EFFECT OF ELEVATED TEMPERATURE ON THE MIXED MODE I/III FRACTURE TOUGHNESS OF ARMCO IRON

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ABSTRACT

The objective of the present study was to investigate the effect of elevated temperature on the mixed mode I/III fracture toughness of Armco iron. Specimens with loading angle $\phi = 45^\circ$, which results in equal contributions from mode I and mode III loading, were tested at temperatures from 298 (RT) to 673 K and the fracture toughness was evaluated using a multiple specimen technique With increase in temperature, the mixed mode I/III fracture toughness increased marginally up to 383 K and markedly in the temperature range between 383 and 473 K. Beyond 473 K, the fracture toughness decreased. This behaviour was found to mirror the trend exhibited by the strain hardening exponent *n* arising from the dynamic strain ageing (DSA) phenomenon in the temperature range 383 to 523 K.

1 INTRODUCTION

While several researchers [1-6] have investigated the effect of mixed mode I/III loading on fracture toughness at room temperature, there are no studies on the effect of elevated temperature on mixed mode I/III fracture toughness. This study was therefore directed to evaluate the effect of temperature on mixed mode I/III fracture toughness. Armco iron was chosen as the test material because Fe is known to exhibit dynamic strain aging (DSA) in the temperature range 383 to 523 K.

2 EXPERIMENTAL PROCEDURE

Armco iron, containing by wt.% 0.008 C, < 0.02 Si, 0.04 Mn, < 0.003 S and < 0.004 P and having a mean linear intercept grain size of 38 μm was selected for the present study.

A modified compact tension geometry [5] and the multiple specimen technique similar to that recommended by Kamat et al [7] was employed to evaluate fracture toughness under mixed mode I/III loading. Tests were performed for $\phi = 45^\circ$, generating equal contributions from mode I and mode III loading components, at 298 (room temperature), 383, 473, 573 and 673 K. Fatigue pre-cracking is precluded in specimens with $\phi = 45^\circ$ because of the proclivity of the fatigue pre-crack to rotate towards mode I orientation. Hence, pre-cracking was done in these specimens by means of wire-cut electrical discharge machining (EDM). A 0.2 mm diameter wire which produced a notch root radius (ρ) of 110 μm was used.

Load versus load-line displacements were recorded using a MTS 880 servo hydraulic testing machine at a ramp rate of 1mm/min. Specimens were fatigue post cracked to delineate the stretch zone and the stable crack extension. Stretch zone is a featureless zone, that appears during blunting, between the fatigue pre-crack and stable crack growth. The stretch zone initially increases with the load –line displacement but saturates once the stretch zone reaches a critical value (SZW_C). The procedure for measuring the critical stretch zone width (SZW_C) using a scanning electron microscope (SEM) was as follows. The specimens were mounted in such a way that the fracture surface was perpendicular to the incident SEM beam. It was then tilted by 45° with respect to the incident SEM beam about an axis parallel to the initial machined notch. SEM micrographs were recorded at magnifications 50 – 100 X within the range 3/8 – 5/8 B, where B is the specimen thickness. The critical stretch zone width (SZW_c) was estimated from the SEM fractographs by averaging the readings taken from six different locations.

3 RESULTS AND DISCUSSION

The load versus load-line displacement plots for different temperatures are shown in Fig. 1. Significant serrations are evident at 473 K while minor serrations were observed at 383 and 573K. The serrations are absent at room temperature and at 673 K. This behaviour is similar to that reported by Srinivas et al [8] for mode I fracture toughness which was explained as due to dynamic strain aging (DSA) in the temperature range 383 to 523 K.

The J value for each specimen loaded to different displacements was calculated using

$$J_t = 2\,U / b\,B_{eff} \qquad \text{----------------------- (1)}$$

where U is the total energy under the load versus load-line displacement plot, b is the ligament ahead of the crack tip and B_{eff} is the effective thickness of the specimen which is $B/\cos\phi$. The J value thus obtained is plotted against the measured crack extension for the same specimen. Representative J-Δa plots for mixed mode I/III specimens ($\phi = 45°$) for two temperatures (RT and 473 K) are shown in Fig 2.

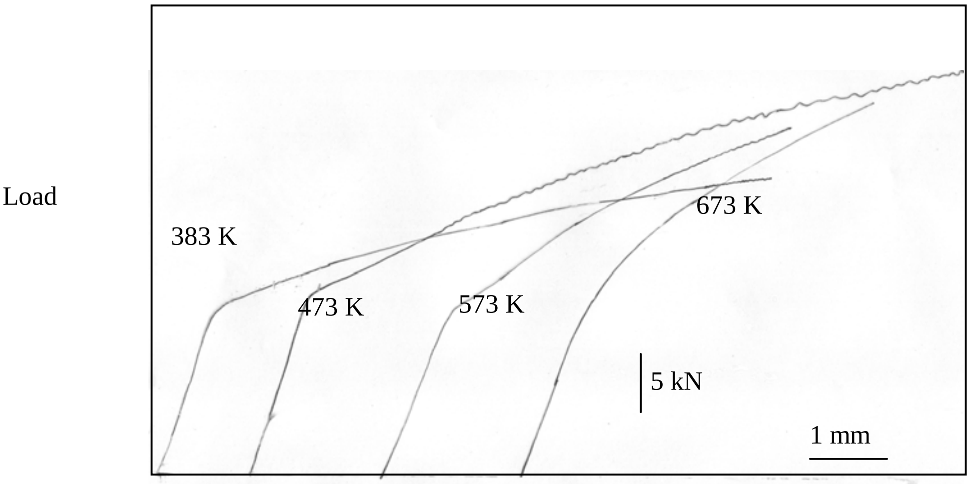

Figure.1 . Load versus load line displacement plots at different test temperatures

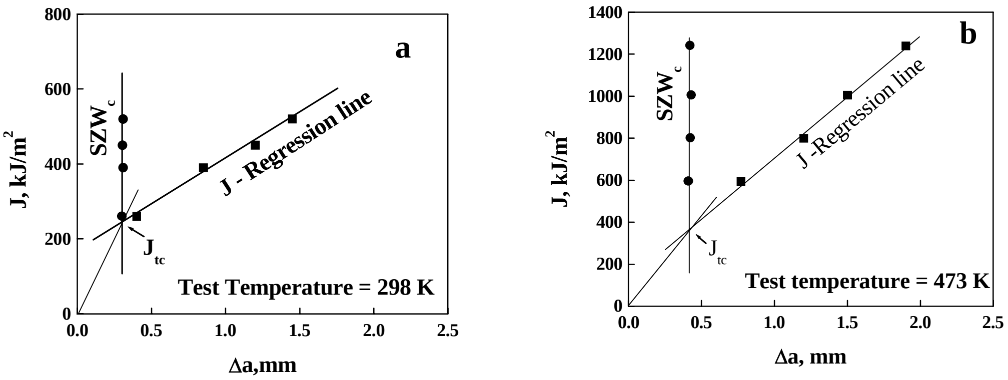

Figure 2 J- Δa plots for test temperatures (a) 298 K and (b) 473 K

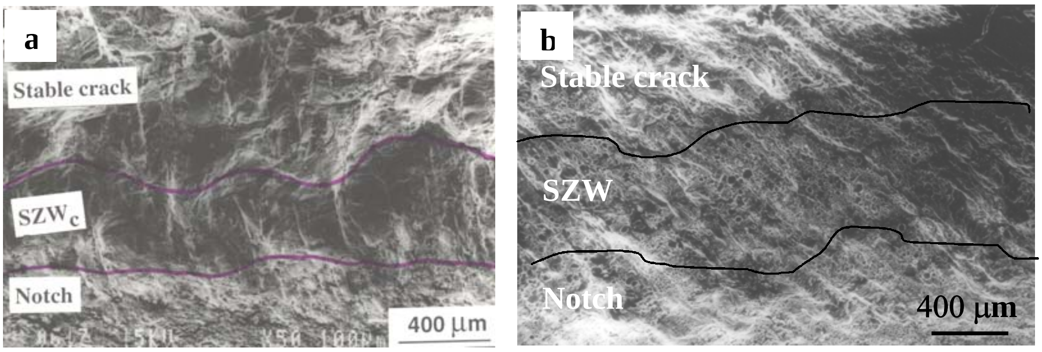

Figure 3. SEM micrographs showing SZW_c at (a) 298 K and (b) 473K

Representative scanning electron micrographs illustrating the critical stretch zone widths (SZW_c) corresponding to RT and 473 K are shown in Figs. 3 a and b respectively. The average experimentally measured critical stretch zone widths (SZW_c) at all test temperatures are given in Table 1. The J versus SZW_c , considering $SZW_c = \Delta a$, is superimposed on the respective J-Δa plots in Figs. 2 a and b for 298 and 473 K. The plot of J versus 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 toughness under mixed mode I/III loading (J_{tc}). The J_{tc} values thus obtained are listed in Table 1.

Table 1. Experimentally measured SZW_c and J_{tc} at different test temperatures

Test Temperature (K)	SZW_c (µm)	J_{tc} kJ/m^2
298 (RT)	305	245
383	340	255
473	424	355
573	350	300
673	330	220

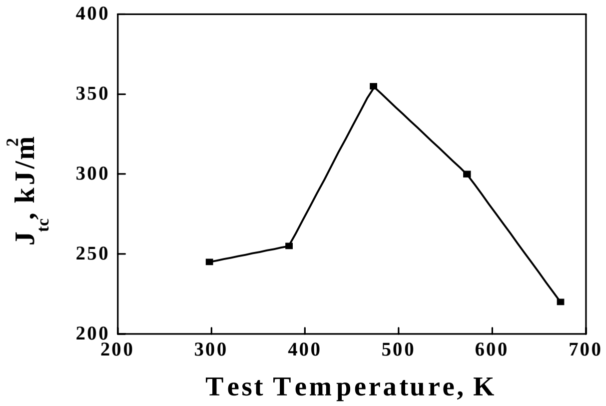

Figure 4. Mixed mode I/III fracture toughness versus test temperature

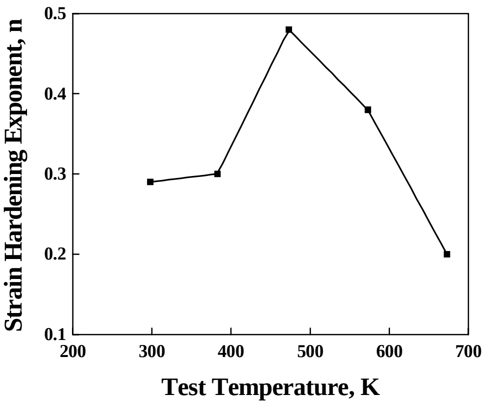

Figure 5. Strain hardening exponent as a function of test temperature

The J_{tc} versus temperature plot is shown in Fig. 4. The mixed mode fracture toughness increases marginally with increase in temperature from RT to 383 K, then increases sharply in the temperature range 383 K to 473 K and then decreases with further increase in temperature. This trend mirrors that exhibited by the strain hardening exponent *n* (Fig. 5) as well as mode I fracture toughness behaviour of Armco iron [8] in the same temperature range. Srinivas et al. [8] have correlated this behaviour with that of strain hardening exponent in the dynamic strain ageing (DSA) temperature regime. In Armco iron, a particle free material, increase in *n* in the DSA regime results in slip dispersal. As void nucleation in Armco iron has been seen to occur by slip band impingement on the grain boundaries or by mutual intersection of slip bands (Figure 6)[8], a higher strain is required to initiate voids, implying a higher strain energy input. Also higher *n* suppresses void growth rate [9]. These two factors contribute to higher mode I fracture toughness in the DSA regime.

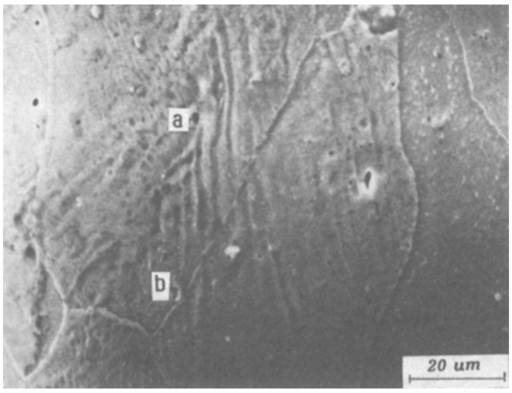

Figure 6 .SEM micrograph showing nucleation of voids (a) by mutual intersection of slip bands and (b)Slip band intersection at grain boundary under mode I loading

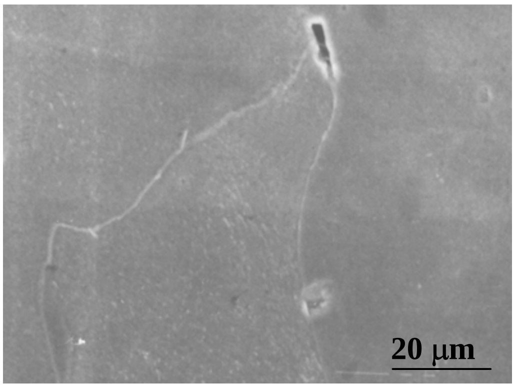

Figure 7. SEM micrograph illustrating void nucleation at the grain boundary ahead of the crack tip under mixed mode I/III loading

The load versus load - line displacement plots under mixed mode I/III loading also exhibit serrations in the temperature regime 383 K to 473 K (Fig. 2) suggesting DSA in the same temperature range even though loading is mixed mode I/III. The fracture mechanism (Fig. 7) [5] under mixed mode loading is also by void nucleation at the intersection of the slip bands with the grain boundary in the trajectory of the crack. Thus the variation of mixed mode I/III fracture toughness with temperature can be attributed to the variation of *n* as a consequence of the DSA phenomenon.

4 CONCLUSIONS

1) The mixed mode I/III fracture toughness of Armco iron increases significantly with increasing temperature beyond 383 K attaining a peak value at 473 K.

2) The variation of mixed mode I/III fracture toughness with temperature is attributed to a similar variation of strain hardening exponent *n* with temperature as a consequence of the DSA phenomenon in the temperature range 383 -523 K.

5 ACKNOWLEDGEMENT

The authors thank Defence Research and Development Organization for providing funding and facilities for carrying out the work. One of the authors (PRR) is grateful to the Indian Space Research Organization for the award of a Professorship.

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