EFFECT OF NOTCH ROOT RADIUS ON MIXED MODE I/III FRACTURE TOUGHNESS OF MILD STEEL UNDER IMPACT CONDITIONS

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ABSTRACT

The objective of the present study was to investigate the effect of notch root radius on the mixed mode I/III fracture toughness of mild steel under impact conditions. Charpy impact specimens with an inclined initial notch (ϕ = 45˚), which results in equal contributions from mode I and mode III loading, and having different notch root radii were tested at room temperature in an instrumented impact testing machine. The mixed mode I/III fracture toughness was determined using a multiple specimen technique as well as using the stretch zone width method. The multiple specimen technique using the energy at maximum load was found to result in unrealistically high values for the mixed mode I/III fracture toughness and therefore the stretch zone width method was considered more appropriate for determining the fracture toughness. The mixed mode fracture toughness was found to increase linearly with increasing notch root radius similar to the behaviour observed for mode I fracture toughness. The approach used by Srinivas and co-workers for calculating the notch root independent mode I fracture toughness was found to be applicable for mixed mode I/III fracture toughness of mild steel under impact conditions.

1 INTRODUCTION

Mixed mode fracture toughness evaluation is gaining importance because, in most practical applications, structures experience complex loading resulting in mixed mode fracture. Fatigue pre-cracking is precluded for mixed mode fracture toughness specimens because of the tendency of the pre-crack to rotate towards mode I orientation during fatigue [1]. Hence, mixed mode fracture toughness evaluation is done with specimens having finite notch root radii and thus it is essential to understand the effect of the notch root radius on mixed mode fracture toughness. While several researchers [2-6] have investigated the effect of notch root radii (ρ) on mode I fracture toughness, there is lack of similar studies under mixed mode I/III loading. Thus, the objective of the present study was to investigate the effect of the notch root radius on the mixed mode I/III fracture toughness of mild steel under impact conditions. Mild steel was chosen as the test material as it is a widely used construction material.

2 EXPERIMENTAL PROCEDURE

Mild steel containing by wt.%, 0.23 C, 1.6 Mn, 0.035 S and 0.03 P in the form of 15 x 30 mm^2 cross-sectional bars were used in the present study. The microstructure consists of 65 vol. % of ferrite with a mean linear intercept grain size of around 20 μm and 35 vol. % pearlite.

A modified Charpy impact specimen geometry [Fig. 1] was used for the mixed mode I/III fracture toughness tests. The inclined notch (ϕ = 45°) results in equal contributions from mode I and mode III loading components. A multiple specimen technique, as well as the critical stretch zone width method similar to that used by Srinivas et al [6], was employed to evaluate the fracture toughness under impact conditions. Tests were performed for notch root radii measuring 110, 200, 400 and 500 μm at room temperature. All tests were carried out on a Tinius-Olsen pendulum

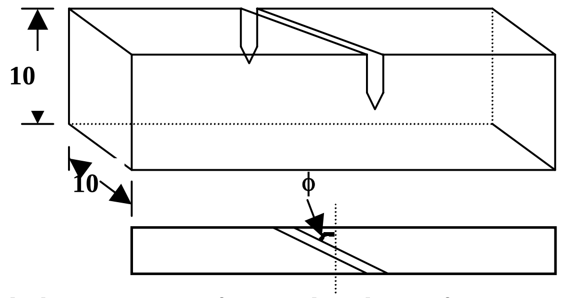

Fig.1 Modified Charpy specimen for mixed mode I/III fracture toughness testing. Dimensions are in mm

instrumented impact testing machine with a pendulum velocity of 5.47 m/s. The load versus deflection and load versus energy plots were recorded.

3 RESULTS AND DISCUSSION

There is no known procedure for the evaluation of mixed mode fracture toughness from an instrumented impact test. Thus an approach analogous to that used for mode I loading was employed. A representative load versus deflection plot obtained from the instrumented impact machine for a specimen with 110 μm notch root radius and an initial crack length of 5 mm is shown in Fig. 2. Fracture toughness was evaluated from the slope of the energy (E_i) at maximum load (P_m) versus the crack length (a) plot using the following equation [7]:

$$J_{tc} = -\,(1/B_{eff})\,(dE_i/da) \qquad \text{----(1)}$$

where $B_{eff} = B/\cos\phi$.

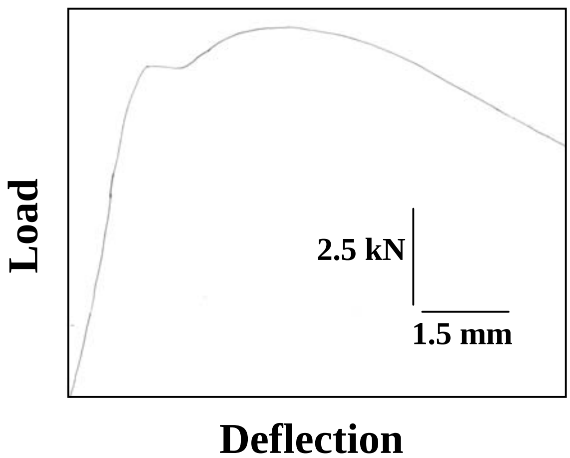

Fig. 2. Load vs. deflection plot obtained from an instrumented impact test for a specimen with a pre-crack length of 5mm

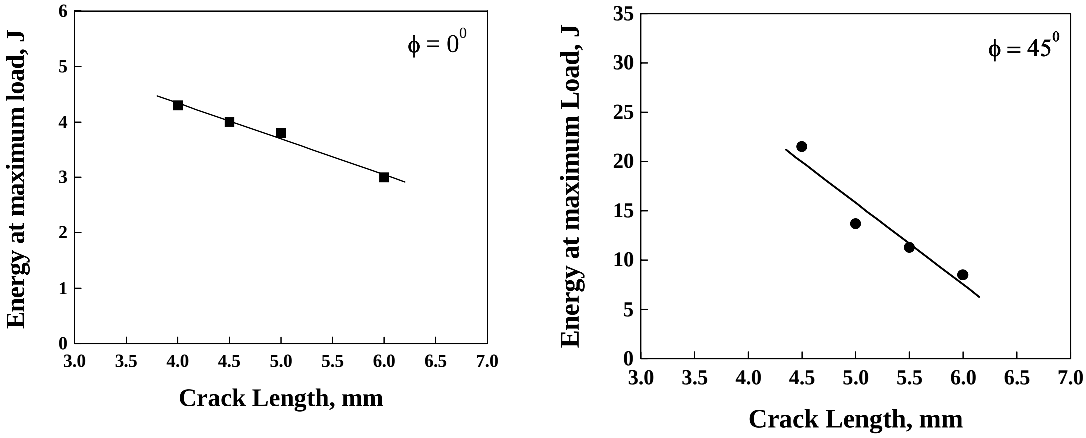

Fig.3. Variation of energy at maximum load with crack length for angles $\phi = 0$ and 45˚

The corresponding variation of energy at maximum load (P_m) with crack length for $\phi = 0$ [6] and 45˚ is shown in Fig. 3. The J_{tc}^{APP} values obtained using the above procedure for the different notch root radii (Table 1) seem abnormally high as compared to the mode I fracture toughness values [6] and the reason may be that the above procedure is not applicable under mixed mode I/III loading especially when the specimens fail in a fully ductile manner (Fig. 2). SEM fractographs depicting SZW_c for all notch root radii are shown in Figs. 4. These figures clearly reveal the formation of a stretch zone for all notch root radii. The critical stretch zone widths measured ($SZW_c^{measured}$) for the four notch root radii are included in Table 1. The apparent J_{tc} values were calculated from the measurements of this stretch zone width and employing the following relation [6] :

$$J_{tc}^{App} = 2\ \sigma_{yt}\ (1.00 - 0.005\phi)\ SZW_c^{measured} \qquad \text{----(2)}$$

where σ_{yt} is the average of yield and ultimate tensile strengths and is equal to 520 MPa for mild steel at impact strain rates [6]. J_{tc}^{App} values so calculated are also listed in Table 1and seem more reasonable compared to the J_{tc}^{App} obtained from the multiple specimen method.

Table 1. J_{tc}^{App} values obtained from the multiple specimen technique and the stretch zone width method for different notch root radii

Notch Root Radius, μm	Loading angle, ϕ	J_{tc}^{App} , kJ/m^2 using the Multiple Specimen Technique	$SZW_c^{measured}$ μm	J_{tc}^{App} , kJ/m^2 using $SZW_c^{measured}$
110	0	65	-	-
110	45	748	235	190
200	45	790	315	254
400	45	850	530	427
500	45	900	640	516

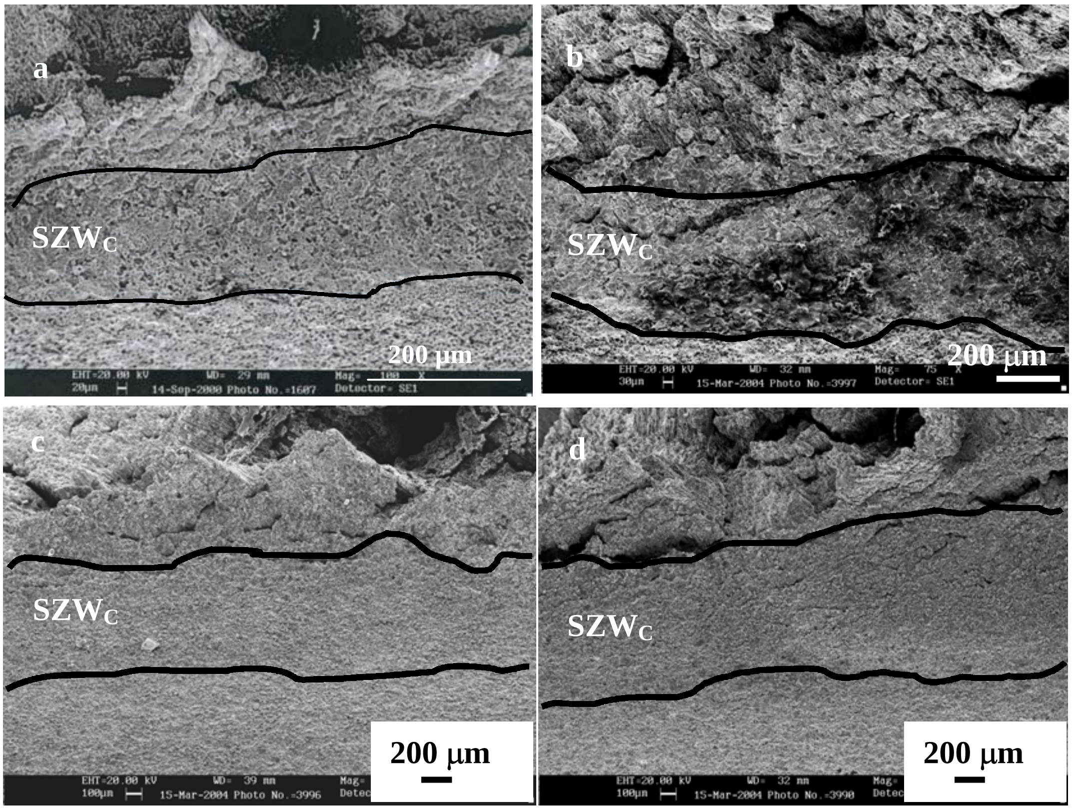

Fig. 4. SEM fractographs showing critical stretch zone width for specimens having notch root radius (a) 110, (b) 200, (c) 400 and (d) 500 μm

The mixed mode I/III fracture toughness J_{tc}^{App} calculated from SZW_C is plotted against the notch root radii in Figure 5 which shows that J_{tc}^{App} increases linearly with increasing ρ. This behaviour is similar to that observed for mode I fracture toughness in other ductile materials [5].

According to Rice [8], for ductile fracture to occur the maximum strain ahead of the notch has to exceed the critical strain over a characteristic distance *l**. This results in the following relation between J^{App} and the notch root radius, ρ, above a critical notch root radius

$$J^{App} = A\,(\varepsilon_y)^{-N}\,(\varepsilon_{crit})^{N+1}\,\sigma_y\,\rho \qquad \text{---- (3)}$$

where ε_y is the yield strain, ε_{crit} is the critical strain for fracture, σ_y is the yield stress, N is the exponent in the Ramberg-Osgood fit to the stress-strain data and A is a parameter which is a function of N. The same criterion should be valid under mixed mode loading which would then predict a linear relationship between the apparent mixed mode fracture toughness and ρ which is in broad agreement with our data (Fig. 5)

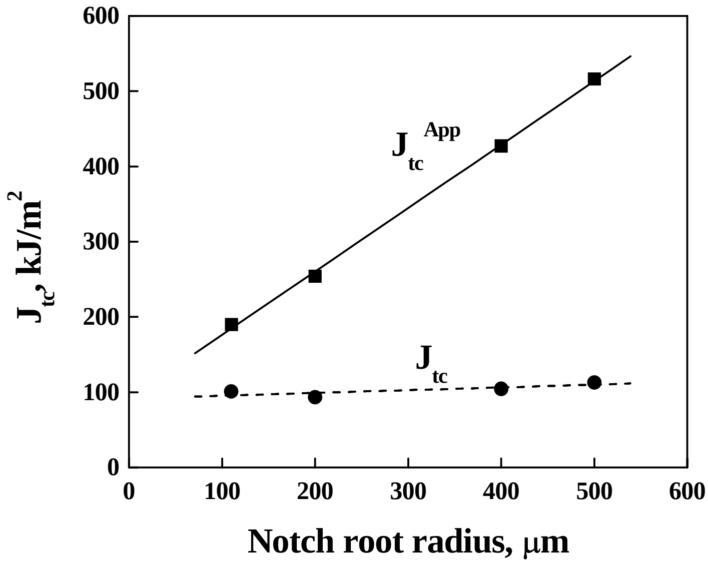

Fig. 5. Variation of J_{tc} with notch root radius

Under mode I loading, Srinivas et al [5] have shown that, for calculating the notch root independent fracture toughness from a specimen with a finite notch root radius, $SZW_C^{measured}$ needs to be corrected. The correction is done by subtracting ρ from $SZW_C^{measured}$ i.e.

$$SZW_c^{corrected} = SZW_c^{measured} - \rho \qquad \text{----- (4)}$$

Using the same argument for mixed mode I/III loading, one can obtain a notch root independent mixed mode fracture toughness ($J_{tc}^{corrected}$) by substituting equation (4) into equation (1). The mixed mode I/III fracture toughness obtained using this approach for specimens with different ρ are plotted against ρ in Figure 5. It is seen that the toughness value is independent of ρ and has a value of 92 kJ/m^2. It is this corrected value of mixed mode I/III fracture toughness that should be used in any comparison with the magnitude of mode I fracture toughness obtained using pre-cracked specimens.

4 CONCLUSIONS

1) The apparent mixed mode I/III fracture toughness of mild steel under impact conditions increases with increasing notch root radius.

2) The notch root independent mixed mode I/III fracture toughness of mild steel can be obtained using the critical stretch zone width corrected for the magnitude of the notch root radius.

5 ACKNOWLEDGEMENT

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