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A FRACTOGRAPHIC STUDY ON EVALUATION OF FRACTURE TOUGHNESS

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INTRODUCTION

Linear elastic plane-strain fracture toughness, K_{Ic}, is obtained according to ASTM standard [1]. Obviously, K_{Ic} tests on high toughness and low yield strength materials are not practical because of minimum size requirements for valid K_{Ic} measurement and of non-linear effects due to material plasticity.

Begley and Landes [2] developed an elastic-plastic J_{Ic} fracture criterion, based on the J-integral proposed by Rice [3]. An excellent correspondence has been recently found between J_{Ic} values obtained according to an R-curve test technique developed by Landes and Begley [4] and K_{Ic} values for some high toughness materials [5]. The J-integral is based on a non-linear elastic approximation to plasticity. Such an approximation is difficult to justify once crack growth initiates due to local unloading in the vicinity of the crack tip. Then, no physical significance should be attributed to the R-curve.

In this paper, we confirm the validity of the J_{Ic} fracture criterion and of a proposed J_{Ic} test method with small specimens over a wide range of temperature for a relatively tough material.

PROPOSED J_{Ic} TEST METHOD

A proposed J_{Ic} test method is established, laying emphasis on examination of the relation between a fractographically derived stretched zone width, SZW, and the J-integral. Specimens, testing equipment, other testing procedure, data analysis and specimen size analysis are identical to those of the J_{Ic} test method developed by Landes and Begley [4]. The procedure of the proposed J_{Ic} test method is summarized as follows.

(1) Specimens should be deeply notched with $a/W \simeq 0.6$ and pre-cracked in fatigue, Figure 1(a), (I).
(2) Load several specimens to different displacement values where no stable crack growth was initiated, Figure 1(a), (II).
(3) Unload each specimen and mark the crack front by fatigue, Figure 1(a), (III). Then, pull the specimen apart by overload, Figure 1(a), (IV).
(4) Measure SZW formed at part (II) in Figure 1(a). Calculate J value from the load versus load line displacement record using the following expression [6],

$$J = 2A / Bb, \qquad (1)$$

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where A is the area under the curve up to the point of unloading, Figure 1(b), B is the specimen thickness and b is the uncracked ligament measured from the end of the fatigue pre-crack. Plot SZW versus J, Figure 1(c).

(5) Pull a virgin specimen apart by overload and measure a critical stetched zone width at initiation of stable crack growth, SZW_c. Although the critical stretched zone forms prior to the initiation of stable crack growth, SZW_c is not affected by the continued stable crack growth [7].

(6) Draw a best fit line to the SZW versus J points and a horizontal line corresponding to SZW = SZW_c.

(7) Mark J_{Ic} at the intersection of these two lines. It is also possible to determine J_{Ic} at a critical J value whether stable fractured region with tear dimpled pattern exists or not.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material tested was Ni-Cr-Mo steel. Chemical composition, heat treatment and mechanical properties are presented in Table 1. All of the specimens tested were of the bend type, compact tension and 3-point bend specimens. The configuration and dimensions of these specimens are shown in Figure 2.

A J_{Ic} test according to the proposed method and K_{Ic} test according to ASTM standard were conducted at room temperature using compact tension specimens ranging from 1/5CT to 1CT, and at low temperature ranging from room temperature to 83K using 3-point bend specimens.

Fractographic examinations were conducted at the midthickness of specimens where plane-strain conditions exist and stable crack growth occurs initially, using a two-stage plastic-carbon replica with chromium shadowing.

RESULTS AND DISCUSSION

Fractographic Examination

Representative fractographs showing the general features in front of the fatigue pre-cracked region are shown in Figure 3; the fractographs (a)∿(d) correspond respectively to the points of unloading A∿D on the load versus load line displacement curve shown schematically in Figure 3. In fractographs (a) and (b), the fracture surface comprises three regions; the fatigue pre-cracked region, the fatigue marked region (cf. procedure (3)) and the stretched zone between these two. There is an abrupt transition from the stetched zone to the fatigue marked region. This suggests that the stretched zone forms as a result of fatigue pre-crack tip plastic blunting, prior to the initiation of stable crack growth. Making a comparison between fractographs (a) and (b), it is obvious that SZW increases with increasing displacement or J value. In fractograph (c), however a narrow region with tear dimpled pattern exists between the stretched zone and the fatigue marked region. This region presumably forms as a result of actual stable crack growth [7]. In a virgin specimen fractured by overload (cf. procedure (5)), the features are similar to those in fractograph (c) except for the fatigue marked region, as shown in fractograph (d). Furthermore, making a comparison between fractographs (c) and (d), it is obvious that SZW_c is not affected by the continued stable crack growth, as described above.

Determination of J_{Ic}

Plots of SZW versus J at room temperature for 1/5CT, 1/2CT and 1CT compact tension specimens are shown in Figure 4. SZW increases abruptly with increasing J value just before J attains to a critical value, J_{Ic}. And, it is clear that the relation between SZW and J is not obeyed by the following equation [4],

$$J = 2\sigma_{flow} \cdot SZW, \tag{2}$$

where σ_{flow} is a stress taken half way between yield stress and ultimate tensile stress. For an apparent J value over J_{Ic}, SZW shows no dependence on J value as represented by symbols of ● ■ ▲ in Figure 4. This value of SZW means SZW_c as described above. Figure 4 shows that SZW_c is nearly equal to 1/5CT, 1/2CT and 1CT. Accordingly, the corresponding J_{Ic} value to SZW_c is nearly constant regardless of specimen thickness. That is to say, it is reasonable to call the J value determined at initiation of stable crack growth J_{Ic}.

The following valid specimen size requirements have been proposed,

$$B,\ a,\ b > \alpha J_{Ic} / \sigma_{flow}, \tag{3}$$

where α was assumed to be between 25 and 50 [8]. The J_{Ic} values obtained here sufficiently satisfy equation (3) as presented in Table 2. Hence, further experiments using smaller specimens must be done to determine minimum size requirements for valid J_{Ic} measurement in this test method.

Figure 5 summarizes the results of the relation between SZW and J for two geometries, compact tension (1/5CT, 1/2CT, 1CT) and 3-point bend specimens, at room temperature. The relation between SZW and J is identical for two geometries. Also, an excellent agreement between J_{Ic} values for each geometry is found as presented in Table 2. It should be emphasized that these J_{Ic} values determined at initiation of stable crack growth show no apparent dependence on specimen geometry, in spite of slight dependence of K_{Ic} values on it.

The relation between SZW and J at room temperature, 213K and 133K for 3-point bend specimens is shown in Figure 6. According to equation (2), this relation should be dependent upon yield stress or σ_{flow}. The dependence upon it in this experiment, however, is not remarkable. It is therefore possible that the relation may be expressed by one curve regardless of test temperature as shown in Figure 6. SZW_c decreases with decreasing test temperature, as represented by symbols ● ■ ▲ in Figure 6. Hence, J_{Ic} values corresponding to these SZW_c decrease with decreasing test temperature.

Evaluation of K_{Ic}

Load at initiation of stable crack growth, P_{in}, lies on a straight part of the load versus crack opening displacement curve as shown in Figure 7. It is therefore expected that small scale yielding and plane-strain conditions may remain at the mid-thickness of the specimen until stable crack growth initiates. An apparent plane-strain fracture toughness, $K_{Ic}(J)$, was calculated from J_{Ic} values according to the following expression [2],

$$K_{Ic}(J) = \left(EJ_{Ic} / (1-\nu^2)\right)^{1/2}, \quad (4)$$

where E is Young's modulus and ν is Poisson's ratio. These converted $K_{Ic}(J)$ are plotted in Figure 8 as well as K_{Ic} and K_Q obtained according to the ASTM standard. It is noted that $K_{Ic}(J)$ is constant regardless of specimen thickness ranging from 5.5 to 25.5mm, and an agreement between $K_{Ic}(J)$ and K_{Ic} is found to be excellent. That is to say, it is possible to evaluate accurately K_{Ic} using at least one-fifth the thickness of the ASTM valid K_{Ic} specimen, according to the proposed J_{Ic} test method.

Similar J_{Ic} test results below room temperature using 3-point bend specimens are shown in Figure 9. An agreement between $K_{Ic}(J)$ and K_{Ic} is also excellent. A further experiment based on the proposed J_{Ic} test method is being continued on evaluation of fracture toughness of low yield strength materials within the ductile-brittle transition temperature region.

CONCLUSIONS

(1) A SZW versus J curve is found to be independent of specimen thickness and geometry tested until stable crack growth initiates.
(2) A SZW versus J curve is independent of test temperature at a low temperature range.
(3) No effects of specimen thickness and geometry on J_{Ic} value are found for a range of specimens tested provided that J_{Ic} is determined at initiation of stable crack growth.
(4) An apparent plane-strain fracture toughness, $K_{Ic}(J)$, is in excellent agreement with K_{Ic} value for a wide range of temperature tested. Therefore, it is possible to evaluate accurately K_{Ic} using smaller size specimen than that of ASTM valid K_{Ic} test, according to a proposed J_{Ic} test method.

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Table 1 Chemical Compositions, Heat Treatment and Mechanical Properties

Chemical composition (%)

C	Si	Mn	P	S	Ni	Cr	Mo	Cu
0.41	0.28	0.75	0.012	0.013	1.79	0.81	0.22	0.06

Heat treatment

Austenitized at 1123K for 40 min., oil quenched
Tempered at 873K for 90 min., water quenched

Mechanical properties

Test Temperature K	Yield Strength MPa	Tensile Strength, MPa	Reduction %	Elongation %
288	1069	1138	54.3	18.2
203	1108	1196	54.8	14.9
133	1216	1304	49.6	14.2
83	1442	1500	42.9	10.4

Table 2 Summary of Results on Fracture Toughness at Room Temperature

Specimen	B mm	SZW_c μ	J_{Ic} kJ/m^2	$K_{Ic}(J)$ $MPam^{1/2}$	$50(J_{Ic}/\sigma_{flow})$ mm
1CT	25.5	6.06	20.8	68.5	0.942
1/2CT	12.5	6.31	19.4	66.4	0.880
1/5CT	5.5	5.91	20.0	67.3	0.907
10×20*	10.0	5.79	19.9	67.0	0.902

* 3-Point Bend Specimen

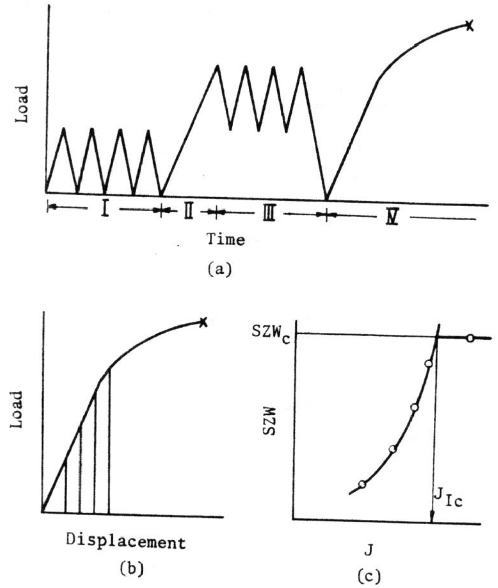
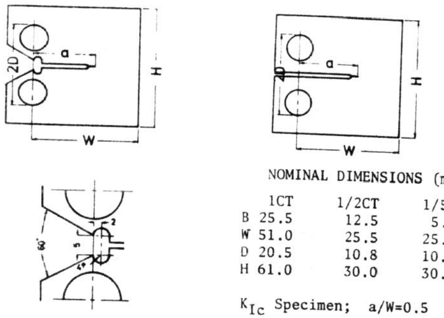


Figure 1 Procedure for J_{Ic} Test



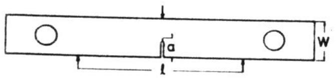
NOMINAL DIMENSIONS (mm)

	1CT	1/2CT	1/5CT
B	25.5	12.5	5.5
W	51.0	25.5	25.5
D	20.5	10.8	10.8
H	61.0	30.0	30.0

K_{Ic} Specimen; a/W=0.5

J_{Ic} Specimen; a/W=0.6

(a) Compact tension Specimen



NOMINAL DIMENSIONS (mm)

B	W	ℓ
20.0	40.0	160.0
10.0	20.0	80.0

K_{Ic} Specimen; a/W=0.5

J_{Ic} Specimen; a/W=0.6

(b) 3-Point Bend Specimen

Figure 2 Configuration and Dimensions of Specimens

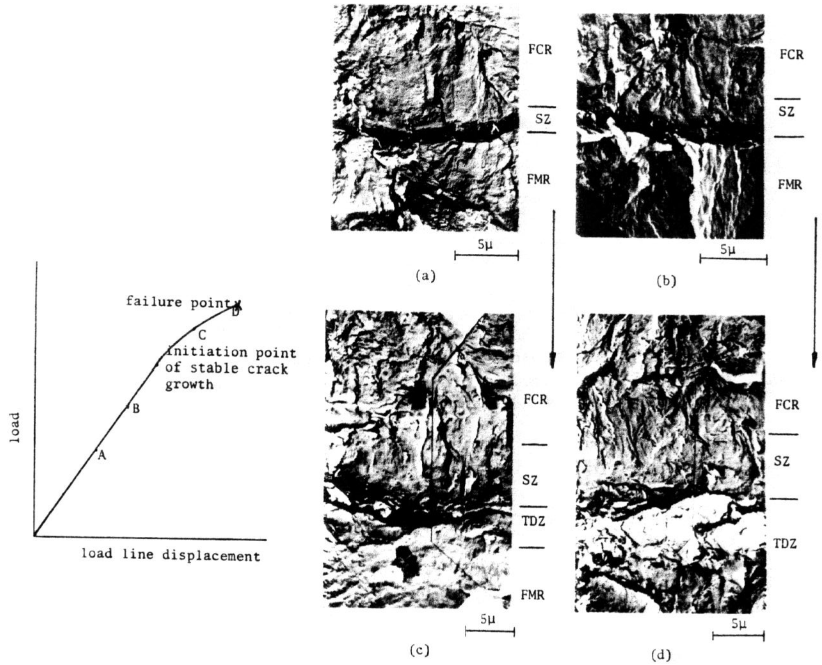


Figure 3 Load versus Load Line Displacement Curve, and Fractographic Fracture of J_{Ic} Test Specimens (1/2CT) Tested at Room Temperature

- FCR : Fatigue Pre-Cracked Region
- FMR : Fatigue Marked Region
- SZ : Stretched Zone
- TDZ : Tear Dimpled Region

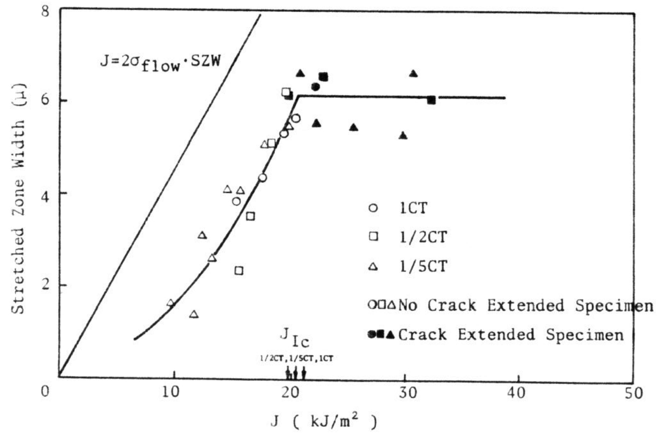


Figure 4 Effect of Specimen Thickness on J_{Ic}

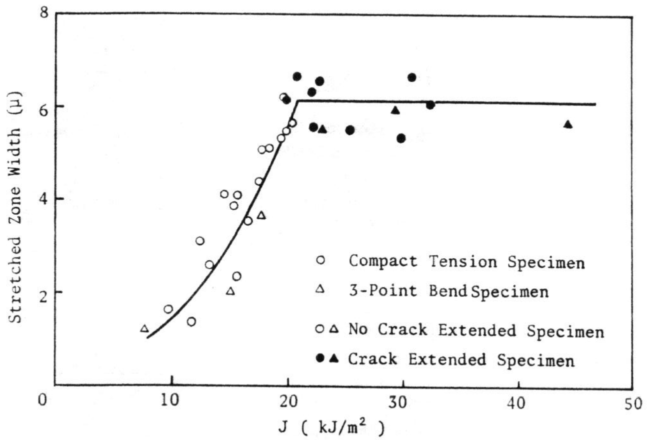


Figure 5 Effect of Specimen Geometry on J_{Ic}

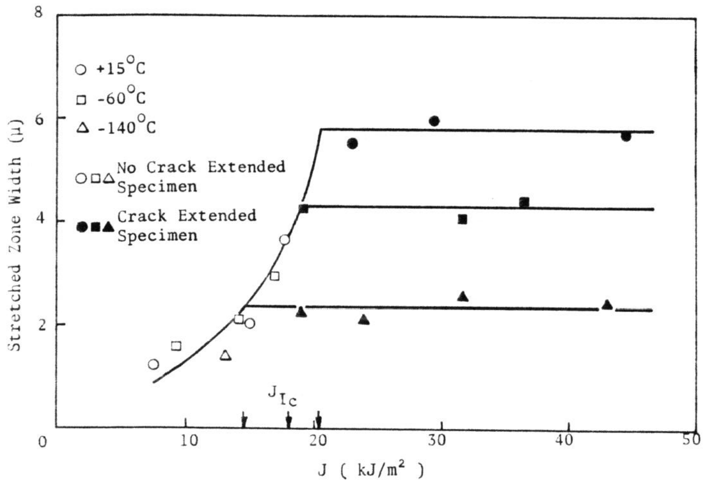


Figure 6 Effect of Test Temperature on J_{Ic}

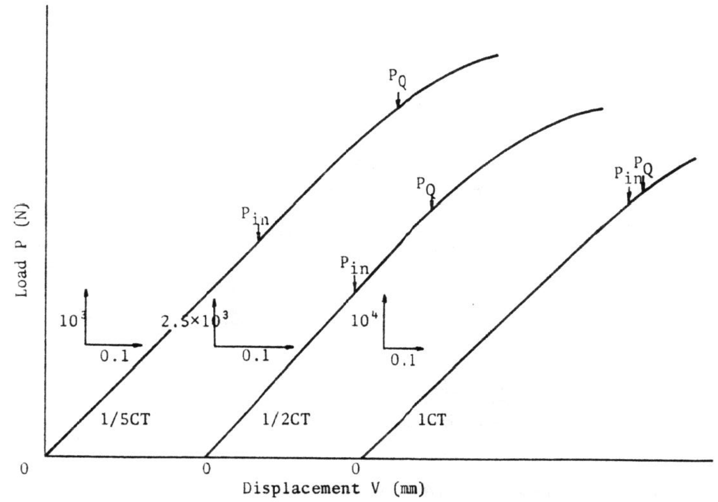


Figure 7 Load versus Displacement Curve

P_{in} : Load at Initiation of Stable Crack Growth
P_Q : Load Determined According to 5% Offset Procedure of ASTM Standard

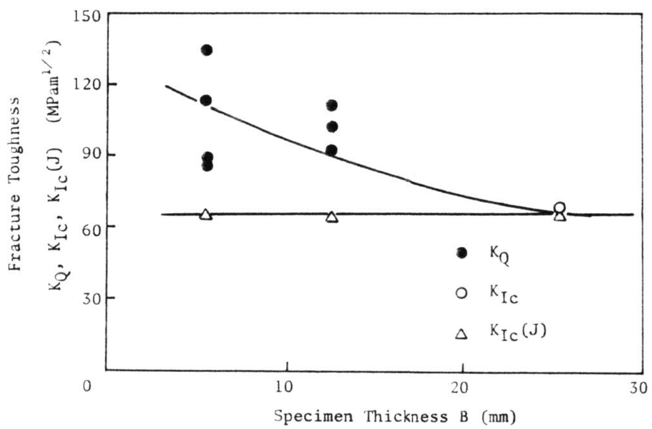


Figure 8 Variation of Fracture Toughness with Specimen Thickness

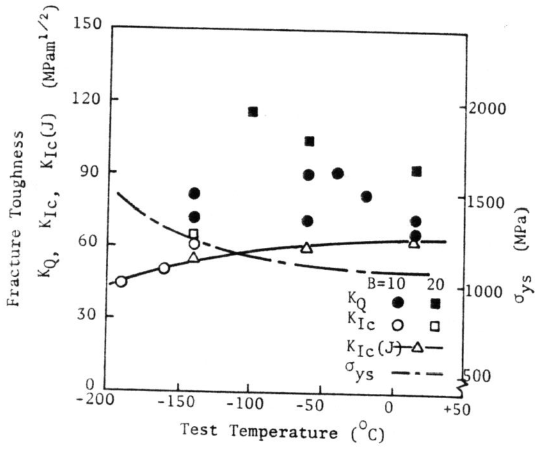


Figure 9 Variation of Fracture Toughness with Test Temperature