parameter t_T is the welding time at the maximum value of the electrode displacement at the tip. The parameter t_N is the time when the nugget starts to form. The parameters t_4 and t_5 are the time when the nugget diameter reaches $4\sqrt{t}$ and $5\sqrt{t}$ (t: plate thickness), respectively. The influence of the welding current on these parameters is shown in Fig.11. The case in which the squeezing force is 2.5 kN and plate thickness is 1.0mm is taken as an example. It is noticed that, the start of nugget formation t_N and the peak value of the electrode displacement at the tip t_T occur almost at the same time. After t_T and t_N, t_4 : the formation of the nugget with diameter $4\sqrt{t}$, t_H : the peak value of the electrode displacement at the top and t_5 : the formation of the nugget with diameter $5\sqrt{t}$ follow in this sequence. All the parameters decrease with the welding current but their time sequence is kept the same.

3.2 Relationship among parameters

To control the welding process, the parameters which characterize the process must be extracted. Figure 10 shows five parameters characterizing the time histories of the electrode displacements and the nugget diameter. It is very important to investigate the relationships among these parameters. **Figure 11** shows these parameters for different values of welding current. The squeezing force and plate thickness are 2.5 kN and 1.0 mm. As seen from the figure, the events occur in the same order regardless of the welding current. First, the displacement at the tip of the electrode reaches the maximum (t_T). Then, start of nugget formation (t_N), nugget size of $4\sqrt{t}$ (t_4), maximum value of electrode displacement at the top (t_H) and nugget size of $5\sqrt{t}$ follow.

Figure 12 shows the effect of the welding current and the squeezing force on the parameter t_N for the cases

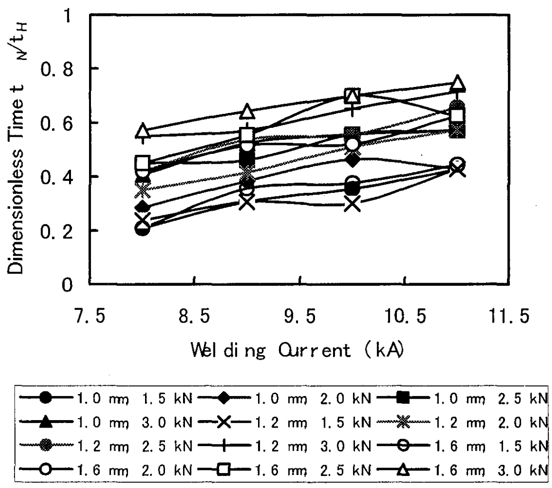

Fig.14 Influence of welding current on dimensionless nugget formation time t_N/t_H with different squeezing forces and plate thickness

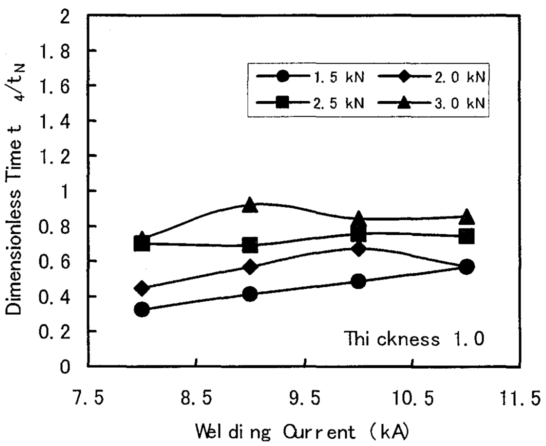

Fig.15 Influence of welding current on dimensionless nugget formation time t_4/t_H with different squeezing forces and plate thickness 1.0x1.0mm

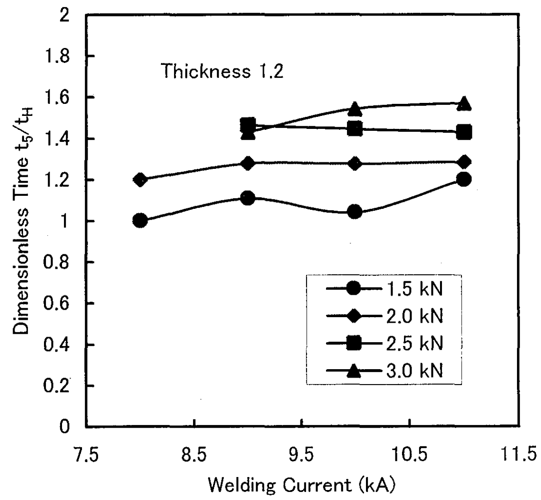

Fig.16 Influence of welding current on dimensionless nugget formation time t_5/t_H with different squeezing forces and plate thickness 1.0x1.0mm

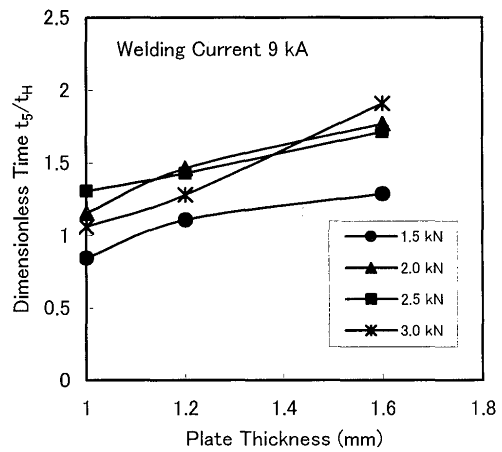

Fig.17 Effect of plate thickness and squeezing force on the dimensionless parameter t_5/t_H.

when the plate thickness is 1.0mm. It can be seen from the figure that the nugget formation time t_N generally becomes longer with the increase of squeezing force. The rate of the increase becomes small when the squeezing force is larger than 2.5kN in this case. It becomes shorter when the welding current increases.

The ratio between the nugget formation time t_N and the parameter t_T for cases with different plate thickness and squeezing force is plotted in **Fig.13**. It is clearly seen from the figure that the dimensionless time t_N/t_T keeps almost 1.0 regardless of the value of welding current, plate thickness and squeezing forces. This means that the parameter t_T could be used to detect the nugget formation in the real welding process. However, the parameter t_T is difficult to measure in the real production line. The electrode displacement at its top is easier to measure. The difference between the displacements at the tip and the top of the electrode is the thermal expansion of the electrode as shown in Fig.9. Since the thermal expansion of the electrode is relatively easy to estimate, the displacement at the top of the electrode can be used instead of that at the tip. The relation between the parameters t_N and t_H for different welding current, squeezing force and plate thickness is shown in **Fig.14**. The dimensionless time parameter t_N/t_H changes between 0.2 and 0.8 according to the current, plate thickness and the squeezing force. It increases with the welding current. The squeezing force has little effect on the dimensionless parameter t_N/t_H. Since the effects of the plate thickness and the squeezing force are opposite, the parameter t_N/t_H is the same for larger thickness with lower squeezing force and that for smaller thickness with larger squeezing force.

Figure 15 shows the time for forming the nugget with its diameter $4\sqrt{t}$ normalized by t_H. The effect of the welding current and the squeezing force is summarized for the cases when the thickness of the plate is 1.0 mm. The dimensionless time parameter t_4/t_H increases with the welding current for given squeezing force. The parameter t_4/t_H increases with the increase of the squeezing force. The variation of the parameter t_4/t_H with the squeezing force becomes relatively small when the welding current is large. Generally, the value of the parameter t_4/t_H is less than 1.0 within the investigated cases. This implies that the nugget size of $4\sqrt{t}$ can be achieved before the electrode displacement at the top reaches the maximum value.

Similarly **Fig.16** shows the time for forming the nugget with its diameter $5\sqrt{t}$ normalized by t_H. The effect of the welding current and the squeezing force is summarized for the cases when the thickness of the plate is 1.2 mm. It can be seen from the figure that the influence of the squeezing force is more significant compared to that of the welding current. The nugget larger than $5\sqrt{t}$ can be achieved only after the electrode displacement reaches the maximum when the squeezing force is larger than 2.0kN. **Figure 17** shows the influence of the plate thickness on the parameter t_5/t_H when the welding current is 9kA. The dimensionless time parameter t_5/t_H increases with the plate thickness. It is also seen from Fig.17 that the parameter t_5/t_H is larger than 1.0 except when the plate thickness is 1.0mm and the squeezing force is less than 2.0kN.

4. Conclusion

The electrode displacements and the nugget formation in the spot welding process were analyzed using the finite element code. The computed results are compared with those of experiments and the following conclusions were drawn.

1) The electrode displacement at its top is compared between the computation and the experiment. Good agreement between them demonstrates the capability of the finite element code developed by the authors.
2) The time when the electrode displacement at the tip reaches the maximum value is closely related to the nugget formation.
3) The peak of the electrode displacement at the tip (t_T) and the formation of the nugget (t_N) appear at almost the same time in the welding process. Then the formation of the nugget with diameter of $4\sqrt{t}$ (t_4), the peak value of the electrode displacement at the top (t_H) and the formation of the nugget with diameter of $5\sqrt{t}$ (t_5) follow.
4) The peak of the electrode displacement at the top (t_H) is delayed due to the thermal expansion of the electrode.
5) The squeezing force and the plate thickness have a large influence on the dimensionless parameters t_4/t_H and t_5/t_H. While, that of the welding current is relatively small.
6) The possibility of controlling the spot welding process based on the electrode displacement is shown through FEM simulation.

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