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

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Abstract

It has been reported that the weldability of the spot weld joint with initial gap is strongly influenced by the contact between electrode and plate. 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, the squeezing process is shown to be divided into three stages with respect to plastic deformation and large deformation. Further, to predict the electrode force required to close the initial gap, two methods, using parametric curves and approximation curves, respectively, are proposed.

KEY WORDS: (Spot Welding) (Initial Gap) (Press Formed Member) (Squeezing Force) (Plastic Deformation) (Large Deformation) (Material Property) (Finite Element Method)

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.

The effect of the initial gap on the weldability has been studied by Nishiguchi *et al.*[1),2)] and it is reported that the weldability, viewed from the nugget formation, is strongly governed by the contact state between the electrode and the plate. Further, based on the knowledge obtained, they proposed welding conditions which are effective to improve the weldability. Since the mechanism how the initial gap influences the weldability has been clarified, it is necessary, as a next step, to generalize the knowledge and to develop a method to predict the allowable initial gap and the ideal welding conditions for given weld joints.

To generalize the knowledge obtained by experiments, the extraction of the dominant phenomena and governing parameters and also nondimensional description based on the mechanical similarity rule are necessary. For this purpose, analytical theories are helpful. Considering the complexity of the welding process which involves electric, thermal, mechanical and metallurgical phenomena, the numerical methods such as the Finite Difference Method (F.D.M.) and the Finite Element Method (F.E.M.) are also versatile tools[3),4)].

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

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 increase of the squeezing force
3) heating and melting process with the electric current with holding the squeezing force
4) cooling process with holding the squeezing force
5) releasing squeezing force

The step which is directly related to the nugget formation and most important is the third step. However, steps which determine the initial state and the constraining condition at the third step are first and second steps. Therefore, to analyze the phenomena in the third step, it is necessary to clarify those in the squeezing process.

The authors analyzed the squeezing process using the F.E.M. and investigated the effect of the weld joint geometry and material properties upon the squeezing force required to close the initial gap. When the initial gap is large, the deformation of the weld joint becomes large and plastic deformation may occur. Thus, as a first step, the effect of the large deformation (geometrical nonlinearlity) and the plastic deformation (material nolinearlity) on the squeezing process of the joint with initial gap were analyzed. The obtained results were generalized using the mechanical similarlity rules. Based on the generalized data, methods to predict the squeezing force required to close the initial gap for the weld joint with given geometry and material properties were

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proposed. Further, the validity of the proposed method was demonstrated using the hat type weld joint as an example.

2. Joint Models with Initial Gap

The forms of the spot weld joints largely depend on the types of the structures, such as automobiles and railroad vehicles, and differ from each other in details. However, to obtain the quantitative relation between the initial gap and the weldability, systematic analyses using standard joint models are necessary. For this reason, standard joint models are proposed and experimental results using these models were reported[5]. The same models are also employed for the numerical analyses in this report.

Figures 1 and **2** show two standard joints. The former is the most fundamental model and will be called as the standard specimen with initial gap. The latter is a model which is closer to the actual weld joint and will be called as the hat type joint specimen with initial gap.

3. Fundamental Characteristics of the Squeezing Deformation

Using the standard specimen with initial gap, the characteristics of the squeezing deformation are examined by the F.E.M. The dimensions of the specimen are,

width : $W = 30$ mm
length : $L = 60$ mm
thickness : $t = 0.8$ mm

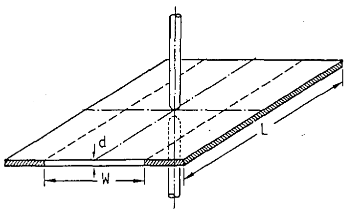

Fig. 1 Standard specimen with initial gap.

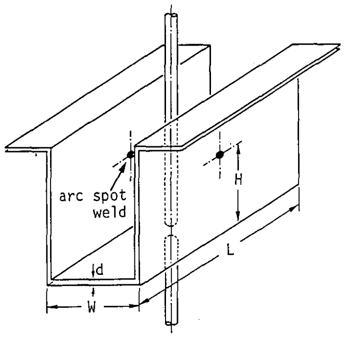

Fig. 2 Hat type joint specimen with initial gap.

The plates in the specimen are assumed to be clamped along the edges parallel to the longitudinal direction. To clarify the effects of plastic deformation and the large deformation, following four types of F.E.M. based on different theories are employed.

(1) elastic small deformation analysis
(2) elastic-plastic small deformation analysis
(3) elastic large deformation analysis
(4) elastic-plastic large deformation analysis

In the elastic-plastic analyses, the material is assumed to be a perfect elastic-plastic material and its yield stress is assumed to be 40 kgf/mm^2 (392MPa). The relation between the electrode displacement δ and squeezing force P obtained by the four types of analyses are compared in **Fig. 3**. Among these results, that by elastic-plastic large deformation analysis is considered to be a result which is the closest to the real physical phenomenon. As it is seen from the figure, the deformation in the squeezing process can be divided into three stages. In the first stage, where the displacement δ is small, neither the effect of the large deformation nor that of plastic deformation are significant, and the characteristics of the deformation can be represented by the elastic stiffness k_e. When the deformation is fairly large as in the second stage, significant effect of the plastic deformation is observed. But, the effect of the large deformation is small. In the stage (3), where δ is very large, the deformation process shows the effect of both plastic and large deformations. Considering that the magnitude of the initial gap expected in the real weld joints is about 2–3 mm, the F.E.M. based on the elastic-plastic large deformation theory is employed in the analyses discussed in the following chapters.

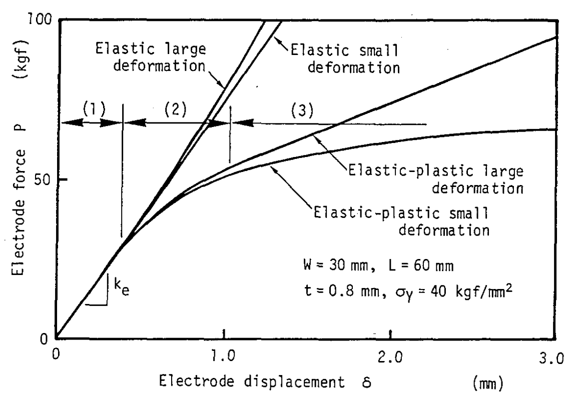

Fig. 3 Effects of plastic deformation and large deformation on squeezing process.

4. Standard Specimen with Initial Gap

4.1 The effect of the strain hardening property

In general, the relation between the electrode displacement and the squeezing force depends on the geometry and the material properties of the joint. Thus, behavior in the squeezing of the weld joint which is made of mild steel is expected to be different from that made of high tensile strength steel[2)].

In this section, the effects of the yield stress and the strain hardening property are examined using the standard specimen as an example. Two types of materials are considered. First type is the perfect elastic-plastic material which corresponds to materials with small strain hardening immediately after the yielding such as mild steels. Second type is the material with significant strain hardening after yielding such as high tensile strength steels. For the strain hardening materials, the relation between the true stress σ^* and the logarithmic strain ϵ^* is assumed to be described by the following equation,

$$\sigma^* = \sigma_p (1 + b\epsilon^*)^n \quad (1)$$

where, σ_p, b and n are material constants. Particularly, σ_p represents the proportional limit and n is the strain hardening index. The strain hardening materials examined are sixteen, which are determined by the combinations of the following sets of material constants.

$n = 0.1, 0.2$
$b = 1000, 2000$
$\sigma_p = 20, 30, 40, 50$ kgf/mm^2

On the other hand four materials with different yield stresses, namely 30, 40, 50 and 60kgf/mm^2, are considered as perfect elastic-plastic materials. In comparing strain hardening materials with perfect elastic-plastic material, stress at 0.2% plastic strain is chosen as the yield stress of the strain hardening material.

The dimensions of the specimen and the size of the initial gap d are,

$W = 30$ mm, $L = 60$ mm
$t = 0.8$ mm, $d = 2.3$ mm

The squeezing force P_c, required to close the initial gap for different materials, were computed and plotted in **Fig. 4** using the yield stress σ_Y as a parameter. As seen from the figure, linear relation between force required to close the initial gap P_c and the yield stress σ_Y can be observed. Also, the relation can be approximately represented by single line for materials with various strain hardening properties including the perfect elastic-plastic materials. This implies that the behavior of the weld joint with various strain hardening property can be predicted from that of an equivalent joint made of perfect elastic-plastic material with same yield stress. Therefore, only perfect elastic-plastic materials are considered in the following discussion.

4.2 Effect of the relative thickness

The effect of the plate thickness on the squeezing process was examined using the model in which $W = 30$mm, $L = 60$mm and $\sigma_Y = 40$kgf/mm^2. Results for the four cases with different thickness, namely $t = 0.6$, 0.9, 1.2, 1.5mm, are presented in **Fig. 5**. The numerical results show that the squeezing force to produce the same amount of the displacement increases with the plate thickness. Further, to generalize the results, mechanical similarity rules are introduced.

Two similarity rules, the one holds for the stiffness in the elastic small deformation and the other holds for the strength under plastic collapse, are introduced. These are described by the following relations,

$$PW^2/(\delta E t^3) = \alpha \quad (2)$$

$$P/(\sigma_Y t^2) = \beta \quad (3)$$

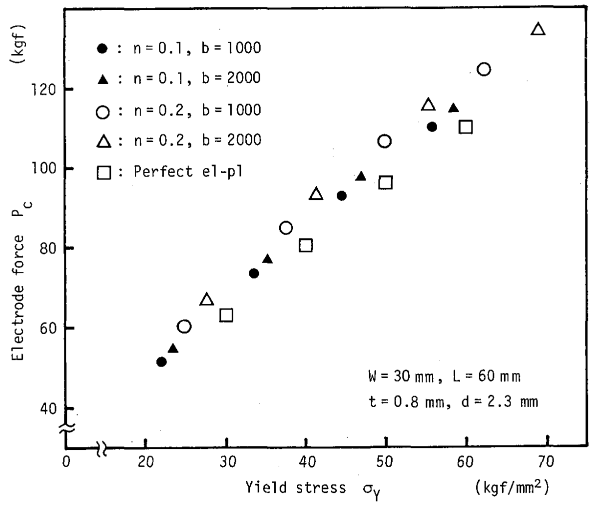

Fig. 4 Relation between yield stress and force required to close initial gap.

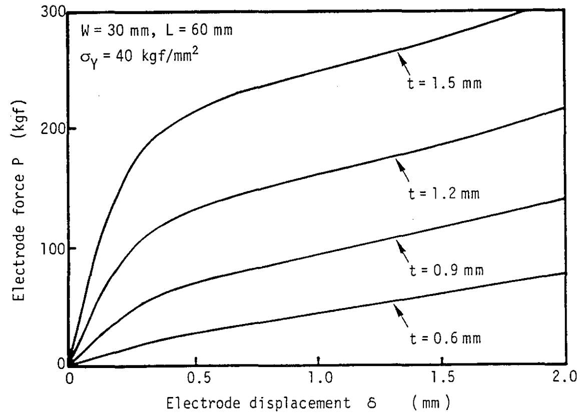

Fig. 5 Effect of plate thickness on squeezing process.

where, α and β are constants. Solving **Eqs.**(2) and (3) for force P and displacement δ, it is obtained that,

$$P = \beta\,(\sigma_Y t^2) \tag{4}$$

$$\delta = (\beta/\alpha)\,(\sigma_Y W^2/Et) \tag{5}$$

Using the above similarity rules, the squeezing force P^* and the displacement δ^* in nondimensional form can be defined as,

$$P^* = P/(\sigma_Y t^2) \tag{6}$$

$$\delta^* = \delta/(\sigma_Y W^2/Et) \tag{7}$$

Following **Eqs.**(6) and (7), Fig. 5 is nondimensionalized to get **Fig. 6**. For comparison, the result obtained by the elastic-plastic small deformation analysis is also shown by the dotted line. If the behavior in the squeezing process follows the elastic-plastic small deformation, all curves for different relative thickness t/W coincide with the dotted line. Thus, the differences appear among curves are due to the effect of large deformation and its effect is large when the relative thickness t/W is small. On the contrary, when the relative thickness is large, as in the case in which t = 1.5 mm (t/W= 0.05), the effect of the large deformation is negligibly small and the force-displacement curve can be approximated by that of the elastic-plastic small deformation analysis.

4.3 Effect of yield stress

In the previous section, it was shown that the effect of the large deformation varies with the relative plate thickness. The effect of the yield stress is examined in this section. **Figure 7** shows the electrode force-displacement curves computed for the standard specimen with different yield stress. The dimensions of the specimen are W = 30, L = 60, t = 0.8 and the yield stress is assumed to be 30, 40, 50 and 60kgf/mm^2, respectively in each case. As it is clearly seen from Fig. 7, the effect of the large deformation increases with the yield stress.

4.4 Approximation curves

As discussed in Chapter 3, the squeezing process of the weld joint with initial gap can be divided into three stages. The first and second stages are governed by elastic-plastic small deformation. The third stage is governed by elastic-plastic large deformation and it can be roughly represented by a straight line. Based on these knowledge, the electrode force-displacement relation can be approximated in the following manner. As shown in **Fig. 8**, the first and the second stage can be approximated using the curve O-A which is the force-displacement curve obtained by the elastic-plastic small deformation analysis. The third stage is approximated by a straight line tangent to the curve O-A. Since the curve O-A is already obtained by F.E.M. analysis at this stage and it dose not depend on relative thickness t/W nor yield stress σ_Y/E, remaining question is how to determine k_3 which is the slope of the line representing the third stage. In general, the slope k_3 is a function of $t/W$and σ_Y/E. To determine such function, the slope k^* obtained for the same cases as presented in Figs. 6 and 7 are plotted against parameter μ in **Fig. 9**. The parameter μ is defined as,

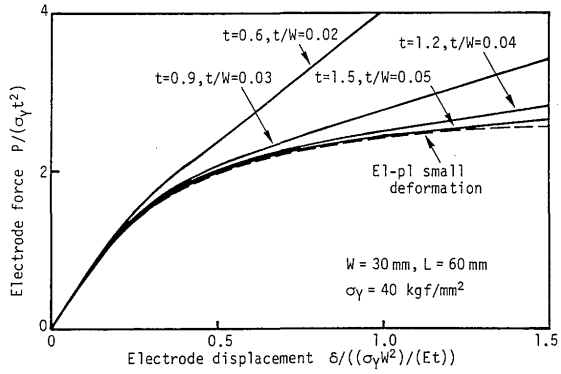

Fig. 6 Nondimensionalized curves showing effect of plate thickness.

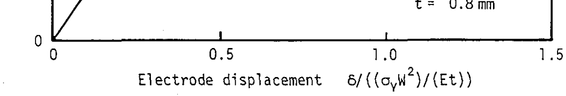

Fig. 7 Nondimensionalized curves showing effect of yield stress.

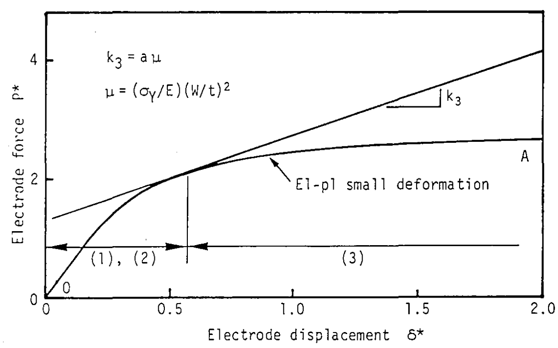

Fig. 8 Approximation of squeezing force-displacement curve.

$$\mu = (\sigma_Y/E)\,(W/t)^2 \tag{8}$$

As seen from Fig. 9, linear relation holds approximately between the parameter μ and k_3. Thus, k_3 can be expressed as,

$$k_3 = a\mu \tag{9}$$

where, a is a constant which depends on the geometrical type of the joints. For the standard specimen with initial gap, the coefficient a is determined to be,

$$a = 0.65 \tag{10}$$

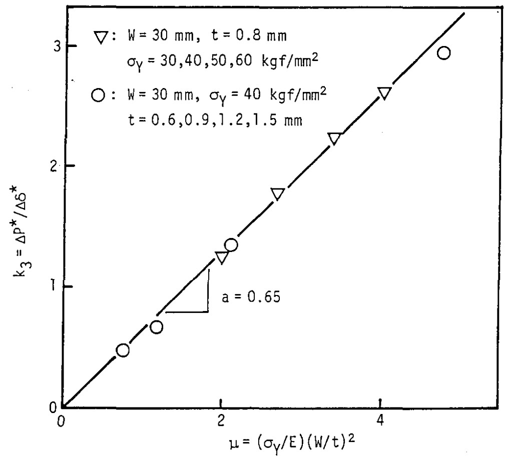

Fig. 9 Estimation of slope of straight line representing the third stage.

Although the F.E.M. analyses are used to determine the approximation curve, it is possible to use experimental results in stead of numerical results. Only two experiments are required for this purpose. One is used to obtain the curve O-A and the other is used to determine the constant a. As it is shown in Fig. 6, the effect of the large deformation is negligible when the relative thickness t/W is larger than 0.05. Thus, the curve O-A can be approximated by the curve for the experiment with large t/W. On the other hand, a specimen with medium thickness, $t/W = 0.03$ for example, is used to determine a. From the value of k_3 obtained for the second experiment, the constant a is determined using Eq.(9). Once the constant a is known, approximation curves can be drawn for arbitrary value of t/W and σ_Y/E. Further, using this approximation curves, the squeezing force required to close the initial gap can be estimated. Its detail will be discussed in section 5.4 using hat type specimen as an example.

4.5 Parametric curves

The approximation curves proposed in the preceding section can be used for the rough estimation. For the accurate estimation, parametric curves can be used as an alternative.

The first and the second stage of the squeezing process show the elastic-plastic small deformation behavior and the effect of the large deformation in the third stage is reflected in the slope of the force-displacement curve. It should be noted that the effect of the large deformation for different dimensions and material properties can be consistently represented by the parameter μ which is defined by Eq.(8). To verify this, Figs. 6 and 7, which are the results of the two different series of analyses with varying plate thickness and yield stress, are superposed in **Fig. 10**. The solid lines and the broken lines in the figure represent the series of curves for which the thickness and the yield stress are changed, respectively. As observed from Fig. 10, two different series of results are put together with μ as a consistent parameter. Thus, if the parametric curves, as shown by Fig. 10, are obtained either numerically or experimentally for the given type of the joint, more accurate estimation of the squeezing force becomes possible.

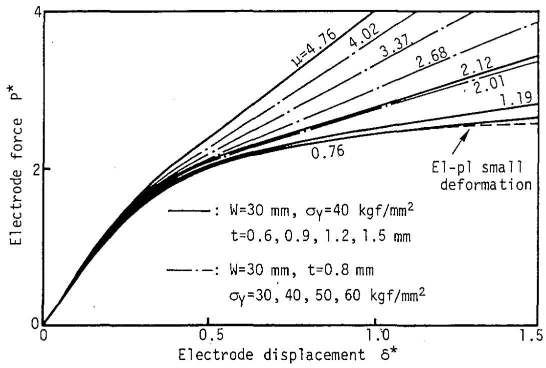

Fig. 10 Parametric curves using μ as a parameter.

5. Hat Type Joint Specimen

5.1 Comparison with experiment

The hat type specimen with initial gap for experiment used by Tanaka *et al.*[5] is shown in **Fig. 11**. The actual initial gap between two press formed members is simu-

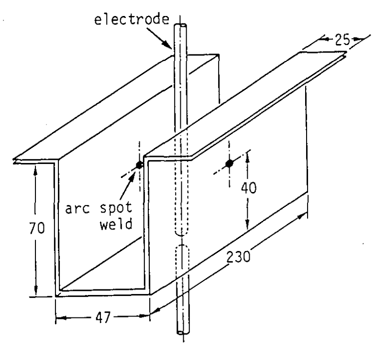

Fig. 11 Hat type joint model for experiment.

lated by a pair of constraining arc spot weldings. On the other hand, **Fig. 12** shows two types of F.E.M. models which are considered in the numerical analyses. **Model-a** is the full model in which the flange and the wall above the constraining spot weld are taken into account and these parts are ignored in **model-b**. The electrode force-displacement relations are compared between experiments and analyses in **Fig. 13**. Results are shown for two cases where the plate thicknesses are 1.4 and 2.3 mm. The yield stresses of the plates σ_Y are 38.7 and 39.7kgf/mm^2, respectively.

Though the computed electrode force is slightly smaller than those of the experiments, good correlation is observed between the numerical and experimental results. The reason for the small value of the electrode force, in other words, large deformation for the same force, in F.E.M. may be the fact that the contact between the electrode and the plate is assumed to be point contact and the electrode force is applied as a concentrated load.

Comparing the numerical results by **model-a** and **model-b**, the difference is not significant. Thus, **model-b** is used for the analyses discussed in the following sections.

5.2 Governing parameters

It was shown that the relative thickness and yield stress are parameters which governs the squeezing deformation of the standard specimen. In case of hat type specimen, which is more complex in geometry, the phenomenon is governed also by some other parameters, such as the relative length and the height of the specimen. The effects of these parameters are examined in this section.

1) effect of relative length

The effect of the relative length upon the squeezing deformation can be considered, essentially, as the end effect. In other words, it comes from the finiteness of the length of the specimen. To clarify the end effect, the squeezing deformations are analyzed for various values of the relative length L/W. For simplicity, only the bottom part of the specimen is idealized as a rectangular plate with the long edges simply supported and the short edges free. The force-displacement curves under a concentrated load at the center of the plate are compared in **Fig. 14**. Four cases with different relative length, such that L/W = 1, 2, 4 and 10, are shown in the figure. It can be seen that the end effect can be neglected if the relative length is greater than 2.0. In case of the standard specimen, which was discussed in Chapter 4, the relative length is 2.0. Thus, the standard specimen is long enough so that the end effect can be neglected.

2) effect of relative height

The effect of the relative height is examined by analyzing the deformation of specimens with different relative height, such that H/W = 0.5, 1.0, 1.5 and 2.0. While, the relative length is kept 2.0 which is the minimum value for

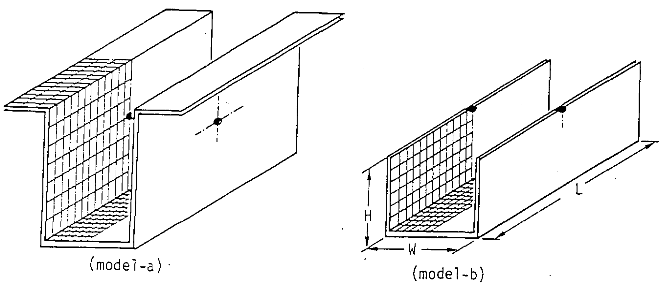

Fig. 12 Hat type joint models for FEM analysis.

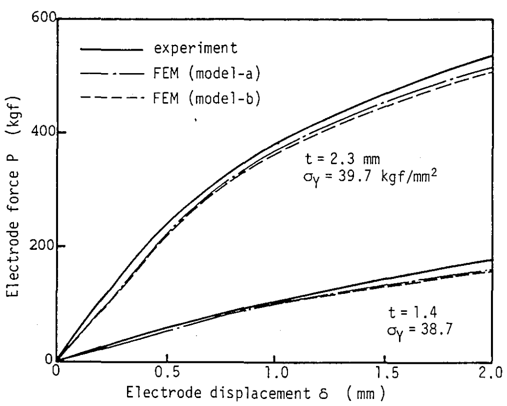

Fig. 13 Comparison of squeezing force-displacement curves between experiments and analyses.

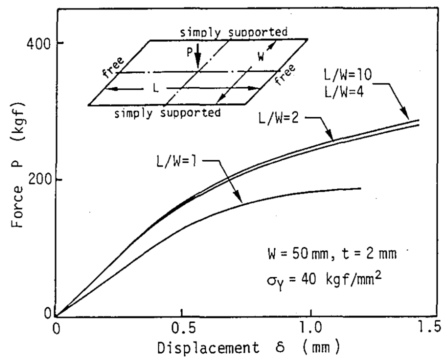

Fig. 14 Effect of relative length L/W on squeezing process.

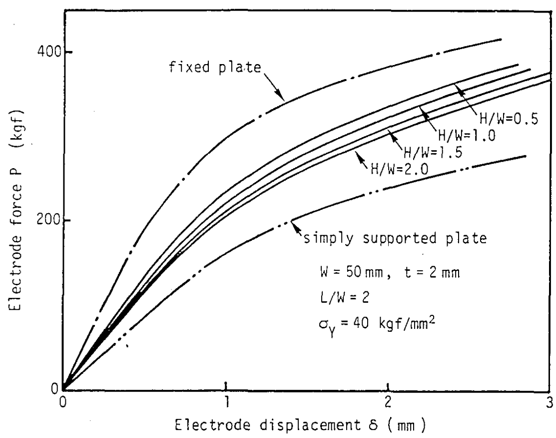

Fig. 15 Effect of relative height H/W on squeezing process.

the end effect to be neglected. The computed electrode force-displacement curves are shown in **Fig. 15.** For comparison, results for a pair of parallel plates which is an idealization of the bottom plates are also shown by broken lines with single dot and double dots. The former curve represents the results for plates with the long edge clamped and it corresponds to the standard specimen which was discussed in Cahpter 4. The latter curve is for the case in which the long edge is simply supported. As seen from the figure, the stiffness of the hat type specimen is small compared to that of the standard specimen. If the relative height between 0.5 and 2.0 is considered, the electrode force for the same electrode displacement increases as the relative height H/W decreases. In general, the squeezing deformation is influenced by the relative height. However, if only the neighbourhood of $H/W = 1.0$ is considered, the change in deformation due to that of H/W is relatively small. Thus, the electrode force-displacement curves in the range $0.5 < H/W < 2.0$ may be approximated by that for $H/W = 1.0$. If the accuracy is required for the estimation, the relative height must be treated as one of the independent governing parameters and curves for different values of H/W must be drawn individually.

3) effects of relative thickness and yield stress

The effects of the relative thickness and yield stress are examined for the case in which $L/W = 2.0$ and $H/W = 1.0$. The electrode force-displacement curves computed for different values of relative thicknesses are shown for two different values of yield stresses, namely $\sigma_Y = 40$ and 30 kgf/mm^2, in **Figs. 16** and **17**. These two figures are nondimensionalized in the same manner as those for the standard specimen. Comparing Fig. 16 or 17 with Fig. 6, the hat type specimen shows the same characteristics as the standard specimen. The effect of the large deformation becomes significant when the relative thickness is small or yield stress is large.

5.3 Approximation curves for hat type specimen

The idea proposed in Section 4.4 is applied to obtain approximate electrode force-displacement curves for the hat type specimen and its validity is examined. As it was shown, only two experiments or F.E.M. analyses are necessary to draw approximate curves. Thus, two curves computed for the case in which the yield stress is 40 kgf/mm^2 are selected. These two curves are curves (a) and (b) in Fig. 16. The curve (a) is the electrode force-displacement curve computed by the elastic-plastic small deformation analysis and it gives the first and second stages of the approximation curves. The curve (b) is the results for the case where $t/W = 0.028$ and it is used to determine the coefficient a in **Eq. 9**. From the curve (b), the slope of the third stage k_3 is given to be,

$$k_3 = 1.8 \tag{11}$$

Using this value and Eq. (9), the coefficient a can be determined, such that,

$$a = k_3/\mu = 1.8/(\sigma_Y/E)(W/t)^2 = 0.74 \tag{12}$$

Once the coefficient a is determined, the slope k_3 for arbitrary value of the plate thickness and the yield stress can be given by the following equation.

$$k_3 = 0.74\,\mu \tag{13}$$

To demonstrate the validity of the proposed approximation, the approximation curves are drawn using the curve (a) and Eq.(13) for the case where $\sigma_Y = 30$ kgf/mm^2 and compared with those computed by F.E.M. in **Fig. 18**. Since the approximation curves and the curves computed by F.E.M., which are represented by broken lines and solid lines respectively, are in good agreement, Fig. 18 proves the validity of the proposed approximation.

5.4 Estimation of squeezing force

When the nondimensionalized curves approximating the electrode force-displacement relations, such as shown in Fig. 18, is available and the dimensions, the magnitude

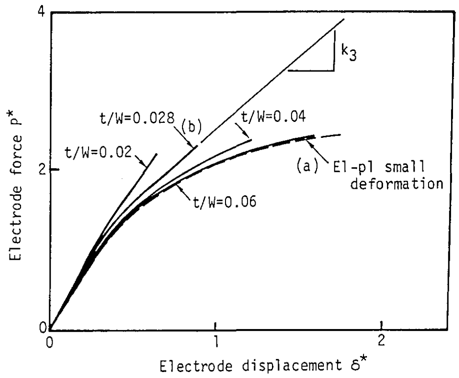

Fig. 16 Effect of thickness of hat type joint ($\sigma_Y = 40$).

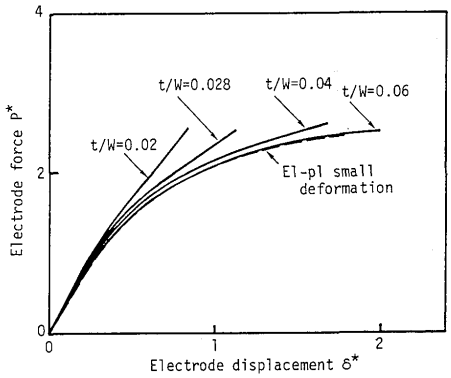

Fig. 17 Effect of thickness of hat type joint ($\sigma_Y = 30$).

of initial gap and the yield stress of the hat type joint are known, the squeezing force required to close the initial gap can be estimated. The estimation can be made by following the procedure shown in **Fig. 19**, such that,

(1) compute parameter μ $\mu = 2.34$
(2) determine slope k_3 $k_3 = 0.74\mu = 1.73$
(3) draw tangential line to the curve corresponding to elastic-plastic small deformation (dotted line) to get the complete approximation curve.
(4) compute nondimensional displacement δ^*
$\delta^* = 1.07$
(5) read P^* from the approximation curve
$P^* = 2.48$
(6) transform P^* to physical value
$P = 55.4$ kgf

6. Conclusion

The squeezing processes of spot weld joints with initial gap are analyzed using F.E.M. The effect of the geometry and the material properties are clarified and following conclusions are drawn.

(1) The deformation in squeezing process of the weld joint with initial gap is divided into three stages, namely elastic small deformation, elastic-plastic small deformation and elastic-plastic large deformation.
(2) Employing the mechanical similarity rules which hold for stiffness in elastic small deformation and strength in small elastic-plastic deformation, the squeezing process can be described in general nondimensional form.
(3) The effect of the large deformation depends on the parameter μ given by Eq. (8).
(4) Two methods, namely which use the approximation curves or parametric curves, to estimate the squeezing force are proposed and their validity is demonstrated through example. Especially, only two experiments or analyses are necessary to obtain the proposed approximation curves.

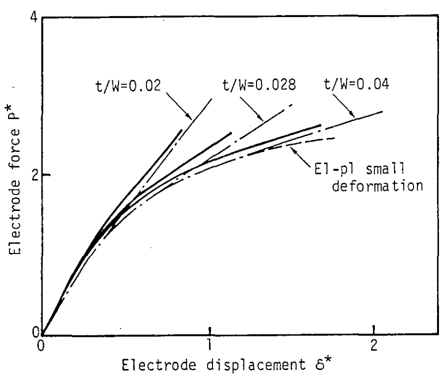

Fig. 18 Comparison between approximate estimation and FEM analysis.

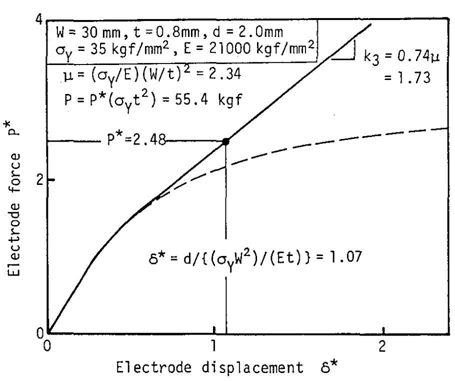

Fig. 19 Procedure to estimate squeezing force for closing gap.

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