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Effect of size and configuration of 3-point bend bar specimens on J–R curves

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Abstract

Elastic–plastic fracture toughness of J_Q values, crack opening displacement (COD) values for crack initiation and J resistance (J–R) curves for crack extension of a 7075-T6 aluminum alloy were measured with 3-point bend bar specimens of different sizes. Width and the thickness of the specimens ranged from 1.25 to 20 mm. The a/W also ranged from 0.125 to 0.5. J_Q and COD values exhibited no appreciable change with specimen size and configuration, while the J range and crack extension increased with ligament size.

1. Introduction

Unlike the pressure vessel of a light water reactor, the first wall of the blanket in a fusion reactor (FWB) is a structure with rather small in thickness (typically less than 5 mm) [1]. It seems likely, therefore, that crack extension during service could be accompanied by through-thickness plastic deformation to an appreciable degree. Therefore, the elastic–plastic fracture toughness may be a more useful indication for evaluating the load bearing capability of an FWB structure than the linear elastic fracture toughness.

Research reactors have been used for irradiation experiments for the development of fusion reactor materials. Because of the high damage rate required for irradiation experiments, the irradiation volume available for fusion reactor materials development tends to be limited. A D–Li stripping reaction neutron source is planned as an irradiation facility for fusion reactor materials development, however the irradiation volume is not expected to be large (500 cc for FWB materials development) [2]. Therefore, it is important to optimize the specimen configuration for elastic–plastic fracture toughness measurement to maximize the utility of the irradiation volume.

2. Experimental procedure

2.1. Material and the specimen

The material used in the present experiment was 7075-T6 high strength aluminum alloy. Levels of yield stress and ultimate tensile strength are 520 and 560 MPa, respectively.

Single notched, 3-point bend bars were used (Fig. 1). The sizes of the specimens are listed in Table 1. The widths W of the specimens were varied in the range from 2.5 to 20 mm. The ligament length (L) ranged between 1.25 and 17.5 mm. The ratio of thickness B and W is changed in a range between 0.125 and 2.

2.2. Test method and measurement

The single specimen method was used to obtain J–R curves from each specimen. The crack lengths during the tests were estimated from the compliance of the specimen.

Vickers impressions were formed on the specimen surface adjacent to the notch, as seen in Fig. 1. The crack opening displacement (COD) at the edge of the notch was measured with a COD gage attached to the Vickers impressions. The compliance was determined from the relation between load (P) and COD at the specimen surface, and the crack length (a) was estimated from the compliance. Displacement at the loading point

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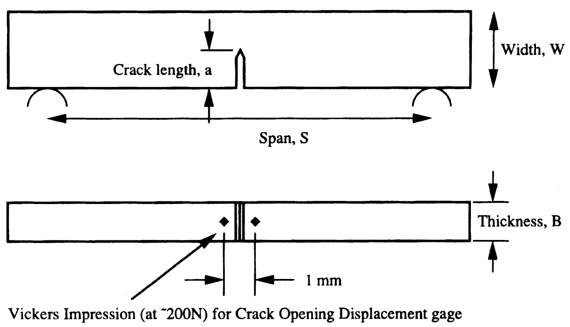

Fig. 1. Location of the Vickers impression for COD gage.

(δ) and P were also recorded to obtain the energy to the specimen. The J–R curve was obtained from the energy to the specimen and the crack length. Except the fatigue precracking, tests and data analysis were carried out referring to the methods described in ASTM-E813 standards [3]. J_Q values from fatigue precracked specimens were slightly smaller by 5–10% than those of the notched only specimens. Because the effect of fatigue precracking was not significant for the present investigation, the notched only specimens were also used for most of the tests.

Table 1
Dimensions and J_Q values of the specimens

Width W	Ligament length $L=(W-a)$	a/W	Thickness B	Span S	J_Q (kJ/m^2)
20	17.5	0.125	2.5	90	78
20	15	0.25	2.5	90	76
20	10	0.5	4.5	90	78
20	10	0.5	2.5	90	76
15	12.5	0.167	5	90	73
15	9.99	0.334	5	90	69
10	7.5	0.25	15	90	79
10	5	0.5	10	90	63
10	8.75	0.125	5	44.5	78
10	7.5	0.25	5	44.5	75
7.5	6.25	0.167	5	44.5	76
7.5	5	0.334	5	44.5	77
5	3.75	0.25	10	44.5	64
5	3.75	0.25	7.5	44.5	71
5	3.75	0.25	5	44.5	79
5	2.5	0.5	10	44.5	65
5	2.5	0.5	7.5	44.5	63
5	2.5	0.5	5	44.5	61
5	4.375	0.125	2.5	19.4	74
5	3.75	0.25	2.5	19.4	82
5	2.5	0.5	2.5	19.4	78
3.75	3.125	0.167	2.5	19.4	82
3.75	2.5	0.334	2.5	19.4	74
2.5	1.875	0.25	5	19.4	71
2.5	1.875	0.25	3.75	19.4	74
2.5	1.875	0.25	2.5	19.4	71
2.5	1.875	0.25	1.75	19.4	74
2.5	1.875	0.25	1.25	19.4	74
2.5	1.25	0.5	5	19.4	63
2.5	1.25	0.5	3.75	19.4	64
2.5	1.25	0.5	2.5	19.4	63

Dimensions are in mm.

3. Results and the discussion

3.1. Load-displacement relation

Two examples of the P–δ relations of the specimens are shown in Fig. 2. The larger specimen ($W=10$, $L=7.5$ and $B=5$) exhibited pop in at the maximum load (see Fig. 2(a)), while the smaller specimen ($W=2.5$, $L=1.875$ and $B=2.5$) did not. The K values for the specimens in Fig. 2(a) and (b) at the maximum load were 50 and 25 MPa m$^{1/2}$, respectively.

Plastic collapse load for plain beam specimens subjected to 3-point bending was also calculated, using widths equal to L for these 3-point bend bar specimens. The calculation was carried out with a flow stress level of 540 MPa, the average value between yield and ultimate tensile stresses. The ratio between the maximum load and the calculated plastic collapse load for the specimen in Fig. 2(a) and (b) was obtained to be 1.2 and 1.6, respectively. This indicates that the ligament deformed plastically to an appreciable level for all the specimens tested, and the degree of the plastic deformation increased with decreasing specimen size.

3.2. Fracture toughness and the crack opening displacement

Examples of the J–R curves are shown in Fig. 3. The crack length was estimated from the compliance of the specimen. The measured values of compliance decreased at the initial stage (for initial several unloading and

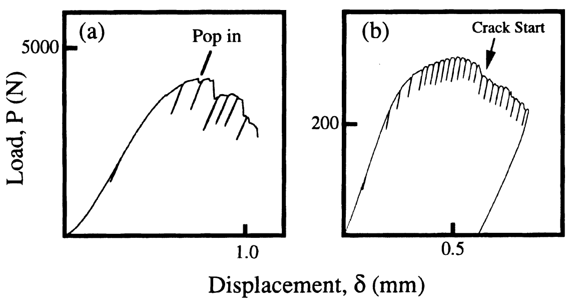

Fig. 2. Load displacement (P–δ) relations of the specimens. The P–δ curves for a larger (a) and a smaller (b) specimens. W, $W-a$ and B for the specimen in (a) are 10, 7.5 and 5 mm, respectively, and those for the specimen in (b) are 5, 3.75 and 2.5 mm, respectively.

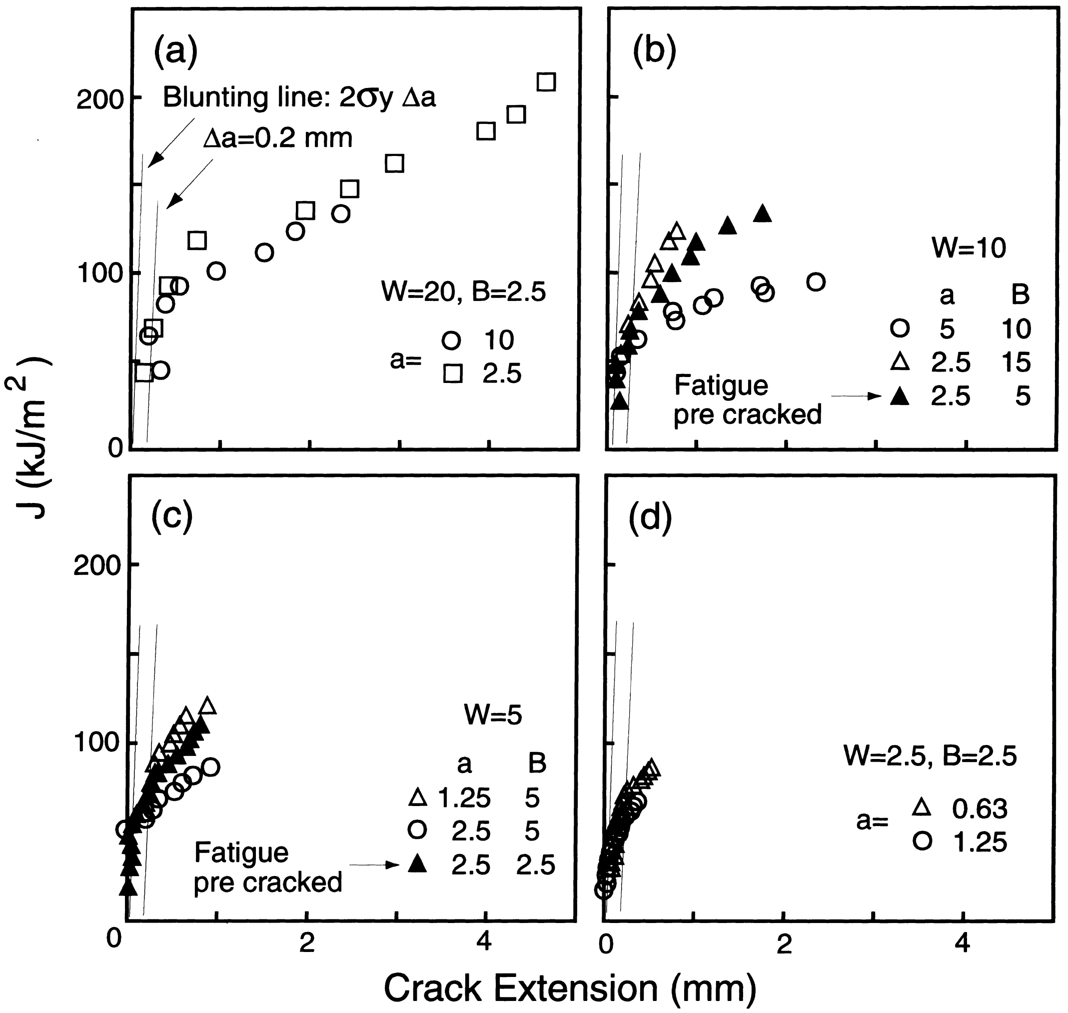

Fig. 3. *J–R* curves for the specimens with different sizes. The *W* for the specimens are: (a) $W = 20$; (b) $W = 10$; (c) $W = 5$; (d) $W = 2.5$ (mm). *W*, *a* and *B* are shown in the figure. The curves for fatigue precracked specimens are also shown in (b) and (c), indicating the effect was not large for the material tested.

reloading cycles) and then increased with δ. The estimated crack length, therefore, decreases at the initial stage, and this was followed by the crack growth with δ.

After the tests, specimens were heat tinted and fractured to measure the initial and final crack length on the fracture surface. The estimated crack length from compliance with Young's modulus of 60 000 MPa correlated well with measured final crack length. The modulus value is, however, smaller than the measured value by 20% (too small for valid results).

The displacement δ to span ratio of the specimen ($= \tan(\delta/S)$) ranged from 0.05 to 0.1. The maximum J value and the final crack growth increased with the ligament length L of the specimen; L for specimens in Fig. 3(a), (b), (c) and (d) are ranging 10–17.5, 5–7.5, 2.5–3.75 and 1.25–1.87, respectively.

As seen in Fig. 3, J_Q values defined by the intersection between the *J–R* curve and the blunting line of $2\sigma_y$ Δa with 0.2 mm off set was not strongly dependent on W, L, B and S.

COD at the original crack tip (CTOD) was estimated from COD at the edge of the notch using Eq. (1).

$$\mathrm{CTOD} = \frac{1/3(W-a)}{a + 1/3(W-a)}\mathrm{COD}. \tag{1}$$

It was assumed in the equation that the rotating center is located at the position distant from the crack tip by one-third of the instantaneous ligament length [4]. The Δa–CTOD relations are shown in Fig. 4 indicating that Δa increased in the range of CTOD larger than 0.1 mm. Most of the CTOD values with 0.2 mm of crack extension ranged from 0.09 to 0.15, and also were not

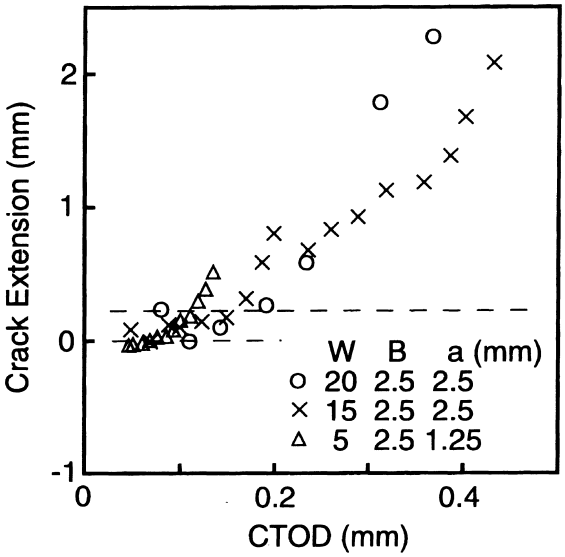

Fig. 4. The Δa–CTOD relations. Crack growth occurred with CTOD ranging 0.1 and 0.2 mm.

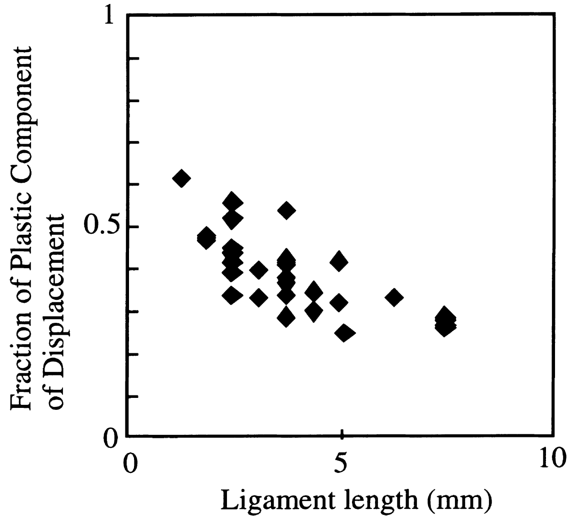

Fig. 6. The fraction of δ_p at the initiation of crack growth as a function of L. The plastic component of δ decreased with L, indicating crack extension force is large for the specimens with large L.

affected by specimen size (see Fig. 5). It has been indicated that CTOD σ_y agrees with J_{IC} [5]. The values with σ_y of 520 MPa ranged between 47 and 74 kJ/m^2, and they are rather close to the J_Q values, ranging 61–82 kJ/m^2 in Fig. 3.

Fatigue precracking was not carried out for most of specimens tested. J–R curves for fatigue precracked specimens are also shown in Fig. 3(b) and (c). The effect of fatigue pre cracking on J–R curve did not seem to be large.

3.3. Effect of the specimen size and configuration

Fig. 5 shows the critical CTOD values as a function of L. The effects of L and B are revealed to be rather small. The smallest B was only 1.25 mm for the specimen with L of 1.875 mm.

On the other hand, δ at 0.2 mm crack extension (δ_c) increased with decreasing L for the specimens with same S. The plastic component of δ (δ_p) increased rapidly with δ after the initiation of plastic deformation. For the

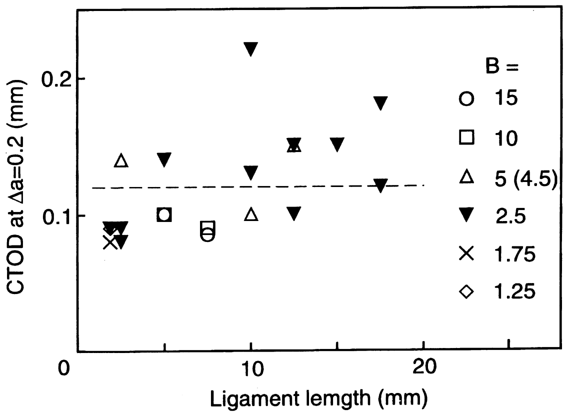

Fig. 5. The critical CTOD at 0.2 mm crack extension as a function of L (same trend for J_Q is obtained). Specimen thickness is chosen to be a parameter. Size dependence of the critical CTOD was small.

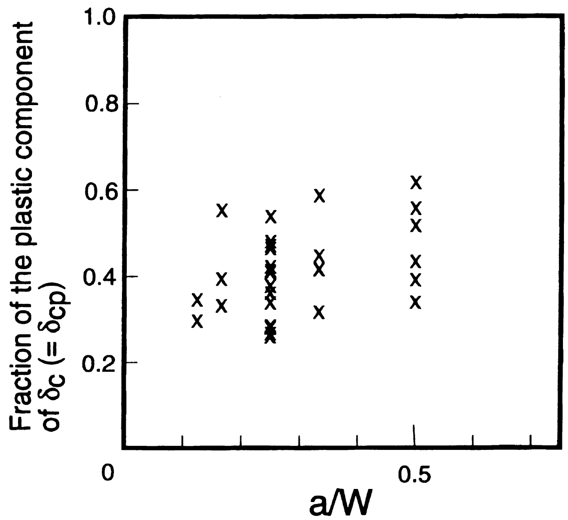

Fig. 7. The fraction of δ_p at the initiation of crack growth as a function of a/W. Effects of a/W was not strong.

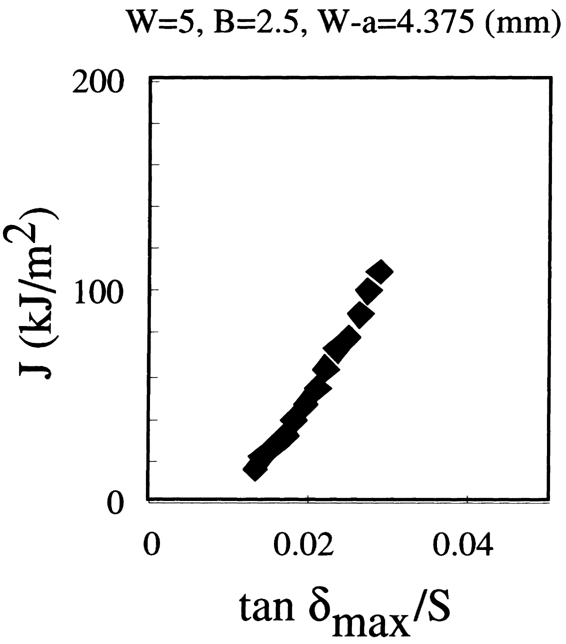

Fig. 8. Relation between J values and the normalized displacement $\tan(\delta/S)$. J increased approximately linearly with $\tan(\delta/S)$.

specimens with large L, δ_c was rather small and the fraction of the plastic component of δ_c (δ_{cp}) was also small, as seen in Fig. 6. This indicates that the maximum J value and the crack extension force are large for such specimens with large L. The value of a/W also affects constraint for deformation at the notch root and is often indicated one of the dominating configuration factor of the specimen. The effect on the fraction of δ_{cp} was not strong, as seen in Fig. 7, although the fraction tended to decrease with a/W ranging 0.16–0.25 only for the specimens with similar L.

The deformation accompanying crack extension should be large for high fracture toughness materials. In practice, the displacement δ for specimen is limited. Therefore, the specimens with capacity to attain higher J value and larger Δa at a fixed $\tan(\delta_{max}/S)$ are suitable for application to high toughness materials.

J values increase approximately linearly with $\tan(\delta/S)$ after crack initiation, as shown in Fig. 8. The gradient of J ($dJ/d\tan(\delta/S)$) also increased linearly with L, as shown in Fig. 9. The results indicate that specimen with longer ligaments are capable of attaining higher J values, and should be suitable for the evaluation of materials with high fracture toughness. The constant $dJ/d\tan(\delta/S)$ during the test suggests that the plastic deformation accompanied with the crack growth is identical.

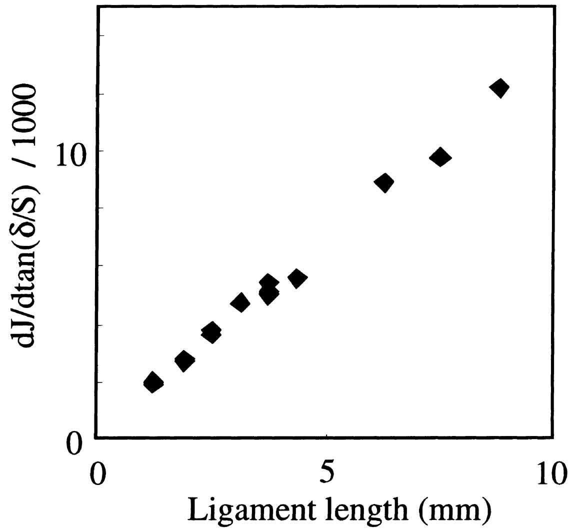

Fig. 9. The ligament length dependence of the gradient of J ($dJ/d\tan\delta$). $dJ/d\tan\delta$ increases linearly with L.

4. Conclusions

1. Effects of width, crack length, ligament length, thickness and span on J_Q and the critical CTOD were rather small for a 7075-T6 aluminum alloy with J_Q values ranging 61–82 kJ/m^2 and specimen sizes ranging 1.25–25 mm.
2. J range and crack growth increased with ligament length.
3. Longer ligaments may be considered for optimizing specimen configuration for elastic–plastic fracture toughness measurement, as far as a/W, B and W are ranging those in the present experiment.

References

[1] Members of the Fusion reactor system laboratory, Concept Study of the Steady State Tokamak Reactor (SSTR), JAERI-M 91-081, Japan Atomic Energy Research Institute, Ibaraki-Ken, Japan.
[2] A. Möslang, C. Antonnucci, E. Daum, J.R. Haines, I. Jitsukawa, K. Noda, S.J. Zinkle, J. Nucl. Mater. 258–263 (1998) 427. Sendai, Japan, 1997.
[3] Standard Test Method for J_{IC}, A Measure of Fracture Toughness, E813-89, Annual Book of ASTM Standards, vol. 03.01, ASTM, 1991.
[4] British Standard Methods for Crack Opening Displacement (COD) Testing, BS5762 (1979).
[5] J.F. Knott, Fundamentals of Fracture Mechanics, Butterworth, London, 1974.