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The essential work of plane stress ductile fracture of a strain-aged steel

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The paper reports the results of an experimental investigation on the essential work of fracture of a strain-aged low carbon (~ 0.1% C) temper-rolled 16-gauge sheet steel which has been subjected to pre-strain levels of 2 to 12% and ageing temperatures of 80 and 100° C. Deep edge-notched tension specimens were used to determine the specific essential work by extrapolating the straight-line relationship between the specific work of fracture (w_f) and ligament length (l) to zero ligament length. The strain-aged steels at 80 and 100° C give approximately the same specific essential fracture work of 0.18 to ~ 0.20 J mm^{-2} which is independent of the amount of prestrain. Advancing crack opening displacements (C.O.D.) have also been analysed, which give 0.60 to 0.63 mm for the strain-aged steels. For comparison, the prestrained but unaged steels have a higher essential work of fracture of 0.275 J mm^{-2} and a larger C.O.D. of 0.73 mm. It is concluded, therefore, that the causes of strain-ageing embrittlement are primarily due to the reduction of both the essential work of fracture and the advancing C.O.D. at the crack tip end region.

1. Introduction

In brittle materials, dissipative work is intimately involved in the fracture process and the plastic zone is small so that linear elastic fracture mechanics is appropriate. However, in ductile materials, thin sheet metals in particular, the inelastic zone of the advancing crack tip is large. Broberg [1–3] suggested that this plastic region should be divided into two regions: an end region where the actual necking and fracture process takes place and a surrounding region where energy flow into the end region is increasingly screened. In some preliminary experiments, Cotterell and Reddell [4] have shown that the work performed at this end region is a material constant for a particular sheet thickness. They call this the specific essential work of fracture (w_e). Plastic work performed in the outer screening region is called the non-essential work (w_p) and is dependent on the specimen geometry.

Strain-ageing of steel has been a subject of considerable research and a critical review was given by Baird [5]. There are two obvious aspects of strain-ageing: one is the increase of yield stress* and the other is the embrittlement of the steel which is usually characterized by a reduction of the total fracture work or an increase in the ductile–brittle transition temperature. It is the latter aspect of strain-ageing on the fracture behaviour of steel to which this paper is addressed. Experiments have been performed by previous investigators on strain-aged mild steels using double edge-notched tension plate specimens to determine the minimum prestrains necessary for the shear-cleavage fracture transitions and the associated changes in the NDT temperatures [6, 7]. However, no fracture mechanics analysis is presented in these investigations. Fracture experiments have also been conducted on strain-aged circumferentially notched tension mild steel

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* The increase of yield stress, whether due to strain-ageing or prestraining, is an important contributor for embrittlement of mild steel.

bars [8]. The results obtained show that the amount of plastic strain measured across the notch root decreases with the amount of prestrain. The total work of fracture measured by the area under the load–deflection curve is also found to decrease with increasing prestrain. Detailed examination of the fractured specimens has shown that the brittle fracture has never occurred but that there is some uniform stretching across the notched section. In these experiments, however, it is not possible to partition the total work of fracture into the essential work (w_e) which is dissipated at the notch tip end region and the non-essential plastic work (w_p) performed in the outer notched section. Moreover, the plastic strain across the notch root is not a useful quantifying parameter for characterizing embrittlement due to strain-ageing as this depends largely on the notch geometry.

It seems to the authors that previous work has not fully explained the mechanics of embrittlement due to strain-ageing. Although the raising of the NDT temperature and the reduction of total work of fracture have been firmly established, little basic understanding of the fracture process has been advanced. Since fracture is elasto–plastic in strain-aged sheet steels before the onset of the shear–cleavage transition the ductile fracture mechanics concepts advanced by Broberg [1–3] and pursued by Cotterell and Reddell [4] should be appropriate.

2. Determination of essential work of fracture in strain-aged steels

Cotterell and Reddell [4] have shown that the deep edge-notched tension specimen is the most appropriate to determine the essential work of fracture in thin sheet metals. When such a specimen yields completely before crack initiation, the plastic region is confined entirely to a circular area about the ligament as shown in Fig. 1. If the ligament (l) is sufficiently large the major portion of the fracture surface is slant fracture and the essential work performed at the end region is proportional to l. The amount of non-essential work done in the plastic region is proportional to the area of this region and hence l^2. Thus the total work of fracture is given by

$$W_f = ltw_e + l^2tw_p \tag{1}$$

where t is the sheet thickness, w_e the specific essential fracture work and w_p the non-essential work performed in the outer region in a specimen with unit thickness and ligament length. Equation 1 may be rewritten as

$$w_f = \frac{W_f}{lt} = w_e + lw_p. \tag{2}$$

Thus if the specific work of fracture, w_f, is plotted against l a straight line should be obtained with a positive intercept giving the specific essential work (w_e). The slope of this straight line also gives the specific non-essential work (w_p) and it may be inferred that when w_p approaches zero, the fracture process will be accompanied by plastic work contribution confined to the necking process zone only. Plastic work consumed outside of this end region is negligible. However, it should be noted that Equation 1 is valid only when the ligament is in a state of plane stress and fracture occurs after complete yielding of the ligament. This imposes upper and lower limits on the ligament length. Cotterell and Reddell [4] suggested that the upper limit is determined by the plastic zone size ahead of a crack tip in a large sheet and the lower limit is governed by the sheet thickness and is of the order of $4t$. Thus the boundaries of the ligament length should be in the range of

$$\frac{l}{\pi}\left(\frac{K_c}{\sigma_y}\right)^2 > l > 4t \tag{3}$$

where K_c is the plane stress fracture toughness and σ_y is the yield stress. Cotterell [9] has also shown that a gross width of specimen three times the ligament length is satisfactory in confining the plastic region to the ligament.

It is proposed in this paper that the fracture mechanics of prestrained and strain-aged sheet steels can be studied more effectively using such

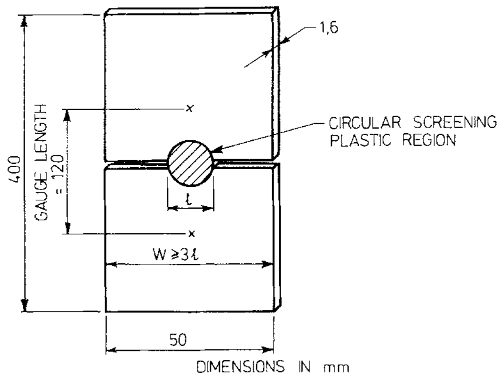

Figure 1 The deep edge-notched tension sheet specimen.

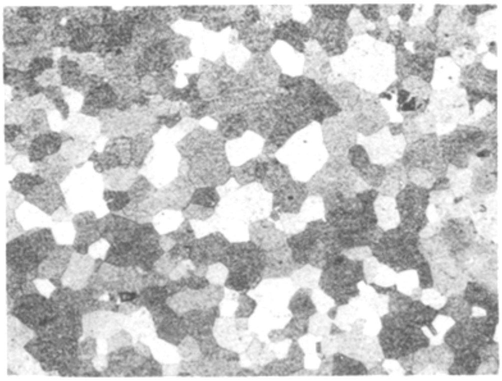

Figure 2 Microstructure of the low carbon temper-rolled sheet steel (× 145).

deep edge-notched tension specimens. For a fully aged low-carbon sheet steel it is expected that the specific essential work (w_e) is a constant and is independent of the amount of prestrain applied to the steel before ageing. Prestrain only affects the non-essential work (w_p) performed in the outer plastic screening region. The embrittlement effects of strain-ageing can be studied by comparing the total work of fracture (W_f), the specific essential work (w_e) and the non-essential work (w_p) of a prestrained but unaged steel.

3. Experimental details

A temper-rolled low carbon (~0.1% C) 16-gauge sheet steel was chosen for the present investigation. In the transverse direction the yield stress is 320 MPa, the ultimate tensile strength is 400 MPa and the elongation at break on 50 mm gauge length is approximately 40%. The microstructure is shown in Fig. 2.

Rectangular specimens of dimensions 400 mm × 50 mm were cut from the sheet metal such that the loading would be transverse to the rolled direction. Scribed marks 120 mm apart were then made on the specimens before they were prestrained in the Shimadzu tensile testing machine. The exact amount of prestrain was measured by the final separation of these two scribed lines. With some experience the prestrains applied could be controlled to within ± 0.5%. For the unaged specimens the nominal mean prestrains were 2.38%, 5.60%, 7.89%, 10% and 11.71%. For those specimens to be aged at 80 and 100° C the amount of prestrains are (2.34, 7.89, 11.71%) and (2.41, 7.97, 12.33%) respectively. Full ageing was assured by measuring the hardness variation with ageing time and the experimental results showed that 4 h at 80° C and 2.5 h at 100° C were adequate. The time for full ageing was apparently independent of the amount of prestrain applied to the specimens before ageing.

Edge notches were finally introduced midway on the long sides of both the unaged and aged rectangular sheets so that a series of specimens with ligament length varying from 5.5 to 17 mm

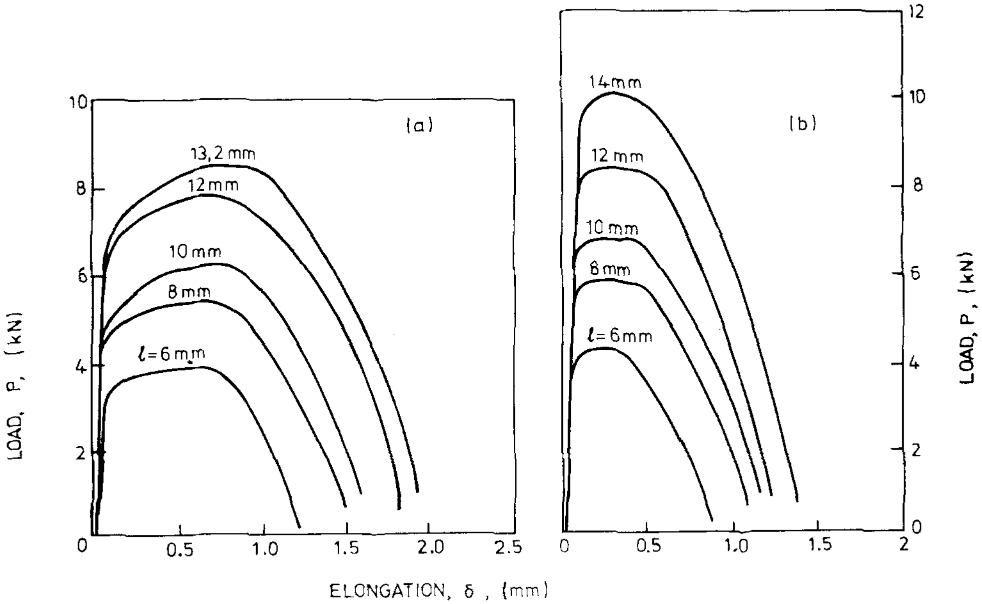

Figure 3 Typical load–deflection diagrams for unaged deep edge-notched tension specimens with varying ligament length (l). (a) 2.38% prestrain, (b) 11.71% prestrain.

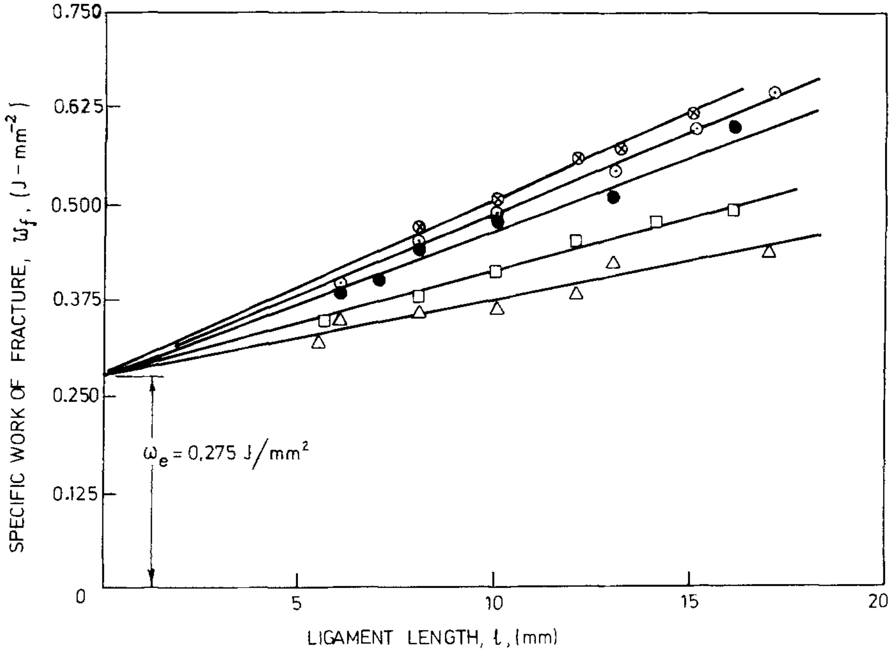

Figure 4 Specific work of fracture against ligament length for unaged specimens with varying amount of prestrain. ⊗ 2.38%, ⊙ 5.60%, ● 7.89%, □ 10%, △ 11.71%.

were obtained. The last 3 mm of the notches were finished with a 0.15 mm blade. Since the average sheet thickness was 1.50 mm, the smallest ligament was approximately $4t$. These specimens were then fractured in the Shimadzu tensile testing machine and the load–elongation curves recorded autographically with an X–Y recorder. The elongation of the specimens was measured over a gauge length of 120 mm with two clip gauges one on each side of the specimen.

4. Results and discussion

The fracture experiments of all the unaged and strain-aged specimens were completely ductile and stable. Typical load–deflection curves for various ligament sizes are shown in Fig. 3a and b. Fracture initiation always occurred at or after the maximum load thus indicating the presence of gross ligament yielding before cracking at the notch tips. From the areas under the load–deflection curves the specific work of fracture (w_f) can be calculated and plotted against the ligament length (l). These results are given in Fig. 4 to 6.

It is obvious that for a given prestrain of the unaged specimens (Fig. 4), all the experimental data lie on a straight line which can be back-extrapolated to give the specific essential work of fracture (w_e). Clearly, for a wide range of prestrain levels, 2 to 12%, the specific essential work is shown to be a constant with a value of 0.275 J mm^{-2}. The amount of prestrain does not seem to have any significant effects on the essential work of fracture. However, the specific non-essential work (w_p) which is given by the slope of the straight line shown in the figure increases with decreasing prestrain. This result can be correlated to the differences in the experimental load–deflection curves such as shown in Fig. 3a and b. For instance, for a given ligament length, the 2.38% prestrain specimens (Fig. 3a), show a large amount of plastic flow whereas the 11.71% prestrain specimens (Fig. 3b), exhibit much less plastic flow around the ligament region.

As shown in Fig. 7 the specific non-essential fracture work (w_p) decreases rapidly with increasing prestrains. From an additional series of experiments conducted on 16% to 30% prestrained specimens, it was found that w_p was constant at about 5 mJ mm^{-3} and did not approach zero as suggested. A theoretical analysis has been developed recently to explain these results and will be presented in a forthcoming publication. The essential fracture work (w_e) for these prestrained specimens was about 0.26 J mm^{-2}. Examination of the fractured surfaces showed that the fracture

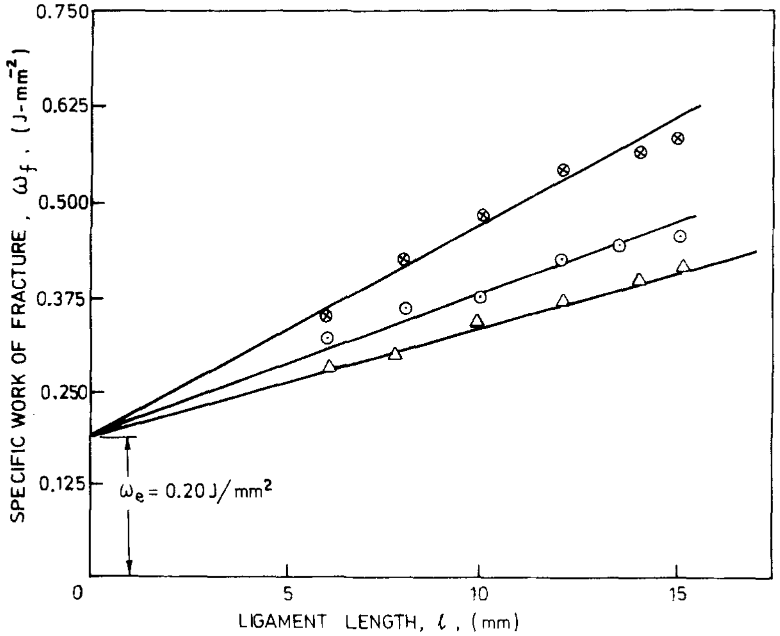

Figure 5 Specific work of fracture against ligament length for strain-aged specimens at 80° C. ⊗ 2.41%, ⊙ 7.97%, △ 12.33%.

was still in plane stress and there was localized necking in the ligament region.

The experimental results of the strain-aged specimens of two ageing temperature (80 and 100° C) and three prestrain levels, (Figs. 5 and 6), fit the straight line relationship of Equation 2 very well. Again the amount of prestrain does not affect the specific essential work but the non-essential work increases with decreasing prestrain for the same reason as the unaged specimens, i.e. larger plastic flow around ligament for smaller prestrains. The specific essential work of fracture for the fully aged steels at 80 and 100° C shows little difference, i.e. 0.20 J mm^{-2} aged at 80° C as opposed to 0.185 J mm^{-2} aged at 100° C. This is probably a result of the fact that temperature

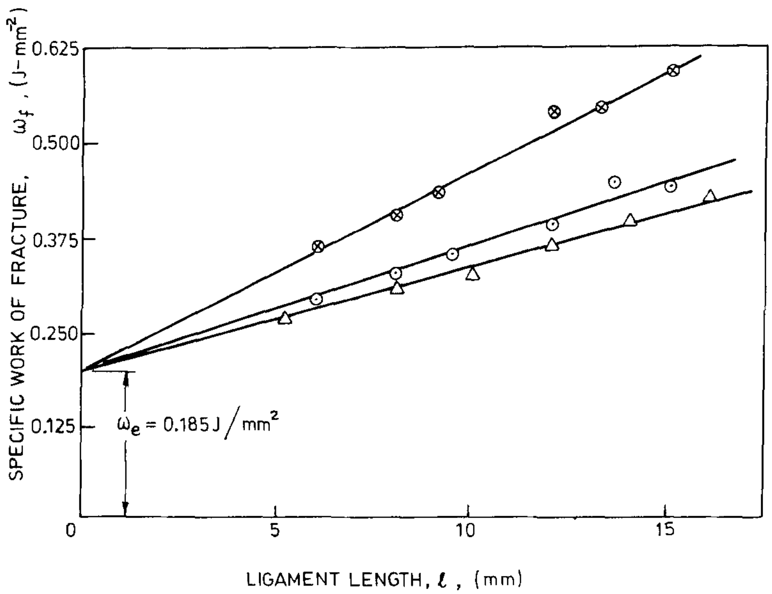

Figure 6 Specific work of fracture against ligament length for strain-aged specimens at 100° C. ⊗ 2.48%, ⊙ 7.77%, △ 11.78%.

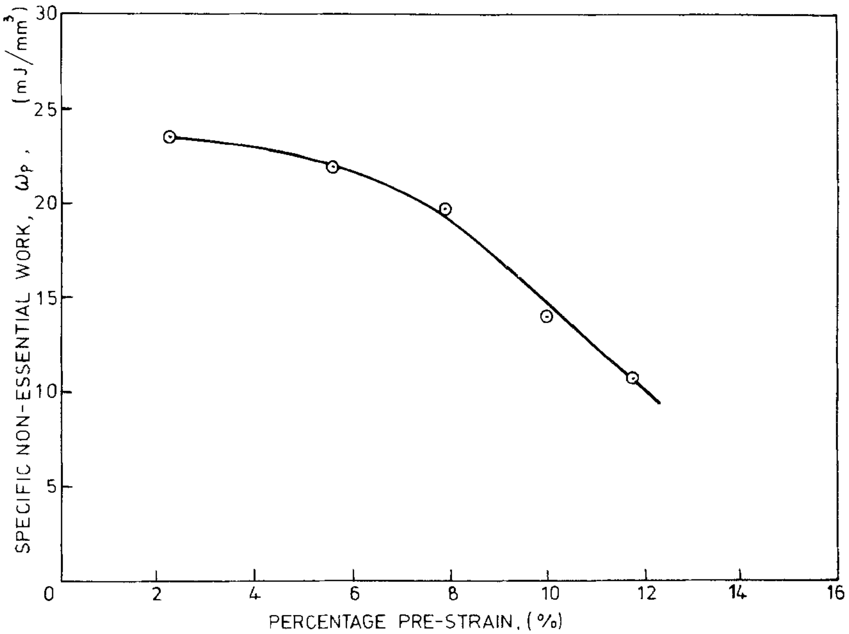

Figure 7 Specific non-essential work against percentage of prestrain for unaged specimens.

only affects the rate of diffusion of interstitial solutes and does not change appreciably the amount of interstitials and precipitates at dislocations at full ageing.

A comparison of the experimental results shown in Fig. 4 to 6 reveals that the primary effects of strain-ageing are to reduce both the total work (w_f) and the specific essential work (w_e) of fracture. A better interpretation of these data may be inferred from Fig. 8 which shows the normalized specific work of fracture, w_f/w_e, for the aged and unaged specimens at two similar

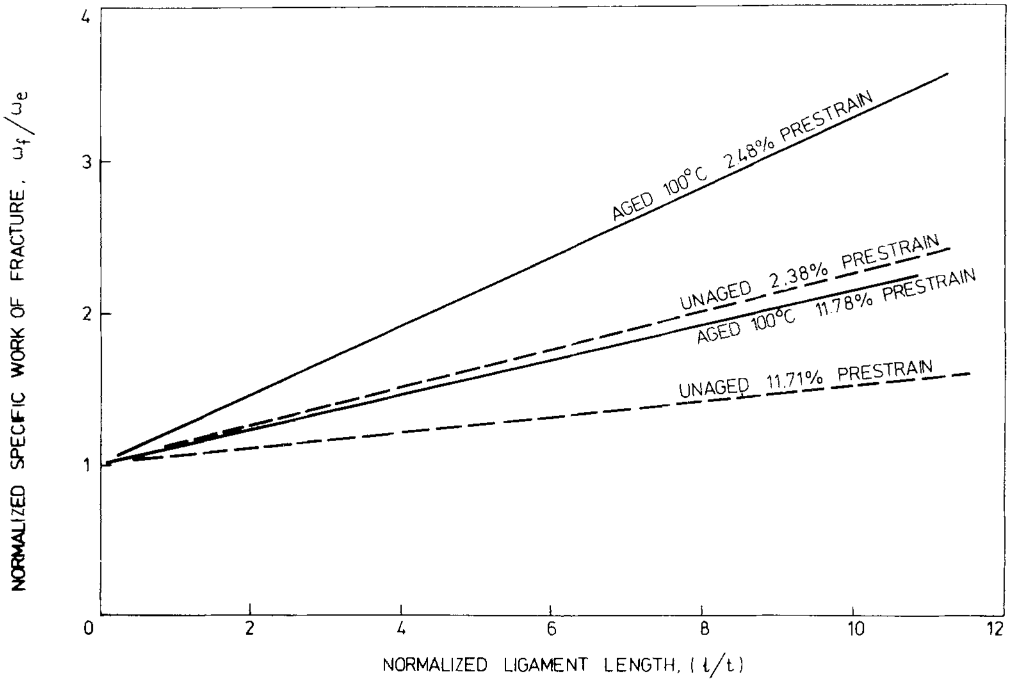

Figure 8 Normalized specific work of fracture against normalized ligament length for unaged and aged specimens at two similar prestrain levels.

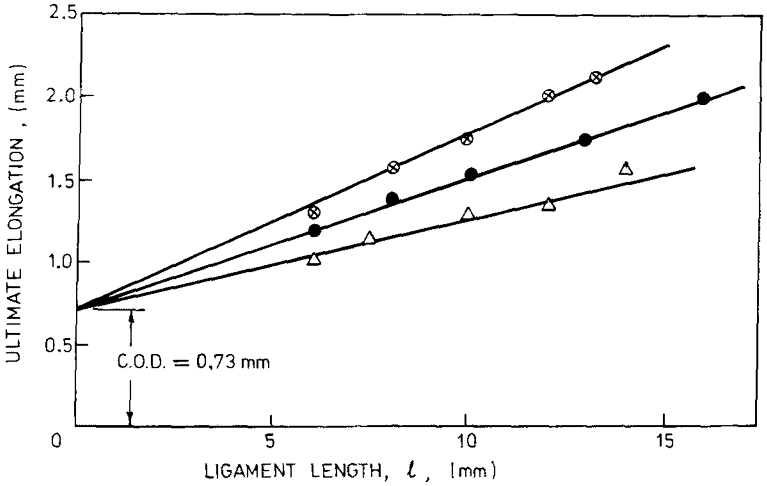

Figure 9 Ultimate elongation against ligament length for unaged specimens. ⊗ 2.38%, ● 7.89%, △ 11.71%.

prestrain levels as a function of the normalized ligament length, l/t. The specific essential work for the unaged specimens forms a much larger proportion of the total work of fracture than for the aged specimens at similar prestrain levels. This is consistent with the fact that more intense necking occurred in the unaged specimens. For both the aged and unaged specimens increasing the prestrain increases the proportion of the total work of fracture to flow to the crack tip end region to perform essential work.

Cotterell [9] has shown that the crack opening displacement (C.O.D.) can be used to give an estimate of the specific essential work. By plotting the ultimate elongation (δ_u) against the ligament length (l) and extrapolating to zero ligament length [4, 9], the C.O.D. of the advancing crack tip may be determined easily (see Equation 6). Since the shape of the load–deflection curve is approximately parabolic, the work of fracture is given by

$$W_f = \tfrac{2}{3} P_m \delta_u, \tag{4}$$

where P_m is the maximum load. As shown in Fig. 3a and b there is geometric similarity between specimens before a crack is initiated and the maximum load according to Hill [10] is

$$P_m = \frac{2}{\sqrt{3}} \sigma_u l t, \tag{5}$$

where σ_u is the ultimate tensile strength. Combining Equations 2, 4 and 5 gives

$$\delta_u = \frac{3\sqrt{3}}{4} (w_e + l w_p)/\sigma_u. \tag{6}$$

Figs. 9 to 11 show the experimental results of the unaged and strain-aged specimens according to Equation 6. The intercept on the vertical axis, $(3\sqrt{3}/4)\ (w_e/\sigma_u)$, gives the advancing C.O.D. at the crack tip end region [4, 9]. Thus for the unaged specimens the advancing C.O.D. is 0.73 mm

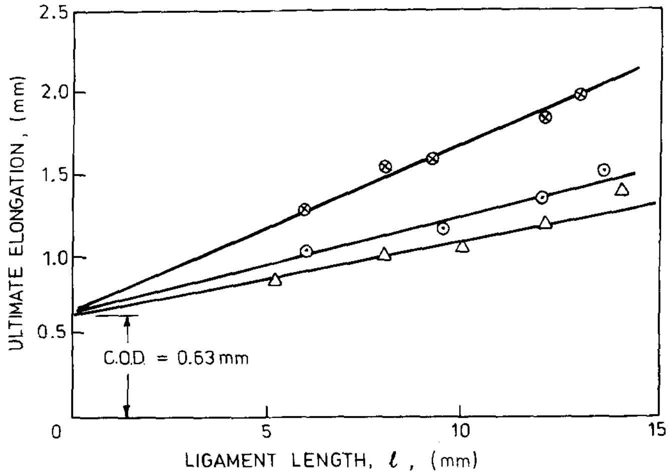

Figure 10 Ultimate elongation against ligament length for strain-aged specimens at 80° C. 2.41%, ⊙ 7.97%, △ 12.33%.

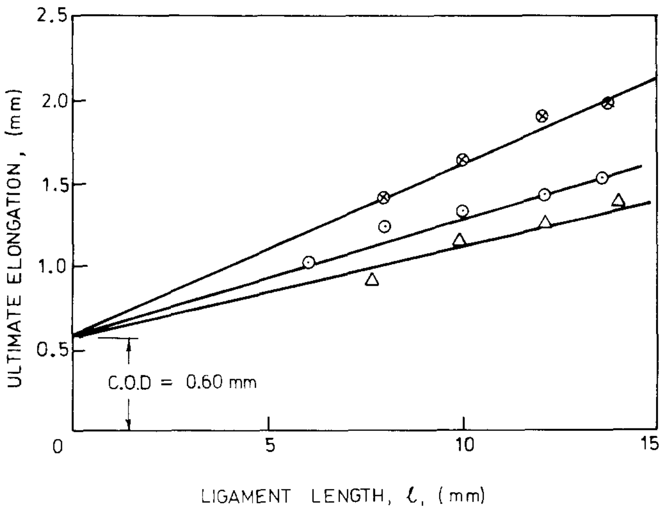

Figure 11 Ultimate elongation against ligament length for strain-aged specimens at 100° C. 2.48%, ⊙ 7.77%, △ 11.78%.

and for the strain-aged specimens at 80 and 100° C the C.O.D. values are 0.63 and 0.60 mm respectively. These results show that the embrittlement effect of strain-ageing is to reduce the crack opening displacement at the notch tip end region. This finding is consistent with the smaller specific essential work of fracture obtained for the strain-aged specimens (see Figs. 4 to 6). It should also be noted that like the specific essential work, these advancing C.O.D. values are apparently independent of the amount of prestrain (see Figs. 9 to 11). Using these C.O.D. values and the appropriate ultimate tensile strengths the specific essential work may be computed from

$$w_e = \frac{4}{3\sqrt{3}}\sigma_u(\text{C.O.D.}). \qquad (7)$$

As shown in Table I the specific essential work calculated from the above equation compares extremely well with those results obtained from the intercepts of Figs. 4 to 6.

Although strain-ageing reduces both the total and specific essential work of fracture (see Figs. 4 to 6), i.e. w_f and w_e, it is not yet clear if the non-essential work (w_p) should also be decreased. The present experimental results (see slopes of straight lines shown in Figs. 4 to 6), however, give similar specific non-essential work values for both the unaged and strain-aged specimens. This is probably a result of the lower ultimate elongation but higher ultimate tensile strength of the strain-aged specimens and vice versa of the unaged specimens.

While the experimental results of the present work are in general agreement with those reported by previous investigators [5–8], such as smaller w_f due to strain-ageing and prestrain and hence larger NDT temperatures, the paper has further clarified the mechanics of the plane stress ductile fracture process in strain-aged low carbon steels. It is the reduction of the specific essential work of fracture, or equivalently the advancing C.O.D. at the crack tip end region, that is principally respon-

TABLE I Specific essential work of fracture for unaged and strain-aged specimens

Condition	Crack opening displacement, C.O.D. (mm)	Ultimate tensile strength, σ_u^* (MPa)	Specific essential work, w_e (J mm^{-2})	
			Eq. (7)	Measured
Unaged	0.73	400	0.230	0.275
Aged at 80° C	0.63	410	0.205	0.200
Aged at 100° C	0.60	430	0.190	0.185

* Although σ_u increases slightly with prestrain only the average value of all the prestrains is used to calculate w_e from Equation 7.

sible for the embrittlement due to strain-ageing. This new finding apparently has not been given in any previous publications on strain-ageing of mild steels.

5. Conclusions

The deep edge-notched tension specimens have been successfully used for determining the specific essential work of fracture (w_e) of both the unaged and strain-aged low carbon steels. It was found that this essential work was independent of the amount of prestrain applied to the specimens. The principal effects of strain-ageing apparently were to reduce the specific essential work (w_e), the total fracture work (w_f) and the advancing C.O.D. at the crack tip end region, i.e. $w_e = 0.275\,\text{J}\,\text{mm}^{-2}$ and C.O.D. = 0.73 mm for the unaged steel as opposed to $w_e = 0.185$ to $\sim 0.20\,\text{J}\,\text{mm}^{-2}$ and C.O.D. = 0.60 to ~ 0.63 mm for the steel strain-aged at 80 and 100° C. Since the specific non-essential work (w_p) remained approximately equal for both unaged and strain-aged specimens it was suggested that the embrittlement of the strain-aged steel was largely due to its reduced specific essential work at the crack tip end region.

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