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EVALUATION OF DYNAMIC FRACTURE TOUGHNESS PARAMETERS BY INSTRUMENTED CHARPY IMPACT TEST

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Abstract—This paper presents methods to determine two fracture mechanics parameters using load–deflection curves obtained from instrumented Charpy impact test. Two fracture mechanics parameters are dynamic fracture toughness (J_d) and material tearing modulus (T_{mat}). J_d is fracture resistance at crack initiation and it is necessary to detect the crack initiation point on the load–deflection curve for measurement of this value. On the other hand, T_{mat} is a parameter to characterize a stable crack growth and it is necessary to estimate an amount of crack extension.

In this study, it is attempted to detect the crack initiation point by calculating the compliance changing rate from a load–deflection curve for the measurement of J_d. Next, J–Δa curve is estimated by using a key curve method and T_{mat} is determined from the slope of it. In addition, T_{mat} is evaluated by combining Kaiser's rebound compliance with Paris–Hutchinson's T_{app} equation. The above results are compared with the ones of the stop block test (which is a multiple specimen technique), and are discussed with respect to their validity; a rather good agreement is ascertained.

1. INTRODUCTION

INSTRUMENTED Charpy impact test is useful to estimate toughness of a material. However, in the present state of things in which the fracture mechanics approach has spread widely, it is important to apply the instrumented Charpy test from the above fracture mechanics viewpoint. At this point, there is a possibility of the instrumented Charpy test spreading as the test method of measuring a dynamic elastic–plastic fracture toughness (J_d)[1]. But its possibility has not been studied thoroughly, especially elastic–plastic fracture mechanics approach is the future problem. The purpose of this study, therefore, is to investigate the method of measuring the dynamic fracture toughness by introducing elastic–plastic fracture mechanics approach.

By the way, elastic–plastic fracture toughness J_{Ic} has been used to evaluate the fracture toughness of low and medium strength steels. J_{Ic} is a fracture resistance at crack initiation. And recently, it is needed to investigate a crack propagation process (transition from stable crack to unstable crack growth) and to evaluate a crack propagation resistance. From this background, tearing modulus conception has been introduced by Paris *et al.*[2]. The tearing modulus conception is based on that unstable crack growth occurs from stable crack growth when T_{app} (applied tearing modulus) reaches T_{mat} (material tearing modulus). From the above background, T_{mat} has been used as a parameter of crack growth resistance. In the case of J_{Ic}, it needs to detect a crack initiation point on the load–deflection curve. On the other hand, in the case of T_{mat}, it is necessary to estimate an amount of crack extension.

Therefore, in this study, it is attempted to detect the crack initiation point calculating a compliance changing rate from the load–deflection curve in the instrumented Charpy test. In the next, J–Δa curve is estimated from the load–deflection curve of single specimen using a key curve method[3], and T_{mat} is determined from a slope of the $J-\Delta a$ curve. Moreover, T_{mat} is also evaluated by combining Kaiser's[4] rebound compliance (C_r) with Paris–Hutchinson's[5] T_{app} equation. The validity of the above methods is examined by comparing with J_d and T_{mat} obtained from a stop block test[6] and the results are discussed.

2. EXPERIMENTAL

2.1 *Material*

Test material is ASTM A533 Grade B Class 1 Steel for reactor pressure vessel (thickness: 134 mm) and chemical composition is shown in Table 1. All specimens were taken longitudinally against rolling direction (L) from 1/4 position of plate thickness.

Table 1. Chemical composition of material (wt%)

C	Si	Mn	P	S	Cu	Ni	Mo
0.18	0.30	1.50	0.004	0.002	0.02	0.67	0.57

2.2 *Measurement of dynamic fracture toughness* J_d

2.2.1. *Stop block test.* Stop block was attached onto the anvil portion of 490 J capacity Charpy testing machine and a specimen in Fig. 1 was loaded. A load–deflection curve was then recorded. In the case of the specimen in Fig. 1(a), a swing angle was 60° (impact velocity: 2.72 m/sec). On the other hand, in the case of specimen in Fig. 1(b), a swing angle was 40° (impact velocity: 1.86 m/sec). By using this stop block, the hammer was stopped compulsorily at any deflection and various crack extensions were able to be obtained. As a result J–Δa curve could be measured in the condition of dynamic loading.

J value was evaluated from Rice's equation,

$$J = \frac{2E}{B(W-a_0)}, \tag{1}$$

where E: the potential energy on the load–deflection curve, B: thickness, W: width, a_0: initial crack length. After the stop block test, specimens were heated for color tinting and then were cloven at liquid nitrogen temperature. Then initial crack length and crack extension were measured by scanning electron microscope according to the method of ASTM E 813. The intercept between the R-curve and the blunting line (which was measured by S.Z.W. method[7]) was identified as J_d.

2.2.2 *Compliance changing rate method.* Conventionally, electrical potential method, unloading compliance technique and acoustic emission (AE) method have been used in order to detect the crack growth point from a pre-crack. But in the case of dynamic loading test, the above techniques have some problems on application. The compliance changing rate (which is calculated from a recorded load–deflection curve according to eqn (2) which will appear later) method was attempted and reported on aluminum alloys by Tseng *et al.*[8]. If this method is applied to the instrumented Charpy test and a success is obtained, it will be very useful from a paractical viewpoint.

The specimen in Fig. 1 were tested using 490 J capacity instrumented Charpy testing machine and the load–deflection curve was recorded.

By connecting the digital memory and micro-computer, the instrumented Charpy testing machine in the present study is able to memorize data of load and deflection and to analyze yield load, maximum load, pre-maximum load energy and post-maximum load energy[9]. Moreover, in order to analyze the load–deflection curve exactly and rapidly, the instrumented Charpy testing machine has been equipped to transmit the data (which are load, deflection, and moving averaged load[9]) to a personal computer using interface (RS-232C).

The compliance changing rate is defined as eqn (2):

$$\frac{\Delta C}{C} = \frac{C - C_{el}}{C_{el}}, \tag{2}$$

where $\Delta C/C$: compliance changing rate, C: assumed linear compliance from original loading point to any point on the load–deflection curve, C_{el}: initial compliance which is determined assuming

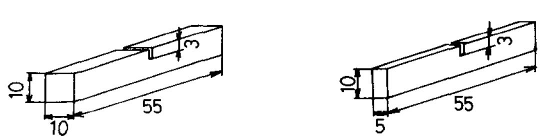

Fig. 1. Test specimen geometries (mm).

linear elastic loading until yield point load P_y, for measuring convenience; i.e., $C_{el} = P_y/\Delta_y$, where Δ_y is the yield point deflection. This $\Delta C/C$ is plotted against the deflection and an initial point where the changing rate of the $\Delta C/C$ is large, after it has risen from zero level, is assumed as a crack initiation point. Then J_d is to be estimated by eqn (1).

2.3 *Evaluation of crack extension and crack growth resistance*

2.3.1 *Estimation of crack extension* Δa *by a key curve method.* The specimen in Fig. 1 and the sub-size (blunt notch) one were used in the instrumented Charpy test and the load–deflection curves were recorded and the key curve method was applied. The fundamental conception of the key curve method[3] is as follows. Comparing the load–deflection curve of the blunt notch specimen without crack extension with the one of fatigue cracked specimen with crack extension, both of the load–deflection curves will cross at the same a/W ratio.

In this study, the key curve function was assumed as follows:

$$\frac{PW}{b_0^2} = k\left(\frac{\Delta_{pl}}{W}\right)^n, \tag{3}$$

where P: load, Δ_{pl}: plastic deflection, b_0: initial ligamemt width, k, n: constants. Namely, the key curve was approximated by the normalized load–deflection curve applying the power-low. The values of n and k were determined fitting the load–deflection curve of the sub-size specimen. In this analysis, the fitting was limited up to the maximum load point deflection, where no noticeable crack extension was existed. Concretely, both sides of eqn (3) were changed to logarithms and the results were fitted by a linear least squares method. A slope of the fitted linear line is n and an intersection is k. And then fitting range was changed to the crack initiation point detected by the compliance changing rate method, and the values of n and k were also determined in the case of the fatigue cracked specimen.

By the way, considering the case of crack growth, eqn (4) is introduced by eqn (3):

$$\Delta a = W - \left\{\left(\frac{PW_{n+1}}{k\Delta_{pl}^n}\right)^{1/2} + a_0\right\}. \tag{4}$$

From eqn (4), an amount of the crack extension Δa was to be estimated to any deflection on the load–deflection curve of the fatigue cracked specimen and the relation between crack extension and deflection was determined. Here, the deflection was corrected to the real deflection deformed only in the specimen by compliance correction[9].

On the other hand, by calculating the J value from eqn (1), J–Δa curve was obtained from the load–deflection curve of single specimen.

2.3.2 *Evaluation of material tearing modulus* (T_{mat}). Material tearing modulus (T_{mat}) is defined by eqn (5)[2]:

$$T_{mat} = \frac{E}{\sigma_0^2}\frac{dJ}{da}, \tag{5}$$

where E: Young's modulus, σ_0: flow stress (averaged by ultimate tensile stress and yield stress: these tensile values were assessed by dynamic bending load[10]), dJ/da: slope of J–Δa curve. In this study, T_{mat} was determined from a slope of J–Δa curve which was obtained by the key curve method and the stop block test.

By the way, in the case of giving the relation between the load and the deflection, Rice *et al.*[11] has given eqn (6) on the three point bend specimen:

$$J = \frac{2}{Bb}\int_0^{\Delta_c} P\, d\Delta_c, \tag{6}$$

where b: remaining ligament width, Δ_c: deflection due to the crack. From eqn (6), Paris and

Hutchinson[4] have shown:

$$T_{\rm app} = \frac{4P^2E}{\sigma_0^2 b^2 B}\left\{\frac{C}{1+C(\partial P/\partial \Delta_c)_a}\right\} - \frac{JE}{\sigma_0^2 b}, \tag{7}$$

where J: J integral value, C: the plastic (no crack portion) compliance C_{nc} and the external compliance C_{ext}. C_{nc} is given by eqn (8):

$$C_{nc} = \frac{1}{4E}\cdot\frac{S^3}{W^3}\left\{1+\frac{12}{5}\left(\frac{W}{S}\right)^2(1+\nu)\right\}, \tag{8}$$

where S: the length between supports and ν: Poisson's ratio.

On the other hand, it has been reported by Kaiser *et al.*[5] that T_{mat} can be determined from the rebound compliance C_r (reciprocal of descending slope from the maximum load) by putting $C_{ext} = C_r$ in the explicit formula for T_{app}, eqn (7), and that a good agreement is observed. And the above has been introduced analytically by Ernst *et al.*[3]. Namely, it has been considered that C_r reflects the material fracture resistance balanced with the spring constant of the applied system and $(\partial P/\partial \Delta_c)_a$ in eqn (7) is given by eqn (9).

$$\left(\frac{\partial P}{\partial \Delta_c}\right)_a = \frac{nP}{\Delta_{pl}+nPC(a)}$$

$$C(a) = \frac{2S^2}{E'W^2}\left[-19.37\frac{a}{W}+8.72\left(\frac{a}{W}\right)^2-6.10\left(\frac{a}{W}\right)^3+2.98\left(\frac{a}{W}\right)^4 -0.82\left(\frac{a}{W}\right)^5+13.54\ln\left(1+2\frac{a}{W}\right)-2.26\ln\left(1-\frac{a}{W}\right) -10.39\frac{a/W}{1+2a/W}-0.57\frac{a/W}{1-a/W}+0.49\frac{\frac{a}{W}\left(2-\frac{a}{W}\right)}{\left(1-\frac{a}{W}\right)^2}\right], \tag{9}$$

where $E' = E/(1-\nu^2)$: plane strain, $E' = E$: plane stress. In this study, plane strain condition was assumed and 0.3 was used as ν value.

In this study, T_{mat} was determined using eqn (7) and C_r near the maximum load, and it was compared with the results in the key curve method and in the stop block test. Here, in calculating eqn (7), the remaining ligament width was estimated from eqn (4) and J values were calculated from eqn (1).

3. RESULTS AND DISCUSSION

3.1 *Dynamic fracture toughness* J_d

J–Δa curve in small amount of crack extension obtained from the stop block test is shown in Fig. 2. J_d values obtained from Fig. 2 are shown in Table 2. As the result of judging the validity about J_d values, all J_d values were invalid.

$$B, a_0, (W-a_0) \geqslant 25\frac{J}{\sigma_0}. \tag{10}$$

Therefore, J_d values obtained from both methods were not values under the plane strain condition; an introduction of side-grooves or an increase of specimen size may be recommended. The above idea is being studied now separately. It was confirmed from Fig. 2 that the J_d values and the slope of J–Δa curve were not independent of the specimen thickness.

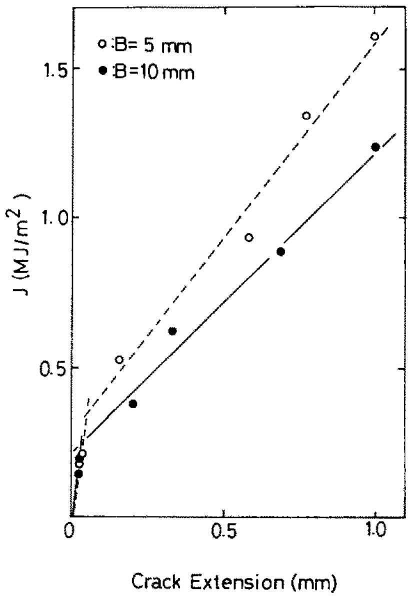

Fig. 2. J–Δa curves obtained from the stop block test.

Next, compliance changing rate–deflection and load–deflection curves are shown in Figs. 3 and 4. Figure 3 is in the case of 10 mm thickness and Fig. 4 is 5 mm thickness. Here, the rising point of $\Delta C/C$ curve from zero level corresponds to the yield point. Crack initiation point detected by the compliance changing rate method agreed with the one by the stop block test. J_d values obtained by the compliance changing rate method is shown in Table 2. Good agreement or lower estimation is observed by the compliance changing rate method comparing with the result of the stop block test. In conclusion, it was found that crack initiation point could be detected by calculating the compliance changing rate in the pre-cracked instrumented Charpy test and it has been confirmed that this method is also useful to the other material[12].

3.2 *Evaluation of crack extension and crack growth resistance*

3.2.1 *Estimation of crack extension.* The n, k values which determined fitting on the plastic deformation range of the load–deflection curve of the sub-size specimen and the fatigue cracked one are shown in Table 3 and a work hardening exponent obtained from static tensile test is also shown in Table 3[10]. The n values determined fitting the load–deflection curve of the sub-size specimen are nearly equal to the work hardening exponent. The same result has also been indicated by Kaiser[5]. In the next, a relation between plastic deflection Δ_{pl} and crack extension Δa obtained from eqn (4) is shown in Fig. 5. The relation between plastic deflection and crack extension determined from the n, k values of the sub-size specimen is closer to the one in the stop block test. This result is also recognized on 5 mm thickness specimen. Consequently, from the above results, the values of n and k determined from the load–deflection curve of the sub-size specimen are used in the subsequent analysis.

By the way, it is considered questionable that the crack extension in the sub-size specimen at the same deflection appeared larger than the one in the fatigue cracked specimen. However, like the

Table 2. J_d values obtained from stop block test and compliance changing rate method

	Thickness B (mm)	J_d (kJ/m^2)	$25 \cdot J_d/\sigma$ (mm)
Stop block test	5	336.1	11.0
	10	253.8	8.5
Compliance changing rate method	5	279.3	9.3
	10	239.1	8.0

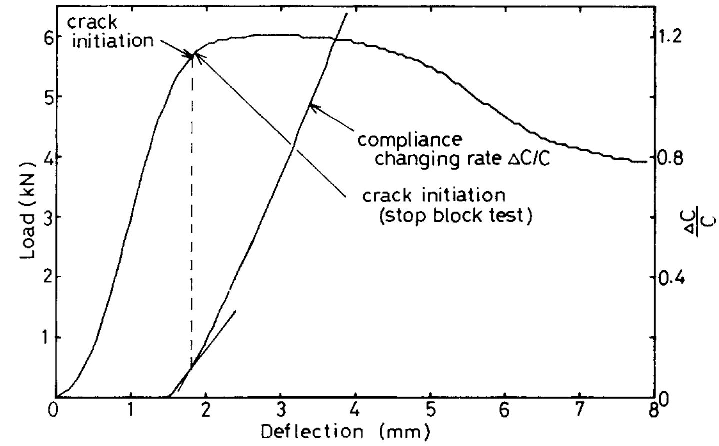

Fig. 3. Curves of load–deflection and compliance changing rate–deflection (B = 10 mm).

present material, in the case that the crack extends fast, the n value determined fitting the load–deflection curve of the fatigue cracked specimen cannot reflect thoroughly the plastic deformation ability, because the range of plastic deformation is too small. However, in some cases, it may become necessary to obtain all information from a fatigue cracked specimen only. In that case, it will be enough to use the n value from the fatigue cracked specimen for a rough estimation.

3.2.2 *Comparison of* J–Δa *curve by various methods.* J–Δa curves determined from the stop block test and the key curve method are shown in Fig. 6. J–Δa curve determined from the stop block test agreed with one determined from the key curve method. Therefore, it is said that the key curve function defined by eqn (3) and the value of n are valid.

In the case of measuring J–Δa curve whilst taking notice of ductile crack extension, the effect of crack extension on estimating the J value must be considered. Therefore, J values were corrected using Garwood's[13] formula of three point bend specimen defined by eqn (11).

$$J_n = J_{n-1}\frac{W-a_n}{W-a_{n-1}} + \frac{2U_4}{B(W-a_{n-1})}, \tag{11}$$

where U_4 refers to the area under the actual test record limited by lines of constant deflection Δ_{n-1} and Δ_n. The result is shown in Fig. 6. It is found from Fig. 6 that J values determined from the stop block test and the key curve method may be overestimated according to the large amount of crack extension. And in the case of corrected crack growth, J value lowered rapidly after the crack

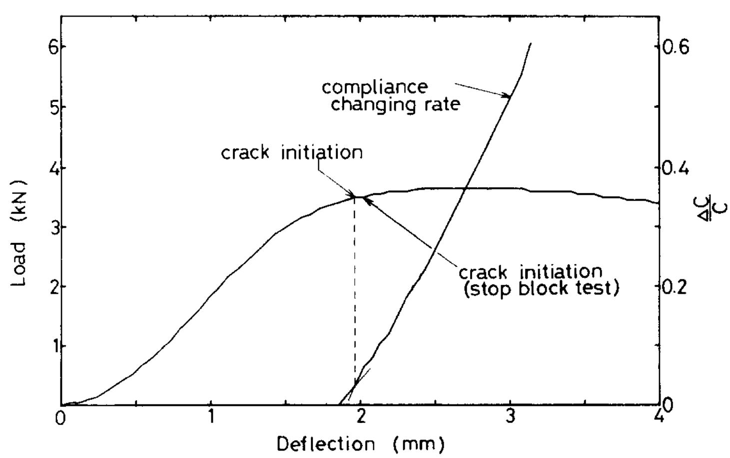

Fig. 4. Curves of load–deflection and compliance changing rate–deflection (B = 5 mm).

Table 3. n, k values obtained from fitting for load–deflection curves

	Thickness B (mm)	n	k	Work hardening exponent
Sub-size specimen	5	0.075	209.0	
	10 $a/W = 0.6$	0.063	407.5	
	10 $a/W = 0.8$	0.079	683.8	0.060
Fatigue cracked specimen	5	0.076	183.1	
	10	0.048	374.1	

extension of about 1 mm. This corresponded to the drop of T_{mat} (see Fig. 10, which will appear later).

Now, according to Paris *et al.*[4], J-controlled growth condition is presented by eqn (12).

$$\left.\begin{aligned} \Delta a &\ll R_H \\ \omega = \frac{b}{J}\frac{\mathrm{d}J}{\mathrm{d}a} &\gg 1 \end{aligned}\right\}, \tag{12}$$

where R_H: size of region of distinctly proportional plastic loading. It has been reported by Shih and Kumer[14] that ω in the eqn (12) is possible until 2.5 for the bend specimen like the CT specimen. In this study, an amount of crack extension at $\omega = 2.5$ is a range of about $0.7 \sim 1.1$ mm. This corresponds to the above result. Therefore, J values and T_{mat} which exceed the above range must be considered as reference values.

On the other hand, the ■ mark in Fig. 6 is a modified J integral value presented by Ernst[15]. The modified J integral value (J_{M}) is defined by eqn (13).

$$J_{\mathrm{M}} = J - \int_{a_0}^{a} \left.\frac{\partial J_{\mathrm{pl}}}{\partial a}\right|_{\delta_{\mathrm{pl}}} \mathrm{d}a, \tag{13}$$

where J_{pl}: the plastic portion of the deformation theory J. Use of this modified J integral has been shown to extend greatly the validity of J controlled growth, even to situations where $\Delta a = 0.3\,b$ (i.e. $\simeq 1.2$ mm in this study) which normally would grossly violate the deformation theory requirement of eqn (12). It is also noticed no J_{M} value drop is seen even at large crack extension. However, the validity of J at large crack extension must be studied more in the future.

3.2.3 *Comparison of material tearing modulus* T_{mat} *by various methods.* It is difficult to evaluate rebound compliance (C_r) in the case of estimation of T_{mat} using eqn (7) from the load–deflection

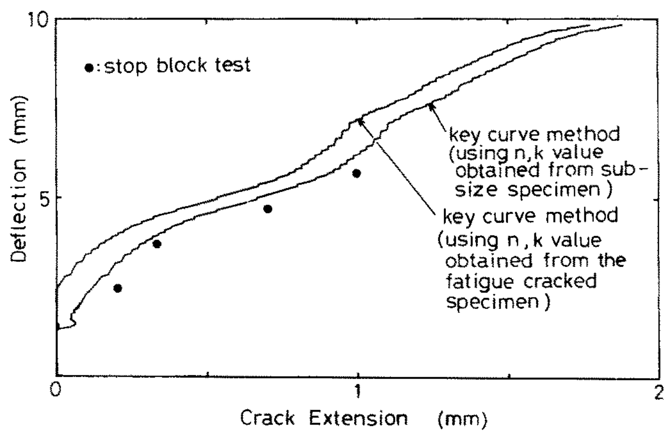

Fig. 5. Relationships between crack extension and deflection ($B = 10$ mm).

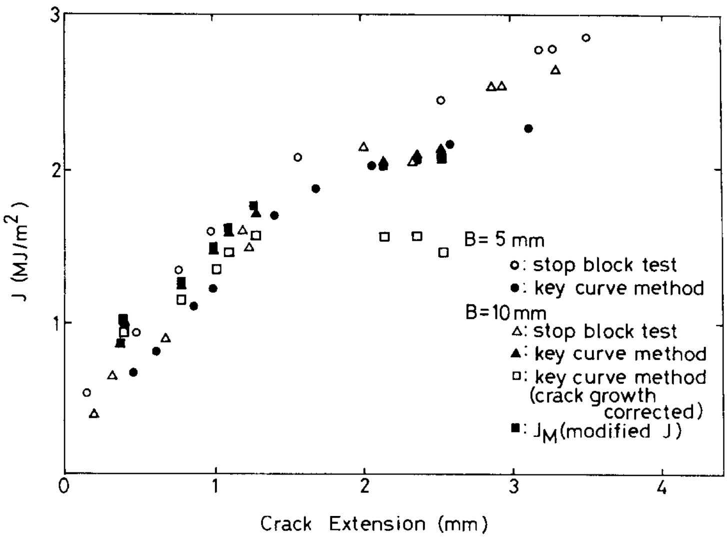

Fig. 6. J–Δa curves obtained from various methods.

curve obtained by the instrumented Charpy test. For a high toughness material, it takes a long time to rupture the specimen and the hammer speed is decelerated. Therefore, the stress wave which is propagated and reflected in the hammer may cause interference in the portion of descending slope from the maximum load (this problem is being studied now) and as a result, the slope may not reflect the material fracture resistance balanced with spring constant of applied system. Therefore, if the descending portion of the load–deflection curve is fitted with polynomial expression like the Kaiser's approach[4], the evaluation of C_r may be mistaken. Then, in this study, C_r was defined as the reciprocal of descending slope from near the maximum load and where the slope becomes most steep in order to estimate the lower bound value; T_{mat} was determined by using eqn (7) for the deflection range where the above defined C_r was regarded as constant.

Relations between T_{mat} and load–deflection curve of the fatigue cracked specimen are shown in Figs. 7 and 8. It is found from Figs. 7 and 8 that material stability against the crack growth is held and T_{mat} determined from eqn (7) is almost equivalent to one determined from the stop block test near the maximum load.

Relations between T_{mat} and crack extension Δa obtained from slopes of J–Δa curves estimated by the stop block test, from the key curve method, from the crack growth corrected key curve method (by Garwood's correction), and from eqn (7) combined with the rebound compliance are

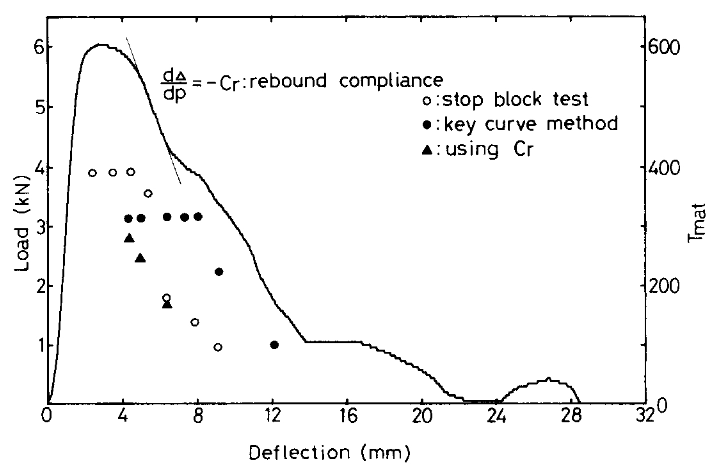

Fig. 7. Curves of load–deflection and T_{mat}–deflection (B = 10 mm).

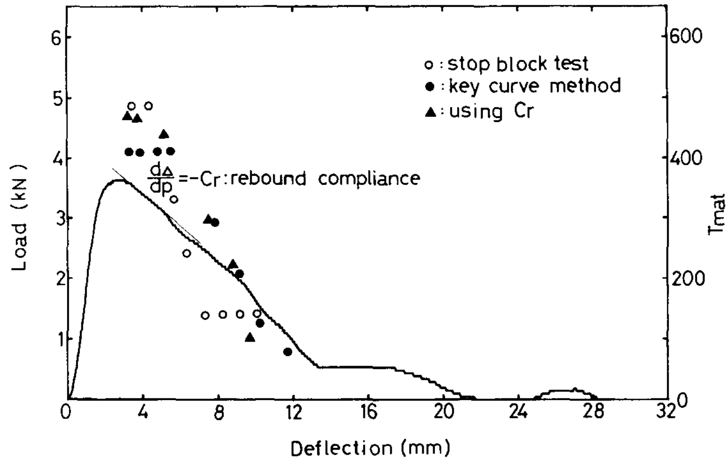

Fig. 8. Curves of load–deflection and T_{mat}–deflection ($B = 5$ mm).

all shown in Fig. 9. It is found from Fig. 9 that T_{mat} obtained for 5 mm thickness specimen is larger than one obtained for 10 mm thickness specimen. Namely, the thickness dependency is ascertained.

4. CONCLUSION

Instrumented Charpy impact test was carried out on a reactor pressure vessel steel ASTM A533 Grade B by introducing the elastic–plastic fracture mechanics approach and the following conclusions have been obtained.

(1) It has been found that the crack initiation point is able to be detected calculating the compliance changing rate, and dynamic fracture toughness J_d can be estimated.
(2) It has been shown that the amount of crack extension is able to be predicted from a load–deflection curve of single specimen by using the key curve method, and that a valid value of T_{mat} can be obtained.
(3) From the above result, it has been found that dynamic fracture toughness characteristics for crack initiation and crack propagation are simply estimated using a precracked Charpy type specimen and carrying out instrumented Charpy test. The present method is considered to be very useful for industrial application.

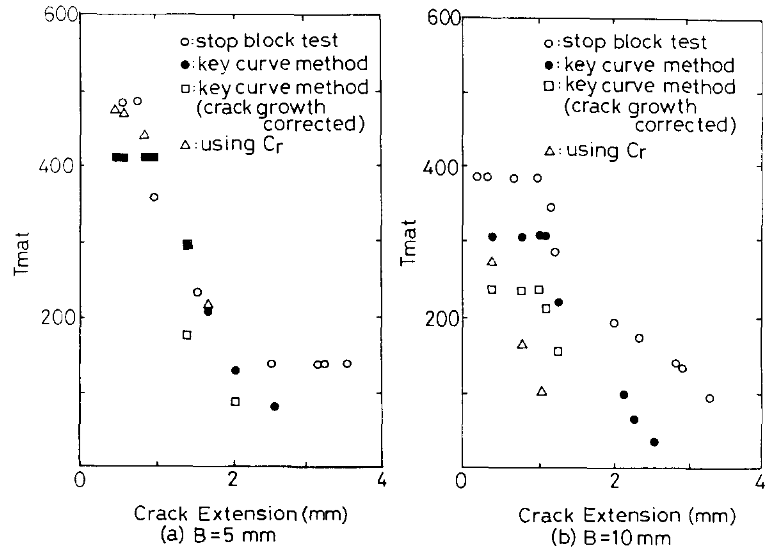

Fig. 9. T_{mat}–crack extension curves evaluated from various methods.

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