OUKA
The University of Osaka
Institutional Knowledge Archive

Title	Dynamical Characteristics of Oblique Y-Groove Weld Cracking Test Specimen of Arbitrary Thickness(Welding Mechanics, Strength & Design)
Author(s)	Ueda, Yukio; Fukuda, Keiji; Kim, You Chul
Citation	Transactions of JWRI. 1984, 13(2), p. 303-310
Version Type	VoR
URL	https://doi.org/10.18910/7905
rights	
Note	

The University of Osaka Institutional Knowledge Archive : OUKA

https://ir.library.osaka-u.ac.jp/

The University of Osaka

Dynamical Characteristics of Oblique Y-Groove Weld Cracking Test Specimen of Arbitrary Thickness†

Yukio UEDA*, Keiji FUKUDA** and You Chul KIM***

Abstract

Welded structures are inevitably accompanied by deformation and residual stresses produced by construction, which sometimes cause initiation of various types of weld cracking. In order to avoid the weld cracking, the oblique Y-groove weld cracking test specimen has been widely used as the cold cracking sensitivity specimen to determine appropriate materials and welding conditions.

In this paper, the dynamical characteristics of the oblique Y-groove weld cracking test specimen of arbitrary thickness are clarified by discussing the restraint stresses and strains produced in this specimen. The results are as follows:

(1) For evaluation of restraint stresses and strains produced perpendicular to the weld line in the weld metal of the oblique Y-groove weld cracking test specimen, the analytical calculation method which was already presented for comparatively thin plates is extended for thicker plates. Then, the restraint stresses and strains under the influence of the ratio of plate thickness to throat thickness can be analytically calculated without conducting three dimensional elastic-plastic analysis.

(2) The magnitude of restraint stresses and strains produced in a slit weld specimen vary with the amount of heat input, that is, they are dependent on the ratio of l/h_{cr}. Judging the severity of the mechanical condition of the specimen from the magnitude of restraint stresses and strains, the infinite plate is the severest. The infinite plate may be replaced by a finite plate of which size ratio is $B/l \geq 4.0$, $L/l \geq 3.7$. Then, the size ratio of the oblique Y-groove weld cracking test specimen is not necessarily the severest.

(3) Among the slit weld specimens with the same size ratio as the oblique Y-groove weld cracking test specimen, the actural size the oblique Y-groove weld cracking test specimen achieves the severest mechanical condition for the specific heat input Q=17000 J/cm.

(4) When the thickness of the oblique Y-groove weld cracking test specimen increases, the restraint strain (the sum of the elastic and plastic components) produced in the weld metal of the first pass also increases. However, the increasing tendency saturates at the plate thickness of approximately h=50 mm for mild steel. From this fact, the necessary plate thickness for the specimen is 50 mm to determine the welding condition for the first pass of thicker plates of mild steel.

(5) For the slit specimen (B/l=1.875, L/l=2.5), the plastic restraint strains increase with an increase of the effective average restraint intensity $(\bar{R}_p)_\eta$, and their increasing tendencies are very similar. Therefore, $(\bar{R}_p)_\eta$ may be used as a simple dynamical measure to compare the severity of the mechanical condition in place of the restraint

KEY WORDS: (Restraint Stress-Strain) (Analytical Calculation Method) (Inherent Shrinkage) (Restraint Intensity) (Slit Weld)

1. Introduction

Welded structures are inevitably accompanied with welding deformation and residual stresses. In this consequence, various types of weld cracking may occur, which threatens to deteriorate the performance of welded structures and influence their security. For this reason, various kinds of cracking tests have been carried aiming to determine appropriate materials and welding conditions for safe joints free from weld cracking prior to actual welding.

Many types of weld cracking test specimens have been presented to meet each purpose[1]. Especially, the handy and self-restraint oblique Y-groove weld cracking test specimen which needs no special equipment has been used most often as a cold cracking sensitivity specimen. This specimen is to determine the preheating temperature for

† Received on October 31, 1984
* Professor
** Research Instructor (Formerly)
*** Research Associate

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

actual welding. Generally, the welding conditions determined by this specimen are more or less severe.

According as thicker plates have been used in many fields, the oblique Y-groove weld cracking test specimen has been adopted from time to time as the cold cracking sensitivity specimen for thick plates by increasing only its plate thickness.

It is very important to know the mechanical conditions produced in this widely used oblique Y-groove weld cracking test specimen. The purpose of this study is to clarify this point.

In this paper, the following three subjects will be investigated: 1) Considering a slit weld test specimen with arbitrary thickness, a calculation method to analytically estimate restraint stress-strain produced by the first pass welding perpendicular to the weld line with consideration of the ratio of plate thickness to throat thickness is presented. 2) Based on the magnitude and the distribution of restraint stress-strain calculated by this method, the mechanical condition of this specimen is clarified. In other words, restraint stress-strain assumed by the oblique Y-groove weld cracking test specimen for the general cases where geometrical shape and heat input vary is clarified. 3) Mechanical conditions are also clarified when the oblique Y-groove weld cracking test specimen is used as the cold cracking sensitivity specimen for thicker plates.

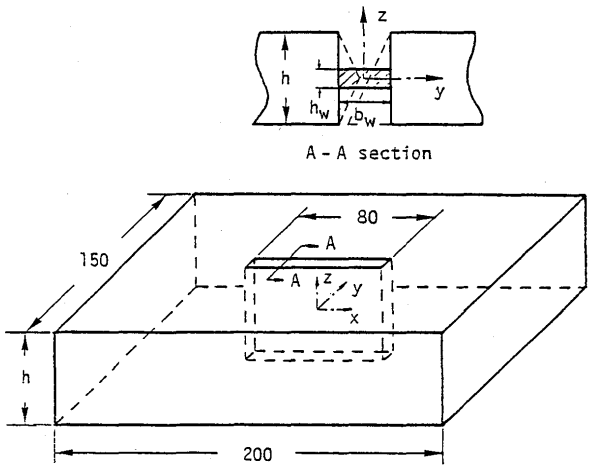

Fig. 1 Oblique Y-groove weld cracking test specimen of arbitrary thickness

2. Inherent Shrinkage and Restraint Stress-Strain in the Slit Weld Test Specimen with Arbitrary Plate Thickness

The authors have already published the analytical calculation method for inherent shrinkage and restraint stress-strain based on inherent shrinkage produced in the weld metal of a slit weld test specimen for relatively thin plates[2]. The calculated results were compared with experimental ones and the validity of the method was confirmed[3]. Nevertheless, when this method is applied to a thicker plate, its thickness is much larger than its throat thickness so that it is necessary to investigate if stress-strain is under the effect of the ratio of plate thickness to throat thickness. In consideration of the effect of throat thickness, an analytical method for restraint stress-strain produced by the first pass welding of the slit weld specimen of a thicker plate is presented here.

2.1 Heat conduction analysis

Inherent shrinkage can be obtained as such dislocation produced along the slit when the weld metal is cooled down approximately to the rigidity recovery temperature T_m[2,4]. In order to analytically obtain this dislocation, an analytical expression which simply and accurately estimates temperature distribution is necessary. For this reason, an analytical solution in disregard of the temperature dependency of physical properties is used to the thermal conduction of the specimen in welding.

An instantaneous heat source q (cal/mm) per unit length is placed along the slit at the center of plate thickness ($z = 0$). When the middle of the slit ($x = y = 0$) at the center of plate thickness ($z = 0$) is cooled to the rigidity recovery temperature T_m, temperature T at an arbitrary point can be systematically expressed using h'_{cr} which includes the all range of the relative magnitude between plate thickness of the base plate h and the critical plate thickness h_{cr}, such as $h < h_{cr}$, $h \geq h_{cr}$, in disregard of the thermal reflection from both surfaces of the plate.

$$T - T_i = \frac{T_m - T_i}{2} e^{-\pi (r/h'_{cr})^2} \{\Phi[\sqrt{\frac{\pi}{2}} \frac{l}{h'_{cr}} (1 + X)] + \Phi[\sqrt{\frac{\pi}{2}} \frac{l}{h'_{cr}} (1 - X)]\} \quad (1)$$

where,

T_m: rigidity recovery temperature (°C)

T_i : initial temperature (°C), $X = 2x/l$

$\Phi(u) = \frac{2}{\sqrt{\pi}} \int_0^u e^{-u^2} du$: error function

$h'_{cr} = h_{cr}^2/h$, $r^2 = y^2$ in this case $h < h_{cr}$

$h'_{cr} = h_{cr}$, $r^2 = y^2 + z^2$ in this case $h \geq h_{cr}$

$h_{cr} = \sqrt{\frac{q}{c\rho (T_m - T_i)}}$: critical plate thickness (mm)

In order to improve accuracy of the temperature distribution calculated from Eq.(1), various constants (density ρ, specific heat c, thermal efficiency ξ, etc.) need to be carefully selected to well correspond to the observed result of the temperature distribution when the weld metal in the middle of the slit ($x = y = 0$) is cooled to the rigidity recovery temperature. In this study, they are determined as follows[3].

T_m = 700°C: rigidity recovery temperature for mild steel, T_i = 15°C, ρ = 7.66 g/cm³, c = 0.188 cal/g·°C, ξ = 0.75

2.2 Inherent shrinkage by three dimensional thermal elastic analysis

The analytical calculation method of inherent shrinkage[2] was developed on the assumption that when the center of plate thickness (z = 0) in the middle of the slit ($x = y$ = 0) is cooled to the rigidity recovery temperature T_m, temperature T (z = 0) at the center of plate thickness in every point of the plate (x, y) distributes uniformly in the plate thickness direction (z-direction) of the point. It is theoretically clarified that this assumption gives highly accurate approximations to the two dimensional problems where unit weld length and infinite plate thickness are dealt with[5]. However, by the first pass welding of slit weld, the temperature distribution of a thicker plate changes along the weld line and in the thickness direction and triaxial stress state appears in the throat. Because of this complicated phenomenon, application of the analytical calculation method becomes difficult. The three dimensional thermal elastic analysis based on the finite element method is conducted here. Comparing its result with the inherent shrinkage shown in Ref. 2), the application limit of the method to estimation of inherent shrinkage S_T due to slit weld of a thicker plate is investigated.

As the temperature distribution using the three dimensional thermal elastic analysis to calculate S_T, temperature in the center of gravity of each finite element is calculated using Eq.(1), the solution of three dimensional heat conduction in an infinite plate, on the assumption that the first pass weld is at the center of the plate thickness, and determined to be uniform in an element. In this analysis, the linear expansion coefficient $\alpha = 1.2 \times 10^{-5}$ (1/°C) and the modulus of elasticity E = 21000 kg/mm² are used.

This analysis is performed on two cases where heat input Q = 17000 J/cm is kept constant and the plate thickness of the oblique Y-groove weld cracking test specimen (**Fig. 1**) is changed to h = 25 and 50 mm.

The calculation result of inherent shrinkage S_T occurred in the throat thickness along the slit is shown by the solid line in **Fig. 2**. The chain line in the figure shows inherent shrinkage obtained by the analytical calculation method presented in Ref. 2). Calculated results show good coincidence with those by the three dimensional thermal elastic analysis. In this figure, " ● " shows the formerly measured inherent shrinkage[3] for h = 25 mm.

Consequently, it is confirmed from the result of three dimensional thermal elastic analysis that inherent shrinkage calculated by the analytical calculation method presented in Ref. 2) gives accurate result also to the first pass weld of a thicker plate.

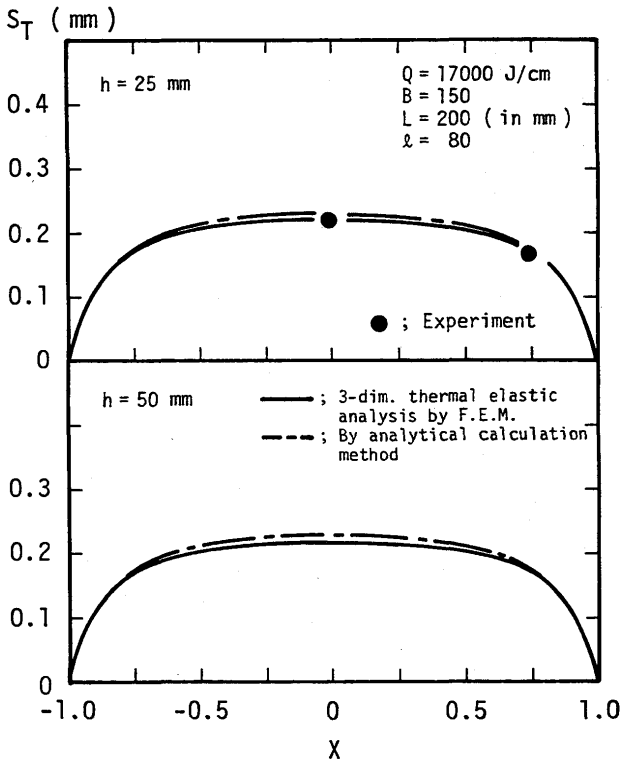

Fig. 2 Distributions of inherent shrinkage: S_T

2.3 Analytical calculation method for restraint stress-strain

If the above mentioned inherent shrinkage is imposed to the throat as a compulsory displacement and three dimensional elastic-plastic analysis is performed, restraint stress-strain produced in the weld metal can be calculated. However, if the plate is thicker, restraint of the throat is so severe that in most cases the weld metal is plastified along the whole slit and the produced restraint stress coincides with yield stress σ_Y of the weld metal along the whole slit. Therefore, severity of this mechanical restraint condition should be discussed based on the magnitude and the distribution of restraint strain (sum of elastic and plastic strain). Considering the effect of the ratio of plate thickness to throat thickness when the weld metal is fully plastic, a method to analytically calculate restraint strain ϵ_w produced by inherent shrinkage without performing three dimensional elastic-plastic analysis is shown here.

When the weld metal is fully plastic, restraint strain ϵ_w can be calculated as the sum of elastic restraint strain ϵ_w^e and plastic restraint strain ϵ_w^p, as follows.

$$\epsilon_w = \epsilon_w^e + \epsilon_w^p \tag{2}$$

where,

$$\epsilon_w^e = \sigma_Y/E \quad : \text{elastic restraint strain} \tag{3}$$

$\epsilon_w^p = (S_T - S_e)/b_w$: plastic restraint strain (4)

S_T: inherent shrinkage (mm)
S_e : elastic deformation of the base plate (mm)
σ_Y: yield stress of the weld metal (kg/mm²)
b_w: slit gap (mm)

S_T and S_e are indispensable to calculate plastic restraint strain ϵ_w^p. S_T is the dislocation occurred in the throat when the center of the throat thickness ($z = 0$) of the weld metal in the middle of the slit ($x = y = 0$) is cooled to T_m. S_T can be calculated by the analytical method shown in Ref. 2). In order to facilitate quantitative evaluation of S_T, a highly accurate estimating equations are shown in appendix.

S_e is the elastic deformation of the base plate. That is, the deformation occurred along the slit due to imposition of uniform stress σ_Y (yield stress of the weld metal) to the throat thickness h_w along the slit. This deformation S_e can be simply calculated using the restraint intensity[6] $(R_p)_\eta$ in consideration of the effect of change of throat thickness under uniformly distributed loads (called hereinafter effective restraint intensity), as follows.

$$S_e = \sigma_Y h_w/(R_p)_\eta \quad (5)$$

where,

$(R_p)_\eta = \eta R_p$: effective restraint intensity under uniformly distributed loads (6)

$$\eta = \frac{1}{1 + \frac{h}{B}\sum_{m=1}^{\infty}\frac{8}{m\pi}\left(\frac{\sin m\pi h_w/h}{m\pi h_w/h}\right)^2 \frac{\sinh^2 m\pi B/h}{\sinh 2m\pi B/h + 2m\pi B/h}} \quad (7)$$

$$R_p = (1 - \beta_p)(E/2)(h/l)\{1/\sqrt{1 - X^2}\} \quad (8)$$

$$\beta_p = 0.6/(L/l)^n + 0.75/(B/l)^{1.82}$$
$$n = 5.8/(B/l)^2 + 2.2 \quad [B/l \geq 1.8,\ L/l \geq 1.5]$$

With these results, as far as the first pass weld of a thicker plate with a slit is concerned and if the weld metal is fully plastic, restraint strain produced in the weld metal perpendicular to the weld line can be simply calculated from Eq.(2) without performing the three dimensional elastic-plastic analysis.

3. Dynamical Characteristics of Oblique Y-Groove Weld Cracking Test Specimen

For the general case where specimen size and heat input change, severity of mechanical restraint conditions of a specimen similar to oblique Y-groove weld cracking test specimen is clarified from the magnitude and the distribution of restraint stress-strain produced in the weld metal. Moreover, the change of mechanical conditions due to increase of the plate thickness of the specimen is investigated.

3.1 Dynamical characteristics of oblique Y-groove weld cracking test specimen

In the analysis, size ratios of the specimen ($B = 150$, $L = 200$, $l = 80$ mm) are kept constant to be $B/l = 1.875$, $L/l = 2.5$ and only the slit length l is variously changed. As a result, the actual size of the specimen similarly changes. Followings are the properties used in the calculations.

$\sigma_Y = 50$: yield stress (kg/mm²)
$Q = 17000$: heat input (J/cm)
$h = 20$: plate thickness of base plate (mm)
$h_w = 5$: throat thickness (mm)
$b_w = 4$: slit gap (mm)

With the above mentioned conditions, (1) plastic restraint strain in the middle of slit ϵ_{wo}^p produced in the weld metal and (2) the average effective restraint intensity $(\bar{R}_p)_\eta$ under uniformly distributed loads are estimated for various cases of l/h_{cr}. They are shown in **Fig. 3**. "●" in the figure shows ϵ_{wo}^p of the oblique Y-groove weld cracking test specimen.

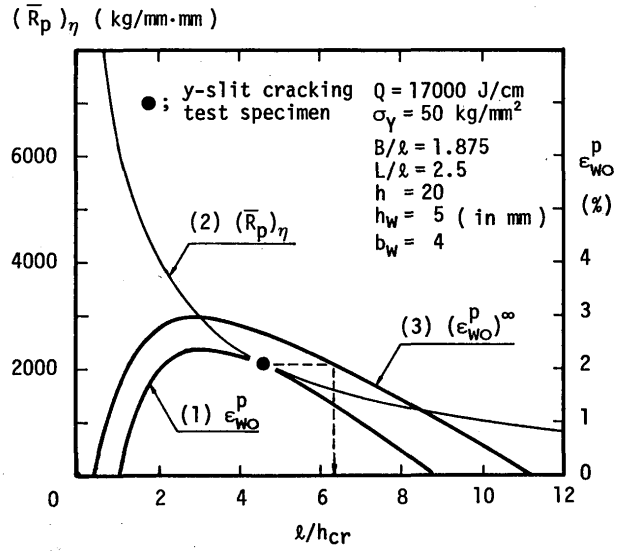

Fig. 3 Relation between l/h_{cr} and plastic strain

According to Fig. 3, the average effective restraint intensity $(\bar{R}_p)_\eta$ (the average value of effective restraint intensity along the whole slit, which can be calculated as a function of geometry) monotonously increases when the slit length is short and shows $(\bar{R}_p)_\eta = 2100$ kg/mm·mm for the oblique Y-groove weld cracking test specimen which is not too large. While, the distribution of plastic restraint strain produced in the weld metal along the slit are determined greatly depending on the ratio l/h_{cr}, its can be classified into three categories[3].

1) If $1.0 \leq l/h_{cr} < 2.9$, the distribution of plastic restraint

strains along the slit is convex and the mechanical conditions are severe at the center of the slit.

2) If $2.9 \leq l/h_{cr} < 4.6$, the distribution is approximately elliptical.
3) If $4.6 \leq l/h_{cr} \leq 10.0$, the distribution is concave and the mechanical conditions are severe at the slit ends.

From above, it is recognized that although the actual size of the oblique Y-groove weld cracking test specimen is small, it has the size ratios to produce the maximum plastic restraint strain among other size of test specimens with heat input Q = 17000 J/cm, which is extremely severe restraint at the middle of the slit.

In this calculation, heat input is kept constant and slit length is variously changed. According as heat input changes, the throat thickness changes. If the ratio of l/h_{cr} is kept the same, the results are quantitatively the same in disregard of the changes of heat input and yield stress[3]. On the other hand, if heat input changes for the same slit length, the ratio of l/h_{cr} changes, too. Therefore, even with the oblique Y-groove weld cracking test specimen, the experiment has to be conducted with consideration of this fact lest the mechanical conditions should be different.

3.2 Application of oblique Y-groove weld cracking test specimen of thicker plates

On the assumption that the first weld is layed along the center of the plate thickness of the specimen, its throat thickness h_w = 5 mm is kept constant while its plate thickness is changed. Other conditions for the analysis are the same as in 3.1.

If only the plate thickness of the oblique Y-groove weld cracking test specimen is changed, (1) both magnitude and distribution of plastic restraint strain ϵ_w^p change in the range of $h < h_{cr}$. (2) In the range of $h \geq h_{cr}$, the magnitude of ϵ_w^p changes but the distribution does not. Distribution of ϵ_w^p in the range of $h \geq h_{cr}$ with h = 25 mm is represented in **Fig. 4**.

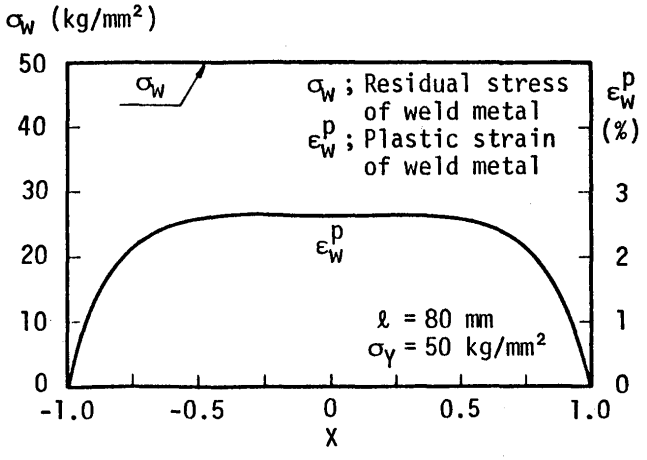

Fig. 4 Distribution of residual stress and plastic strain along slit

Shown in the **Fig. 5** in accordance with an increase of the plate thickness are;

(1) plastic restraint strain $\epsilon_{wo}^p \sim (h < h_{cr})$ at the middle of the slit always calculated under the condition of $h < h_{cr}$ neglecting an increase of the plate thickness of the base plate h larger than the critical plate thickness h_{cr},
(2) $\epsilon_{wo}^p \sim (h > h_{cr})$ calculated on the assumption of $h > h_{cr}$ even when $h < h_{cr}$, which is the contrary to (1),
(3) the average effective restraint intensity $(\bar{R}_p)_\eta$ under uniformly distributed loads in consideration of the effect of the ratio of plate thickness to the throat thickness and
(4) average restraint intensity $\bar{R}_p$ calculated on the assumption that the restraint intensity is simply proportional to the plate thickness. Moreover, shown by " ● " and " ○ " in the same figure are respectively;
(5) plastic restraint strain $(\epsilon_{wo}^p)^\infty$ at the middle of the slit of a specimen whose slit length and thickness are 80 mm and 100 mm, respectively, and the size ratios is equivalent to an infinite plate[7], that is, B/l = 4, L/l = 3.7 and
(6) the average effective restraint intensity $(\bar{R}_p)_\eta^\infty$ under uniformly distributed loads in the same specimen as for (5).

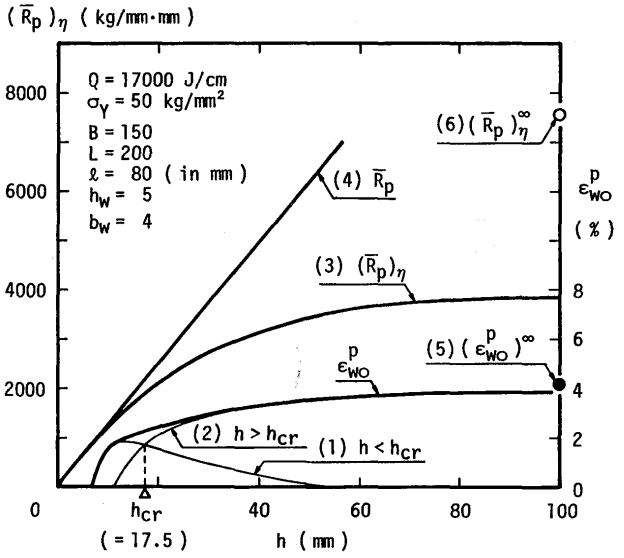

Fig. 5 Effect of plate thickness on effective restraint intensity and plastic strain

According to Fig. 5, the ϵ_{wo}^p-h curves for the ranges (1) and (2) intersect at the point of $h = h_{cr}$ (thin line). This is because in disregard of the ranges $h < h_{cr}$ and $h \geq h_{cr}$, the heat conduct solution for the infinite plate thickness was used neglecting the influence of thermal reflection from both surfaces of the plate for the whole region. As for the region where the effect of the finite plate thickness is evident, the influence of thermal reflection from both surfaces of the plate is considered. As shown by the

continuous solid curve line (a thick line connecting (1) and (2)), it tends to increase monotonously according to the increase of the plate thickness to converge to a certain value. On the other hand, the effective restraint intensity of a welded joint $(\bar{R}_p)_\eta$ tends to converge to a certain value without showing simple proportion to the plate thickness.

Plastic restraint strain ϵ^p_{wo} at the slit center of the oblique Y-groove weld cracking test specimen with the plate thickness of its base plate $h = 50 \sim 60$ mm indicates over 90% of the plastic strain $(\epsilon^p_{wo})^\infty$, " • ", estimated in a specimen equivalent to an infinite plate with $h = 100$ mm. This proves that the specimen with plate thickness of this degree is subjected to approximately the maximum restraint. Accordingly, on determining the welding conditions for the first pass weld of a thicker plate, the size ratios of the specimen are kept the same as for the oblique Y-groove weld cracking test specimen except the plate thickness which is to be set $h = 50$ mm for mild steel. Even if the plate thickness increases more than 50 mm, the mechanical restraint condition becomes little severer. In this relation, the average effective restraint intensity $(\bar{R}_p)_\eta$ in this specimen ($B = 150$, $L = 200$, $l = 80$, $h = 50$, $h_w = 5$ (mm)) exhibits 50% of the average effective restraint intensity $(\bar{R}_p)^\infty_\eta$, shown by " ○ " in the figure, estimated in an infinite plate with the same slit length $l = 80$ mm and the different plate thickness $h = 100$ mm. Therefore, in a simple view of restraint intensity, this specimen cannot be regarded the same as an infinite plate with infinite plate thickness[8].

In Fig. 5, the plastic restraint strain ϵ^p_{wo} at the middle of the slit and the average effective restraint intensity $(\bar{R}_p)_\eta$ increase not proportionally but monotonously with

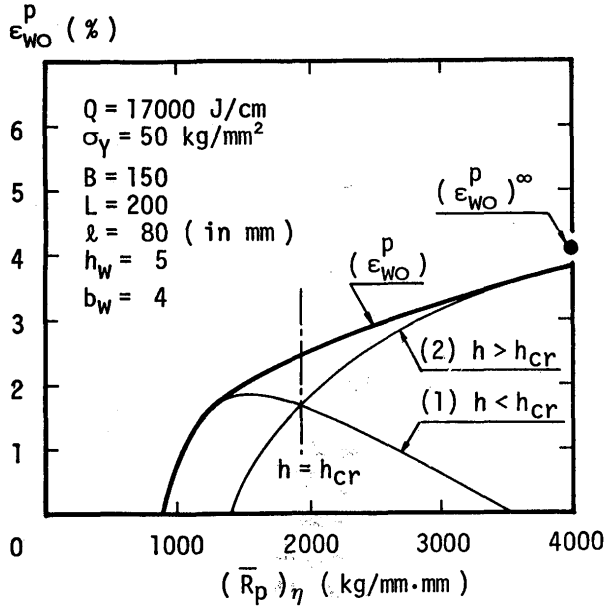

Fig. 6 Relation between plastic strain and effective restraint intensity

an increase of the plate thickness. Based on this, the relation between ϵ^p_{wo} and $(\bar{R}_p)_\eta$ is indicated in **Fig. 6**. ϵ^p_{wo} and $(\bar{R}_p)_\eta$ are related to monotonously increase. Therefore, if the size ratios of the specimen are kept constant, the effective restraint intensity may be used as a simple dynamical measure in the relation with its plastic restraint strain to show severity of mechanical conditions.

4. Relation between Oblique Y-Groove Weld Cracking Test Specimen and Maximum Restraint Specimen

It is known that with $Q = 17000$ J/cm and specimen size ratios of $B/l = 1.875$ and $L/l = 2.5$, the oblique Y-groove weld cracking test specimen exhibits, in spite of its smallness in size, approximately the maximum restraint stress-strain in weld metal under variation of l/h_{cr}. The specimen which exhibits the maximum mechanical restraint is discussed here in consideration of the formerly mentioned influential factors.

Plastic restraint strain $(\epsilon^p_w)^\infty$ produced in the weld metal of an infinite plate with a slit and the plate thickness of $h = 20$ mm is calculated under variation of l/h_{cr}. The value of $(\epsilon^p_w)^\infty$ at the middle of the slit, $(\epsilon^p_{wo})^\infty$, is shown in Fig. 3. $(\epsilon^p_w)^\infty$ produced in the weld metal of an infinite plate is larger than ϵ^p_w in a finite plate. In another words, if l/h_{cr} is the same, the severest restraint state is induced in an infinite plate.

On the other hand, plastic restraint strain has the same inclination in both infinite and finite plates under various l/h_{cr}:

(1) the magnitude becomes the largest when $l/h_{cr} = 2.5 \sim 3.5$ and
(2) restraint becomes the severest at the middle of the slit.

Consequently, the specimen which exhibits the maximum mechanical restraint is as follows.

(1) The ratio of the slit length l and the critical plate thickness h_{cr}, l/h_{cr}, is between 2.5 and 3.5.
(2) With $B/l \geq 4.0$ and $L/l \geq 3.7$ which are the size ratios equivalent to an infinite plate, the specimen exhibits more than 95% of the restraint stress and strain to be produced in an infinite plate and is regarded to approximate an infinite plate.

For example, when heat input is $Q = 17000$ J/cm ($h_{cr} = 17.5$ mm), the possible maximum restraint state is induced in the specimen with slit length $l = 55$ mm, specimen width $B = 220$ mm and specimen length $L = 200$ mm.

Another specimen which can replace the oblique Y-groove weld cracking test specimen keeping the same severity of mechanical conditions is considered. In this case, the previously stated infinite plate (Fig. 3) can be utilized to determine the specimen size. As formerly mentioned, when heat input changes, the relative propor-

tion of l/h_{cr} also changes even if the oblique Y-groove weld cracking test specimen is used. Therefore, special attention should be paid, lest the test be misled to different mechanical conditions. The specimen size have to be carefully selected so as to make its plastic restraint strain ϵ^p_{wo} equal to that of the oblique Y-groove weld cracking test specimen.

ϵ^p_{wo} produced in the oblique Y-groove weld cracking test specimen is represented by " ● " in Fig. 3. It is known a close study of the figure that the value of ϵ^p_{wo} is equal to that of an infinite plate, $(\epsilon^p_{wo})^\infty$, at the point where $l/h_{cr} = 6.35$ (broken line). When heat input is specified, slit length l is determined to satisfy $l/h_{cr} = 6.35$ and the specimen sizes are determined as plate width $B \geq 4l$, plate length $L \geq 3.7l$, so that the mechanical condition at the middle of the slit becomes the same as that for the oblique Y-groove weld cracking test specimen. For example, in case of plate thickness $h = 20$ mm and heat input $Q = 17000$ J/cm ($h_{cr} = 17.5$ mm), the dimension of the equivalent specimen is as follows, $l = 110$ mm, $B \geq 440$ mm and $L \geq 410$ mm. This idea also applies to a slit welded joint of a practical structure.

5. Conclusion

Generally, the oblique Y-groove weld cracking test specimen is used to determine welding conditions with which weld cracks may not occur. In this paper, mechanical restraint conditions induced in a welded oblique Y-groove weld cracking test specimen are theoretically clarified.

The main results are as follows.

1) In order to analyze restraint stress and strain produced in the throat section of the oblique Y-groove weld cracking test specimen with an arbitrary plate thickness, the analytical calculation method[2] already developed for thin plates has been extended. Highly accurate estimating equations have been derived for inherent shrinkage which is the source of restraint stress and strain.
2) As far as the first pass weld of the oblique Y-groove weld cracking test specimen of a thicker plate is regarded, the weld metal is mostly plastified in the whole slit. Using the inherent shrinkage mentioned in 1), analytical estimating equations have been derived to simply calculate restraint strain (the sum of elastic and plastic restraint strains) in consideration of the effect of the ratio of base plate thickness to the throat thickness without performing a three dimensional elastic-plastic analysis.
3) In general, the magnitude of restraint stress and strain produced in a slit weld specimen varies depending on the heat input, even if the size ratios of the specimen are kept constant. Investigation of the severity of mechanical restraint conditions using restraint strain indicates that if heat input is fixed, the severest mechanical restraint conditions are always given by a slit weld specimen of an infinite plate. With the size ratios of $B/l \geq 4$, $L/l \geq 3.7$, a specimen of a finite plate can approximate this condition. The oblique Y-groove weld cracking test specimen has such size ratios as to give milder mechanical restraint conditions than a specimen of an infinite plate.
4) If the size ratios of the oblique Y-groove weld cracking test specimen ($B/l = 1.875$, $L/l = 2.5$) are fixed and heat input of $Q = 17000$ J/cm is applied, approximately the severest restraint strain is produced in the oblique Y-groove weld cracking test specimen of the practical size ($B = 150$, $L = 200$, $l = 80$ (mm)).
5) Welding conditions for the first pass weld of a thicker plate has been determined using the oblique Y-groove weld cracking test specimen. Plastic restraint strain produced in the weld metal tends to increase in accordance with its plate thickness. Judging from the magnitude of the plastic restraint strain, the mechanical restraint condition scarcely becomes severer even how the plate thickness increases more than 50 mm for mild steel.
6) If only the plate thickness of the oblique Y-groove weld cracking test specimen is varied, it is known from the correlation between the average effective restraint intensity $(\bar{R}_p)_\eta$ under uniformly distributed loads and the plastic restraint strain produced in the weld metal (Fig. 6) that the average effective restraint intensity is useful as a simple dynamical measure to make comparison of relative severity of restraint conditions.
This also applies to slit weld specimens.
7) If it is possible to estimate restraint strains produced in slit welded joints of a practical structure, handy slit weld specimens (including the oblique Y-groove weld cracking test specimen) in which the same restraint strains as that in the practical structure is produced can be used.

Appendix

Estimating Equations of Inherent Shrinkage: S_T

In order to facilitate quantitative evaluation of inherent shrinkage S_T, accurate equations are formulated adopting the least square method. S_T can be estimated as the sum of thermal deformation along the slit of an infinite plate (analytical solution), S^∞_T, and additional deformation due to the effect of a finite plate, ΔS_T[2]. That is,

$$S_T = S^\infty_T + \Delta S_T \qquad \text{(a-1)}$$

The first term in the right side of the above equation, S_T, can be formulated as follows.

$$S_T^{\infty} = S_{TO}^{\infty}(1 - X^{m_1})^{m_2} \quad [l/h'_{cr} \geq 3] \qquad \text{(a-2)}$$

where,

$$S_{TO}^{\infty} = S_T^{\infty}(X=0)$$
$$= 2\alpha(T_m - T_i)h'_{cr}[1 - 0.68/(l/h'_{cr})^{0.6258}]$$
$$m_1 = 6.9116e^{-3.3271/(l/h'_{cr})}$$
$$m_2 = 0.63 - 0.5754e^{-19.5708/(l/h'_{cr})}$$
$$X = 2x/l$$

If a rectangular plate satisfies the size of $B/l \geq 2(h'_{cr}/l)$ and $L/l \geq 1 + 2(h'_{cr}/l)$ with which the effect of thermal reflection from its boundaries can be neglected and the specimen size ratios of $B/l \geq 1.8$, $L/l \geq 2.0$, ΔS_T can be formulated as follows.

$$\Delta S_T = 0.6366\alpha(T_m - T_i)h'_{cr}(c_2 - c_1)\sqrt{1 - X^2}/(1 - \beta_p) \qquad \text{(a-3)}$$

where,

$$\left.\begin{aligned} c_1 &= 1.25/(L/l)^{2.15} \\ &\quad [2 \leq L/l < 0.9675(B/l)^{0.8186}] \\ c_1 &= 1.36/(B/l)^{1.76} \\ &\quad [L/l \geq 0.9675(B/l)^{0.8186}] \end{aligned}\right\} \qquad \text{(a-4)}$$

$$c_2 = 2\beta_p[1 - e^{-(\pi/4)(l/h'_{cr})^2}][2 - 1.5649/(l/h'_{cr})^{0.4694}]$$
$$[l/h'_{cr} \geq 1] \qquad \text{(a-5)}$$

β_p: shown in Eq.(8)

These equations enable simple calculation of inherent shrinkage S_T with the maximum error of ±5% in both its distribution along the slit and magnitude.

References

1) e.g. K. Horikawa et al; Study on Weld Cracking Behavior in Large Structures (Part 1), JSSC (Society of Steel Construction of Japan), 11-113, 33-46 (in Japanese).

2) Y. Ueda, K. Fukuda and Y.C. Kim; Analytical Calculation Method of Restraint Stresses and Strains due to Slit Weld in Rectangular Plates, IIW (Inernational Institute of Welding) Doc. X-1037-83, and Trans. JWRI, Vol. 11, No. 1 (1982) 105-113, and J. JWS (Japan Welding Society), 50-9 (1981) 930-937 (in Japanese).

3) Y. Ueda, K. Fukuda, Y.C. Kim and R. Koki; Characteristics of Restraint Stress-Strain of the Slit Weld in a Finite Rectangular Plate and the Significance of Restraint Intensities as a Dynamical Measure, IIW Doc. X-1038-83, Trans. JWRI, Vol. 11, No. 2 (1982) 105-113, and J. JWS, 51-8 (1982) 636-643 (in Japanese).

4) K. Satoh, H. Nakajima and N. Suzuki; Restraint Stresses-Strains in Slit Weld, J. JWS, 45-4 (1976) 309-315 (in Japanese).

5) K. Satoh, S. Matsui and M. Kobayashi; Process of Constraction during First-Pass Welding and Cooling (Part 1), J. JWS, 35-3 (1966) 36-46 (in Japanese).

6) Y. Ueda, K. Fukuda and Y.C. Kim; Effective Restraint Intensities of a Thick Finite Plate, Trans. of JWRI, Vol. 12, No. 1 (1983) 105-112, and J. JWS, 52-2 (1983) 104-109 (in Japanese).

7) Y. Ueda, K. Fukuda and Y.C. Kim; Restraint Intensities of a Slit in a Finite Plate, IIW Doc. X-1036-83, Trans. JWRI, Vol. 7, No. 1 (1978) 11-16, and J. JWS, 48-10 (1979) 851-858 (in Japanese).

8) K. Horikawa et al. Study on Weld Cracking Behavior in Large Structures (Part 2), JSSC, 11-114 (1975) 24-28 (in Japanese).