Finite Element Simulation of Seam Welding Process †

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Abstract

To produce sound nugget, it is necessary to select the most suitable conditions, such as the squeezing force, the welding current, the welding speed, the electrode shape and the mode of current. To determine them, large numbers of experiments, which require significant cost and time, have to be conducted. One of the effective solutions for this problem is computer simulation. Thus, a finite element method for the seam welding is developed and the appropriate conditions are studied through numerical simulation. In this research, the effects of the mode and the value of the welding current and the welding speed on the formation of the nugget are examined by using newly developed method. In case of the continuous current mode, periodic instability appears in the process and continuous and uniform nugget is not produced. This periodicity is closely related to the contact area between the electrode and the work. It is also found that a current with discontinuous mode is preferable to achieve a good nugget because the contact state is stabilized by the cooling effect of the electrodes.

KEY WORDS: (Seam Welding) (Finite Element Method) (Simulation) (Nugget Formation) (Weldability) (Welding Condition) (Pulsed Current)

1. Introduction

Seam welding and spot welding are typical joining methods for thin metal sheets. In particular, seam welding is widely employed for the fabrication of fuel tanks of automobiles and the gas tanks of LNG carriers which require water or air tightness. In case of these tanks, leakage is not allowed for safety reasons. Highly reliable welding procedures which produce high quality welding are required. In general, the quality of the weld is strongly dependent on the maintenance of the welding machines and the selection of optimum welding conditions.

In case of an LNG carrier, the number of plates to be joined and the combination of their thickness have wide variations. It may be necessary to spend considerable time and effort to conduct experiments for the selection of the optimum welding conditions for all possible cases. One of the solutions to avoid this is the effective use of computer simulation such as FEM[1-4]. Thus, a two-dimensional finite element method based on the thermal-elastic-plastic theory is developed in this study and its versatility is examined.

Seam welding is one of the fusion welding methods, which uses Joule heating as the heat source. As it is illustrated in **Fig.1**, the parts to be welded are squeezed by the electrode force. A pulsed welding current is applied through the electrodes during their rotation. The parts are melted by Joule heating and the size of the nugget is controlled by the cooling effect of the electrodes. If the welding conditions are selected appropriately, sound continuous nuggets can be formed. As mentioned, seam welding is an ideal welding method to produce airtight joints. Since, high welding speed is achieved without special skill once the welding conditions are correctly set, it is widely employed for the welding of not only mild steel but also aluminum alloys and stainless steels.

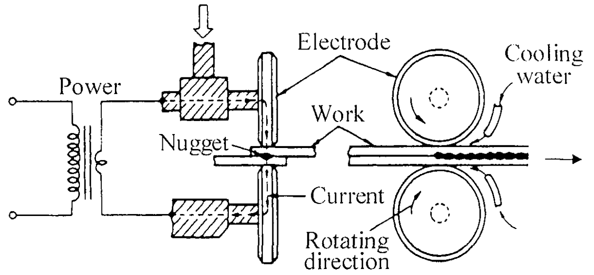

Fig.1 Schematic explanation of seam welding.

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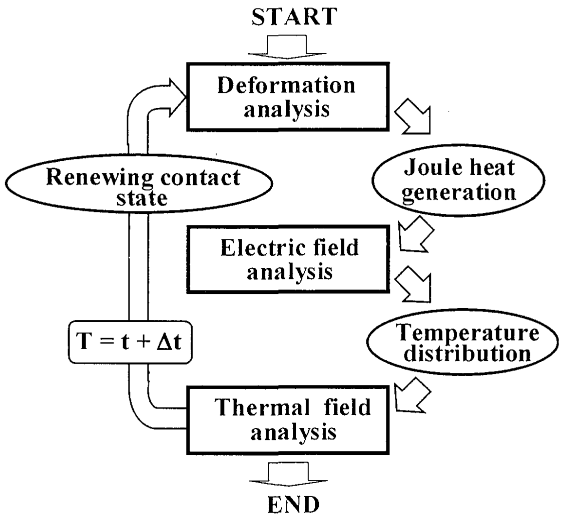


Fig.2 Procedure of analysis.

The weldability, or the formation of a sound nugget, is influenced by various factors, such as electric current, electrode force, welding speed and shape of electrode tip. If the current is not continuous AC, the mode of the pulsed current is also influential. The influence of these factors is examined using the proposed FEM.

2. Method of Analysis

2.1 Procedure of computation

FEM simulation of the seam welding consists of three parts, namely the deformation analysis, the electric field analysis and the thermal field analysis as shown in **Fig.2**. As the first step, the deformation of the system under the applied electrode force and the contact state between electrode/work and work/work are computed. Then, the electric field and the current density under the present contact states are computed. From the current density, the Joule heat generation is estimated and the thermal field is computed[3]. Such a cycle is repeated for small time increments until a sufficiently long weld is made.

2.2 Contact problem

One of the most important points in the seam welding is how to trace the contact state as accurately as possible. In the proposed method, contact elements are introduced between electrode/work and work/work as shown in **Fig.3**. In the initial state, there is a gap between work/work, for example, and the contact element is out of contact. When out of contact, the contact element has neither stiffness nor electric or thermal conductivity. Under the application of the electrode force, the gap becomes small. The contact element becomes in contact when the vertical component of the strain in the contact element ε_y reaches -1.0. When it is in contact, large

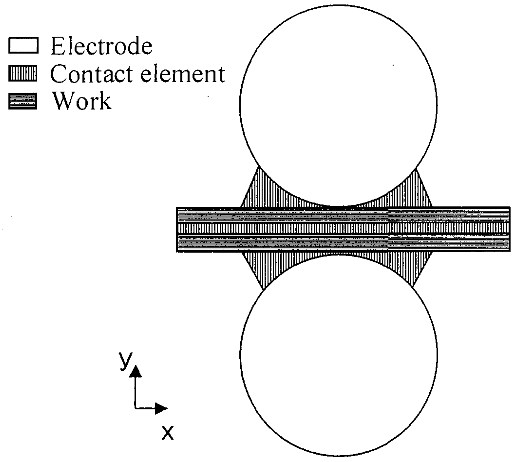


Fig.3 Modeling using contact element.

enough stiffness is given to the contact element. The same values of the electric and thermal conductivity of the bulk materials are given to the contact element. When the strain becomes larger than -1.0, the contact element returns to out of contact. Then, the stiffness, the electric and the thermal conductivities are set to zero. However, if the contact element experienced a temperature higher than the melting point of the work, it is considered to be joined and this procedure is not applied.

3. Simulation Model and Conditions for Analysis

3.1 Simulation model

The physical phenomena in seam welding are three-dimensional. Considering the capability of computers, it is possible to analyze the seam welding as a three-dimensional problem. However, the authors attempted to develop computer codes in the step by step manner starting from the two-dimensional models which are basically close to the axisymmetric code developed for the spot welding[3,4]. As it is illustrated in **Fig.4**, there are two possible two-dimensional models. One is the model in the longitudinal cross-section, which is suitable to study the formation of the nugget in the longitudinal direction. The other is the model in the transverse cross-section, which is suitable to examine the effect of the shape of electrode tip. In the former case, deformation, electric current and heat flux are not allowed in the z direction. While, those in the x direction are restricted in the latter case. In the present research, a two-dimensional model in the longitudinal cross-section is developed.

3.2 Model to study

The seam welding analyzed by the proposed method is illustrated in **Fig.5**. The diameter and the tip width of the electrode are 69 mm and 3.5 mm, respectively. The

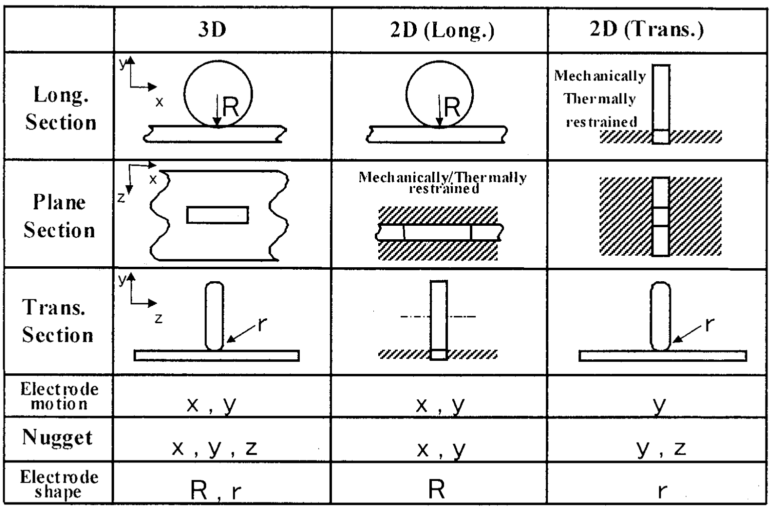


Fig.4 Two types of two-dimensional models.

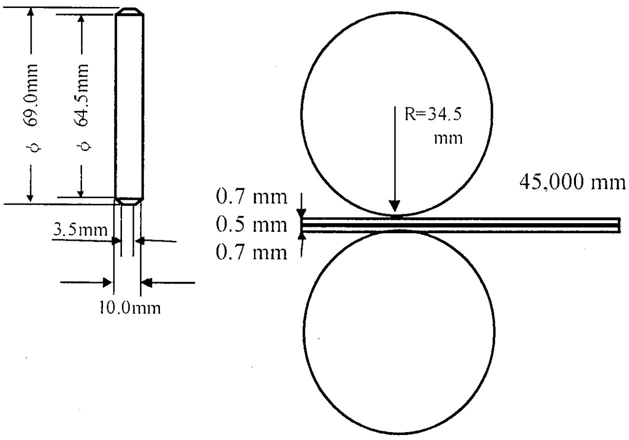


Fig.5 Shape of electrode.

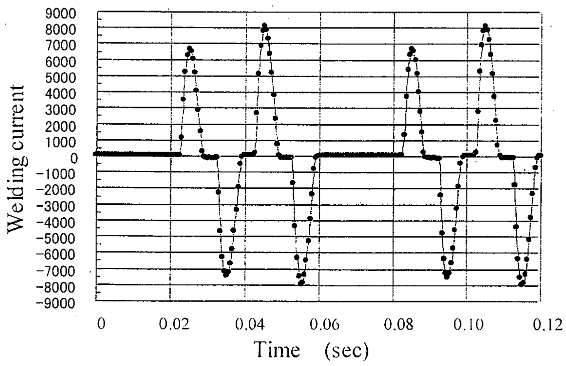


Fig.6 Current mode used in practice.

welding of three plates is analyzed. The thicknesses of the plates are 0.7 mm, 0.5 mm and 0.7 mm. The influence of the mode and the magnitude of the current and the welding speed on the nugget formation is investigated using the proposed method.

Figure 6 shows one example of the current mode used in the shipyard, where the typical welding condition employed in practice is shown in **Table 1**. It is a pulsed current with 2-cycle on/1-cycle off mode. For the FEM simulation, this current mode is idealized using the

Table 1 Typical welding condition employed in practice.

Effective current	3.6～4.6 kA
Welding speed	1400～1600mm/min
Electrode force	1500 N
Current mode	AC 50Hz Pulse current

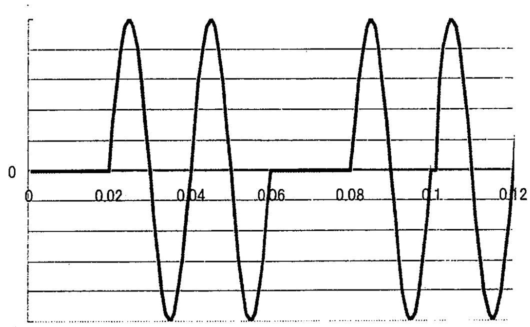


Fig.7 Current mode used in simulation.

sinusoidal curve as shown in **Fig.7**.

3.3 Temperature dependent material properties

The material properties of the INVAR and the copper are shown in **Table 2**, **Figs. 8, 9** and Eq.(1).

$$\rho = (0.0095 \times T + 2.11) \times 10^{-5} \quad (0 \le T \le 1083)$$
$$= 11.02 \times 10^{-5} \quad (1083 \le T) \qquad (1)$$

3.4 FEM model

Considering the symmetry, half of the model is subdivided into the finite element mesh as shown in **Fig.10**. The procedure to give the electrode force and the rotational motion of the electrode is explained in **Fig.11**. As shown in the figure, the force is applied at the center

Table 2 Material constants of INVAR and copper.

	Unit	INVAR	Copper
Thermal conductivity	J/mm/s/°C	Fig. 9	0.314
Specific heat	J/g/°C	Fig. 9	0.389
Resistivity	Ω·mm	Fig. 9	Eq.(1)
Density	g/mm³	8.14×10^{-3}	8.9×10^{-3}
Poisson's ratio	—	0.259	0.348
Linear thermal expansion	1/°C	Fig. 9	1.77×10^{-5}

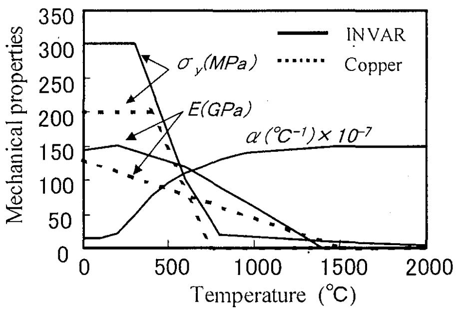


Fig.8 Temperature dependent mechanical properties.

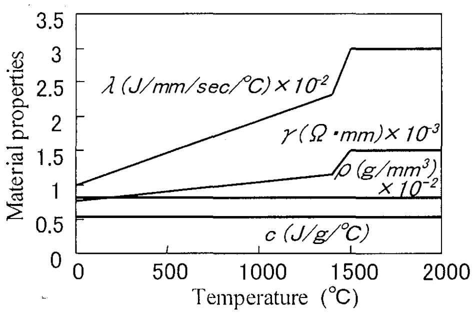


Fig.9 Temperature dependent material properties.

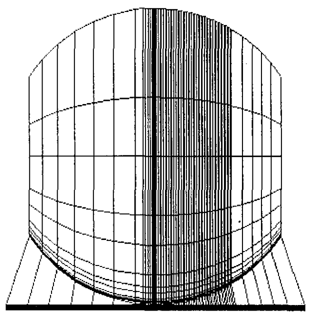


Fig.10 Mesh divison.

of the electrode. To move the electrode, the translational displacement is applied to the center of the electrode. While, displacement representing both the translation and the rotation is applied to the top of the electrode.

4. Computed Results

4.1 Effect of current mode

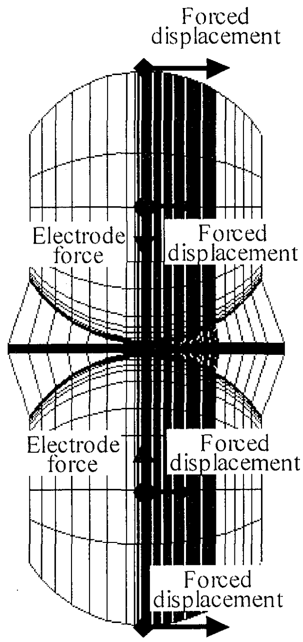
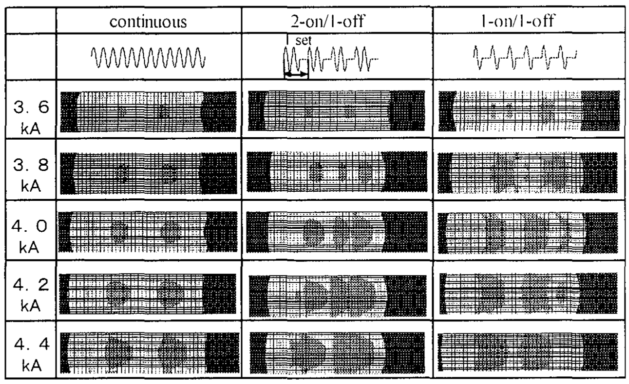


Fig.11 Procedure to apply electrode force and rotation.



Welding speed: 1,500 mm/min Electrode force: 1,500 N

Fig.12 Influence of current mode on nugget formation.

Figure 12 shows the influence of the mode and the magnitude of the current on the formation of the nugget. In the figure, the distributions of the highest temperature 0.24 second after the start of the welding are presented. The assumed welding speed and the electrode force are 1,500 mm/min and 1,500 N, respectively. Three types of current modes, namely continuous AC, 2-cycle on/1-cycle off and 1-cycle on/1-cycle off modes are compared. The range of the current is from 3.6 kA to 4.4 kA. Before the computation, a fairly uniform and continuous nugget was expected to be formed in the analysis. However, the computed results show that the formation of the nugget is not stable. Fluctuation with relatively long period is observed in the nugget formation and a continuous nugget is not formed. When the current is increased, the size of the nugget becomes larger but the fluctuation remains. In case of the pulsed current, the formation or the heat generation is strongly

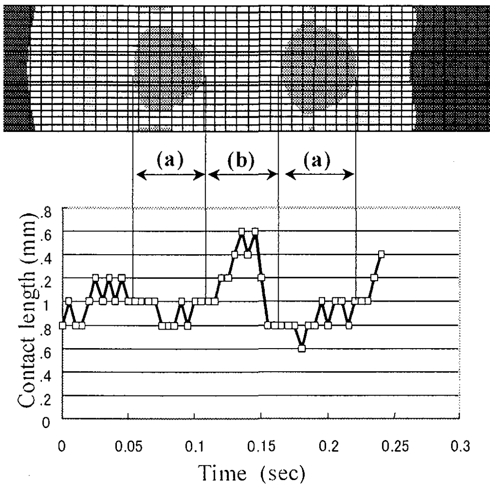


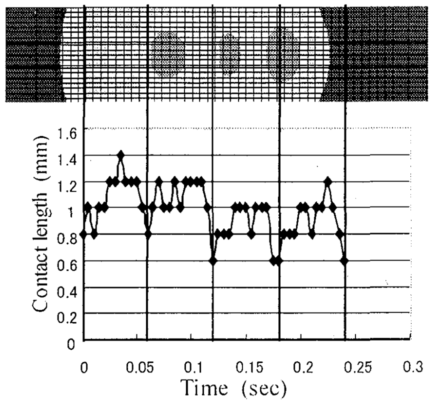
Fig.13 Relation between contact length and nugget formation (continuous AC).

governed by the current mode when the current is small. However, the nugget is not fully developed. When the current is increased, the size of the nugget becomes larger but the controlling effect of the pulsed current is lost and the fluctuation as in case of the continuous current appears. This phenomenon is closely related to the contact state between electrode/work and work/work as will be discussed in the next section.

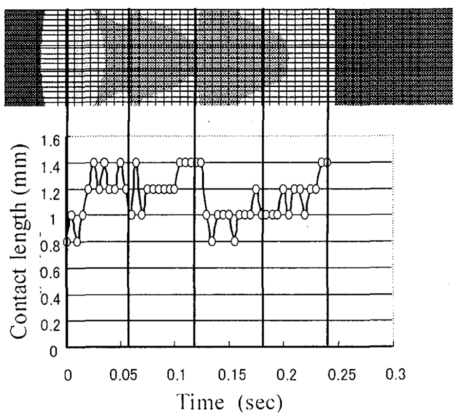
4.2 Relation between nugget formation and electrode/work contact

The case of continuous AC is closely examined in **Fig.13**. The highest temperature distribution and the time history of the contact length between the electrode and the work are shown for the case when the welding speed, the electrode force and the current are 1,500 mm/min, 1,500 N and 4.2 kA, respectively. The abscissas of the two figures in Fig.13 are adjusted so that the time corresponds to the location of the electrode at that moment. It is clearly seen that the nugget is formed when the contact length is small and heat generation is large due to the current concentration. With the growth of the nugget, the work becomes soft and the contact length increases. This results in a reduction of the current density and the heat generation. With the temperature drop, the nugget disappears. When the work is cooled and the electrode moves to the unheated part of the work, the contact length becomes small again and the same process is repeated with a roughly 0.1 second period.

In case of 2-on/1-off current mode, the relation between the nugget formation and the contact length is closely examined in the same manner. **Figure 14** shows the computed results for the cases when the current is 3.8 kA and 4.4 kA, respectively. The period of the 2-on/1-off current mode is 0.06 second. When the current is small, the contact length changes regularly with a 0.06 second



(a) Current = 3.8 kA



(b) Current = 4.4 kA

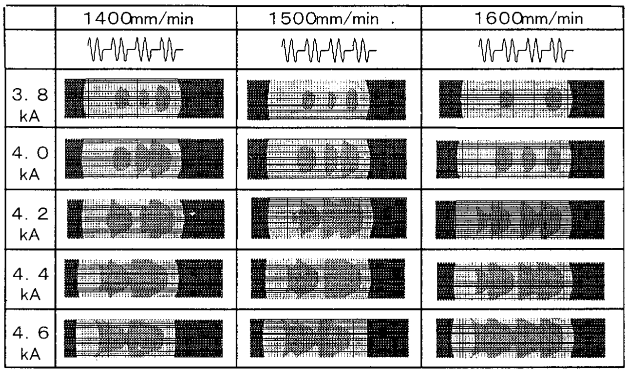
Fig.14 Relation between contact length and nugget formation (pulsed current).

period. The value of the current becomes the smallest at the beginning of the cycle. Similar cyclic change is also observed in the temperature distribution.

When the current is increased to 4.4 kA, the nugget size becomes large. But, the periodic change is not observed either in the contact length or the temperature distribution. It is clearly seen that the contact area does not return to the minimum value at the start of the current cycle. As a general trend, the length of the contact becomes larger when the current is large.

4.3 Effect of welding speed

The effect of the welding speed on the nugget formation is examined using the cases in which the welding speed is 1,400 mm/min, 1,500 mm/min and 1,600 mm/min as examples. As it is seen from **Fig.15**, a fluctuation with long period tends to appear when the current is large. This tendency is slightly reduced when the welding speed is large. However, a welding condition, which produces a continuous and stable nugget, is not found within the range, which corresponds to the real seam welding process in the shipyard.



Current mode: 2-on/1-off Electrode force: 1,500 N

Fig.15 Influence of welding speed on nugget formation.

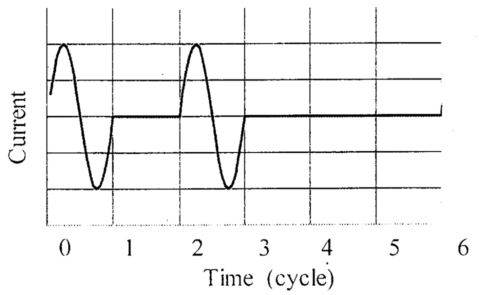


Fig.16 Modified current model for enhanced cooling by electrode.

This may be explained by the fact that the heat flow in the width direction is not allowed in the two-dimensional model as shown in Fig.4. This results in slow cooling and fast and unstable nugget growth compared to the real three- dimensional situation. To clarify this point, the effect of cooling is examined in the next section.

4.4 Effect of cooling by electrode

The cooling takes place in two ways. One is the heat flow into the electrode. The other is the heat flow in the work itself, especially in the width direction. In case of the two-dimensional model in longitudinal cross-section, the former is considered but the latter is not. To compensate the cooling effect of the work itself, the cooling by the electrode is artificially enhanced. This can be done by reducing the welding speed by half to give longer time for the current off period as shown in **Fig.16** to keep the heat input the same.

The computed highest temperature distribution in both the work and the electrode is shown in **Fig.17**. As seen from the figure, a continuous nugget is formed in a stable manner. Also, the relation between the nugget formation and the length of contact between the electrode and the work is shown in **Fig.18**. The length of contact shows the periodic variation synchronized with the current cycle with a period of 0.12 sec. This

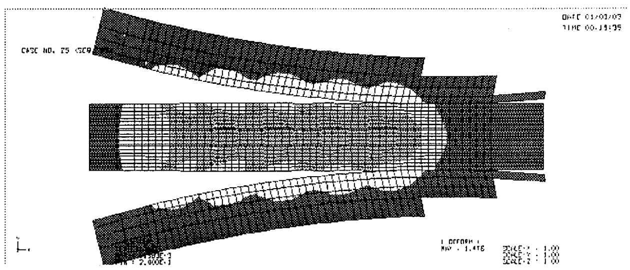


Fig.17 Highest temperature distribution under enhanced cooling by electrode.

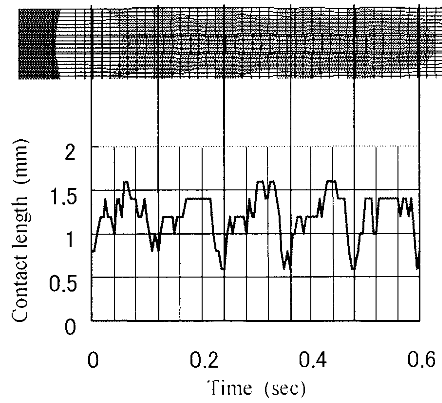


Fig.18 Relation between contact length and nugget formation (modified pulsed current).

computed results tells us that sufficient cooling of the nugget during the current off period is important to suppress the fluctuation in the nugget formation and to achieve a sound continuous nugget. At the same time, it tells us that the three-dimensional simulation in which the cooling effects are fully taken into account is necessary for the quantitative prediction of seam welding process.

5. Conclusions

The authors are planning to develop a three dimensional FEM code to select the appropriate welding conditions based on computer simulations. As the first step toward the goal, a two-dimensional FEM, which models the longitudinal cross-section, is developed. Newly developed code is applied to the seam welding of INVAR plates and the influence of the mode and the magnitude of the current and the welding speed on the nugget formation is studied. Through this study, the following conclusions are drawn.

(1) In the case of the continuous AC, instability with long period is observed in nugget formation. This phenomenon is attributed to the unstable contact state between the electrode and the work.

(2) In the case of the pulsed current, nugget size becomes larger with the current. When the welding speed becomes larger, the tendency for the nugget formation to become stable due to the pulsed current is slightly observed.

(3) Within the range of the welding parameters employed in the actual welding, a sound continuous nugget is not formed in the two-dimensional FEM simulation. This can be explained that the heat flow in the width direction is not allowed in the two-dimensional analysis and the cooling of the nugget is slow compared to the real situation.

(4) To compensate inadequate cooling, period of off current is increased in the current mode and the welding speed is reduced to maintain the same heat input. Using such modified current mode, a sound continuous nugget is achieved in the two-dimensional analysis.

(5) The above computed results demonstrate the potential capability of the FEM simulation as a method to determine the welding condition.

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