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Recent Trend of Researches on Restraint Stresses and Strains for Weld Cracking†

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This paper describes the present status of researches on restraint stress and strain in relation to weld cracking, based on the information obtained from the results of investigation so far performed mainly in Japan. Two kinds of approach are included, which are the concept of the restraint intensity and analyses by the finite element method. The former is rather macroscopic and is of practical usefulness to avoid weld cracking in real structures. The latter gives more precise information about local stress and strain in weld and transient thermal stresses during welding. Future problems to be solved are also discussed.

1. Introduction

Concerning weld cracking, there are unlimited number of factors, both mechanical and metallurgical, which influence the initiation of crack. However, the mechanism of the cracking may be simply stated from the mechanical aspect that the weld crack initiates when the stress and strain induced at a point reach the critical values. Therefore, it will be easilly understood that fundamental problems are to obtain more accurate information concerning the criterion of weld cracking and the stress-strain history at a point where the crack initiation is expected.

When our attension is limited to mechanical characteristic of the cracking, the stress and strain history is most concerned in the entire course of weld thermal cycle. To the present, it is very difficult to collect such documents that give complete information on the stress and strain history. One of main reasons to this fact may be pointed out that it has been very difficult to estimate it both experimentally and theoretically. However, concerning the weld joints under external restraint, a typical example of which is both ends-clamped joint as shown in **Fig. 1,** the reaction force induced, or the intensity of restraint, well predicts the weld crack initiation without detail knowledge on the stress and strain history at a point where weld cracking is expected. Accordingly researches in this field have been mainly directed to evaluate the intensity of restraint of the weld joint.

The question is naturally arised whether the concept of the intensity of restraint can be applied always to predicting the initiation of weld crack or not. In general, thermal stresses induced during welding are attributed to the restraint of free thermal expansion by the surrouding continuum or structural elements. As far as weld joint is externally restrained, the concept could be applied. On the other hand, the problems of cracking in weld joints free from external restraint do not appear to belong to the same kind. In this case, the crack initiation should be discussed by the stress and strain in the weld, which produced by the internal restraint, that is the restraint due to the different rate of cooling during the cooling stage of the thermal cycle. Therefore, to the latter problem, a different approach is neccessary, that is, the evaluation of the local stress and strain is basically required either theoretically or experimentally.

Based on the above discussion, it may be reduced that the weld joint is always subjected to stress and strain by the internal restraint and in some cases, superposed those by the external restraint. Although it is fundamentally required in any cases to obtain the local stress and strain at a point where the crack initiation is expected, the concept of the intensity of (external) restraint well predicts the condition of the crack initiation within the practical degree of accuracy in simple cases, without consideration of the existence of stress and strain by the internal restraint.

In this paper, the present status of researches on restraint stress and strain will be described in relation to weld cracking based on the information obtained from the results of investigation performed mainly in Japan, with the intention to reply the request made at the Joint Meeting of Commissions IX and X of the annual assembly of the IIW, held at Stokholm in 1971.

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2. Fundamental Concept of Intensity of Restraint

As mentioned in Introduction, the intensity of restraint of weld joint is one of measures to evaluate susceptibility of weld cracking from mechanical aspect. The basic concept of the intensity of restraint was first introduced for simple butt weld joint about thirty years ago[1]. Recently, extensive studies were made on the same type of weld joint. Fundamental relation of restraint stress and deformation in weld versus the intensity of restraint was found[3], and critical intensity of restraint for weld root cracking was obtained for various kinds of steel[2)-6)].

Here, the basic concept of the intensity of restraint will be described on a simple butt weld joint of two bars, which is rigidly clamped at its both ends in the entire course of welding (**Fig. 1**). This type of weld cracking test is well known as RRC weld cracking test (rigidly restrained cracking test).

When two bars are connected by welding without any external restraint, thermal contraction is followed during the process of cooling, as seen in **Fig. 2.** In this case, the joint is free from restraint and no reaction stress is expected. On the other hand, when the joint is rigidly restrained, any shrinkage of the joint is not allowed at the entire length and this induces reaction stress in the joint. As the total free contraction, S, is same under a specified welding condition regardless of the length of joint, the more restraint stress is induced for the shorter length, in **Fig. 2.** In this case, the reaction stress produces elongation in the joint by the same amount as the free contraction. These elongations in the base metal and weld metal are denoted by λ_b and λ_w respectively. They should hold the following relation at any stage of cooling.

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

When the plate thickness h is sufficiently large as compared with the throat depth h_w, the 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 $P(=\sigma_w \cdot h_w)$ may be obtained as illustrated in **Fig. 3.** The line OYW represents the

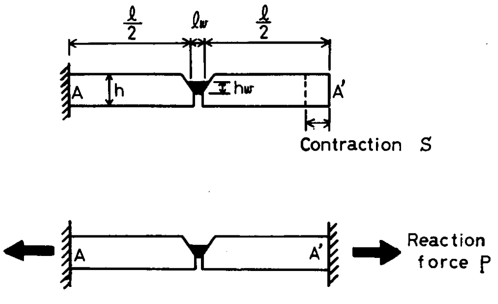
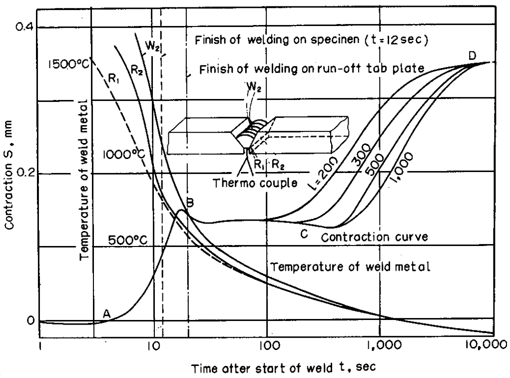
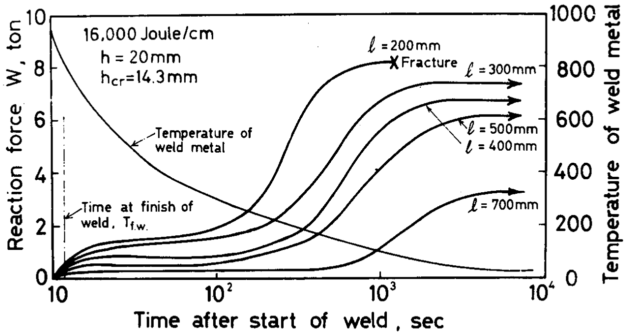


Fig. 1. Simple butt weld joint under restraint.

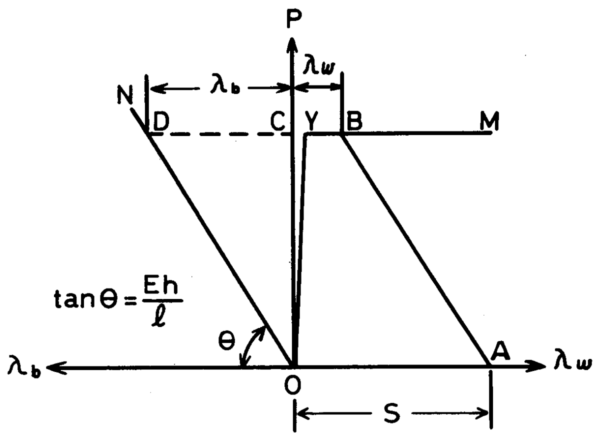


(a) Effect of gauge length l on contraction process.



(b) Effect of restraining gauge length on reaction force.

Fig. 2. Contraction and reaction force of mild steel welds.



(c)

Fig. 3. Relationship of reaction force versus deformation of base plates and weld metal under restraint.

relationship between P and λ_w and the line ON represents the relationship between P and λ_b. Taking $S=\overline{OA}$ and $\overline{AB}//\overline{ON}$, one may obtain $\lambda_b=\overline{CD}$, $\lambda_w=\overline{BC}$ and $P=\overline{OC}$. The gradient of the line ON, or Eq. (2)

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

where E is Young's modulus of the material, indicates the stiffeness of the base metal against the reaction force, and it is so called as "Intensity of Restraint".

When the length of specimen becomes shorter, the stiffness would be greater, and the inclination of the line ON becomes steeper. Consequently, a greater reaction force will be induced in the joint and a smaller elongation will be observed in the base metal and a larger elongation in the weld under the same welding condition as before. The degree of stiffness of the base metal, or the intensity of restraint, influences the resulting reaction force and then, the restraint stress in the weld.

The average restraint stress in the weld, σ_w is simply calculated by

$$\sigma_w = \frac{P}{h_w} = \frac{S}{h_w}\left(\frac{K}{1+K/K_w}\right) \tag{3}$$

in which K_w is the stiffness of the weld metal. The actual length of the weld metal which produces the elongation, λ_w is usualy small compared with that of the base metal. Accordingly, in the case where the restraint stress is so small that the stress in the weld, σ_w is within the elastic range, the elongation, λ_w can not be large. This implies that the stiffness of the weld metal is very large and Eq. (3) can be reduced in the form,

$$\sigma_w = \frac{S}{h_w} K = m \cdot K \tag{4}$$

This equation indicates proportionality between the intensity of restraint and the restraint stress in the weld. In the above equation, m is a numerical factor given by

$$m = \frac{S}{h_w} = \alpha\sqrt{\frac{\theta_s H \tan\beta}{c}} \tag{5}$$

where

α : coefficient of thermal expansion (°C^{-1})
θ_s : melting temperature of weld metal (°C)
2β: bevel angle of weld groove
c : specific heat of the material (cal/gr.°C)
H : specific deposited heat (cal/gr)

The m value is independent to the plate thickness and weld heat input, and usualy it takes a value between 3.8×10^{-2} and 5.5×10^{-2} for manual arc welds of steels.

As understood from Eq. (4), when the intensity of restraint becomes large, the stress, σ_w may reach the yield stress. Then, Eq. (4) is no longer effective, since the elongation, λ_w becomes large due to yielding and the stiffness of the weld metal is no more large enough to neglect the fraction, K/K_w with respect to unity in Eq. (3). Consequently, under the assumption that the weld metal is elastic perfectly plastic the restraint stress in the weld, σ_w can not exceed the yield stress, and the elongation in the portion is obtained by the following equation, derived from Eq. (3),

$$\lambda_w = S\left(1 - \frac{\sigma_Y}{m \cdot K}\right) \tag{6}$$

These relations are illustrated in **Fig. 4.** Thus, the intensity of restraint is related to both restraint stress and deformation in weld.

There has been conducted a series of experimental studies of RRC test on various kinds of steels, such as mild steel[3], HT60[3], HT75[4,5] HT80[3], and HT100[6]. Some examples of the test results on the relation of σ_w versus K are shown in **Fig. 5.**

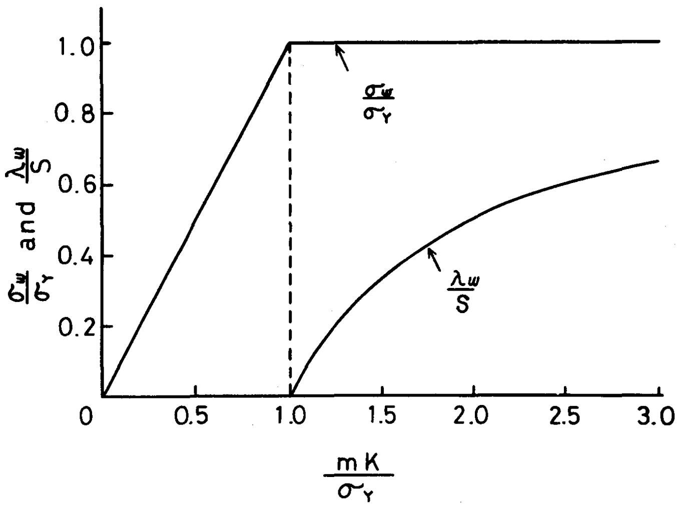


Fig. 4. Relationship between reaction stress σ_Y and deformation of weld λ_w versus restraint intensity K.

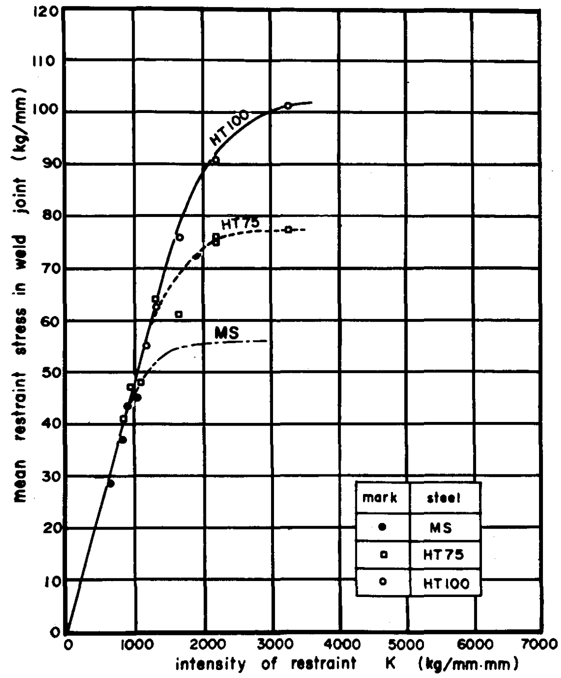


Fig. 5. Relation between mean restraint stress and intensity of restraint K in 100 ton test.

In a range of smaller intensity of restraint, linearity in the relation between the intensity of restraint and reaction stress is observed for all kinds of steel. On the other hand, the average critical stress for the initiation of weld cracking takes different values for different materials and different preheating temperatures[3,4,7,8]. The critical stress is rather lower for the steels having higher strength, well within the elastic range. Thus, the critical stress, in this case, can be predicted directly by the intensity of restraint, that is from Eq. (4).

So far discussed is the average stress and deformation induced in the weld under restraint. The actual stress at the point where weld crack initiates is supposed to be higher than the average since there is geometrical factor which produces stress and strain concentrations. A simple method to estimate the local stress and strain is to magnify the average ones by the concentration factor. Experiment[9] by photo-elasticity reveals that the stress concentration factor of oblique y-groove weld ranges between 2.9 and 3.4 at the root and 1.5 and 1.7 at the toe. Strictly speaking, the above method may overestimate the stress and underestimate the strain if the result of elastic stress analysis is applied. Usually, redistribution of stress is taken place by plastic upsetting and plastic strain in the weld is produced in the entire course of welding. This will be delt later in Chapter 5.

3. Intensity of Restraint in Two-dimensional Stress Field

3. 1 Slit Weld

In a slit weld, in which a slit is made in a plate and welding is done into a part of the slit, the weld may be a short or tack weld, or a continuous long weld. For short weld, the intensity of restraint will be rather simply calculated in a similar way to one-dimensional analysis described in the previous chapter. On the other hand, for continuous weld, the intensity of restraint will be influenced by the welding sequence, environmental conditions etc., and two-dimensional stress analysis will be required for obtaining it. Therefore, the problem will become of more complex nature.

Here, in order to understand general characteristics of restraint in the two-dimensional stress field, the slit weld in an infinite plate will be discussed for two cases, a short weld and a continuous long weld, (**Fig. 6**).

When a short weld is made in the slit, the final shrinkage and resulting stress are supposed approximately uniform in the weld, (**Fig. 6 b, c**). In this case, the intensity of restraint is evaluated[10] by direct application of the definition made in the previous chapter. It varies along the slit according to the location of the

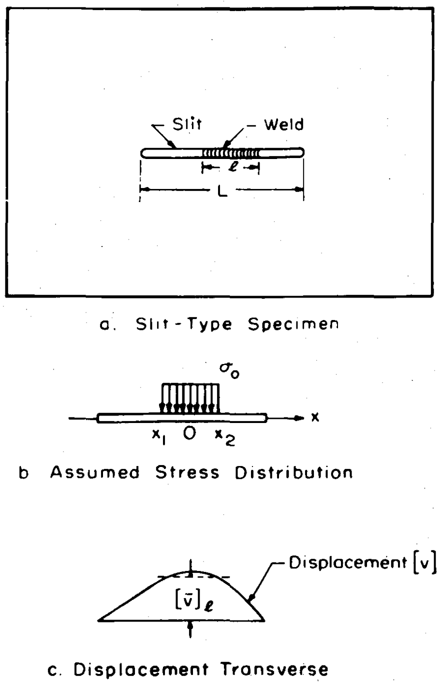


Fig. 6. Analysis of degree of constraint K of a slit-type weld.

weld and it is the highest at the ends. An analytical result is shown in the following,

$$K=\frac{\pi}{2}\,\frac{Eh}{L}\,\frac{l}{L}\,\frac{1}{\phi} \tag{7}$$

where

$$\phi=\sum_{n=1}^{\infty}\left[\int_{\theta_1}^{\theta_2} \sin\theta\cdot\sin n\theta\; d\theta\right]^2$$

$$x_1=\frac{L}{2}\cos\theta_1\,,\quad x_2=\frac{L}{2}\cos\theta_2$$

By the slit weld, transverse displacement occurs over the length of slit. If an additional weld is laid, the transverse displecement is superposed to the previous one. As a result, two short welds produce larger displacement than single short weld[11]. This implies that the intensity of restraint is smaller in two short welds than that in single one based on the definition. With the same reason, it should be lower in a continuous long weld.

In the following, the intensity of restraint will be obtained for the case of a continuous weld[12]. In the analysis, the materials, the base and weld metals, are assumed elastic perfectly plastic. The thickness of base plate, h, is usually larger than that of weld, h_w, and the base plate is assumed to behave elastically under any magnitude of the reaction force, including the case where the weld metal reaches general yielding.

Concerning mechanical conditions induced in the weld during cooling, two simple conditions are considered:

(a) The resulting reaction force is uniform along the slit.
(b) The shrinkage of the weld is uniform along the slit.

The actual condition is supposed to exist between the above two conditions and rather close to the latter. The analysis will be performed under this loading conditions.

When a uniform dislocation is provided along the slit, the elastic stress analysis gives a result on transverse stress distribution in the weld as

$$\sigma_w = \frac{h}{h_w} \sigma_b = \frac{mEh}{2\pi} \left(\frac{1}{L+2x} + \frac{1}{L-2x} \right) \qquad (8)$$

In order to cover the entire slit length by plastic region, it should be satisfied, at least, that $\sigma_w = \sigma_Y$ at $x=0$. Thus, the slit length below which plastic region covers the entire slit length is calculated as

$$L_c = \frac{mEh}{\pi \sigma_Y} \qquad (9)$$

It is seen from Eq. (8) that the stress becomes infinitely large in the vicinity of the ends of slit, at $x = \pm \frac{L}{2}$ regardless of the slit length, and plastic upsetting should occur in the weld of this portion, (**Fig. 7**).

The extent of the plastic portion, L_1, When $L \geq L_c$ is calculated from Eq. (8), by putting the condition that $\sigma_w = \sigma_Y$ at $x = L - 2L_1$

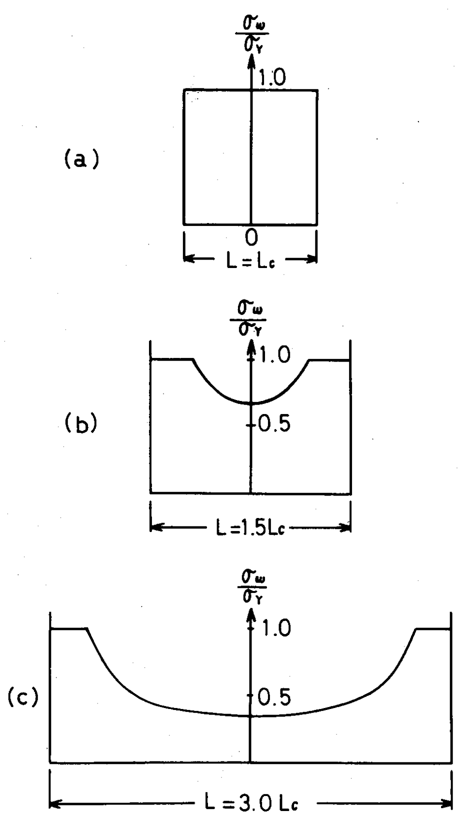


Fig. 7. Examples of distribution of reaction stress along the weld line.

$$2L_1 = L\left\{1 - \sqrt{1 - \frac{L_c}{L}}\right\} = \frac{L_c}{2} \times \left\{1 + \frac{1}{4}\left(\frac{L_c}{L}\right) + \frac{1}{8}\left(\frac{L_c}{L}\right)^2 + \cdots\cdots\right\} \qquad (10)$$

Based on the results obtained on the stress and deformation along the slit, the intensity of restraint is calculated for a slit weld following the difinition made for the one-dimensional stress field.

In the case where the yielded zone covers the entire length, that is $L \leqq L_c$ the average value of the intensity of restraint is

$$K = \frac{\sigma_Y}{m} \frac{2L_c}{L} \qquad (11\text{-}1)$$

or $$K = \frac{2Eh}{\pi L} \qquad (11\text{-}2)$$

Equation (11-2) is the same as the one obtained from Eq. (7) by putting $l = L$.

When the yielded zone is limited only near the ends of slit, that is $L > L_c$, K is expressed separately for the elastic and plastic portions as

$$K = \frac{\sigma_Y}{m} \frac{\pi^2}{4} \frac{L_c}{L} \frac{L_1}{L} \frac{1}{\psi} \quad \text{for plastic} \qquad (12)$$

$$K = \frac{\sigma_Y}{m} \frac{1}{2} \frac{L_c}{L - 2L_1} \log \frac{L - L_1}{L_1} \quad \text{for elastic} \qquad (13)$$

where $$\psi = \sum_{n=1,3,5\cdots}^{\infty} \frac{1}{n} \left[(I'_n)^2 + \frac{L_c}{L} I'_n I''_n \right]$$

$$I'_n = \int_0^{\theta_1} \sin\theta \sin n\theta \, d\theta$$

$$I''_n = \int_{\theta_1}^{\pi/2} \frac{\sin n\theta}{\sin\theta} \, d\theta$$

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

The intensity of restraint calculated from Eqs. (11), (12) and (13) is shown as functions of $\frac{L}{L_c}$ by the curve AB, BC and FG respectively in **Fig. 8.** When $L \leq L_c$, it decreases rapidly as the slit length increases, and it

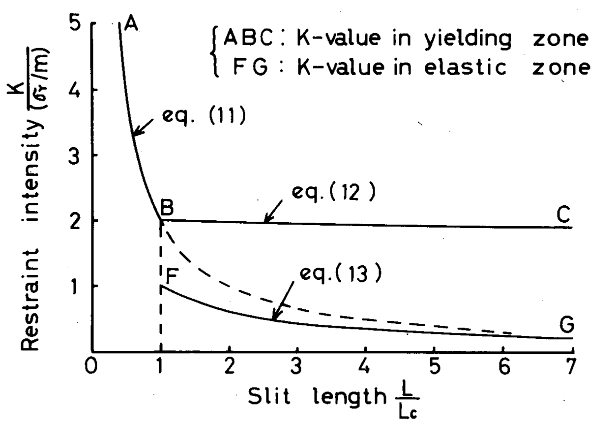


Fig. 8. Restraint intensity in slit weld as a function of L/L_c

is the same as the one in RRC-test of the restraining length $\frac{\pi}{2}L$. When $L > L_c$, although the intensity of restraint in the elastic portion decreases and tends to zero as the slit length increases, in the plastic portion at the slit ends it is nearly equal to $\frac{2\sigma_Y}{m}$ independent to both the slit length and the plate thickness.

3. 2 Slit-type Weld Cracking Specimens

Various kinds of weld cracking test have been used for investigating susceptibility of weld cracking. Here, the discussion will be limited to so-called slit-type weld cracking test such as Tekken- and Lehigh-types. In order to apply the result of the weld cracking tests to actual welding works, it will be practically important to select a common parameter to correlate both the test specimens and real structures. The intensity of restraint is considered to predict the condition of the crack initiation within the practical degree of accuracy without paying special regard to local mechanical history. Thus, the intensity of restraint is regarded as a good measure for this purpose and many investigators have directed their effort to evaluate the intensity of restraint experimentally[13][14][15][16] and analytically[10][16][17][18].

In the analyses are assumed three types of loading conditions used in calculation, which may be produced by weld shrinkage: The shrinkage produces
(a) a uniform stress along the slit[10],
(b) a uniform displacement (dislocation)[18], or
(c) a parabolic distribution of dislocation[17].
As discussed in the previous section, plastic upsetting is always observed at least in the vicinity of the ends of slit. This affects the intensity of restraint. When the slit length is smaller than a limit, that is $L < L_c$, plastic zone is spread all over the slit length. This implies that the reaction stress is almost equal to the yield stress of the weld and the assumption (a), the shrinkage producing a uniform stress, will be reasonable in evaluating the intensity of restraint. On the other hand, in the case of long slit length, the intensity of restraint is rather small in most portion of the slit and the assumption (b), imposing a uniform dislocation, will be a good approximation. Furthermore, elastic-plastic analysis would provide more reliable results. When a uniform stress is imposed along the slit, the corresponding elastic displacement is of an elliptical from. An elliptical distribution of dislocation is very similar to a parabolic one. Thus, the assumption (c) may be regarded as a similar assumption to the assumption (a).

Experimental results of restraint stress induced by welding on slit-type specimen reveal that the value of restraint intensity is proportional to the thickness of specimen[15], and it is well represented by a form

$$K = K_0 \cdot h \tag{14}$$

In Eq. (14), K_0 is so-called as restraint coefficient.

Table 1 is a summary of the values of the restraint coefficient so far obtained for various slit-type specimens as illustrated in **Figs. 9** and **10**. It includes the results obtained by three kinds of methods, (a) calcu-

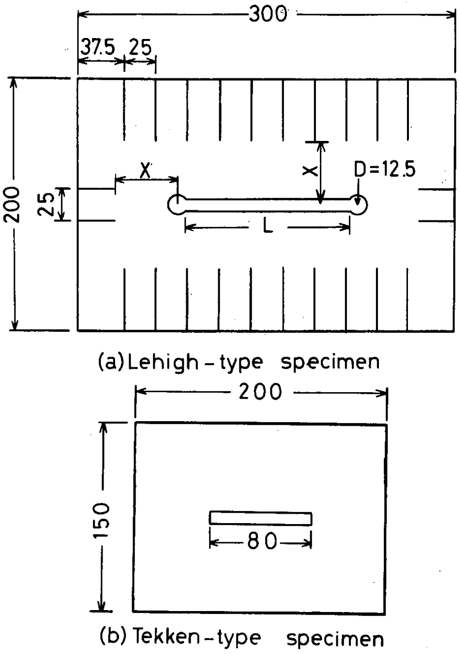


Fig. 9. Weld cracking test specimens.

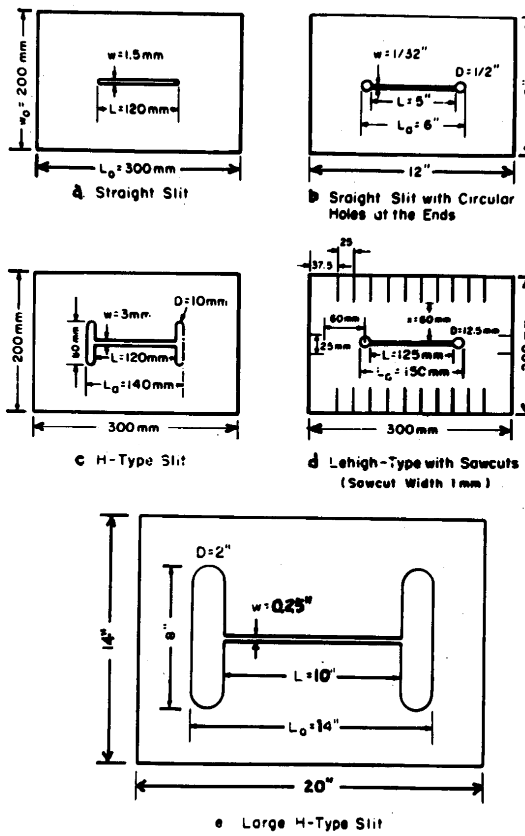


Fig. 10. Joint configurations used in obtaining restraint intensity by computer analysis.

Table 1. Summary of the values of restraint coefficient of slit type weld cracking specimens.

No	Type of Specimen	Size of Specimen mm	Slit Length mm	Restraint Coeff; (K_o) kg/mm.mm	Remark
1	Tekken-Type[18] (Straight Slit)	200 × 150	80	113	a
2	Tekken-Type[13] (H-Slit)	200 × 150		59	b
3	Rectangular Plate[16] (Straight Slit)	300 × 200	150	28	c
4	ditto	300 × 200	120	82	a
5	Straint Slit, Circular Holed 12 mm o, at its ends	300 × 200	138	31	c
6	ditto	300 × 200	125	49	a
7	H-Slit with Saw Cut[15]	200 × 150	80	Saw cut x= 0 mm; 65 10 ; 58 20 ; 48 30 ; 35 40 ; 27	c
8	H-Slit[10]	300 × 200	120	40	a
9	Lehigh-Type[13]	300 × 200	75	x= 40 mm; 34 50 ; 54 70 ; 60 80 ; 66 90 ; 68 100 ; 75	b
10	Lehigh-Type[13]	300 × 200	125	x= 40 mm; 11 50 ; 21 60 ; 27 70 ; 34 80 ; 36 100 ; 44	b
11	Lehigh-Type[10]	300 × 200	125	x= 60 mm; 31 100 ; 48	a
12	Large H-Type Slit[10]	500 × 350	250	6	a

*: Intensity of restraint $K = K_0 \times$ (plate thickness)
a: Analysis by finite element method
b: Experiment with a loading device
c: Obtained from the test results of restraint stress and deformation induced by welding

lated results by finite element method, (b) experimental results with a loading device and (c) estimated results from actual restraint stress and dislocation by welding. The values of the restraint coefficient obtained by the method (b) almost agree with those by the method (a) (**Fig. 11**). However, difference is found in some cases between methods (a) and (b) as seen in No. 3 and No. 4 in **Table 1.** This may be attributed to the fact that the breadth of slit gives appreciable effect to stress and deformation near the ends of the slit.

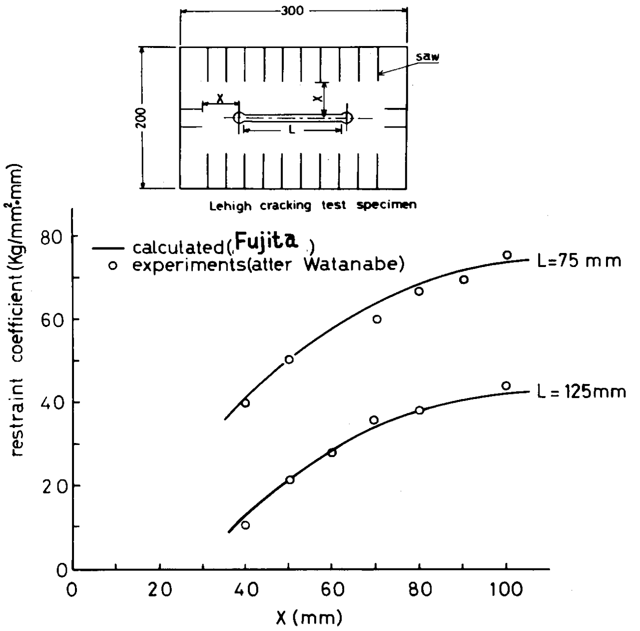


Fig. 11. Restraint coefficient of Lehigh-type weld cracking specimens.

4. Intensity of Restraint in Real Structures

In real structures, there are several types of connections, not only butt weld but also fillet weld. In contrast with butt weld, relation between the intensity of restraint and weld cracking is not completely clarified yet in fillet weld and this problem will not be discussed in this paper. Furthermore, there are their combined types, such as butt weld of plates being constrained by stiffeners. Butt welded connections so far dealt are constrained by simple tension. On the other hand, the combined connection mentioned above is constrained by the stiffeners in the perpendicular direction to the weld line (**Fig. 12**).

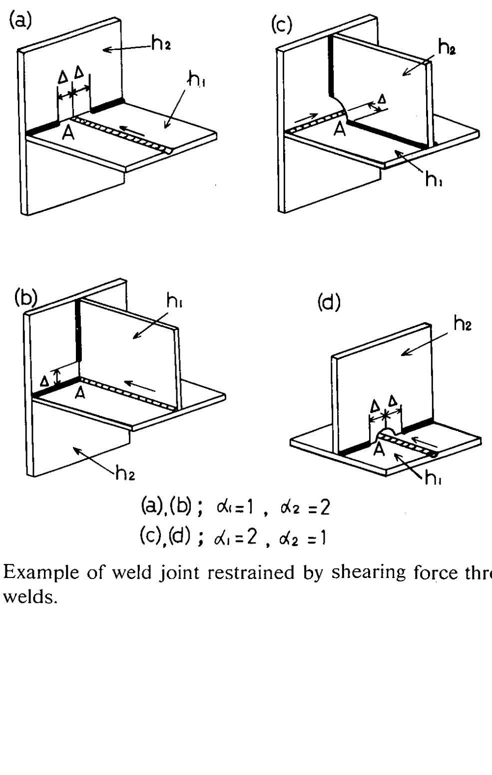


Fig. 12. Example of weld joint restrained by shearing force through fillet welds.

Shear rigidity of fillet weld which connects the plates and stiffener is theoretically analysed. Based on the result of analysis, the intensity of restraint of this type of connection is calculated in the following way[19].

Near the end of fillet weld line, large shearing stress is induced under loading due to abrupt change of stress flow and the material is easily subjected to plastic upsetting there[20]. The yielding is limited just to a small portion near the end. In the analysis, this plastic upsetting is neglected and the material is assumed to be perfectly elastic. The plate is not completely effective for shearing forces transmitted from the stiffener along the weld line, especially for a certain distance from the intersection of the plate and stiffener. The concept of effective width is introduced in the analysis. The intensity of restraint of this type is obtained by the following expression.

$$K = \frac{E\mu}{2\alpha_1\left(\frac{B_{eq}}{x_0}\right)\left(\frac{\Delta}{x_0}+1\right)} \tag{15}$$

in which

$$\mu = D/E$$

$$\frac{B_{eq}}{x_0} = \frac{\pi}{(3+\nu)\left\{-E_i\left(\frac{-\Delta}{x_0}\right)\right\} exp\left(\frac{\Delta}{x_0}\right)}$$

$$\frac{1}{x_0} = \sqrt{\frac{\mu J_1}{(B_{eq}\cdot h_1)}} \tag{16}$$

$$J_1 = \left(1+\frac{\alpha_1}{\alpha_2\beta}\right) / \alpha_1$$

$$\beta = \frac{h_2}{h_1}$$

where

E: modulus of elasticity of material (kg/mm²)

D: displacement coefficient of fillet weld (kg/mm.mm)

ν: Poisson's ratio

$E_i(-x)$: Logarithmic integral $\left(\equiv -\int_x^\infty \frac{e^{-x}}{x}dx\right)$

α_1. α_2 : numerical coefficient of effective width with respect to welding plate and restraining plate (=1 or 2)

h_1, h_2 : thickness of plate with respect to welding plate and restraining plate (mm)

Figure 13 shows the value of $\alpha_1 K$ as a function of $h_1/\Delta J_1$ which are calculated from Eqs. (15) and (16). Usually, the value of J_1 ranges between 1.5 and 2 when $\alpha_1=1$, and 1 and 1.5 when $\alpha_1=2$, and the value of Δ is not less than the thickness h_1 of the welded

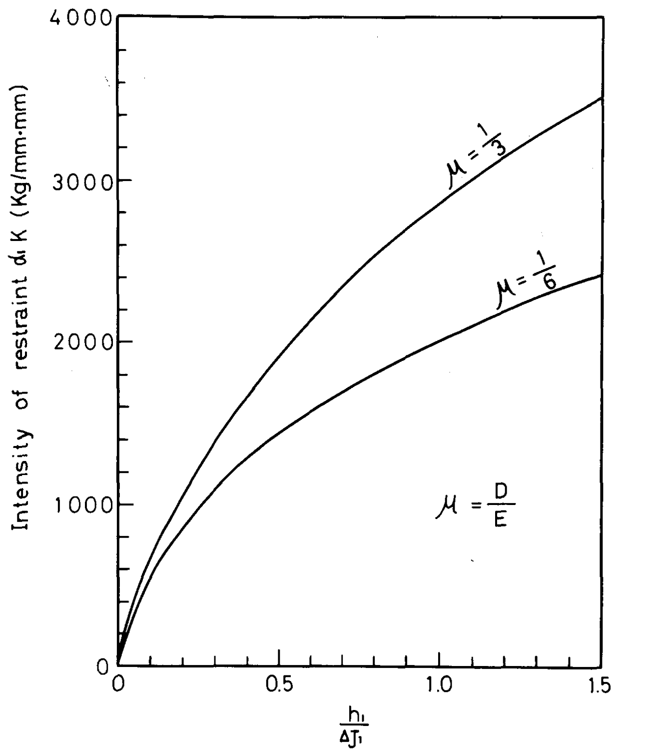


Fig. 13. Intensity of restraint at the intersection of butt and fillet joints.

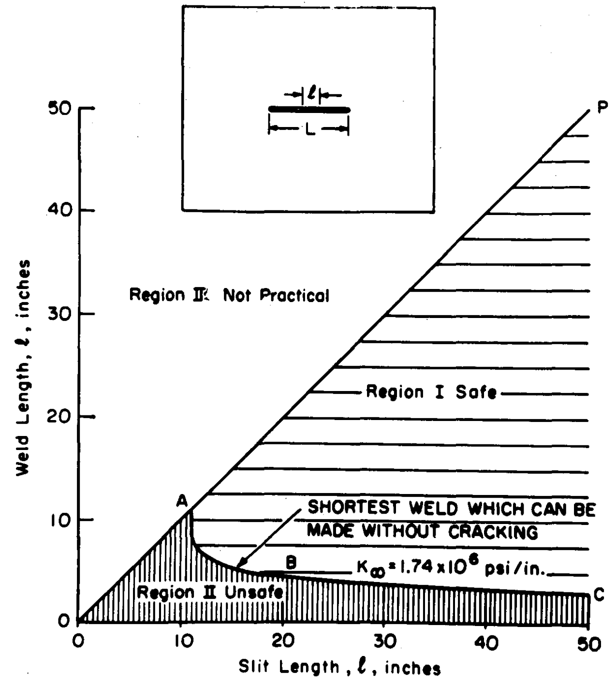


Fig. 15. Relationship between the length of slit in an infinite plate and weld length which gives the K value of 1.74 ×10 psi/in.

plate. The intensity of restraint for this type of connection, therefore, will be estimated at most 1600～2250 kg/mm.mm when $\alpha_1=1$ and 1000～1450 kg/mm.mm when $\alpha_1=2$.

Equation (7) in Section 3. 1 can be used to estimate the intensity of restraint for tack weld of real structures. Some calculations were made on the intensity of restraint when tack weld of length l is located at the center of slit[10]. The results are shown in **Fig. 14,** in which K is defined as $\overline{K}=K/(\frac{Eh}{L})$. From the results, safe tack weld length without cracking, when it is laid at the center of a slit in an infinitely large plate, is obtained as **Fig. 15.**

Before the high speed electronic computer has been advanced, it was difficult to calculate the intensity of restraint of weld connections appeared in real structures, even of simple specimens, except in one-dimensional case. Therefore, actual measurement of the restraint intensity was important and this is still true since experiments will give the real value in any complex structures.

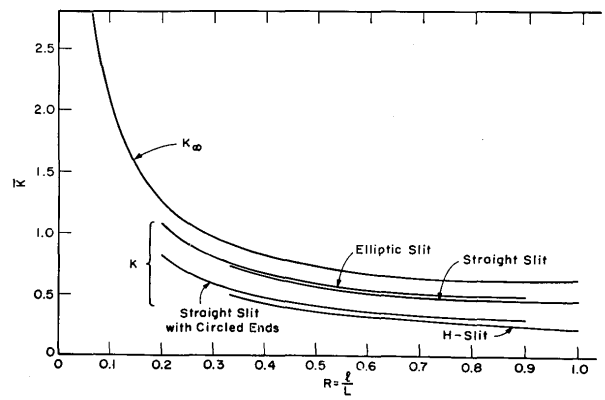


Fig. 14. Relationship between weld length to slit length ratio, R, and nondimentional degrees of constra different cases being studied, $K_\infty$for an infinite plate and K for finite plates.

Table 2 is a summary of the measured values of restraint intensity for weld connections of real structures including ships[21)19)], bridges[22)23)24)], building frames[25)] and spherical containers[26)]. Judging from the experimental results, the magnitude of the restraint intensity in real structures will be usually less than 40h except for special cases such as slit weld and tack weld. (**Fig. 16**). The result is introduced in the final report of JSSC on the determination of preheating temperature in real steel constructions based on the P_w concept[15)22)].

5. Local Stress-Strain in Weld

In the preceeding two chapters, cold weld cracking was discussed for butt weld under a certain degree of structural constraint based on the concept of the intensity of restraint. The average stress and strain in the weld is calculated from the final restrained force which can be estimated by the intensity of restraint and the welding condition. This concept has not been extended to other type of weld connection than the first pass weld of butt joint and this is not directly applicable to weld cracking of fillet weld, in multilayer

Table 2. Summary of measured restraint intensity of weld connections in real structures

Weld Joint at	Plate Thickness; (h); mm	Restraint Coeff; (K_o) Kg/mm.mm	Restraint Intensity; (K) Kg/mm.mm	Remarks
Ship[21]				
Trans. Bulkhead	16	102	1640	
Longi. Bulkhead	13.5	93	1260	Tack Weld
Side Shell	20	44	890	l=80 mm
Bottom Shell	28	25	690	
	28	26	730	
	28	28	780	
Upper Deck	32	40	1280	
	32	38	1220	
Ship				
Deck Longi. Girder	30	29	880	Continuous Long Weld
	30	18	550	
	30	13	400	
	30	13	380	
Bridge				
Corner Weld (Box Shape Member)	50-75	16	800	Tack Weld l=100 mm
		69	3440	
		68	3420	
		40	1980	
Bridge				
Coner Weld (Box Shape Member)	32-38	11	340	Continuous Long Weld
Diaphragm & Web Plate	19-38	11	200	
Diaphragm & Flange Plate	25-50	14	700	
Bridge				
Disphragm & Flange Plate	40-60	45	1800	Continuous Long Weld
Building Frame				
Beam Column Connection	12	41	490	Continuous Long Weld
	28	39	1090	
	34	19	630	

Note: The K-values of continuous long weld shows maximum value measured.

weld, etc., regardless of structural constraint.

In these cases, restraining field is produced by uneven temperature distribution during cooling. The portion at lower temperature restores its strength earlier than the other still at higher temperature and constrains free contraction of the latter portion. Consequently, in place of the intensity of restraint local stress and strain including their histories would be possible to represent a more general initiation condition of weld cracking, such that weld crack initiates when local stress and strain reach critical values. Before the finite element method has been developed, an analysis, was limited to one-dimensional stress field[27][28],

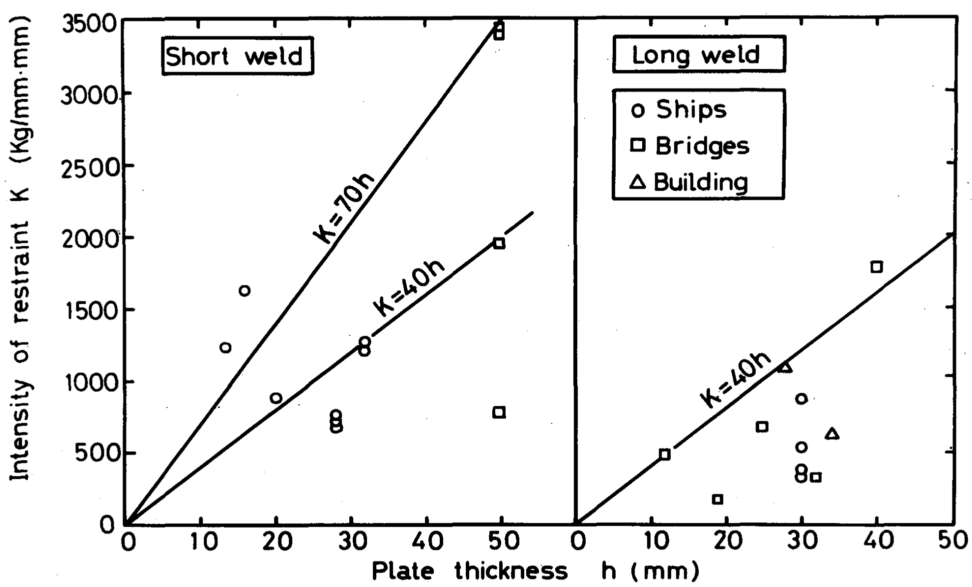


Fig. 16. Restraint intensity of weld joints in real structures.

and very special cases of two-dimension[29]. A general method of thermal elastic-plastic analysis was presented with consideration of temperature dependent properties based on the finite element method and the result of analysis indicates the potentiality of the method[30)31)]. Recently, similar methods are also used[32)33)].

Concerning local stress and strain produced in the weld of butt joint, a series of thermal elastic-plastic analysis was carried out on the RRC Test specimens of a mild steel and a high strength steel[34] (HT-80), as illustrated in **Fig. 1.** The mechanical properties of the weld and base metals for both cases are assumed as shown in **Fig. 17,** taking account of their temperature dependency. The analysis is performed in the entire

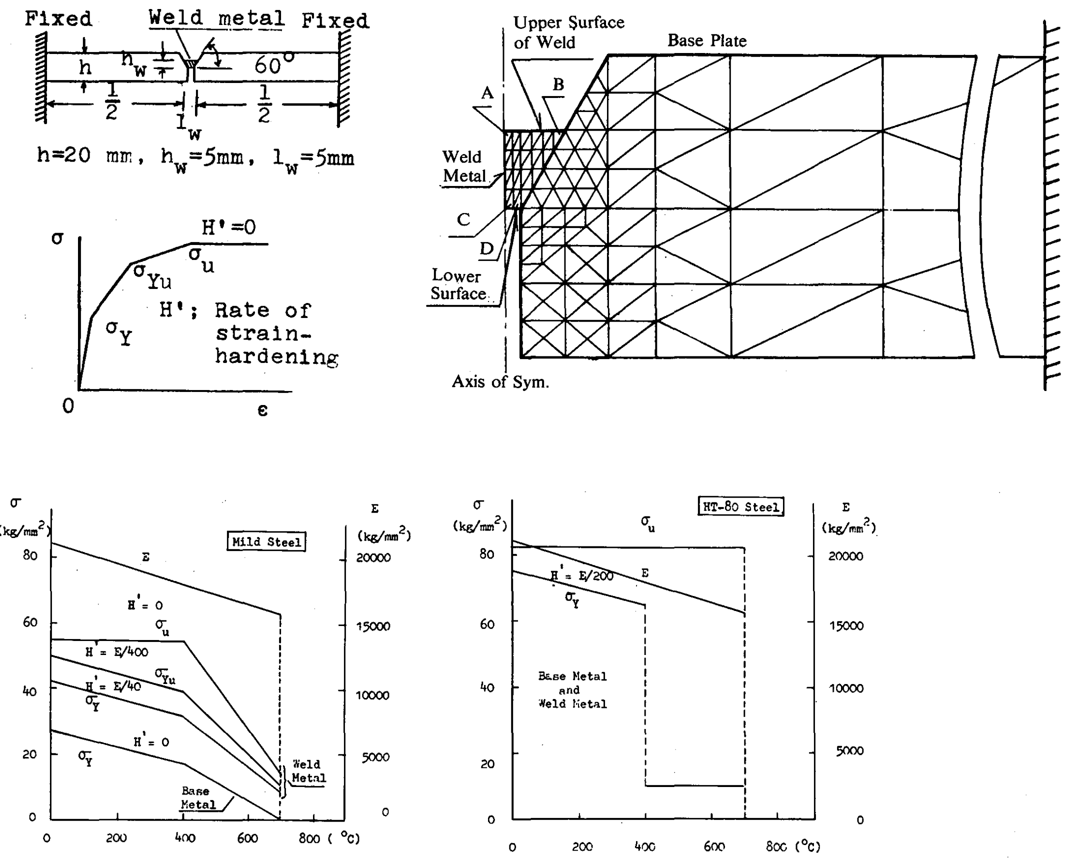


Fig. 17. Mechanical properties dependent on temperature.

course of welding, from a melting temperature, 1500℃ to room temperature, 15℃. Computed local stresses and strains are shown on the specimens of 250 mm length in **Fig. 18.** The plastic strains are induced both in a high temperature range and a low temperature range. On the other hand, stresses are produced partly in an intermediate temperature range and mostly in a lower temperature range. These results are summarized in **Fig. 19,** with respect to the intensity of restraint.

According to the test results, weld crack initiates in the specimen of mild steel at a length of 250 mm and of high strength steel at 600 mm[3]. The calculated final restraint forces are very close to the experimental ones. In this respect, the magnitude of peak local stress and strain would be estimated. The peak local stress reaches the assumed ultimate strength for both steels even through the average one is in the plastic range in the case of mild steel and well within the elastic range in high strength steel. Peak local strains produced in the lower temperature range are approximately 2.0 % and 0.3 % for mild steel and high strength steel, respectively. Both final stress and strain attained are varying inversely with respect to their yield stress.

There are observed some differences of the behaviors during cooling between mild steel and high strength steel[35][36]. These differences are explained mainly by three reasons. Higher level in the yield stress of material delays yielding of the material. In high strength steel, A_r transformation occurs at rather lower temperature with larger magnitude of expansion and the material restores its strength by very small amount before reaching this transformation temperature, (**Fig. 20**). This reduces the final restraint force[3]. Concerning weld cracking, diffusible hydrogen has an important effect to reduce weldability. In high strength

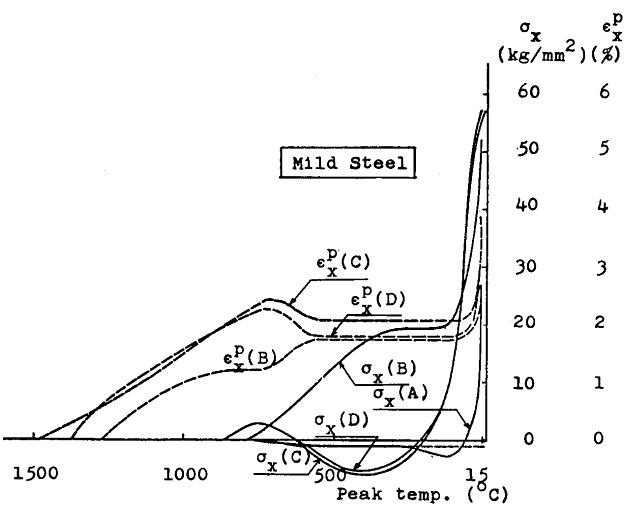


Fig. 18. Thermal stresses and strains in the weld during cooling.

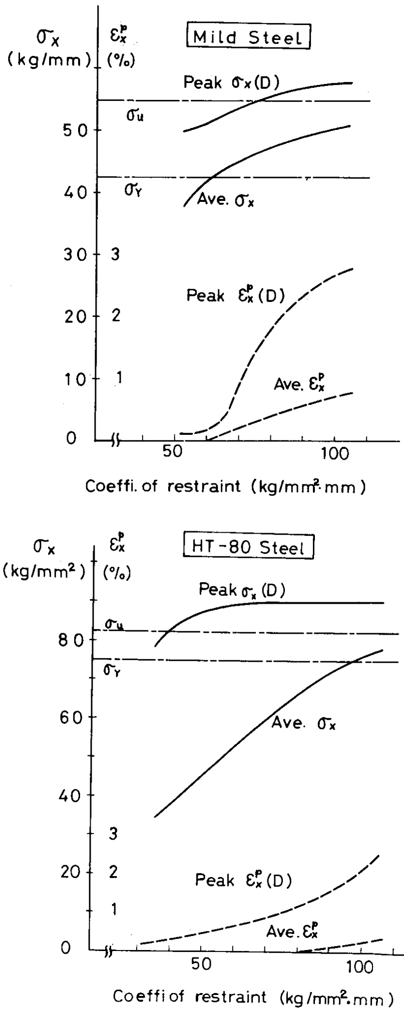
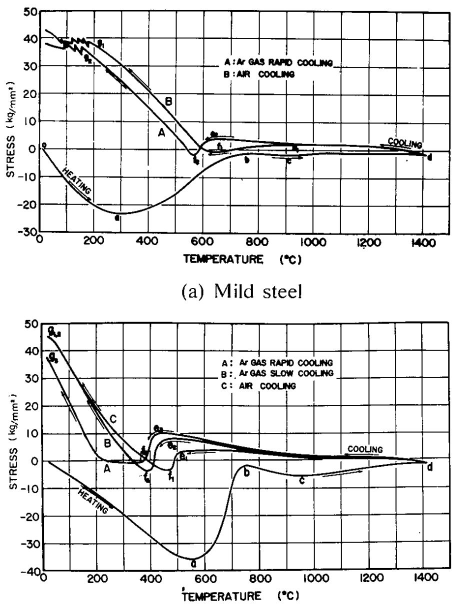


Fig. 19. Computed restraint stresses and strains produced in lower temperature range with respect to coefficient of restraint.



(a) Mild steel

(b) HY80 steel

Fig. 20. Thermal stress developed in mild steel (a) and HY80 steel (b) during weld thermal cycle.

steel, the crack initiates at rather lower stress level[37].

In relation to hot cracking, local strain at high temperature just below solidification temperature range is also interesting. In relating to end cracking in one-side automatic welding seam, some studies are now undertaken in Japan[38)39)].

Restraint stress and strain in fillet weld are analysed. Most part of the weld and heat affected zone is subjected to high stress, above the yield stress, and small plastic strain, less than 1.0 % at highest[40].

6. Transient Stress-Strain and Deformation of a Plate under a Moving Heat Source

In welding, molton metal is supplied continuously into the groove along the weld line. Thus, the base plate is subjected to a moving heat source during the process of welding. Accordingly, analysis of the behavior of plates in welding is expected to be performed under the condition that the plate is subjected to a continuous heat supply by a moving heat source.

To this problem, the elastic analysis is regarded as the first approximation. The elastic analyses were made both in Japan[41] and USSR[42] separately, and provided useful information about transient stress and strain in the plate. Recently, the analysis is being extended to the problem of transient tearing stress in front of a moving heat source, in particular at the end of plate[43].

In order to increase reliability to the result of analysis, the temperature dependent properties should be taken into account. Assuming the mechanical properties of material (mild steel) as shown in **Fig. 21,** a thermal elastic-plastic analysis was made on a bead-on-plate under a moving line heat source[40]. The result furnishes valuable information about transient stress and strain induced in the weld, as examples, transverse stresses are illustrated in **Fig. 22 a** and longitudinal ones in **Fig. 22 b.**

As seen in **Fig. 22,** the portion of molton metal

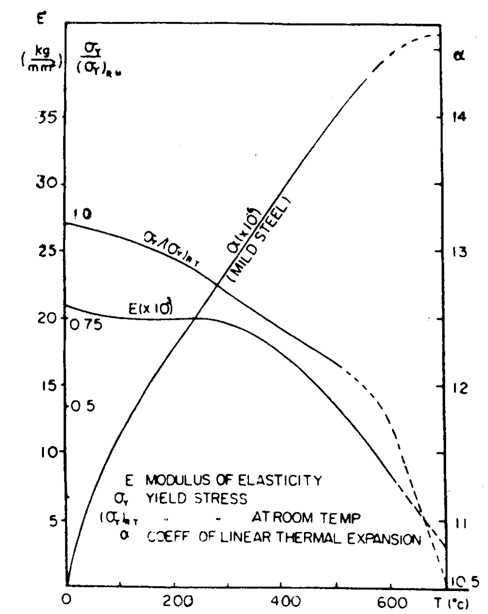
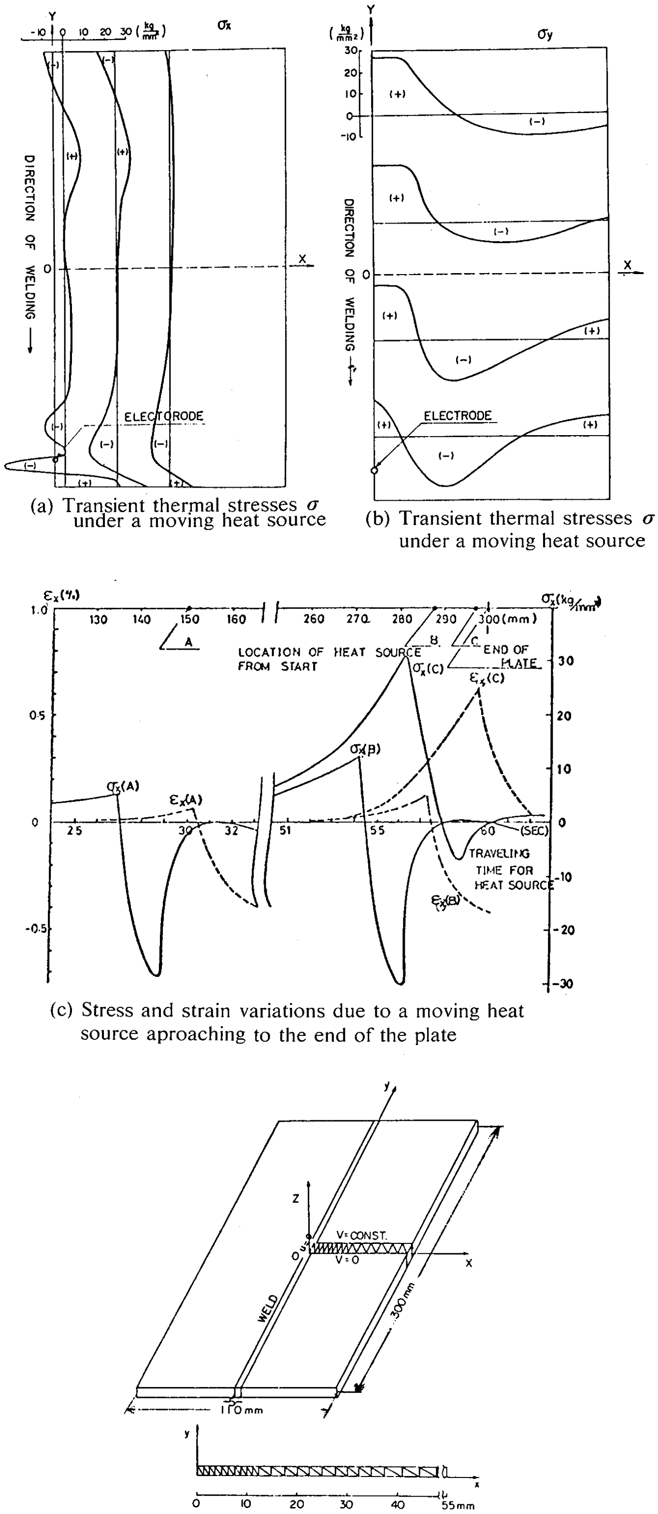


Fig. 21. Mechanical properties dependent on temperature.



(a) Transient thermal stresses σ under a moving heat source

(b) Transient thermal stresses σ under a moving heat source

(c) Stress and strain variations due to a moving heat source aproaching to the end of the plate

(d) A plate and its coordinatcs

Fig. 22. Transient thermal stresses and strains.

does not take any stress, and large expansion strain occurs in its vicinity, but stresses are very small due to less resistance of the material at high temperature. The temperature changes rapidly in front of the moving heat source, where thermal transverse stress is compressive and large. Apart from the heat source, the transverse stress decreases except the case where the heat source is approaching the end of the plate. Concerning longitudinal stress, large tensile stress is produced along the moving line of the heat source in a short time after it has passed.

When a weld is laid along the longitudinal center line of a rectangular plate, the transient stress distribution is analysed by the finite element method under three different types of loading and supporting conditions[44]. The first one is an analysis of the rectangular plate under a moving heat source. The second is an analysis of the plate which is subjected to an instantaneous plane heat source along the center line. The third one is an analysis of an infinitely long plate under an instantaneous plane heat source. The last condition suggests that the analysis is performed only on a narrow strip perpendicular to the center line. After a time has passed and the peak temperature cools down below 1000 °C, fairly similar longitudinal and transverse stress distributions are produced in a transverse section at the center by any of the three types of condition.

More simplified analysis is possible to this kind of ploblem under the following assumptions;

(a) The mechanical properties of the material are not influenced by temperature,

(b) Transverse planes remain planes in the entire course of loading[45].

In general, the analysis furnishes rational result under these assumptions, as far as the resulting residual stresses are concerned. However, the following points should be noted as for the assumptions. The assumption (a) is not appropriate to such material as high strength steels which reveal larger volume expansion during lower temperature range of A_r transformation. As for the assumption (b), the analysis is not applicable to a portion where temperature changes rapidly, such as the portion around a heat source.

As an application of the theories described above, deformation of the plates under a moving heat source is obtained by finite element method in relation to end cracking of one-side automatic welding beam. According to computer analyses of thermo-elasticity, large tearing force and displacement are induced in the tab plate set at the end of welding seam. (**Fig. 23**)[46]. The tearing force induces large transverse displacement in weld metal during solidificantion at a certain distance apart from the end of the plate (**Fig. 24**)[43].

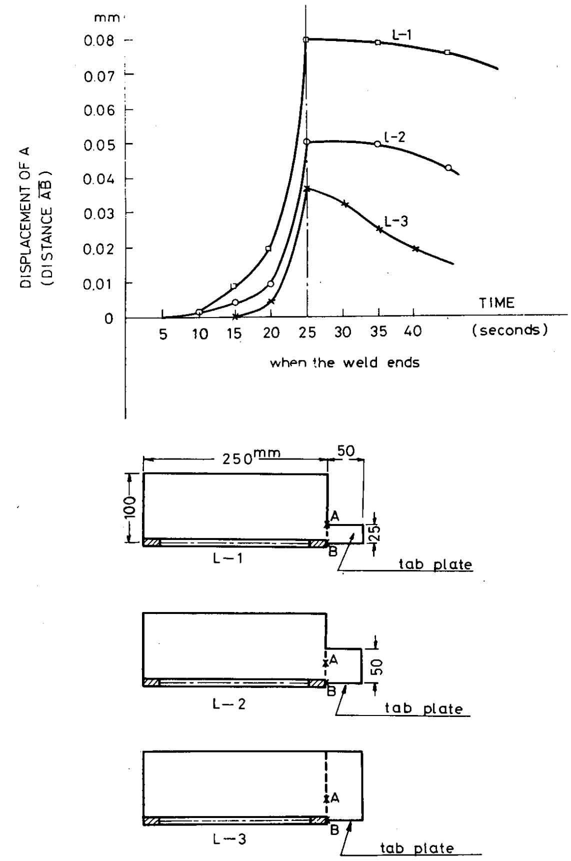


Fig. 23. Displacements at the end of weld.

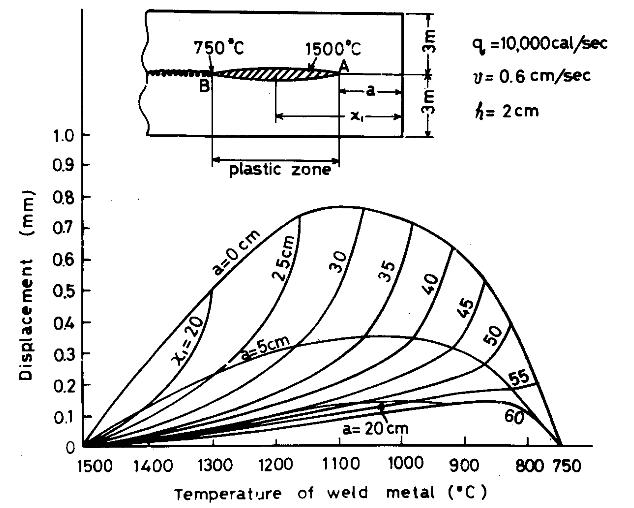


Fig. 24. Displacement of weld metal during solidification at a distance x cm apart from the end of plate.

This will be one of the reasons for the cracking concerned.

7. Discussion and Future Problems

The preceding four chapters were devoted to describe the present status of researches on restraint stress and strain in relation to weld cracking from the mechanical aspect. Many information has been given from both mechanical and metallurgical points of view.

However, there are still many problems to be solved concerning weld cracking even from the mechanical aspect.

As seen so far, the intensity of restraint well predicts the possibility of weld cracking under the external structural constraint, especially in one-dimensional stress field. This concept is extended to two-dimensional stress field and is shown to be applicable to simple connections such as butt weld including structural elements consisting of plates and stiffeners. The concept of the restraint intensity has been introduced in the weldment cracking parameter P_w connected with metallurgical factors[15], and it becomes of practical usefulness to avoid weld cracking in real structures.

When a structure becomes complex, however, the type of weld connections is complicated. The welding sequence and relating conditions may easily influence the degree of restraint of a joint in relation to structural constraint, and the concept may not be applicable as a direct measure to the mechanical condition of welded joint. During welding, the connection is subjected to not only tension but also bending and shear, and the restraint intensity in bending and shear should be introduced. Moreover, the concept of intensity of restraint is applicable only in the case where the joint is under external constraint.

There is an important problem which has not been studied. It is the problem about the propagation of weld crack in the welding stress field. A weld crack initiated may propagate through the weld metal or into the plate under the welding stress induced by the following welding. This is often experienced in welding works of real structures. It should be solved with the aid of fracture mechanics.

There is another approach becoming possible with the aid of an elaborated method of analysis, that is the finite element method. It is tending to express the initiation condition in a little more general way by local stress and strain at a point where the initiation is expected. Although this approach has just been started, it is expected to provide new information about local stress and strain in welds such as multi-layer weld, fillet weld, etc., in connection with weld heat input. This is supposed to be direct and general to a certain extent in comparison with the former, but it requires extensive analysis and a concise expression of the initiation condition would be needed in connection with the diffusion of hydrogen and phase transformation in weld during cooling.

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