THE PLANE STRAIN FRACTURE STRAIN OF STEELS

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ABSTRACT

The plane strain tensile test is described. The 'plane strain sensitivity' of steel is shown not to be a simple function of yield stress - the orientation and type of void forming particles being important factors. For a forging steel the plane strain fracture strain is shown to be related to the work hardening rate. The use of plane strain fracture strains for the prediction of fracture toughness values is discussed.

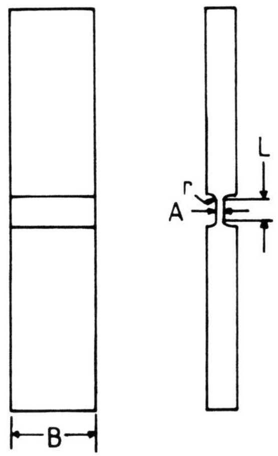

Fig.1 Clausing's plane strain tensile test piece, B=25.40 mm, L=6.35 mm, A=2.03 mm, r=1.59 mm (ref.1)

KEYWORDS

Crack opening displacement; forging steels; fracture toughness; hydrostatic stresses; plane strain tensile test; steels; work hardening.

INTRODUCTION

The plane strain tensile test was proposed and first used by Clausing (ref.1). The design of Clausing's test piece is shown in fig.1. The strain in the B-direction (see fig.1) was demonstrated to be approximately zero; hence the name 'plane strain' tensile test. Clausing found that fracture strains measured on these test pieces were considerably smaller than those measured on conventional cylindrical (uniaxial) test pieces, but were almost identical to the ductile fracture initiation strains at the notch roots of Charpy test pieces. This behaviour is ascribable to there being higher hydrostatic components of stress in the plane strain tensile test piece and the Charpy test piece than there are in the uniaxial tensile test piece. It was suggested that the plane strain tensile test piece was therefore well suited for fracture studies.

Since then there have been several studies reported in which the plane strain tensile test has been used to characterise a wide range of steels. Some of these studies are mentioned in the present paper, together with original results for a forging steel with an approximate composition of 0.34%C, 3.2%Ni, 0.96%Cr, 0.68%Mo, 0.22%V (see refs.2 and 3 for further details of this steel and experimental procedures). The relationship between the plane strain fracture strain, $\varepsilon_f(PS)$, and other tensile properties are discussed below, followed by a discussion of the relationship between $\varepsilon_f(PS)$ and fracture toughness. Note that throughout this paper, tensile fracture strains are defined by the local reductions in area.

YIELD STRESS

For the structural steels used by Clausing for his first plane strain tensile tests, it was found that the 'plane strain sensitivity', defined by the ratio of the plane strain fracture strain to the uniaxial fracture strain, $\varepsilon_f(PS)/\varepsilon_f(U)$, showed a marked dependence on yield stress, σ_y, and that there was little scatter on a plot of $\varepsilon_f(PS)/\varepsilon_f(U)$ against yield stress (see the 'structural steels' results in fig.2). The decrease in $\varepsilon_f(PS)/\varepsilon_f(U)$ with increasing yield stress was mainly due to the variation in $\varepsilon_f(PS)$, $\varepsilon_f(U)$ remaining rather constant.

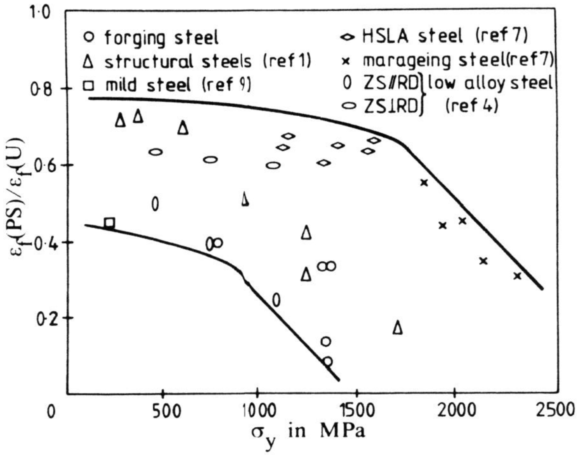

Fig.2 The variation with yield strength of the ratio of plane strain fracture strain to uniaxial fracture strain. 'R' stands for rolling direction and 'ZD' for zero strain direction in the test piece.

However, adding more recent data to Clausing's original plot creates a very broad scatter band (see fig.2). This is perhaps not surprising, since the type of particle initiating the voids that eventually coalesce to give ductile fracture would be expected to have an influence on $\varepsilon_f(PS)/\varepsilon_f(U)$.

In particular note the results of Sailors (ref.4) which show that $\varepsilon_f(PS)/\varepsilon_f(U)$ depends on the orientation of the rolling direction with respect to the direction of zero strain. The ratio $\varepsilon_f(PS)/\varepsilon_f(U)$ has a greater dependence on σ_y if the rolling direction is perpendicular to the zero strain direction than if it is parallel.

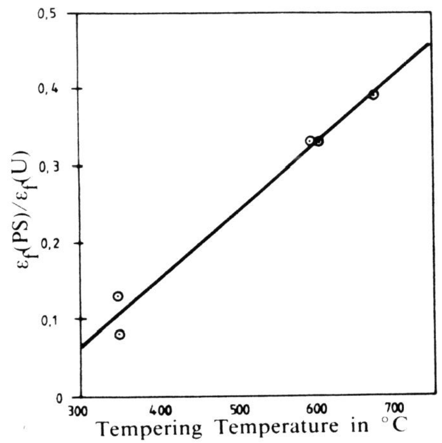

Fig.3 The variation with tempering temperature of the ratio of plane strain fracture strain to uniaxial fracture strain. data for the forging steel.

Also note the results for the forging steel. For a yield stress of about 1350 MPa, $\varepsilon_f(PS)/\varepsilon_f(U)$ may be as low as 0.08 or as high as 0.33; and for a yield stress of 780 MPa, $\varepsilon_f(PS)/\varepsilon_f(U)$ is not much higher than its highest value for a yield stress of about 1350 MPa. However, if $\varepsilon_f(PS)/\varepsilon_f(U)$ is plotted as a function of tempering temperature a much more straightforward pattern appears (see fig.3). This suggests that $\varepsilon_f(PS)/\varepsilon_f(U)$ is more dependent on the tempered martensitic microstructure than it is on the yield strength *per se*.

It may be concluded therefore that generally speaking there is a trend towards there being lower $\varepsilon_f(PS)/\varepsilon_f(U)$ ratios for higher yield strengths, but the relationship is not as simple as that implied by Clausing.

WORK HARDENING RATE

The work hardening rate R is here defined to be the average work hardening rate between 0.2% plastic strain and the instability strain, as measured on uniaxial tensile test pieces. The relationship between R and the plane strain fracture strain for the forging steel is shown in fig.4. Note that when R is plotted against tempering temperature it shows a minimum at about 600°C and $\varepsilon_f(PS)$ apparently shows a slight maximum at about 600°C (see fig.5). Therefore when R is plotted against $\varepsilon_f(PS)$, R decreases monotonically as $\varepsilon_f(PS)$ increases.

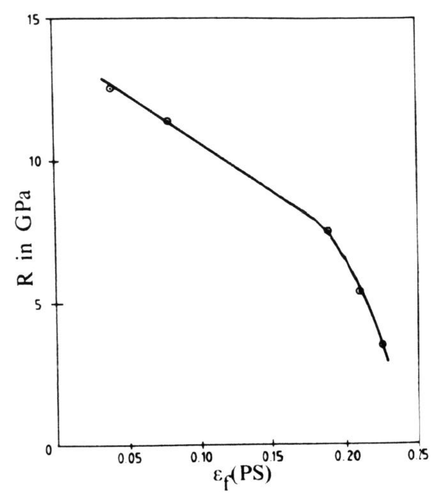

Fig.4 The variation of the work hardening rate with plane strain fracture strain. Data for the forging steel.

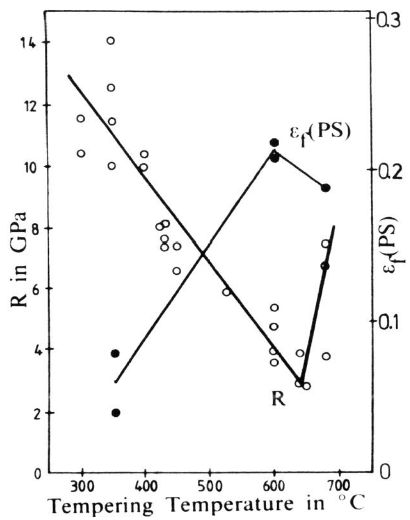

Fig.5 The plane strain fracture strain and the work hardening rate plotted against tempering temperature. Data for the forging steel.

This relationship is explicable if the interaction between dislocations and carbides is responsible for the ductile fracture micromechanisms in addition to the work hardening mechanisms. It is proposed therefore that the initiation of voids at carbide particles is caused primarily by the impingement of dislocation pile-ups on the carbides, and that once initiated the voids rapidly grow and coalesce to give final fracture.

For low tempering temperatures (about 350°C), there would still be quite a high dislocation density present in the microstructure, and also quite large inter-lath cementite particles. Because the dislocation density would be high and the carbides large, the high work hardening rate at these temperatures would be due to large amounts of dislocation/dislocation interaction and dislocation/carbide interaction. The pile-up of dislocations against the carbide/matrix interfaces would lead to low fracture strains.

For intermediate tempering temperatures (about 600°C), there would be a somewhat lower dislocation density present and large inter-lath carbides. In addition there would be a fine dispersion of small alloy carbides. The dispersion of alloy carbides keeps the yield stress approximately at its 350°C value, but after a small amount of plastic strain the small carbides would be by-passed and would not contribute significantly to the strengthening mechanisms. The value of ultimate tensile stress, σ_u, at 600°C was however lower than that at 350°C. Therefore the work hardening rate at 600°C was lower than that at 350°C. The fine dispersion of small alloy carbides would tend to promote fine slip, and may therefore reduce the amount of tangling of dislocations around the larger carbides. Also the reduced dislocation density would tend to give higher fracture strains.

At higher tempering temperatures (about 680°C), there would be a very low dislocation density, the large elongated carbides present at 600°C would have coarsened and spheroidised, and the small alloy carbides would have redissolved. The yield stress drops rapidly with increasing tempering temperature in the range 600-680°C due to the dissolution of the fine alloy carbides, whereas σ_u is not affected to such a great extent. Therefore the work hardening rate is greater for a tempering temperature of 680°C than 600°C. The low dislocation density would tend to give higher fracture strains, but presumably this effect is offset by the dissolution of the alloy carbides and the coarsening of the larger carbides which would tend to give lower fracture strains. Therefore the net effect is that the fracture strain is slightly reduced.

FRACTURE TOUGHNESS

The plain strain fracture strain has been shown to correlate well with the fracture initiation strain at the root of a Charpy test piece (ref.1), but it is not obvious that ε_f(PS) could be taken to be equal to the fracture strain ahead of a sharp crack. Assuming no necking takes place, the ratio σ_m/σ_y (where σ_m is the hydrostatic stress) is approximately 0.6 in the plane strain tensile test piece. Rice and Tracey (ref.5) predicted that σ_m/σ_y was approximately 0.5 at the crack tip, but at a distance ahead of the crack tip corresponding to twice the crack opening displacement the ratio σ_m/σ_y rises to approximately 2.0. Mackenzie, Hancock and Brown (ref.6) demonstrated that the fracture strain could show a strong dependence on the ratio σ_m/σ_y for σ_m/σ_y values varying between 0.5 and 2.0. Nevertheless the stress state ahead of a crack more closely resembles the stress state in the plane strain tensile test piece than in a uniaxial test piece, and values of ε_f(PS) have been taken to be crack tip fracture strains, by Schwalbe (ref.7) among others, with some measure of success.

Fracture toughness predictions may be made assuming that ductile fracture initiation occurs when $\varepsilon_f(PS)$ is achieved over a critical distance. Such a model was used for the forging steel. The critical distance was taken to be about 40 μm, and a normalised version of the strain distribution in ref.8 was used. A comparison of the predicted initiation crack opening displacement values, δ_i, with the measured values is shown in fig.6. The good agreement demonstrates that the model is reasonable. Note that both the $\varepsilon_f(PS)$ and the δ_i values are low for the temperature of 350°C, higher for 600°C and lower again for 680°C.

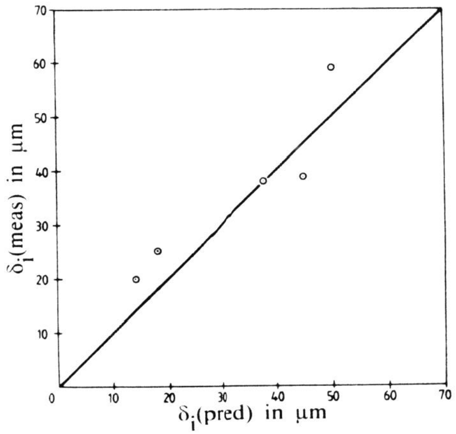

Fig.6 Comparison of measured initiation crack opening displacement values with predictions made using the plane strain fracture strain. Data for the forging steel.

A totally different approach to the use of $\varepsilon_f(PS)$ values was proposed by Lereim (ref.9) for predicting δ_i values of materials that show a tendency towards delamination with the planes of delamination being perpendicular to the crack tip. Here, the regions of material between planes of delamination ahead of the crack tip were compared to plane strain tensile test pieces. According to the model, which seems to give reasonably accurate predictions, δ_i may be calculated by integrating the strain in the regions between the delaminations, the maximum strain (i.e. that immediately ahead of the crack tip) being equal to $\varepsilon_f(PS)$.

CONCLUSIONS

(1) There is no simple, unique relationship between the 'plane strain sensitivity', $\varepsilon_f(PS)/\varepsilon_f(U)$ and yield stress.

(2) There was an inverse relationship between the plain strain fracture strains and the work hardening rates of the forging steel.

(3) The plain strain fracture strain is a useful parameter for using in models from which fracture toughness may be predicted. It can be used both in models that require the attainment of a critical strain at a critical distance, and also in models where the plain strain tensile test piece is regarded as representing the material between planes of delamination.

ACKNOWLEDGEMENTS

The authors wish to thank the Ministry of Defence, Procurement Executive, for providing the financial support of this work; Professor R.W.K. Honeycombe F.R.S. for providing the necessary research facilities at the department of Metallurgy and Materials Science, Cambridge University; and Dr J.D. Evensen for valuable discussions.

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