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An Analytical Approach to the Problem of Restraint Intensity in Slit Weld†

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Abstract

Reaction stress and strain in weld will be one of the important factors which influence on cold cracking in steel welds. Significance of restraint intensity as a measure of the reaction stress and deformation of weld is described. Analysis is made on the reaction stress and deformation of weld in slit weld, and relationship between the results and the restraint intensity is obtained. The restraint intensity of weld cracking test specimens of slit type is also discussed.

1. Introduction

There exsist several factors which influence on weld cracking in steel welds. Reaction stress and strain in weld joint will be one of these factors. About thirty years ago Naka[1] established a theory of reaction stress in restraint weld and introduced a parameter named "Restraint Intensity" which is defined as the force per unit weld length necessary to produce uniform elastic change of unit maginitude in root gap. Recently, Satoh and Matsui[2] conducted a series of research on the effect of restraint on cold cracking in heavy steel plate. They used the restraint intensity as a measure of the reaction stress in the first-pass welding of heavy steel plates and obtained the value of critical restraint intensity for several kinds of steel by the RRC-weld cracking test. The concept of the restraint intensity was introduced into the weldment cracking parameter P_w proposed by Ito and Bessyo.[3]

The restraint intensity in the researches of Naka[1] and Satoh Matsui[2] is concerning the one-dimensional stress field, or the restrained weld joint of which weld length is comparatively short. In fabrication of real structures, however, the restraint or reaction stress is not always uniform along a weld line. How to determine the restraint intensity in this case will be an important problem in practical welding works.

As an example of the restraint intensity in a complex structure, Masubuchi and Ich[4] obtained an analytical solution of the restraint intensity in a slit weld, in which welding bead is laid into a slit in an infinitely large plate. They made also a computer analysis of the restraint intensity for weld cracking test specimens of slit type. In their research, although the restraint of weld cracking test specimens is relatively evaluated in each other, the relationship between the restraint intensity and the reaction stress and strain in weld is not obtained.

The present research describes at first significance of the restraint intensity in one-dimensional stress field in relation to reaction stress and deformation of weld. Analysis is made on the reaction stress and deformation in slit weld, and the restraint intensity connected to the results is obtained. The restraint intensity of weld cracking test specimens is also discussed.

2. Restraint intensity in the RRC-weld cracking test

The author and his colaborator[2] have developed the RRC-weld cracking test of which schematic illustration is shown in **Fig. 1 (a)**. It is such that a certain length of a specimen or restraining gauge length is kept constant during welding and cooling to realize a both-ends fixed weld joint as shown in **Fig. 1 (b)**. Hindered contraction between A and A′ developes reaction force, from which deformation of base metal λ_b and of weld metal λ_w are resulted. In the both-ends fixed joint the sum of λ_b and λ_w should be equal to free contraction S between A and A′ at any instant during cooling, or

$$\lambda_b + \lambda_w = S \tag{1}$$

When the plate thickness h is sufficiently large as compared with the throat depth h_w, behavior of the base metal will be elastic even if the average reaction stress σ_w in weld exceeds its yield stress σ_Y, and the reaction force per unit weld length $P(=\sigma_w h_w)$ may be obtained as illustrated in **Fig. 1 (c)**: The line OYM represents the relationship between P and λ_w and the line ON represents the relationship between P and λ_b. Takeing $S=\overline{OA}$ and AB//ON, one may obtain $\lambda_b=\overline{CD}$, $\lambda_w=\overline{BC}$ and $P=\overline{OC}$. The gradient of the line ON, or

$$\tan\theta = \frac{Eh}{l} \equiv K \tag{2}$$

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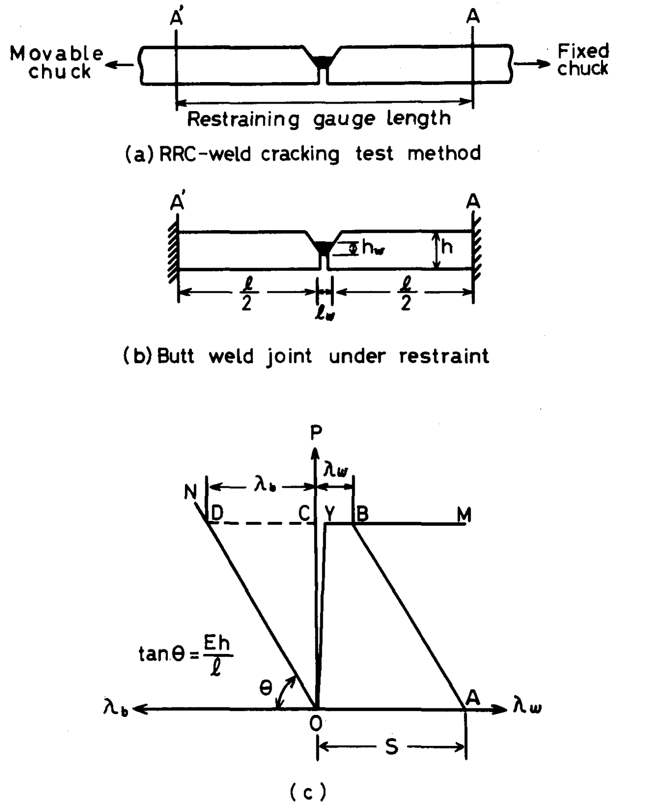

Fig. 1. Relationship of reaction force versus deformation of base plates and weld metal under restraint.

where E is Young's modulus of the material, represents the reaction force per unit weld length necessary to produce average elastic change of unit magnitude in root gap along weld line, and it is defined "Restraint Intensity". The reaction force P will increase as the K-value increases under a given contraction S, and will increase as S increases under a given value of K.

The reaction stress σ_w and the deformation in weld will be obtained as functions of the restraint intensity K. When the K-value is small, the reaction force P will be less than the yield force $P_Y(=\sigma_Y h_w)$ and the deformation λ_w will be the order of the elastic deformation. The reaction force P will be nearly proportionate to the free contraction S from **Fig. 1 (c),** or the reaction stress σ_w is given by

$$\sigma_w = \frac{P}{h_w} = K \cdot \frac{S}{h_w} \tag{3}$$

In the first pass welding of the heavy plates of which thickness his larger than a critical thickness h_{cr} given by[2)]

$$h_{cr} = \sqrt{\frac{Q}{c\rho\theta_s}} \tag{4}$$

where c : specific heat of the material (cal/gr·°C)
ρ : density of the material (gr/cm³)
θ_s : melting temperature of weld metal (°C)
Q : welding heat input per unit weld length (cal/cm),

the free contraction S after cooled to room temperature is independent of h and is proportionate to h_{cr} (or $\sqrt{Q}$) as given by

$$S = \alpha\theta_s h_{cr} \tag{5}$$

where α is coefficient of thermal expansion (°C^{-1}). While, the throat depth h_w increases with increase in welding heat input Q. Assuming the cross-sectional shape of weld metal a triangle of which bevel angle is 2β, h_w is given by

$$h_w = \sqrt{\frac{Q}{H\rho\tan\beta}} \tag{6}$$

where H is specific heat of electrode used[5)](cal/gr). From eqs. (3) thru (6), the reaction stress σ_w is represented in the form

$$\sigma_w = mK \tag{7}$$

in which m is a numerical factor given by

$$m = \frac{S}{h_w} = \alpha\sqrt{\frac{\theta_s H\tan\beta}{C}} \tag{8}$$

The value of m in steel welds is calculated as $m = 3.8\times10^{-2} \sim 5.5\times10^{-2}$ by taking $\alpha = 1.3\times10^{-5}$ °C^{-1}, $\theta_s = 1500$°C, $c = 0.12$cal/gr·°C, $H = 1.2\times10^3 \sim 2.5\times10^3$ cal/gr, $2\beta = 60°$. When the K-value exceeds the value of $\frac{\sigma_Y}{m}$, general yielding occurs in weld. The deformation of weld λ_w in this case is obtained as S-λ_b from **Fig. 1 (c).** It is given as

$$\lambda_w = S\left(1 - \frac{\sigma_Y}{mK}\right) \tag{9}$$

As shown in eqs. (7) and (9), the restraint intensity K could be used as a measure of the deformation λ_w as well as the reaction stress σ_w in weld under restraint. **Figure 2** shows the relationship between σ_w and λ_w versus K.

3. Reaction stress and deformation in slit weld

3. 1 Description of the problem

The above discussion has been made for one-dimensional stress field or the case such that the restraint intensity is uniform along a weld line. However, in weld joints of real structures, restraint is not always uniform along a weld line. As an example, **Fig. 3** shows a slit weld, in which a slit is made in a plate and welding is done into the slit. Restraint of weld will be higher at the ends than at the middle part of

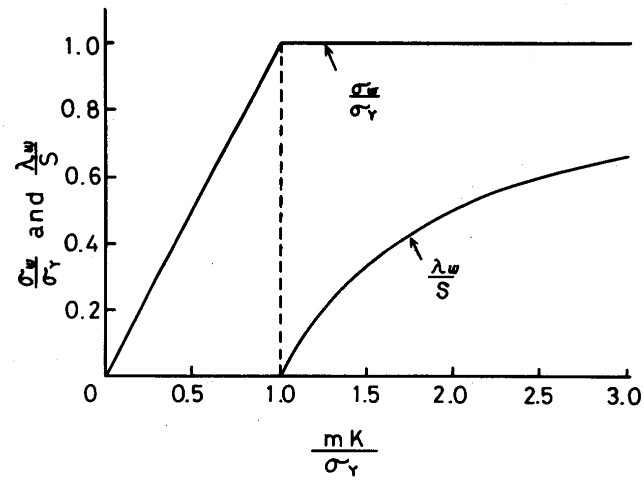

Fig. 2. Relationship between reaction stress σ_w and deformation of weld λ_w versus restraint intensity K.

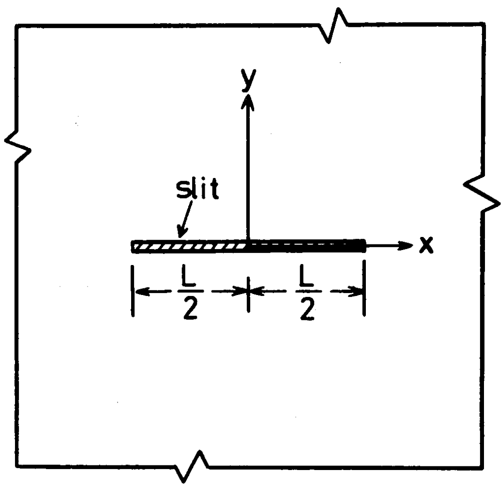

Fig. 3. Slit weld.

the slit. Discussion will be made for the slit weld under the following assumptions:

1. The size of the plate is sufficiently large as compared with the slit length L.

2. The plate thickness h is larger than the critical thickness h_{cr} given by eq. (4). Transverse stress σ_b in the plate along the weld line is given by

$$\sigma_b = \frac{h_w}{h}\,\sigma_w \tag{10}$$

and therefore it will be enable us to make elastic analysis concerning stress-strain in the plate even when general yielding occurs in the weld.

3. Free transverse contraction S is uniform along the weld line and is given by eq. (5).

3. 2 Yielding length and distribution of the reaction stress

If the weld metal has sufficiently high yield stress or the material is perfect elastic body, the transverse stress σ_b would be obtained as elastic stress due to transverse dislocation S uniformly distributed along the slit. Thus, the reaction stress σ_w in weld is given by

$$\sigma_w = \frac{h}{h_w}\cdot\sigma_b = \frac{mEh}{2\pi}\left(\frac{1}{L+2x} + \frac{1}{L-2x}\right) \tag{11}$$

from which the σ_w value becomes infinitive at the ends of the slit or $x = \pm\frac{L}{2}$. Since the cross section of weld metal has a finite value of breadthin real weld joint, the reaction stress at the ends should become a finite value. The slit being assumed a rectangular from of L $\times$B, the end effect will vanish at a distance from the end nearly equal to the breadth of the slit according to Saint-Venant's principle, and eq. (11) will be applied except for the end parts. When $L \gg B$, the reaction stress at a distance from the end equal to the breadth of the slit or $x = \pm(\frac{L}{2} - B)$ is given from eq. (11) by

$$\sigma_w = \frac{mEh}{4\pi B} \tag{12}$$

When $m = 4.5\times10^{-2}$, $E = 2.1\times10^4$ Kg/mm², h = 20mm and B = 4 mm, σ_w becomes 377 Kg/mm². For current high-strength steels of structural use, therefore, general yielding would occur in the weld near the ends of the slit even when the slit is sufficiently long.

When general yielding occurs near the ends of the slit, the distribution of the reaction stress σ_w and the transverse displacement λ_b along the edge of the slit will become as illustrated schematically in **Fig. 4 (a).** Since it is comparatively difficult to obtain exact solution of the length of the yielding part L_1, an approximate solution will be led in this paper.

In **Fig. 4 (b),** the curve DCD′ shows the reaction stress obtained from eq. (11), and it exceeds the yield stress at the point B (B′). The curve ABCB′A′ may be taken as an approximate solution of the reaction stress, and the yielding length L_1 may be given by the legth $\overline{AB}$ ($\overline{A'B'}$) although it is smaller than its exact value. The σ_w-value at x = 0 increases as L decreases. When the slit length L is smaller than a certain length L_c given by

$$L_c = \frac{mEh}{\pi\sigma_Y} \tag{13}$$

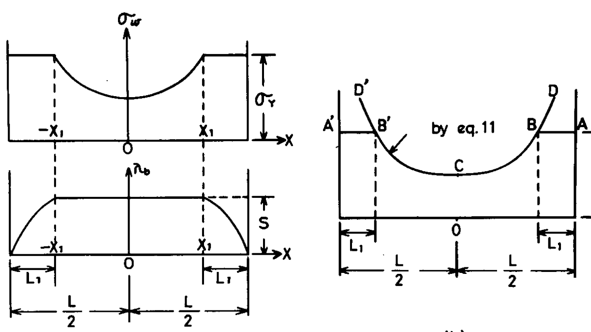

Fig. 4.

general yielding zone in the weld covers the slit length. When L exceeds L_c, general yielding will occur at least in the end parts of length L_1. The L_1-value can be obtained from eq. (11) by putting $2x = L - 2L_1$ and $\sigma_w = \sigma_Y$,

$$2L_1 = L\left\{1 - \sqrt{1 - \frac{L_c}{L}}\right\}$$
$$= \frac{L_c}{2}\left\{1 + \frac{1}{4}\left(\frac{L_c}{L}\right) + \frac{1}{8}\left(\frac{L_c}{L}\right)^2 + \cdots\cdots\right\} \quad (14)$$

Figure 5 shows the yielding length as a function of $\frac{L}{L_c}$. It decreases to $\frac{L_c}{4}$ when $L \gg L_c$.

The L_c value given by eq. (13) is an important factor for determining the distribution of the reaction stress. **Table 1** shows $\frac{L_c}{h}$ in steel weld for several yield stress levels of weld metal. The distribution of the reaction stress σ_w along the slit is different by $\frac{L}{L_c}$. When $L \leqq L_c$, $\sigma_w = \sigma_Y$ all over the slit length. When $L > L_c$, σ_w is less than yield stress except for the yielding zone of length L_1 near the ends of the slit. If it is assumed that the reaction stress in the elastic zone is approximately given by eq. (11), the elastic stress is represented by

$$\sigma_w = \frac{\sigma_Y}{2}\left(\frac{L_c}{L+2x} + \frac{L_c}{L-2x}\right) \quad (15)$$

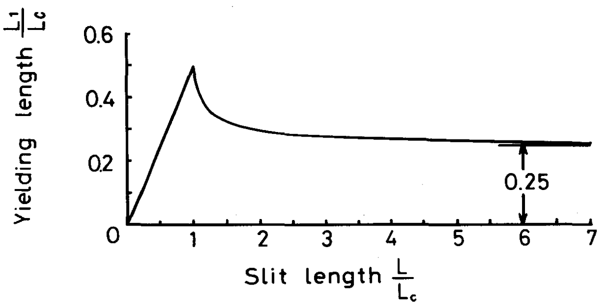

Fig. 5. Yielding length as a function of $\frac{L}{L_c}$.

Table 1. Critical slit length L below which yielding zone covers all over the slit length.*

Yield stress of weld metal σ_Y Kg/mm²	$\frac{L_c}{h}$	L_c in mm when h = 25 mm	h = 50 mm
50	6.0	150	300
60	5.0	125	250
70	4.3	110	220
80	3.8	94	188
90	3.4	84	168

* $m = 4.5 \times 10^{-2}$, $E = 2.1 \times 10^4$ Kg/mm²

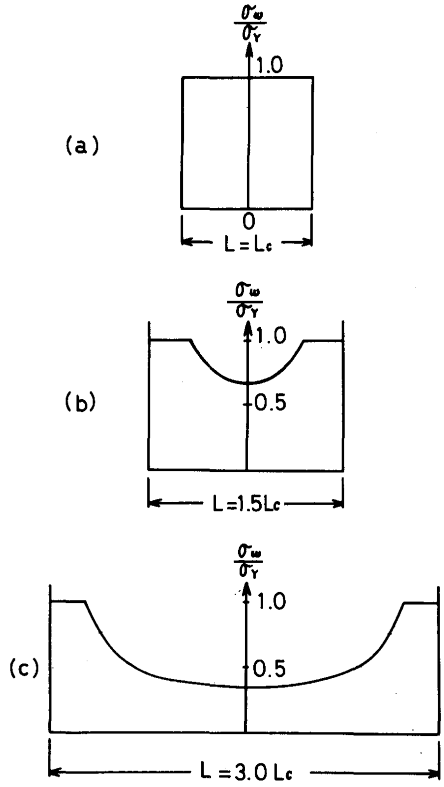

Fig. 6. Examples of the distribution of the reaction stress along the weld line.

Figure 6 shows examples of the distribution of the reaction stress.

3. 3 Deformation of weld in the yielding zone

In the yielding zone, the transverse displacement λ_b is smaller than the free contraction S as shown in **Fig. 4 (a)** and plastic deformation will be produced in the weld. In this paper, average value of the deformation of weld λ_w in the yielding zone will be led from the equation

$$\lambda_w = S - \lambda_b \quad (16)$$

When $L \leqq L_c$, the reaction stress equal to the yield stress σ_Y is uniformly distributed along the slit, and the corresponding stress in the plate σ_b is equal to $\frac{h_w}{h}\sigma_Y$. When uniform stress $\sigma_o = \frac{h_w}{h}\sigma_Y$ is applied along both edges of the slit as shown in **Fig. 7,** the distance between both edges decreases. The distribution of the transverse displacement λ_b becomes an elliptical form as given as[6]

$$\lambda_b = \frac{2Lh_w\sigma_Y}{Eh}\sqrt{1 - \left(\frac{2x}{L}\right)^2} \quad (17)$$

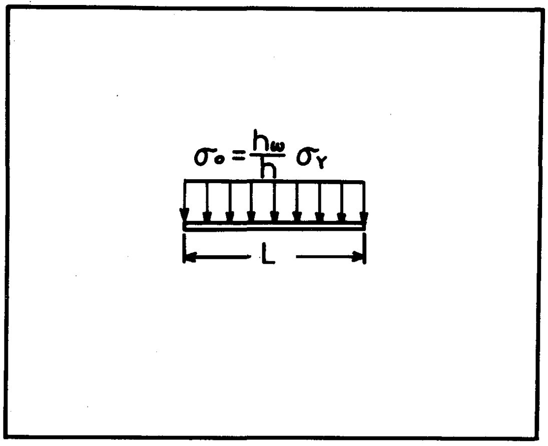

Fig. 7.

from which average value of λ_b is obtained;

$$\bar{\lambda}_b=\frac{1}{L}\int_{-L/2}^{L/2}\lambda_b dx=\frac{\pi h_w \sigma_Y L}{2Eh}=S\cdot\frac{1}{2}\frac{L}{L_c} \tag{18}$$

$$\therefore \bar{\lambda}_w=S\left(1-\frac{1}{2}\frac{L}{L_c}\right) \tag{19}$$

when $L>L_c$, the yielding zone is limited at the ends of the slit, each length of which is L_1. The average value of the transverse displacement in the yielding zone will be obtained by Kihara-Masubuchi's method[6]: A new variable θ as shown in **Fig. 8,** which represents a location along the slit, being introduced insted of x, the transverse stress, which is produced by a transverse displacement along the edges of the slit represented by

$$\lambda_b=\sum_{n=1}^{\infty}A_n \sin n\theta \tag{20-1}$$

is given by

$$\sigma_b=\frac{E}{2L}\sum_{n=1}^{\infty}\frac{nA_n \sin n\theta}{\sin\theta} \tag{20-2}$$

When $\sigma_b=\frac{h_w}{h}\sigma_w$ is given by a function of θ, A_n is obtained from eq. (20-2) as

$$A_n=\frac{4Lh_w}{\pi Eh}\cdot\frac{1}{n}\int_0^{\pi}\sigma_w \sin\theta \sin n\theta d\theta$$

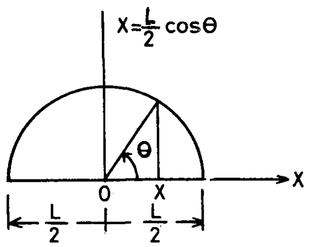

Fig. 8.

and the transverse displacement is given by

$$\frac{\lambda_b}{S}=\frac{4}{\pi^2}\frac{L}{L_c}\sum_{n=1}^{\infty}\frac{1}{n}\left(\int_0^{\pi}\frac{\sigma_w}{\sigma_Y}\sin\theta \sin n\theta d\theta\right)\sin n\theta \tag{21}$$

Thus, for the distribution of the reaction stress as shown **Fig. 6 (b), (c),** the average value of the transverse displacement in the yielding zone is obtained as the following equation.

$$\bar{\lambda}_b=S\cdot\left(\frac{2}{\pi}\right)^2\frac{L}{L_c}\frac{L}{L_1}\psi \tag{22}$$

where

$$\left.\begin{aligned}\psi&=\sum_{n=1,3,5\cdots}^{\infty}\frac{1}{n}\left[(I'_n)^2+\frac{L_c}{L}I'_n I''_n\right]\\ I'_n&=\int_0^{\theta_1}\sin\theta \sin n\theta d\theta\\ I''_n&=\int_{\theta_1}^{\pi/2}\frac{\sin n\theta}{\sin\theta}d\theta\end{aligned}\right\} \tag{23}$$

$$\therefore \bar{\lambda}_w=S\left\{1-\left(\frac{2}{\pi}\right)^2\cdot\frac{L}{L_c}\cdot\frac{L}{L_1}\psi\right\} \tag{24}$$

In eq. (24), $\frac{L_1}{L}$ is determined from eq. (14) for a given value of $\frac{L}{L_c}$. The θ_1-value is also determined for a given value of $\frac{L}{L_c}$ as

$$\sin^2\theta_1=\frac{L_c}{L} \tag{25}$$

Thus, the average deformation of weld in the yielding zone is obtained from eqs. (19) and (24) as a function of $\frac{L}{L_c}$. The result calculated is shown in **Fig. 9.** When $0<\frac{L}{L_c}\leq 1$, $\frac{\bar{\lambda}_w}{S}$ changes linearly from 1 to 0.5. When $\frac{L}{L_c}>1$, it decreases quite slowly and looks almost constant.

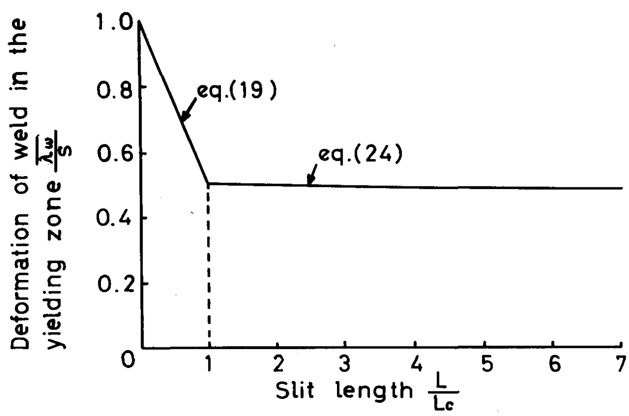

Fig. 9. Average deformation of weld in the yielding zone as a function of $\frac{L}{L_c}$.

4. Restraint intensity in slit weld

Using the reaction stress and the weld deformation in the previous paragraph, restraint intensity in slit weld will be obtained in relation to that of the RRC-weld cracking test or one-dimensional stress field.

The relationship of restraint intensity K versus reaction stress σ_w and weld deformation λ_w in one-dimensional stress field is given by eqs. (7) and (9) respectively. Substituting eqs. (19) and (24) in eq. (9), the restraint intensity in the yielding zone of the slit weld is represented by the following equations;

when

$$\frac{L}{L_c} \leqq 1, \quad K = \frac{\sigma_Y}{m} \frac{2L_c}{L} \qquad (26\text{-}1)$$

$$\text{or} \quad K = \frac{2Eh}{\pi L} \qquad (26\text{-}2)$$

when

$$\frac{L}{L_c} > 1, \quad K = \frac{\sigma_Y}{m} \frac{\pi^2}{4} \frac{L_c}{L} \frac{L_1}{L} \frac{1}{\psi} \qquad (27)$$

In the same way, the restraint intensity in elastic zone, when $L > L_c$, can be obtained by substituting the average value of the elastic stress given by eq. (15) in eq. (7);

$$K = \frac{\sigma_Y}{m} \frac{1}{2} \frac{L_c}{L - 2L_1} \log \frac{L - L_1}{L_1} \qquad (28)$$

Curve ABC in **Fig. 10** shows the K-value in the yielding zone as a function of $\frac{L}{L_c}$ calculated from eqs. (26-1) and (27). When $\frac{L}{L_c} \leqq 1$, the K-value decreases rapidly as $\frac{L}{L_c}$ increases. In the range of $\frac{L}{L_c} > 1$, the K-value decreases quite slowly as $\frac{L}{L_c}$ increases. It looks almost constant equal to $\frac{2\sigma_Y}{m}$. Curve FG in **Fig. 10** shows the K-value in the elastic zone calculated from eq. (28). It decreases to zero when $\frac{L}{L_c} \gg 1$.

Equation (26-2) which gives the K-value of the slit weld when $\frac{L}{L_c} \leqq 1$ is the same representation as in the paper of Masubuchi[4]. Comparing eq. (26-2) to eq. (2), this means that the K-value in the slit weld of length L smaller than L_c is the same as in the RRC-weld cracking test of the restraining length $l = \frac{\pi}{2} L$. When $\frac{L}{L_c} > 1$, or $\frac{L}{h} > \frac{mE}{\pi \sigma_Y}$, however, the K-value in the yielding zone is nearly equal to $\frac{2\sigma_Y}{m}$ as shown in **Fig.10** and it is independent to both the slit length and the plate thickness. Dotted line in **Fig. 10** shows the K-value calculated from eq. (26-1) in the range of $\frac{L}{L_c} > 1$. It approaches to the curve FG as $\frac{L}{L_c}$ increases. When $\frac{L}{L_c} > 1$, therefore, the K-value obtained from eq. (26-2) gives only the restraint intensity in the elastic zone.

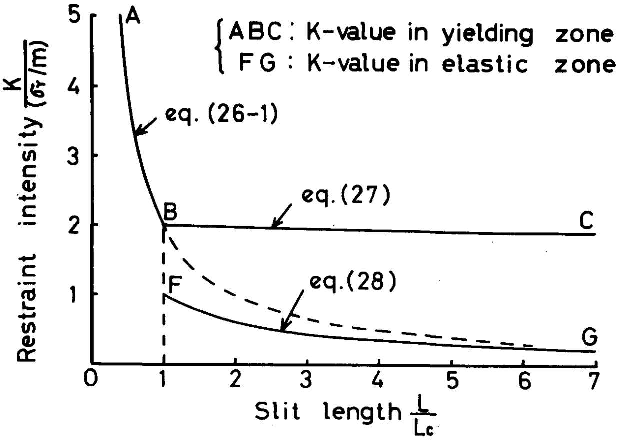

Fig. 10. Restraint intensity in slit weld as a function of $\frac{L}{L_c}$.

5. Restraint intensity of weld cracking specimens

Many researches[7)8)4)] have been made on the restraint of slit type weld cracking specimens such as Tekken-, Lehigh- and H-type. Some of the earlier studies were experimental, but quite recently numerical studies are made by using finite element method. In these studies, uniform stress σ_0 is applied along both edges of the slit as shown in **Fig. 7** and average of the transverse displacement along the slit $\bar{\lambda}_b$ is obtained. The restraint intensity is determined as a form

$$K = K_0 h \quad \text{where} \quad K = \frac{\sigma_0}{\bar{\lambda}_b} \qquad (29)$$

The author and his colaborator obtained experimentally[7)] and numerically the K_0-value of Lehigh- and Tekken-type specimens as shown in **Fig. 11.** The

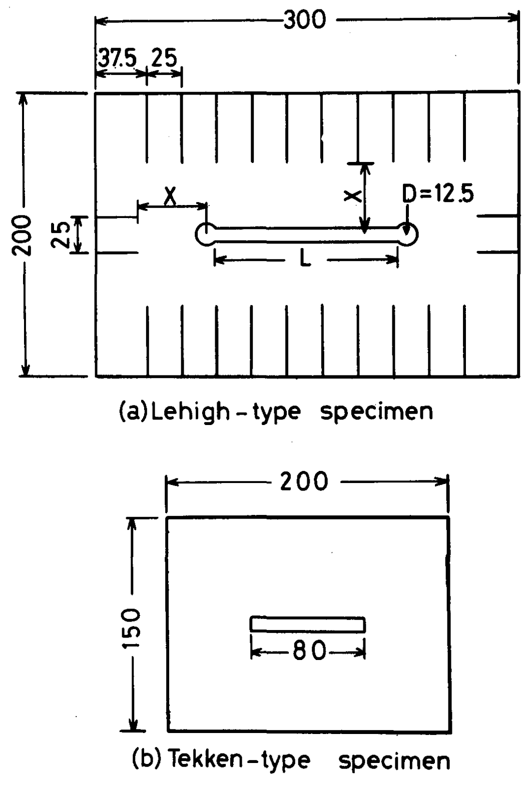

Fig. 11. Weld cracking test specimens.

Table 2. The K_o-values for weld cracking test specimens.

Slit length (L) mm	X mm	K_o Kg/mm²-mm	$\bar{K}=\frac{K_oL}{E}$	Minimum value of $\frac{h}{\sigma_Y}$
(1) Lehigh-type specimen*				
75	40	34	0.121	0.835
	50	54	0.193	0.526
	70	60	0.214	0.474
	80	66	0.236	0.430
	90	68	0.243	0.418
	100	75	0.268	0.379
125	40	11	0.065	2.58
	50	21	0.125	1.35
	60	27	0.161	1.05
	70	34	0.202	0.835
	80	36	0.214	0.789
	100	44	0.262	0.645
(2) Tekken-type specimen**				
80		113	0.430	0.252

* Measured values[7]
** Calculated value by finite element method

results are summarized in **Table 2** with the nondimensional restraint intensity $\bar{K}$ defined by Masubuchi[4]. Since these values are obtained according to the definition given by eq. (29), the significance of the K_o-value will be changed by the thickness of the specimen: When the thickness is larger than a critical value h_o, general yielding of weld will cover the slit length and the K_o-value will be related to the average deformation of weld as given by

$$\bar{\lambda}_w = S\left(1-\frac{\sigma_Y}{mK_o h}\right) \tag{30}$$

When the thickness is sufficiently smaller than h_o, on the other hand, general yielding will be limitted to both ends of the slit and the K_o-value will become only the measure of average reaction stress in the elastic zone.

The critical plate thickness, above which the relationship of eq. (30) is introduced between the weld deformation and the restraint intensity obtained from eq. (29), may be led from the condition that when $\sigma_o=\frac{h_w}{h}\sigma_Y$, the transverse displacement λ_b at the center of the slit should be less than free contraction S. If it is assumed that the distribution of transverse displacement is an elliptical form even in this case, λ_b at the center of the slit is equal to $\frac{4}{\pi}\bar{\lambda}_b$. Therefore, the avove condition is represented by

$$\frac{4}{\pi}\frac{h_w\sigma_Y}{K_o h} \leqq S$$

or

$$\frac{h}{\sigma_Y} \geqq \frac{4}{\pi}\frac{1}{mK_o} \tag{31-1}$$

or

$$\frac{h}{\sigma_Y} \geqq \frac{28.4}{K_o} \quad (\text{When } m=4.5\times10^{-2}) \tag{31-2}$$

In the right column of **Table 2** are shown the minimum values of $\frac{h}{\sigma_Y}$. The minimum h-value is proportionate to yield stress level of weld metal.

When thickness of plate is above the minimum value, average deformation of weld is given by eq. (30). In Tekken-type weld cracking test, for example, the $\bar{\lambda}_w$-value is given as a function of h as shown in **Fig. 12,** from which average strain produced in weld metal will be estimated: When $h=30$ mm, $\sigma_Y=70$Kg/mm², $S=0.3$ mm and average breadth of weld is assumed 4 mm, the average strain $\bar{\varepsilon}_w$ is estimated as

$$\bar{\varepsilon}_w=\frac{0.540\times0.3}{4}\doteqdot0.04$$

When thickness of plate is less than the minimum value, yielding zone will be produced only at the end parts of the slit, in which the restraint intensity will be independent to the plate thickness.

6. Conclusion

The results obtained in this research are summarized as follows:

(1) In the first-pass welding of heavy plates, the restraint intensity is fairly related to the deformation of weld as well as the reaction stress. The relationship is shown in **Fig. 2** for one-dimensional stress field.

(2) The distribution of the reaction stress in slit

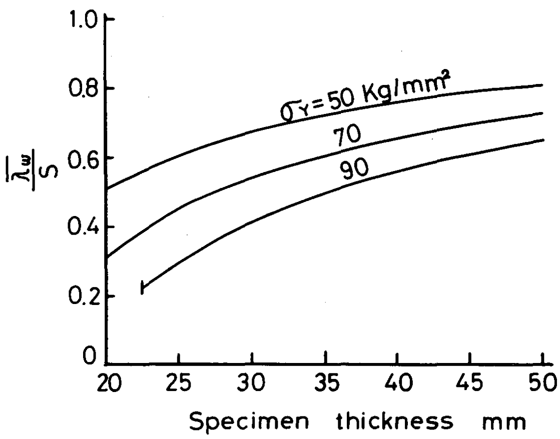

Fig. 12. Average value of weld deformation $\bar{\lambda}_w$ in Tekken-type weld cracking test.

weld depends upon $\frac{L}{L_c}$, in which L is the slit length and L_c is a material constant. (See **Table 1**). When $L \leqq L_c$, general yielding in weld occurs over all the slit length. When $L > L_c$, yielding zones are limited near the ends of the slit. The length of the yielding zone decreases to $0.25L_c$ when $L \gg L_c$. The deformation of weld in the yielding zone is also obtained as shown in **Fig. 9.**

(3) The restraint intensity in the slit weld is obtained as shown in **Fig. 10** as a function of $\frac{L}{L_c}$. When $L \leqq L_c$, the restraint intensity is the same as the one in the RRC-weld cracking test of the restraining length $l = \frac{\pi}{2}L$. When $L > L_c$, the restraint intensity in the yielding zone is nearly equal to $\frac{2\sigma_Y}{m}$ and it is independent to the slit length and the plate thickness. The restraint intensity in the elastic zone decreases down to zero as the slit length increases.

(4) The restraint intensity of weld cracking specimens obtained in the previous studies is quantitatively connected to the deformation or average strain in weld only when the plate thickness exceeds a certain value depending upon the yield stress level of weld metal.

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