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Revised Cold Cracking Parameter P_{HA} and its Applications*

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Abstract

In the author's previous report IIW IX-1232-82, a new and generalized cold cracking parameter was introduced, so that the conditions leading to various types of hydrogen-induced cracking in welded high-strength steels can be analyzed and predicted using the data obtained from the standard JIS-y (Tekken type) cracking test. In this report, the P_{HA} formula has been made more accurate using additional JIS-y test data. Additional information and figures are presented to make the P_{HA} application procedure more accessible.

Verification of the effectiveness of P_{HA}-analysis has been made through several tests such as on the effect of groove shape and eccentric weld location, single-bevel groove RRC test by Fikkers and Muller, heel cracking test by Tanaka and Kitada, critical maximum hardness in JIS-y test, Harasawa-Hart test, and Yurioka single-bevel groove 30 kJ/cm test.

It is also shown that P_{HA} parameter is practically identical to Yurioka cracking index CI for lower carbon content range, and P_{HA} becomes identical to Ito-Bessyo cracking parameter P_w in the case of severe restraint in JIS-y test, but P_{HA} has wider fields of applications.

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-1232-82 [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.

The purpose of this report is to revise the previous P_{HA} formula into a more reasonable and accurate form, using additional JIS-*y* (Tekken type) test data. Verification of P_{HA} analysis of various test results is also performed.

Notations

JIS-*y* test; oblique-Y-groove root cracking test in JIS (Tekken test).
Hc; critical hydrogen concentration at 100°C for crack initiation, eq. (1).
H_D; diffusible hydrogen content of electrode (JIS), eq. (3)
$(U_B)cr$; ratio of Hc to initial hydrogen concentration of weld metal, eq. (1), (4).
$\Phi=\sum D_i \cdot \Delta t_i$; thermal factor for hydrogen diffusion, eq. (4).
D; diffusion constant, function of temperature, eq. (4).
t; time after solidification of weld metal.
t_{100}; time to cool from solidification to 100°C.
$(t_{100})cr$; critical value of t_{100}, minimum necessary to prevent cold cracking, eq. (11).
P_{HA}; cracking parameter, eq. (9).
Pcm; Ito-Bessyo carbon equivalent, eq. (6).
Pw; Ito-Bessyo cracking parameter, eq. (13).
CEN; Yurioka carbon equivalent, eq. (26).
CI; Yurioka cracking index, eq. (25).
Q; arc energy, weld heat input, eq. (20).
T_0; critical preheating temperature, minimum necessary to prevent cold cracking, eq. (12).
T_p; preheating temperature, eq. (20).
$t_{8/5}$; time to cool from 800 to 500°C, eq. (21), (22).
$H\max$; maximum hardness in the HAZ, eq. (22).
$(H\max)cr$; critical maximum hardness, maximum to prevent cold cracking, eq. (23).
$NSC\text{–}S$; formula to estimate maximum hardness, eq. (22).
h; thickness of specimen.
R_F; intensity of restraint of a joint before welding, eq. (18).
R_{Fy}; equivalent intensity of restraint and the R_F in JIS-*y* test, eq. (18).
σ_w; restraint stress (average value across the weld throat), eq. (15).
σ_l; concentrated stress value across the weld throat, eq. (15).
k; stress concentration ratio at the site of root crack initiation, eq. (16).

2. Critical Hydrogen Concentration Hc

2.1 *Calculation of Hc*

As was described in detail in the previous report [1], the value Hc of critical hydrogen concentration in

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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:

$$Hc = (\lambda H_D')(U_B)cr \tag{1}$$

where

Hc (ml/100 g HAZ): critical hydrogen concentration in the HAZ at 100°C at the location of crack initiation, 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 $H_o \doteqdot H_F$,

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

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

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 followig formula:

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

The value of U_B can be calculated with the following equation, proposed by Coe and Chano [2] and modified by Fujii [3] for JIS-*y* test (17 kJ/cm) specimen:

$$U_B \equiv \sum_{n=1}^{\infty} \frac{1}{n\pi}\left(2 \sin\frac{0.2n\pi}{h} - \sin\frac{0.4n\pi}{h}\right)\exp\left(-\frac{n^2\pi^2\Phi}{h^2}\right), \tag{4}$$

where

Φ (cm²) $\equiv \sum D_i \cdot \Delta t_i$ = thermal factor for hydrogen diffusion,

h: thickness of specimen (cm in this equation),

D (cm²/s): diffusion constant (function of temperature, [4]),

t (s): time elapsed after solidification of weld metal,

t_{100} (s): time to cool from solidification to 100°C.

In this equation it is assumed that diffusion constant is uniform everywhere, local accumulation of hydrogen due to stress concentration does not occur, and evolution of hydrogen from the root of weld (2 mm root gap in JIS-*y* specimen) can be neglected. The value of U_B, as shown in Fig. 1, decreases gradually with an increase of thermal factor Φ and is very slightly affected by specimen thickness h only at high values of thermal factor.

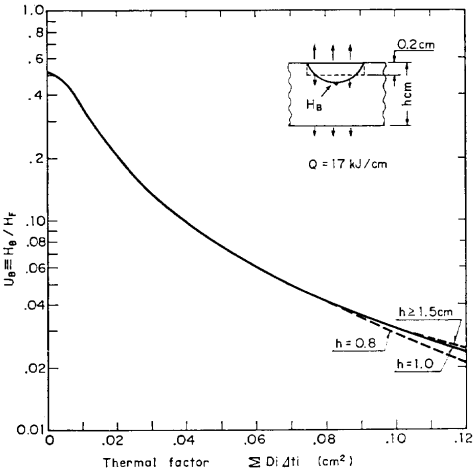

Fig. 1 Decrease of hydrogen concentration at bottom fusion line as related to increase of thermal factor.

U_B eq. (4) was introduced originally for the standard weld heat input of Q=17 kJ/cm in JIS-*y* test. However, it can be applied also to other heat inputs, as may be understood from the following reason. The root crack initiation in the HAZ in JIS-*y* test is observed to occur at a local spot inside 0.2 to 0.3 mm away from the root of weld. The hydrogen concentration at this spot is seriously affected by the evolution of hydrogen from the root surface of 2 mm width. Terasaki et al., [5] found in their recent FDM computer calculation, considering the hydrogen evolution from the root, that the hydrogen concentration at the spot of initiation, for example, 0.3 mm away from the root, is approximately one half of the value given by eq. (4), in which the evolution from the root is neglected. Moreover, the hydrogen concentration is independent of the throat thickness, provided the throat thickness is over 4 mm. Therefore, eq. (4) should be replaced by Terasaki's equation. However, since the Terasaki value is closely proportional to eq. (4), the value of cracking parameter P_{HA}, as defined by

$$P_{HA} \equiv -\log\,(U_B)cr,$$

will yield only a constant difference, for example log (1/2), between Terasaki and eq. (4). Therefore, in discussion of the relation between P_{HA} and critical cooling time $(t_{100})cr$, which is the final cbject of this report, eq. (4) is sufficient and can be used for any weld heat input which can yield a weld throat thicker than 4 mm.

The experimental relational equation between thermal factor and cooling time t_{100}, from solidification to 100°C, is given by the following [1]:

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

which was obtained under test conditions of Q=8 to 45 kJ/cm, plate thickness h=9 to 20 mm, and preheating temperature T_p=20 to 200°C.

The relation between preheating temperature and cooling time t_{100} is given experimentally by Fig. 2 (JSSC) [6].

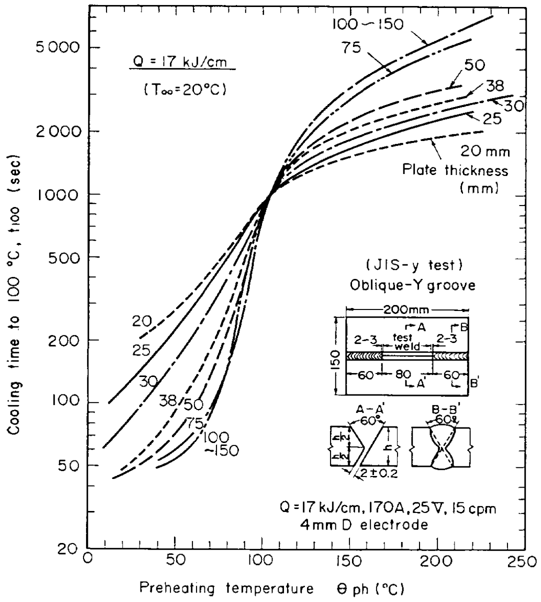

Fig. 2 Relationship between cooling time t_{100}, preheating temperature and plate thickness for JIS-y test with weld heat input of 17 kJ/cm.

When the critical preheating temperature T_p in JIS-*y* test is known, $(t_{100})cr$ value can be determined from Fig. 2, thermal factor from eq. (5), $(U_B)cr$ from Fig. 1, and finally the required *Hc* is given by eq. (1).

2.2 *Experimental equation for Hc*

Experimental values for critical hydrogen concentration *Hc* 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 Figs. 3 and 4 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 *P*cm [7]:

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

Sixty-nine new data have been added to those in the previous report [1].

The values of log *Hc* seem to decrease linearly with an increasing *P*cm, that is,

$$\log Hc = a - bP\text{cm}\,. \qquad (7)$$

Regression analysis yielded the values of *a* and *b* as shown in Table 1.

The measured values of constants *a* and *b* in Table 1 are different from those obtained in the previous report [1] only for thickness 20 mm. Those values for mild restraints less than 750 kgf/mm·mm are not necessarily reliable, because of the shortage of test data now available.

The relation between specimen thickness and intensity of restraint in JIS-y test was given with a figure in the previous report [1]. It is shown here in Table 2, which may be more convenient for readers.

Measured values of constants *a* and *b* are shown in Fig. 5 with circles and triangles. Four straight lines were adopted to approximate the measured values

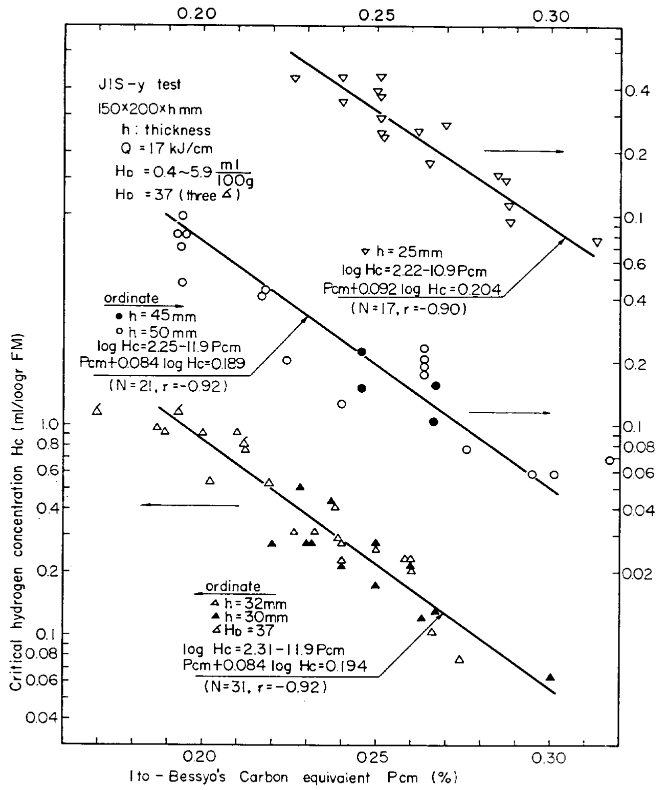

Fig. 3 Effects of Pcm on critical hydrogen concentration Hc in JIS-y test of three thicknesses.

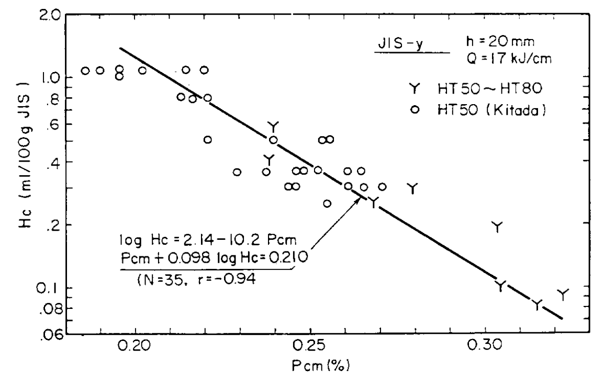

Fig. 4 Effect of Pcm on critical hydrogen concentration Hc in JIS-y test of 20 mm thickness.

Table 1 Constants in log Hc=$a-b$ Pcm.

Thickness h (mm)	Intensity of restraint R_{Fy} (kgf/mm·mm)	Measured constant a	Measured constant b	Constant used in P_{AH}−eq. a	Constant used in P_{AH}−eq. b
50	3390	2.25	11.9	2.248	11.90
30	2720	2.31	11.9	2.312	11.90
25	2440	2.22	10.9	2.229	11.06
20	2090	2.14	10.2	2.135	10.13
—*	1000	2.03	8.9	2.030	8.90
—*	750	1.97	8.3	1.993	8.27
—*	500	1.98	7.6	1.968	7.62
—**	250	—	—	1.943	6.97
**	0	—	—	1.918	6.32

Remarks *) Mild restraint was attained with side-slotted JIS-y specimens of thicknesses of 20 to 32 mm. [7].
**) Extrapolation from R_{Fy}=1000 to 500

Table 2 Intensity of restraint R_{Fy} (kgf/mm·mm) and specimen thickness h (mm) for JIS-y test (Ueda et al.).

h	10	15	20	25	30	40	50	60	80	100
R_{Fy}	1200	1700	2090	2440	2720	3110	3390	3595	3875	4010

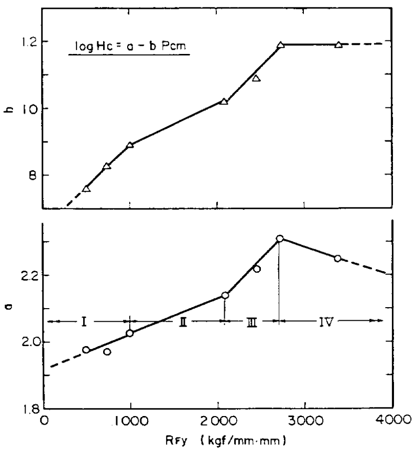

Fig. 5 Observed values of constants a and b, with P_{HA} approximation by straight lines.

and the four figure values of a and b in Table 1 were obtained for P_{HA} equation.

3. Cracking Parameter P_{HA}

3.1 *Introduction of cracking parameter P_{HA}*

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 Pcm, 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 the following equation is the very parameter to determine the critical condition for root crack initiation.

$$\left.\begin{aligned} P_{HA} &\equiv \log(\lambda H_D') + F = -\log(U_B)cr, \\ F &\equiv -\log Hc = bP\text{cm} - a. \end{aligned}\right\} \quad (8)$$

Using the values of constants in Table 1, the following formulae for P_{HA} are obtained for each restraint range:

$$\left.\begin{aligned} &P_{HA} \equiv \log(\lambda H_D') + F, \\ &\text{For low-hydrogen electrode;} \\ &\qquad P_{HA} = \log(0.6H_D) + F, \\ &\text{For high-cellulose electrode;} \\ &\qquad P_{HA} = \log(0.24H_D) + F. \end{aligned}\right\} \quad (9a)$$

$$\left.\begin{aligned} &\text{for } R_{Fy} < 1000 \text{ kgf/mm·mm} \\ &\quad F = (6.32 + 2.60 \times 10^{-3}R_{Fy})P\text{cm} - 0.1 \times 10^{-3}R_{Fy} - 1.92, \\ &\text{for } 1000 \leqq R_{Fy} < 2090 \\ &\quad F = (7.71 + 1.19 \times 10^{-3}R_{Fy})P\text{cm} - 0.1 \times 10^{-3}R_{Fy} - 1.93, \\ &\text{for } 2090 \leqq R_{Fy} < 2720 \\ &\quad F = (4.55 + 2.67 \times 10^{-3}R_{Fy})P\text{cm} - 0.268 \times 10^{-3}R_{Fy} - 1.58, \\ &\text{for } 2720 \leqq R_{Fy} \\ &\quad F = 11.9P\text{cm} + 0.089 \times 10^{-3}R_{Fy} - 2.55, \end{aligned}\right\} \quad (9b)$$

where
H_D (ml/100 g, JIS)...diffusible hydrogen content (see eq. (3)),
R_{Fy} (kgf/mm·mm)...equivalent intensity of restraint (see Table (2)),
Pcm (%)...Ito-Bessyocarbon equivalent (see eq. (6)).

3.2 *Comparison with JIS-y test data*

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 calculated curve:

$$P_{HA} = -\log(U_B)cr = fn\{(t_{100})cr\}, \quad (10)$$

which is closely approximated by the following equation:

$$(t_{100})cr(s) = -510 + 2251P_{HA} - 648P_{HA}^2 + 740P_{HA}^3 \quad (11)$$

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

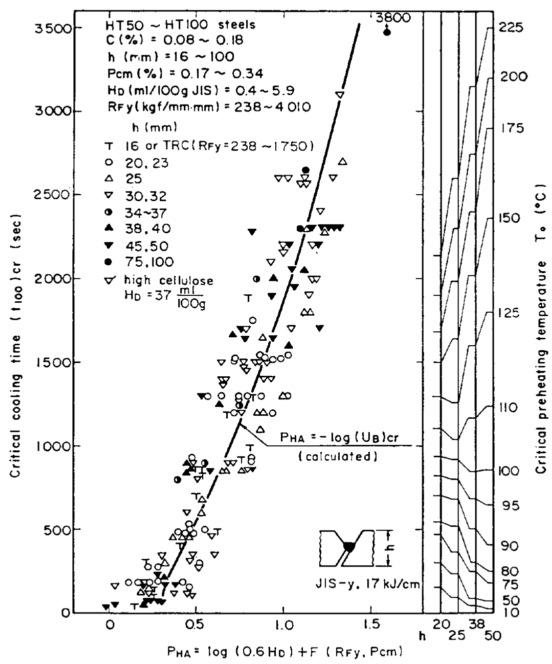

Fig. 6 Relationship between critical cooling time $(t_{100})_{cr}$ and cracking parameter P_{HA} for JIS-y test of HT50 to HT100 steels.

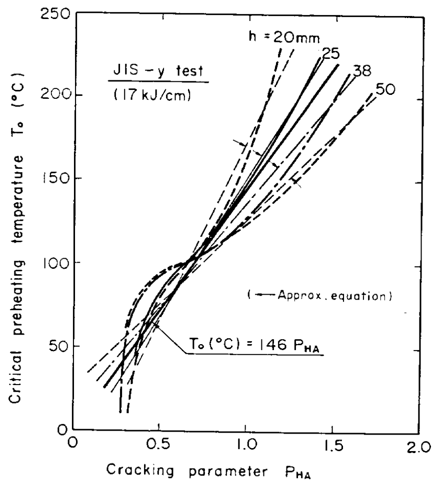

Fig. 7 Relationship between critical preheating temperature T_o, cracking parameter P_{HA} and specimen thickness h in JIS-y test.

JIS-y test is shown in Fig. 2. From Fig. 2 and eq. (11), the relationship between the critical preheating temperature T_o and P_{HA} is obtained in Fig. 7 for typical values of thicknesses. The relationship may be approximated by the following equations:

$$\left.\begin{aligned} \text{for } h = 20\text{ mm}, \quad T_o\,(^\circ\text{C}) &= 217P_{HA}-41\,, \\ 25\text{ mm}, \quad &= 167P_{HA}-14\,, \\ 38\text{ mm}, \quad &= 125P_{HA}+13\,, \\ 50\text{ mm}, \quad &= 100P_{HA}+27\,. \end{aligned}\right\} \quad (12)$$

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

$$T_o\,(^\circ\text{C}) = 146P_{HA}, \quad (12')$$

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

3.3 *Comparison with Ito-Bessyo Pw*

Ito and Bessyo [7] introduced in 1969 the following cracking parameter Pw based on a number of JIS-y test data:

$$\left.\begin{aligned} Pw\,(\%) &\equiv P\text{cm} + H_D/60 + R_{Fy}/40{,}000 \\ &= fn\{(t_{100})cr\}, \\ To\,(^\circ\text{C}) &= 1440Pw - 392 \text{ for JIS-y test}\,. \end{aligned}\right\} \quad (13)$$

This Pw is for severe restraint of 1000 to 3300 kgf/mm·mm, for low hydrogen contents of 1 to 5 ml/100 g (JIS), and for steels of low carbon contents (0.07 to 0.18%) of HT50 to HT100 strength grades.

Under the same test conditions as were used by Ito and Bessyo, the present P_{HA} formula gives the following cracking parameter P_H, which is deduced using the analytical procedure which was described in the previous report [1]:

$$\begin{aligned} P_H &= P\text{cm} + 0.997(H_D/60) + R_{Fy}/42{,}000 \\ &= fn\{(t_{100})cr\}, \end{aligned} \quad (14)$$

which is practically equivalent to Ito-Bessyo Pw in the severe restraint range.

4. 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 develop 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 value of σ_l, may be considered to be 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 [8] in the elastic range:

$$\left.\begin{aligned} \sigma_l &= k\sigma_w(1+B\gamma)/(1+C\gamma^2)\,, \\ \sigma_{w\gamma} &= \sigma_w/(1+C\gamma^2)\,, \\ \sigma_w &= mR_F = 0.042R_F\,, \\ \sigma_r &= \sigma_w(1+B\gamma)/(1+C\gamma^2)\,, \end{aligned}\right\} \quad (15)$$

where,

σ_l (kgf/mm²): the maximum value of concentrated transverse stress at the location of crack initiation.

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

σ_w (kgf/mm²): restraint transverse stress, average across weld throat for the case of $\gamma=0$,

$\sigma_{w\gamma}$ (kgf/mm²): average restraint stress for eccentric weld, $\gamma \neq 0$,

σ_r (kgf/mm²): local restraint stress near the root of eccentric weld.

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

$B \fallingdotseq 0.8$: coefficient related to the increase of local surface stress on weld root, caused by the bending of base metal due to eccentric weld location [8].

C=0.64 for JIS-y specimen and C=3 for RRC or TRC specimen [8].

The values of k are [1, 8]:

$$k = \left.\begin{cases} 8 & \text{for single or double bevel groove,} \\ 4 & \text{for oblique-Y, symmetric-Y or U-groove,} \\ 3.5 & \text{for double-V groove,} \\ 1.5 & \text{for V-groove or toe of weld.} \end{cases}\right\} \quad (16)$$

For the JIS-y test,

$$\sigma_l = 4\text{ m } R_{Fy} = 0.168R_{Fy}\,, \quad \text{(elastic range)}. \quad (17)$$

Equating the two eqs. (15) and (17) of σ_l, the equivalent intensity of restraint R_{Fy} is given as follows:

$$R_{Fy} = \frac{k}{4}R_F\left(\frac{1+B\gamma}{1+C\gamma^2}\right), \quad \text{(groove weld)}. \quad (18)$$

Matsui et al. [9] clarified that restraint stress in a single pass weld is not affected by weld heat input. Therefore, R_{Fy} eq. (18) is available regardless of heat input.

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

Any weld; $\sigma_l = k'\sigma_w$, (k' is different from eq. (16)),

JIS-y, 17 kJ/cm; $\sigma_l = 4\times 0.042 R_{Hy} = 0.168 R_{Fy}$

Equating the above two values of σ_l yields,

$$R_{Fy} = 6.0k'\sigma_w, \quad \text{(grooveless weld)} . \qquad (19)$$

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

$$R_{Fy} = 315 \text{ (kgf/mm·mm)},$$

which means a very mild restraint.

It should be noted here that the above formulae, eqs. (18) and (19), of equivalent intensity of restraint have been introduced using the elastic formulae of eq. (15). They may 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. (18) is very useful in explaining experimental data as will be shown later. This fact may suggest that strain concentration proceeds almost linearly even after yeilding of weld metal, and the value of concentrated strain is more intimately related with cracking than restraint stress.

5. Cooling Time and Maximum Hardness

5.1 *Cooling time t_{100}*

In Japan, the cooling time t_{100}, from solidification to 100°C, of fusion line, is considered one of the best measures to assess cold cracking phenomena. It is affected by preheating temperature, weld heat input, specimen thickness and dimensions, procedure of preheating (uniform or local), cooling condition, ambient temperature, etc. Eight charts to read t_{100} values for various conditions were presented in the previous report [1].

When a finite plate specimen is uniformly preheated, bead welded and then cooled in still air without directly touching a steel bed, the cooling time t_{100} can be estimated with satisfactory accuracy using the following equation by putting $T=100$°C and $t=t_{100}$(s):

$$T - T_\infty = \left(\frac{240\eta Q}{c\rho h\sqrt{4\pi\kappa t}} + T_p - T_\infty\right)\exp\left(-\frac{\alpha S}{c\rho V}t\right) \qquad (20)$$

where

T (°C); weld metal temperature,
T_∞ (°C); ambient temperature,
T_p (°C); preheating temperature,
Q (kJ/cm); arc energy (weld heat input),
η; arc energy transfer efficiency, 0.8 (SMAW), 1.0 (SAW),
t (s); time after solidification,
h (cm); specimen thickness (cm, not mm here),
S (cm^2); surface area of specimen,
V (cm^3); volume of specimen,
$c=0.128$ (cal/g°C); specific heat of steel,
$\rho=7.8$ (g/cm^3); density of steel,
$\kappa=0.146$ (cm^2/s); thermal diffusivity,
$\alpha=0.00035$ (cal/cm^{2}s°C); heat transfer coefficient.

This equation is valid for T below approximately 400°C.

5.2 *Cooling time $t_{8/5}$*

The cooling time $t_{8/5}$, from 800 to 500°C, is an important factor which is necessary in estimating the maximum hardness in HAZ. The analytical equation to calculate $t_{8/5}$ is very complicated, but the value of $t_{8/5}$ can be calculated with satisfactory accuracy with the following equations developed by the author:

$$t_{8/5}\text{(s)} = F\frac{\gamma}{(600-T_p)^\delta}Q^{(\alpha+\beta T_p)} \qquad (21)$$

where

$F=1$ for bead-on-plate long weld,
$F=0.9$ for groove weld (first pass),
$F=0.67$ for fillet weld (first pass) on plate thicker than 20 mm,
$F=0.45$ to 0.67 for fillet weld on plate thinner than 20 mm.

The values of constants are shown in Table 3.

Table 3 Constants for calculating $t_{8/5}$

h (mm)	Q (kJ/cm)	T_p (°C)	γ	δ	α	β
≧20	6–15	20–200	993	1.22	0.94	0.00070
20	15–50	do.	966×10^5	3.30	1.61	−0.00068
25	do.	do.	1.31	0.274	1.15	0.00111
30	do.	do.	3.51	0.345	0.97	0.00103
≧40	do.	do.	63200	1.87	0.96	−0.00004

5.3 *Estimation of Hmax*

The maximum hardness in the HAZ of welded high strength steels is an important measure for evaluating weld-zone ductility, cold cracking susceptibility, and stress corrosion cracking susceptibility.

It would be very convenient if Hmax could be predicted simply from carbon content, Pcm, and cooling time. To this end, the author developed a new formula, NSC-S, as follows [10]:

NSC-S formula:

$$\left.\begin{aligned} &H\text{max (Hv10)} = (187+64C+485P\text{cm}) \\ &\qquad -(97+680C-441P\text{cm})\arctan X, \\ &X \equiv \frac{Y+(0.501+7.90C-11.01P\text{cm})}{(0.543+0.55C-0.76P\text{cm})}, \\ &Y \equiv \log t_{8/5}, \end{aligned}\right\} \qquad (22)$$

where

C (%): carbon content,
Pcm (%): eq. (6),
$t_{8/5}$ (s): cooling time, from 800 to 500°C.

Although *Pcm* is not effective for steels of carbon contents over 0.18% as far as cold cracking is concerned, the above formula for *H*max is available even for higher carbon content steels of 0.35%.

6. Applications of P_{HA} Analysis

6.1 *Effect of groove shape and eccentric weld location*

It has been shown experimentally by many authors that the values of critical preheating temperatures are seriously affected by groove shape and weld location. It was shown in the previous report [1] that this fact can be explained quantitatively by the present P_{HA} analysis with the help of the idea of equivalent intensity of restraint R_{Fy}, eq. (18), but not at all by Ito-Bessyo *Pw*, eq. (13). The same fact has been ascertained again with the revised formula of P_{HA}, eq. (9).

6.2 *Comparison with Fikkers-Muller RRC test data*

Typical examples from the RRC test results of Fikkers and Muller [11] on 25 mm thick mild steel and HT50, Mn-Si and Mn-Si-V (Ti) (Nb) steel plates, are shown in Fig. 8. A 45-degree single-bevel groove with a root gap of 1 mm was used with a low hydrogen electrode:

$$H_D \text{ (IIW)} = 4-5 \text{ ml/100 g and by eq. (3)}$$

$$H_D \text{ (JIS)} = 1.7-2.5$$

and weld heat input of 19 and 25 kJ/cm without preheating. The critical condition for root crack initiation is given by the border line between the open circles and shaded circles in Fig. 8. The present P_{HA} criterion is shown by straight and bent broken lines, and seems to agree satisfactorily with experimental data. It should be noted that the steels with carbon contents of less than 0.20%, for which the *P*cm carbon equivalent is reliable, have been plotted in Fig. 8. Moreover, the following conversion of restraint should be adopted in this case:

$$R_{Fy} = kR_F/4 = 2R_F\ .$$

For the left figure (25 kJ/cm), estimated cooling time $(t_{100})cr=260$ (s), and $P_{HA}=0.365$ and $F=0.225$. For the right figure, estimated cooling time $(t_{100})cr=152$ (s) and $P_{HA}=0.312$ and $F=0.172$. The values of t_{100} were estimated assuming them equivalent to the case of JIS-y test.

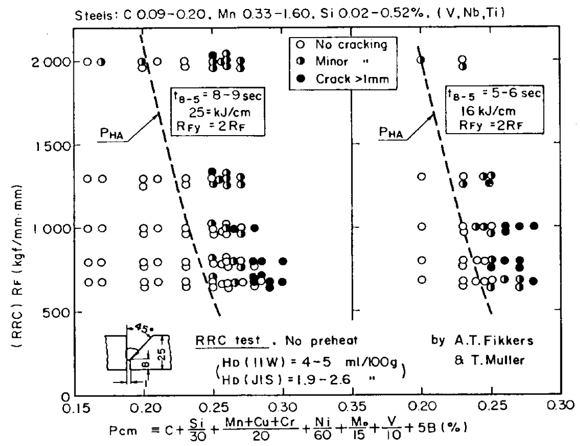

Fig. 8 Comparison of P_{HA}-estimated critical condition (broken lines) with Fikkers-Muller test data on mild and HT50 steel plates.

6.3 P_{HA} *analysis of heel crack*

The heel crack is a root crack in the HAZ of a single-pass fillet weld on a *T*-joint. It occurs 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. It was shown in the previous report [1] that heel cracking can be P_{HA}-analyzed quantitatively. Tanaka and Kitada test results [12], namely, the effect of *P*cm on the critical preheating temperature to avoid heel cracking, and the relation between critical preheating temperatures of JIS-y test and heel cracking test, were both quantitatively explained with the P_{HA} analysis as was described in detail in the previous report [1]. The same conclusion has been ascertained also with the revised P_{HA} formula in this report.

6.4 *Critical Hmax for JIS-y root cracking*

The value of critical maximum hardness $(H\max)cr$, over which HAZ root crack occurs in JIS-y test, can be estimated by means of P_{HA} and NSC-S formulae as was reported by the author previously [13]. One example is shown here, recalculated with the revised formulae in this report.

Using eq. (7) ($\log Hc = a - b\,P\text{cm}$), eq. (9) ($P_{HA}$), and eq. (11) $(t_{100})cr - P_{HA}$), the value of critical $(H\max)$ *cr* can be estimated by the following procedure as a function of carbon content *C*% and intensity of restraint R_{Fy}, for the case, for example, of without preheating:

$$\left.\begin{array}{l}
h \text{ (thickness)} \rightarrow R_{Fy} \rightarrow (a \text{ and } b) \\
(h,\ Q = 17 \text{ kJ/cm, JIS-y,} \\
\qquad T_p = 20°\text{C}) \rightarrow (t_{100})cr = fn(h) \\
\qquad\quad \downarrow \rightarrow t_{8/5} \qquad\quad \downarrow \rightarrow P_{HA} \\
\left.\begin{array}{r} (R_{Fy},\ P_{HA},\ H_D) \rightarrow P\text{cm} \\ C\% \\ t_{8/5} \end{array}\right\} \rightarrow \begin{array}{l}(H\max)cr \\ \text{(by NSC-S eq.)}\end{array}
\end{array}\right\} \quad (23)$$

Estimated values of critical *H*max are shown in Fig. 9. The values are compared for three levels of carbon content, C%=0.10, 0.15 and 0.18. In every case, the $(H\max)cr$ values decrease with increasing values of hydrogen content H_D and intensity of restraint R_{Fy}. However, the decrease is not so serious in the case of mild restraint.

It should be noted here that, for the same value of *H*max, a lower carbon content HAZ is more crack resistant than a higher carbon content HAZ. This important finding resulted from the P_{HA}-analysis of critical hardness, and one example of $(H\max)cr$ is shown in Fig. 10 as follows.

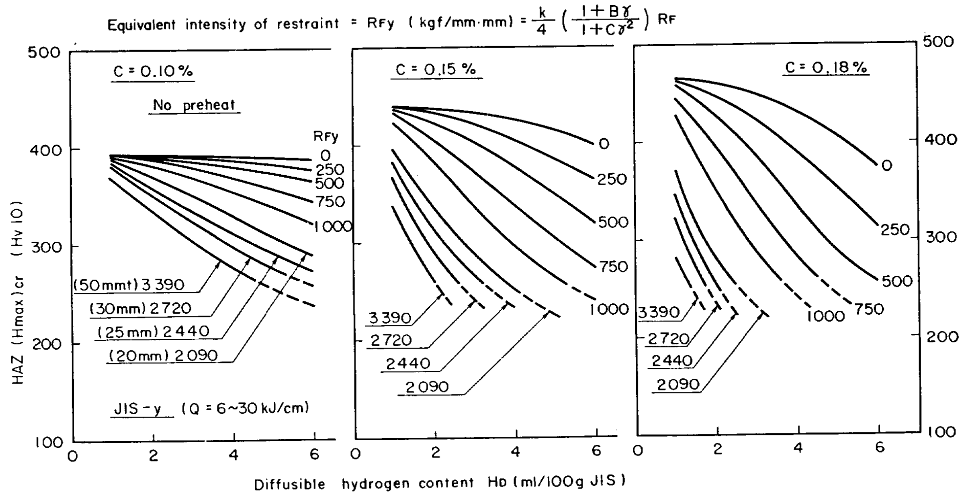

Fig. 9 Critical values of Hmax to prevent root cracking in one pass weld HAZ as related to diffusible hydrogen content H_D and equivalent intensity of restraint R_{Fy} for JIS-y test without preheating.

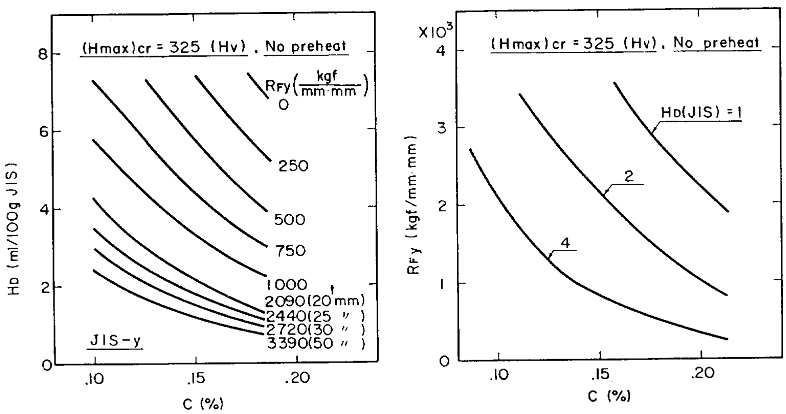

Fig. 10 Relationship between C%, H_D and R_{Fy} for the critical value of (Hmax)cr=325 in JIS-y test without preheating.

In the recent fabrication of offshore steel structures, it is frequently specified in the welding procedure test that the maximum hardness in the HAZ should not exceed 325 Hv, that is,

$$H\text{max} \leqq 325 \text{ (Hv)}$$

For the condition as specified, the relationship between carbon content, diffusible hydrogen content and intensity of restraint in the JIS-y test without preheating (and heat input Q=6 to 30 kJ/cm) is given in Fig. 10.

When using Fig. 10 in practical fabrication, it should be remembered that the restraint in the JIS-y test specimen is generally far more severe than that actually observed in practical structures of the same plate thickness as JIS-y specimen [14]. Examples of measured values of restraint in practical structures, indicate that the intensities of restraint R_F of butt joints are less than 40 times the plate thickness;

$$R_F \text{ (kgf/mm·mm)} \leqq 40 \times h \text{ (mm)}, \tag{24}$$

For example, in welding the first pass in a double-V butt joint of 30 mm thick plate in practical fabrication, we may assume as follows:

$$R_F = 40 \times 30 = 1{,}200 \text{ kgf/mm·mm}.$$

Since for a double-V groove, k=3.5 and γ=0 in eq. (18),

$$\therefore R_{Fy} = 1{,}200 \times 3.5/4 = 1{,}050 \text{ kgf/mm·mm}.$$

When H_D=4.0 ml/100 g (JIS), which is usual for HT50 strength steel electrodes for offshore application, the left side figure in Fig. 10 requires the condition for R_{Fy}=1050:

$$C \leqq 0.13\%$$

to secure Hmax≦325w ithout preheating. If C% =0.10, a higher value of H_D=5.5 is permissible.

The critical values of Hmax for 100°C preheating were also estimated. The Hmax values in this case are naturally far greater than those of the condition without preheating. The hydrogen concentration near the root of JIS-y (17 kJ/cm) weld at the instant of t_{100}, is reduced by approximately half by 100°C preheating from that of the weld without preheating. Therefore, initial hydrogen content H_D may be doubled by 100°C preheating.

6.5 *Critical Hmax in Harasawa-Hart cracking test*

Harasawa and Hart [15] conducted a root cracking test with H-type-slotted self-restraint specimens on

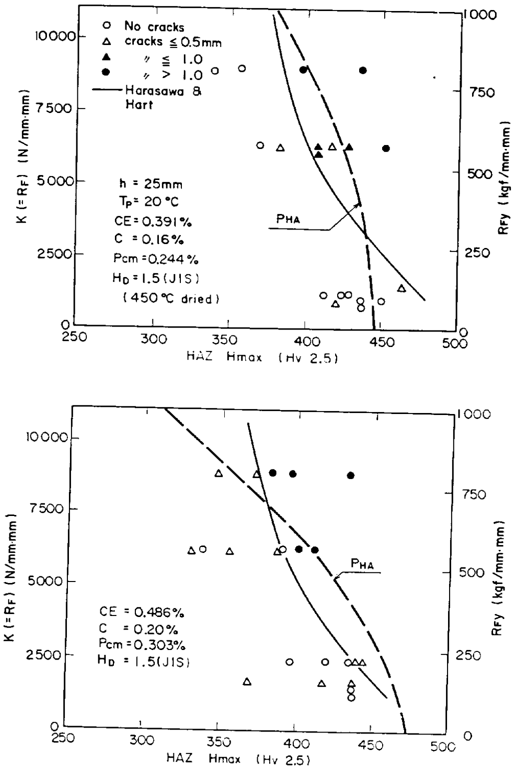

Fig. 11 Comparison of P_{HA}-estimated critical Hmax (broken line) with Harasawa-Hart test result (solid line) for double-V groove cracking test.

three 25 mm thick high-strength steel plates. Double-V groove butt joints were welded in a single pass without preheating and with various values of weld heat inputs, diffusible hydrogen contents and intensities of restraint. Critical values of *H*max were determined in conjunction with restraint as shown, for example, in Fig. 11 with a solid-line curve. Comparison with P_{HA} prediction was made by the author in the previous report [13]. One example is shown here recalculated with the revised P_{HA} formula as follows.

For the tested double-V groove, R_F is identical to the K in Fig. 18 in the Hart report, and $k=3.5$ and $r=0$, therefore,

$$F_{Fy}=(3.5/4)R_F=0.875R_F=0.875K\,.$$

P_{HA}-estimation of (*H*max)*cr*, without preheating can be performed according to the procedure described in the preceding article 6.4. The estimated values, shown in Fig. 11 with a broken-line curve, seem to agree satisfactorily with Hart data.

Moreover, the observed HAZ *H*max values as affected by cooling time $t_{8/5}$ agreed well with the estimated values by NSC-S *H*max formula in eq. (22).

6.6 *Yurioka single-bevel* 30 *kJ/cm test*

Yurioka et al. [16] conducted a root cracking test of heavy plates with a high heat input of 30 kJ/cm. They used *H*-slotted type self-restraint cracking test specimens of single-bevel groove for 50 to 100 mm thick HT50, HT60 and HT80 steels. The intensity of restraint R_F was varied from 295 to 3520 kgf/mm·mm and $R_{Fy}=2R_F$. The measured values of critical

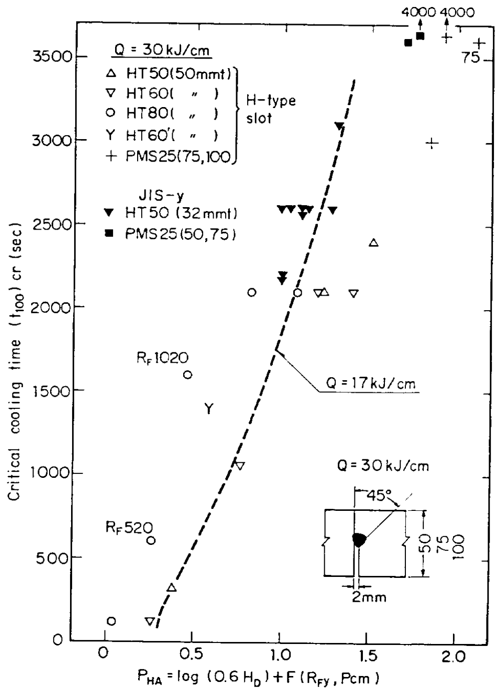

Fig. 12 Comparison of P_{HA}-estimation (broken line) with Yurioka test result for single-bevel groove cracking test with 30 kJ/cm heat imput.

cooling time $(t_{100})cr$ are shown in Fig. 12 against P_{HA}. Although the values are widely scattered, they seem to agree qualitatively with the calculated curve for JIS-y 17 kJ/cm. The critical cooling time $(t_{100})cr$ was calculated from preheating temperature using eq. (20).

6.7 *Comparison with Ito-Bessyo Pw or Yurioka CI*

It was indicated that Ito-Bessyo cracking parameter *Pw*, eq. (13) in article 3.3 is very close to the P_{HA} cracking parameter P_H in severe restraint range.

Yurioka and his co-workers [17] proposed a simple formula for the cracking index, CI, which is defined by the following:

$$\mathrm{CI}\equiv\mathrm{CEN}+0.15\log H_D+0.30\log(0.017\mathrm{Kt}\,\sigma_w)\,, \qquad (25)$$

where

$$\left.\begin{aligned}\mathrm{CEN}(\%)&\equiv\mathrm{C}+\mathrm{A(C)}\{\mathrm{Si}/24+\mathrm{Mn}/6+\mathrm{Cu}/15\\&\quad+\mathrm{Ni}/20+(\mathrm{Cr}+\mathrm{Mo}+\mathrm{Nb}+\mathrm{V})/5+5\mathrm{B}\},\\\mathrm{A(C)}&\equiv0.75+0.25\tanh\{20(\mathrm{C}-0.12)\}.\end{aligned}\right\} \qquad (26)$$

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 0.18%.

It was proved [1] that the cracking index CI is practically identical to P_{HA} both in mild and severe restraint ranges, provided steels have lower carbon content than 0.18%. The same conclusion was ascertained also with the revised formula of P_{HA}.

6.8 *Comparison with Implant test data*

P_{HA}-analysis of Implant cracking test data is now in progress and will be reported soon. Generally speaking, the equivalent intensity of restraint R_{Fy} of Implant test data is rather low, mostly smaller than 1000 kgf/mm·mm. The P_{HA} equation (9b) in this mild restraint range is not necessarily verified with abundant data of JIS-y, RRC-y, or TRC-y test.

6.9 *Precautions in applications of* P_{HA}

The P_{HA} formula (eq. 9), the relation $(t_{100})cr$ to P_{HA} (eq. 11), and the relation To to P_{HA} (eq. 12) were all derived from the JIS-y test data of weld heat input 17 kJ/cm. Therefore, some remarks on the effect of heat input may be desirable:

eq. (9), P_{HA}-formula······independent of heat input,
eq. (11), $(t_{100})cr-P_{HA}$ ···do., provided weld throat depth is over 4 mm (heat input over 7 kJ/cm),
eq. (12), $To-P_{HA}$·········seriously affected by heat input, because $t_{100}-T_0$ depends on heat input,
eq. (18), $R_{Fy}-R_F$·········independent of heat input.

Since P_{HA} employs Pcm, it should be applied only to steels of lower carbon contents of less than approximately 0.18%. It should be applied only to single pass welds, not to multipass welds.

7. Conclusions

In the previous report [1], a new 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 revised into a more reasonable and accurate form by adding new JIS-y test data to the previous ones. It has been ascertained that the revised P_{HA} formula and the analyses of various experimental test results agree satisfactorily with experimental findings. Verification of the effectiveness of P_{HA}-analysis has been done for various cases such as: (1) effect of groove shape and eccentric weld location, (2) Fikkers-Muller RRC test with single bevel groove, (3) Tanaka-Kitada heel cracking test, (4) critical maximum hardness in JIS-y test, (5) Harasawa-Hart root cracking test with double-V groove, (6) Yurioka single bevel groove 30 kJ/cm root cracking test, and (7) comparison with Ito-Bessyo Pw and Yurioka cracking index CI.

In this report, additional information such as formulae to estimate cooling times of t_{100} and $t_{8/5}$ are presented together with a convenient formula NSC-S to estimate maximum hardness.

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