On the Equivalent Thickness of a Side-Grooved Specimen*

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Fracture toughness tests of side-grooved specimens were carried out to investigate the equivalent thickness of a side-grooved specimen. The effects of a side groove on the stretched zone width and stable crack growth were also investigated. From the results, the equivalent thickness for the J_{IC} value was in a range between $B_{e1}(=\sqrt{B \cdot B_N})$ and $B_{e2}(=B - (B - B_N)^2/B)$. Although the thickness B_{e2} can be utilized from the viewpoint of a conservative estimation, it is reasonable to use the thickness B_{e1} which also gives good estimations for the blunting line.

Key Words: Fracture, Fracture Toughness, Side Groove, Equivalent Thickness, Stretched Zone Width, Stable Crack Growth

1. Introduction

In fracture toughness evaluations, adequate thickness of a specimen is required to obtain the effective plain strain fracture toughness. It is known that if a side groove is introduced in a thin specimen, the stress-strain state near the crack tip, which is equivalent to that of a thick standard specimen without a side groove, can be developed. Therefore, the effective plain strain fracture toughness can be obtained by using a thin specimen with a side groove. The introduction of the side groove is a useful method when the size and number of specimens cut from the components are restricted. However, since the equivalent thickness of a side-grooved specimen has not yet been clarified^{(1)~(4)}, the net-section thickness B_N has often been utilized to evaluate the fracture toughness in a side-grooved specimen. Therefore, the equivalent

thickness of the side-grooved specimen must be obtained in order to evaluate J_{IC} accurately.

In the present paper, fracture toughness tests of side-grooved specimens with wide-ranged thicknesses, as well as standard smooth specimens, were carried out using materials with various strengths to investigate the equivalent thickness of a side-grooved specimen. Detailed observations of fracture surfaces were carried out, and the effects of the side groove on the stretched zone width and the stable ductile crack growth were also investigated.

2. Experimental Procedures

The materials used were JIS SM 50 A, JIS HT80 and AISI 4340 steels; the former two steels were used in the as-received condition while the latter was oil-quenched at 1108 K for 30 min and subsequently tempered at 823 K for 1 h. The chemical compositions and mechanical properties of the materials used are shown in Tables 1 and 2, respectively. The specimens were machined from the L - T direction.

The standard and side-grooved specimens, the shapes and dimensions of which are shown in Fig. 1, were prepared as follows: (1) A standard specimen

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was used to evaluate the J_{IC} value according to the JSME standard⁽⁵⁾ (JSME S 001-1981) [Fig. 1(a)]. (2) The side-grooved specimen with a groove depth ratio of 0.25 [$= (B - B_N)/B$; B : the nominal thickness, B_N : the net-section thickness], the groove angle of 45° and the notch root radius of 0.5 mm [Fig. 1(b) and (c)] was used to investigate the effect of the strength level on the equivalent thickness. (3) The HT80 steel side-grooved specimens with the nominal thicknesses of 25.4, 12.7, 6.4 and 4.0 mm [Fig. 1(b) and (c)] were used to investigate the effect of thickness on the equivalent thickness. (4) The specimens with the U-shaped groove [Fig. (b) and (d)] used to investigate the effect of the groove shape on the equivalent thickness. The fatigue precrack was

Table 1 Chemical compositions of the materials used (wt%)

Steel	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V
SM 50 A	0.18	0.04	1.31	0.011	0.038	0.11	0.02	0.11	—	—
HT 80	0.11	0.26	0.91	0.009	0.001	0.22	0.92	0.39	0.25	0.03
4340	0.40	0.27	0.78	0.011	0.003	—	1.65	0.92	0.23	—

Table 2 Mechanical properties of the materials used

Steel	σ_y (MPa)	σ_B (MPa)	σ_T (MPa)	ϵ_T	Elong. (%)
SM 50 A	403	585	494	1.38	39.2
HT 80	790	836	813	1.43	24.3
4340 *	1101	1181	1141	0.81	16.0

* Quenching 835°C/30min, oil quenched
Tempering 550°C/60min, air cooled

Fig. 1 Fracture toughness test specimens

introduced by a servohydraulic fatigue test machine under the condition of a low K_{fmax} which satisfied the JSME standard. The length of the precrack a was set equal to 0.6W, where W was the effective width of CT specimen. The side grooves were machined after fatigue precracking.

The fracture toughness tests were carried out using a Shimadzu Autograph DSS-10T at the crosshead speeds of 1~2 mm/min. Details of the fracture toughness test were outlined according to the JSME standard.

The equation recommended in the JSME standard was used to calculate the J -value. The test variables used to obtain the equivalent thickness of the side-grooved specimen were as follows: B (nominal thickness), B_N (net thickness), $B_{e1} = \sqrt{B \cdot B_N}$ ⁽⁶⁾ and $B_{e2} = [B - (B - B_N)^2/B]$ ⁽⁷⁾. The root-mean-square and arithmetical mean thicknesses between B and B_N may be a variable for the equivalent thickness. However, since these two thicknesses are in the range between B_{e1} and B_{e2} , the thicknesses of B_N , B_{e1} , B_{e2} and B are used in the present study. Since the depth ratio of the side grooves introduced in the present study, $(B - B_N)/B$, was constant and equal to 0.25 for all specimens used, the thicknesses B_N , B_{e1} and B_{e2} were given as follows based on the nominal thickness of B : $B_N = 0.75B$, $B_{e1} = 0.866B$ and $B_{e2} = 0.938B$. Therefore, the relationship among the thicknesses was given as:

$$B_N < B_{e1} < B_{e2} < B.$$

3. Results

3.1 J_{IC} values evaluated by the R -curve method

Figures 2, 3 and 4 show the relationships between the J value and Δa for SM50A, 4340 and HT80 steels, respectively. From these results, the J_{IC} values evaluated using the test variable equivalent thicknesses and the J_{IC} values of side-grooved specimens

Fig. 2 J - Δa curve for SM 50 A steel

Fig. 3 J - Δa curve for 4340 steel

(c) Thickness of 12.7mm, V-shaped groove

(a) Thickness of 25.4mm, V-shaped groove

(d) Thickness of 6.4mm, V-shaped groove

(b) Thickness of 25.4mm, U-shaped groove

(e) Thickness of 4.0mm, V-shaped groove

Fig. 4 J - Δa curves for HT 80 steel

normalized by those of the standard specimens, $J_{IC}-R$ [$= (J_{IC})_{\text{side-groove}} / (J_{IC})_{\text{standard}}$], are listed in Table 3. As can be seen from the Table, the normalized values of $J_{IC}-R$ were in the range 1.08 to 0.97 for the thickness of B_{e1} and 0.99 to 0.90 for the thickness of B_{e2} .

From the results for HT 80 steel side-grooved specimens, as shown in Table 3, the effects of groove shape and nominal thickness on the J_{IC} value were undetected. Since the thickness needed to obtain an effective plain strain fracture toughness according to the JSME standard is wider than 5.4 mm for HT 80 steel, the net thickness of $B_N=4.8$ mm does not satisfy this thickness condition in the case of the side-grooved specimen with the nominal thickness of 6.4 mm. In the case of the side-grooved specimen with the nominal thickness of 4.0 mm, none of the thicknesses from B_N to B satisfy the thickness condition. However, the J_{IC} values obtained using these side-grooved specimens with thin thicknesses were in good agreement with that obtained using the standard specimen with adequate thickness, as shown in Table 3. The thickness condition used to obtain the effective plain strain fracture toughness is given as

$$B \geq 25 J_{IC} / \sigma_f$$

Based on the present results, the constant of 25 may be reduced to less than 18 for side-grooved specimens.

Table 3 Values of J_{IC} , m and dJ/da

Material	Specimen	Equivalent thickness	J_{IC} (kJ/m ²)	$J_{IC}-R$ *	Blunting line m **	$m-R$ **	R-curve dJ/da (kJ/m ²)
SM 50 A	Standard	—	90.3	—	2.38	—	324.7
	Side groove	B_N	101.6	1.13	2.60	1.09	248.9
		B_{e1}	87.6	0.97	2.24	0.94	213.4
		B_{e2}	80.9	0.90	2.07	0.87	196.7
		B	75.6	0.84	1.93	0.81	182.9
4340	Standard	—	60.0	—	1.35	—	135.3
	Side groove	B_N	71.5	1.19	1.48	1.10	88.1
		B_{e1}	62.0	1.03	1.27	0.94	75.4
		B_{e2}	57.2	0.95	1.18	0.87	69.7
		B	53.7	0.90	1.10	0.82	64.8
HT 80	Standard	—	174.4	—	2.32	—	514.8
	Side groove	B_N	216.2	1.24	2.51	1.08	376.7
		B_{e1}	180.5	1.04	2.13	0.92	353.8
		B_{e2}	163.8	0.94	2.02	0.87	333.3
		B	148.3	0.84	1.90	0.82	330.3
	Side groove	B_N	196.5	1.13	2.53	1.09	366.5
		B_{e1}	169.5	0.97	2.18	0.94	315.1
		B_{e2}	156.4	0.90	2.01	0.87	290.9
		B	146.1	0.84	1.88	0.81	271.2
	Side groove	B_N	218.3	1.25	2.73	1.18	450.9
		B_{e1}	188.0	1.08	2.35	1.01	386.1
		B_{e2}	173.5	0.99	2.16	0.93	356.0
		B	161.9	0.93	2.01	0.87	330.8
	Side groove	B_N	201.1	1.15	2.56	1.10	541.6
		B_{e1}	176.3	1.01	2.21	0.95	453.0
		B_{e2}	163.2	0.94	2.04	0.88	416.1
		B	154.4	0.89	1.91	0.82	378.7
	Side groove	B_N	216.6	1.24	2.69	1.16	608.7
		B_{e1}	183.8	1.05	2.30	0.99	522.1
		B_{e2}	169.3	0.97	2.12	0.91	481.3
		B	155.8	0.89	1.97	0.85	448.0

*1 $J_{IC}-R$: $(J_{IC})_{\text{side-groove}} / (J_{IC})_{\text{standard}}$

*2 m : $J / \sigma_f \cdot \Delta a$

*3 $m-R$: $(m)_{\text{side-groove}} / (m)_{\text{standard}}$

3.2 Effect of side groove on stretched zone width

Figure 5 shows the distribution of the critical stretched zone width SZW_c in the thickness direction for HT80 steel specimens. In the figure, the critical stretched zone width is reduced by the mean width obtained according to the JSME standard. From the figure, an almost uniform distribution in the thickness direction was found for the 1TCT specimen with a side groove, the thumbnail-like distribution in which the width is wider in the center and shorter at the side regions, was more significant as the thickness was reduced. However, even in the thin side-grooved specimen with a thickness of 4 mm, the shape of the distribution was almost identical to that for the 1TCT standard specimen without a side groove. Therefore, the side groove can be considered to affect the stretched zone width. The uniform distribution of the stretched zone width prior to the stable crack initiation was observed even for the standard specimen without a side groove, as shown in Fig. 6, as well as for the side-grooved specimen with a thickness of 4 mm.

The values of $m-R$, where the slopes of the blunting lines evaluated using the various equivalent thicknesses are reduced by the slope for the standard specimen. [$= (m)_{\text{side-groove}} / (m)_{\text{standard}}$], are listed in Table 3. It is found from the Table that the blunting line evaluated by the equivalent thickness of B_{e1} is in good agreement with that for the standard specimen.

3.3 Effect of side groove on stable crack growth

Figure 7 shows the distributions of the length of a stable crack in the thickness direction for HT 80 steel specimens. In the figure, the distributions at the point of the longest crack in each specimen shown in Fig. 4 are shown. From the figure, in the 1TCT standard specimen, the thumbnail-shape of the crack front was

Fig. 5 Distribution of the critical stretched zone width

observed. That is, the crack length was long in the center region and short in the side region. On the contrary, in the 1TCT specimen with a side groove, the crack length was long in the side region and short in the center region. However, a reduction in the thickness of the side-grooved specimen produced a change in the shape of the distribution of the crack length; i.e., the shape approached the thumbnail-shape which was found in the standard specimen. The R -curve for the side-grooved specimen with the thickness of 4 mm was almost identical to that of the standard specimen, as shown in Fig. 4(e). This result seems to correspond to the fact that the shapes of the crack front for both specimens are almost identical. It is speculated that the stress-strain states near the tip of the stable crack for both specimens are almost identical. According to Fig. 7, the thickness which realizes uniform crack growth in the thickness direction may be slightly wider than 12.7 mm: If the thickness is wider than this, the effect of the stress concentration due to the side groove is significant, and the stable crack on each side will advance. On the contrary, if the thickness is less than 12.7 mm, the effect of plastic constraint due to the side groove is reduced, and the stable crack in the central region will advance. According to the values of dJ/da shown in Table 3, the slope of the R -curve, where the stable crack grows uniformly in the thickness direction, will be approximately 400 kN/m^2 .

4. Discussion

4.1 The equivalent thickness of a side-grooved specimen

Before publishing the standard for the J_{IC} test method (JSME S001-1981 and ASTM E813-81), a

Fig. 6 Distribution of stretched zone width before and after stable crack initiation for the HT 80 standard specimen

series of round-robin tests were carried out. Based on the results tested in ASTM, the ranges of scattering of J_{IC} values obtained by the R -curve method were $\pm 20\%$ for HY130 steel and $\pm 13.8\%$ for A 533 B steel. Based on the results tested in JSME, the ranges of scattering of J_{IC} values obtained by the fractographic method were $\pm 4.6\%$ for HT80 steel and $\pm 22.5\%$ for HT60 steel. A relatively large amount of scattering of J_{IC} values was found from these results. Here we let the range of scattering of J_{IC} values be $\pm 10\%$, considering that the range of scattering in the tests performed in the same laboratory will be smaller than those in the round-robin tests. As can be seen from Table 3, even in this case, the J_{IC} values evaluated by using the thicknesses of both B_{e1} and B_{e2} were in this range of scattering. Therefore, the equivalent thickness would be in the range from B_{e1} to B_{e2} .

Many fracture toughness tests have been carried out using side-grooved specimens to investigate the effect of a side groove on the J - R curve. In these experiments, the thickness B_N has been often utilized⁽¹⁾⁻⁽⁴⁾. The systematic study on the equivalent thickness to evaluate the J_{IC} value of a side-grooved specimen has only been carried out by Ohji et al.⁽¹⁰⁾ They carried out J_{IC} tests using side-grooved specimens with thicknesses of 24, 16 and 8 mm for two kinds of steels. They concluded that the scattering of the J_{IC} values was too wide to obtain an obvious conclusion about the equivalent thickness. The values of J_{IC} - R calculated from the results of Ohji et al. [Table 3 in Ref.10] were in the range from 0.86 to 1.38 for the thickness of B_{e1} and in the range from 0.80 to 1.26 for the thickness of B_{e2} . Although the ranges of scattering were wider than those in the present study, they were of the same order as those in the ASTM and JSME round-robin tests. Considering the difference between the J_{IC} values evaluated using B_{e1} and B_{e2} was even

Fig. 7 Distribution of length of a stable crack

smaller than the range of scattering of J_{IC} values, the results of Ohji et al. support the above conclusion that the equivalent thickness will be in the range from B_{e1} to B_{e2} .

The relationship between the equivalent thickness and the material properties is qualitatively speculated as follows. Since the plastic deformation is larger for materials with low strength and high ductility, the constraint due to a side groove tends to be relaxed, and consequently the equivalent thickness may be estimated to be thinner. On the other hand, since the relaxation of the constraint due to a side groove is not significant for the materials with low ductility and high strength, the equivalent thickness may be estimated to be thicker. However, in the present results, the obvious tendency corresponding to this speculation could not be found.

The blunting lines evaluated by the thickness of B_{e1} were in good agreement with those for the standard specimen, as seen from Table 3. The authors believe that the thickness of B_{e2} gives the most conservative evaluation for $J_{IC}^{(11)}$. However, considering the consistency between the J_{IC} and the blunting line evaluations, the use of B_{e1} as the equivalent thickness is recommended.

4.2 The J_{IC} -value evaluation by the fractographic method

It is well known that the J_{IC} values evaluated by the fractographic method tend to be higher than those by the R -curve method^{(5),(12)}. The authors⁽¹³⁾ have shown that the higher J_{IC} values obtained by the fractographic method have resulted from the apparent stretched zone width enlarged by the microcrack nucleated in the blunting region and grown with a deformation. It has also shown that J_{IC} values evaluated using the SZW_o , where the enlarged microcrack

region width is subtracted from the SZW_c , are in good agreement with those evaluated by the R -curve method. In the present study, the detailed fractographic observation of HT 80 steel was carried out. Figure 8 shows the J - Δa relationship for the HT 80 steel specimen with the thickness of 6.4 mm, where the J values are calculated by the thickness of B_{e1} . As can be seen from the figure, although the J_{IC} value obtained by the fractographic method using the SZW_c is higher than that by the R -curve method, the J_{IC} value by the fractographic method using the SZW_o is in good agreement with that by the R -curve method. The values of SZW_c , SZW_o and J_{IC} for the specimens tested are shown in Fig. 9. In the figure, the J_{IC} values of the side-grooved specimens were evaluated by the equivalent thickness of B_{e1} . The J_{IC} values based on the SZW_c were barely influenced by the thickness of the specimen and shape of the side groove, and were almost equal to the value of 260 kJ/m². However, J_{IC} values were higher than those evaluated by the R -curve method (174 kJ/m²). On the contrary, the J_{IC} values based on the SZW_o occurred in the narrow range of scattering and were in good agreement with those evaluated by the R -curve method independent of thickness and side-groove shape.

Ohtsuka et al.⁽¹⁴⁾ have reported that the critical stretched zone width changes with the stress state near the crack tip. According to their report, the SZW_c for the U -shaped side-grooved specimen will be narrower than that for the V -shaped side-grooved specimen. From Fig. 9, no significant difference between them was found, i.e., they were almost identical. It is also speculated that the thinner specimen has the lower mechanical constraint and, consequently, the wider SZW_c . From Fig. 9, it is seen that the values

Fig. 8 Determination of J_{IC} value by the fractographic method

Fig. 9 Relationship of the thickness of the specimen, SZW_c and J_{IC} value

of SZW_c were independent of the thickness of the specimen. Therefore, in the range of the present shape of the side groove and thickness of specimen, they seem to influence not the mean value of SZW_c as indicated in the JSME standard, but instead the distribution of the stretched zone width in the thickness direction.

5. Conclusions

Fracture toughness tests of side-grooved specimens for materials with strengths ranging from 500 to 1 200 MPa (JIS SM 50 A, HT 80 and AISI 4340 steels) were carried out to investigate the equivalent thickness of a side-grooved specimen when evaluating the J_{IC} value. Effects of the side groove on a stretched zone width and ductile stable crack growth were also discussed. The results obtained are summarized as follows.

(1) The equivalent thickness used to evaluate the J_{IC} value was in the range between B_{e1} and B_{e2} . Although the thickness B_{e2} can be used from the viewpoint of the conservative evaluation, the thickness of B_{e1} , which also gives a good evaluation for the blunting line, is recommended.

(2) The critical stretched zone width was uniformly distributed in the thickness direction for thick side-grooved specimens; with reducing the thickness, the shape of the distribution changed to the thumb-nail-shape. Even for the side-grooved specimen with the thickness of 4 mm, the shape of the distribution was almost identical to that for the standard specimen with the thickness of 25.4 mm.

(3) The ductile crack length of the side-grooved specimens was longer in the center region of the thickness and shorter in the side region for thinner specimens. However, with increasing thickness, the shape of the distribution of the ductile crack length was changed; the length was short in the center region and long in the side region. The slope of the R-curve, dJ/da , varied according to the change of the shape of the distribution. The uniform distribution of the ductile crack in the thickness direction can be obtained if a suitable combination of the side-groove depth and thickness is realized.

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