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CAN STRETCH ZONE MEASUREMENTS PROVIDE A GOOD ESTIMATE OF FRACTURE TOUGHNESS?

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ABSTRACT

Stretch zone measurement on the fracture surfaces is often used for ductile fracture estimations. However, it is not clear whether to use the stretch zone width or stretch zone depth for such evaluations. Both these dimensions have been used by several researchers for correlation with fracture toughness. While some researchers claim the use of stretch zone width, others recommend stretch zone depth for ductile fracture estimation. Moreover, a unified procedure for stretch zone depth measurement is not available in the literature. In this work, a method is proposed for stretch zone depth measurement and influence of prestrain on ductile fracture of two varieties of Cu-strengthened HSLA steels have been examined through both stretch zone width and stretch zone depth measurenments. Results are compared with the variation in fracture toughness (J_i) with prestrain. It is noted that the stretch zone depth measurements could predict the nature of variation in fracture toughness with prestrain for both the steels than the stretch zone width. It is therefore concluded that stretch zone depth measurements can be a useful method whenever the trend in the fracture toughness variation with respect to material/process parameter is to be examined. However, J estimated from stretch zone width provides a better approximation of the toughness and the nature of variation would also follow a similar trend as J_i only beyond the inhomogeneous yielding zone of these steels.

KEYWORDS

Fracture Toughness, Stretch Zone Width, Stretch Zone Depth, HSLA Steels

INTRODUCTION

Ductile fracture behaviour of materials is usually characterised by the J-integral – an elastic plastic fracture mechanics parameter. The procedure of ductile fracture toughness evaluation involves identifying a critical J value corresponding to a specific ductile crack extension on the J versus crack extension plot, known as the J resistance (J-R) curve. However, this procedure has been proven to be erroneous for high toughness materials when ASTM standards [1] are followed to characterise the critical fracture toughness J_{IC} [2-6]. An alternate method for such materials is to measure the extent of plastic blunting of the crack tip on the fracture surface of the tested specimen and correlate it to J_i on the J-R curve.

In an earlier work to study the influence of prior deformation on the ductile fracture behaviour of Cu-strengthened HSLA steels used for ship building applications [7], it was noted that the critical fracture toughness, J_i, was retained up to 2% prestrain beyond which it was observed to be decreasing. This observation is significant, since normally one would expect the fracture toughness to decrease with prestrain. However, in order to confirm whether the initial retention in fracture toughness is real or the method of determination of J_i from the J resistance curve fails to take into consideration the effect of prestrain, the alternate method was explored.

The initiation regime fracture of ductile materials leaves an imprint of the phenomena in terms of a characteristic featureless region called the stretch zone followed by tearing which can be observed under a scanning electron microscope (SEM). This stretch zone represents the extent of crack tip blunting prior to actual crack extension and thus has a correlation with the initiation fracture toughness of the material. The size of this stretch zone is a characteristic of the material. Several attempts have been made to measure this stretch zone dimension and obtain an appropriate correlation with ductile fracture toughness [8-16]. Normally, in highly ductile materials, stretch zone would have two components *viz*., stretch zone width (*SZW*) and stretch zone depth (*SZD*). Both *SZW* and *SZD* are closely related to fracture toughness. However, there is no agreement on which of these stretch zone dimensions should be used for determining critical fracture toughness. Some researchers have used *SZW* [10-14] while others have used *SZD* [15,16] for obtaining ductile fracture toughness. Moreover, while *SZW* measurements can be made easily under SEM, direct *SZD* measurements are difficult due to complications in observing the specimen end-on under SEM. In this work, a procedure for *SZD* measurement is proposed, and an attempt is made to relate both *SZW* and *SZD* to ductile fracture toughness. The appropriateness of using *SZW* and *SZD* for ductile fracture determination is discussed by comparing the nature of variation of respective fracture toughness estimations with prestrain and that of J_i obtained from *J-R* curves.

EXPERIMENT

Material

The materials employed in this investigation are two varieties of quenched and tempered Cu-strengthened HSLA steels designated as HSLA-80 and HSLA-100. The chemical composition and the mechanical properties of the two steels are given in Table 1 and Table 2 respectively. The microstructure of HSLA-80 was acicular ferrite while that of HSLA-100 was observed to be tempered bainite. The materials were available in the form of 20mm (HSLA-80) and 25mm (HSLA-100) thick plates.

TABLE 1

CHEMICAL COMPOSITION OF HSLA STEELS IN WT. %

Steel	C	Mn	P	S	N	Si	Cr	Mo	Al	Nb	Ni	Cu
HSLA-80	0.05	1.00	0.009	0.001	0.01	0.34	0.61	0.51	0.025	0.037	1.77	1.23
HSLA-100	0.06	0.84	0.011	0.003	0.008	0.25	0.74	0.58	0.023	0.03	3.47	1.54

TABLE 2

MECHANICAL PROPERTIES OF HSLA STEELS

Steel	σ_{YS} MPa	σ_{UTS} MPa	%El	Uniform Elong. %#	%RA	n†	Hardness VHN	Charpy Energy J	YS/UTS
HSLA-80	650	715	24.2	10.5	75.8	0.12	250	218	0.91
HSLA-100	840	884	21.6	8.1	73.5	0.08	300	192	0.95

† obtained from $\sigma = k\varepsilon^n$, σ = true stress, ε = true strain, in plastic range

over 25mm gauge length

Fracture Toughness Test

Specimen blanks of 5mm x 20mm cross-section were cut from the plates and single edge notch bend (SENB) specimens were prepared after prestraining them in tension to 1%, 2%, 3%, 4% and 5% of total strain. *J* tests were carried out by employing single specimen unloading compliance method. A location independent CCL relation was used for crack length measurements [17]. The *J* and the crack opening displacement, δ, values at each unloading were calculated and a plot of *J* versus Δa obtained. The departure of the *J* resistance curve from the experimental blunting line drawn to the initial linear region of the *J* resistance curve is taken as J_i.

Stretch Zone Measurement

Fracture surfaces extracted from the tested specimens are examined under SEM such that the plane of fracture is normal to the electron beam. A representative stretch zone feature is recorded at mid-thickness of the specimen. The specimen is then tilted through 45^o about an axis through the crack front. While tilting, care is taken to ensure that there is no lateral shift of the specimen. A record of the stretch zone in this tilted view is also made.

The stretch zone boundaries in both untilted and tilted conditions are traced on to a transparency sheet. Horizontal grid lines are superimposed over these tracings and a number of (as many as 35) measurements made. Correspondence between untilted and tilted measurements is maintained by noting reference features in both the cases. The scheme is shown in Fig. 1. While the untilted view give *SZW*, *SZD* is calculated from a geometric inter-relation between the untilted and tilted conditions that is derived below with reference to Fig. 2.

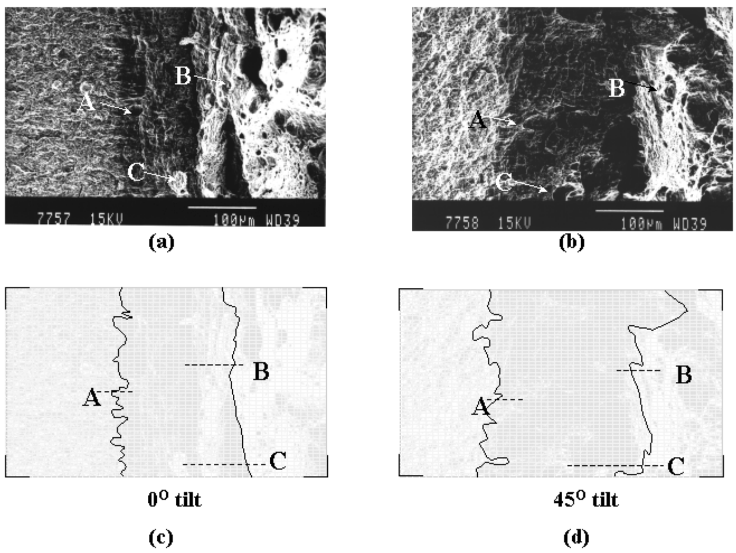

Figure 1: Typical stretch zone in (a) untilted and (b) 45^o tilted view and (c) & (d) the measurement procedure with reference locations

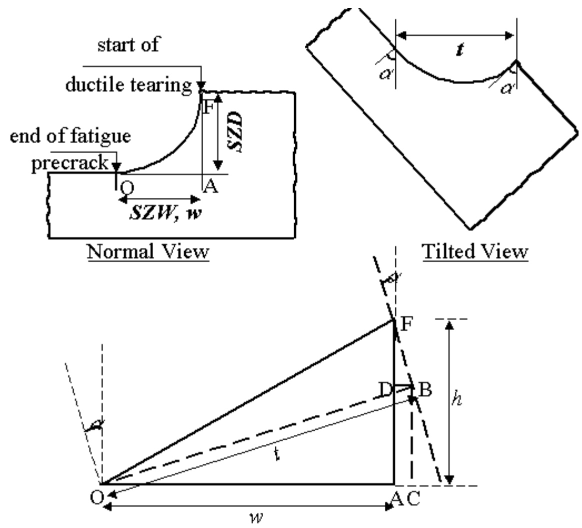

Figure 2: Geometrical inter-relation between normal and tilted configuration of specimen

From Fig. 2, $\text{OC} = \text{OB}\cos\alpha = t\cos\alpha$ since $\text{OB} = t$,

and $\text{DB} = \text{AC} = \text{OC} - \text{OA} = t\cos\alpha - w$ since $\text{OA} = w$

Similarly, $\text{DA} = \text{BC} = \text{OB}\sin\alpha = t\sin\alpha$,

and $\text{FD} = \dfrac{\text{DB}}{\tan\alpha} = \dfrac{t\cos\alpha - w}{\tan\alpha}$

F denotes the point at which the stretch zone ends and ductile tearing starts. Hence FA is the *SZD* of height *h*. Therefore, it can be written that

$$SZD = h = \text{FD} + \text{DA}$$

$$= \frac{t\cos\,\alpha + t\,\sin\alpha\,\tan\alpha - w}{\tan\,\alpha} + \tan\alpha \qquad (1)$$

If the specimen is tilted through an angle $\alpha = 45^{\circ}$ the Eqn. 1 becomes

$$SZD = h = \sqrt{2}\,t - w \qquad (2)$$

The measurements made in the untilted and tilted conditions thus refer to *SZW*, *w* and *t* respectively. Using Eqn. 2, the *SZD, h*, is calculated for each pair of *w* and *t* measured. Average of all the *w* and *h* measurements were considered as the *SZW* and *SZD* respectively. The exercise was carried out for both the steels at all prestrain levels.

Fracture Toughness from Stretch Zone Geometry

As *SZW* is equivalent to the critical value of Δa at which ductile fracture initiates, a vertical to the ordinate is drawn at Δa = *SZW* on the experimentally derived J-Δa plot. Intersection of this vertical with the *J* resistance curve is taken as the initiation toughness from *SZW* measurements, J_{SZW}.

For evaluating the initiation toughness from *SZD* measurements, J_{SZD}, the J-δ plot for the same set of experimental data is constructed. A vertical at the ordinate corresponding to δ = *2SZD* is drawn. Intersection of this vertical with the J-δ curve is noted as J_{SZD}.

RESULTS AND DISCUSSION

Effect of Prestrain on Stretch Zone Geometry

Variation of the mean *SZW* and *SZD* of HSLA-80 and HSLA-100 with prestrain is shown in Fig.3. The magnitude of *SZD,* for both the HSLA steels remained constant up to ~2% prestrain, beyond which it decreased markedly. This nature of variation is similar to the variation of J_i that was described earlier. However, the same is not true for *SZW*. In case of HSLA-80, *SZW* showed a decreasing trend while for HSLA-100, it showed an increasing trend with prestrain. The nature of variation of *SZD* with prestrain thus strongly qualifies the use of *SZD* for determining the fracture toughness.

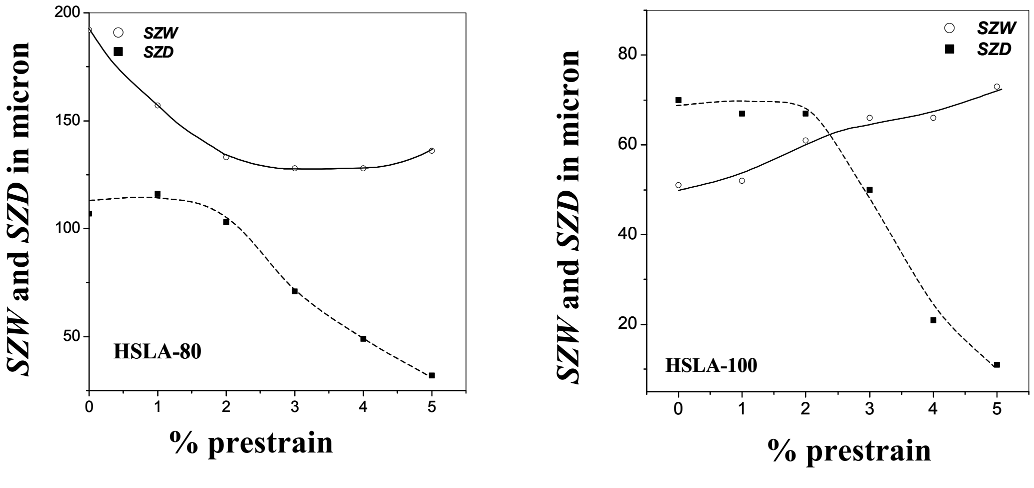

Figure 3: Variation of stretch zone dimensions with prestrain

Variation of J_{SZW} and J_{SZD} with Prestrain

The variation of J_{SZW} and J_{SZD} with imposed prestrains is depicted in Fig.4 and Fig. 5 for HSLA-80 and HSLA-100 steels respectively. Included in the plots are the J_i values at various prestrains for comparison. It may be noted from these figures that the nature of variation of J_{SZD} with prestrain is similar to that of J_i for both the steels. The magnitude of J_{SZD}, however, is lower than that of J_i through the entire range of prestraining investigated for both the steels. J_{SZW} in both the steel does not reflect the trend exhibited by J_i.

It decreases with prestrain for HSLA-80 and does not show a systematic variation (at least up to 2% prestrain) for HSLA-100 steel. Nonetheless, it is interesting to note that the magnitude of J_{SZW} compares well with that of J_i at prestrains greater than ~2% in both the steels. This is thought to be significant from the point of view that both the steels exhibit non-homogeneous deformation up to a strain level of about 1.5 to 2.5%, which is manifested in the form of Luders stretch (in HSLA-80) or low hardening rates (HSLA-100) during tensile deformation of the steels.

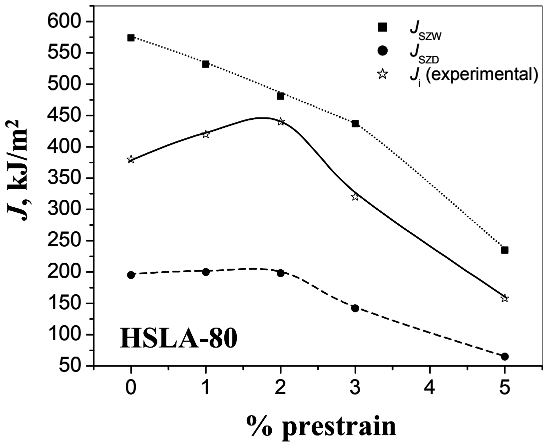

Figure 4: Variation of J_{SZW}, J_{SZD} and J_i with prestrain for HSLA-80 steel

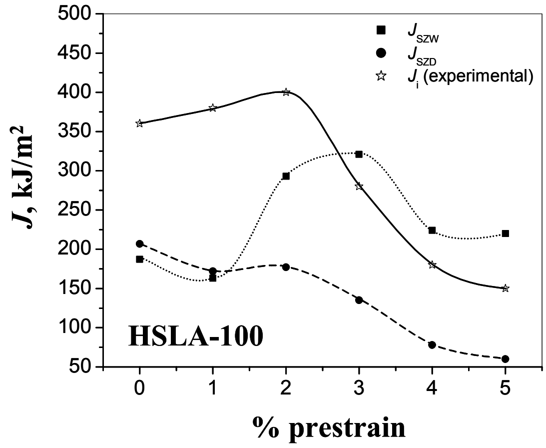

Figure 5: Variation of J_{SZW}, J_{SZD} and J_i with prestrain for HSLA-100 steel

The failure of *SZW* or *SZD* in predicting the trend and magnitude of J_i with prestrain can be attributed to a number of reasons. Inaccuracies in identifying the start and end of stretch zone extents may reflect in the measurement of *w* and *t*. Restricting measurements to the mid-thickness of specimens may produce significant contributions to the average stretch zone geometry originating from the flanks of the crack front. Minor errors will also be included due to non-consideration of elastic components of blunting/stretching that are recovered on unloading. By far the most important source of error can be traced to the occurance of secondary cracks within the blunted crack profiles (see Fig. 6) that have been observed in both the steels. Such cracks may influence the determination of J_{SZW} and J_{SZD} in the following ways:

(i) secondary cracks will contribute to the compliance of the specimen and result in the enhancement of the crack length measured during testing by the compliance technique. This will lead to a lower value of J_{SZW} and J_{SZD} to be read from experimental plots.

(ii) post test measurements of *SZW* and *SZD* are liable to be significantly different to the values existing at the time of testing.

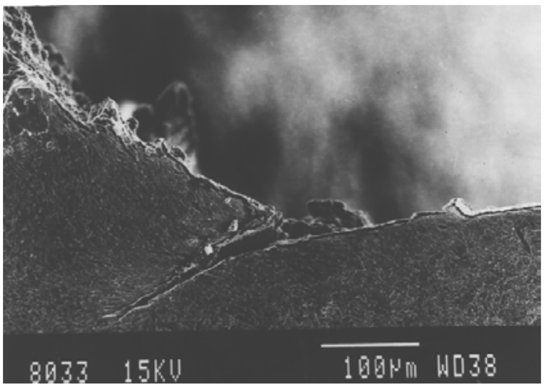

Figure 6: Presence of a secondary crack in the blunted profile of crack

CONCLUSIONS

From the investigation carried out on initiation toughness measurement via stretch zone geometry in HSLA steels, it can be concluded that

(i) use of *SZD*, in preference to *SZW*, provides a better appreciation of the trend of variation of ductile fracture toughness with external conditioning influence like prestrains.

(ii) SZW provides a better measurement of ductile fracture toughness when material deformation through non-homogeneous processes is absent.

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