Title	Dynamical Aspect of Cold Cracking Parameter(Welding Mechanics, Strength & Design)
Author(s)	Ueda, Yukio; Kim, You Chul
Citation	Transactions of JWRI. 1984, 13(1), p. 77-86
Version Type	VoR
URL	https://doi.org/10.18910/3791
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Dynamical Aspect of Cold Cracking Parameter†

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Abstract

In order to specify welding conditions for prevention of weld cracking, various kinds of weld cracking tests are conducted. The oblique Y-groove weld cracking test specimen has been widely used as a cold weld cracking susceptibility test specimen or to specify preheating temperature for actual welding. From the results of the cracking tests using this specimen under various conditions, the cold cracking parameters were proposed for the purpose of simple estimation of the weldability and susceptibility.

In this paper, a series of theoretical analyses are performed for restraint stress-strain produced in the weld metal of the oblique Y-groove weld cracking test specimen, varying the kind of steel, heat input, preheating temperature and the base plate thickness. Then, the mechanical characteristics of this specimen are clarified. Moreover, the dynamical measure in the cold cracking parameters (P_w and P_{HA}) are examined from the dynamical view point.

The main results obtained in this investigation are as follows:

(1) *Even though the size of the specimen is specified, the distribution and magnitude of restraint stress-strain along the slit vary if the kind of steel, preheating temperature, plate thickness, etc. vary. Whereas, if the plate thickness is the same, the restraint intensity is constant irrespective of these changes.*

(2) *Analyzing the data of approximately 500 cracking tests, the validity and practicability of the proposed restraint strain to use as a dynamical measure are demonstrated.*

(3) *Critical restraint strains for cold cracking of three kinds of high strength steel are estimated.*

(4) *A new selecting method of the critical preheating temperature T_i^* for prevention of cold cracking with the aid of the critical restraint strain is developed.*

(5) *For three kinds of high strength steel, simple and accurate expressions for T_i^* are derived.*

KEY WORDS: (Dynamical Measure for Cold Cracking) (Restraint Stress-Strain) (Critical Restraint Strain) (Critical Preheating Temperature) (Cold Cracking Parameter) (Restraint Intensity)

1. Introduction

Welded structures are inevitably accompanied with welding deformation and residual stress-strain which may cause various weld crackings. These weld crackings threaten to lower the strength or the safety of welded structures. Therefore, it is required to specify the welding conditions under which no weld cracking occurs. Among many researches on this subject, there has been one which aims at development of a simple estimation method of the welding conditions under which cold cracking can be prevented using the oblique Y-groove weld cracking test specimens. In this research, *200* kinds of high strength steel were tested. Based on the results, the chemical compositions of steel, accumulation of diffusible hydrogen in the weld metal and restraint intensity of a welded joint were considered to be the three major factors of cold cracking susceptibility. Using these, a cold cracking susceptibility parameter P_w was proposed[1]. Moreover, the selecting method of preheating temperature for prevention of cold cracking were shown using this P_w[2].

Even more researches have been carried out on this subject on the basis of P_w. Improving the estimation method of diffusible hydrogen which is one of the factors of cracking included in P_w, a new cold cracking parameter, P_{HA}, has recently been proposed[3].

In this paper, the oblique Y-groove weld cracking test specimen which has been widely used as a cold cracking susceptibility specimen as mentioned above is used. Regarding the restraint stress-strain produced in the weld metal as a measure representing the severity of mechanical restraint conditions, a series of theoretical analyses of restraint stress-strain are performed varying the kind of steel, heat input, preheating temperature, plate thickness and so on. Based on these results, the mechanical characteristics of this specimen are clarified. Furthermore, the cold cracking susceptibility parameters, P_w and P_{HA}, are investigated from the dynamical point of view.

2. Dynamical Characteristics of oblique Y-groove Cold Cracking Test Specimen

In order to clarify the dynamical characteristics of the oblique Y-groove weld cracking test specimen (**Fig. 1**), a series of theoretical analyses are performed by the analytical calculation method of restraint stress-strain produced in the weld metal perpendicular to the weld line which was developed by the authors for the slit welded

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Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

joints[4),10)]. At the same time, the applicability of the dynamical measure composed of the cold cracking susceptibility parameters, P_w and P_{HA}, that is restraint intensity as a dynamical measure is investigated.

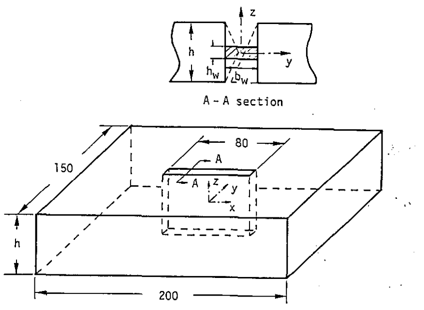


Fig. 1 Oblique Y-groove weld cracking test specimen

2.1 Restraint intensity

Among restraint intensities of the oblique Y-groove weld cracking test specimen which are presently used as a simple dynamical measure of cold cracking, those under uniformly distributed loads and uniform displacement were paid attention, and for their simple and accurate calculation, generalized estimating equations of effective restraint intensity were proposed for every combination of geometrical dimensions in consideration of the ratio of throat thickness to base plate thickness, eccentricity from the center of plate thickness and variation of the groove shape[5)]. Assuming that the first pass for the oblique Y-groove weld cracking test specimen is laid at the center of its plate thickness, the estimating equation of the average effective restraint intensity $(\bar{R}_p)_\eta$ under uniformly distributed loads along the slit is introduced below.

$$(\bar{R}_p)_\eta = \eta\ (0.0059Eh) \qquad (1)$$

where,

$\eta = exp\ [(5.6 - h)/80.3] \qquad [5 < h \leqslant 100]$

: correcting coefficient[5)] for small ratio of throat thickness to base plate thickness and for example, the above equation η is the approximating equation with throat thickness $h_w = 5\ mm$ $(Q = 17000 J/cm)$.

h: base plate thickness (mm),

$E = 21000\ (kg/mm^2)$: Young's modulus.

2.2 Restraint stress-strain

Even with the same specimen size ratios, the distribution along the slit and magnitude of restraint stress-strain produced in the weld metal of a slit weld specimen vary greatly depending on the relative proportion of the critical plate thickness h_{cr} which is a function of heat input to the slit length l: h_{cr}/l[6)].

Keeping the same specimen size ratios, B/l and L/l, base plate thickness h, heat input Q and initial temperature T_i, and varying only the slit length l (as a result, the actual specimen size similarly changes), the restraint strain ϵ_w produced in the weld metal is calculated by the analytical calculation method. The restraint strain ϵ_{wo} at the center of the slit and restraint intensity $(\bar{R}_p)_\eta$ are shown against l/h_{cr} in **Fig. 2**. That for the oblique Y-groove weld cracking test specimen is indicated by 「●」. The Y-groove test specimen, in spite of its small size, bears extremely severe restraint, that is, with the heat input $Q=17000J/cm$, the restraint stress reaches the yield stress in the weld metal of the whole slit and the restraint strain is approximately the maximum value for variation of l/h_{cr}. This inclination is common to all kinds of steel **(Table 1)**.

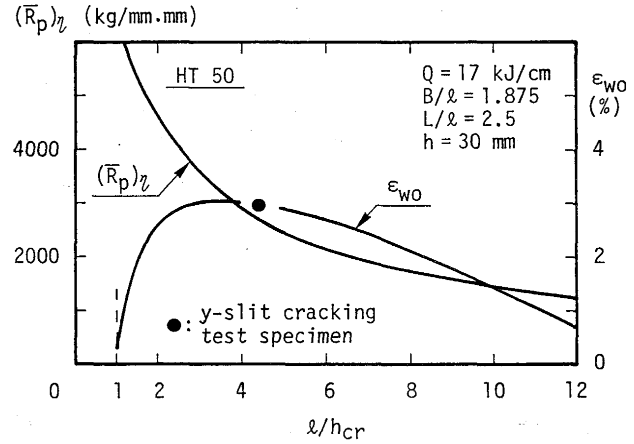


Fig. 2 Relation between l/h_{cr} and restraint strain

Table 1 Mechanical property and phase transformation temperature of various materials

	Yield strength $\sigma_Y(kg/mm^2)$	Tensile strength $\sigma_U(kg/mm^2)$	T_p (°C)	T_m (°C)	T_{mf} (°C)
MS	40	30 - 50	780 - 600	700	700
HT 50	49	50 - 62	750 - 540		660
HT 60	55	62 - 75	610 - 360		480
HT 80	74	75 - 95	520 - 400		450

T_p : Phase transformation temperature range during cooling
T_m : Mechanical rigidity recovery temperature
T_{mf} : Virtual mechanical rigidity recovery temperature

On the contrary, the value of restraint intensity $(\bar{R}_p)_\eta$ of the Y-groove test specimen which can be calculated as a function of geometrical dimensions is not so large for this specimen size ratio.

2.3 Effects of various factors on restraint stress-strain

The effects of various factors such as the kind of steel, heat input, preheating temperature and base plate thickness on the restraint stress-strain produced in the weld metal of the oblique Y-groove weld cracking test specimen are investigated.

2.3.1 Effect of phase transformation at cooling stage

When the effect of phase transformation on residual stress-strain is considered, the kinds of steel for steel structures (including high strength steel) can be classified into two groups; (1) one (mild steel (MS), *50 kg* class high strength steel (HT50), etc.) in which the phase transformation at the cooling stage occurs when the weld metal is cooled approximately to the mechanical rigidity recovery temperature T_m (about *700*°C) and (2) the other (*60kg*(HT60), *80kg* class high strength steel (HT80), etc.) in which the phase transformation occurs at relatively lower temperature than T_m. The temperature region of phase transformation for each high strength steel is shown in Table 1[7].

For the kinds of steel in which the effect of phase transformation at the cooling stage is remarkable, the analytical treatment of the mechanical properties at the phase transformation region and the analytical calculating method were proposed in Ref. 8). In the simplified analytical calculation method of the restraint stress-strain of the steel in which the effect of transformation expansion is remarkable, the transformation expansion is idealized to occur at the intermediate point of the phase transformation temperature region and assumed not to depend on the history of the formerly produced stress-strain. In the actual analysis, this intermediate temperature was regarded as the virtual mechanical rigidity recovery temperature T_{mf} and the validity of the calculated results of the following restraint stress-strain by this method was confirmed in comparison with the results of the thermal elastic-plastic analyses and the experiments. T_{mf} of each high strength steel discussed in this paper is indicated in Table 1.

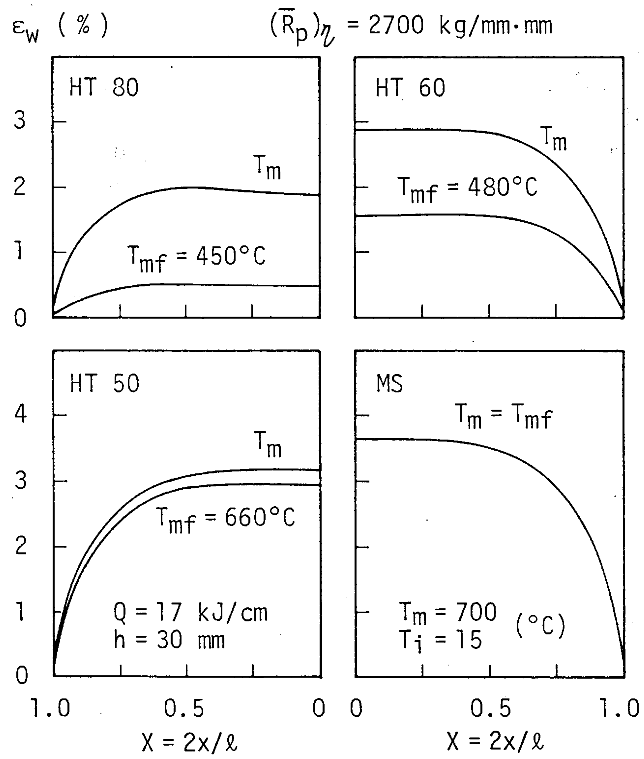


Fig. 3 Effect of phase transformation on restraint strain

Restraint stress-strain of various kinds of steel are calculated by the analytical calculation method introduced in Ref. 8). The results are shown in **Fig. 3**. The restraint stress-strain of MS, HT50, etc. can be accurately calculated irrespective of the effect of phase transformation because the phase transformation occurs around the mechanical rigidity recovery temperature T_m (*700*°C). Whereas, the restraint stress-stain of HT60, HT80, etc. are greatly influenced by the phase transformation because the phase transformation occurs in the temperature region (between *600* and *350*°C) in which the mechanical rigidity of the weld metal is considerably recovered.

On the other hand, restraint intensity $(\bar{R}_p)_\eta$ is a function of only geometrical dimensions and is indifferent to the phase transformation (difference of the kind of steel). Therefore, it is not reasonable to widely use restraint intensity as a measure to systematically estimate the severity of mechanical restraint condition for various kinds of steel, different types of joint, etc..

2.3.2 Effect of heat input

The effect of heat input on restraint stress-strain is discussed.

The throat thickness of the weld metal is determined according to the changes of heat input *Q* (*J/cm*) and the type of groove. In case of the Y-groove with a groove

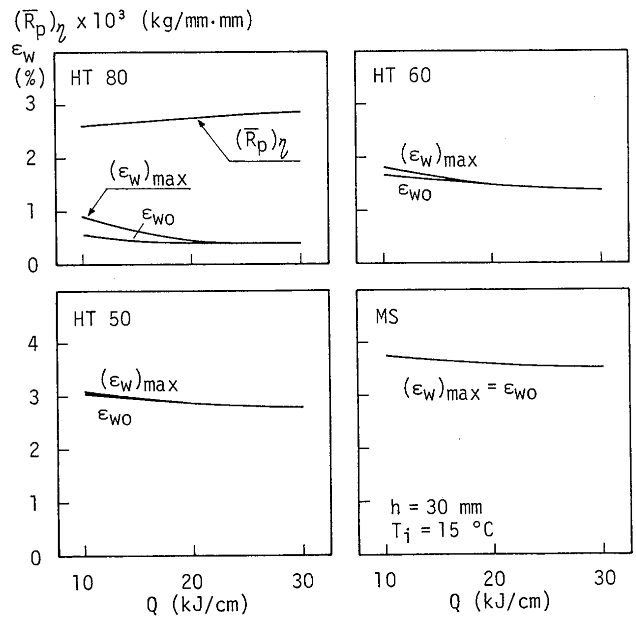


Fig. 4 Effect of heat input on restraint strain

angle of *60* degrees, the throat thickness, h_w, can be obtained as follows[9]:

$$h_w = 0.0383\sqrt{Q} \ (mm) \qquad (2)$$

Keeping the same base plate thickness $h = 30\ mm$ and initial temperature $T_i = 15°C$ and varying only heat input Q, restraint stress-strain is calculated in consideration of the change of throat thickness accompanying the change of Q. The relation between restraint strain ϵ_w and heat input is shown in **Fig. 4.** ϵ_{wo}, $(\epsilon_w)_{max}$ indicates restraint strain at the center of the slit and the maximum value of restraint strain along the slit, respectively. Restraint strain, decreasing a little according to the increase of heat input, inclines to converge to a certain value.

While the effective restraint intensity $(\bar{R}_p)_\eta$ is constant irrespective of the kind of steel, though inclining to increase a little in accordance with the increase of throat thickness which accompanies the increase of heat input.

2.3.3 Effect of preheating temperature (Initial temperature)

Normally, preheating temperature, T_i, for actual welding is specified by testing the oblique Y-groove weld cracking test specimen under the conditions similar to the actual welding. In order to investigate the effect of preheating temperature, restraint stress-strains of various kinds of high strength steel are obtained by varying the preheating temperature.

Calculated results of restraint strain ϵ_{wo} at the center of the slit of various kinds of high strength steel are shown in **Fig. 5**.

It is generally known that preheating temperature accelerates the dissipation of diffusible hydrogen and lowers the cold cracking susceptibility of steel. The magnitude of restraint strain ϵ_{wo} at the center of the slit varies depending mainly on the phase transformation temperature and the yield stress which vary among the kinds of steel. However, in any kind of steel, the restraint strain produced in the weld metal decreases according as the preheating temperature rises (Fig. 5). This tendency is remarkable in HT50 and HT60. Therefore, one of the very applicable and practical methods for prevention of cold cracking from HT50 and HT60 is the preheating temperature which is effective not only on accelaration of the dissipation of diffusible hydrogen but also on the decrease of restraint strain of the weld metal. While, in case of HT80, the effect of preheating temperature is mainly on acceleration of the dissipation of diffusible hydrogen and not on the decrease of restraint strain.

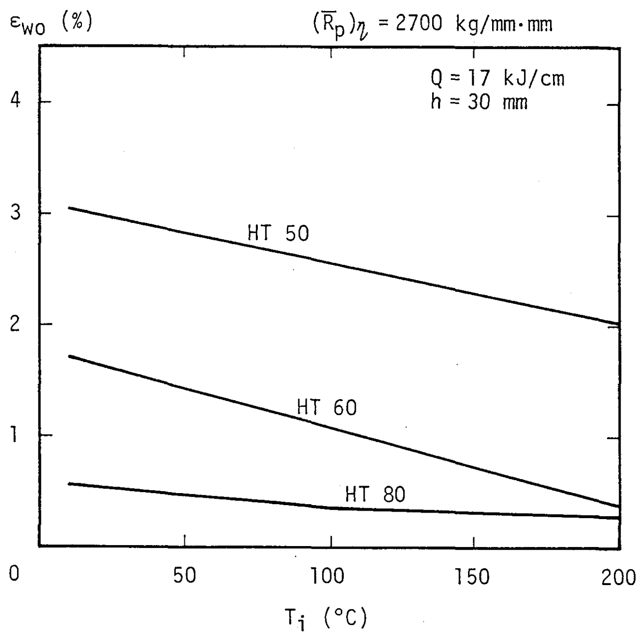


Fig. 5 Effect of preheating temperature on restraint strain

On the other hand, restraint intensity $(\bar{R}_p)_\eta$ is constant irrespective of variety of preheating temperature. Therefore, the severity of mechanical restraint condition due to the change of preheating temperature cannot be discussed using the restraint intensity.

2.3.4 Effect of base plate thickness

In recent years, very thick plates have been used in various fields. Following this, in order to estimate weld cracking susceptibility of thick plates, the oblique Y-groove weld cracking test specimen has been used from time to time varying only its base plate thickness. It was clarified for mild steel and the others in which the effect of transformation expansion accompanying the phase transformation at the cooling stage can be neglected that the mechanical restraint condition becomes approximately the maximum when the base plate thickness is $h = 50\ mm$ and other sizes of the specimen are the same as the oblique Y-groove weld cracking test specimen[10]. In this section, it is investigated how far the above-mentioned discussion can be applied to various kinds of high strength steel.

Keeping the heat input $Q = 17000 J/cm$ and initial temperature $T_i = 15°C$ constant and varying the base plate thickness and the kind of steel, restraint stress-strain is calculated. Calculated results of restraint strain ϵ_{wo} at the center of the slit are shown in **Fig. 6** (the thin line shows the case when the influence of thermal reflection from the both sides of the plate is neglected).

In any kind of steel, restraint strain increases according to the increase of the plate thickness, though such tendency differs depending on the ratio of restraint strain of the weld metal to yield strain $\epsilon_Y = \sigma_Y/E$ (σ_Y: yield stress of weld metal). Therefore, restraint strain is shown not by a smooth curved line but by a bent line. Moreover,

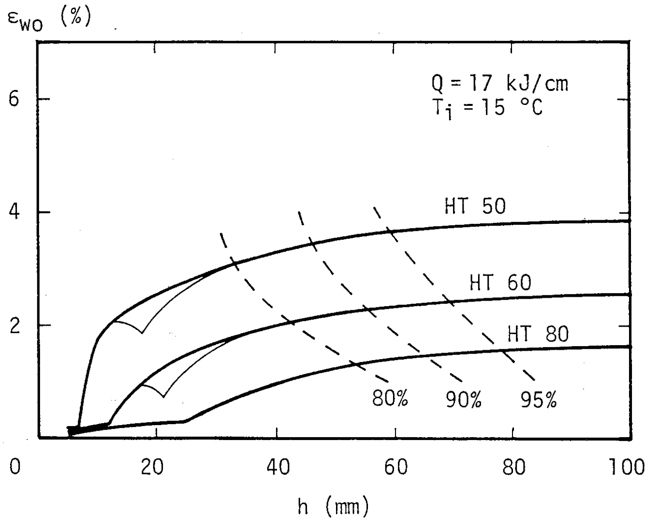


Fig. 6 Effect of plate thickness of base plate on restraint strain

restraint strain in each kind of steel is inclined to converge to a certain value. In contrast with such curved line, the isopleth of *80*, *90* and *95%* of the converged value in each steel is connected by broken lines. According to these curves, in case of the steel (MS, HT50, etc.) in which the phase transformation by cooling occurs at relatively high temperature, restraint strain becomes more than *90%* of the convergent value when the plate thickness of the specimen is *50 mm*, and the mechanical restraint conditions would not become severer even though the plate thickness is increased. As for the steel such as HT60, HT80, etc. in which phase transformation occurs at relatively low temperature, restraint strain becomes more than *90%* of the convergent value with the plate thickness of about *60* to *70 mm*, respectively.

On the other hand, the above-mentioned change of plate thickness is represented by the restraint intensity $(\bar{R}_p)_\eta$ and shown in the relation with the restraint strain

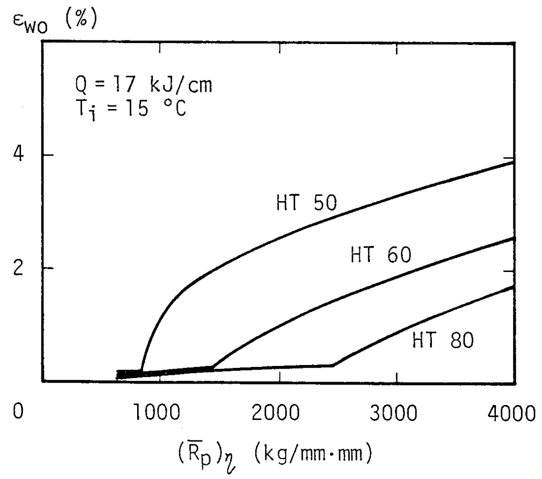


Fig. 7 Relation between effective restraint intensity and restraint strain

ϵ_{wo} at the center of the slit in **Fig. 7**. In any kind of steel, restraint strain increases according as restraint intensity increases. However, they are not depicted by a smooth curved line but are divided into elastic and plastic regions. As both restraint strain and restraint intensity are inclined to increase in each region, it seems possible to use restraint intensity for estimation of relative severity of the mechanical restraint condition for every kind of steel.

3. Qualification of Dynamical Measure for Cold Cracking

It may be simply stated from the mechanical point of view that cold cracking initiates when the dynamical measure (restraint intensity and restraint stress-strain) exceeds the certain critical value. The critical value is determined by the metallurgical factor (ductility, etc.). Therefore, according as the ductility of steel lowers, the cold cracking susceptibility becomes higher.

The test results obtained for determining the critical preheating temperature of the oblique Y-groove weld cracking test specimen for prevention of its cold cracking are analyzed. These results, including two experimental ones by the high cellulose electrode, were used by Suzuki et al.[3] on proposing P_{HA}. On analyzing the experimental results, the kinds of steel are briefly classified into three (HT50, HT60, HT80) based on their tensile strength (Table 1). As the result of this analysis, the critical value for cold cracking can be defined.

On the other hand, diffusible hydrogen makes steel brittle accumulating at defects, dislocation, etc., and then it is considered to lower the ductility of steel. Accordingly, both the chemical compositions of steel, P_{cm}, and the accumulation of diffusible hydrogen, H_D, are regarded as metallurgical measure. P_s expressed by Eq.(3) is regarded as a metallurgical measure. The second term of Eq.(3) expresses the effect of diffusible hydrogen and the coefficient takes different values for systematic treatment of diffusible hydrogen contained in electrodes of both low hydrogen and high cellulose type[3].

$$P_s = P_{cm} + 0.088\, Log\, (\lambda H_D) \qquad (3)$$

where,

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

$\lambda = 0.6$: low hydrogen type

$\lambda = 0.24$: high cellulose type

H_D: diffusible hydrogen content per 100g of deposited metal by JIS Z 3113.

The cold cracking susceptibility parameters, P_w and P_{HA}, were presented based on the experimental results by the oblique Y-groove cold cracking test specimen of various kinds of high strength steel. Restraint intensity was ap-

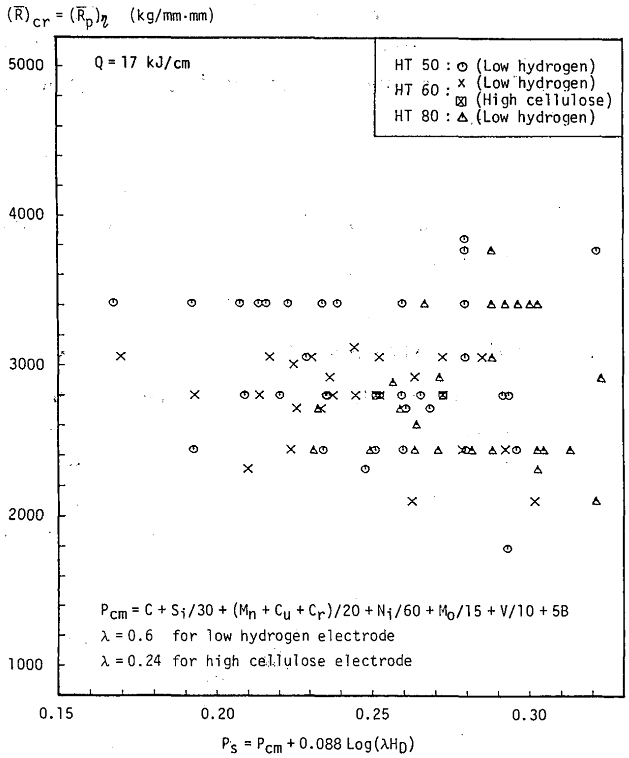


Fig. 8 Relation between P_s and critical effective restraint intensity

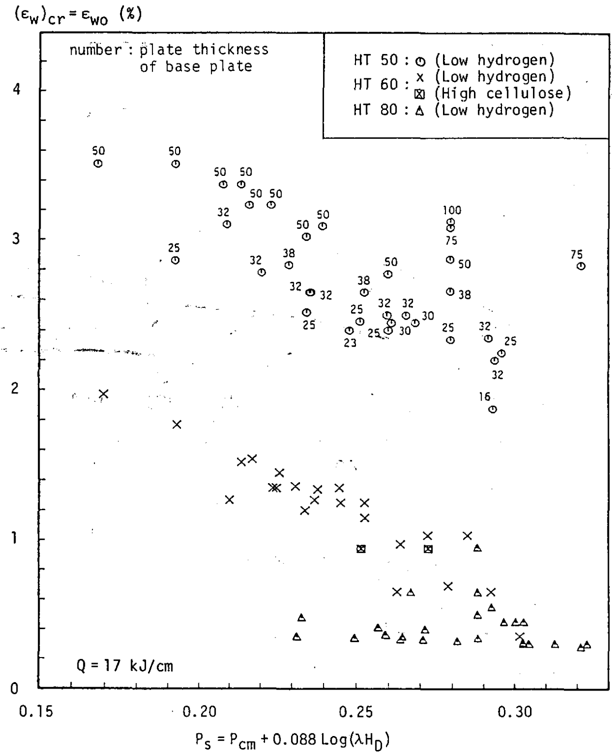


Fig. 9 Relation between P_s and critical restraint strain of high strength steels

plied as a dynamical measure to these parameters.

In the previous chapter, not only the dynamical characteristics of the oblique Y-groove weld cracking test specimen was clarified based on restraint strain but also the applicability of the restraint intensity as a measure to represent the severity of mechanical conditions was clarified. The above mentioned experimental values of critical preheating temperature for prevention of cold cracking are expressed in the relation with a metallurgical measure, P_s, and restraint intensity as in **Fig. 8**. If the formerly mentioned mechanical view is followed, cracking must occur with small restraint intensity as P_s increases (ductility decreases). Nevertheless, this inclination cannot be observed and the data for the relation between the metallurgical measure P_s and the critical restraint intensity $(\bar{R})_{cr}$ for cracking (Fig. 8) scatter irrespective of the kind of steel. As a result, it is impossible to use restraint intensity as a measure to represent the severity of mechanical restraint conditions.

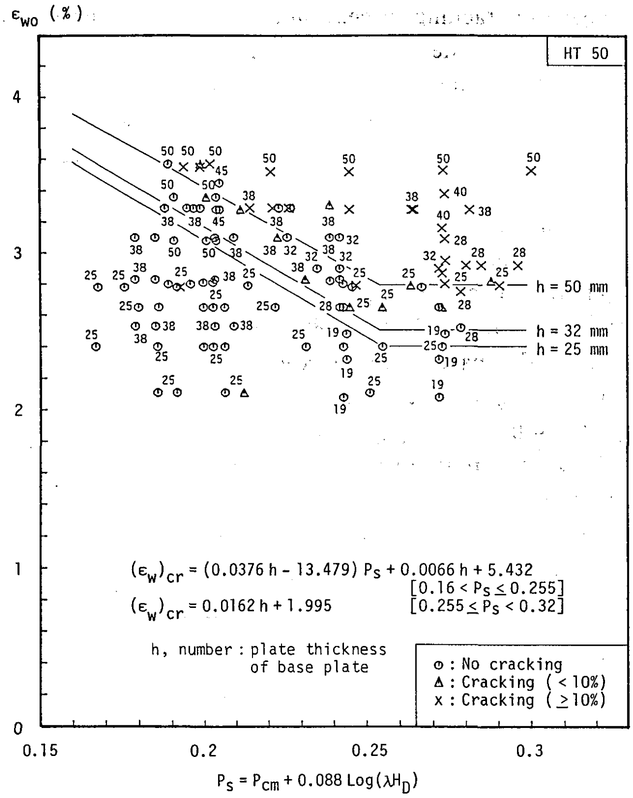
The restraint intensity[5)] is basically a function of only the base plate thickness since the specimen size is the same except the thickness. Therefore, the restraint intensity is constant with the same base plate thickness even though the kind of steel (phase transformation in the cooling stage and strength differ) and preheating temperature vary. This implies that the same mechanical condition is assumed.

Therefore, the restraint intensity (a dynamical measure) which is included in the cold cracking susceptibility parameters, P_w and P_{HA}, cannot be used as a dynamical measure for the two dimensional restraint state (thermal expansion and shrinkage vary along the weld line). Because of this reason, another measure is required to represent simply and generally the severity of mechanical restraint conditions. In this regard, the authors have clarified the general characteristics of restraint stress-strain produced by the slit weld. They have also proposed the restraint strain ϵ_w (the sum of elastic and plastic restraint strains) as a measure to represent the severity of mechanical restraint conditions[6)], which can be analytically calculated.

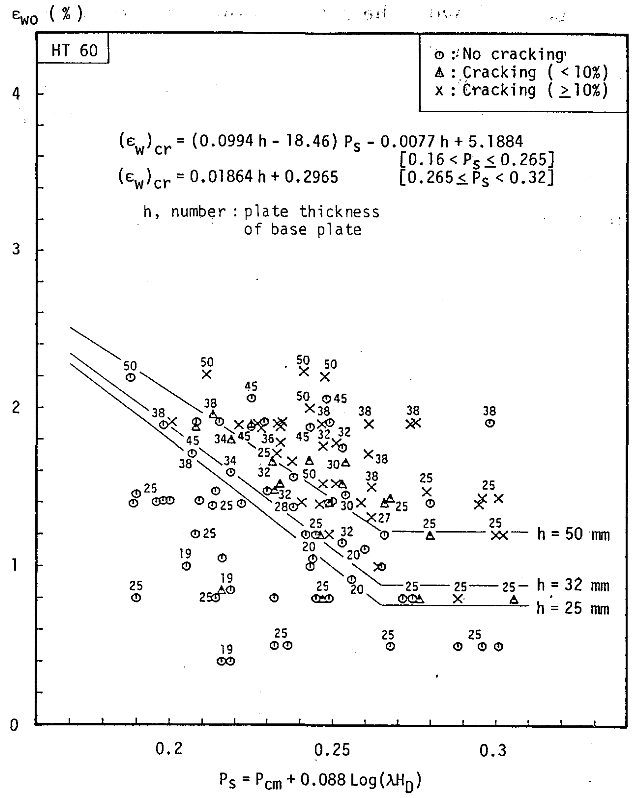
3.1 Dynamical measure of cold cracking and critical restraint strain

In this section, the restraint strain ϵ_w is used as the dynamical measure and the critical restraint strain $(\epsilon_w)_{cr}$ is determined by analyzing one of the test result groups obtained for determining the critical preheating temperature. Then, another group of the experimental results for *200* kinds of steel obtained by Ito and Bessho[11)] are sorted out by applying the critical restraint strain, and the validity of the critical restraint strain as a dynamical measure is investigated.

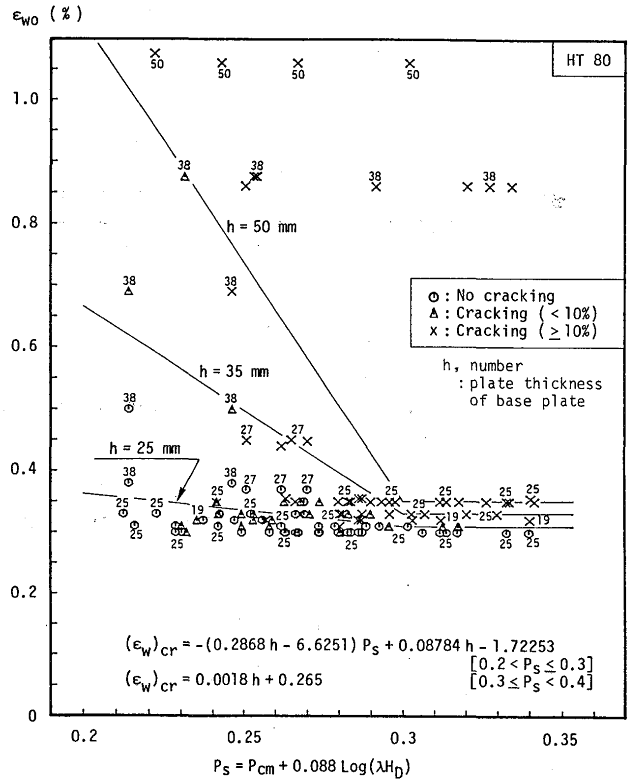
The test results of critical preheating temperature for prevention of cold cracking are represented in relation with the metallurgical measure, P_s, and the dynamical



(a) HT 50



(b) HT 60



(c) HT 80

Fig. 10 Application of proposed critical restraint strain for prevention of cold cracking

measure i.e. restraint strain (at the center of the slit) as in Fig. 9. The numbers in the figure indicate the base plate thickness. In any kind of steel, as ductility lowers (P_s increases), cracking occurs with smaller restraint strain. Accordingly, the critical restraint strain $(\epsilon_w)_{cr}$ can be defined for every kind of steel taking account of the base plate thickness and advantage of restraint strain to be used as a dynamical measure in stead of restraint intensity becomes obvious.

Thus obtained critical restraint strain can be formulated in terms of P_s and the base plate thickness h as follows:

(1) Critical restraint strain for HT50

$$(\epsilon_w)_{cr} = (0.0376h - 13.479)P_s + 0.0066h + 5.432 \quad [0.160 < P_s \leqslant 0.255]$$
$$(\epsilon_w)_{cr} = 0.0162h + 1.995 \quad [0.255 \leqslant P_s < 0.320] \quad (4)$$

(2) Critical restraint strain for HT60

$$(\epsilon_w)_{cr} = (0.0994h - 18.46)P_s - 0.0077h + 5.1884 \quad [0.160 < P_s \leqslant 0.265]$$
$$(\epsilon_w)_{cr} = 0.01864h + 0.2965 \quad [0.265 \leqslant P_s < 0.320] \quad (5)$$

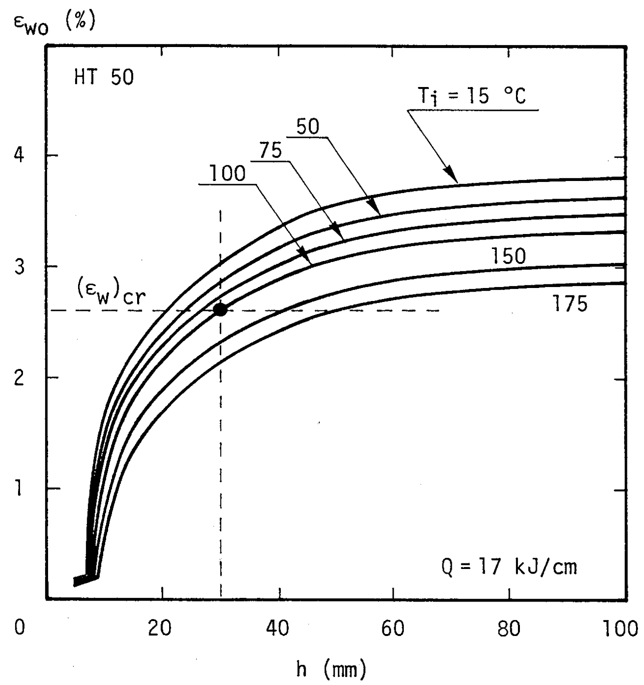
(3) Critical restraint strain for HT80

$$(\epsilon_w)_{cr} = -(0.2868h - 6.6251)P_s + 0.08784h - 1.72253 \quad [0.2 < P_s \leqslant 0.3]$$
$$(\epsilon_w)_{cr} = 0.0018h + 0.265 \quad [0.3 \leqslant P_s < 0.4] \quad (6)$$

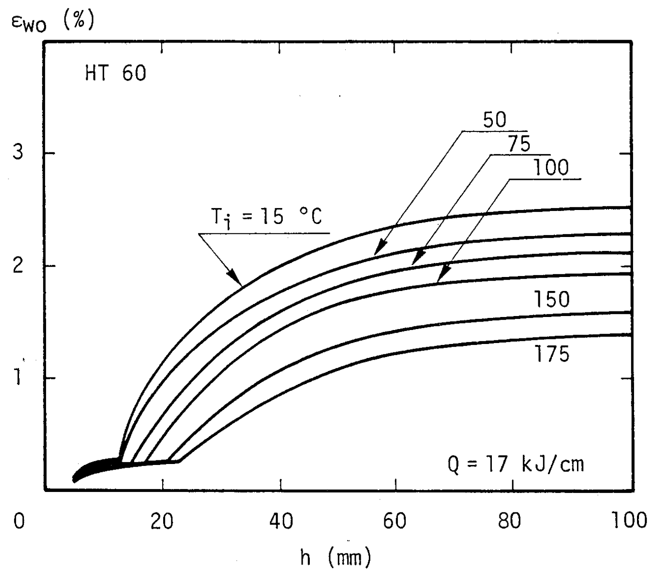
In contrast with these expressions of critical strains, the critical restraint strain $(\epsilon_w)_{cr}$ for cracking should be basically determined only by the kind of steel irrespective of the plate thickness. This may be explained by the following reasons.

The influence of variation in base plate thickness and preheating temperature is taken into account for restraint strain which is proposed as a dynamical measure but not for the metallurgical measure P_s adopted in this paper. The cooling time to *100*°C or the room temperature differs among thick and thin plates even with the same preheating temperature. It is well understood that the difference of cooling time influences the hardness of steel, the accumulation of residual hydrogen, etc., so as to change the cracking susceptibility. If these influences are considered in the metallurgical measure, it should be possible to accurately prescribe the critical restraint strain for each kind of steel irrespective of plate thickness.

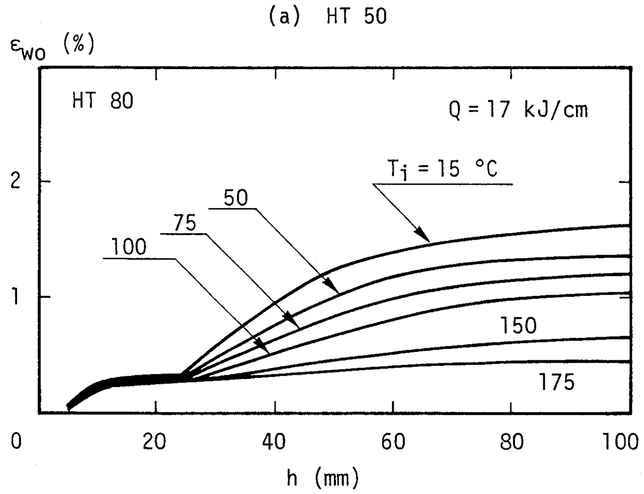
Using the experimental results[11] by the oblique Y-groove weld cracking test specimen (*487* kinds of steel) and being classified into three kinds of steel based on their tensile strength, the relation between restraint strain and metallurgical measure P_s is shown in **Figs. 10** (a), (b) and (c) for HT50, HT60 and HT80, respectively. The numbers indicate the base plate thickness. The critical restraint strains $(\epsilon_w)_{cr}$ obtained in the previous section are depicted by the solid lines. $(\epsilon_w)_{cr}$, though determined from the entirely different experimental results, expresses the critical region for cracking very well showing its good applicability and practicability.



(a) HT 50



(b) HT 60



(c) HT 80

Fig. 11 Estimation of preheating temperature for prevention of cold cracking

3.2 Estimation of preheating temperature for prevention of cold cracking

Using the critical restraint strain $(\epsilon_w)_{cr}$ expressed by Eq.(4), (5) or (6), the critical preheating temperature T_i^* required for prevention of cold cracking can be simply estimated as follows.

If the object for welding is specified, the kind of steel and the plate thickness are known and diffusible hydrogen contained in the electrode can be measured. Then, the metallurgical measure P_s can be calculated by Eq.(3). With this P_s, the critical restraint strain can be estimated by Eq.(4), (5) or (6) according to the kind of steel.

Next, under these specification, restraint strain ϵ_{wo} should be calculated for different preheating temperature T_i and the resulting restraint strain should not exceed the critical value, $(\epsilon_w)_{cr}$. In this paper, varying the kind of steel, base plate thickness h and preheating temperature T_i, restraint strain ϵ_{wo} is obtained by the analytical calculation method [4),10)]. The results are shown in **Figs. 11** (a), (b) and (c).

Taking a plate of HT50 and its thickness of *30 mm* as an example, the critical restraint strain $(\epsilon_w)_{cr}$ was estimated by Eq.(4) and it is indicated by 「●」 in Fig. 11 (a) against the specified plate thickness $h = 30\ mm$. For prevention of cold cracking, preheating temperature is required to be higher than 「●」. In this case, it should be higher than *100*°C. Similarly, the critical preheating temperature T_i^* can be simply estimated for other kinds of steel.

If the base plate thickness is constant, the relation between ϵ_{wo} and T_i can be derived for every kind of steel from Figs. 11 (a), (b) and (c) for HT50, HT60 and HT80.

$$\epsilon_{wo} = \epsilon_{wo}(T_i) \qquad (7)$$

The condition for prevention of cold cracking is obtained as,

$$\epsilon_{wo}(T_i) \leqslant (\epsilon_w)_{cr} \qquad (8)$$

If Eq.(8) is solved for T_i, the critical preheating temperature T_i^* can be expressed as a function of P_s and h as follows:

(1) Critical preheating temperature for HT50 ($15 \leqslant h \leqslant 50$)

$$T_i^* \geqslant -(6.48h - 2324)P_s + 3.6524h - 542.62 \qquad [0.160 < P_s \leqslant 0.255]$$
$$T_i^* \geqslant 2h + 50 \qquad [0.255 \leqslant P_s < 0.320] \qquad (9)$$

(2) Critical preheating temperature for HT60 ($15 \leqslant h \leqslant 50$)

$$T_i^* \geqslant -(14h - 2600)P_s + 5.31h - 604 \qquad [0.160 < P_s \leqslant 0.265]$$
$$T_i^* \geqslant 1.6h + 85 \qquad [0.265 \leqslant P_s < 0.320] \qquad (10)$$

(3) Critical preheating temperature for HT80 ($20 \leqslant h \leqslant 50$)

$$T_i^* \geqslant (5.4h + 755)P_s - 0.02h - 146.5 \qquad [0.2 < P_s \leqslant 0.3]$$
$$T_i^* \geqslant 1.6h + 80 \qquad [0.3 \leqslant P_s < 0.4] \qquad (11)$$

where, in case of T_i^* being below room temperature, preheating is unnecessary.

Then, the critical preheating temperature can be determined directly by specification of the kind of steel, base plate thickness h and P_s without calculation of restraint strain.

4. Conclusion

Using the oblique Y-groove weld cracking test specimen which has been widely used in specifying the cold cracking susceptibility and the preheating temperature for actual welding, theoretical analyses of restraint stress-strain produced in the weld metal were performed. Based on these results, the dynamical characteristics of the specimen were clarified. Moreover, the applicability of restraint intensity as a dynamical measure was investigated. The cold cracking susceptibility parameters P_w and P_{HA} were also investigated from the dynamical point of view.

Accuracy of the cold cracking susceptibility parameters, P_w and P_{HA}, were investigated from the dynamical point of view and validity and usefulness of the newly proposed dynamical measure, restraint strain, were demonstrated.

The main results are as follows:

(1) Even with the specified specimen size, the distribution and magnitude of the restraint strain vary if the kind of steel (phase transformation temperature at the cooling stage, yield stress and ultimate strength differ among the kinds), preheating temperature, etc. vary. However, if the plate thickness is the same, the restraint intensity is constant irrespective of the changes of the kind of steel and preheating temperature. This implies that the same dynamical conditions are presumed. Accordingly, it is not reasonable to use restraint intensity as a dynamical measure to represent the severity of dynamical conditions.

(2) Having analyzed the experimental results of cold cracking tests, the validity and practicability of restraint strain which was already proposed as a dynamical measure to represent the severity of mechanical conditions in place of restraint intensity are demonstrated for the general cases in which the kind of steel, preheating temperature, base plate thickness, etc. vary.

(3) For three kinds of high strength steel (HT50, HT60 and HT80), the critical restraint strain $(\epsilon_w)_{cr}$ for cold cracking is estimated from the experimental results and its simple formula is derived.

(4) A new selecting method of the critical preheating temperature T_i^* for prevention of cold cracking is developed with the aid of the restraint strain ϵ_w.

(5) For each kind of high strength steel, simple expression for T_i^* is derived. The accuracy of the expression is very high since the prediction agrees well with the experimental one.

Acknowledgement

The authors wish to thank Professor K. Satoh and other members of the Welding Structural Committee, JWS, and

Dr. H. Suzuki of Nippon Steel, Ltd. for their advicable discussion and suggestions. They also wish to thank Mr. Hsu Chingzhou, Department of Naval Architecture of Osaka University, for his help in performing theoretical analyses and analyzing the experimental results.

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