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Prevention Against Cold Cracking by the Hydrogen Accumulation Cracking Parameter P_{HA}*

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Abstract

In our previous report IIW IX–1195–81, a new formula for cracking parameter P_{HA} was introduced in order to analyze and predict the critical conditions leading to various types of hydrogen-induced cold cracking in welded high-strength steels.

In this report, the formula for P_{HA} has been given in a more reasonable form by means of a different and simpler procedure for its introduction and by adopting a more rigorous formula for the intensity of restraint of the JIS-y test specimen.

The idea of equivalent intensity of restraint R_{Fy}, which directly concerns the magnitude of local stress concentration near the root of a one-pass weld in a butt-joint, has proven to be very useful in explaining quantitatively the effects of various groove shapes and eccentric weld locations on the values of critical cooling time for the prevention of root cracking.

Moreover, experimental findings on heel cracking (HAZ root cracking in a short fillet weld in a T-joint) of HT50 steels are satisfactorily explained by P_{HA} analysis.

Nomographs and figures are supplied for calculating P_{HA}, cooling times and preheating temperatures.

1. Introduction

Based upon the premise that hydrogen-induced cracking in a steel weld occurs only when the local hydrogen concentration at the instant of crack initiation exceeds a critical value which depends on HAZ (heat-affected -zone) ductility and locally concentrated stress, a new cracking parameter P_{HA} was developed and described in the authors' previous report IIW Doc. IX–1195–81 [1]. P_{HA} analyses of cases of hydrogen-induced cracking in welded high-strength steels have been very useful in establishing the value of critical preheating temperature necessary to avoid cracking, as well as in correlating different cracking test data with those of the JIS-y (oblique-Y groove, Tekken type) test.

In the previous report, the values for intensity of restraint of the JIS-y test specimen were set as follows:

$$R_{Fy}=70\times h, \quad \text{for thickness } h\leqq 40 \text{ mm}$$
$$=2800 \text{ kgf/mm}\cdot\text{mm} \quad \text{for} \quad h>40 \text{ mm.}$$

As this is a rough approximation, the authors employed in this report a more rigorous formula of restraint which was first introduced by Ueda and his co-workers [2].

The slight increase in restraint stress due to an increase in weld heat input, as proposed by Kirihara et al. [3], was ignored in the present report which relies upon the recent experimental evidence presented by Terasaki and his co-workers [4].

Moreover, a simplified procedure is introduced in this report for deducing the cracking parameter P_{HA}. The validity of the parameter is demonstrated through additional experimental evidence.

2. Critical Hydrogen Concentration H_c in JIS-y test

2.1 *Measured values of critical hydrogen concentration*

As was described in detail in the previous report [1], the value H_c of critical hydrogen concentration in the HAZ at 100°C near the root of a weld where a root crack initiates in a JIS-y test specimen, can be calculated with the following equation assuming uniform diffusion of hydrogen:

$$H_c=(\lambda H_D')(U_B)cr \qquad (1)$$

where

H_c (ml/100 g HAZ): critical hydrogen concentration at the fusion line, assuming uniform diffusion of hydrogen.

$(U_B)cr$: critical value of $U_B\equiv H_B/H_o$, ratio of hydrogen concentration H_B at the fusion line where a root crack initiates, to the initial as-deposited concentration H_o, where $H_o\fallingdotseq H_F$.

H_F (ml/100 g FM): diffusible hydrogen content per 100 g of fused metal.

$$\left.\begin{array}{l} H_F=\lambda H_D', H_D' \text{ is effective diffusible hydrogen content,} \\ \lambda=0.60 \text{ and } H_D'=H_D \text{ for low-hydrogen electrode,} \\ \lambda=0.48 \text{ and } H_D'=H_D/2 \text{ for high-cellulose electrode.} \end{array}\right\} \quad (2)$$

H_D (ml/100 g): diffusible hydrogen content per 100 g of deposited metal by JIS Z 3113, glycerine displacement procedure, convertible to the IIW mercury displacement value through the following formula:

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$$H_D(\mathrm{JIS}) = 0.67\ H_D(\mathrm{IIW}) - 0.8 \quad \text{(IIW Doc. II–698–74)} \qquad (3)$$

$$\left.\begin{aligned} U_B &\equiv \sum_{n=1}^{\infty} \frac{1}{n\pi}\,(2\sin n\pi L - \sin 2n\pi L)\ \exp(-n^2\pi^2 L^2 \tau), \\ \tau &\equiv \frac{1}{l_e^2}\int_{\mathrm{MP}}^{\theta} D(t)dt = \sum D_i \cdot \Delta t_i / l_e^2, \\ L &\equiv l_e/h, \end{aligned}\right\}\ \text{Coe and Chano} \qquad (4)$$

where

h(mm): thickness of test specimen,
l_e(mm): effective weld thickness for hydrogen diffusion, $l_e = 0.20$ cm for weld heat input $Q = 17$ kJ/cm (Fujii).
τ: time factor for hydrogen diffusion,
D(cm^2/sec): diffusion constant,
t(sec): time elapsed after solidification,
t_{100}(sec): time to cool to 100°C from solidification.

$$\sum D_i \Delta t_i = 6.87 \times 10^{-4} \exp\{0.412\,(\log t_{100})^2 - 0.101 \log t_{100}\} \qquad (5)$$

The time factor for JIS-y standard test of 17 kJ/cm,

$$\tau_{17} \equiv \tau_{100} \text{ for } 17\ \mathrm{kJ/cm} = (\sum D_i \Delta t_i)_{100} / (0.2)^2 \qquad (5)'$$

Experimental values for critical hydrogen concentration H_c in the JIS-y standard test of the authors' and other reporters on various HT50 to HT80 steels, 20 to 50 mm thick, are plotted in Fig. 1 for different thickness values of 20 to 23 mm, 25 mm, 30 to 32 mm, and 45 to 50 mm, against Ito-Bessyo's carbon equivalent Pcm [5]:

$$P_{cm}(\%) = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B \qquad (6)$$

The values of log H_c seem to decrease linearly with an increasing P_{cm}, that is,

$$\log H_c = a - b\ P_{cm}\,. \qquad (7)$$

Regression analysis yielded the values of a and b shown in Fig. 1.

The values of intensity of restraint in the JIS-y test were set as follows in the previous report [1] for the sake of simplicity:

$$R_{Fy}\ (\mathrm{kgf/mm \cdot mm}) = \left.\begin{aligned} &70\,h, && \text{for } h \leqq 40\ \mathrm{mm}, \\ &2800, && \text{for } h > 40\ \mathrm{mm}. \end{aligned}\right\} \qquad (8)$$

In this report, however, a new formula, proposed by Ueda, Fukuda and Kim [2], is adopted as a better alternative. The $(\bar{R}_p)_\eta$ in Fig. 2 is the mean value of intensity of restraint as related to specimen thickness, calculated assuming uniform loading along the y-groove. It gives somewhat higher values than eq. (8).

Values of log H_c are compared in Fig. 3 with in-

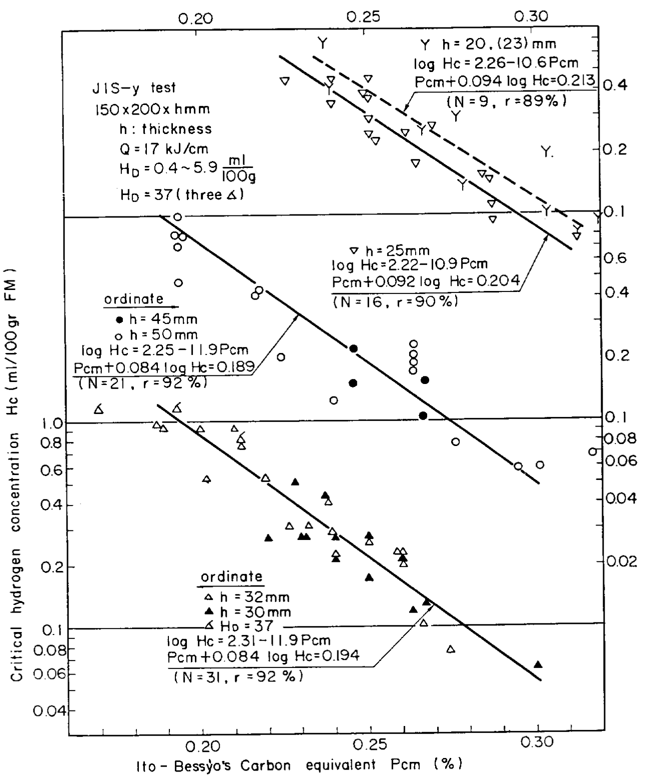

Fig. 1 Effects of Pcm and plate thickness on the critical hydrogen concentration Hc in the JIS-y test, including three 32 mm steels with high cellulose electrode.

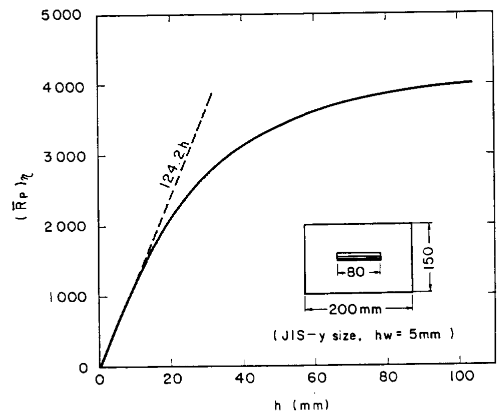

Fig. 2 Effective intensity of restraint (mean value) for the JIS-y test specimen (Ueda, and Kim).

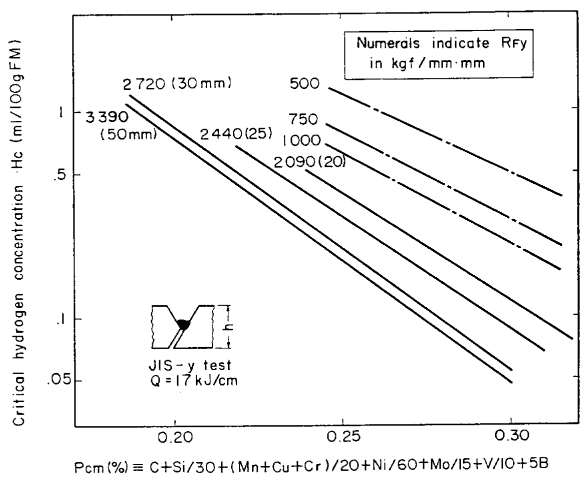

Fig. 3 Relationship between critical hydrogen concentration H_c, carbon equivalent P_{cm} and intensity of restraint R_{Fy} in JIS-y test (Q = 17 kJ/cm).

Table 1. Constants in $\log H_c = a - b\ P_{cm}$

Thickness h (mm)	Intensity of restraint R_{Fy} (kgf/mm·mm)	Constant	
		a	b
50	3,390	2.25	11.9
30	2,720	2.31	11.9
25	2,440	2.22	10.9
20	2,090	2.26	10.6
—	1,000	2.03	8.9
—	750	1.97	8.3
—	500	1.98	7.6

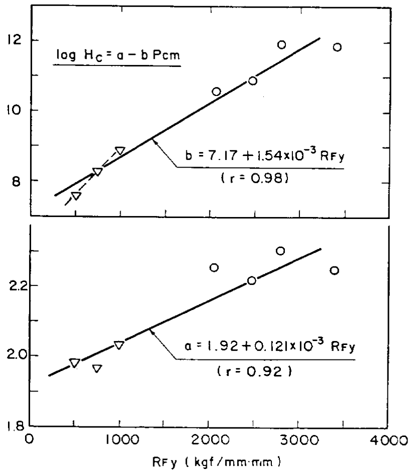

Fig. 4 Values of constants a and b as they relate to R_{Fy}.

dicated values of R_{Fy}. The four straight solid lines are from Fig. 1, while the three chain lines are from the previous report [1]. The values of constants a and b in eq. (7) are shown in Table 1 and Fig. 4.

Regression analysis of the constants a and b in Fig. 4 yields the following equations:

$$\left.\begin{aligned} a &= 1.92 + 0.121 \times 10^{-3}\ R_{Fy}, \\ b &= 7.17 + 1.54 \times 10^{-3}\ R_{Fy} \end{aligned}\right\} \qquad (9)$$

2.2 *Cracking parameter for each range of restraint*

A formula for cracking parameter P_H for a narrow range of restraints between R_1 and R_2 can be deduced as follows [1]:

Suppose the relationship between H_c and P_{cm} is given for each restraint as follows:

$$\left.\begin{aligned} &\text{For } R_1, \quad P_{cm} + A_1 \log H_{c1} = F_1, \\ &\text{For } R_2, \quad P_{cm} + A_2 \log H_{c2} = F_2 \end{aligned}\right\}$$

For an arbitrary intensity of restraint R_F which is $R_1 \geqq R_F \geqq R_2$, the following equation may be a good approximation:

$$P_{cm} + A_2 \log H_c = F_2 - (R_F - R_{F2})/D$$

Putting $R_F = R_2$, the above equation becomes identical to the second one for R_2 and for R_1 it will become equal to the first one, provided that the following value of D is adopted:

$$D = (R_1 - R_2)/[F_2 - F_1 A_2/A_1 + (A_2 - A_1) P_{cm}/A_1]$$

and accordingly

$$P_H \equiv P_{cm} + A_2 \log H_c + R_F/D = F_2 + R_{E2}/D \equiv E \qquad (10)$$

The above formula of P_H is the required cracking parameter for the restraint range between R_1 and R_2.

(1) Severe restraint range (h=20 to 50 mm)

Since R_1=3,390 kgf/mm·mm for thickness h=50 mm, and R_2=2,090 for h=20 mm, eq. (10) gives:

$$\left.\begin{aligned} &P_{cm} + 0.094 \log H_c + R_{Fy}/42{,}300 = 0.263, \\ &\quad \text{for } h = 20 \text{ to } 50 \text{ mm.} \end{aligned}\right\} \qquad (11)$$

For low hydrogen electrodes,

$$\log H_c = \log\{\lambda H_D'(U_B)cr\} = \log\{0.6\ H_D(U_B)\,cr\}.$$

Hence, from eq. (11),

$$P_{cm} + 0.094 \log H_D + R_{Fy}/42{,}300 = fn\{(t_{100})cr\} \qquad (12)$$

The JIS-y test data from Ito and Bessyo [5] are for H_D=1 to 5 ml/100 g and h=19 to 50 mm. For the limited range of H_D,

$$\log H_D \fallingdotseq 10.1\ (H_D/60) - 0.087\ .$$

Therefore, eq. (12) is transformed into:

$$\left.\begin{aligned} &P_{cm} + 0.95(H_D/60) + R_{Fy}/42{,}300 = fn\{(t_{100})cr\}\ , \\ &\quad \text{for } h = 20 \text{ to } 50 \text{ mm}, H_D = 1 \text{ to } 5 \text{ ml/100 g}\ . \end{aligned}\right\} \qquad (13)$$

This is almost equivalent to Ito-Bessyo's cracking parameter P_w, that is,

$$P_w \equiv P_{cm} + (H_D/60) + R_{Fy}/40{,}000 = fn\{(t_{100})cr\} \qquad (14)$$

(2) Extremely severe restraint range (h=30 to 50 mm)

For this range, the following is obtained:

$$\left.\begin{aligned} &P_{cm} = +0.084 \log H_c + R_{Fy}/134{,}000 = 0.214, \\ &\log H_c + 11.9\ P_{cm} + 0.089 \times 10^{-3}\ R_{Fy} = 2.55, \\ &\quad \text{for } h = 30 \text{ to } 50 \text{ mm}, R_{Fy} = 2{,}720 \text{ to } 3{,}390. \end{aligned}\right\} \qquad (15)$$

(3) Mild restraint range ($R_{Fy} \leqq 1000$ kgf/mm·mm)

For the mild restraint range of R_{Fy}=500 to 1000 kgf/mm·mm the value of constant b in Fig. 4 should change with R_{Fy} along the broken line, that is,

$$b = 6.32 + 2.6 \times 10^{-3} R_{Fy}, \text{ (for } R_{Fy} = 500 \text{ to } 1{,}000). \quad (16)$$

Hence the following is obtained for the mild restraint range:

$$\left.\begin{aligned} &P_{cm} + 0.132 \log H_D + R_{Fy}/14{,}700 = 0.324, \\ &\quad \text{for } R_{Fy} = 500 \text{ to } 1{,}000 \text{ kgf/mm·mm.} \end{aligned}\right\} \qquad (17)$$

3. Hydrogen accumulation cracking parameter P_{HA}

3.1 *Hydrogen accumulation ratio*

The critical hydrogen concentration H_c so far defined was calculated assuming uniform diffusion of hydrogen and ignoring local accumulation of hydrogen at locations with high stress concentration.

In the JIS-y test, high stress concentration occurs at a coarse-grained HAZ area near the root of the weld. The microstructure of this area also differs greatly from the microstructure of the weld metal and base metal, resulting in a considerable difference in the value of the diffusion constant for hydrogen. It is well known that in such an area hydrogen tends to accumulate locally, as was pointed out in the previous report [1].

Therefore, it may be assumed that the hydrogen concentration which directly affects cold crack initiation is not the value H_c, but the accumulated concentration $N \times H_c$. As the accumulation ratio N will increase as restraint becomes more severe, the critical value of H_c will become smaller. This tendency is clearly shown in Fig. 3.

Assuming the value of N at $R_{Fy}=3{,}200$ kgf/mm·mm ($h=43$ mm) is N_H, and using the value of constants a and b in Table 1, the following equation is produced:

$$\log N_H/N = -0.39 + 0.121 \times 10^{-3}\, R_{Fy} + (4.93 - 1.54 \times 10^{-3}\, R_{Fy}) P_{cm}.$$

Since $N=1$ for $R_{Fy}=0$, the following is obtained:

$$\log N = 1.54 \times 10^{-3}\, R_{Fy}\, P_{cm} - 0.121 \times 10^{-3}. \qquad (18)$$

The values of accumulation ratio N are shown in Fig. 5 against R_{Fy} for three representative values of P_{cm}. The ratio N increases as the values of restraint and carbon equivalent increase, but it levels off for high restraint over 3,200 kgf/mm·mm.

For example, for $P_{cm}=0.25\%$, the following is obtained:

$$N = \exp(0.00061\, R_{Fy}).$$

This is very similar to the theoretical equation which was deduced by us from the calculation by Satoh et al. [6]:

$$N = \exp(0.00045\, R_{Fy}).$$

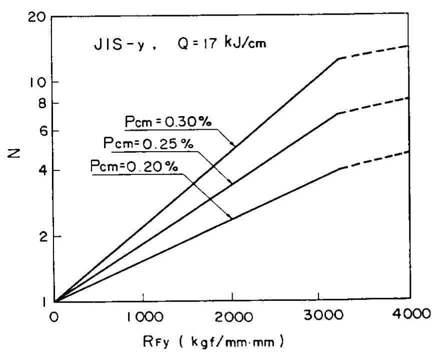

Fig. 5 Ratio N of hydrogen accumulation.

3.2 *Cracking parameter P_{HA}*

Substituting eqs. (9) and (16) into eq. (7), and from eq. (15), formulae for calculating $\log H_c$ are obtained for (17 kJ/cm) JIS-y test data.

Since

$$\left.\begin{aligned} &F \equiv -\log H_c = -\log(\lambda H_D') - \log(U_B)cr, \\ &\therefore\ \ F + \log(\lambda H_D') = -\log(U_B)cr, \end{aligned}\right\} \qquad (19)$$

the following equations are obtained:

$$P_{HA} \equiv \log(\lambda H_D') + F = -\log(U_B)cr \qquad (20)$$

$$\left.\begin{aligned} &\text{for } R_{Fy} \leqq 1{,}000 \text{ kgf/mm·mm} \\ &\quad F \equiv (6.32 + 2.60 \times 10^{-3} R_{Fy}) P_{cm} - 0.121 \times 10^{-3} R_{Fy} - 1.92, \\ &\text{for } 1{,}000 < R_{Fy} \leqq 3{,}200 \\ &\quad F \equiv (7.17 + 1.54 \times 10^{-3} R_{Fy}) P_{cm} - 0.121 \times 10^{-3} R_{Fy} - 1.92, \\ &\text{for } R_{Fy} > 3{,}200 \\ &\quad F \equiv 11.9\, P_{cm} + 0.089 \times 10^{-3} R_{Fy} - 2.55. \end{aligned}\right\} \qquad (21)$$

In order to prevent root cracking in the JIS-y test under standard weld heat input of 17 kJ/cm, it is necessary to know the value of the critical cooling time $(t_{100})cr$ for any combination of P_{cm}, H_D and R_{Fy}. Since the value of $(U_B)cr$ is defined by the value of $(t_{100})cr$, the parameter P_{HA} which is defined by eq. (20) is the very parameter to determine the critical condition for root crack initiation.

Observed values of critical cooling time $(t_{100})cr$ in JIS-y test are shown in Fig. 6 against the parameter P_{HA}. The plotted values seem to be correlated with the parameter. The solid-line curve is a theoretical curve:

$$P_{HA} = -\log(U_B)cr = fn\{(t_{100})cr\},$$

which is closely approximated by the following equation:

$$(t_{100})cr(\text{sec}) = 1{,}145\, P_{HA}^2 + 864\, P_{HA} - 171.$$

Moreover, the theoretical curve is practically linear in the range of $R_{Fy} < 1{,}500$ kgf/mm·mm, that is:

$$(t_{100})cr(\text{sec}) = 2{,}238\, P_{HA} - 562, \ (\text{for } Q = 17 \text{ kJ/cm}). \qquad (22)$$

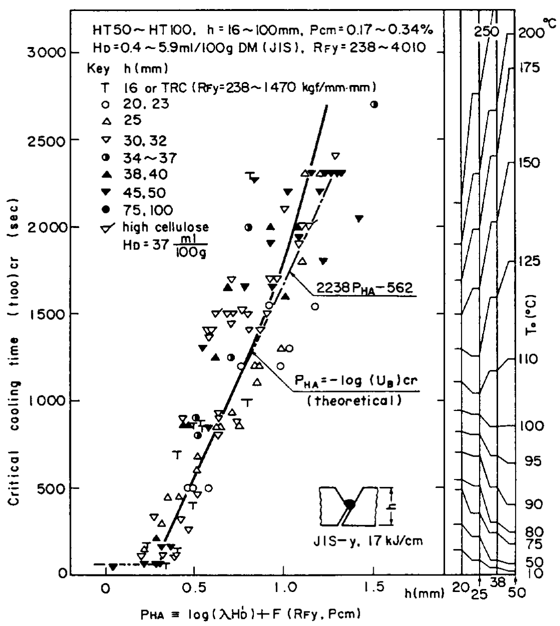

Fig. 6 Relationship between critical cooling time $(t_{100})_{cr}$ and cracking parameter P_{HA} for the JIS-y test with weld heat input of 17 kJ/cm.

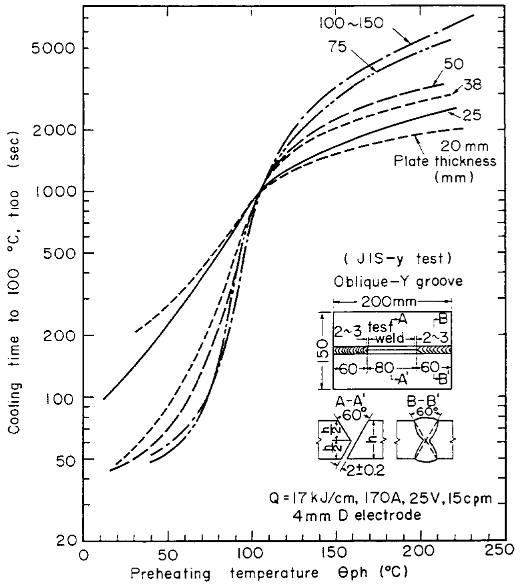

Fig. 7 Relationship between cooling time to 100°C, preheating temperature and plate thickness for the JIS-y test specimens (Q=17 kJ/cm) (JSSC).

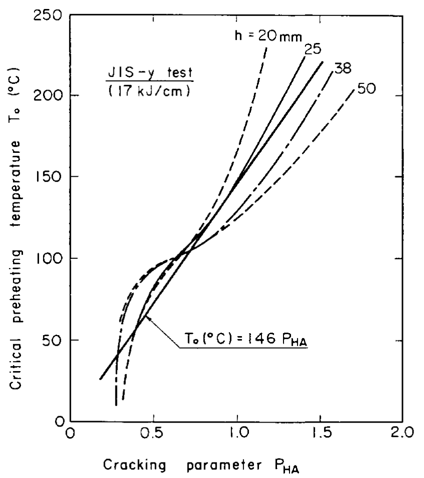

Fig. 8. Relationship between critical preheating temperature T_0, cracking parameter P_{HA} and specimen thickness h in the JIS-y test.

In Fig. 6, values of critical preheating temperatures are shown on the ordinate on the right-hand side. It should be noted that the temperatures correlate differently to the cracking parameter P_{HA} depending on plate thickness. In contrast, cooling time $(t_{100})cr$ correlates regardless of plate thickness.

The relationship between the cooling time, preheating temperature and specimen thickness in the JIS-y test is as shown in Fig. 7. From Fig. 7 and eq. (22), the relationship between the critical preheating temperature and P_{HA} is obtained in Fig. 8 for typical values of thickness. The relationship may be approximated by the following equations:

$$\left.\begin{array}{lll} \text{for } h=20\text{ mm}, & T_o(°\text{C}) & =217\ P_{HA}-41, \\ 25\text{ mm}, & & =167\ P_{HA}-14, \\ 38\text{ mm}, & & =125\ P_{HA}+13, \\ 50\text{ mm}, & & =100\ P_{HA}+27. \end{array}\right\} \quad (23)$$

Thus, in average, for 20 to 50 mm thicknesses,

$$T_o(°\text{C})=146\ P_{HA}, \quad (24)$$

which is applicable only to the JIS-y test specimens, uniformly preheated and air cooled after welding.

The relationship between the critical cooling time and cracking parameter P_{HA} in the present report is only slightly different from that in the previous report [1], where the intensity of restraint was set as eq. (8) instead of the present Fig. 2.

4. Effect of weld heat input

As was described in the previous report [1], weld throat depth increases with an increase in weld heat input. According to Kirihara [3], Terasaki [4] and the present authors, the following experimental equation holds for weld throat in groove welds.

$$h_{wQ}^2(\text{mm}^2)=3.113+1.765\ Q,\ (\fallingdotseq 2Q), \quad (25)$$

where

h_{wQ}(mm): throat depth of a groove weld,
Q(kJ/cm): weld heat input (arc energy).

Typical values of throat depth are shown in Table 2.

Table 2. Weld heat input and throat depth.

Q kJ/cm	6.0	7.5	10	12.5	15	17.5	20	22.5	25	27.5	30
h_{wQ} mm	3.5	4.0	4.5	5.0	5.5	6.0	6.3	6.6	6.9	7.2	7.3

In the present report, the effect of weld heat input on restraint stress (average value across throat section) is neglected as proposed by Terasaki [3].

The relationship eq. (22) between P_{HA} and the critical cooling time $(t_{100})cr$ was introduced in the case of weld heat input of 17 kJ/cm. It was assumed in the previous report that the relationship should be modified from eq. (22) when different heat inputs are concerned. This is because the weld throat thickness becomes greater with an increase in heat input and retards hydrogen evolution from the weld metal, and accordingly the critical cooling time should be made longer to avoid hydrogen cracking.

This reasoning seems to be right for bead-on-plate weld. However, in the case of a groove weld, hydrogen is released into air not only from the weld face surface, but also from the root surface which is about 2 mm wide in the case of the JIS-y specimen. Since the severest stress concentration occurs at the critical location of root crack initiation, on the fusion line about 0.3 mm away inside from the root of weld the hydrogen concentration H_B at the critical location may be seriously affected by the existence of the root surface.

A recent computer analysis, conducted by Professor Terasaki and the present authors, on the hydrogen concentration H_B at the critical location of root crack initiation revealed that the concentration is determined by the initial deposited hydrogen concentration and the cooling time t_{100}, regardless of the magnitude of throat thickness in the case of throat thickness greater than approximately 4 mm. Therefore, we may conclude that eq. (22) is also valid for any weld heat input greater than about 6 kJ/cm.

For any weld heat input greater than 6 kJ/cm:

$$(t_{100})cr\,(\mathrm{sec})=2{,}238\ P_{HA}-562. \qquad (26)$$

5. Equivalent intensity of restraint

The mechanical effect of the intensity of restraint R_{Fy} of a joint on cold cracking works through the concentrated stress σ_l which exists at the location of crack initiation. Therefore, the value of intensity of restraint R_{Fy} in the JIS-y test ($Q=17$ kJ/cm) which gives the same σ_l, may be considered equivalent to R_F of the joint in question, as far as the restraint effect is concerned.

The values of concentrated stress σ_l in a groove weld which is eccentrically located from the center of plate thickness, are given as follows [7] in the elastic range:

$$\left.\begin{aligned} &\sigma_l=k\sigma_w(1+B\gamma)/(1+C\gamma^2),\\ &\sigma_{w\gamma}=\sigma_w/(1+C\gamma^2),\\ &\sigma_w=m\mathrm{R_F}=0.042\ \mathrm{R_F},\\ &\sigma_r=\sigma_w(1+B\gamma)/(1+C\gamma^2), \end{aligned}\right\} \qquad (27)$$

where,

σ_l (kgf/mm^2): the maximum value of concentrated transverse stress at the location of crack initiation.

k: stress concentration ratio at the location of crack initiation [1], $k\equiv\sigma_l/\sigma_r$.

σ_w (kgf/mm^2): restraint transverse stress, average across weld throat for the case of $\gamma=0$.

$\sigma_{w\gamma}$(kgf/mm^2): average restraint stress for eccentric weld, $\gamma\neq0$ [7].

σ_r (kgf/mm^2): local restraint stress near the root of eccentric weld.

$\gamma\equiv\eta/(h/2)$: eccentricity of bead location from plate thickness center, η is the distance between weld throat center and thickness center, γ is positive when the weld is located on the face side of plate and negative when on the root side.

$B\fallingdotseq0.8$: coefficient related to the increase of local surface stress on weld root, caused by the bending of base metal due to eccentric weld location [7].

$C=0.64$ for JIS-y specimen and $C=3$ for RRC or TRC specimen [7].

The values of k are [1, 7]:

$$k=\left\{\begin{array}{ll} 8 & \text{for single or double bevel groove,}\\ 4 & \text{for oblique-Y, symmetric-Y or U-groove,}\\ 3.5 & \text{for double-V groove,}\\ 1.5 & \text{for V-groove or toe of weld.}\end{array}\right\} \qquad (28)$$

For the JIS-y test,

$$\sigma_l=4\ m\ \mathrm{R_{Fy}}=0.168\ \mathrm{R_{Fy}},\quad \text{(elastic range)}. \qquad (29)$$

Equating the two eqs. (27) and (29) of σ_l, the equivalent intensity of restraint R_{Fy} is given as follows:

$$\mathrm{R_{Fy}}=\frac{k}{4}\ \mathrm{R_F}\left(\frac{1+B\gamma}{1+C\gamma^2}\right),\quad \text{(groove weld)}. \qquad (30)$$

In the case of a weld without a groove, the following procedures should be used:

Any weld; $\sigma_l=k'\sigma_w$, (k' is different from eq. (28)),
JIS-y, 17 kJ/cm; $\sigma_l=4\times0.042\ R_{Fy}=0.168\ R_{Fy}$

Equating the above two values of σ_l,

$$\mathrm{R_{Fy}}=6.0\,k'\sigma_w,\quad \text{(grooveless weld)}. \qquad (31)$$

For example, concerning a toe crack of a long HT80 steel bead weld, $\sigma_w\fallingdotseq$(yield stress)/2=35 and $k'=1.5$. Thus,

$$\mathrm{R_{Fy}}=315\ (\mathrm{kgf/mm\cdot mm}),$$

which means a very mild restraint.

It should be noted here that the above formulae, eqs. (30) and (31), of equivalent intensity of restraint have been introduced by means of the elastic formulae of eq. (27). They do not hold after weld metal yielding, which occurs under normal restraint, for example, 1,000 kgf/mm·mm for HT50 steel or 1,700 for HT80 steel, and over. In spite of this plausible contradiction, eq. (30) is very useful in explaining experimental data as will be shown later. This fact may suggest that strain concentration proceeds almost linearly even after yielding of weld metal, and the value of concentrated strain is more intimately associated with cracking than restraint stress.

6. Applications of P_{HA} analysis

6.1 *Effect of groove shape and eccentric weld location*

It has been shown experimentally by Matsui [8], Inagaki [9], Kirihara [10], Kataoka [11] and Bada [12] and their co-workers, that the values of critical preheating temperatures are seriously affected by groove shape and weld location. The experimental values of the critical cooling times $(t_{100})cr$ obtained by those researchers for various groove shapes of oblique-Y, double-V, symmetric-Y, single bevel, double bevel, and V, and for eccentric weld locations, in JIS-y size specimens, are shown in Fig. 9. Those values of critical cooling times correlate satisfactorily with the new cracking parameter P_{HA} (left-hand figure). Correlation with Ito-Bessyo's parameter P_w (eq. 14), however, is obviously very poor. It is because the P_w-prediction is only valid for the oblique-Y groove.

6.2 *Analysis of heel crack*

The heel crack is a root crack in the HAZ of a single-pass fillet weld on T-joint. It ocucrs in a tab-test or in setting up a strong back or foothold on a high-strength steel plate, as well as in intermittent fillet welds.

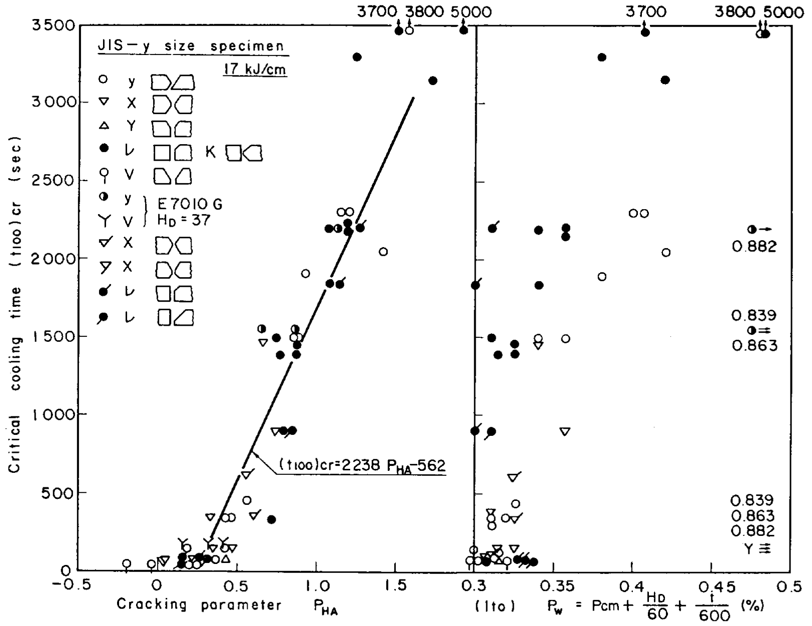

Fig. 9 Correlation between critical cooling time and cracking parameter P_{HA} or P_w (Ito-Bessyo) for various groove shapes and weld locations (root cracking in the HAZ in the JIS-y size specimens, 17 kJ/cm).

Tanaka and Kitada [13] performed extensive experiments on heel cracking of HT50 steels welded with low-hydrogen electrodes. They found that the T-joint specimen shown in Fig. 10 could reproduce heel cracks in practical fabrication. Moreover, they showed that heel cracking is affected greatly by the thickness of the web plate, and that the severest cracking occurs in specimens with thicknesses of about 8 to 14 mm and no cracking occurs in specimens 20 mm thick. Fillet welding on both sides prevented cracking. They concluded that the cracking was attributable to HAZ hardening and vertical expansion and contraction in the web plate due to the thermal cycle of the weld.

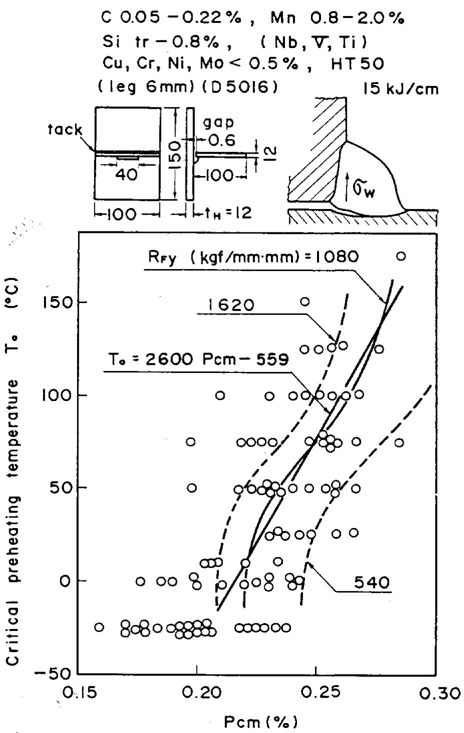

Fig. 10 Critical preheating temperature to avoid heel cracking in HT50 steels of C-Mn-(X) type (test data by Tanaka Kitada) (t_H= 12 mm, H_D=4.0 ml/100 g JIS).

The problem of heel cracking can be P_{HA}-analyzed as follows. The magnitude of the restraint stress near the root and across the fusion line may reasonably be assumed to be of the order of the yield strength of the weld metal, that is, about 45 kgf/mm^2 in the case of a HT50 grade electrode and $k'=4$. Hence, by eq. (31), with $\sigma_w=\sigma_Y=45$ kgf/mm^2,

$$R_{Fy}\ (\text{heel crack})=24\ \sigma_w=1{,}080\ \text{kgf/mm}\cdot\text{mm}.$$

Since H_D=4.0 ml/100 g (JIS) for the HT50 electrodes, eq. (20) gives:

$$P_{HA}=8.83\ P_{cm}-1.67.$$

As the fillet leg length is 6 mm and Q=15 kJ/cm, eq. (26) yields:

$$(t_{100})cr(\text{sec})=19{,}762\ P_{cm}-4{,}299 \qquad (32)$$

For the test specimen in Fig. 10, h=12+12 mm, the measured relationship between preheating temperature T_o and cooling time t_{100} is as follows:

T_o (°C)	0	25	50	75	100	125	150
t_{100} (sec)	35	80	260	520	780	940	1040

Therefore, eq. (32) can be converted into a relationship between T_o and P_{cm}, which is shown in Fig. 10 with a solid-line curve, of which an approximation is:

$$T_o(°\text{C})=2{,}600\ P_{cm}-559. \qquad (33)$$

This P_{HA}-prediction of critical preheating temperature seems to agree satisfactorily with the test data by Tanaka and Kitada.

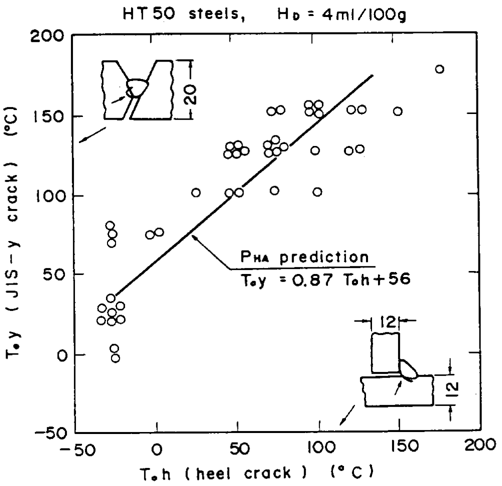

Fig. 11 Comparison of critical prehetaing temperature for heel cracking versus JIS-y root cracking (HT50 steels, test data by Tanaka and Kitada).

Tanaka and Kitada [13] compared heel cracking with JIS-*y* root cracking. They showed that the critical preheating temperatures T_{oh} in the heel cracking of 12 mm thick HT50 steel plates, were consistently lower than those T_{oy} of 20 mm thick oblique-Y tests, as shown in Fig. 11. This fact can be explained by P_{HA} theory as follows:

The critical preheating temperature T_{oy} of the standard JIS oblique-Y test on a 20 mm thick plate is as follows under P_{HA} theory:

$$T_{oy}(°C)=2{,}254\ P_{cm}-429 \tag{34}$$

The value of T_{oh} for heel cracking of 12 mm thick plates is given by eq. (33). Thus, from eqs. (33) and (34),

$$T_{oy}(°C)=0.87\ T_{oh}+56. \tag{35}$$

This P_{HA}-prediction is shown in Fig. 11 with a straight line and seems to agree with the test data.

6.3 *Relationship between CI and P_{HA}*

Yurioka and his co-workers [14] proposed a simple formula for the cracking index, CI, which is defined by the following:

$$CI\equiv CEN+0.15\log H_D+0.30\log(0.017\ K_t\ \sigma_w), \tag{36}$$

where

$$\left.\begin{aligned}&CEN\equiv C+A(C)\{Si/24+Mn/6+Cu/15\\&\quad+Ni/20+(Cr+Mo+Nb+V)/5+5B\},\\&A/(C)\equiv 0.75+0.25\tanh\{20(C-0.12)\}.\end{aligned}\right\} \tag{37}$$

The new formula CEN is a carbon equivalent which can be applied both to low-carbon content and high-carbon content steels, in contrast to P_{cm} which is reasonable only for a low carbon content of less than about 0.17%. By the way, the IIW carbon equivalent seems to be adequate only for high carbon content over about 0.18%.

For carbon contents ranging from 0.02 to 0.19%,

$$CEN\doteqdot 1.54\ P_{cm}.$$

The value of $X\equiv 0.017\ K_t\ \sigma_w$ in the third term in eq. (36) is in practice 2 to 6 and the following approximation holds:

$$\log X=0.00378+0.134\ X\doteqdot 0.134\ X.$$

Therefore, eq. (36) becomes:

$$CI\doteqdot 1.54\ P_{cm}+0.15\log H_D+0.30\times 0.134\ (0.017\ K_t\ \sigma_w), \tag{38}$$

(1) Elastic range (mild restraint) in JIS-*y* test

For $\sigma_w<\sigma_Y$ (yield stress of weld metal), $\sigma_w=0.042\ R_{Fy}$, $K_t=4$, and eq. (38) yields the following:

$$CI=1.54\{P_{cm}+0.097\log H_D+R_{Fy}/13{,}423\} \tag{39}$$

which is similar to the P_{HA} formula in the case of mild restraint, eq. (17):

$$P_{cm}+0.132\log H_D+R_{Fy}/14{,}700=0.324.$$

(2) Severe restraint range (plastic range)

In this case, Terasaki and Satoh [4] propose the following formula for restraint stress:

$$\sigma_w=\sigma_Y+0.014\ (R_{Fy}-R_{Fyield}).$$

In this case, eq. (38) yields the following:

$$CI=1.54\ \{P_{cm}+0.097\log H_D+R_{Fy}/40{,}323\}+\text{const.} \tag{40}$$

This is very similar to the P_{HA} formula under severe restraint, eq. (12):

$$P_{cm}+0.094\log H_D+R_{Fy}/42{,}300=fn\{(t_{100})cr\}.$$

Therefore, it may be concluded that cracking index CI is almost equivalent to the cracking parameter P_{HA}.

7. Conclusions

In our previous report [1] of IIW Doc IX-1195-81, a new formula, i.e., cracking parameter P_{HA}, was introduced in order to analyze and predict the critical conditions leading to various types of hydrogen-induced cold cracking in welded high-strength steels.

In this report, the formula for P_{HA} has been given in a more reasonable form by means of a different and simpler procedure for its introduction and by adopting a more rigorous Ueda formula for the intensity of restraint of the JIS-*y* (Tekken) test specimens.

The main conclusions are as follows:

(1) The values of critical hydrogen concentration H_c for JIS-*y* test HAZ root cracking, if calculated assuming uniform diffusion of hydrogen, grow smaller, as the carbon equivalent P_{cm} and/or intensity of restraint R_{Fy} become larger, that is:

$$\log H_c=a-b\ P_{cm},$$

where the constants *a* and *b* (positive) are functions of R_{Fy} (Table 1, Figs. 3 and 4).

(2) The above-mentioned fact seems to indicate

that the accumulated hydrogen concentration $N \times H_c$ in the high stress concentrated area of crack initiation, is a factor directly affecting cracking. The value of N of the hydrogen accumulation ratio is given in eq. (18) and in Fig. 5 as a function of P_{cm} and R_{Fy}. Values of N for severe restraint are 4 to 12.

(3) The formula for cracking parameter P_{HA} has been introduced by considering the effect of accumulation ratio N. It takes three slightly different forms (eqs. 20 and 21) depending on the intensity of restraint. It correlates satisfactorily with the observed values of critical cooling time in the JIS-y tests (Fig. 6).

For $Q = 17$ kJ/cm, $(t_{100})_{cr}$ (sec) $= 2{,}238\ P_{HA} - 562$,

and the values of critical preheating temperature for the JIS-y test are given by:

$T_o(°C) = 167\ P_{HA} - 14$, for $h = 20$ to 25 mm,

$T_o(°C) = 125\ P_{HA} + 13$, for $h = 38$ to 50 mm,

and in average $T_o(°C) = 146\ P_{HA}$.

(4) The idea of equivalent intensity of restraint R_{Fy} (eq. 30), which is directly associated with the magnitude of local stress concentration near the root of one-pass weld metal in a butt-joint, is shown to be very useful in explaining quantitatively (Fig. 9) the effects of various groove shapes and eccentric weld locations on the values for critical cooling time.

(5) Values of preheating temperatures which prevent heel cracking (root HAZ cracking in a short T-type fillet weld) can be predicted using the P_{HA} theory and agree satisfactorily with experimental values (Figs. 10 and 11).

(6) The present cracking parameter P_{HA} is almost identical to Ito-Bessyo's cracking parameter P_w (eq. 14) in a severe restraint range. It is also shown that the cracking index CI, recently proposed by the authors to simplify the matter [14], is approximately equivalent to P_{HA}.

(7) Nomographs are proposed for calculating the cracking parameter (Fig. 13).

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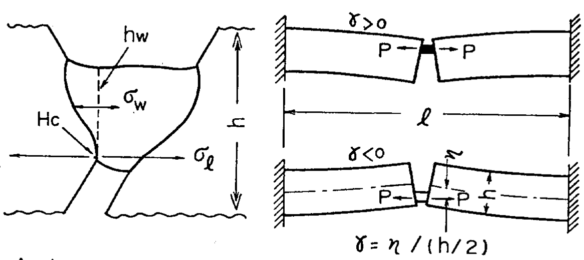

(a) stress concentration (b) bending of plates

Fig. 12 Notations for calculating R_{Fy}.

8. How to use the P_{HA} analysis

The present P_{HA} analysis is effective only for a single

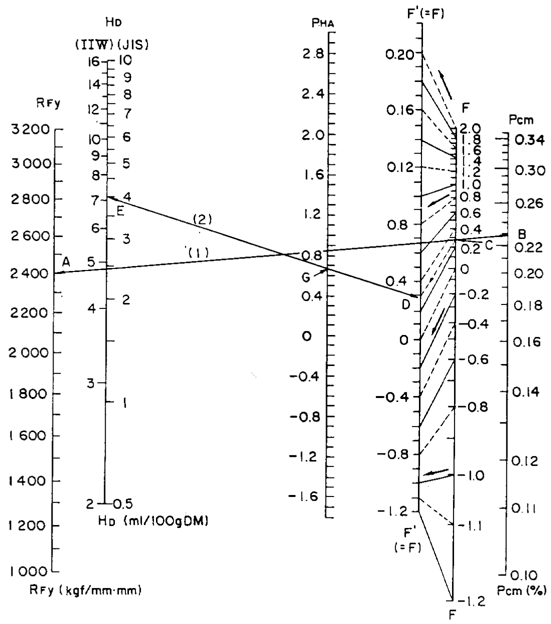

Fig. 13(a) Nomograph to calculate F for $R_{Fy} = 1{,}000$ to 3,200 kgf/mm·mm, and to calculate P_{HA} for all ranges of $R_{Fy} = 0$ to 7,000 (see Fig. (b) for F-value).
(1) Get the F-value (point C) joining A (R_{Fy}) and B (P_{cm}). Move to point D on F′F′ line.
(2) Get the P_{HA}-value (point G) joining D (F) and E (H).

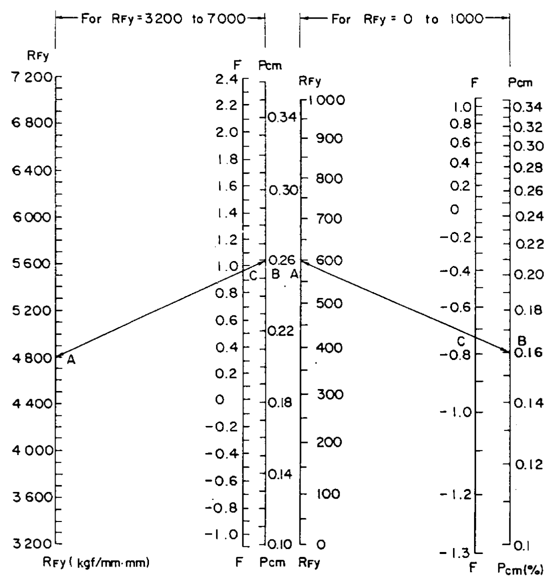

Fig. 13(b) Nomograph to calculate F for R_{Fy} ranges of 0 to 1,000 and 3,200 to 7,000 kgf/mm·mm.

pass weld in the range of weld heat inputs $Q=6$ to 30 kJ/cm. However, it could be applied to a multipass weld if the hydrogen concentration were given at the location of crack initiation. The following procedure should be taken in using the cracking parameter P_{HA}.

(1) Calculate R_{Fy}, equivalent intensity of restraint.

R_F (kgf/mm·mm): intensity of restraint of a joint, see Appendix 1 and reference [15].

R_{Fy}(kgf/mm·mm): equivalent intensity of restraint of any joint in which the restraint is R_{Fy}, is given by eqs. (30) and (31).

The intensity of restraint of the JIS-*y* test specimen under the standard weld heat input of 17 kJ/cm is identical to R_{Fy}, see Fig. 2.

(2) Calculate the value of the cracking parameter P_{HA} by eqs. (20) and (21) or by nomographs Fig. 13.

$$P_{HA} \equiv \log(\lambda H_D') + F.$$

(3) Calculate the value of critical cooling time $(t_{100})_{cr}$ by eqs. (26), regardless of the weld heat input (arc energy).

(4) Obtain the value of T_o, critical preheating temperature, for the $(t_{100})_{cr}$, from the relationship between T_o, t_{100}, Q, plate thickness, joint geometry and uniform or local preheating procedure. The relationship should be predetermined or may be calculated by ref. [16], see Appendix 2. If the relationship is not given, the value of T_o can be estimated approximately by the following equation, in the case of test specimens which are similar in size to the JIS-*y* test specimens and uniformly preheated and slowly cooled after welding:

$$\left.\begin{aligned} T_o(^\circ\mathrm{C}) &= 167\ P_{HA} - 14, \quad \text{for } h=20\sim25\ \mathrm{mm} \\ &= 125\ P_{HA} + 13, \quad \text{for } h=38\sim50\ \mathrm{mm} \end{aligned}\right\}$$

However, it is not applicable to a welded joint locally preheated; then see Fig. 14.

An approximate estimation of the cooling time (t_{100}) for a heat input and plate thickness is given by Yurioka et al. [17], see Appendix 2 and Fig. 14 (a) to (h).

Examples of R_F and R_{Fy} at the root of weld:

JIS-*y* test specimen of thickness (mm) × 150 × 200 (mm);

R_F (kgf/mm·mm), see Fig. 2, $R_F = R_{Fy} = (R_p)_\eta$.

JIS-*y* test with any Q(kJ/cm);

$R_{Fy} = R_F$.

JIS-*y* size specimen, with any groove shape other than oblique-*y*;

$R_F = R_F$ (JIS-*y*), but $R_{Fy} \neq R_F$ (JIS-*y*).

JIS-*y* size specimen with single bevel groove, weld at the center of thickness;

$k=8$, $\gamma=0$,

$\therefore\ R_{Fy} = 2 \times R_F$.

Single bevel groove weld with full penetration;

$k=1.5$, $\gamma = -(h/2 - h_w/2)/(h/2) = -(h-h_w)/h$, where h_w is the throat depth.

For RRC test, $B=0.8$ and $C=3$,

$$\therefore\ R_{Fy} = \frac{1.5(1+0.8\gamma)}{4(1+3\gamma^2)} R_y$$

$R_F = Eh/l$, where E is Young's modulus, h is plate thickness and l is the restraining distance in the RRC test.

Underbead cracking test, with a long test bead;

$k'=1\sim1.5$. $R_{Fy} = 6 \times 1.5\ \sigma_w = 9 \times$ (transverse residual stress.), $\sigma_w = \sigma_{Yw}/2 =$ (weld metal yield stress)/2.

$\therefore\ R_{Fy} = 4.5\ \sigma_{Yw}$

Implant test; $R_{Fy} = \sigma_w/0.042$,

for specimen of 8–7 D mm, $\sigma_w = 0.75\ (\sigma_{imp})$;

$\therefore\ R_{Fy} = 17.9\ (\sigma_{imp})$,

do. 8–4 D mm, $\sigma_w = 0.62\ (\sigma_{imp})$;

$\therefore\ R_{Fy} = 14.8\ (\sigma_{imp})$.

CTS test; pending.

Appendix 1 Intensity of restraint, R_F

"Intensity of rsetraint" in a groove weld joint before welding is defined by Satoh and his co-workers [15] as:

"the magnitude of force per unit weld length which is necessary to displace elastically the root gap by a unit length."

In the RRC test, Fig. 12 in which l is the restraint distance, R_F is given by

$$R_F\ (\mathrm{kgf/mm \cdot mm}) = Eh/l,$$

where $E=21{,}000$ kgf/mm² is Young's modulus, h (mm) is the plate thickness.

The magnitude of R_F in the JIS-*y* test specimen is given experimentally or by FEM analysis with computer, for example, Fig. 2. It increases with an increase of plate thickness and levels off near at $h \geq 50$ mm.

Measurements of R_F in real structures indicated that in most cases $R_F < 40\ h$.

For more details, see ref. [15].

Appendix 2 Estimation of cooling time t_{100}

The value of cooling time t_{100} can be calculated with computer using Terasaki and his-co-workers formula [16]. However, a good approximation is given by Yurioka et al. [17], as shown in Fig. 14 (a) to (h).

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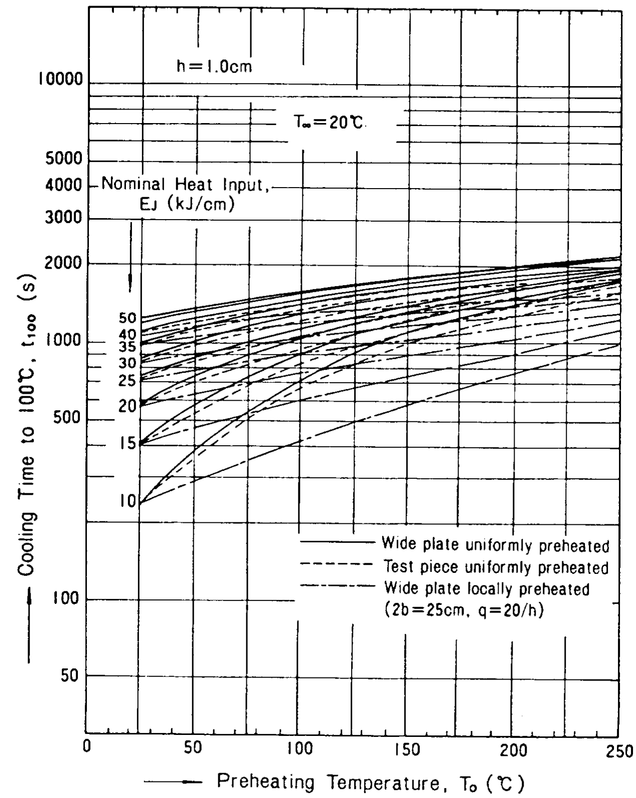

Fig. 14(a) Cooling time to 100°C (h=1.0 cm)

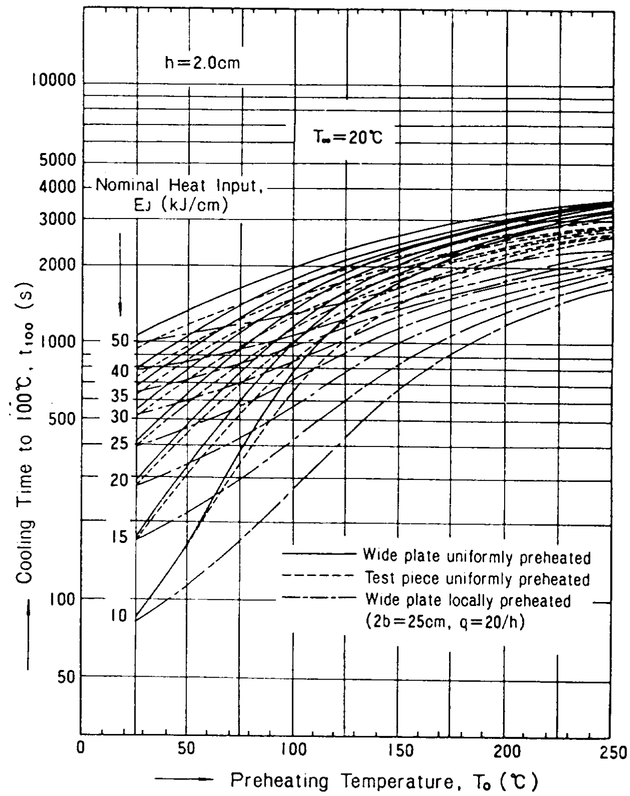

Fig. 14(b) Cooling time to 100°C (h=2.0 cm)

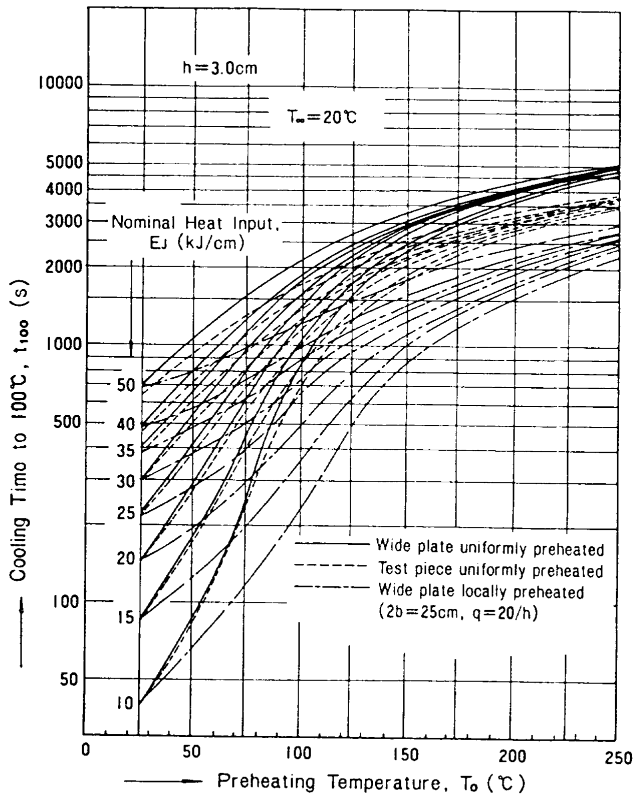

Fig. 14(c) Cooling time to 100°C (h=3.0 cm)

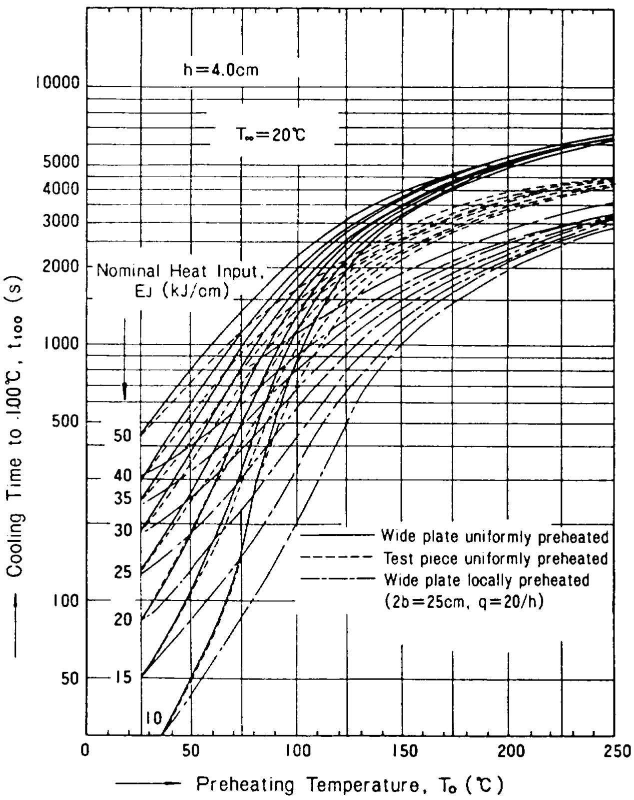

Fig. 14(d) Cooling time to 100°C (h=4.0 cm)

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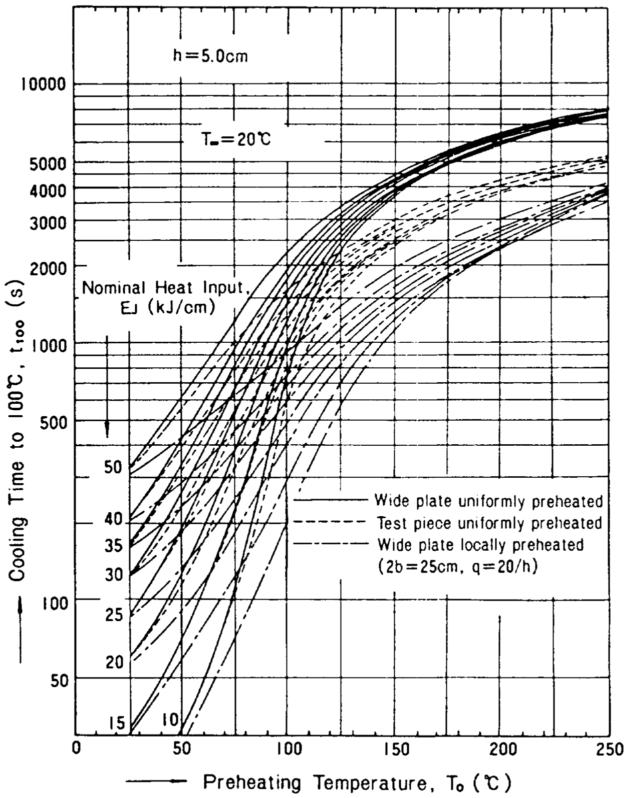

Fig. 14(e) Cooling time to 100°C (h=5.0 cm)

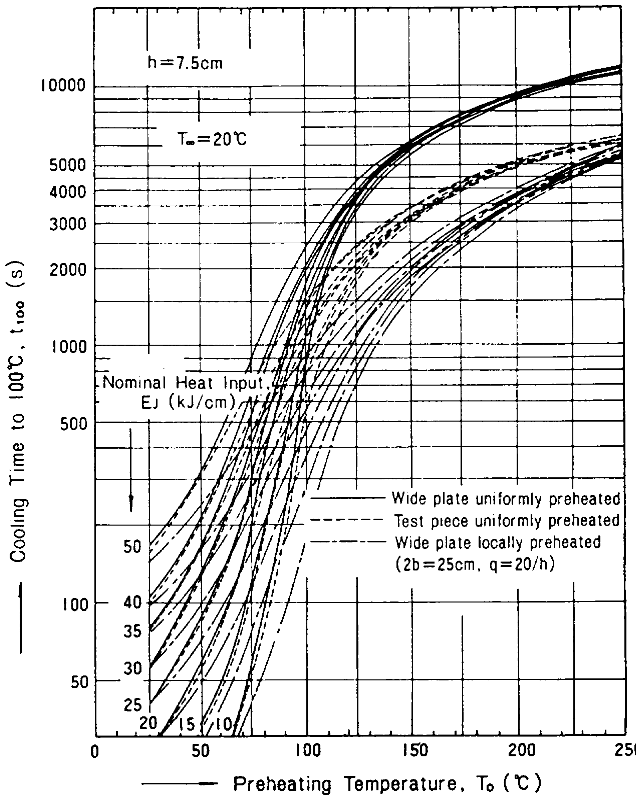

Fig. 14(f) Cooling time to 100°C (h=7.5 cm)

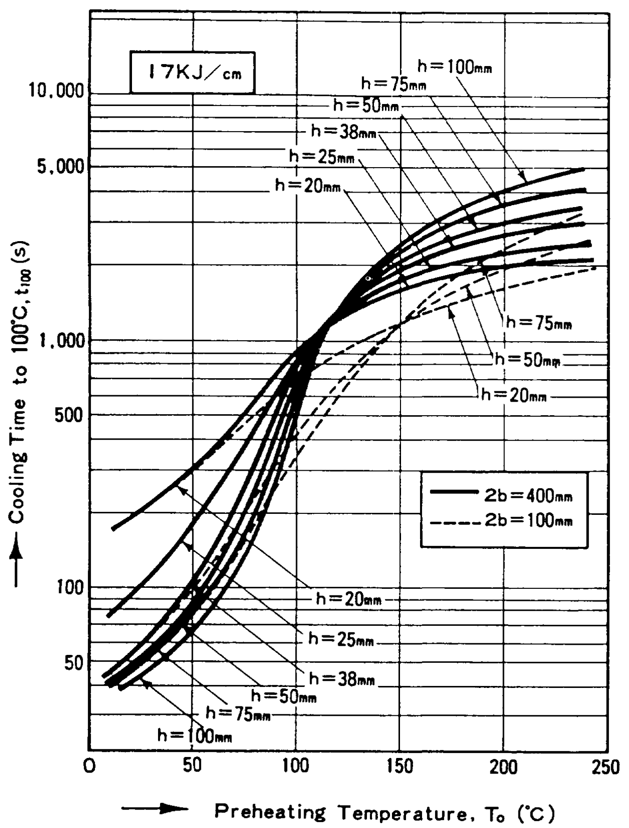

Fig. 14(g) Relation of cooling time to preheating temperature (17 kJ/cm)

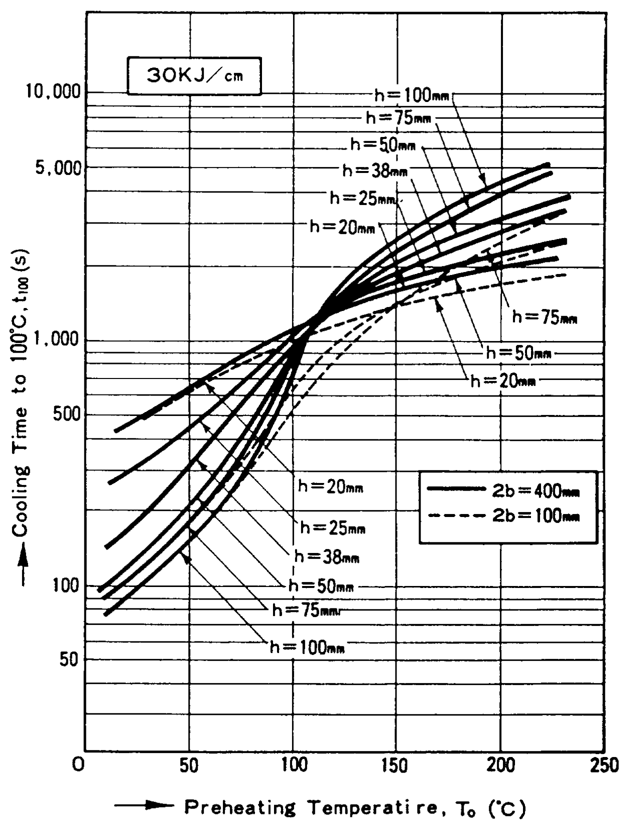

Fig. 14(h) Relation of cooling time to preheating temperature (30 kJ/cm)

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