Finite Element Analysis Aided Fracture Toughness Evaluation in Tear Test of Aluminum Alloys

T. KOBAYASHI, M. NIINOMI and Y. TAKABAYASHI
Department of Production Systems Engineering, Toyohashi University of Technology, 1–1, Hibarigaoka, Tempaku-cho, Toyohashi 440, Japan

ABSTRACT

An estimation method of fracture toughness parameters from the tear test is studied with a help of the finite element analysis. J_C values evaluated from the tear test show a tendency to become constant in the notch depth range of a/W ≧ 0.3 for every notch root radius (ρ) and material. The correction factor C to estimate J_{IC} in CT specimen ($J_{IC(CT)}$) from the tear test specimen with the ratio of a/W=0.3 and ρ ≦ 0.05mm is derived. It is also shown that crack extension resistance, i.e., tearing modulus T_{mat}, from the tear test coincides directly with one from the test of CT specimen.

KEYWORDS

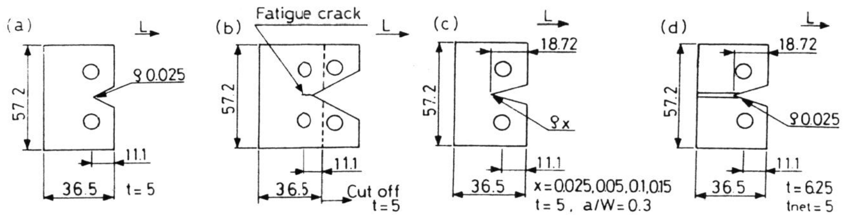
Finite element analysis; fracture toughness; J integral; tearing modulus; tear test; aluminum alloys; correction factor.

INTRODUCTION

Tear test method has been widely utilized as a simple toughness evaluation one of the thin plates of aluminum alloys. This method is very effective for the development of new alloys. However, fracture characteristic values obtained from this method can not be directly applicable as the fracture toughness value obtained from the fracture toughness tests using the specimens such as CT ones or three-point bending ones (Knoll et al., 1964; Kaufman et al., 1965; Kobayashi, 1982). Therefore, a relationship between fracture characteristic value obtained from the tear test and fracture toughness value obtained from the fracture toughness test has been investigated and a good correlation has been recognized between them in the previous paper (Kobayashi et al., 1988). However, it is considered to be more important to evaluate the fracture toughness values directly from the tear test. Therefore, a direct evaluation method of fracture toughness values i.e. liner elastic fracture toughness value K_{IC} or elastic-plastic fracture toughness value J_{IC} from the tear test was investigated with the help of the finite element analysis (FEA).

EXPERIMENTAL

The materials used in this study were five types aluminum alloys of 2017-T4 (as received), doubly T4 treated 2017-T4', 5083-O, 7022-T651 and 7022-T6. The specimens shown in Fig.1 were machined from these alloys. The toughness evaluation test was carried out using an Instron type testing machine at a cross head speed of 8.3×10^{-6} m/sec. Displacement was measured using a clip gage at the front surface of specimens, and then converted to the load-line displacement (Rao et al., 1986). Detection of the crack initiation point and measurement of the crack extension length were carried out using the DC electrical potential method (EPM) (Schwalbe et al., 1981). In addition, the fracture toughness parameters using standard CT specimens were measured according to the methods of ASTM E399 and E813.



(a) Standard tear test specimen, (b) Precracked tear test specimen, (c) Deep notched tear test specimen, (d) Deep notched tear test specimen with U-type side grooves (a/W=0.3)

Fig.1. Specimen geometries.

In standard and precracked tear test specimens, the numbers of nodes and elements for the FEA are 549 and 229, respectively. In deep notched tear test specimens, the numbers of nodes and elements are 603 and 251, respectively. In CT specimens, the numbers of nodes and elements are 339 and 129, respectively. In the FEA, the plane-strain condition and strain incremental theory were adopted, and the crack was assumed to initiate when the plastic strain of the element near the crack or notch tip reached the fracture strain ε_f^* under plane-strain condition, where

$$\varepsilon_f^* = 1/3\ \varepsilon_f\ , \qquad (1)$$

ε_f: uniaxial tensile fracture strain.

On the other hand, the path independent integral was applied for evaluating J integral in tear test with the help of the FEA in this study. The calculation of the path independent J integral was carried out using the equation proposed by Rice (1986).

RESULTS AND DISCUSSION

Fracture toughness values obtained from CT specimens

The plane-strain fracture toughness value K_{IC} (or K_Q), elastic-plastic fracture toughness value J_{IC} and crack extension resistance toughness value Tmat obtained from CT specimens in each material were shown in Table 1. The following J_{IC} and T_{mat} values obtained from CT specimens were expressed as $J_{IC(CT)}$ and $T_{mat(CT)}$ values, respectively.

Table 1. Fracture toughness parameters obtained from CT specimens.

Material	$K_{IC(CT)}$ (MPa$\sqrt{m}$)	$J_{IC(CT)}$ (kN/m)	T_{mat}
2017-T4	31.8*	20.6	14.0
2017-T4'	44.5*	27.0	19.0
5083-O	30.8*	30.7	75.2
7022-T651	18.1	6.4	1.5
7022-T6	29.2	11.8	4.8

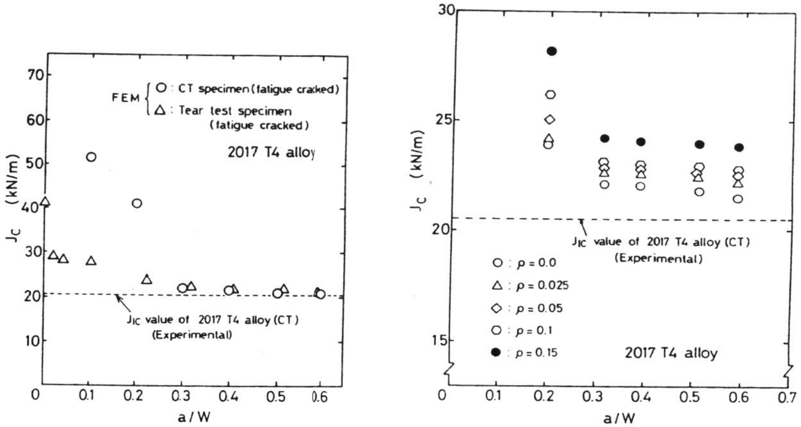
*: K_Q

Variation of J integral values with a/W ratio

The variation of J_C values with a/W ratio in CT and precracked tear test specimens of 2017-T4 alloys examined by the FEA is shown in Fig.2(a). J_C values calculated by the FEA in the precracked tear test and CT specimens are in agreement with the experimental $J_{IC(CT)}$ values in the range of a/W $\geq$ 0.3. A similar tendency was recognized in other alloys. A dotted horizontal line in the figure indicates the experimental fracture toughness value $J_{IC(CT)}$ evaluated from the fracture toughness test using CT specimens of 2017-T4 alloys. A dotted line in the following each figure also indicates a level of the experimental $J_{IC(CT)}$ value in each alloy.

Kobayashi et al. (1988, 1981) have reported that the notch root radii affect the fracture characteristic values obtained from tear test specimens. Therefore, the variation of J_C values with the change in ρ from 0.0 to 0.15mm (see Fig.1(c)), was investigated by the FEA in this study. A variation of J_C values with ρ in 2017-T4 alloys is shown against a/W ratio in Fig.2(b). As shown in Fig.2(b), there is tendency that J_C values are nearly constant with every notch root radius in the range of a/W $\geq$ 0.3 although the absolute values have a small difference among notch root radii. The similar tendency was recognized in other alloys. This tendency is similar to that recognized in CT specimens. Therefore, it is considered to be possible to evaluate the fracture toughness value directly from the tear test by finding a correlation between the calculated convergence value of J_C and the experimental fracture toughness value $J_{IC(CT)}$.

Correction of J_C values obtained from deep notched tear test



(a) Comparison with CT and tear test specimens.

(b) Effect of notch root radius ρ.

Fig.2 Predicted variation of J_C values with a/W in tear test specimens of 2017-T4 alloys by FEA.

A direct evaluation method of the fracture toughness value $J_{IC(CT)}$ from the tear test was investigated by finding a correlation between J_C and $J_{IC(CT)}$ values at each notch radius ρ for the deep notched tear test specimen of a/W=0.3 shown in Fig.2(b). The correction factors were determined according to the following method for the specimens with different root radii for evaluating the fracture toughness value $J_{IC(CT)}$ from these J_C values. The relationship between J_C values calculated for a/W=0.3 type deep notched tear test specimens by the FEA and $J_{IC(CT)}$ values obtained from CT specimens are assumed to be expressed by the following equation:

$$J_{IC(CT)} = CJ_C \quad , \tag{2}$$

where C is correction factor. The C value of each notch root radius in each alloy is determined by substituting $J_{IC(CT)}$ and J_C values into Eq.(2). Assuming that the correction factor C is dependent on the nondimensional flow stress σ_{flow}/E and work hardening exponent n as expressed by Eq.(3):

$$C = \alpha(\sigma_{flow}/E)^{\beta}\, n^{\gamma} \quad , \tag{3}$$

where σ_{flow} is flow stress $(=(\sigma_{0.2}+\sigma_B)/2)$, $\sigma_{0.2}$ is 0.2% proof stress, σ_B is tensile strength, E is Young's modulus, n is work hardening exponent, and α , β and γ are constants. Eq.(3) is expressed in a logarithmic term into series for determining α , β and γ values as followings:

$$\log C = \log \alpha + \beta \log(\sigma_{flow}/E) + \gamma \log n \quad , \tag{4}$$

$$\beta x + \gamma y - z + \log \alpha = 0 \quad , \tag{5}$$

where

$$x = \log(\sigma_{flow}/E) \; , \quad y = \log n \; , \quad z = \log C \; . \tag{6}$$

Eq.(5) is equivalent to a plane equation in solid geometry. Then, x,y and z values obtained from each material are plotted in the space coordinates (x,y,z). The plane equation approximated by these points is determined. Eventually, α , β and γ values which are common in each alloy are determined. α , β and γ values are determined for each notch root radius of ρ = 0.0∿0.15mm using the aforementioned process. α , β and γ values determined using the aforementioned process are shown in Table 2.

Table 2. Values of correction factor C calculated on each notch root radius.

ρ	0.0	0.025	0.05	0.1	0.15
α	1.82	3.05	2.44	3.04	4.29
β	0.052	0.107	0.08	0.166	0.222
γ	0.16	0.265	0.25	0.27	0.18

Effect of correction factor in deep notched tear test specimens

Tear tests were carried out using a/W=0.3 type deep notched tear test specimens with changing the notch root radius ρ from 0.0 to 0.15mm on 2017-T4, 5083-O and 7022-T651 alloys for ascertaining the effectiveness of the correction factor determined in the previous section. Then, J_C value was calculated by the following Rice's equation (7) (Rice et al., 1973) using the area under the load-displacement curve obtained from test up to the crack initiation point detected by the EPM.

$$J_C = 2E_i/Bb \quad , \tag{7}$$

Table 3. Fracture toughness values obtained from deep notched tear test specimens (a/W=0.3).

	ρ (mm)	0.0	0.025	0.05	0.1	0.15
2071-T4	J_C (kN/m)	22.27	23.11	24.21	25.64	26.67
	J_C' (kN/m)	20.75	20.86	20.9	21.7	23.19
	$\Delta J_C/J_{IC(CT)}$(%)*	1.03	1.26	1.46	5.34	12.6
5083-O	J_C (kN/m)	33.0	34.0	35.4	39.2	43.96
	J_C' (kN/m)	31.0	31.0	31.0	33.2	35.1
	$\Delta J_C/J_{IC(CT)}$(%)*	0.98	0.98	0.98	8.14	14.4
7022-T651	J_C (kN/m)	7.18	7.54	7.92	8.83	9.35
	J_C' (kN/m)	6.43	6.43	6.43	7.08	8.17
	$\Delta J_C/J_{IC(CT)}$(%)*	0.47	0.47	0.47	10.6	27.7

*: $\Delta J_C/J_{IC(CT)} \times 100 = (J_C'-J_{IC(CT)})/J_{IC(CT)} \times 100$

where E_i is crack initiation energy, B is specimen thickness, b is ligament length (= W-a), W is specimen width and a is notch length. J_C' value for each material and notch root radius, which is determined by modifying J_C value with substituting C value determined using α , β and γ values shown in Table 2 into the following equation, is shown in Table 3.

$$J_C' = CJ_C \quad , \qquad (8)$$

where C is correction factor. The error ΔJ_C between modified J_C' values and $J_{IC(CT)}$ values were calculated. The calculated error for each ρ are shown in Table 3 on 2017-T4, 5083-O and 7022-T651 alloys. Every error value is within about 2% in the range of $\rho \leqq 0.05$mm as shown in Table 3. This fact indicates that modified J_C' values coincided relatively well with $J_{IC(CT)}$ values. Therefore, it is considered to be convenient to adopt a notch root radius in the range of $\rho \leqq 0.05$mm for evaluating the accurate fracture toughness value. That is, it is found that the usual notch root radius of ρ = 0.025mm is sufficient.

Proposition of a/W=0.3 type deep notched tear test method

Getting the above-mentioned results together, the a/W=0.3 type deep notched tear test method is newly proposed below (see Fig.3). Standard tear test size specimen with a notch of root radius ρ = 0.025mm and a/W=0.3 is adopted. Displacement measured at the surface front of specimens using a clip gage is converted to that of the load-line. The J_C value is calculated by putting the area under the load-deflection curve up to the crack initiation point into the Rice's simple Eq.(7). Then, the $J_{IC(CT)}$ value is calculated by multiplying the J_C value by the correction factor C which is determined using material constants obtained from tensile tests. It is possible to use the simple compliance changing rate method (Kobayashi *et al.*, 1986) to detect the crack initiation point instead of the DC EPM, in which a relatively complex form of equipment is used, except for 5083-O alloy.

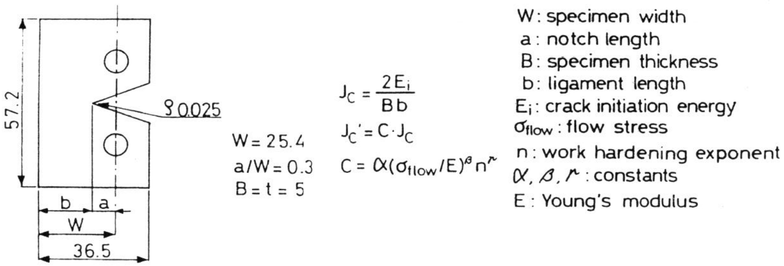


Fig.3 Recommended estimation method of fracture toughness using tear test method.

Evaluation of tearing modulus (T_{mat}) in tear test

It was investigated to evaluate T_{mat} in the a/W=0.3 type deep notched tear test specimen without side grooves from the gradient of the R curve within the crack extension Δa=1mm, which was calculated using the J integral equation for CT specimens. In this case, the crack extension was measured by the EPM. Relationship between $T_{mat(tear)}$ obtained from tear test specimens and $T_{mat(CT)}$ obtained from CT specimens is shown in Fig.4. $T_{mat(tear)}$ and $T_{mat(CT)}$ are in agreement with each other. In this case, the effect of the notch root radius is considerably small. Therefore, it can be said that it is possible to evaluate $T_{mat(CT)}$ directly from $T_{mat(tear)}$ in the range of $\rho \leqq 0.05$mm which is favorable for the evaluation of J_{IC} value.

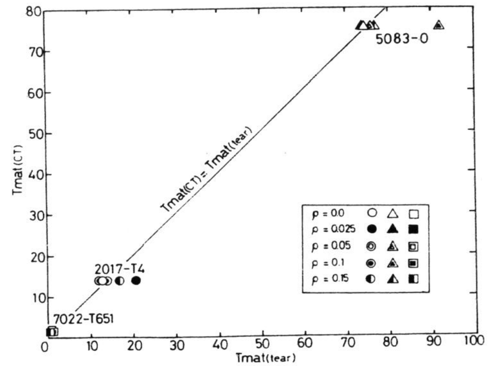


Fig.4 Comparison between $T_{mat(CT)}$ and $T_{mat(tear)}$ (a/W=0.3)

Evaluation of fracture toughness value using deep notched tear test specimen with side grooves

The tear test was carried out using side grooved deep notched tear test specimens of 2017-T4, 5083-O and 7022-T651 alloys. Then, J_C values were calculated by substituting the net specimen thickness B_{net} into B in the Eq.(7). These values are shown in Table 4. The crack initiation point detected by the DC EPM was well agreed with the maximum load point in every material. J_C' value modified using the correction factor C is in good agreement with $J_{IC(CT)}$ value within about 2% in each material as shown in Table 4. Therefore, it is found that the crack initiation point is simply estimated by adding the side grooves to the a/W=0.3 type deep notched tear test specimen, and it is possible to evaluate $J_{IC(CT)}$ value accurately adopting the correction factor C.

Table 4. Comparison of fracture toughness values obtained from side grooved tear test specimens (a/W=0.3) and CT specimen.

	2017-T4	5083-0	7022-T651
J_C (kN/m)	22.9	34.34	7.57
J_C' (kN/m)	20.7	31.2	6.45
$\Delta J_C/J_{IC(CT)}$(%)*	0.49	1.63	0.78

*: $\Delta J_C/J_{IC(CT)} \times 100 = (J_C' - J_{IC(CT)})/J_{IC(CT)} \times 100$

CONCLUSIONS

(1) The variation of J_C values of the tear test with the change in the notch root radius and a/W ratio was investigated using the FEA, and it was recognized that the J_C value had a tendency to be constant in the range of $a/W \geqq 0.3$ for every notch root radius and material.
(2) The correction factor C for the direct evaluation of $J_{IC(CT)}$ value obtained from CT specimen from the tear test was determined from the correction between the convergent value of J_C and the fracture toughness value $J_{IC(CT)}$. The $J_{IC(CT)}$ value was evaluated accurately in the range of $\rho \leqq 0.05$mm by multiplying the J_{IC} value which was calculated by the Rice's simple J integral equation in the tear test using a/W=0.3 type deep notched tear test specimens by the correction factor C.
(3) $T_{mat(tear)}$ obtained from the a/W=0.3 type deep notched tear test specimen was in agreement with $T_{mat(CT)}$ obtained from the CT specimen.
(4) It was confirmed that the fracture toughness value $J_{IC(CT)}$ could be evaluated more simply from the tear test using the a/W=0.3 type deep notched tear test specimen with side grooves without using the DC EPM, because the crack initiation point is in agreement with the maximum load point by adding the side grooves.

REFERENCES

Kaufman, J.G. and H.Y. Hunsicker (1965). ASTM STP 381, 290.
Knoll, A.H. and J.G. Kaufman (1964). Materials Research and Standards, 4, 151.
Kobayashi, T., E. Kato, N. Shimizu and Y. Ueda (1981). Aluminum, 57, 118.
Kobayashi, T. (1982). J. Japan Inst. Light Met., 32, 539.
Kobayashi, T., M. Niinomi and K. Ikeda (1988). J. Japan Inst. Light Met., 38, 9.
Rao, B.N. and A.R. Acharya (1986). Eng. Frac. Mech., 32, 539.
Rice, J.R., P.C. Paris and J.G. Merkle (1973). ASTM STP 536, 231.
Rice, J.R. (1968). Trans. ASME, Ser E, 35, 231.
Schwalbe, K.H. and D. Hellman (1981). J. of Testing and Evaluation, 9, 218.