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Mechanical Study on the Effect of Initial Gap upon the Weldability of Spot Weld Joint†

— Prediction of Contact Area in Squeezing Process —

Hidekazu MURAKAWA* and Yukio UEDA**

Abstract

It has been reported that the weldability of the spot weld joint with initial gap is strongly influenced by the contact between the members to be welded. The state of contact during the welding largely depends on the deformation in the squeezing process. On the other hand, the characteristics of the deformation change with the geometry of the joint and the material property. Thus, the authors analyzed the deformation under squeezing process by the Finite Element Method to clarify the effects of geometry and material properties. Based on the numerical analyses, it is shown that a mechanical similarity rule holds for the contact behavior during the squeezing process. Further, a general and yet relatively simple procedure is proposed to predict an allowable size of the initial gap to get sound welds.

KEY WORDS : (Spot Welding) (Initial Gap) (Press Formed Member) (Squeezing Process) (Contact Force) (Contact Area) (Finite Element Method) (Allowable Initial Gap)

1. Introduction

To reduce the body weight with maintaining required strength, high tensile strength steel is widely employed in automobiles. However, the press formability of the high tensile strength steel is relatively poor compared to that of the conventional mild steel and it causes large initial gap between press formed members to be welded. The increase of the initial gap in spot weld joint reduces the spot weldability. It has been reported that the effect of the initial gap on the nugget formation is strongly governed by the contact state between the plates^{1,2)}.

The process of the spot welding can be divided into the following five stages.

- (1) from the beginning of the squeezing to the initial contact between plates (workpieces).
- (2) process in which the contact area between workpieces increases due to the additional application of the squeezing force.
- (3) heating and melting process by the electric current with holding the squeezing force.
- (4) cooling process with holding the squeezing force.
- (5) releasing squeezing force

The stage which is directly related to the nugget formation and the most important is the third stage. However, stages which determine the initial state and the constraining condition at the third stage are the first and second stages. Therefore, to analyze the phenomena in

the heating and melting process, it is necessary to clarify those in the squeezing process.

If the initial gap exists between the members to be welded, the relation between the electrode force and the electrode displacement during the squeezing process can be schematically shown as in Fig. 1. The point A corresponds to the first contact between workpieces. The curve O-A represents the first stage in the spot welding process. The curve A-B corresponds to the second stage in which the contact area increases with the squeezing force. If it is assumed that sufficient size of contact area is obtained at point B, the required squeezing force can be

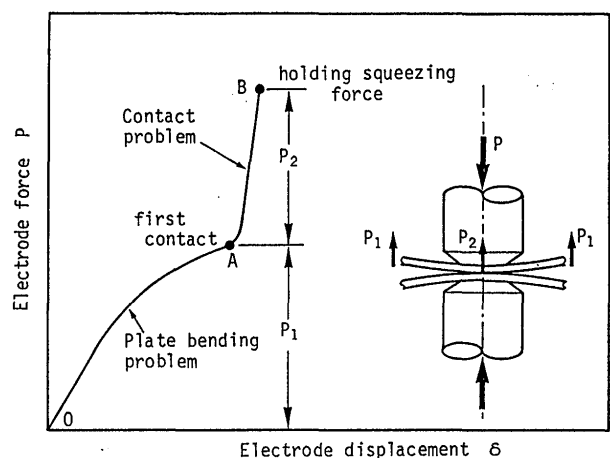


Fig. 1 Deformation in squeezing process.

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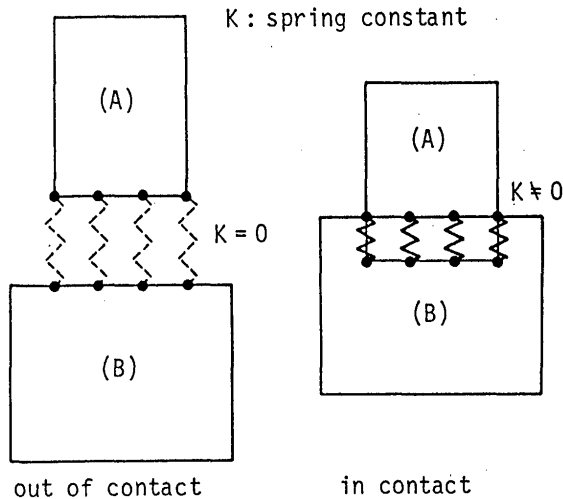


Fig. 2 Spring element between nodes on contact surface.

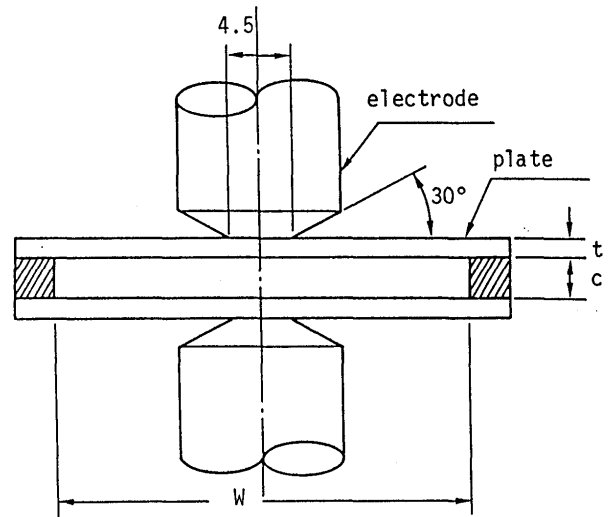


Fig. 3 Circular joint model with initial gap.

divided into two parts, namely P_1 and P_2 . The first part denoted by P_1 is the squeezing force required to close the initial gap. The second part P_2 is the additional force necessary to obtain sufficient contact area. Therefore, to predict how much squeezing force is required to get sufficient contact, it is necessary to know both P_1 and P_2 . The squeezing force P_1 can be predicted from a nondimensionalized general curve which has been proposed by the authors³. In this report, the second part of the squeezing process is closely examined to establish a general procedure to predict P_2 . The second stage in the squeezing process involves the contact problem in addition to large elastic-plastic deformations. To count the precise local deformation and the contact state near the electrode, axisymmetric 2-dimensional Finite Element Method is employed in this study.

2. Finite Element Model

2.1 Theory

To analyze the squeezing deformation in the second stage, elastic-plastic large deformations and the contact between the workpieces and electrode-workpiece must be considered. The elastic-plastic behavior is represented by the incremental plastic theory based on the J_2 flow rule in the Finite Element Method used in this study.

The joint model considered is an ideal circular joint and the problem is treated as an axisymmetric 2-dimensional elastic-plastic large deformation problem. Hence, the strain-displacement relation considering the large deformation is given by the following equations.

$$\begin{aligned} \epsilon_r &= u_{r,r} + \frac{1}{2}\{(u_{r,r})^2 + (u_{z,r})^2\} \\ \epsilon_{rz} &= \epsilon_{zr} = \frac{1}{2}(u_{z,r} + u_{r,z}) + \frac{1}{2}(u_{r,r}u_{r,z} + u_{z,r}u_{z,z}) \end{aligned}$$

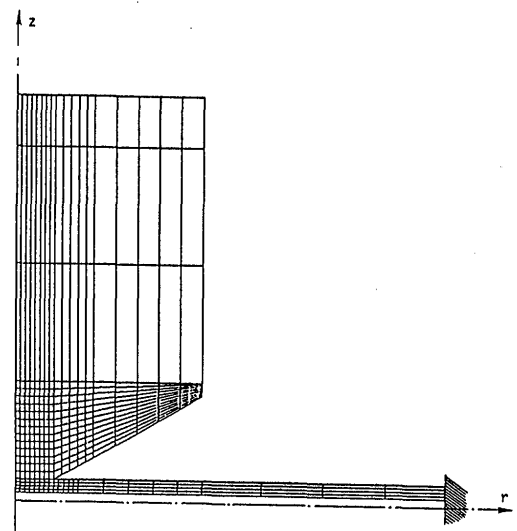


Fig. 4 Finite element mesh division.

$$\begin{aligned} \epsilon_z &= u_{z,z} + \frac{1}{2}\{(u_{r,z})^2 + (u_{z,z})^2\} \\ \epsilon_\theta &= (1/r)u_r + \frac{1}{2}(1/r^4)u_r^2 \end{aligned} \tag{1}$$

Where, terms with underline represent the effect of the large deformation.

The contact state changes with the applied squeezing force. To consider the change in contact state, spring elements are introduced between nodes which may contact each other as shown in Fig. 2. When the nodes are separated, the stiffness of the spring K is assumed to be zero. If the nodes are in contact, the stiffness of the spring is set to be very large to tie these nodes in contact.

2.2 Joint Model

The joint model considered is a circular joint shown in Fig. 3. The joint has the initial gap and its size is denoted by c . Considering the symmetry, upper half of the joint is

analyzed as an axisymmetric problem using the mesh division shown in Fig. 4.

To clarify the effects of initial gap c , yield stress σ_Y of the material, plate thickness t and joint diameter W , six models as shown in Table 1 are considered. Series computations with changing the magnitude of the initial gap from 0.02 mm to 2.0 mm are done for the above six models.

The electrode is assumed to have a flat tip with diameter $D = 4.5$ mm. Young's modulus and the yield stress of the electrode are assumed to be $E = 12000$ kgf/mm² (118 GPa) and $\sigma_Y = 25$ kgf/mm² (245 MPa), respectively. The materials for both workpiece and electrode are assumed to show no strain hardening.

3. Computed Results and Discussions

3.1 Effect of Initial Gap

When the initial gap exists, the squeezing process can be divided into two stages, namely the process before the first contact and that after the first contact. The former can be treated as a simple plate bending problem of weld

joint composed of plates. Whereas in the latter case, the contact state changes with the squeezing force and it has to be treated as a contact problem.

The state of contact between workpieces shows strong effects upon the nugget formation. The final contact state at the end of the squeezing process is determined through the squeezing process after the initial contact. However, the process after the initial contact is strongly affected by the first part of the squeezing process before the first contact. In other words, it changes with the size of the initial gap c . To clarify the effect of the initial gap c , the relation between the initial gap and the contact state are closely examined by comparing the results for different values of c .

The relations between the electrode force and the displacement at the center of the palte for various values of the initial gap are shown in Fig. 5. The results for the model(1), in which $\sigma_Y = 40$ kgf/mm² (392MPa), $t = 0.8$ mm, $W = 50$ mm, are shown as examples. When the initial gap exists, the electrode force-displacement relations before the first contact follow the same curve regardless of the size of the initial gap. However, those for the deformation after the first contact change with the initial gap and the electrode force increases rapidly with the electrode displacement.

To closely examine the phenomena after the first contact, the relations between the contact force P_2 and the contact area A are shown for the same cases in Fig. 6. It is observed that the contact area increases very rapidly and it reaches the saturated value when the initial gap is small. The saturated contact area for cases in which $c = 0.02$ mm and $c = 0.2$ mm is larger than A_0 shown on the vertical axis. The area A_0 represents the area of the flat tip of the electrode. On the other hand, when the initial gap is large, the contact area increases slowly and the saturated contact area becomes smaller than A_0 . Further,

Table 1 List of Joint Models

Model	Thickness t	Diameter W	Yield stress σ_Y	Young's Modulus E	Parameter μ
(1)	0.8 mm	50 mm	40 kgf/mm ² (392 MPa)	21000 kgf/mm ² (206 GPa)	7.44
(2)	0.8 mm	50 mm	20 kgf/mm ² (196 MPa)	21000 kgf/mm ² (206 GPa)	3.72
(3)	0.8 mm	50 mm	60 kgf/mm ² (588 MPa)	21000 kgf/mm ² (206 GPa)	11.16
(4)	0.8 mm	35 mm	40 kgf/mm ² (392 MPa)	21000 kgf/mm ² (206 GPa)	3.65
(5)	0.8 mm	25 mm	40 kgf/mm ² (392 MPa)	21000 kgf/mm ² (206 GPa)	1.86
(6)	1.25 mm	50 mm	24 kgf/mm ² (235 MPa)	21000 kgf/mm ² (206 GPa)	1.83

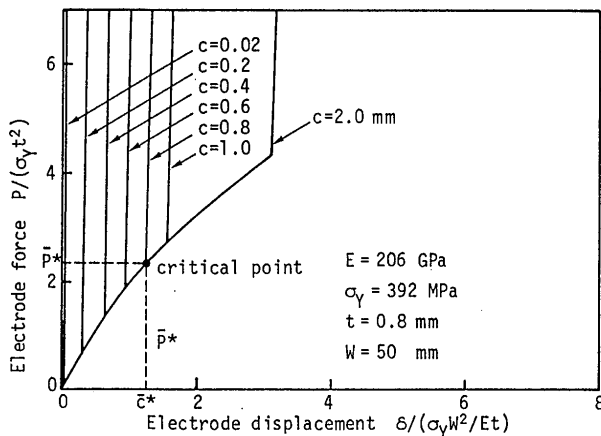


Fig. 5 Electrode force-displacement curves for different values of initial gap.

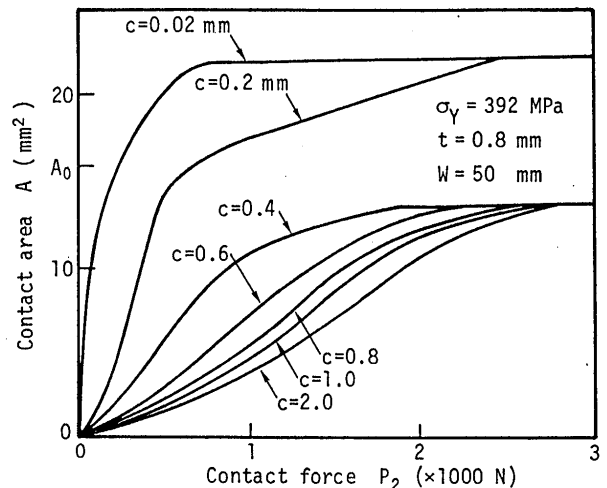


Fig. 6 Contact force-contact area curves ($\sigma_Y = 392$ MPa).

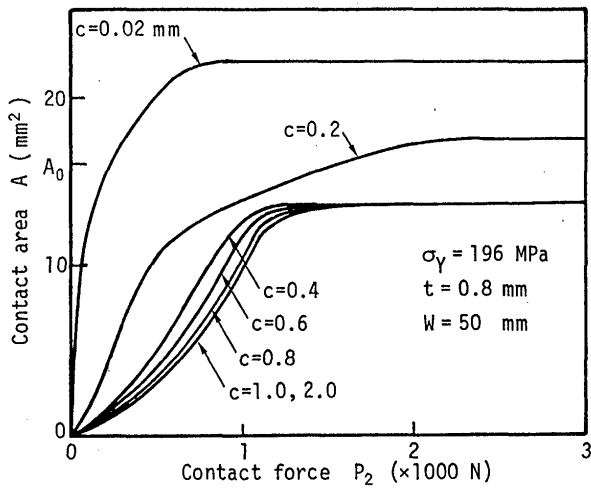


Fig. 7 Contact force-contact area curves ($\sigma_Y = 196$ MPa).

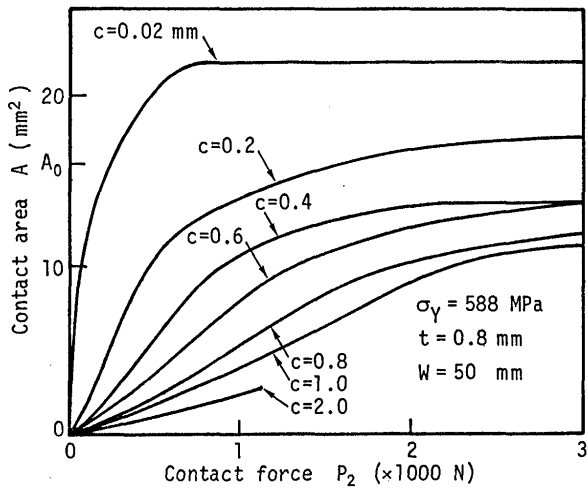


Fig. 8 Contact force-contact area curves ($\sigma_Y = 588$ MPa).

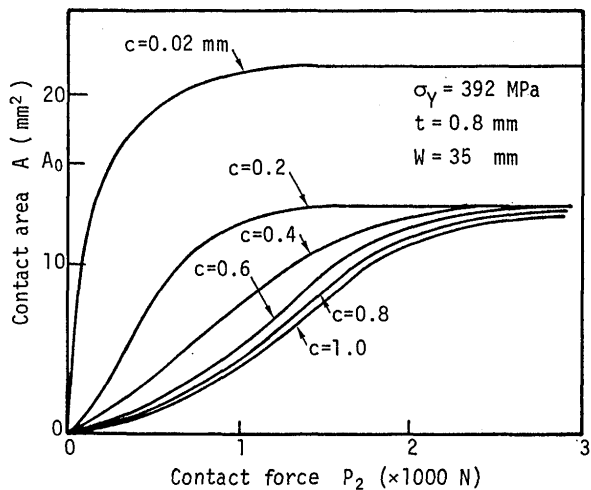


Fig. 9 Contact force-contact area curves ($W = 35$ mm).

if the initial gap exceeds a certain limit, the contact force-area curves tend to fall on the same curve. This phenomena can be observed also for the rest of five models as shown in Figs. 7-11.

For convenience, the saturated contact force-area curve for large initial gap is referred to as critical curve. Also, the minimum value of the initial gap for which the contact force-area curve can be approximated by the critical curve is called as critical initial gap c^* . Further, as shown in Fig. 5, the point and the squeezing force at the initial contact corresponding to the critical initial gap is designated as critical point and critical squeezing force P^* , respectively. When these values are nondimensionalized, they are denoted by \bar{c}^* and \bar{P}^* .

It is summarized from the above results that the relation between the contact force and the contact area can be approximated by a critical curve regardless of the

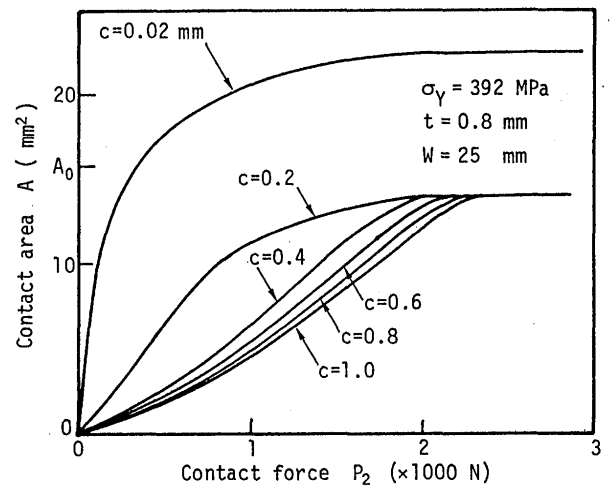


Fig. 10 Contact force-contact area curves ($W = 25$ mm).

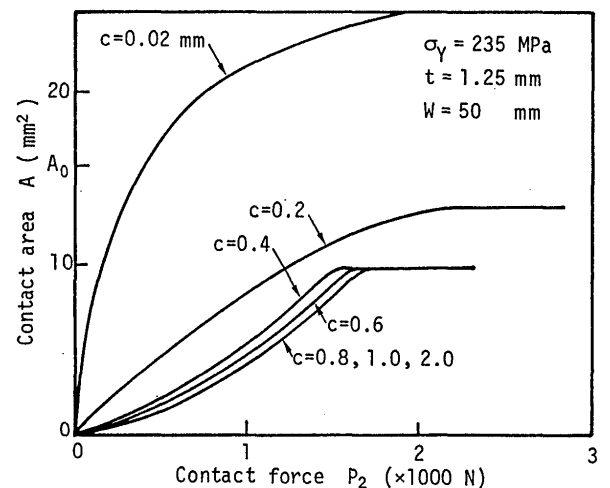


Fig. 11 Contact force-contact area curves ($t = 1.25$ mm).

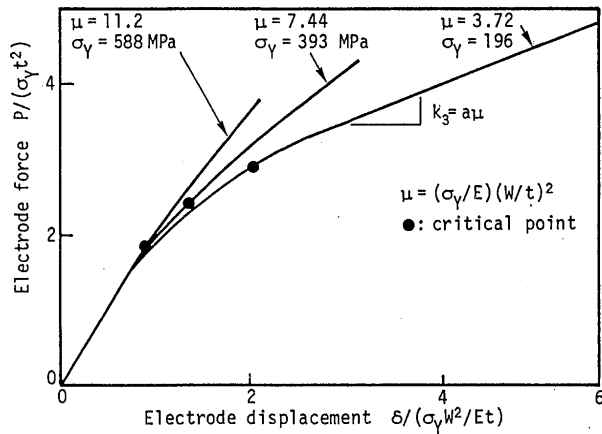


Fig. 12 Effect of yield stress on squeezing deformation before the first contact.

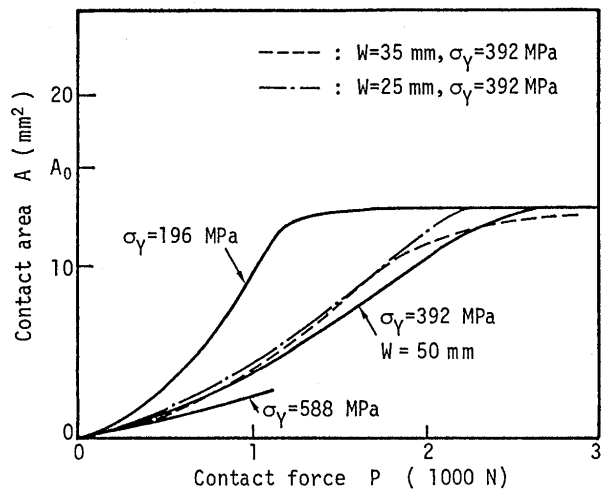


Fig. 13 Comparison of contact force-area curves for various joint models at critical state.

size of the initial gap when the gap is greater than the critical initial gap. Noting this, the effects of the yield stress, the diameter and the thickness of the joint model are clarified through close examination of the critical curves.

3.2 Effect of yield stress

The effect of the yield stress is examined for both before and after the first contact. The characteristics in the former stage, which can be treated as a plate bending problem, are determined by yield stress σ_Y , Young's modulus E , diameter W and plate thickness t of the joint model. In Fig. 12, the electrode force-displacement curves before the first contact are compared among the cases in which the dimensions are same ($t = 0.8$ mm, $W = 50$ mm) and the yield stresses are different ($\sigma_Y = 196, 392, 588$ MPa). The curves shown in the figure are computed for large initial gap and the critical point are shown by solid circles. Since the curves are nondimensionalized

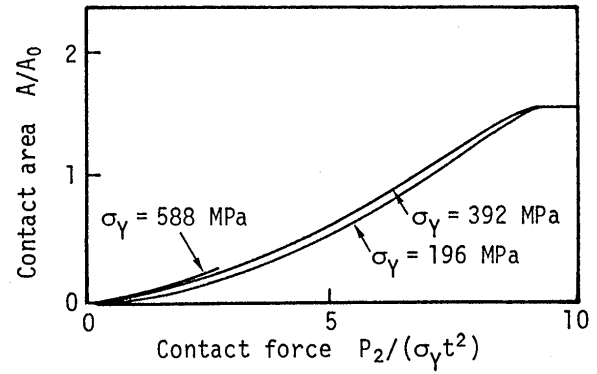


Fig. 14 Comparison of contact force-area curves for models with different yield stresses in nondimensional form.

according to the mechanical similarity rules³⁾, all force-displacement curves coincide each other when the displacement is small. When the displacement is large and the effect of the large deformation is significant, the force-displacement curve almost becomes a straight line. As it has been discussed by the authors³⁾, the slope of the straight part of the curve represents the degree of the effect of large deformation and it is proportional to a parameter μ which is defined as

$$\mu = (\sigma_Y / E)(W/t)^2 \quad (2)$$

For the same three models, the critical curves which describe the behavior after the first contact are plotted by three solid lines in Fig. 13. The critical curves shown in the figure are the contact force-area curves computed for the cases with the largest gap $c = 2.0$ mm, which is greater than the critical initial gap. As seen from the figure, larger force is required to get the same contact area when the yield stress is large.

In general, physical values which determine the behavior after the first contact are the yield stress σ_Y , Young's modulus E , diameter W and plate thickness t of the joint model. In addition to these, the diameter of the electrode tip D is also an important parameter which influences the behavior. Thus, the contact area and the contact force are nondimensionalized by the following equation.

$$\begin{aligned} \bar{A} &= A/A_0 \\ \bar{P}_2 &= P_2 / (\sigma_Y t^2) \end{aligned} \quad (3)$$

where

$$\bar{A}_0 = (\pi/4)D^2$$

Following the above equations, Fig. 13 is nondimensionalized to get Fig. 14. Since the three curves almost coincide with each other, it is seen that a similarity rule holds among cases with different yield stresses.

3.3 Effect of joint diameter

The same comparison is made among cases with different diameters ($W = 50, 35, 25$ mm). The yield stress and plate thickness are kept same and they are assumed to be $\sigma_Y = 392$ MPa and $t = 0.8$ mm. The nondimensional electrode force-displacement curves before the first contact are shown in Fig. 15. Due to the fact that the relative sizes of the electrode diameter D compared to that of the joint W are different, small variation is observed even in the small deformation range. In general, this variation is expected to decrease when D/W becomes small. On the other hand, the critical curves for the process after the first contact are shown in Fig. 16. Since the three lines show close agreement, it can be seen that the same similarity rule holds for the change in the joint diameter as that for the yield stress if the electrode diameter D , the plate thickness t and the yield stress σ_Y are same. However, this similarity is expected to hold when the D/W is small and some effect may appear when D/W is large.

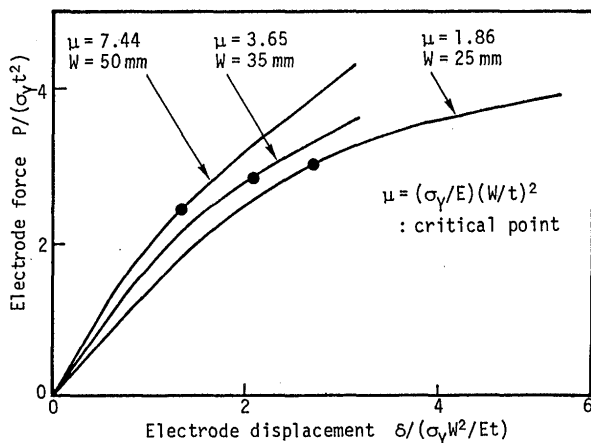


Fig. 15 Effect of diameter of the joint on squeezing deformation before the first contact.

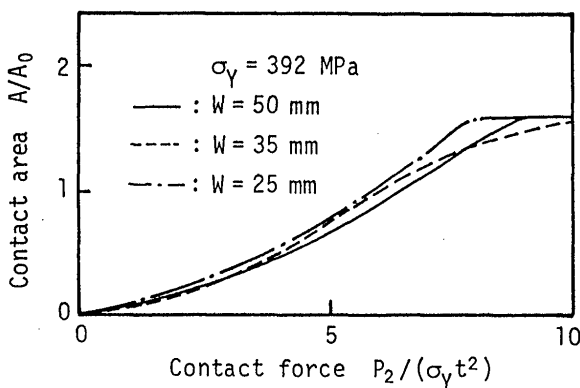


Fig. 16 Comparison of contact force-area curves for models with different diameters in nondimensional form.

3.4 Effect of plate thickness

It has been shown that the similarity rule in the behavior after the first contact holds for changes in yield stress and joint diameter if the electrode diameter D is same. The effect of the plate thickness is examined in the same manner. For this purpose, the contact force-area curves for different plate thicknesses ($t = 0.8$ and 1.25 mm) with same yield stress, electrode diameter and joint diameter ($\sigma_Y = 392$ MPa, $D = 4.5$ mm, $W = 50$ mm) are compared in Fig. 17. As it is seen from the figure, clear difference is observed between two curves. Thus, the similarity rule does not hold for the change in t/D . In other words, the characteristics of the deformation after the first contact changes with t/D .

3.5 Estimation of critical gap and critical squeezing force

The effects of initial gap, yield stress, joint diameter

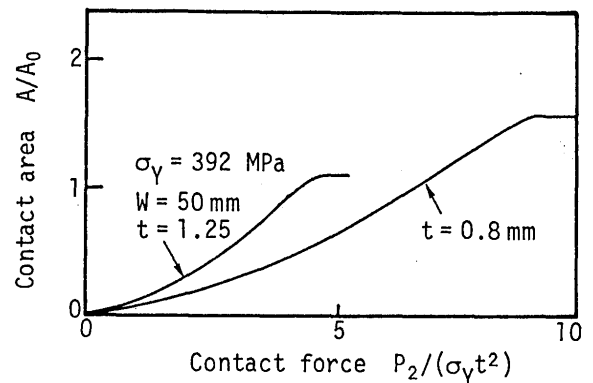


Fig. 17 Comparison of contact force-area curves for models with different plate thicknesses in nondimensional form.

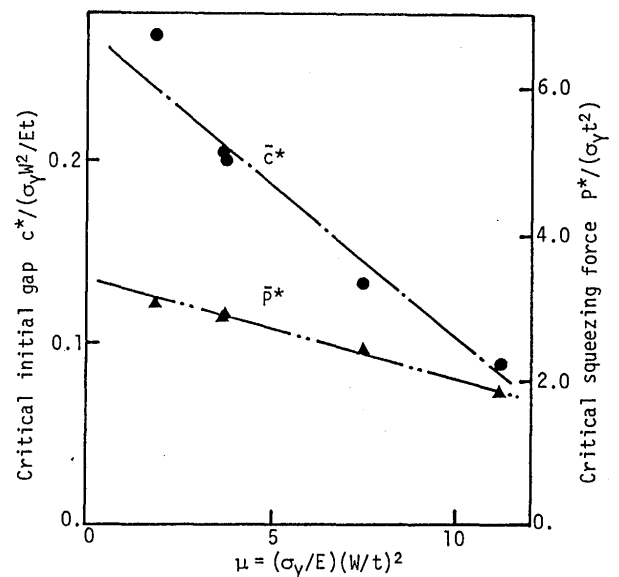


Fig. 18 Prediction of critical initial gap and critical squeezing force through μ .

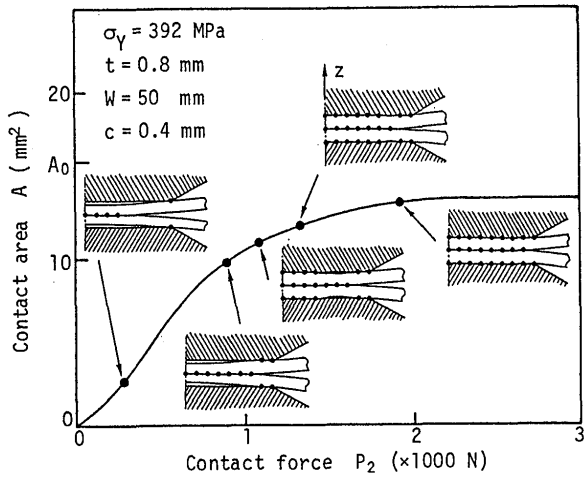


Fig. 19 Change of contact state in squeezing process ($c = 0.4$ mm).

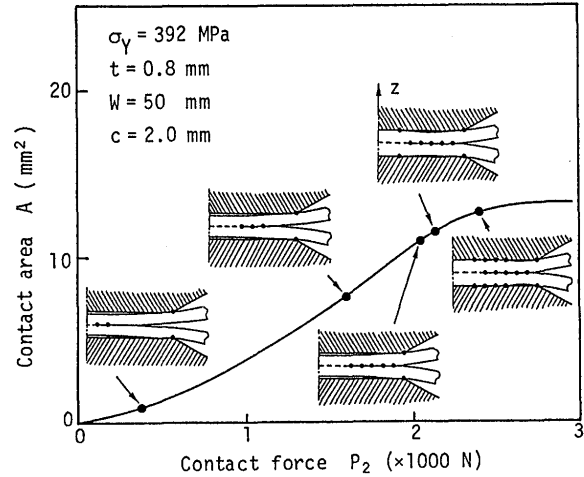


Fig. 20 Change of contact state in squeezing process ($c = 2.0$ mm).

and plate thickness upon the contact state in the squeezing process are clarified by examining the critical curves. It has been shown that the similarity rule holds if t/D is same and the squeezing behavior can be characterized in a unified manner for joints with different yield strength and dimensions. However, the critical gap c^* , giving the minimum gap size for which the contact force-area curve can be approximated by the critical curve, changes with yield stress and joint diameter as shown in Figs. 12 and 15. Therefore, to predict the entire squeezing process including before the first contact, the critical initial gap must be known.

Since the critical initial gap depends on the bending deformation before the first contact, the relation between the critical initial gap and the parameter $\mu = (\sigma_Y/E)(W/t)^2$ is examined. The nondimensionalized values of the critical initial gap and the critical squeezing force are plotted against μ in Fig. 18. Although it is difficult to discuss in rigorous manner, the relations can be approximated by straight lines within the range of the parameter considered in Fig. 18. Once the approximate lines are drawn, the critical initial gap and the critical squeezing force can be predicted for given joint with arbitrary yield stress and dimensions. The procedure is as follows.

- (1) calculate the parameter μ using given yield stress and dimensions
- (2) read the values c^* and P^* from Fig. 18

Although, only ideal circular joint is discussed here, the predicted values may be applied to any form of joint such as joint with channel shape by introducing the concept of equivalent joint diameter. To get an answer for the question how to define the equivalent joint diameter, further study is necessary.

3.6 Classification of contact state

In the preceding sections, only the contact area is discussed. The pattern of contact also changes with the increase of squeezing force and other factors. The difference in contact patterns when the initial gap is different is examined in this section. Figures 19 and 20 show the change of contact state together with the contact force-area curves. Two cases in which the initial gap is small ($c = 0.4$ mm) and the initial gap is large ($c = 2.0$ mm) are compared for the model(1) as an example. The nodes in contact are shown by solid circles.

When the initial gap is small, contact between the workpieces starts from the center and extends outward in monotonous manner. Whereas if the initial gap is large, the region in contact is extending from the center in the beginning. With the increase of contact force, the contact at the center is lost and the contact pattern becomes ring shape. The former type circular contact is considered to be ideal and the ring shape as in the latter case is not desirable to get sound nuggets because the path of electric current becomes relatively narrow. Therefore to eliminate such contact in ring shape, it is necessary either to reduce the initial gap or to apply large squeezing force to suppress the gap at the center.

Only the electrode with flat tip is discussed in this study. In general, the contact states between workpieces largely depend on the electrode shape, t/D and other factors. Effect of these must be also clarified in the future work.

4. Prediction of Allowable Initial Gap

Based on the knowledge obtained in the preceding chapter, a general procedure to determine an allowable

maximum initial gap to obtain sound welds is proposed in this chapter.

4.1 Definition of problem

given conditions

- (1) The thickness of the plate composing the joint is fixed. The yield stress σ_Y and joint diameter W may change.
- (2) The size of the electrode tip diameter D is fixed.
- (3) The maximum squeezing force of the welding machine P_{max} is given and fixed.
- (4) The minimum contact area between the workpieces to get sound welds A_{min} is given.

objective: determine the maximum allowable initial gap for which the contact area greater than the required contact area A_{min} is obtained under the maximum squeezing force.

4.2 Curves to be prepared

- (1) nondimensionalized critical curve (Fig. 21)

In the first step, select two sets of combination of σ_Y and W (σ_{Ya}, W_a), (σ_{Yb}, W_b) which give the minimum and the maximum values of the parameter μ among the possible combinations. Perform serial computation by F.E.M. for the above two cases with changing the size of the initial gap and determine the critical initial gap c^* , the critical squeezing force P^* and the critical curve. Nondimensionalize the critical curves obtained for two different values of parameter μ and compare them. If the two critical curves coincides within the acceptable difference, accept these curves as the critical curve.

- (2) $\bar{c}^* - \mu, \bar{P}^* - \mu$ curves (Fig. 22)

The $\bar{c}^* - \mu$ and $\bar{P}^* - \mu$ curves can be obtained by plotting the nondimensionalized values of the critical initial gap \bar{c}^* and the critical squeezing force \bar{P}^* against the parameter μ and draw straight lines

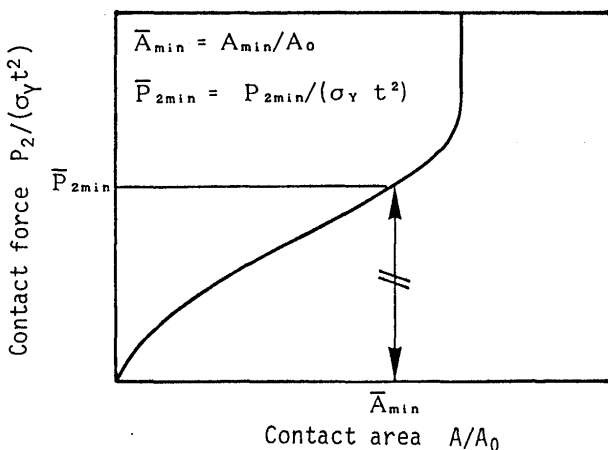


Fig. 21 Contact force-area curve at critical state.

between the plotted two points.

- (3) electrode force-displacement curve (Fig. 23)

As discussed in the reference³, the electrode force-displacement curve before the first contact can be approximated by the elastic-plastic small deformation curve and a straight line tangent to it. The slope of the straight line is given as

$$k_3 = a \mu \tag{4}$$

Further the elastic-plastic small deformation curve can be approximated by that for a case with the largest initial gap among those corresponding to the smaller value of μ . The constant a can be determined from the result for larger value of μ .

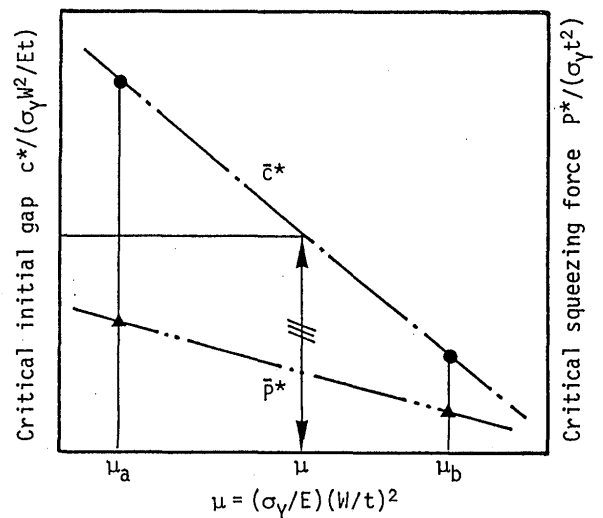


Fig. 22 Critical initial gap- μ and critical squeezing force- μ curves.

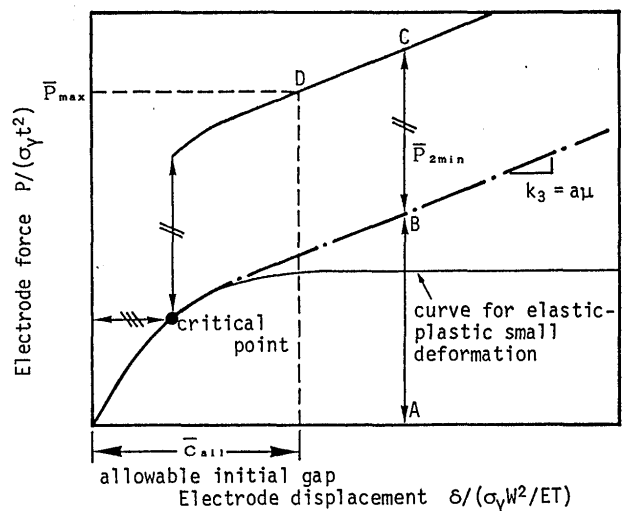


Fig. 23 Electrode force-displacement curve and the procedure to predict allowable initial gap.

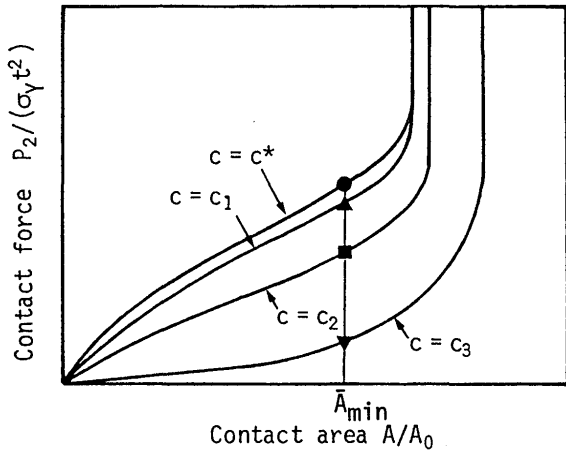


Fig. 24 Contact force-area curves and contact forces required to get contact area A_{min} .

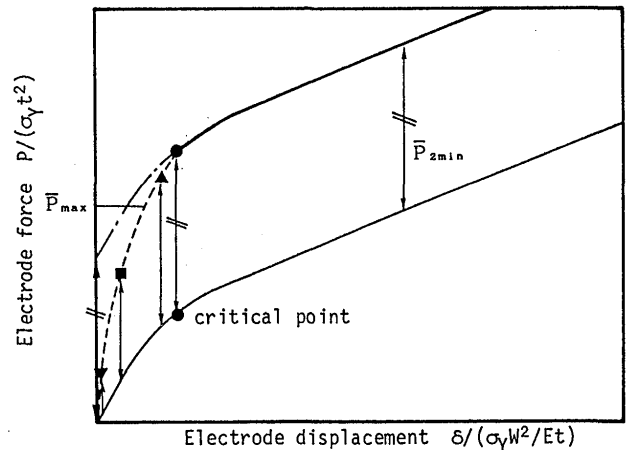


Fig. 25 Procedure to predict the allowable initial gap when the gap is smaller than the critical initial gap.

4.3 Estimation of allowable initial gap

Assuming the three kinds of curves discussed in the above are prepared, the procedure to predict the allowable initial gap is presented in the following.

- (1) Compute the parameter μ using the yield stress σ_y and the joint diameter W given for the joint.
- (2) The slope of the straight line in the squeezing force-displacement curve k_3 is obtained by using the relation given by Eq.(4).
- (3) Complete squeezing force-displacement curve before the first contact by drawing a tangential line with slope k_3 to the elastic-plastic small deformation curve.
- (4) Read the critical initial gap c^* from the \bar{c}^* - μ curve as shown in Fig. 22 and plot it on Fig. 23.
- (5) Using Fig. 21, read the value of the contact force \bar{P}_{2min} corresponding to the minimum contact area A_{min} .
- (6) In Fig. 23, three points A, B and C are shown for the case in which the initial gap is larger than the critical initial gap c^* . The figure tells us that the squeezing force corresponding to AB is required to close the initial gap. The additional force BC is necessary to get the required minimum contact area A_{min} . It should be noted that the force BC is equal to \bar{P}_{2min} in Fig. 21. By plotting the point similar to point C with changing the size of initial gap c , the thick solid line in Fig. 23 is obtained. This line shows the force necessary to obtain the sufficient contact area for the given initial gap. Therefore, from the point D which is corresponding to the maximum squeezing force, the allowable initial gap c_{all} is obtained.

Since the initial gap under the practical situation is expected to be larger than the critical initial gap c^* , the allowable initial gap is obtained by the above procedure. However, for the case in which the initial gap is smaller

than c^* , the concept of critical curve nor the similarity rule can not be applied. Because of this reason, it is difficult to predict the allowable gap in a rational and general manner. For such cases, the following two approximate methods can be used.

- (a) Since the similarity rule can not be applied, perform a serial computations with changing the initial gap using the exact value of yield stress and joint diameter of the given joint. From these computation, the contact force to get the contact area A_{min} is found as shown in Fig. 24. Plot these values on the electrode force-displacement curve as shown by the dotted line in Fig. 25.
- (b) The contact force required to get A_{min} for the initial gap smaller than c^* is assumed to be same as \bar{P}_{2min} as shown by the chain line in Fig. 25. The allowable initial gap obtained by the chain line gives a conservative estimation.

5. Conclusion

The squeezing process of a spot weld joint with initial gap, especially that of after the first contact, is analyzed by using the Finite Element Method. Based on these numerical simulation, the effect of the yield stress and the dimensions of the joint upon the contact state between the workpieces are closely examined and the following conclusions are drawn.

- (1) If the initial gap exceeds a certain limit, the contact force-area curves tend to fall on the same curve. For convenience, the saturated contact force-area curve for large initial gap is referred to as critical curve.
- (2) A mechanical similarity rule holds for the critical curve with respect to the variation of the yield stress and the joint diameter. In other words, the critical curves for different yield stresses and joint diameters

coincide with each other if they are nondimensionalized.

- (3) When the initial gap is large, contact pattern in ring shape may appear.
- (4) Based on the characteristics of the squeezing deformation stated in (1) and (2), a rational and general procedure to predict the allowable initial gap is proposed.

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