FEM Simulation of Spot Welding Process (Report III) †

- Controlling of Welding Current Using Electrode Displacement for Formation of Large Enough Nugget without Expulsion -

Hidekazu MURAKAWA*, Jianxun ZHANG** and Hiroyuki MINAMI***

Abstract

In the case of press formed parts, the gap between lap joints is unavoidable. Normally, the variation in the size of the gap is fairly large. If the variation of the initial gap exceeds certain limits, it is difficult to make sound spot welding joints without expulsion. In this report, FEM analysis is employed to study the influence of the initial gap on weldability. The validity of the computed results is examined by comparison with experiments. Generally, the nugget grows faster and the expulsion occurs earlier when the initial gap is large. Through the serial computations in this study, close correlation between the electrode displacement and the nugget formation and the occurrence of expulsion is found. Using this correlation, a method to control the welding current based on the electrode displacement is proposed. Feasibility of the proposed method is demonstrated through a simple example

KEY WORDS: (spot welding) (nugget formation) (Expulsion) (Real time control) (Initial gap) (Electrode displacement) (FEM) (Cyber laboratory)

1. Introduction

The welding conditions for resistance spot welding are selected to produce sound nuggets without the expulsion. However, the parameters influential in the welding process, such as the welding current, thickness of the work and the wear of the electrode tip, always involve variations. If the weldability lobe is wide enough, relatively small variations in these parameters can be accepted within the tolerance. However, if the variations exceed certain limits, the sound welding cannot be achieved by the preset welding conditions. Dynamic or real time control based on the monitoring[1] can be an effective way of solving this problem. To design such control systems, the following questions need to be answered.

(1) How the variation of the parameter influences the phenomena?
(2) What kind of physical value should be monitored?
(3) How the welding process can be controlled?

To obtain an answer to the first question, for example, large numbers of experiments must be conducted. Also, it may be necessary to install a new measuring system for the development of innovative monitoring. If the development of the controlling system is carried out entirely based on the physical experiments, large investments and long time periods are required. On the other hand, the demand for the investment and time can be saved if the cyber laboratory, which costs almost nothing to built a new apparatus and can conduct thousands of experiments over a week or so, is employed.

In this report, a Finite Element Method (FEM)[2,3], which can be considered as an example of a cyber laboratory, is used to propose a controlling system and to examine its feasibility. The works welded in the automobile production lines consist of press formed parts. Normally, the variation of the gap between these parts is fairly large and it is difficult to ensure the required nugget size without expulsion. Thus, the effect of the initial gap on the weldability need to be clarified using FEM. Through the close examination of the computed results, strong correlations among the electrode displacement, nugget size and the occurrence of expulsion are found. Further, the idea of controlling the welding process based on the monitoring of the

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electrode displacement is proposed and its feasibility is demonstrated.

2. Spot Welding Specimen with Gap

The specimen to study the effect of the initial gap on the weldability is shown in **Fig.1**. The plate is the mild steel of 1.2 mm thickness. The geometry of the specimen is rectangular as shown in Fig. 1. The initial gap is made by the spacers. The welding conditions are presented in **Table 1**. The electrode is the dorm type as shown in **Fig. 2**. The squeezing force is 2 kN and the welding time is 12 cycles (0.2 sec). **Figure 3** shows the model for computation. Since the simulation code used for the analysis is the axisymmetric thermal-elastic-plastic FEM, the model is a circular model. The mesh division is shown in **Fig.4**. The mechanical and the physical properties of the plate are assumed to be temperature dependent as shown in **Fig.5**.

Table 1 Welding condition.

Power	Direct current
Plate	Mild steel (t=1.2mm)
Electrode type	Dome type electrode
Squeezing force	2 kN
Welding time	12 cycles (0.2sec)
Initial Gap	0mm and 2mm

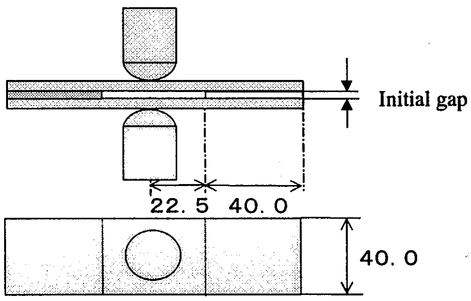


Fig.1 Spotwelding specimen with gap for experiment.

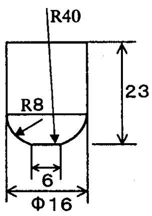


Fig.2 Dorm type electrode.

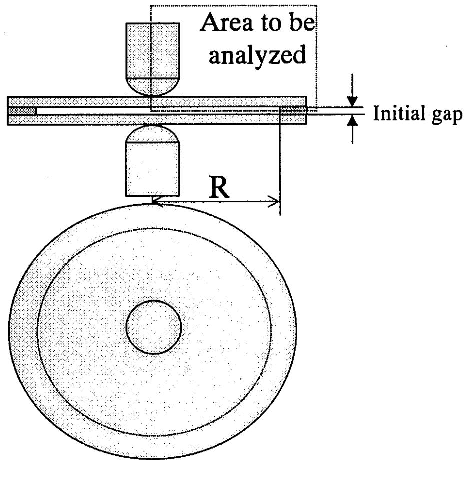


Fig.3 Model for FEM analysis.

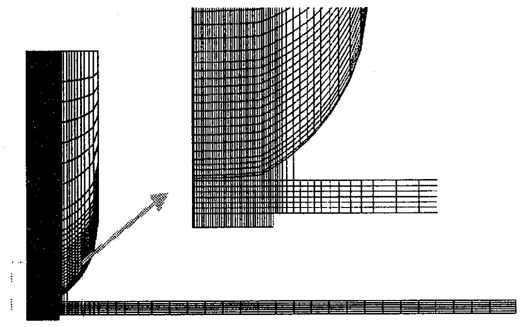


Fig.4 Mesh division for FEM analysis.

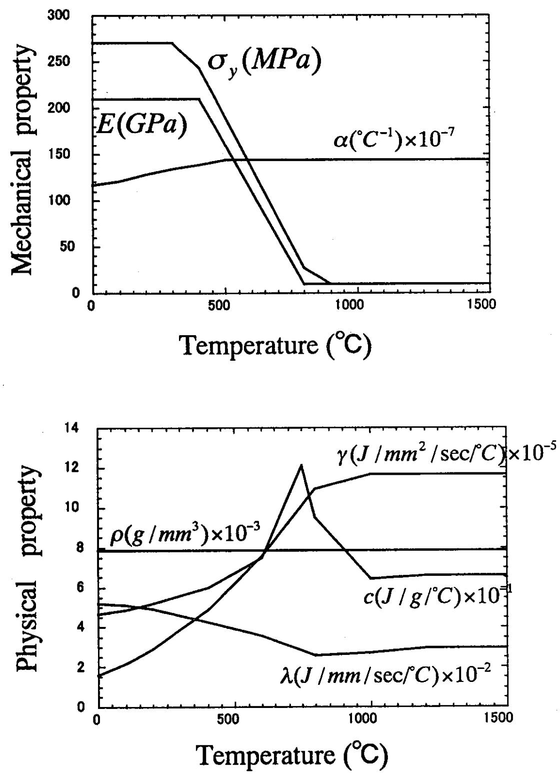


Fig.5 Mechanical and physical properties of mild steel.

3. Equivalent Circular Model

To compare experiment with the computation on the same bases, an equivalent circular model corresponding to the rectangular specimen is determined in the following manner. Since the deformation of the plate during the squeezing process must be the same between the equivalent models, the radius of the circular model is determined based on the load-displacement curve of the electrode. **Figure 6** shows the measured and the computed load-displacement curves. Among the computed curves for different values of radius R, that for R=75 mm is the closest to the experiment. Thus, R=75 mm is selected as the radius of the equivalent model.

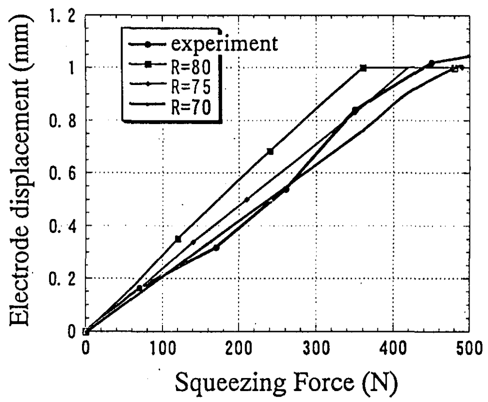


Fig.6 Electrode displacement-load curve compared between experiment and computation.

4. Definition of Expulsion in Computation

In the FEM analysis, the diameter of the nugget is defined as the width of the interface between the plates to be welded. The interface within the nugget must be in contact and the maximum temperature experienced must be higher than the melting point of the steel. The diameter of the contact area can be easily traced in the computation. Thus, the occurrence of expulsion in computation is defined as the moment when the diameter of the nugget exceeds that of the contact as shown by **Fig.7**.

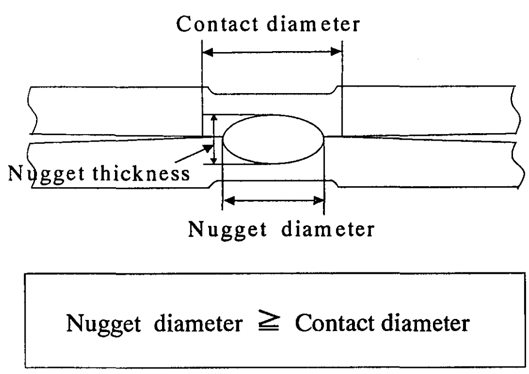
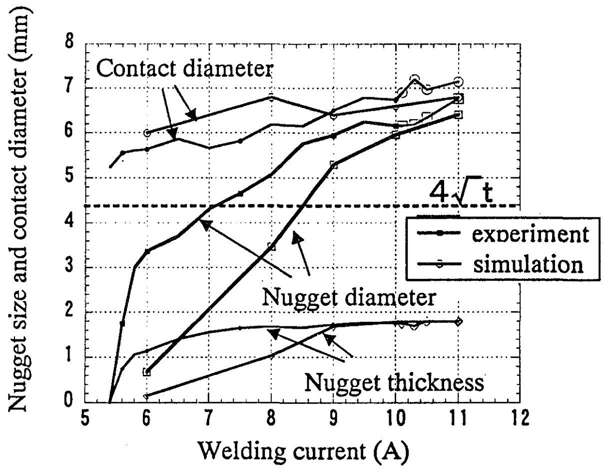


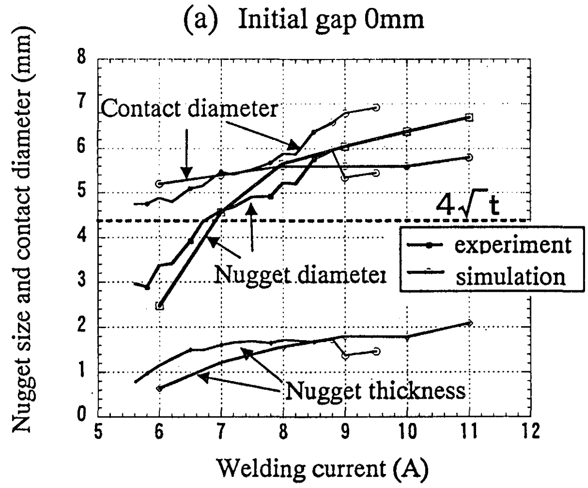
Fig.7 Definition of expulsion in computation.

5. Comparison with Experiment

The effect of the welding current on the diameter and the thickness of the nugget and the contact diameter after 12 cycles (0.2 sec) are compared between the computations and the experiments in **Figs.8(a)** and **(b)**. The results for the specimens without and with the initial gap are shown in the figures, respectively. The initial gap is 2 mm in the latter case with initial gap. As seen from these figures, very good correlation is observed in the case with initial gap, while significant difference is observed in the case without initial gap. The reason for this phenomenon is closely examined later. From the comparison between the nugget diameter and the contact diameter, it can be seen that expulsion does not occur within the range of the current between 5.5 and 11 kA in case of computations without initial gap. In cases with initial gap, the expulsion occurs when the current is larger than 8 kA. The same phenomenon is also observed in the experiments.



(a) Initial gap 0mm



(b) Initial gap 2mm

Fig.8 Nugget size and contact diameter compared between experiments and computations.

6. Difference between Experiment and Computation

To clarify the reason for the difference observed between the experiments and computations, the effect of the gap size on nugget formation is examined. As seen from **Fig.9(a)**, the influence of the gap size is not significant in the experiment. Similarly, the effect of the gap size is generally small in the case of computation except for the case without the initial gap shown in **Fig. 9(b)**. Though the case without a gap seems exceptional, the phenomenon is changing continuously with the gap size. Only the rate of change is very large when the gap is close to zero. Thus, the difference observed between the experiment and the computation is explained by the fact that perfectly flat surfaces are not possible in experiments. A possible secondary explanation is that the surface resistance of the specimen is not considered in the present computation. Though the effect of the surface resistance is small in general, its influence becomes significant in the case without initial gap which involves the delicate contact problem.

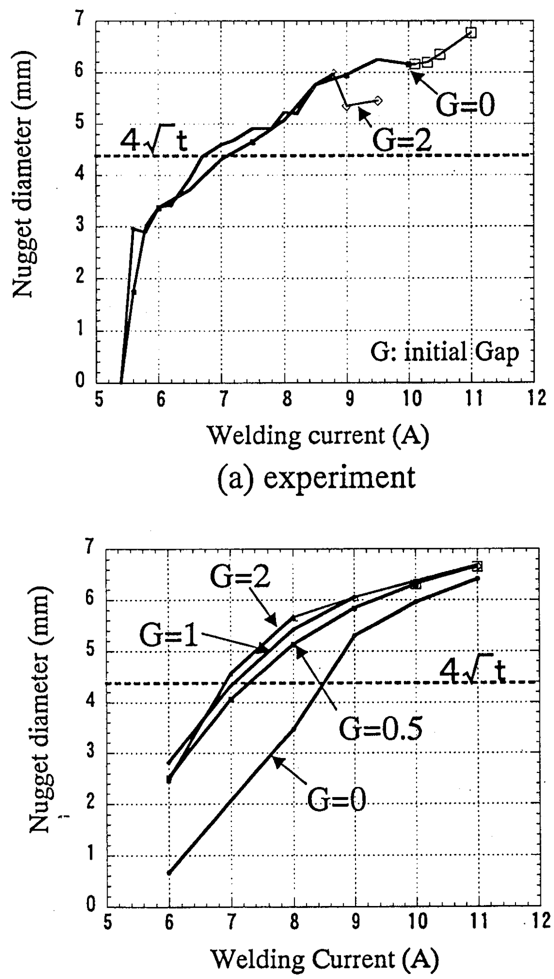


Fig.9 Effect of initial gap on nugget formation.

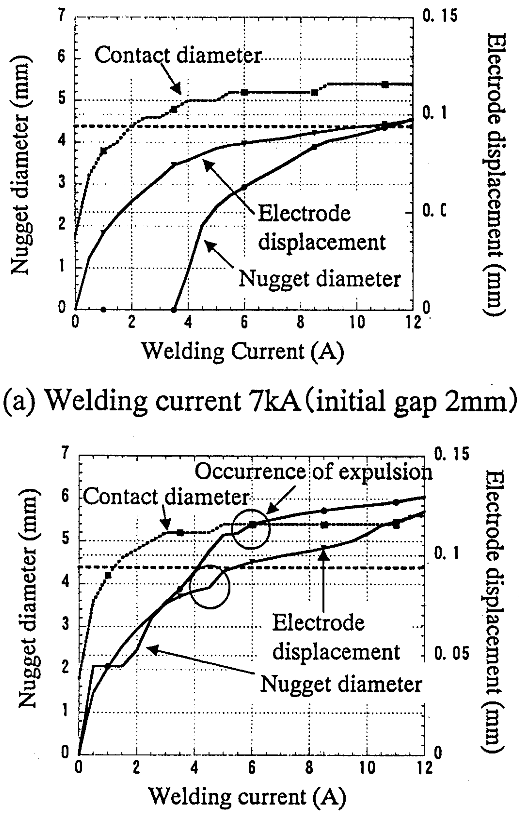
7. Relation between Expulsion and Electrode Displacement

Unlike the laboratory test, the welding process in an industrial production line involves various variations such as the initial gap. Thus, to prevent the expulsion, a method which can be used under possible variations must be developed. Generally, controls based on the monitoring in process can be applied. The control must be able to ensure the formation of a nugget with sufficient diameter and to prevent the expulsion at the same time. However, the physical values which can be monitored during the process are limited. Through the serial computations conducted in this study, electrode displacement is found to be the best parameter to reflect the formation of the nugget and the occurrence of expulsion.

Figures 10(a) and **(b)** show the time history of the nugget diameter, contact diameter and the electrode displacement for cases with welding currents of 7 kA and 9 kA, respectively. The initial gap is 2 mm in these cases. The nugget with a sufficiently large diameter over $4\sqrt{t}$ is formed within 12 cycles without expulsion when the current is 7 kA. When the current is increased to 9 kA, expulsion occurs or the nugget diameter exceeds the contact diameter at about 6 cycles. It is also noticed that the rate of change of the electrode displacement suddenly increases just before the moment of expulsion defined on the basis of size of nugget diameter relative to the contact diameter.

Unlike the contact diameter and the nugget size, the electrode displacement can be measured in the process if the conditions such as the stiffness of the welding system are satisfied. Thus the relation between the electrode displacement and the nugget formation and the occurrence of expulsion is summarized in **Figs.11(a)-(c)**. In these figures, the nugget diameter is plotted against the electrode displacement for different values of welding current. The curves, after the occurrence of the expulsion, are indicated by dashed lines. As is seen from the figures, nugget diameter-electrode displacement curves in the final stage of welding almost coincide with each other regardless of the value of the welding current. Also, the occurrence of the expulsion is clearly observed from the curves.

The horizontal dashed line shows the nugget diameter of $4\sqrt{t}$. The electrode displacement at which the required nugget size is achieved and the expulsion is prevented is indicated as δ_c in the figures. Comparing the figures for different initial gap, it is seen that the value of δ_c changes with the initial gap. As summarized in **Fig.12**, δ_c decreases slowly with an increase of the initial gap.



(a) Welding current 7kA (initial gap 2mm)

(b) Welding current 9kA (initial gap 2mm)

Fig.10 Relation between electrode displacement and occurrence of expulsion.

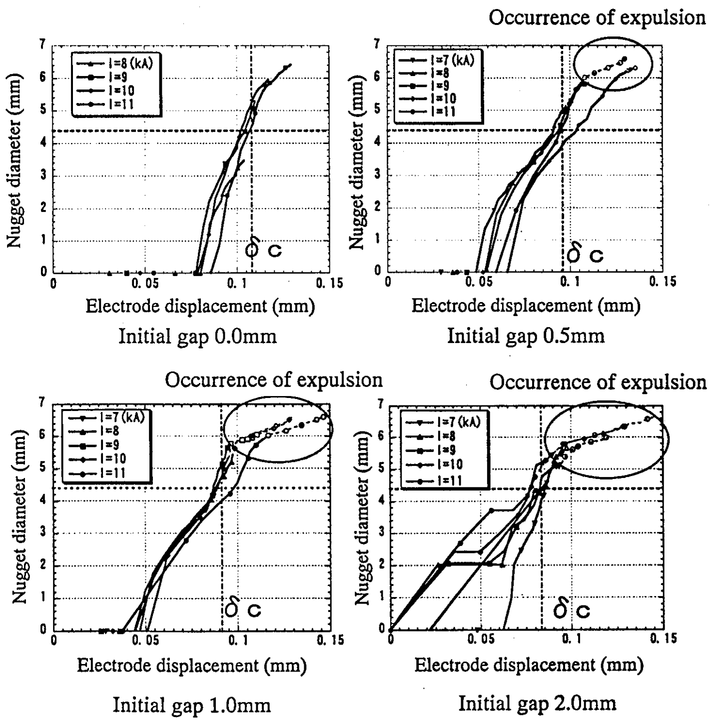


Fig.11 Correlation among electrode displacement, nugget formation and expulsion.

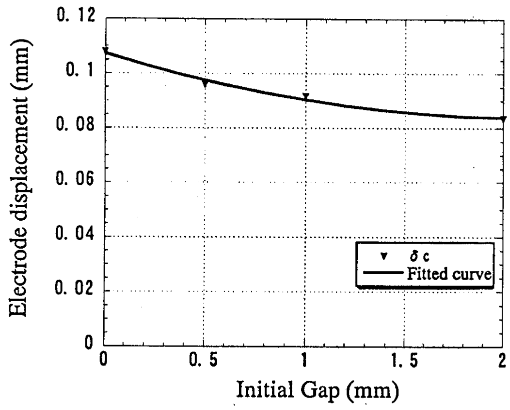


Fig.12 Relation between initial gap and critical electrode displacement.

8. Controlling Welding Current Using Electrode Displacement

It is relatively easy to generate the curve relating initial gap and δ_c through serial experiments or FEM simulations. Though the initial gap changes from one spot welding joint to another, it can be estimated from the relation between the electrode displacement and force. Knowing the initial gap and the δ_c –initial gap curve, it is possible to control the welding process. **Figure 13** shows a very simple example for controlling the welding current. Since the phenomenon is almost independent for the welding current, the current can be reduced after the electrode displacement reaches δ_c. In this example, the welding current is reduced to 6.5 kA.

The simulated results without and with control are presented in **Figs.14(a)** and **(b)**. Welding of the specimen with different initial gaps is examined. As observed in Fig. 14(a), the expulsion occurs in the specimen with an initial gap of 2 mm when no control is applied. When the current is controlled according to the diagram in Fig. 13, the expulsion is prevented as shown in Fig. 14(b).

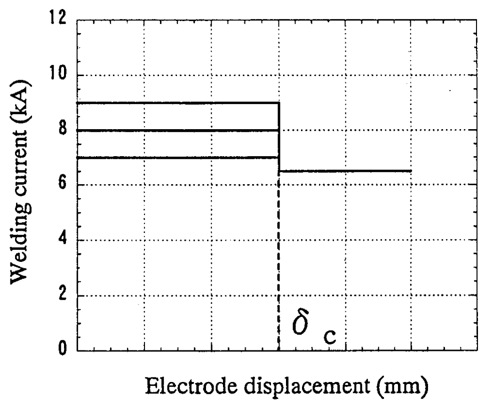
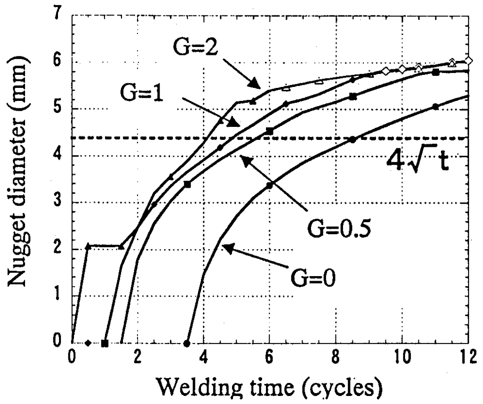
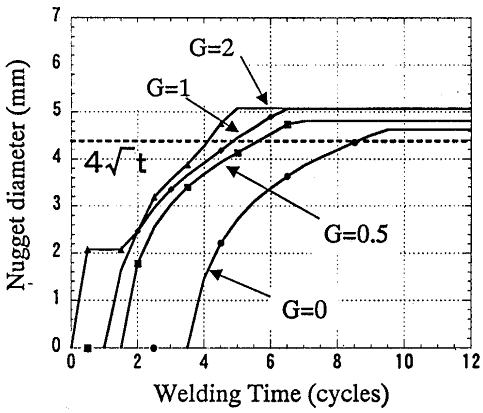


Fig.13 Control of welding current using electrode displacement.



(a) Without control (9kA)



(b) With control (9kA)

Fig.14 Effectiveness of welding current control using electrode displacement.

9. Conclusions

FEM is applied to clarify the influence of the initial gap on the formation of the nugget and the occurrence of the expulsion. Based on serial computations, a method to control the welding current using the electrode displacement as the input signal is proposed. The conclusions drawn from the present study are summarized in the following.

(1) The radius of the circular model for FEM analysis equivalent to the rectangular specimen for the experiment is determined based on the electrode displacement-load curve.

(2) The effect of the initial gap on the formation of the nugget and the occurrence of expulsion is relatively small, except for the case with an extremely small gap. The influence of the initial gap observed in experiment generally agrees with the analysis. Generally, the nugget grows faster and the expulsion occurs earlier when the initial gap is large.

(3) The formation of the nugget and the occurrence of the expulsion are closely related to the electrode displacement. The relationship among the electrode displacement, the nugget size and the occurrence of expulsion is influenced by the size of the initial gap. But the effect of the welding current is small.

(4) The welding current can be controlled using the critical electrode displacement δ_c as a threshold. The critical electrode displacement decreases with the initial gap size.

(5) In the present report, a specimen with only one geometry under given squeezing force is studied. To derive a general conclusion, further study on the effects of the size of the specimen and the squeezing force is necessary.

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