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MIXED MODE I/III FRACTURE TOUGHNESS OF MILD STEEL

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ABSTRACT

One of the main limitations of the mixed mode fracture toughness evaluation is the lack of standard test procedures especially for ductile materials. The objective of the present work was to establish the slope of the blunting line under mixed mode I/III loading using stretch zone width measurements and to study the effect of mixed mode I/III loading on the fracture toughness of mild steel. Mild steel was chosen as the test material as it is a widely used structural material. Fracture toughness tests were carried out employing modified single edge notched three point bend specimens with initial crack orientation angles of 0, 30 and 45°. A crack with a notch root radius of 110 µm was introduced to a depth of 0.5 W, where W is the width of the specimen, using wire cut electrical discharge machining. A multiple specimen technique similar to that recommended by ASTM E-813 was used for determining the mixed mode I/III fracture toughness. The blunting line slope for the different crack orientations was determined using stretch zone width measurements and was superimposed on the respective J-R curves to determine the mixed mode I/III fracture toughness. The mixed mode I/III fracture toughness of mild steel was found to decrease significantly with increasing mode III loading component. The effect of mixed mode I/III loading on fracture toughness of mild steel was explained on the basis of the fracture mechanism as well as the nature of the deformation fields ahead of the crack tip under mixed mode I/III loading.

Key words: Mixed mode I/III fracture toughness, mild steel, stretch zone width, blunting line

INTRODUCTION

Mixed mode fracture toughness evaluation is gaining importance, as the loading experienced at the tip of the crack in a structure in most practical applications could be very complex resulting in mixed mode fracture. One of the main limitations of the mixed mode fracture evaluation is the lack of standard test procedures. In recent years, test procedures for the determination of mixed mode I/III fracture toughness has been suggested for both brittle [1] and ductile [2] materials. In the procedure for evaluation of mixed mode I/III fracture toughness for ductile materials (J_{tc}), Manoharan et. al.[2] have suggested an empirical relation for the determination of the slope of the blunting line which is as follows

$$m_{i/iii} = \frac{m_i \operatorname{Cos} \phi + m_{iii} \operatorname{Sin} \phi}{\operatorname{Cos}\phi + \operatorname{Sin}\phi} \qquad \text{--- (1)}$$

where $m_i = 2\,\sigma_{yt}$, $m_{iii} = 2\,\tau_{yt}$ and ϕ is the crack orientation angle with respect to the mode I crack. Kamat et. al. [3] in their study on mixed mode I/III fracture toughness on Armco iron have shown that the experimentally measured blunting line slope under mixed mode I/III loading was significantly greater than that predicted by expression (1) suggested by Manoharan et.al. [2]. They have also obtained an expression for blunting line for Armco iron, which is given below

$$m_{i/iii} = 4\,\sigma_{yt}\,(1.005 - 0.00524\,\phi) \qquad \text{--- (2)}$$

The present investigation is aimed at establishing the slope of the blunting line under mixed mode I/III loading using stretch zone width measurements as well as to study the effect of mixed mode I/III loading on the fracture toughness in mild steel. Mild steel was chosen as the test material as it is a widely used construction material.

EXPERIMENTAL PROCEDURE

Mild steel, containing in weight percent, 0.23C,1.6Mn, 0.035S and 0.03P in the form of 15 x 30 mm^2 rectangular cross-sectional bars was used in the present study. The microstructure consisted of 65 vol.% ferrite with a mean linear intercept grain size of around 20 μm and 35 vol.% pearlite. The mechanical properties of mild steel are given in Table 1.

A multiple specimen technique similar to that recommended by ASTM E 813 [4] was used for determining the mixed mode I/III fracture toughness. The modified single edge notched 3-point bend specimen geometry is shown in fig.1. Fracture toughness tests were performed at ϕ =30° and 45°. Fracture toughness results for pure mode loading (ϕ =0°) were taken from an earlier study [5]. Fatigue pre cracking is precluded in specimen with ϕ =30° and 45° because of the proclivity of the fatigue pre-crack to rotate towards mode I orientation. Hence, pre-cracking was done for all specimens by means of wire cut electrical discharge machining (EDM). A 0.2 mm diameter wire, which resulted in a notch root radius of 110 μm was used for this purpose.

All fracture toughness tests were carried out on an Instron 8500+ servo hydraulic testing machine at a displacement rate of 1mm /min. The specimens were post-cracked by fatigue to delineate the stretch zone and stable crack extension. To measure the stretch zone width, the fractured surfaces were examined under Scanning Electron Microscope (SEM) with the fracture surfaces tilted at an angle of 45° with respect to the incident beam about an axis parallel to the machined notch. SEM pictures were recorded at magnifications of 50-100X within the range of 3/8 to 5/8 of specimen thickness, six measurements were taken and averaged.

RESULTS

Load Vs Load line displacements for ϕ =0°, 30° and 45° exhibit a load drop immediately after the linear portion similar to yield drop in tensile tests. The load drop in fracture toughness tests, known as pop-in, is attributed to the yielding phenomenon [6] as there is no evidence of unstable crack extension either prior to or after the formation of stretch zone width (fig.2).

The J_t value for each specimen was determined using the following expression

$$J_t = \frac{2\,U}{b\,B_{eff}} \qquad \text{---3}$$

where U is the total energy under load Vs load line displacement plot, b is the ligament ahead of the crack and $B_{eff} = B/\cos\phi$ where B is the thickness and ϕ is the loading angle. The J_t value thus obtained is plotted as a function of crack extension as shown in figs. 3 and 4 for ϕ = 30 and 45 ° respectively. The plot of J- Δa for ϕ = 0 is reproduced from an earlier study [5] in fig. 5 for fatigue precracked specimen. Blunting line having a slope given by expression (1) intersects the J – Δa curve yielding J_{tc} values of 140 and 90 kJ/m^2 for ϕ = 30 and 45°, respectively.

An alternative method for J_{tc} calculation, based on stretch zone width measurements was also employed. Representative scanning electron micrograph illustrating the critical stretch zone width for ϕ = 30 and 45° are given in fig. 2. The critical stretch zone width values for all three loading angles are given in table 2 along with the corresponding J_{tc} data. The J_t vs szw_c, assuming $szw_c = \Delta a$, is superimposed on the respective J-Δa plots in fig.3 and 4 for the two loading angles. The plot J_t Vs szw_c is nominally a straight line parallel to the y-axis and the point where it intersects the J - Δa regression line is then the initiation fracture toughness J_{tc}. Also, the straight line joining the above intersection point and the origin describe the blunting behaviour of the material. The J_{tc} values obtained using this method are also given in Table 2.

DISCUSSION

Blunting Line

Table 3 shows that the experimentally measured blunting line slopes under mixed mode I/III loading conditions agree reasonably well with that predicted by expression (1) suggested by Manoharan et.al. However, an empirical fit to the data results in the following equation for the blunting line slope under mixed mode I/III loading

$$m_{i/iii} = 2\sigma_{yt} (1.005 - 0.00524\,\phi) \qquad \text{-- 4}$$

This condition is very similar to that found earlier for Armco iron [3].

The only difference between the two equations is the constraint factor. Several investigators [7-10] have found that the constraint factor is a function of the work hardening exponent, n. For Armco iron which has $n > 0.2$ the constraint factor is 2 whereas for mild steel where $n = 0.15$ the constraint factor is 1. Thus it appears that a generalized expression for blunting line slope under mixed mode I/III loading can be written as

$$m_{i/iii} = 2\,(C.F.)\,\sigma_{yt} (1.005 - 0.00524\,\phi) \qquad \text{-- 5}$$

Currently studies are underway, to verify the applicability of the above expression to other materials.

Mixed Mode Fracture Toughness

The variation in the measured fracture toughness with loading angle ϕ is shown in fig. 6. The fracture toughness decreases with increasing ϕ. Srinivas et.al. [11] have suggested a technique for the estimation of initiation fracture toughness J_{Ic} for ductile materials using blunt notch specimens. Their study showed that critical stretch zone width in the fatigue-precracked condition and blunt notch condition are related and could be expressed as

$$SZW_c^{fp} = (SZW_c^{\rho} - \rho) \qquad \text{--6}$$

where SZW_c^{fp} is the critical stretch zone width in the fatigue-cracked specimen, SZW_c^{ρ} the measured critical stretch zone width for blunt notch specimen have notch root radius ρ. Thus it is possible to estimate the notch root independent fracture toughness (that is the fracture toughness determined using fatigue – precracked specimens) from the measured SZW_c^{ρ} by means of the following expression

$$Jtc = 2\,(C.F.)\,\sigma_{yt}\, f(\phi)\,(SZW_c^{\rho} - \rho) \qquad \text{--7}$$

where $f(\phi) = (1.005 - 0.00524\phi)$ with ϕ in degrees.

The corrected stretch zone width and the calculated notch root independent fracture toughness for different loading angles are given in Table 4. The variation of notch root independent toughness under mixed J_{tc}, as a function of ϕ is included in fig.6. The fracture toughness decreases significantly with increasing ϕ. The decrease in fracture toughness with increasing loading angle is similar to that found in other ductile materials which fails by classical void nucleation and growth mechanism and has been attributed by Kamat and Hirth [12] to a autocatalytic shear localization-void nucleation model.

CONCLUSIONS

1. The experimentally measured blunting line slope under mixed mode I/III loading was found to nearly match with that predicted by expression (1) suggested by Manoharan et.al.
2. The fracture toughness of mild steel decreased significantly with increased mode III loading.

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Table –1 Mechanical Properties of mild steel.

Properties	Value
Lower Yield Strength, MPa	300
U.T.S, MPa	477
Elongation in 25 mm GL	31
n	0.15

Table –2 Critical szw and J_{tc} values for mild steel

Loading angle ϕ degrees	szw$_c$ measured μm	J_{tc} from empirical blunting line kJ/m^2	J_{tc} from szw$_c$ measurement kJ/m^2
0	318	--	247
30	187	140	135
45	137	90	85

Table –3 Blunting line slopes for mild steel under mixed mode I/III loading

Loading angle ϕ degrees	Blunting line slope calculated using expression (1) (MPa)	Blunting line slope measured experimentally (MPa)
30	635	658
45	582	590

Table-4 Corrected values of szw & J_{tc} for mild steel

Loading angle ϕ degrees	Notch root radius µm	Measured szw_c µm	Corrected szw_c µm	J_{tc} (calculated from corrected szw_c) kJ/m^2
0	110	318	208	162
30	110	187	77	51
45	110	138	28	16

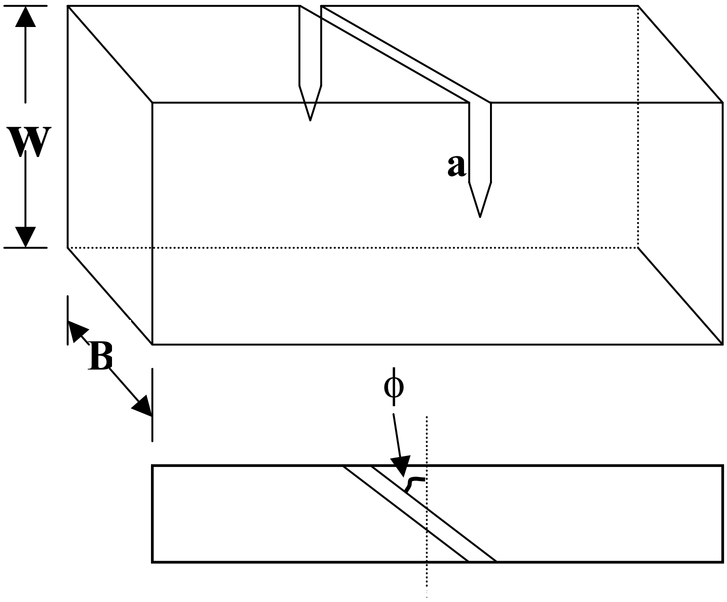

Fig.1. SENB specimen geometry used for mixed mode I/III fracture toughness evaluation of mild steel

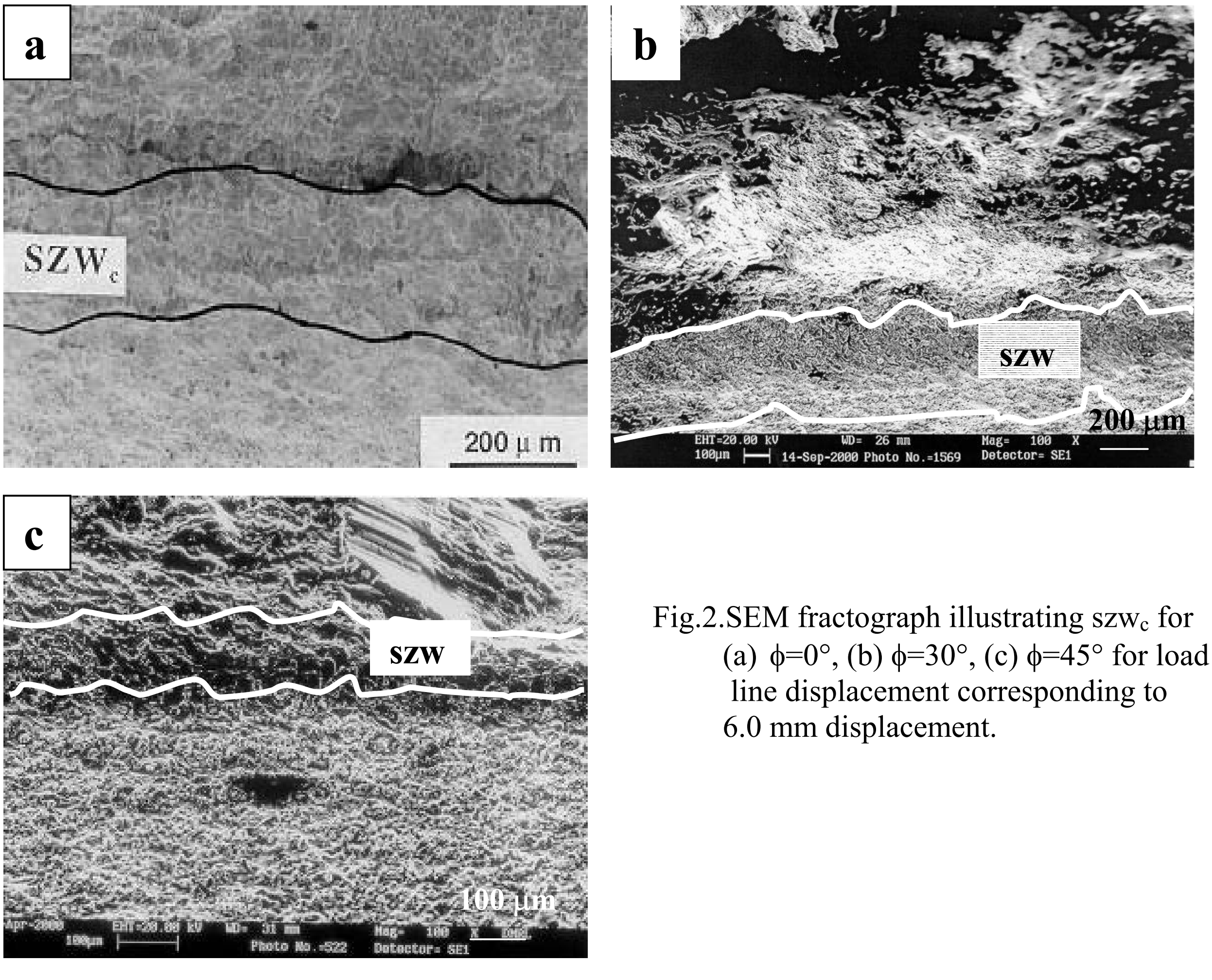

Fig.2.SEM fractograph illustrating szw_c for (a) ϕ=0°, (b) ϕ=30°, (c) ϕ=45° for load line displacement corresponding to 6.0 mm displacement.

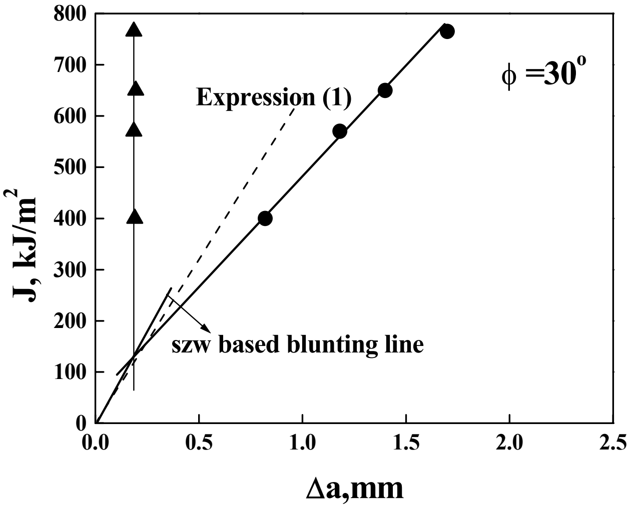

Fig.3 J - Δa plot of mild steel for ϕ =30°

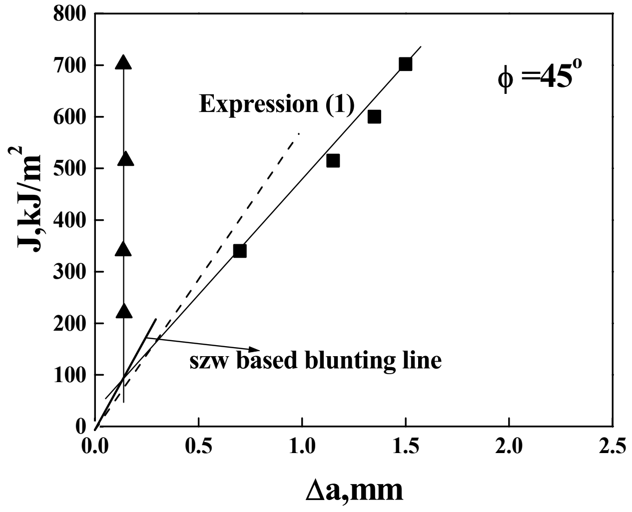

Fig.4. J - Δa plot of mild steel for ϕ =45°

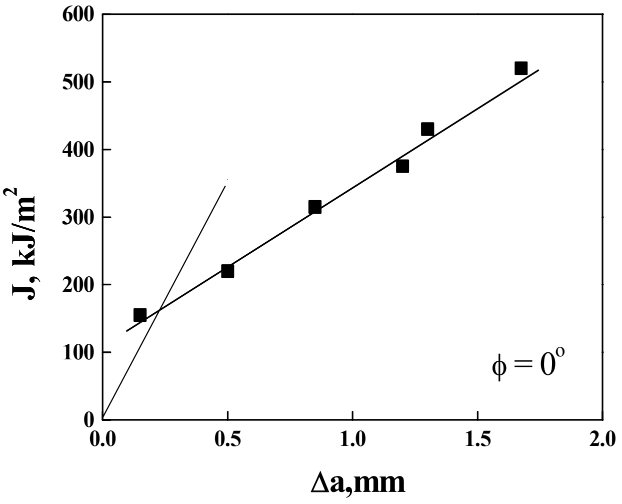

Fig. 5 J - Δa plot of mild steel for ϕ = 0°

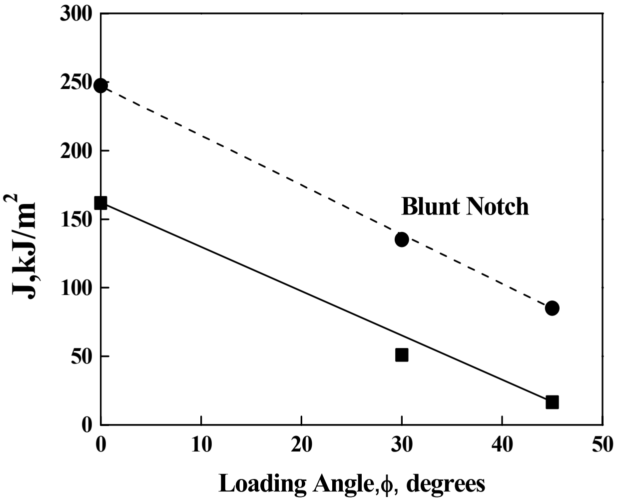

Fig.6. Variation of mixed mode I/III fracture toughness with loading angle