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Rapid Determination of the Fracture Toughness of Metallic Materials Using Circumferentially Notched Bars

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Three types of material whose fracture toughness tests were previously performed by using circumferentially notched bars, namely (1) a dual-phase steel with three different morphologies; (2) an Al-Zn-Mg-Cu-wrought alloy; and (3) Al-Si-cast alloys with three different Si contents, were investigated in terms of accuracy and reliability of the testing method. Also, the advantages of using circumferentially notched bars for fracture toughness determination of metallic materials were discussed. With the help of stress concentration factors, which are associated with the bluntness of the notch, correction factors for the fracture toughness calculations are derived. The corrected fracture toughness values are found to be close to the uncorrected ones, implying that the testing procedure is reliable.

Keywords Al-Si-cast alloys, Al-Zn-Mg-Cu-wrought alloy, dual-phase steel, fracture toughness

1. Introduction

There are a number of fracture-toughness measurement techniques of metallic materials, which are standardized by different institutions. For example, a standard test method for plane-strain fracture toughness (K_{IC}) of metallic materials is given by the American Society for Testing and Materials (ASTM) (designation E399),[1] and the crack opening displacement fracture toughness measurement method is standardized both by the British Standards Institution (BSI) (BS 5762)[2] using bend specimens, and by ASTM (E1290)[3] using either a three-point bend or compact tension specimens. The ASTM Standard Test Method is argued to be one of the most accurate ways to measure K_{IC} of low-ductility, high-strength alloys.[4] These methods, however, are difficult and exhausting to perform, and the specimen preparation procedure is tedious. Particularly, the fatigue precracking must be done with utmost care, and if the precrack is not appropriate, the whole fracture toughness test is invalid. Ule et al.[5] argue that the measured fracture toughness was affected by the eccentricity of the fatigued area. They measured the eccentricity of the fatigue precracked region and found an underestimation of fracture toughness with increasing eccentricity.

A rapid and at the same time reliable technique has always been sought, and the most familiar and easy to machine specimen type, that is, a cylindrical specimen with a circumferential notch, has attracted much attention for this purpose.[4,6-9] Notched round specimens have been widely used for the determination of mechanical properties of materials.[10-14] The advantages of using circumferentially notched bars for fracture toughness testing can be summarized as follows:

- The plane strain condition can be obtained because the circumferential crack has no end in the plane stress region compared with the standard specimen geometries[9];
- Because of the radial symmetry of heat transfer, the microstructure of the material along the circumferential area is completely uniform[5];
- The specimens are easy to machine;
- The fracture toughness test is easy to perform.

It has been argued that a circumferentially notched cylindrical specimen without a fatigue precrack can be readily used for a rapid determination of the fracture toughness of a metallic material. In the previous studies,[6-8] fracture toughness of three metallic materials were measured by using circumferentially notched cylindrical specimens and in this investigation, the validity and the accuracy of the technique is discussed.

2. Experimental Materials and Methods

The materials inspected in this study are of three different types whose mechanical properties were determined previously.[6-8] The compositions and the heat-treatment procedures of the alloys are as follows:

- A low-carbon steel[6] with 0.097% C, 0.49% Mn, and very low Si, S, and P contents. This alloy was heat treated to obtain three different dual-phase steels with different microstructures and named as MSA, MSB, and MSC;
- An Al-Zn-Mg-Cu-wrought alloy[7] having a composition of 5.68% Zn, 2.56% Mg, and 1.72% Cu with a relatively low impurity level. The alloy was examined under peak-aged condition;
- Al-Si casting alloys,[8] which were cast in metal molds in the University Laboratories. The Si content of the alloy A5 is 5%, A8 is 8%, and A11 is 11% by weight. Other elements are approximately the same in all the alloys as follows: 1.1% Cu, 0.9% Mg, 0.9% Ni, 0.5% Fe, 0.2% Zn. All the compositions were examined in (1) as-cast condition

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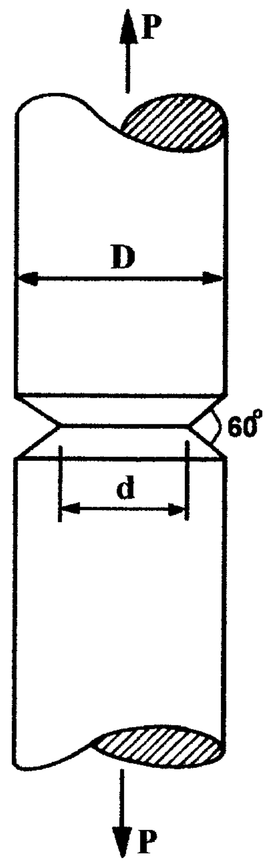

Fig. 1 The geometry of the specimen used for the fracture toughness determination of the alloys

and, spheroidized at 520 °C for (2) 8 h, (3) 24 h, and (4) Na-modified conditions.

After determining the mechanical properties of the alloys by tensile testing, cylindrical specimens having circumferential notches with 1 mm depth and 60° angles (Fig. 1) were used to measure the notch tensile strength of the alloys. The notch root radii of the specimens were measured on a Conturoscop C4P measuring unit (Mahr, Germany). A measuring probe moves along the specimen where the measurement to be performed. With the change in the profile, the probe moves up and down and alters the current back in the unit. A computer is attached to the system to draw the topographic map of the measured specimen. The measured profile of a sample with a 60° notch and approximately 1 mm depth is shown in Fig. 2. An average value of 0.095 mm was measured as the radius of curvature of the notch tips with 60° angles. This average value was used in all the calculations.

The tension tests were performed on a universal testing machine. Four specimens were prepared and tested for each material and condition.

3. Results and Discussion

3.1 Mechanical Properties

In Table 1, unnotched tensile properties, notched tensile strength values, and notch strength ratios (NSRs) are given

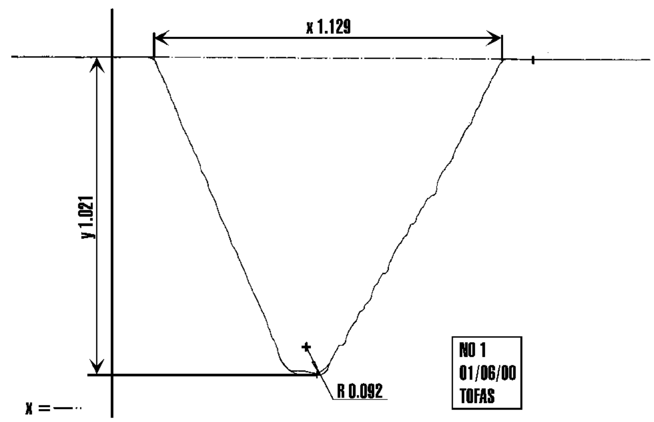

Fig. 2 The measured profile of a sample with a 60° notch

Table 1 Fracture Toughness and Notch Strength Data of the Material for Different Notch Depths

Material	σ_{YS}, MPa	σ_{UTS}, MPa	*D*, mm	*d*, mm	σ_{NTS}, MPa	NSR
MSA-1	545	865	10	8	829.4	0.96
MSA-2				6	1064.7	1.23
MSB-1	445	729	10	8	874.9	1.20
MSB-2				6	1192.7	1.64
MSC-1	401	703	10	8	797.7	1.13
MSC-2				6	1038.7	1.48
7075-1	520	594	7	5	741	1.25
7075-2				3	845	1.42
A5-AC	NA	184.4	10	8	185.2	1.00
A5-8	NA	212.5	10	8	219.9	1.03
A5-24	NA	228.7	10	8	240.2	1.05
A5-Na	NA	180.6	10	8	319.0	1.77
A8-AC	NA	229.0	10	8	185.3	0.81
A8-8	NA	230.7	10	8	262.5	1.14
A8-24	NA	241.8	10	8	246.0	1.02
A8-Na	NA	257.8	10	8	314.4	1.22
A11-AC	NA	238.8	10	8	190.3	0.80
A11-8	NA	266.1	10	8	242.4	0.91
A11-24	NA	266.6	10	8	272.2	1.02
A11-Na	NA	268.5	10	8	326.8	1.22

together with the specimen diameters (*D*) and the diameter of the notched sections (*d*) for each alloy. Unfortunately, the yield strength values of the Al-Si-cast alloys were impossible to measure accurately because of the brittleness of the materials. It can be seen from Table 1 that the dual-phase steel is a high-strength, Al-Zn-Mg-Cu alloy is a medium-strength, and the Al-Si cast alloy is a low-strength alloy.

3.2 Fractography

The fractured specimen surfaces of the alloys are given in Fig. 3. Dual-phase steels exhibit mostly ductile fracture, except the MSC alloy, which reveals mostly cleavage (brittle) cracking of the ferrite grains (Fig. 3a). The aluminum (Al) alloy is a ductile material, which is evident from the fracture surface (Fig. 3b). In the Al-Si-cast alloys, the crack followed the brittle phase, namely silicon (Si), and displayed a brittle fracture appearance (Fig. 3c).

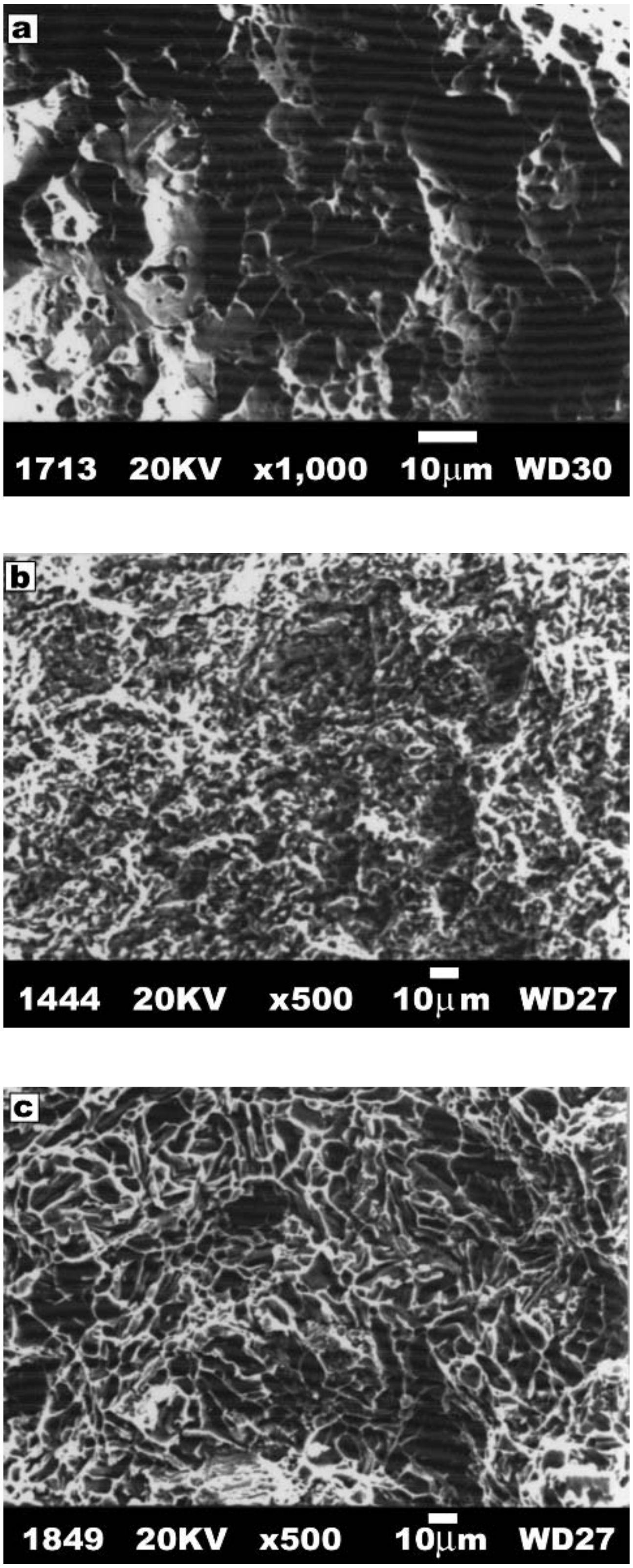

Fig. 3 Scanning electron microscopy (SEM) micrographs of the fracture surfaces of the alloys. **a)** MSC dual phase steel showing mostly cleavage cracking. **b)** Al-Zn-Mg-Cu alloy whose fracture is predominantly by microvoid coalescence. **c)** Al-%11 Si alloy spheroidized for 24 h where the fracture is through the Si second phase

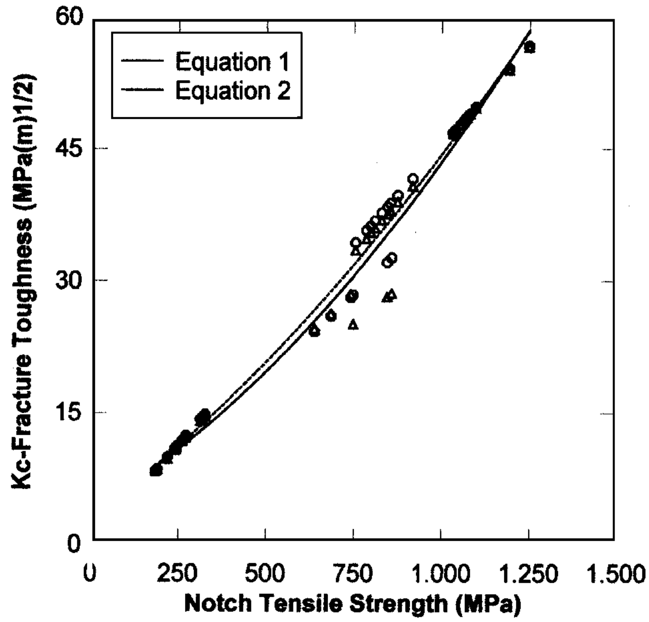

Fig. 4 The relationship between the notch tensile strength and the fracture toughness values of the alloys calculated by using both Eq 1 and 2. Distinct regions on the graph represent different groups of materials

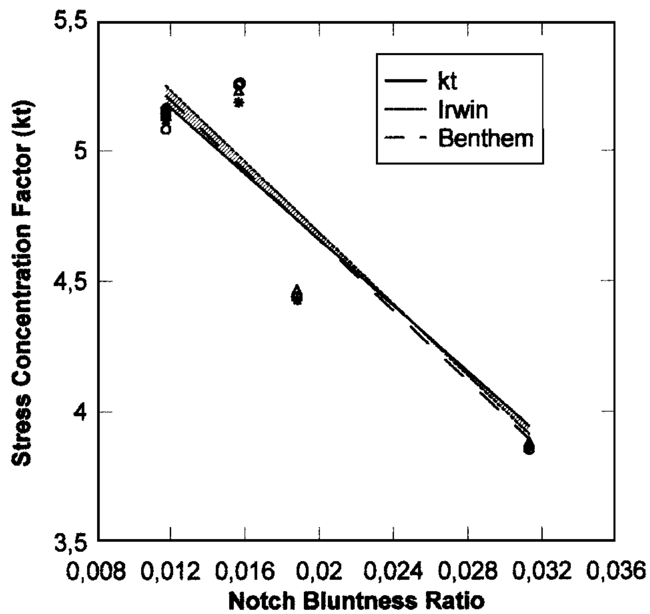

Fig. 5 The relationship between notch bluntness ratio (ρ/d) and k_t

3.3 NSR

The macroscopic yield strength of notched specimens of ductile materials is usually higher than that of unnotched specimens because of the constraint of plastic flow. NSR is argued to be a comparative index of plane strain fracture toughness and is given as the ratio of the sharp notch tensile strength to the yield strength.[15] However, according to Dieter,[16] NSR = σ_{NS}/σ_{UTS}, and this latter equation is used to calculate the notch

Table 2 Stress Concentration Factors, Fracture Toughness, Correction Factors, and the Corrected Fracture Toughness Values

Material	ρ/d	k_t	k_{t1} (Eq 5)	C_1	k_{t2} (Eq 6)	C_2	K_c (MPa$\sqrt{m}$) Eq 1	K_c (MPa$\sqrt{m}$) Eq 2	±% between Eq 1 and Eq 2	K_c Corrected by C_1 (MPa$\sqrt{m}$) Eq 1	K_c Corrected by C_1 (MPa$\sqrt{m}$) Eq 2	K_c Corrected by C_2 (MPa$\sqrt{m}$) Eq 1	K_c Corrected by C_2 (MPa$\sqrt{m}$) Eq 2
MSA-1	0.01175	5.15	5.15	1	5.116	0.993	36.7 ± 0.3	37.7	2.7	36.7	37.7	36.4	37.4
MSA-2	0.01567	5.258	5.224	0.994	5.184	0.986	48.1 ± 0.9	48.3	0.4	47.8	48.0	47.4	47.6
MSB-1	0.01175	5.161	5.15	0.998	5.116	0.991	38.8 ± 1.7	39.7	2.3	38.7	39.6	38.5	39.3
MSB-2	0.01567	5.25	5.224	0.995	5.184	0.987	53.8 ± 4.0	54.1	0.6	53.5	53.8	53.1	53.4
MSC-1	0.01175	5.15	5.15	1	5.116	0.993	35.3 ± 0.4	36.2	2.5	35.3	36.2	35.1	35.9
MSC-2	0.01567	5.255	5.224	0.994	5.184	0.986	46.9 ± 3.2	47.2	0.6	46.6	46.9	46.2	46.5
7075-1	0.0188	4.44	4.463	1.005	4.428	0.997	28.3 ± 2.2	28.1	0.7	28.4	28.2	28.2	28.0
7075-2	0.0313	3.856	3.878	1.006	3.865	1.002	28.0 ± 0.5	32.1	14.6	28.2	32.3	28.1	32.2
A5-AC	0.01175	5.153	5.15	0.999	5.116	0.993	8.2 ± 1.2	8.4	2.4	8.2	8.4	8.1	8.3
A5-8	0.01175	5.081	5.15	1.014	5.116	1.007	9.6 ± 0.2	10.0	4.2	9.7	10.1	9.7	10.1
A5-24	0.01175	5.136	5.15	1.003	5.116	0.996	10.6 ± 0.6	10.9	2.8	10.6	10.9	10.6	10.9
A5-Na	0.01175	5.144	5.15	1.001	5.116	0.995	14.1 ± 0.7	14.5	2.8	14.1	14.5	14.0	14.4
A8-AC	0.01175	5.15	5.15	1	5.116	0.993	8.2 ± 0.6	8.4	2.4	8.2	8.4	8.1	8.3
A8-8	0.01175	5.143	5.15	1.001	5.116	0.995	11.6 ± 1.1	11.9	2.6	11.6	11.9	11.5	11.8
A8-24	0.01175	5.157	5.15	0.999	5.116	0.992	10.9 ± 0.5	11.2	2.8	10.9	11.2	10.8	11.1
A8-Na	0.01175	5.145	5.15	1.001	5.116	0.994	13.9 ± 1.7	14.3	2.9	13.9	14.3	13.8	14.2
A11-AC	0.01175	5.137	5.15	1.003	5.116	0.996	8.4 ± 0.5	8.6	2.4	8.4	8.6	8.4	8.6
A11-8	0.01175	5.137	5.15	1.003	5.116	0.996	10.7 ± 1.1	11.0	2.8	10.7	11.0	10.7	11.0
A11-24	0.01175	5.131	5.15	1.004	5.116	0.997	12.0 ± 0.2	12.4	3.3	12.0	12.4	12.0	12.4
A11-Na	0.01175	5.128	5.15	1.004	5.116	0.998	14.4 ± 0.7	14.8	2.8	14.5	14.9	14.4	14.8

ρ, radius of curvature at the crack tip; ρ/d, α (notch bluntness ratio); k_t, k_{t1}, k_{t2}, stress concentration factors; K_C, fracture toughness; C_1, C_2, correction factors.

strength ratio of the alloys as given in Table 1. Because the NSRs are over one for the Al-wrought alloy and the dual-phase steels (except thick specimens of MSA), these materials are considered to be notch insensitive. However, the cast alloys (i.e., Al-Si alloys) seem to be more prone to notches, and notch sensitivity is observed especially in the as-cast alloys whose second-phase particles, namely Si, are not spheroidized.[8]

3.4 Fracture Toughness Calculations

Fracture toughness (K_C) values of the alloys were calculated at the onset of fracture of the circumferentially notched round specimens by using the following equation[16]:

$$K_C = \frac{P_F}{D^{3/2}} \times \left[1.72\left(\frac{D}{d}\right) - 1.27 \right] \qquad \text{(Eq 1)}$$

where d and D are the diameters of the notched and unnotched sections of the cylindrical specimen, and also by the following equation[4];

$$K_C = 0.454\sigma_{NTS}D^{1/2} \qquad \text{(Eq 2)}$$

The relationship between the notch tensile strength and the fracture toughness of the three alloys is demonstrated in Fig. 4. Because the fracture toughness values were calculated by using the fracture loads of the notched specimens, an increase in fracture toughness with the increase in notch tensile strength is evident.

An early work on the stress intensity factor at the notch tip of a notched bar was by Paris and Sih.[17] They suggest a solution as follows:

$$K_I = \sigma\sqrt{\pi D} \times f\left(\frac{d}{D}\right) \qquad \text{(Eq 3)}$$

where $f(d/D)$ is a dimensionless function depending on the specimen dimensions. They argue that for simplification $f(d/D)$ can be taken as equal to 0.233 where, between d/D from 0.48-0.86, it gives quite accurate solutions. The calculations with Eq 3 were found to be in close agreement with those of Eq 1 and 2.

3.5 Stress Concentration Factor

Stress concentration factor k_t describes the effect of crack geometry on the local crack-tip stress level. k_t increases with increasing crack length and decreasing crack radius (Fig. 5) and in the simplest form it is given as follows:

$$k_t = 2\sqrt{\frac{a}{\rho}}$$

where ρ is the radius of curvature at the crack tip. Since

$$K_I = \sigma\sqrt{\pi a}$$

therefore, stress concentration factor estimation can be simply defined as follows;

$$k_t = \frac{2K_I}{\sigma\sqrt{\pi\rho}} \qquad \text{(Eq 4)}$$

at the notch tip for a sharp notch.

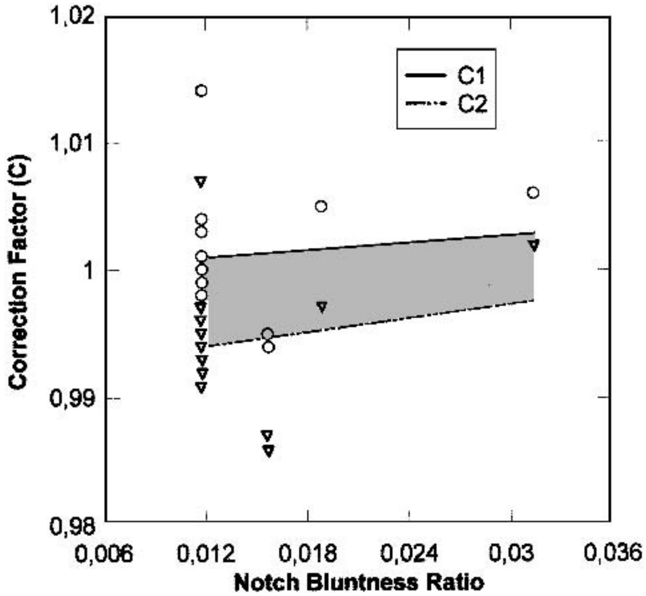

Fig. 6 The relationship between the notch bluntness ratio and the correction factor

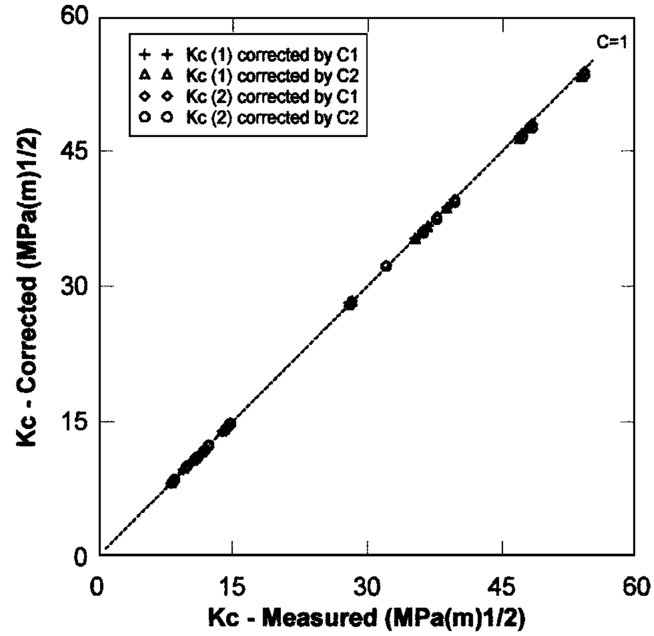

Fig. 7 The relationship between the measured and the corrected fracture toughness both by C_1 and C_2

For circumferentially notched blunt bar under tension, two expressions given by Irwin and Benthem and Koiter as investigated by Shabara et al.[18] are discussed below.

According to Irwin, the stress concentration factor is defined as

$$k_{t1} = \frac{2}{\sqrt{\pi\alpha}} \sqrt{\frac{8\pi\left[1-\left(\frac{d}{D}\right)^2\right]}{\left[5+3\left(1-\left(\frac{d}{D}\right)^2\right)\right]^2}} \quad \text{(Eq 5)}$$

where $\alpha = \rho/d$ (notch bluntness ratio).

According to Benthem and Koiter

$$k_{t2} = \sqrt{\frac{2}{\alpha}}\frac{1}{2}\left[1+\frac{1}{2}\frac{d}{D}+\frac{3}{8}\left(\frac{d}{D}\right)^2-0.363\left(\frac{d}{D}\right)^3 + 0.731\left(\frac{d}{D}\right)^4\right]\sqrt{1-\frac{d}{D}} \quad \text{(Eq 6)}$$

The relationship between the notch bluntness ratio and the stress concentration factor can be seen in Fig. 5. The decrease in the stress concentration factor with the increase in notch bluntness is evident, that is, the stress concentration is more severe when the crack is sharper.

Two correction factors, C_1 and C_2, are used to correct the fracture toughness values of the alloys in this investigation, where

$$C_1 = \frac{k_{t1}}{k_t} \text{ and } C_2 = \frac{k_{t2}}{k_t}$$

In Table 2, stress concentration factors, fracture toughness of the alloys, correction factors, and the corrected fracture toughness values are given.

In Fig. 6, the relationship between the notch bluntness ratio versus the correction factors C_1 and C_2 are shown diagrammatically. There seems to be no apparent relationship between α and the correction factors, which vary between 0.99 and 1.1. The shaded area shows the region between the curve-fit lines of C_1 and C_2. Shabara et al.[18] also found no relationship between ρ/d and C, up to notch bluntness ratio of 0.033; however, with the increase in ρ/d, the correction factor starts decreasing after this value. Akkourri et al.[19] studied the influence of notch root radius on fracture toughness (J_{IC}) of three point bend mild steel specimens and found no effect of notch root radius on fracture toughness if the radius is less than 0.85 mm.

In Fig. 7, the relationship between the fracture toughness and the corrected fracture toughness values by C_1 and C_2 for the alloys are shown diagrammatically. This diagram reveals that there is not much difference between the calculated and the corrected fracture toughness values. This suggests that the fracture toughness measurement procedure by using circumferentially notched bars is an accurate and a reliable method.

4. Conclusions

In conclusion, because the specimen preparing and the testing procedures are straightforward, circumferentially notched cylindrical specimens can be readily used for rapid determination of fracture toughness of metallic materials. Fracture toughness measurement of metallic materials by using circumferentially notched round specimens is observed to be an accurate and reliable procedure.

References

1. Anon: "ASTM Designation E399, Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials" in *Annual Book of*

ASTM Standards, Part 3, American Society for Testing and Materials, Philadelphia, PA, 1988, pp. 680-715.
2. Anon: "BSI Standard BS5762" in *Methods for Crack Opening Displacement (COD) Testing*, British Standards Institution, London, UK, 1979, pp. 1-14.
3. Anon: "ASTM Designation E399, Standard Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement" in *Annual Book of ASTM Standards*, Part 3, American Society for Testing and Materials, Philadelphia, PA, 1993, pp. 952-61.
4. S. Kang and N.J. Grant: "Notch Tensile Testing as a Measure of the Toughness of Aluminum Alloys," *Mat. Sci. Eng.,* 1985, *72*, pp. 155-62.
5. B. Ule, B. Leskocsek, and B. Tuma: "Estimation of Plane Strain Fracture Toughness of AISI M2 Steel From Precracked Round-Bar Specimens," *Eng. Fract. Mech.,* 2000, *65*, pp. 559-72.
6. A. Bayram, A. Uguz, and M. Ula: "Effect of Microstructure and Notches on the Mechanical Properties of Dual-Phase Steels," *Mater. Charact.,* 1999, *43*, pp. 259-69.
7. A. Bayram and A. Uguz: "The Effect of a Notch on the Tensile Properties of a Commercial 7075-Al Alloy," *Metall.* 1999, *53*(9), pp. 486-89.
8. A. Bayram and A. Uguz: "The Effect of Spheroidising and Na-Modification on the Mechanical Properties of Al-Si Cast Alloys," *Metall.,* 1999, *53*(3), pp. 131-34.
9. D.M. Li and A. Bakker: "Fracture Toughness Evaluation for an RSP Al Alloy Using Circumferentially-Cracked Cylindrical Bar Specimens," *Eng. Fract. Mech.,* 1997, *57*, pp. 1-11.
10. K. Kobayashi, H. Imada, and T. Majima: "Nucleation and Growth of Creep Voids in Circumferentially Notched Specimens," *JSME Int. J.A.-Solid M.,* 1998, *41*, pp. 218-24.
11. J. R. Donoso, F. Labbe, and H. Argomedo: "A Calibration Function for Notched Cylindrical Tension Specimens, Based on the Common Format Equation: Numerical and Experimental Data Analysis," *Eng. Fract. Mech.,* 1996, *54*, pp. 617-28.
12. J. Toribo: "A Fracture Criterion for High-Strength Steel Notched Bars," *Eng. Fract. Mech.,* 1997, *57*, pp. 391-404.
13. D.B. Lanning, G.K. Haritos, and T. Nicholas: "Influence of Stress State on High Cycle Fatigue of Notched Ti-6Al-4V Specimens," *Int. J. Fatigue,* 1999, *21*(Suppl. S), pp. S87-S95.
14. A. Valiente and J. Lapena: "Measurement of the Yield and Tensile Strengths of Neutron-Irradiated and Post-Irradiation Recovered Vessel Steels With Notched Specimens," *Nucl. Eng. Des.,* 1996, *167*(1), pp. 11-22.
15. Anon: "ASTM Designation E602, Standard Method for Sharp-Notch Tension Testing With Cylindrical Specimens" in *Annual Book of ASTM Standards*, Part 3, American Society for Testing and Materials, Philadelphia, PA, 1988, pp. 964-72.
16. G.E. Dieter: *Mechanical Metallurgy*, SI edition, McGraw-Hill, Singapore, 1988, pp. 316 and 358.
17. P.C. Paris and G.C. Sih: "Stress Analysis of Cracks" in *ASTM STP*, No. 381, American Society for Testing and Materials, Philadelphia, PA, 1965, pp. 30-83.
18. M.A.N. Shabara, A.A. El-Domiaty, and M.D. Al-Ansary: "Estimation of Plane Strain Fracture Toughness From Circumferentially Bluntly Notched Round-Bar Specimens," *Eng. Fract. Mech.,* 1996, *54*, pp. 533-41.
19. O. Akkouri, M. Louah, A. Kifani, G. Giger, and G. Pluvinage: "The Effect of Notch Root Radius on Fracture Toughness J_{IC}," *Eng. Fract. Mech.,* 2000, *65*, pp. 491-505.