DETERMINATION OF BLUNTING LINE FOR ARMCO IRON UNDER MIXED MODE I / III LOADING

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ABSTRACT

The blunting line for Armco iron under mixed-mode I/III loading was experimentally determined by employing the stretch zone width method and compared with that obtained from the commonly used empirical relation. It was found that the mixed mode I/III fracture toughness of Armco iron determined using the SZW based blunting line was significantly lower than that determined on the basis of the commonly used empirical relation.

Key words : Blunting line, mixed - mode, stretch zone width, Armco Iron

INTRODUCTION

One of the main problems in evaluating the mixed-mode fracture toughness is the lack of standard test procedures. In recent years, test procedures for the determination of mixed mode I / III fracture toughness of brittle (Kumar et al, 1994) and ductile (Manoharan et al, 1990) materials have been suggested. These suggested test procedures recommend a method for data analysis and define parameters such as critical mode I fracture toughness component (K_{ic}, J_{ic}), critical mode III fracture toughness component (K_{iiic}, J_{iiic}) and critical total fracture toughness (K_{tc}, J_{tc}) for characterizing the mixed mode fracture toughness behaviour.

For evaluating the mixed mode ductile fracture toughness (J_{tc}) Manoharan et al (1990) have suggested an empirical equation for the determination of slope of the blunting line as

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

where $m_i = 2\sigma_{yt}$ (twice the average of yield and ultimate strength of the material), $m_{iii} = 2\tau_{yt}$ (twice the average of shear yield and shear tensile strength) and ϕ the crack orientation angle with respect to mode I crack. The basis for this formula is the theoretical blunting line suggested in ASTM standard E813 (1994) for determination of J_{Ic}. The ASTM suggested blunting line (ASTM E 813, 1994), though found to be applicable for medium and high strength materials (Landes and Begley, 1974, Underwood, 1976 and Paris et al., 1979), becomes questionable when it is applied to low strength and high work hardening materials. Several investigators (Mills, 1981, Chipperfield, 1976, Paranjape and Banerjee, 1976, Yin et al., 1983, Doig et al., 1984, Srinivas et al., 1987, 1994) have observed that for low strength and high strain hardening materials (n > 0.2) the ASTM suggested blunting line *overestimates* the crack extension due to blunting. Recent studies (Srinivas et al., 1987, 1994) on Armco iron and its binary alloys possessing low strength and high strain hardening exponent (n > 0.2) have shown that the blunting line has a slope of 4 σ_{yt} for these materials. This is shown for Armco iron of 38µm grain size in Fig.1. The J_{IC} value derived using ASTM blunting line is 265 kJ/m^2 while the blunting line based on SZW measurements, which yielded a slope of $4\sigma_{yt}$, is 190 kJ/m^2, resulting in a overestimation in J_{IC} by 40%. In view of these observations, the present paper is aimed at determining the blunting line for Armco iron experimentally under mixed mode I/III conditions and comparing the same with that obtained from empirical relation given in equation (1).

EXPERIMENTAL

Armco iron, containing in weightpercent, 0.008C, < 0.02Si, < 0.04Mn, < 0.003S and < 0.004 P and having an equiaxed mean linear intercept grain size of 38µm was considered for the present study. The modified compact tension specimen (Fig.2) having a thickness of 25mm and width of 50mm and a notch orientation of 30° ($\phi = 30°$) with respect to mode I crack orientation ($\phi = 0$ for mode I) was used for the mixed mode I/III tests. The specimens were pre-cracked by wire cut EDM using 0.15mm diameter wire. The primary advantage of the modified compact tension geometry is that it is subjected to proportional loading and one gets mixed mode loading at the crack tip because of the initial slanted notch. Multiple specimen technique similar to that recommended by ASTM E - 813 (1984) for J_{Ic} was employed to evaluate the fracture toughness J_{tc}. To delineate the stretch zone, fatigue post - cracking was carried out. The fracture surfaces were examined in a ISI 100A scanning electron microscope (SEM). The specimen is mounted in such a way that the fracture surface was perpendicular to the incident beam. It is then tilted by 45° with respect to incident SEM beam about an axis parallel to the initial machined notch. SEM pictures were recorded at magnifications of 20 to 100X within the range of each specimen thickness of 3/4 to 5/8 B, where B is the specimen thickness. SZW_C was estimated from the length measured on the SEM fractographs. A schematic representation of stretch zone width estimation is shown in Fig.3.

RESULTS AND DISCUSSION

Tensile properties of Armco Iron of grain size 38µm are given in Table 1. The load vs load line displacement curve (Fig.4) for Armco iron of 38 µm grain size under mixed mode I / III conditions shows pop-in behaviour similar to that seen under mode I conditions (Fig.1 inset). As explained earlier (Srinivas et al., 1990), the pop-in observed in the load vs LLD plot is attributed to the yield phenomenon and not considered for the estimation of J_{Ic} at pop-in load since no unstable crack extension is associated with the pop-in. The same procedure is adopted for J_{tc} evaluation.

The J - Δa plot, where Δa is crack extension, for Armco iron of 38 µm grain size under mixed mode I/III condition is shown in Fig.4. The blunting line based on expression (1) does not intersect the J-R curve (Fig.4). As shown in Fig.1, the blunting line slope of $4\sigma_{yt}$, instead of ASTM suggested $2\sigma_{yt}$, is valid for Armco iron and hence the slopes m_i and m_{iii} are modified accordingly as $4\sigma_{yt}$ and $4\tau_{yt}$, respectively, leading to the following expression

$$m_{i/iii} = \frac{4\sigma_{yt} \operatorname{Cos} \phi + 4\tau_{yt} \operatorname{Sin} \phi}{\operatorname{Cos} \phi + \operatorname{Sin} \phi} \qquad --- \quad (2)$$

The blunting line with a slope corresponding to expression (2) which is equal to 828 MPa is included in Fig.4. It is seen that the J - R curve intersects the blunting line with a slope based on expression (2). The intersection point of J - R curve and blunting line based on expression (2) is considered as J_{tq}. The magnitude of J_{tq} thus determined is 286 kJ/m^2.

To verify, whether or not the blunting line based on expression (2) results in a conservative J_{tq} value, stretch zone width measurements were carried out. It is known that in fracture toughness testing of ductile materials the initial crack gradually blunts giving rise to a stretched zone. Real crack extension occurs only when the SZW reaches a critical value, SZW_c. The maximum crack extension due to blunting is thus equal to SZW_c.

Scanning electron micrographs, shown in Fig. 5, corresponding to displacements 2.5, 4 and 6 mm reveal a critical stretch zone width values of 265, 282 and 275µm, respectively. The J data for these displacements is plotted against SZW_c assuming $SZW_c = \Delta a$ in Fig.4. The plot of experimentlaly detrmined J vs SZW_c is nominally a straight line parallel to the y axis and intersects the J - regression curve. The straight line joining the intersection point and the origin describes the blunting behaviour of the material (Schwalbe et al., 1988). This method yields a blunting line slope of ~ 1000 MPa and J_{tq} value of 260 kJ/m^2.

Thus it can be observed that the J_{tq} value obtained using the blunting line based on expression (2) is nearly 10% higher than that obtained through SZW_c based blunting line, while the empirical blunting line based on expression (1) does not intersect the J - R curve. The present study suggests that the blunting line should be determined experimentally in order to use it with confidence for measuring mixed mode fracture toughness. Further studies are in progress to determine the blunting line slopes for different notch orientations so as to arrive at an empirical relation similar to expression (2), which can then be used routinely for mixed mode I / III fracture toughness tests for highly ductile and strain hardening materials.

CONCLUSIONS

1. The experimentally determined blunting line slope was 1000 MPa which was about 25% higher than that obtained using the empirical relation given an equation (2). The empirical blunting line given in equation (1) did not intersect J - R curve.

2. The mixed mode I / III fracture toughness of Armco iron was found to be significantly lower (~ 10%) when the experimentally determined slope is used instead of the empirical slope.

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Table 1. Mechanical Properties of Armco iron having 38µm Grain Size

Yield Strength, MPa	208
Ultimate Tensile Strength, MPa	299
Strain Hardening Exponent ($\sigma = K\varepsilon^n$)	0.30
Shear Yield Strength, MPa	104*
Ultimate Shear Strength, MPa	149.5*

* Shear values are considered as 1/2 of respective tensile values.

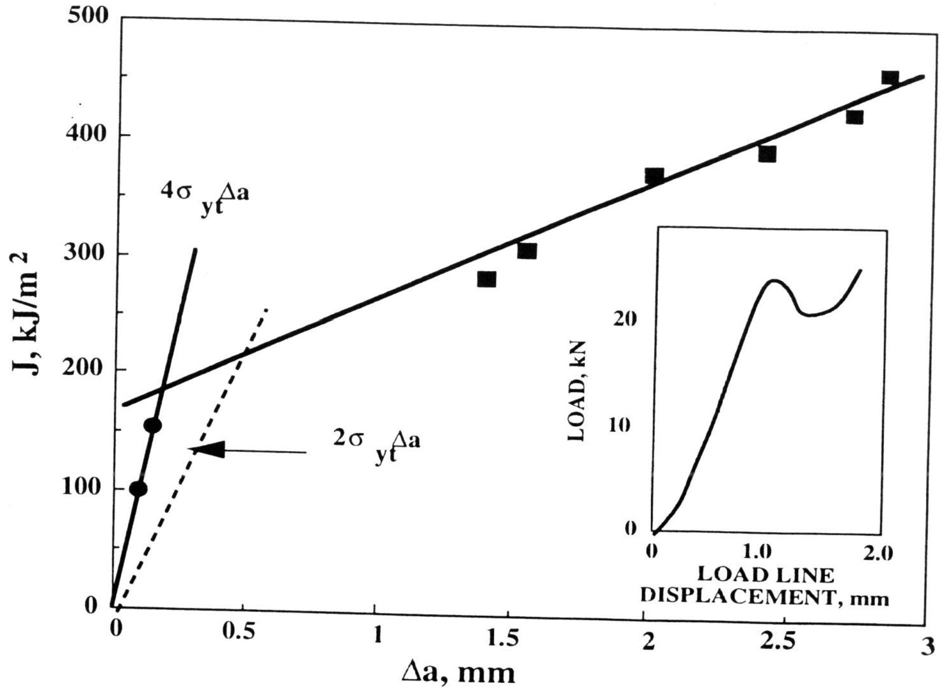

Fig.1.J - Δa plot under mode I loading for Armco iron. Load - line - displacement plot is shown in the inset to illustrate the pop-in behaviour.

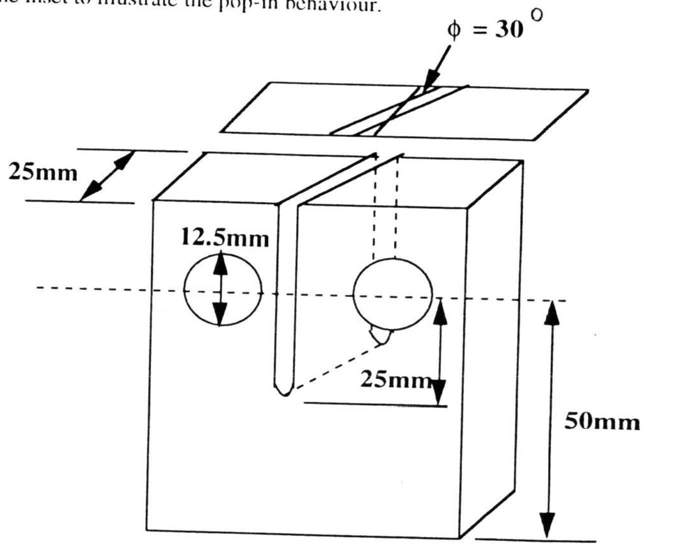

Fig.2.Modified compact tension specimen geometry for mixed mode I / III fracture toughness tests.

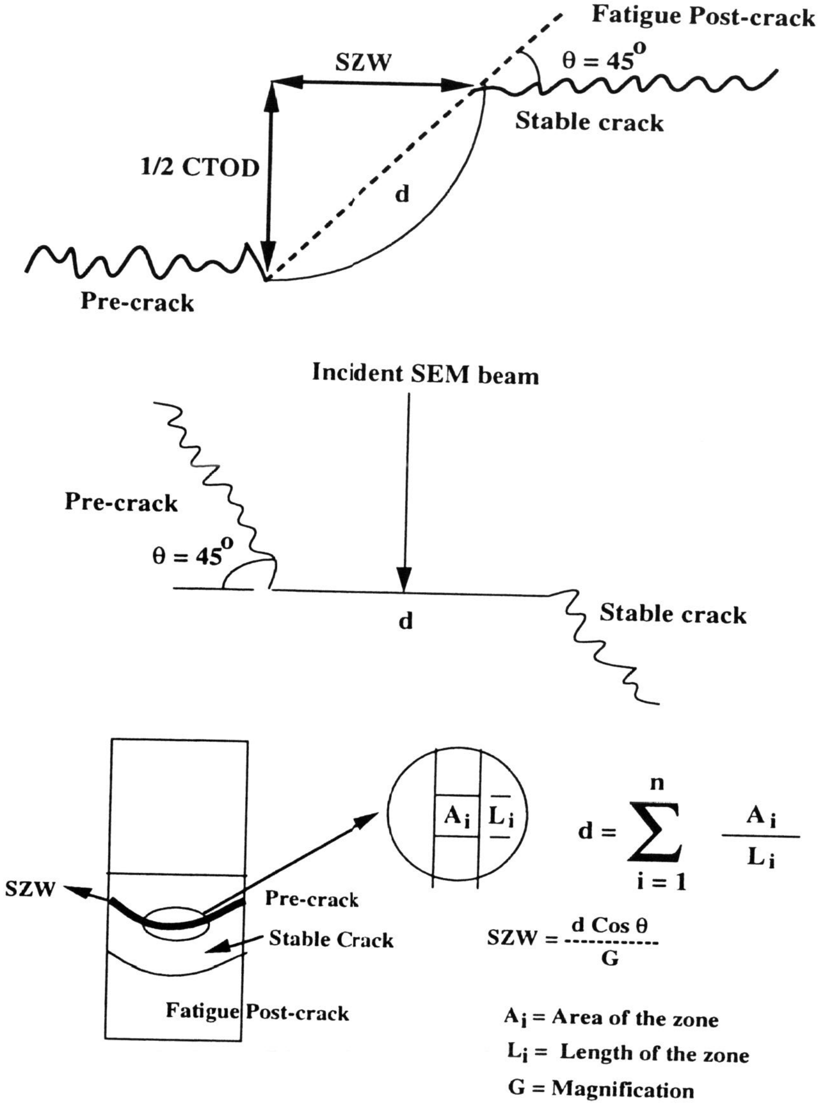

Fig.3. Schematic representation of stretch zone width estimation.

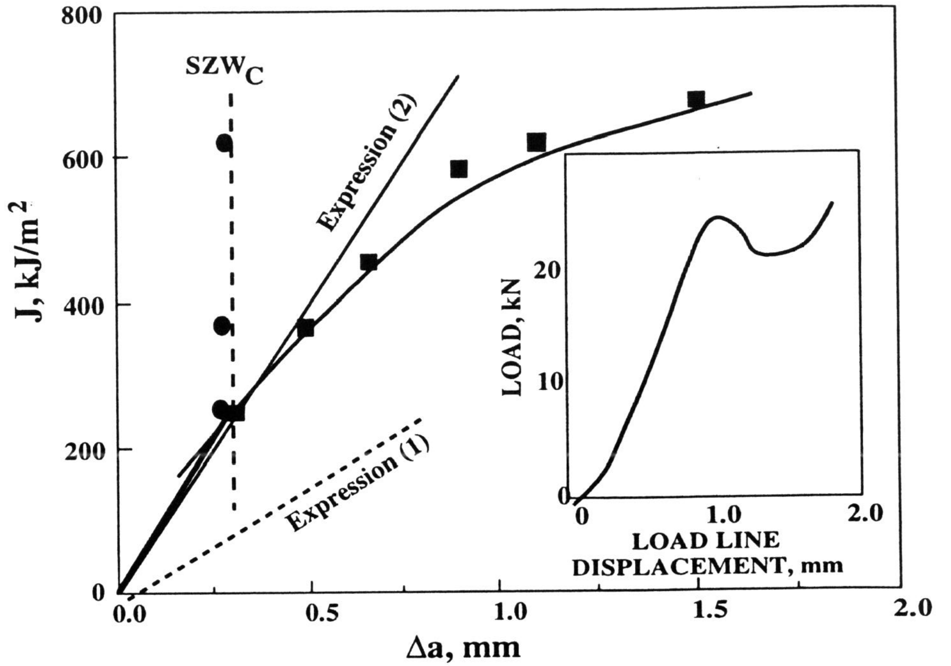

Fig.4.J - Δ a plot under mixed mode - I / III loading. Inset is load versus load - line displacement plot.

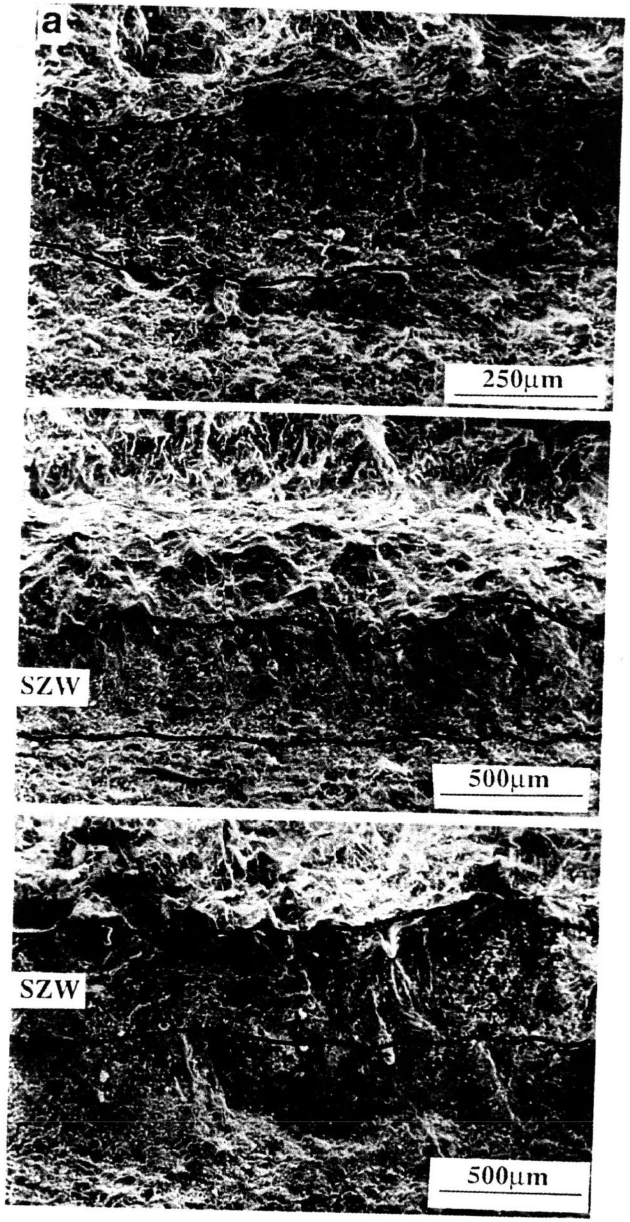

Fig.5.SEM fractography illustrating the stretch zone width in specimens corresponding to load-line displacements of (a) 2.5 mm (b) 4.0 mm and (c) 6.0 mm, respectively.