The Fracture Toughness Evaluation by Instrumented Charpy V-Notch Test for Irradiated Narrow-Gap Mig Weldment

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Summary

In nuclear Reactor Pressure Vessel (RPV) fabrication, submerged arc welding (SAW) or electroslag welding (ESW) have been employed for main weld seams, including the core region. Recently, a new welding process, so called Narrow Gap MIG welding, was developed and applied to the RPV of BWR plant. It has already been confirmed that the weld metal and the heat affected zone of the Narrow Gap MIG weldment have excellent mechanical properties, especially fracture toughness, in comparison with conventional welding processes. However the Narrow Gap MIG welding is also going to be applied to the RPV core region, so it is important to evaluate the fracture toughness in an irradiated condition.

In order to evaluate the resistibility to nonductile failure of the irradiated Narrow Gap MIG weldment, the fracture toughness was obtained by means of two empirical correlations between the fracture toughness and the charpy V-notch impact test results. One was developed by the Author based on the empirical correlations already proposed by S.T.Rolfe et al. and T.Iwadate et al. Fracture toughness, K_{Ic} and K_{Id}, are obtained by means of K_{Ic} and K_{Id} master curves from the upper shelf energy, transition temperature of 50% shear fracture of charpy V-notch impact test. The other was proposed by H.Takahashi et al. and was based on the critical plastic energy concept including the effect of strain rate and notch tip acuity on fracture toughness. The fracture toughness, K_{Ic} and K_{Id}, are obtained from the load - displacement curve of an instrumented charpy V-notch impact test. The irradiation embrittlement of the Narrow Gap MIG Weldment was also examined by the method presently used in practice, determining the transition temperature shift at 30ft-lb absorbed energy.

The welded test coupon was made by the same welding procedure as that in shop fabrication of the RPV using 164mm thickness SA533 Gr.B Cl.1 plate and it was irradiated with a neutron flux level of approximately 1.0×10^{19}nvt (>1Mev) at 288°C (550°F).

The irradiation embrittlement of the Narrow Gap MIG Weldment is lower than conventional weldment because of its low Cu and P content. The fracture toughness of irradiated weld metal speculated by two empirical correlations are higher than the K_{IR} curve specified by ASME Code Sec.III Appen.G and it is concluded that the Narrow Gap MIG Weldment has sufficient resistibility to nonductile failure after irradiation. It was confirmed that both of the empirical correlations studied in this paper were applicable to the fracture toughness evaluation of the irradiated weld metal.

1. INTRODUCTION

The Narrow Gap MIG Welding process had been developed [1] and applied to fabrication of Reactor Pressure Vessel (RPV) of BWR plant under construction in Japan. It had been already assured that weld metal and heat affected zone (HAZ) of the unirradiated Narrow Gap MIG Weldment had superior mechanical properties, especially the resistibility to nonductile failure, in comparison with conventional welding processes. The objective of this study is to assure the integrity of the Narrow Gap MIG Weldment in irradiated condition.

It is required by NRC 10CFR50 Appen. G [2] to evaluate the fracture toughness during operation of nuclear plant by the surveillance using charpy V-notch impact specimen because there exists the limitation on the specimen size and the difficulty of the test performance due to radioactivity. Therefore, in order to make quantitative and more accurate evaluation, it is desirable that fracture toughness, K_{Ic} or K_{Id}, is obtained directly by charpy V-notch impact test of irradiated material.

This paper is a proposal to make some empirical correlation between the fracture toughness and the charpy V-notch impact test results for the irradiated Narrow Gap MIG weld deposit metal and their irradiated embrittlement is also examined by the method presently used in practice, determining the transition temperature shift at 30ft-lb absorbed energy. This study predicts a good correlation between the actual measurement of fracture toughness and the fracture toughness derived from the charpy V-notch impact test results.

2. MATERIAL

The base metal used for preparation of the welded test coupon was JIS specification, equivalent to SA-533 GR.B Cl.1 with 164mm thickness. The chemical composition and mechanical properties of the material tested are shown in Table-1. The welding was performed by the Narrow Gap MIG welding process and the weld metal characteristics are also shown in Table-1. Manufacturing history of test coupon and welding condition are shown in Fig.1 and Fig.2.

The test specimens of weld metal and HAZ were taken from the location 1/4T×T(T:plate thickness) so that the axes of test specimens were normal to the welding direction and principal rolling direction of base metal.

3. TEST FACILITY

3.1. MATERIAL IRRADIATION

Material irradiation was conducted in the Japan Material Test Reactor (JMTR) using C-7 lattice position. Fluence determination was based on measurement with four iron neutron dosimeter wires contained in the capsule. The average neutron fluence was 1.1×10^{19}nvt (>1Mev) for weld metal and 0.9×10^{19}nvt (>1Mev) for HAZ. Irradiation period was of approximately 490 hours. Irradiation temperature was controlled at $288^{\circ}C \pm 25^{\circ}C$ by He Gas in the capsule and monitored continuously by means of ten thermocouples attached to the test specimens.

3.2. TEST METHOD

The charpy V-notch impact test was conducted for unirradiated weld metal and HAZ according to ASME Sec.II SA-370. The dynamic tear test using a pre-cracked charpy specimen was also conducted for unirradiated weld metal. The impact test of irradiated weld metal and HAZ was conducted in the Hot Laboratory of JMTR, utilizing the remote control automatic instrumented charpy impact test machine.

The load displacement curve was obtained for irradiated weld metal at three temperatures in addition to measurement of the absorbed energy, lateral expansion and percent of shear fracture. The displacement of the test specimen was known from the location of the hammer edge measured by the potentiometer attached to the hammer shaft of the charpy impact test machine. The load was measured by strain gages attached to each face of the hammer.

4. FRACTURE TOUGHNESS STUDY

Fracture toughness, K_{Ic} and K_{Id}, were obtained in two ways below, from instrumented charpy V-notch test results, for the evaluation of the resistibility to nonductile failure of the irradiated Narrow-Gap MIG weld metal.

4.1. FRACTURE TOUGHNESS STUDY BY K_{Ic} AND K_{Id} MASTER CURVE (METHOD-1)

In recent studies it was shown that the upper shelf existed in the fracture toughness transition curve as well as the charpy V-notch transition curve(Cv curve). S.T.Rolfe et al. [3] proposed that the upper shelf fracture toughness ($K_{Ic}(u.s)$) could be correlated with the upper shelf energy of Cv curve as below.

$$\left(\frac{K_{Ic}(u.s)}{\sigma_y}\right)^2 = 647\left(\frac{vE(u.s)}{\sigma_y}\right) - 6.35 \qquad (1)$$

where, $K_{Ic}(u.s)$: upper shelf fracture toughness
$vE(u.s)$: upper shelf energy of Cv curve
σ_y : static yield strength at the upper shelf temperature of Cv curve

T.Iwadate et al. [4] reported that $K_{Ic}/K_{Ic}(u.s)$ of various materials could be plotted versus T-Tk in the narrow scatter band as shown in Fig. 3, where T is the test temperature and Tk is the fracture toughness transition temperature representing the half value of $K_{Ic}(u.s)$ in the K_{Ic} transition curve. In this study, the K_{Id} Master Curve was newly developed by the Author as well as the K_{Ic} Master Curve by means of the procedure which was applied to development of the K_{Ic} Master Curve proposed by T.Iwadate et al., and it was confirmed that both K_{Ic} and K_{Id} Master Curves could be expressed by the equation described below.

$$K_{Ic},\ K_{Id} = \left[0.092 + 0.408\ \mathrm{EXP}\{0.02\times(T - Tk)\}\right]\times K_{Ic}(u.s) \qquad (2)$$

It is necessary to know Tk in order to develop K_{Ic} and K_{Id} transition curves using master curve equation (2). In this study the new method to derive K_{Ic} and K_{Id} transition curves from tension test and charpy impact test has been established based upon the empirical correlation of fracture toughness transition temperature (Tk), the static yield strength at room temperature(σ_{ys}) and the transition temperature of 50% shear fracture of Cv test (vTrs).

Fig. 4 shows this correlation of various materials between σ_{ys} and ΔT(=vTrs-Tk), where ΔT is represented by two curves for K_{Ic} and K_{Id}, respectively, and the following equations were developed for K_{Ic} and K_{Id}, respectively.

$$\Delta T(K_{Ic}) = 0.03\,\sigma_{ys}^2 - 5.32\sigma_{ys} + 230$$
$$\Delta T(K_{Id}) = 0.004\,\sigma_{ys}^2 - 1.6\sigma_{ys} + 52 \qquad (3)$$

So it is possible to predict Tk from eq. (3) when the static yield strength, σys, of the material is known.

4.2. FRACTURE TOUGHNESS STUDY BY THE CRITICAL PLASTIC STRAIN ENERGY CONCEPT (METHOD-2)

H.Takahashi et al. speculated fracture toughness for various strain rate and notch tip acuity from instrumented charpy V-notch impact test result based on the Critical Plastic Strain Energy Concept [5]. They proposed the eq. (4) shown below which correlated fracture toughness ($K^*cd(V)$) under dynamic condition for charpy V-notch specimen with the total plastic strain energy absorbed within specimen up to the initiation of brittle fracture (U) and dynamic yield strength at the test temperature.

$$K^*cd(V) = \frac{Y\,\sigma_{yd}}{\sqrt{Wo}}\sqrt{\beta\left(\frac{U}{A}\right)C} \qquad (4)$$

where, Y : the geometrical factor of the specimen

$$= 1.93 + 3.07\left(\frac{C}{W}\right) + 14.53\left(\frac{C}{W}\right)^2 - 25.11\left(\frac{C}{W}\right)^3 + 25.8\left(\frac{C}{W}\right)^4$$

C : notch depth W : specimen width

σ_{yd} : dynamic yield strength expressed as

$$\sigma_{yd} = \frac{P_{GY}}{1.24x16}$$

P_{GY} : the load by which the whole cross sectional area of specimen is yielded

A : cross sectional area of specimen

β : constant independent of specimen configuration, strain rate, notch acuity and test temperature.

Wo : constant dependent on notch acuity

H.Takahashi et al. [5] also proposed the correlation between $K^*cd(V)$ and fracture toughness obtained on a pre-cracked specimen for static condition, $K^*cs(fc)$, and the correlation between $K^*cd(V)$ and fracture toughness obtained on a pre-cracked specimen for dynamic condition, $K^*cd(fc)$, as follows.

$$\frac{K^*cs(fc)}{K^*cd(V)} = \left(\frac{\dot{e}_o}{\dot{e}_s}\right)^{\alpha fRTeff}\left(\frac{\dot{e}_d}{\dot{e}_o}\right)^{\alpha o\,\alpha fRTeff} \qquad (5)$$

$$\frac{K^*cd(fc)}{K^*cd(V)} = \left(\frac{\dot{e}_o}{\dot{e}_d}\right)^{\alpha fRTeff}\left(\frac{\dot{e}_d}{\dot{e}_o}\right)^{\alpha o\alpha fRTeff} \qquad (6)$$

$$K^*cd(V) = K^*o\left(\frac{\dot{e}_o}{\dot{e}_d}\right)^{\alpha o\alpha fRTeff} \qquad (7)$$

where, $\dot{e}_o$: constant determined for each material

$\dot{e}_s, \dot{e}_d$: average strain rate at the crack tip estimated for static and dynamic test, respectively

αf : constant determined for each material at each irradiated condition

K^*o : constant determined for each material

αo : constant dependent on notch tip acuity

R : Gas Constant

Teff is expressed as $\frac{1}{Teff} = \frac{1}{T} - \frac{1}{To}$

To : constant determined for each material at each irradiated condition

T : test temperature

$K^{*}cs(fc)$ and $K^{*}cd(fc)$ are calculated by eq. (5) and eq. (6), respectively, using the known value, $K^{*}cd(V)$. And it had been empirically confirmed by H.Takahashi et al. that $K^{*}cs(fc)$ and $K^{*}cd(fc)$ were approximately equal to K_{Ic} and K_{Id}, respectively.

5. EVALUATION

5.1 EVALUATION OF IRRADIATION EMBRITTLEMENT

Irradiation embrittlement of RPV material is usually evaluated by the increase of vTr30 comparing with the trend curve provided in NRC Regulatory Guide 1.99 [6]. As shown in Table-2 the increase of vTr30 of weld metal and HAZ are +19°C and +14°C, respectively, and they follow the trend curve drawn for material containing 0.08 wt % Cu and 0.008 wt % P as shown in Fig. 5. It is concluded from this figure that the irradiation embrittlement of the weld metal and HAZ is reasonable. Fig. 5. also shows several irradiation embrittlement data representing various neutron fluence and chemical composition[7] [8]. Irradiation embrittlement of the Narrow-Gap MIG weld metal and HAZ is very slight in comparison with conventional weld metal and HAZ

5.2 EVALUATION OF THE RESISTIBILITY TO NONDUCTILE FAILURE

The resistibility to nonductile failure of the irradiated weld metal is also evaluated quantitatively using fracture toughness, K_{Ic} and K_{Id}, speculated by Method-1 and Method-2, mentioned previously.

In RPV design the K_{IR} curve specified by ASME Sec. III Appen.G [9] is usually used as the criteria for nonductile failure. The RPV is designed so that the stress intensity factor, K_I, calculated from the applied stress of the RPV becomes lower than the K_{IR} curve. As shown in Fig. 7, all speculated fracture toughness, K_{Ic} and K_{Id}, are scattered above the K_{IR} curve. It means that the weld metal has sufficient resistibility to nonductile failure in the irradiated condition, if the RPV is designed according to the K_{IR} curve, where the RT_{NDT} of the irradiated weld metal is estimated from the increase of vTr30 and the RT_{NDT} obtained for unirradiated weld metal.

In order to make a comparison with conventional weld metal, the speculated K_{Id} of the weld metal are shown in Fig. 6 with the K_{Id} of irradiated and unirradiated SAW weld metal [10]. The K_{Id} of irradiated SAW weld metal are obtained in the higher temperature range. But it is supposed from these data that K_{Id} of irradiated SAW weld metal will be scattered in the range slightly lower than the range of the irradiated Narrow Gap MIG weld metal in the lower temperature range. On the other hand, both K_{Id} in unirradiated condition are scattered approximately in the same range. The difference in decrease of K_{Id} due to irradiation, between SAW weld metal and the Narrow Gap MIG weld metal, may be derived from the difference in residual elements, Cu and P, as well as the increase of vTr30. But further study is needed to make it clear that residual elements are effective on the fracture toughness decrease due to irradiation.

6. DISCUSSION

The applicability of Method-1 and Method-2 to fracture toughness evaluation of the irradiated weld metal is discussed below.

Method-1 was developed based on the correlation between charpy V-notch impact test results and fracture toughness obtained by a pre-cracked large specimen with thickness over 25mm (1in.). In order to investigate the difference in fracture toughness due to specimen configuration, the dynamic bend test with pre-cracked 25mm thickness specimen and the instrumented charpy impact test with pre-cracked charpy specimen were conducted for SA533 B eq. 163mm thickness plate in unirradiated condition. K_{Id} obtained by large specimen provide the transition curve at the temperature range about 20°C higher than that of the charpy specimen as shown in Fig. 8. As mentioned previously, K_{Id} of the unirradiated Narrow Gap MIG weld metal was obtained by the dynamic tear test with a pre-cracked charpy specimen. K_{Id} calculated by Method-1 from the charpy V-notch impact test results of the unirradiated weld metal is shown in Fig. 9 to make a comparison with the K_{Id} obtained by the dynamic tear test. The K_{Id} transition curve calculated by Method-1 is located at the temperature range about $20 \sim 30$°C higher than that of the dynamic tear test and it has the same tendency as that found on the test for SA533 B eq. plate mentioned before. From these discussions, it is speculated that K_{Id} calculated by Method-1 for the irradiated weld metal will be approximately equal to K_{Id} obtained by the irradiated pre-cracked large specimen and will be lower than K_{Id} obtained by the irradiated pre-cracked charpy specimen.

In order to investigate the applicability of Method-2, the instrumented charpy V-notch impact test was also conducted for the unirradiated weld metal at -20°C using the same machine as the irradiated weld metal. $K^{*}cd(fc)$ for the unirradiated weld metal was calculated by eq. (4) and (6) from the load - displacement curve.

As mentioned previously, K_{Id} of the unirradiated weld metal were obtained by dynamic tear test using pre-cracked charpy specimen. The applicability of Method-2 is evaluated by comparing K_{Id} obtained by dynamic tear test with $K^{*}cd(fc)$ calculated for the same test condition as the dynamic tear test, the same strain rate and pre-cracked specimen. As shown in Fig. 9, $K^{*}cd(fc)$ is slightly lower than K_{Id} obtained by dynamic tear test. From this discussion, it is considered that the fracture toughness evaluation for the irradiated weld metal by Method-2 is more conservative than that by a pre-cracked charpy specimen.

From these discussions, it is concluded that both Method-1 and Method-2 provide a good correlation with actual K_{Ic} and K_{Id} test results and it is confirmed that both methods can be applied to the fracture toughness evaluation of the irradiated weld metal. But, further studies will be necessary to make these speculation methods more accurate since the data are limited.

7. CONCLUSION

(1) The Narrow Gap MIG weld metal and HAZ indicate slight irradiation embrittlement because of low Cu and P content in comparison with conventional weldment and this irradiation embrittlement is considered reasonable because the increase of vTr30 follows the trend curve of NRC Regulatory Guide 1.99.

(2) The speculated fracture toughness, K_{Ic} and K_{Id}, of the irradiated Narrow Gap MIG weld metal are higher than the K_{IR} curve specified by ASME Sec.III Appen.G. It is considered that the Narrow Gap MIG weld metal in the RPV of BWR plant will have sufficient resistibility to nonductile failure at the end of plant life provided that the RPV will be designed according to the K_{IR} curve, because fast neutron fluence of the RPV of BWR plant is usually lower than 1.0×10^{19}nvt (>1Mev) to which the weld metal tested in this study was exposed.

(3) It is considered that the fracture toughness speculated in two ways, namely Method-1 and Method-2, from the instrumented charpy V-notch impact test are applicable to the fracture toughness evaluation of irradiated weld metal, and both speculation methods should be used simultaneously for more accurate evaluation. It is recommended for data accumulation that surveillance tests of commercial plant should be conducted by instrumented charpy test machine, and these accumulated data will provide quantitative and more accurate estimation of plant life.

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Table−1 Chemical Composition and Mechanical Properties

	Chemical Composition								
	C	Si	Mn	P	S	Ni	Mo	Cu	V
Base Metal (SA533GR. B Cl. 1 eq.)	0.17	0.26	1.46	0.005	0.003	0.70	0.57	0.03	0.007
Weld Metal	0.066	0.33	1.06	0.006	0.007	0.93	0.36	0.028	0.002

	Mechanical Properties			
	Tensile Strength (kg/mm^2)	Yield Strength (kg/mm^2)	Elongation (%)	RT_{NDT} (°C)
Base Metal (SA533GR. BCl.1 eq.)	65.0	51.0	28.0	−45
Weld Metal	69.5	63.3	26.9	−60

Table 2 Charpy V−Notch Impact Test Results of Narrow Gap MIG Weldment

CONDITION	MATERIAL	vTr 30 (°C)	vTrs (°C)	RT_{NDT} (°C)	⊿T (°C)	Adjusted RT_{NDT} (°C)	$vE_{(U.S)}$ (kg-m)	Fluence (> 1Mev, 10^{19}nvt)
Unirradiated	Weld Metal	−43	−32	−60	—	—	18.1	—
	HAZ	−90	−46	−60	—	—	22.6	—
Irradiated	Weld Metal	−24	− 5	—	+19	−41	16.6	0.9
	HAZ	−76	−42	—	+14	−46	19.6	1.1

NOTE vTr 30 : Transition Temp. of 30ff−lb Absorbed Energy
vTrs : Transition Temp. of 50% Shear Fracture
$vE_{(U.S)}$: Upper Shelf Energy
⊿T : Increase of vTr 30

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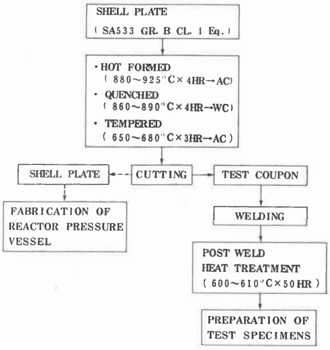

Fig. 1 Heat Treatment and Preparation Sequence of Test Specimen

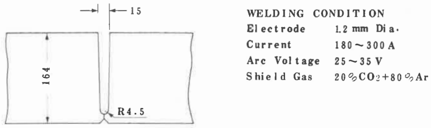

Fig. 2 Edge Preparation and Welding Condition of Test Coupon

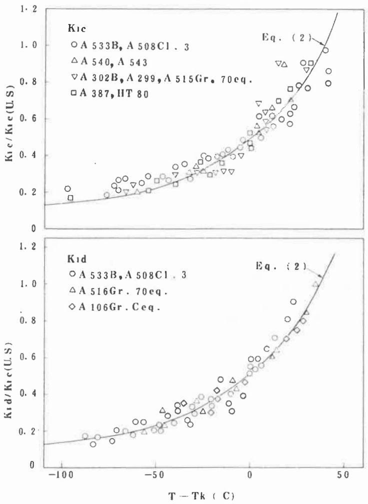

Fig. 3 The Correlation Between K_{Ic} / K_{Ic}(u.s), K_{Id} / K_{Ic}(u.s) and T-Tk of Various Materials [4].

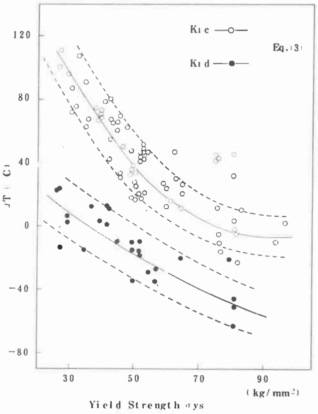

Fig. 4 The Correlation Between ΔT(=vTrs - Tk) and Yield Strength of Various Materials.

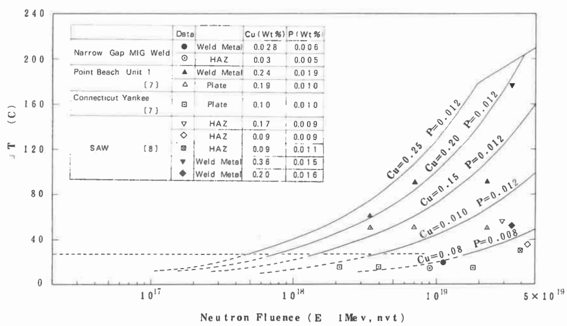

Fig. 5 The Trend Curve of NRC Regulatory Guide 1.99 Which Predicts the Increase of vTr30 due to irradiation and Several Data Representing Various Chemical Composition and Fluence

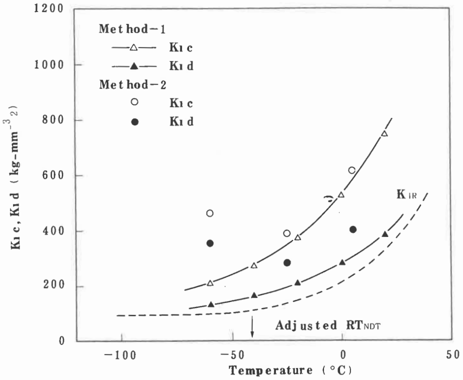

Fig. 6 K_{IR} Curve Specified in ASME Code Sec. III and the Fracture Toughness of the Irradiated Narrow Gap MIG Weld Metal (1.1×10^{19} nvt at 288°C), Which is Derived From the Empirical Correlations, Method-1 and Method-2.

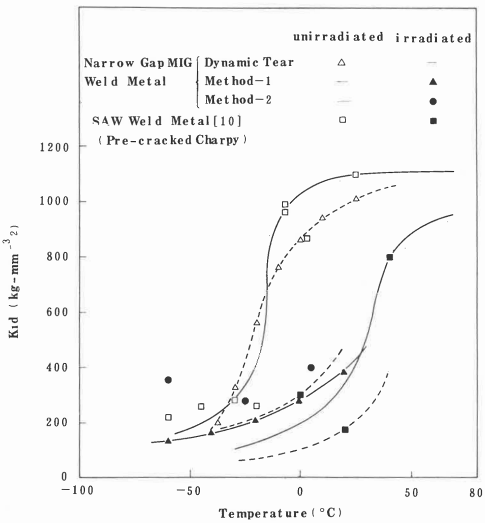

Fig. 7 Dynamic Fracture Toughness of the Irradiated Narrow Gap MIG Weld Metal (1.1×10^{19} nvt at 288°C), and Comparison with the Dynamic Fracture Toughness of the Irradiated SAW Weld Metal (2.5×10^{19} nvt at 288°C).

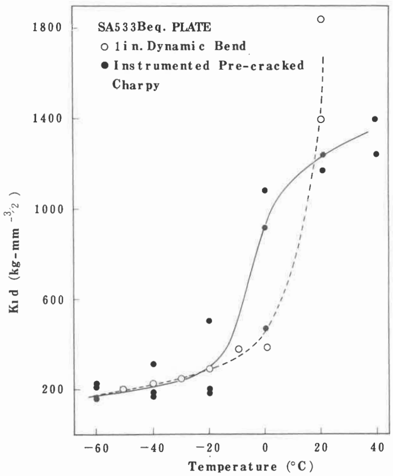

Fig. 8 The Difference of Dynamic Fracture Toughness due to the Difference of Specimen Configuration of SA 533B eq. Plate.

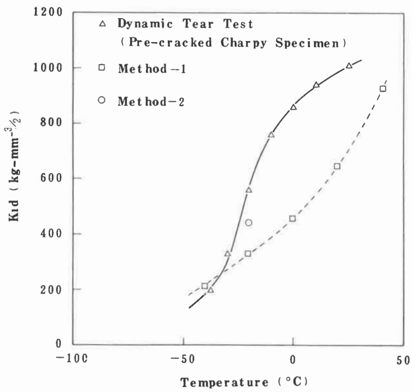

Fig. 9 The Correlation Between K_{Id} obtained by Dynamic Tear Test Using Pre-Cracked Charpy Specimen and K_{Id} Derived From Empirical Correlations, Method-1 and Method-2, of the Unirradiated Narrow Gap MIG Weld Metal.