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DUCTILE FAILURE CRITERIA FOR BLUNTING CRACKS

M. J. Cowling and J. W. Hancock*

INTRODUCTION

In predicting ductile failure ahead of an opening and blunting crack it is necessary to understand the behaviour of material in the states of stress ahead of the crack tip. To evaluate material behaviour in such stress states Mackenzie, Hancock and Brown [1] carried out a series of notch tensile tests of varying notch geometry. Using an analysis of the stress and strain distribution in the neck of a tensile specimen due to Bridgman [2] it is possible to evaluate the effect of stress state on ductility. The ductile failure mechanism observed in the notch tensile tests [1] was one of hole nucleation at inclusions and subsequent growth and coalescence of these holes at failure initiation. Mackenzie, Hancock and Brown suggested that such multi-axial failure data could be applied to other plastic stress-strain fields, notably those ahead of cracks and notches. It is however implicit in this work that the failure mode should be the same in the Bridgman notches used to produce the data as the new stress and strain fields to which the data is to be applied. Similarly Mackenzie et al. indicate that although the strain to failure is a function of stress state it cannot be sufficient for the failure condition to be satisfied at a point, but rather, a minimum amount of material, characteristic of the scale of the physical events, must be involved. In wrought steels the mechanism of failure in the Bridgman notches depends on the orientation of the stress system with respect to the rolling plane as shown in Figures 1 and 2. Here the minimum possible amount of material that could be involved would be of the order of the hole size (100μm), although Mackenzie et al. initially used the hole spacing (200μm).

The present investigation is concerned with determining whether the mechanisms of failure ahead of cracks are the same as those in Bridgman notches and whether the scale of events leading to the concept of the material size parameter is independent of the stress and strain field involved.

One of the materials used in this investigation was a low alloy high strength steel of composition as given in Table 1. The effect of stress state on ductility at failure initiation was obtained from a series of notch tensile tests [1] and is shown in Figure 3. The state of stress is characterised by the ratio of the mean stress (σ_m) to the effective stress ($\bar{\sigma}$) and ductility by the effective plastic strain $\bar{\varepsilon}_p$. To examine failure from a crack tip tests were carried out on small plane strain double edge fatigue cracked specimens of the geometries shown in Figure 4. The specimens were tested in a servohydraulic testing machine under displacement control from a transducer mounted across the crack mouth. With this system of control and as a result of metallographic examination it was observed that failure initiation was characterised by an abrupt

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*Department of Mechanical Engineering, University of Glasgow, Glasgow, UK.

decrease in average stress. Hence it was possible to stop tests and unload specimens at the point of failure initiation. The material investigated was in the form of 90mm. thick plate and therefore two series of tests were carried out, one with the specimen axis orientated in the through-thickness or short transverse (S.T.) direction, and the other with the specimen axis parallel to the surface of the plate at 90° to the following direction (long transverse, L.T.).

Two double edge fatigue cracked specimen geometries with ligament to shoulder ratios of 1:4 and 1:10 respectively, were used in this work. From an examination of the plastic zone shapes in an etching study on a high nitrogen steel, and, a comparison with the slip line fields of Ewing [3] and Prandtl [4] the 1:10 specimen was shown to develop a constraint compatible with the Prandtl field (constraint factor 2.1). The crack blunting mechanism is assumed to be that arising from a logarithmic spiral slip line field. In contrast in the 1.4 specimen the slip line field essentially consists of diagonal bands extending from the crack tip to the shoulders of the specimen. The crack tip slip line field detail, to be consistent with this, is taken as a triangle of uniform strain rate ahead of a square blunting tip in contrast to the round blunting tip implied in the log spiral field.

Application of the ductile failure data of Figure 3, with the minimum likely material size parameter of 100µm, to the stress and strain fields straight ahead of the crack tips gives the openings to initiate failure shown in Table 2 for the two different fields. The corresponding crack tip events leading to failure initiation in the 1:4 specimen in both orientations are shown in Figures 5 and 6. These should be compared with the events shown in Figures 1 and 2. The size, shape and orientation of the holes is very similar and in addition it should be noted that failure occurs straight ahead of the crack.

The agreement between the predicted and observed crack tip openings is encouraging and suggests that multi-axial failure data may indeed be applied to the stress and strain fields ahead of blunting cracks. However it is important to note that the failure may not always occur straight ahead of the crack tip or in a similar mode to the Bridgman notches, but may occur in shear bands as shown in Figure 7. Here the hole growth delineates the slip line field. This type of failure has been observed by other workers [5] and the mechanism of failure is described in detail by Nagpal et al. [6].

CONCLUSIONS

For the three stress and strain fields examined the mechanisms of ductile failure are identical and the scale of events leading to the concept of a material size parameter is independent of the stress and strain field involved. Good agreement has been obtained between predicted and measured crack tip openings at failure initiation.

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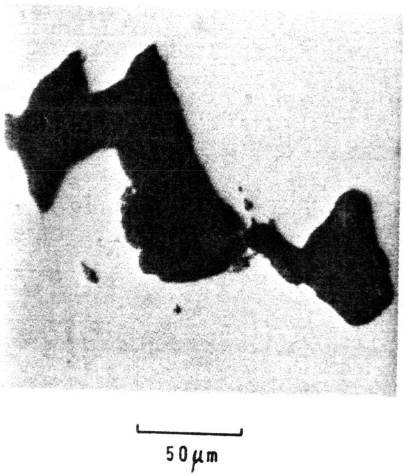

Figure 1 Failure Initiation at the Centre of a Notch Tensile Specimen (L.T.)

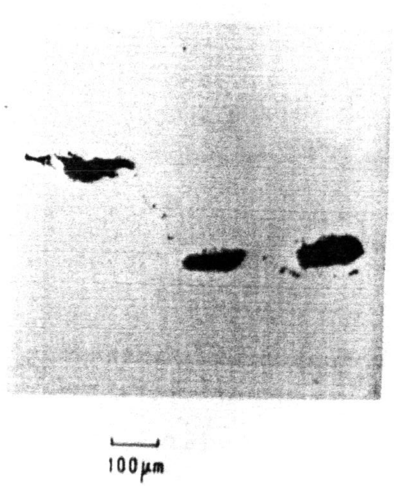

Figure 2 Failure Initiation at the Centre of a Notch Tensile Specimen (S.T.)

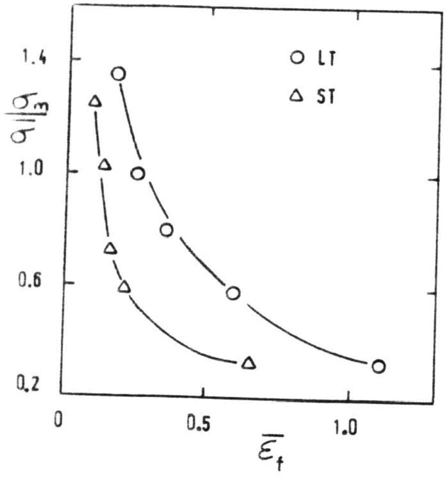

Figure 3 The Effect of Stress State on the Effective Plastic Strain to Failure Initiation

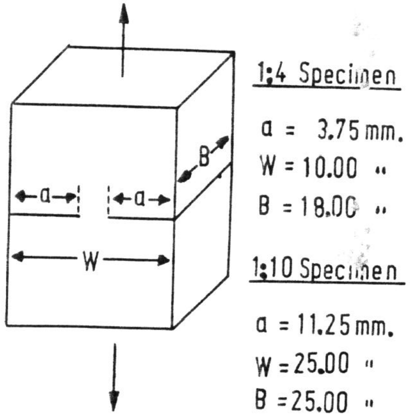

Figure 4 Double Edge Crack Specimen Geometry

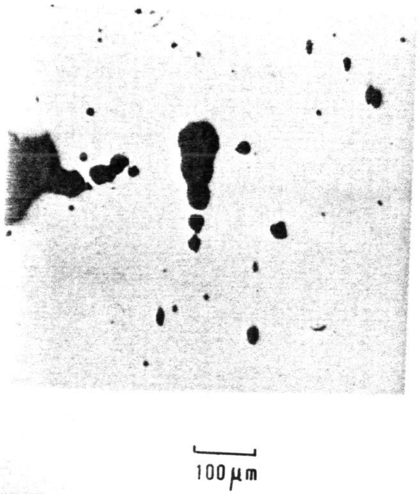

Figure 5 Failure Initiation at a Crack Tip (L.T.)

Figure 6 Failure Initiation at a Crack Tip (S.T.)

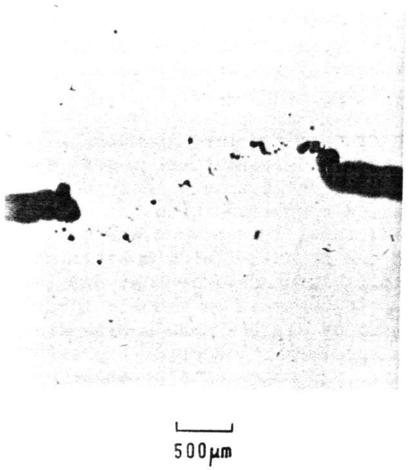

Figure 7 Shear Band Type Failure

Table 1 Steel Composition (wt%)

Carbon	0.18	Manganese	0.25	Silicon	0.25	Phosphorus	0.015
Sulphur	0.015	Nickel	2.75	Chromium	1.40	Molybdenum	0.40
Vanadium	0.02	Titanium	0.02	Cobalt	0.03	Copper	0.20

Table 2 Comparison of Predicted and Measured Crack Openings (μm)

	1:4		1:10	
	S.T.	L.T.	S.T.	L.T.
Predicted	240	350	80	105
Measured	210	302	77	90