Fracture 1977, Volume 2, ICF4, Waterloo, Canada, June 19 - 24, 1977

THE INITIATION OF CLEAVAGE BY DUCTILE TEARING

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The classical theory of brittle fracture, often attributed to Orowan [1] suggests that brittle failure occurs at a critical value of the largest principal stress, and much work has been concerned with the determination of the maximum stress in elastic-plastic stress-strain fields. However it now seems likely that instead of having to satisfy such a criterion at an infinitely small point, a certain amount of material should be involved. This characteristic volume of material will be of a similar scale to the physical events leading to failure. Ritchie, Knott and Rice [2], in discussing slip initiated cleavage at low temperatures, have used a criterion of a critical stress occurring over a distance of 1 grain diameter and have related this to cleavage from cracked carbides. Similarly, in a discussion of ductile failure initiation by hole nucleation growth and coalescence, Mackenzie, Hancock and Brown [3] have used a criterion of a critical strain, which is a function of the state of stress, over a distance related to inclusion spacing. Hence in both ductile and cleavage initiated failure criteria have been suggested involving failure over a distance 'a material size parameter'. The material size parameter for cleavage failure is in general different to that for ductile failure.

The present work is concerned with the intermediate conditions where failure at a crack tip starts by ductile tearing but changes to fast cleavage failure. The initiation of ductile failure at a blunting crack resharpens the crack and results in a relatively abrupt change in the stress levels and stress states ahead of the crack. An attempt has been made to simulate these changes and to relate them to the cleavage criterion of Ritchie, Knott and Rice, and the ductile criterion of Mackenzie, Hancock and Brown.

The material used in this investigation was a low carbon iron containing a distribution of approximately 1% (volume) of iron oxide inclusions. The strain to initiate ductile failure in this material was determined in a number of stress states, using circumferentially notched tensile specimens [3] of the geometries shown in Figure 1. The stress and strains in these specimens may be conveniently estimated by using an analysis originally applied to the neck of tensile specimens by Bridgman [4] which compares favourably with more recent finite strain numerical analyses [5, 6]. Failure initiates at the centre of such specimens at an effective plastic strain $\bar{e}^p$ given, in terms of principal strains by

$$\bar{e} = \left\{\frac{2}{9}\left(e_1 - e_2\right)^2 + \left(e_2 - e_3\right)^2 + \left(e_3 - e_1\right)^2\right\}^{1/2}$$

Similarly the state of stress is characterised by a non-dimensional parameter $(\sigma_m/\bar{\sigma})$ where

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$$\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$$

$$\bar{\sigma} = \left\{\frac{1}{2} (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right\}^{1/2}$$

(σ_1, σ_2 and σ_3 being principal stresses)

The failure strain of the material as a function of stress state as shown in Figure 2.

To examine the behaviour of the material in the vicinity of sharp cracks, double edge fatigue cracked specimens were tested in a servo-hydraulic testing machine using displacement control from a transducer mounted across the mouth of the cracks. A fracture surface of a double edge cracked specimen is shown in Figure 3. The transition from ductile tearing, at the original crack tip, to cleavage fracture is distinct. Figure 4 shows crack extension at failure initiation in a polished section of a double edge cracked specimen. The crack opening at crack extension in a 10:1 shoulder to ligament ratio specimen in which the crack tips blunt in a log spiral ship line field is 170 μm. Failure initiation occurs by ductile hole growth and tearing over a distance of 100 - 150 μm.

The state of stress and strain at failure initiation is shown (using an analysis due to Rice and Johnson [7]) in Figure 5. Using this with the stress state data of Figure 2 as suggested by Mackenzie et al. [3] and a material size parameter for ductile failure of 100 μm predicts a crack opening of 159 μm at crack extension which is consistent with the observed value of 170 μm. At initiation the blunt crack is sharpened by coalescence with holes nucleated at inclusions and the new crack tip radius corresponds to the hole radius of approximately 40 μm (Figure 4). As before it is assumed that the new crack tip starts to blunt according to a logarithmic spiral slip line field (approximating the material behaviour as rigid non-hardening plastic). On this basis Figure 6 shows the maximum principal stress, normalised with respect to $\bar{\sigma}$, ahead of the crack at three intermediate openings and at failure initiation from the original crack tip. The maximum principal stress distribution after ductile initiation is also shown. The effect of the new slip line field associated with the re-sharpened crack tip is to cause an increase in stress level and stress state in a considerable volume of material which has previously undergone significant strains. For example, consider a point 250 μm from the original fatigue crack tip. At ductile failure initiation this had been subjected to a strain of $\bar{\epsilon}^P = 0.04$ and was at a stress state (σ_m/σ) of 1.72. After ductile initiation this point is 150 μm from the new crack tip and subject to a stress state of 2.1. From Figure 6 it is clear that material over a distance of ∿ 70 μm is subjected to an increase in stress level at fracture initiation.

It is possible to simulate changes in stress state by the use of circumferentially notched tensile specimens. In this investigation material was prestrained in uniaxial tension to a strain of $\bar{\epsilon}^P = 0.2$ and then one of the three most severe notches shown in Figure 1 (D, C, A) was machined into the specimen and the specimen retested. This gave the three stress state and strain histories shown in Figure 7. None of the three specimen geometries failed catastrophically but examination of the fracture surfaces showed that failure initiation in the two most severe notches (C and D) was cleavage near general yield in the centre of the specimens. Areas of cleavage of the order of 1 or 2 grain diameters were observed at the centre of the fracture surface. In the 'A' notch specimen geometry there was no evidence of any cleavage failure. The increase in maximum principal stress, at yielding, produced by the machining of the notch for the three notch geometries is shown in Figure 8. Notch tensile specimens of the 'C' and 'D' geometries which were not subjected to the prestrain failed in a completely ductile manner and contributed to the data of Figure 2. Cleavage failure was estimated to occur in the Bridgman notches at maximum principal stresses of 0.66 kN mm^{-2} and 0.71 kN mm^{-2} over the area of two or three grains but not at 0.54 kN mm^{-2}, the maximum principal stress in the 'A' notch specimen. Hence the critical stress level for cleavage failure in this material lies between 0.54 and 0.66 kN mm^{-2} but the manner in which this stress is achieved is important since cleavage does not occur in non-prestrained notches where the maximum principal stress, before ductile failure, reaches 0.75 kN mm^{-2} in the 'D' notch.

In the double edge fatigue cracked specimen an increase in maximum principal stress is experienced by the material over a distance of approximately 70 μm (Figure 6).

CONCLUSIONS

A combination of the ductile failure criterion suggested by Mackenzie et al. [3] and the cleavage criterion proposed by Ritchie et al. [2] provides a basis for the understanding of cleavage failure initiated by ductile tearing. However the present results indicate that the stress state history of a material affects the mode of failure which is not simply a function of the current values of stress and strain.

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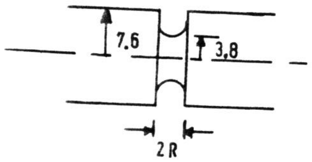

SPECIMEN	R
A	3.80
C	1.90
D	1.27
E	6.34

ALL DIMENSIONS mm.

Figure 1 Notch Tensile Specimen Geometry

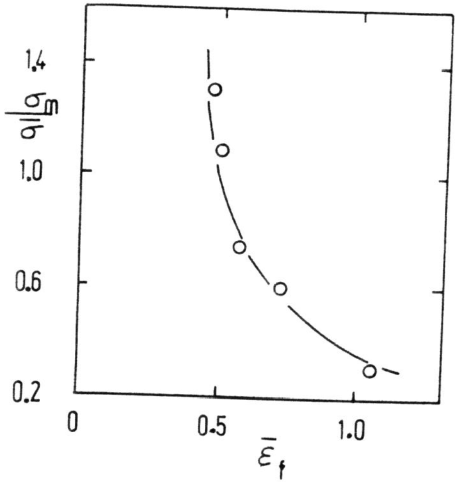

Figure 2 The Effect of Stress State on the Effective Plastic Strain to Failure Initiation

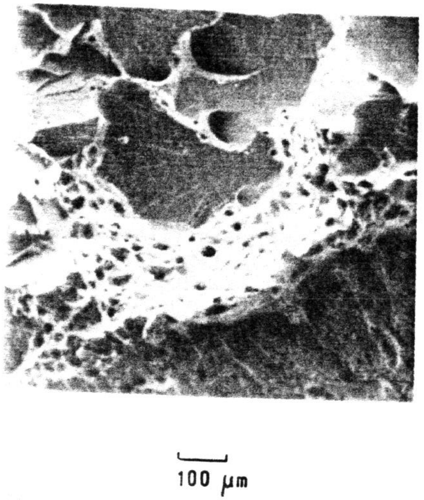

Figure 3 Fracture Surface of a Double Edge Cracked Specimen

Figure 4 Crack Extension at Failure Initiation

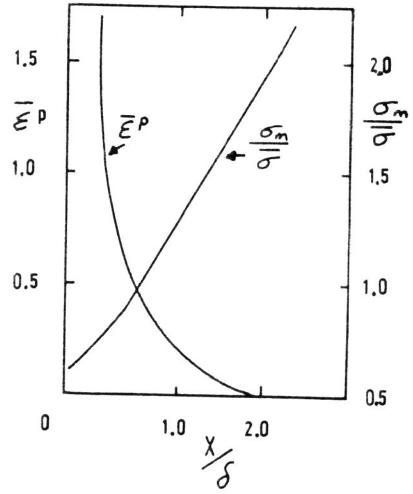

Figure 5 Stress State and Strain Distribution in the Vicinity of a Crack Tip [7]

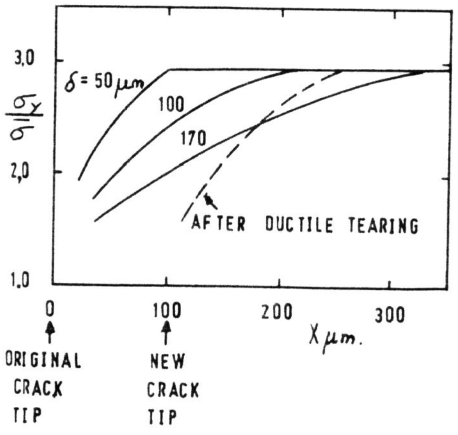

Figure 6 Maximum Principal Stress Distribution

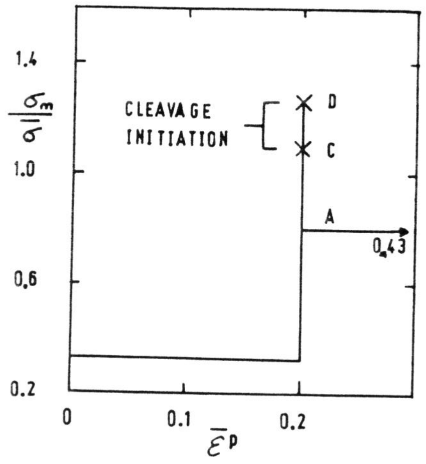

Figure 7 Stress State and Strain History for Three Notch Tensile Specimens

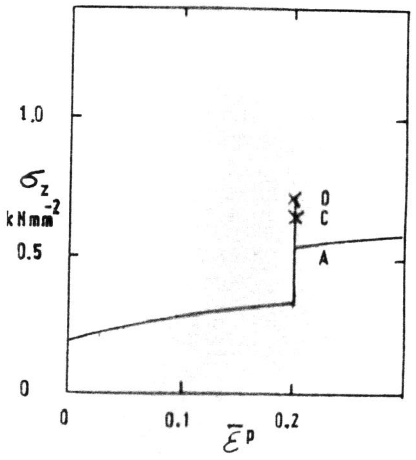

Figure 8 Maximum Principal Stress History for Three Notch Tensile Specimens