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# Numerical Simulation of Fuzzy Control for Resistance Spot Welding by Monitoring Electrode Temperature†

WU Yanming*, SERIZAWA Hisashi** and MURAKAWA Hidekazu***

**Abstract**

*It is well known that resistance spot welding is a complex process in which coupled interactions exist between electrical, thermal, mechanical, and metallurgical phenomena. Because of this complexity, it is very difficult to obtain insightful information of welding process through the most ambitious experiments alone. In this paper, the thermo-elastic-plastic FEM is used to simulate the process of resistance spot welding. The effect of the welding current and squeezing force on the properties of spot welding is examined, in particular, from the aspect of the relation between the electrode temperature and the nugget formation in spot welding. Through this study, it is found that a sound nugget can be achieved when the electrode temperature is controlled within an acceptable range. Based on this knowledge, a fuzzy control method in which the welding current is modified in real time by monitoring electrode temperature is proposed. It is demonstrated that sound spot welding joints with large enough nuggets can be achieved by using the proposed fuzzy control method. It is also shown that the weldability lobe can be expanded by employing the fuzzy control.*

**KEY WORDS**: (Spot Welding) (Nugget Formation) (Aluminum Alloy) (Fuzzy Control)

## 1. Introduction

Spot welding is one of the resistance welding processes that is used for the fabrication of sheet metal assemblies. The process is widely used for joining low carbon steel and aluminum components for automobiles, trucks, trailers, buses, and cabinets, as well as office furniture, and many other products. The major advantages of the resistance spot welding are high speed and adaptability for automation in high volume and high rate production.

In this research, a fuzzy theory is applied to control the process of nugget formation and its effectiveness is examined through numerical simulations using the finite element method.

## 2. Influential Factors in the Spot Welding Process

### 2.1 Formation of Nugget

In resistance spot welding, the work pieces to be joined are squeezed by a pair of electrodes as shown in **Fig.1**. Then, the electric current is applied through the electrodes and the nugget is formed by Joule heating. To achieve strength in the joint, a proper nugget size must be maintained. In general, nugget diameter $d_n$ must satisfy the following condition to achieve sufficient joint strength.

$$d_n \geq 4\sqrt{t} \tag{1}$$

where: $t$ is the thickness of the work piece. Since the nugget diameter is the most influential parameter in the joint strength, it is very important to maintain a large enough nugget.

On the other hand when the size of nugget is too large, expulsion may occur. The expulsion occurs when the nugget diameter $d_n$ exceeds the contact diameter between work pieces $d_c$ as shown in Fig.1. Therefore, the diameter of the nugget must satisfy the following equation.

$$d_n \leq d_c \tag{2}$$

The spot welding process and the quality of the joint are influenced by many factors, such as welding current, thickness of work, squeezing force, material of work pieces, electrode shape etc. It is well known that resistance spot welding is a complex process in which coupled interactions exist between electrical, thermal, mechanical,

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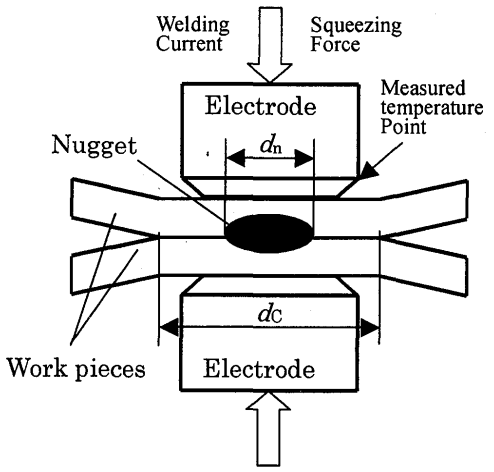


Fig.1 Schema of spot welding.

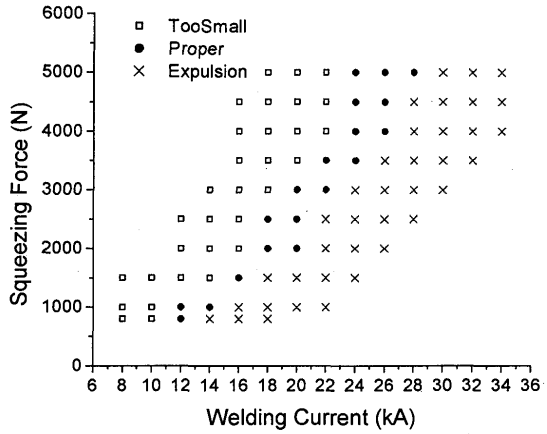


Fig.2 Relationship between squeezing force, welding current, and nugget size.

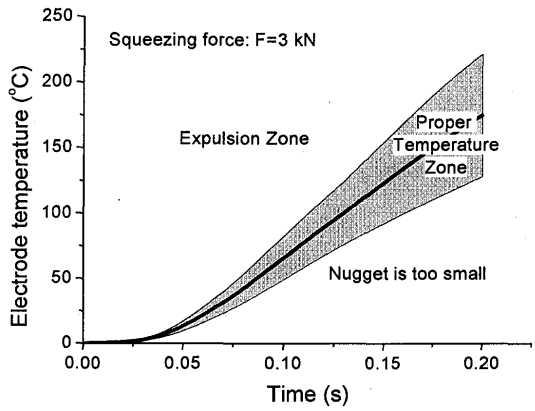


Fig.3 Acceptable electrode temperature range to obtain sound weld.

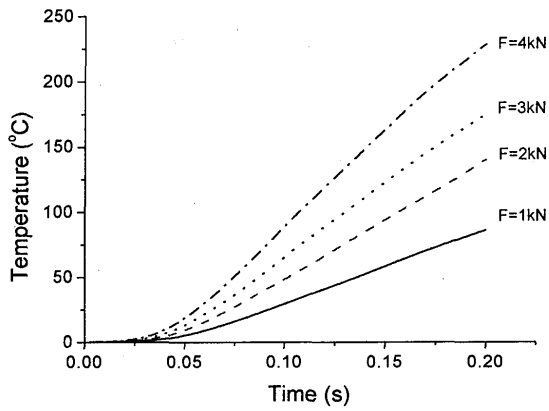


Fig.4 Influence of squeezing force on average electrode temperature.

and metallurgical phenomena. Because of this complexity, it is very difficult to obtain insightful information of welding process through even the most ambitious experiments alone. On the other hand, numerical modeling provides a powerful tool for understanding such a complex process[1, 2].

The influences of the welding current and the squeezing force on the formation of nugget are examined by a serial FEM simulation. The results are as summarized in **Fig. 2**. The material of the work pieces is assumed to be an aluminum alloy and their thickness is 1 mm. The open squears represent the cases in which the diameter of nugget is too small to satisfy the **Eq.(1).** The solid circles represent the cases in which sufficiently large nuggets are obtained without expulsion. The cross symbols represent the cases in which expulsion occurs.

Through the serial computations, it is found that the size of weld nugget generally increases with an increase of welding current. If current is too small the size of nugget is too small to satisfy the requirement. On the other hand, expulsion occurs when the current is too large. Thus, the welding current and the squeezing force must be appropriately controlled to obtain a sound weld.

### 2.2 Electrode Temperature

To control the welding process, we need to monitor the process. Various parameters can be monitored, such as the voltage, the electrode displacement and the electrode temperature. Through the serial computation, a close relation is observed between the formation of sound nuggets and the time history of the temperature at the tip of the electrode. The time histories of the electrode temperature for the cases of sound nugget can be plotted within the shaded zone in **Fig.3**. In these cases, the squeezing force is assumed to be 3 kN. When the electrode temperature is higher than this zone, the nugget grows quickly and the expulsion occurs. When the electrode

temperature is lower than this zone, the nugget growth is so slow that the size of the nugget does not satisfy **Eq. (1).** The influence of the squeezing force on the electrode temperature is summarized in **Fig.4**. When the squeezing force is large, the temperature at the tip of the electrode becomes higher. This may be explained by the contact area between work pieces. The contact area between work pieces increases with the squeezing force and the electric current density is concentrated at the electrode tip. Due to this current concentration, the electrode temperature becomes higher.

## 3 Fuzzy Control System

The structure of the fuzzy control system is shown in **Fig.5**. In the figure, the *e* is the error between the target temperature and the real temperature, the *ec* is the change of error *e*, and the output *u* is the proportional ratio of welding current. The welding current is real time controlled according to the following equation:

$$I = u \times I_0 \tag{3}$$

where, $I_0$ is the initial welding current.

The structure of fuzzy controller is shown in **Fig.6**. Fuzzification is the process that converts a crisp input such as the electrode temperature into a fuzzy set so that it can be operated by the fuzzy controller system. The scopes of the error and the error change are called the basic universe. *E*, *EC*, *U* is the discourse universe of Error, Error Change, and Output control data, respectively.

The basic universe of error is [-*a*, *a*], and the basic universe of error change is [-*b*, *b*], the universe of discourse in fuzzy sets of error and error change are all [-6,6], and then the quantification factors are given as the followings,

$$K_e = 6/a \tag{4}$$

$$K_{ec} = 6/b \tag{5}$$

$$e' = K_e e \tag{6}$$

$$ec' = K_{ec} ec \tag{7}$$

The linguistic variables of Error and Error Change are as follows: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PL (Positive Large). The membership functions of Error and Error Change are triangular type defined as in **Fig.7**.

The linguistic variables of *U* are as follows: MIN (Minimum), VS (Very Small), S (Small), M (Medium), L (Large), VL (Very Large), MAX (Maximum). The membership functions of welding current are also triangular types defined as in **Fig.8**.

The control rules can be deduced from experiments and experiences. The rules are given in the following format,

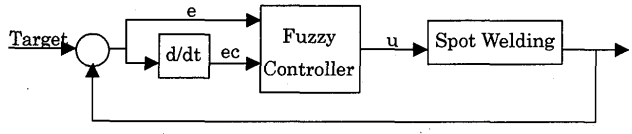


Fig.5 Structure of fuzzy control system.

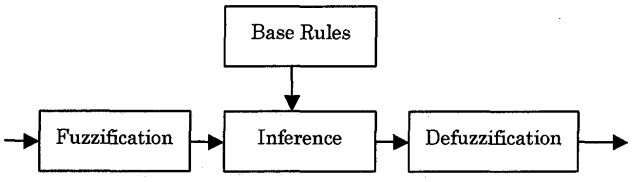


Fig.6 Block diagram of fuzzy controller.

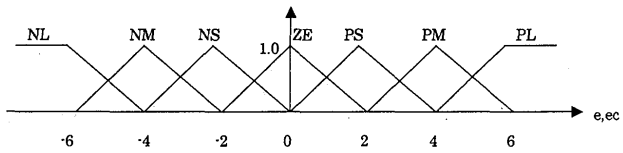


Fig.7 Membership functions of e and ec.

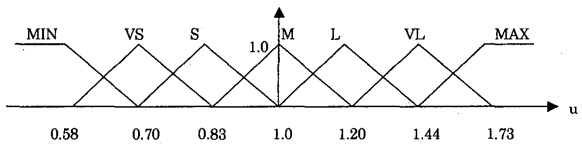


Fig.8 Membership functions of u.

If *E* is $E_i$ and *EC* is $EC_j$ then *U* is $U_{ij}$.

Where $E_i$, $EC_j$, $U_{ij}$., is the fuzzy set of the universes of *E*, *EC* and *U*, respectively.

This rule can be interpreted using the following fuzzy relation matrix:

$$R = \bigcup_{ij} (E_i \times EC_j) \times U_{ij} \tag{8}$$

This is written:

$$\mu_R(X,Y,Z) = \vee[\mu_{Ei}(x) \wedge \mu_{ECj}(x)] \wedge \mu_{Uij}(x) \tag{9}$$

In this system, there are 49 rules as shown in **Table 1**:

Table1 Fuzzy control rules.

| | | EC | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | PL | PM | PS | ZE | NS | NM | NL |
| E | PL | MIN | MIN | MIN | MIN | MIN | VS | S |
| | PM | MIN | MIN | VS | VS | S | M | M |
| | PS | MIN | VS | VS | S | M | M | L |
| | ZE | VS | S | S | M | L | L | VL |
| | NS | S | M | M | L | VL | VL | MAX |
| | NM | M | M | L | VL | VL | MAX | MAX |
| | NL | L | VL | MAX | MAX | MAX | MAX | MAX |

Since each rule is described by a fuzzy relation matrix $R_i$, the fuzzy relations of the system defined by the rules is defined as the following equation.

$$R = R_1 \vee R_2 \vee \cdots \vee R_n = \vee R_i \qquad (10)$$

Inference Engine: Mamdani Max-Min type is used in this paper.

$$U = (E \times EC) \circ R \qquad (11)$$

$$\mu_U(z) = \vee \mu_R(X,Y,Z) \wedge [\mu_{Ei}(x) \wedge \mu_{ECj}(x)] \qquad (12)$$

Defuzzification: the centroid, or center of area, method is used to calculate a crisp output for the system. In theory, this calculation can be accomplished by multiplying each value of the membership function with its position in the U-axis, and summing all these products. Then it is divided by the total area, i.e.

$$u^* = \sum_{i=1}^{n} \mu(U_i)U_i \Big/ \sum_{i=1}^{n} \mu(U_i) \qquad (13)$$

## 4. Controlling Welding Current Using Electrode Temperature

To obtain a sound welding joint by resistance spot welding, the electrode temperatures can be one of the parameter to be monitored and to be kept within an appropriate range. The target temperature is the average temperature shown as Fig.3. Because the range of temperature is very narrow at the start period, and since it becomes wider as time increases, the basic universe should be changed with time. Therefore the quantification factors are set as the following equations.

$$K_e = \frac{1}{50t} \quad (t < 0.1\text{s}) \qquad K_e = 0.2 \quad (t \geq 0.1\text{s}) \qquad (14)$$

$$K_{ec} = \frac{1}{25t} \quad (t < 0.1\text{s}) \qquad K_{ec} = 0.4 \quad (t \geq 0.1\text{s}) \qquad (15)$$

where $t$ is the time.

By using the proposed control method, the resistance spot welding with different initial conditions are simulated. Two cases, namely cases A and B, are selected for the discussion. In case A, the initial welding current is 16 kA and the squeezing force is 3 kN. In case B, the initial welding current is 26 kA and the squeezing force is also 3 kN.

The results of the case A are shown in **Fig.9**. The time history of the nugget diameter and the contact diameter between the work pieces for cases without controlling the welding current, i.e. with the welding current is kept at

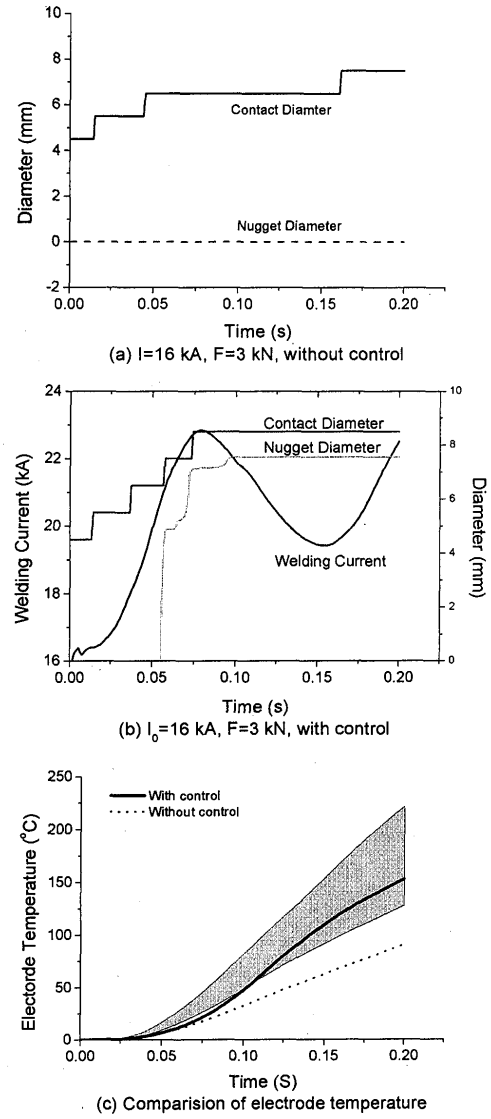


Fig.9 Fuzzy control results (Case A: $I_0$=16 kN).

16kA throughout the welding, and with control are shown in Figs.9 (a) and (b). When the welding current is not controlled, the welding current density is too small and the electrode temperature becomes lower than the target temperature range as shown in Fig. 9 (c). In this case, a nugget is not formed. On the other hand when the current is controlled, the electrode temperature is kept within the acceptable region which is shown as the shaded zone and the nugget with sufficient size is obtained. At the same time, the nugget size is kept smaller than the contact diameter so that the expulsion does not occur as shown in Fig. 9 b). In this case, the initial current is low and the electrode temperature is lower than the acceptable value at the beginning of the welding. To recover the electrode temperature, the current is increased according to the fuzzy control as shown in Fig. 9 b). The increase of the current is directly reflected to the growth of the nugget. The nugget

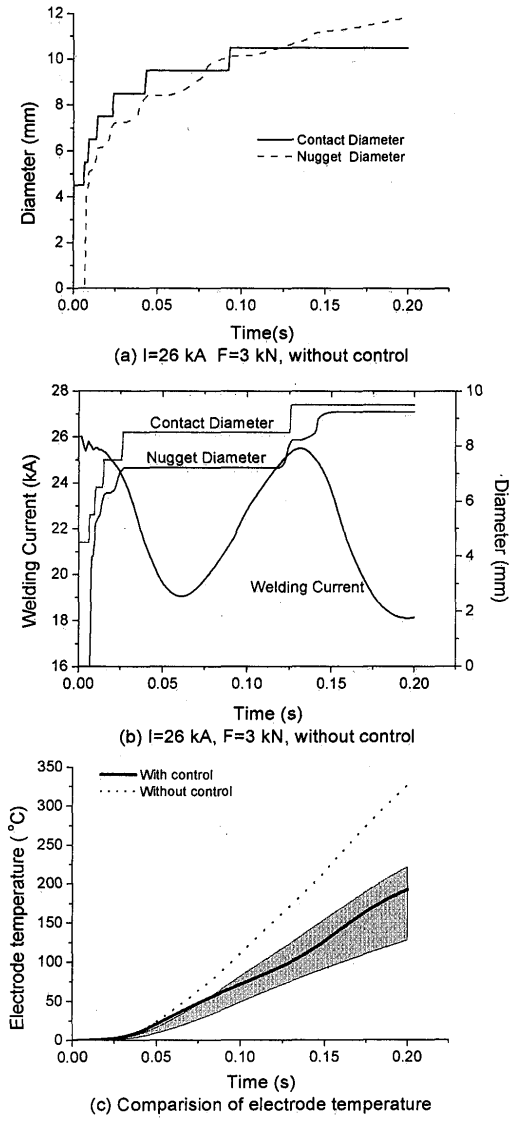


Fig.10 Fuzzy control results (Case B: $I_0$=26 kN).

growth is also controlled by the decrease of the current. Finally, a large enough nugget is formed without expulsion.

Similarly the results for the case B are shown in **Fig.10**. As opposed to the case A, the initial current is high in this case. When the current is kept at 26 kA without control, the nugget diameter exceeds contact diameter as shown in Fig.10 (a) and the expulsion is likely to occur. As seen from Fig.10 (c), the electrode temperature becomes higher than the acceptable temperature range in this case. On the other hand, when the welding current is controlled, the electrode temperature is maintained within the acceptable region and the nugget size is kept smaller than the contact diameter as shown in Fig.10 (b). Since the initial current is high, both the electrode temperature and the nugget

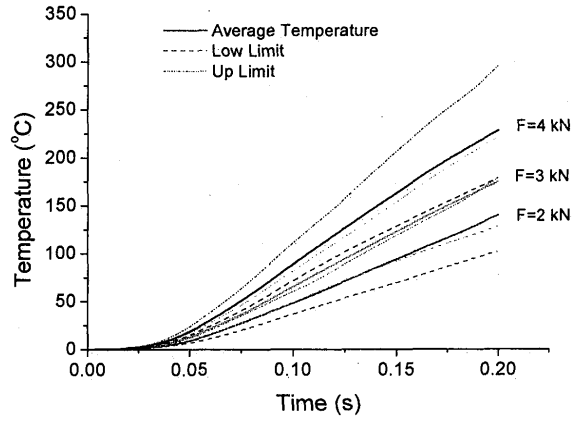


Fig.11 Influence of squeezing force on acceptable temperature zone.

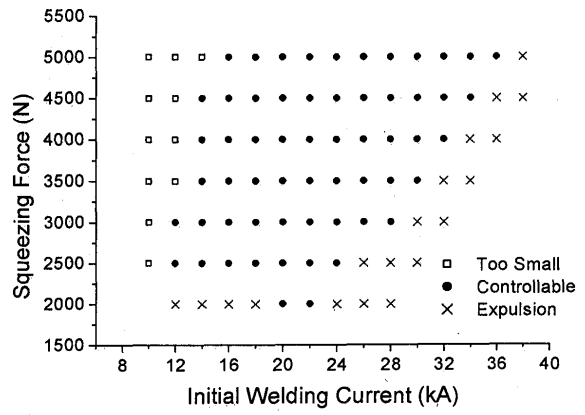


Fig.12 Controllable zone using one target temperature curve (F=3 kN).

diameter increase very quickly. The rapid nugget growth is detected from the electrode temperature exceeding the target region and the current is controlled as shown in Fig. 10 (b). Finally, a large enough nugget is formed without expulsion as in case A.

## 5. Discussion

In general, a target electrode temperature changes with the given squeezing force as shown in **Fig.11**. Thus, the curves of the target temperature for different values of squeezing force must be obtained as a database to introduce the proposed fuzzy control. At the same time it is noticed that the acceptable temperature ranges overlapped each other, although the target temperature curves themselves are different, and it may be possible to control the current by using a fixed target temperature curve. To examine this possibility, the target temperature curve for which the squeezing force $F$ is 3 kN is selected and the

weldable lobe is generated by changing the squeezing force and the initial current. As seen from the comparison between Fig.12 and Fig.2, the weldability lobe is expanded by introducing the fuzzy control even when the fixed target temperature curve is used.

Though it is found that the monitoring of electrode temperature is effective, the thermocouple for monitoring can be placed at a point with a certain distance from the electrode tip or the nugget in real situation. This introduces a time lag between the monitored temperature and the nugget formation. Because of this, a fairly large oscillation is observed in the welding current, which is controlled adaptively in real time.

## 6. Conclusion

A fuzzy theory is applied to control the process of nugget formation and its effectiveness is examined through numerical simulations using the thermo-elastic-plastic FEM. Through the present study, the following conclusions are drawn.

(1) The electrode temperature is one of the key parameters for an effective monitor of the spot welding process and a sound spot weld joint can be achieved by controlling the electric current based on the monitored electrode temperature.

(2) With the help of the fuzzy controlled method, the welding current can be controlled adaptively in real time, and the temperature can be controlled with in an acceptable range so that the nugget formation in the controlled.

(3) It is also demonstrated that the weldability lobe may be broadened by employing the fuzzy control.

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