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Mechanisms of deformation in the fatigue of polyethylene pipe

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The mechanisms of failure of externally notched sections of polyethylene pipe under pressure have been investigated. Previous communications had suggested that the origins of branching fracture features could be localized shear deformation and this is confirmed. It is shown that craze-like forms which occur at the crack tip can have a different structure to that of a craze.

1. Introduction

Previous work [1, 2] has shown that the mechanisms of failure of notched sections of polyethylene gas and water pipe under pressure are complex, involving the development, growth and breakdown of both craze-like forms (CLF) and branching fracture features (BFF). These structures give rise to morphological features of the fracture surface in both creep and fatigue failures. Furthermore BFF and CLF interact to develop a characteristic failure pattern. There was evidence [1] to suggest that BFF were caused by localized shear deformation. The origins of these failure modes are uncertain, but this communication reports our progress in elucidating the mechanisms and gives further consideration to the formation of shear bands in polyethylene.

There is scant literature giving support to the existence of shear bands in polyethylene in any other than highly oriented material where their presence, as in the case of metals, can be related to structural anisotropy and geometrical strain softening. Friedrich [3] and Liu and Harrison [4] have reported discreet diffuse shear bands in polypropylene both at low temperatures in compression and at ambient temperatures at high rates of strain in tension. Way *et al.* [5], showed that diffuse stress-whitening preceded "craze" formation during tensile deformation of polypropylene, although this depended on the type of microstructure. Although Way *et al.* thought that "crazing" was the yield mechanism in their work, it seems possible in the light of the work of Liu and Harrison [4] that the diffuse stress-whitening which preceded "crazing" as observed by Way *et al.* was associated with shear banding. Moreover, Rose and Meurer [6] showed that shear bands, when they form within regions of oriented polyethylene, intersect to cause intensive strain concentrations. This is very similar to the hypothesized formation of cavities in glassy polymers by the interaction of shear bands (which has been related to craze growth and termination [7]). If, indeed, shear bands do exist in pipe material, then it is reasonable to postulate that they could interact with the formation and growth of crazes or craze-like forms.

In addition, the work of Rose and Meurer [6] points to the fact that the size and method of manufacture of test specimens has an important influence on the deformation modes as these depend upon structural orientation. This may be one of the reasons for the apparent general complexity of the stress-whitening process and it could partly explain the vast variety of fracture characteristics exhibited by semi-crystalline thermoplastics.

Kitagawa and Yammaura [8] compared the mechanisms of fracture in notched bend tests of polypropylene and polycarbonate. Both materials showed similar patterns of variation in strength with temperature. Although polycarbonate developed shear bands both at the elastic/plastic boundary and in the plastic zone at the notch root, polypropylene deformed by multiple crazing. Kitagawa suggested that there were shear bands present in the case of polypropylene but thought that they were not visible due to the polymers opacity. However, in Kitagawa' and Yammaura's work, as temperature increased, the terminal fracture nucleus initiated further from the notch root; by the coalescence of crazes in the case of polypropylene but due to stress intensification at the elastic/plastic boundary (caused by plastic constraint) in polycarbonate. Other studies have shown similar findings [9, 10].

The questions arise as to whether shear bands occur in the failure of polyethylene pipeline materials and if they do, in what way do they interact with the failure process? Our initial investigations [1, 2], looking at the creep and fatigue of polyethylene pipe, suggested that shear bands may influence failure in the notched pipe geometry, although the evidence was only derived by comparison of the fracture surfaces with those of metals. This led us to investigate further the sub-surface deformations associated with fracture and particularly those which accompanied drastic changes in fatigue lifetime.

2. Experimental procedure

2.1. Materials and testpieces

The material used was B.P. pipe-grade polyethylene of

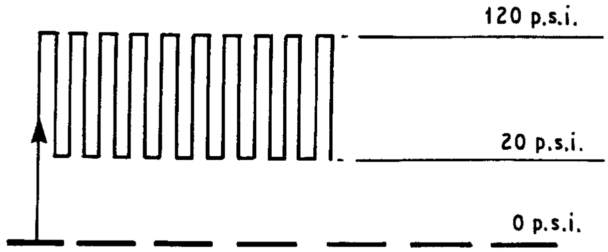

Figure 1 Square-wave load form.

nominal density 0.94 g cm^{-3} and its physical and chemical specifications conform to that standard.

2.2. Methods

Tests were conducted on sections of pipe with longitudinal external notches. These were internally pressurized with water at 80 °C using a cyclic load pattern as shown in Fig. 1. It was found that prestressing the notched pipe to a significant level above the subsequent fatigue cycle load range extended the fatigue lifetime up to the point whereby sufficient prestress level caused the complete inhibition of failure by fatigue. Results of these tests and details of testpieces and test conditions are published elsewhere [11]. This led us to investigate more closely the mechanism of increase in longevity under fatigue-loading conditions.

2.3. Microscopy and failure analysis

Microtomed sections were taken and viewed in transmitted polarized light using a Ziess optical microscope.

Scanning electron microscopy (SEM) was conducted on freeze-fractured surfaces; the method of freeze fracture has been reported in a previous communication [1]. Specimens were sputtered with gold–palladium prior to SEM examination.

The structure of craze-like forms (CLF) was also investigated by making replicas of freeze-fractured sections. The plastic replicas were coated with carbon, followed by shadowing with gold–palladium. As the replicas were highly contoured, dissolving the plastic in preparation for transmission electron microscopy caused them to collapse (this being a well-known limitation of the surface-replication technique), thus the replicas with plastic *in situ* were viewed directly in the SEM. The magnification and resolution were limited by the potential procedural damage to the replica. Any incidental damage was readily identified and excluded from the study. This is an important point, because any direct observation of CLF material usually results in damage owing to its high orientation, unless expensive and time-consuming measures are taken.

3. Results and discussion

The results are shown in Figs 1–17. Fig. 2 is a micrograph taken in transmitted polarized light of a microtomed section on a transverse plane to the fracture plane. This fracture was produced by the cyclic load pattern shown in Fig. 1. The top left of the micrograph is the notch root. No prestress prior to fatigue was used. The fracture surface is shown in Fig. 3.

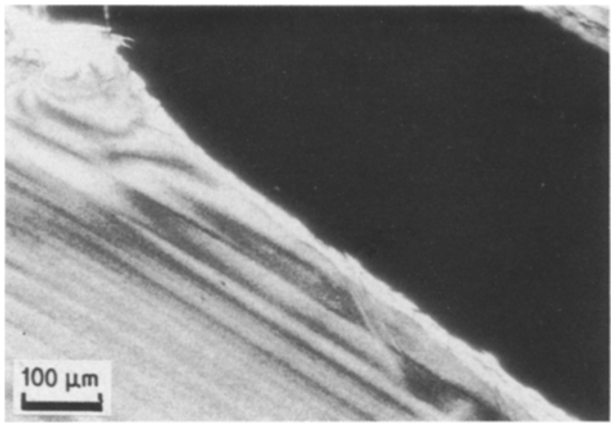

Figure 2 Transverse section through the origin of a fatigue fracture showing the plasticity underlying the fracture origin (top left) (transmitted polarized light).

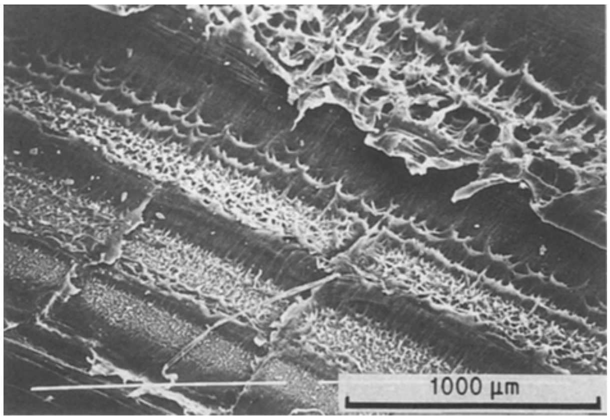

Figure 3 Fatigue fracture surface corresponding to Fig. 2.

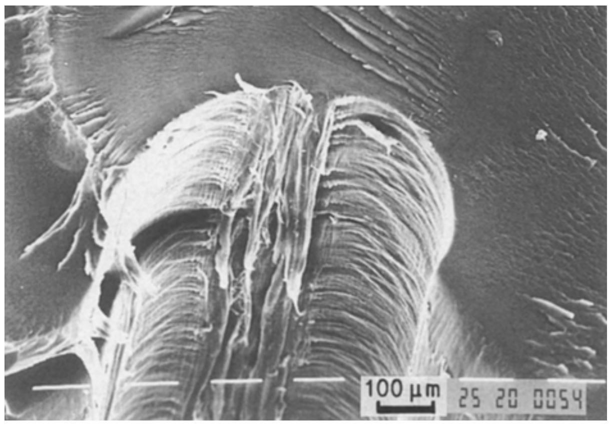

Figure 4 Blunted notch root due to initial cycle of overload prior to fatigue.

Fig. 2 reveals fringes below the fracture surface at the notch root. It seems likely that these fringes map orientation due to plastic flow as the photoelastic activity of polyethylenes is generally low and they do not interact strongly to produce a large number of

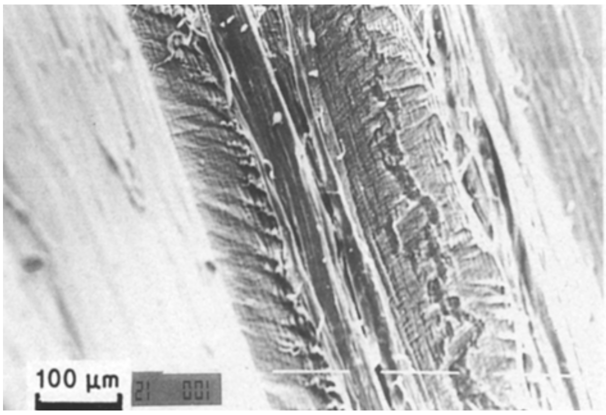

Figure 5 Looking into a blunted notch root revealing striations and tearing (see middle right).

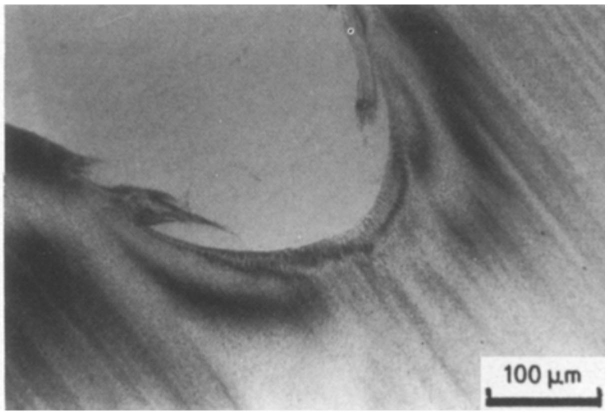

Figure 8 Microtomed section of blunted notch root showing some optical fringes and structure around the notch root.

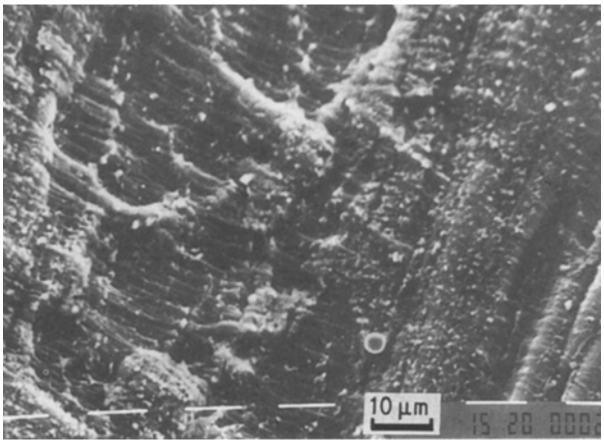

Figure 6 Looking into the region of tearing in Fig. 5 revealing fibril formation.

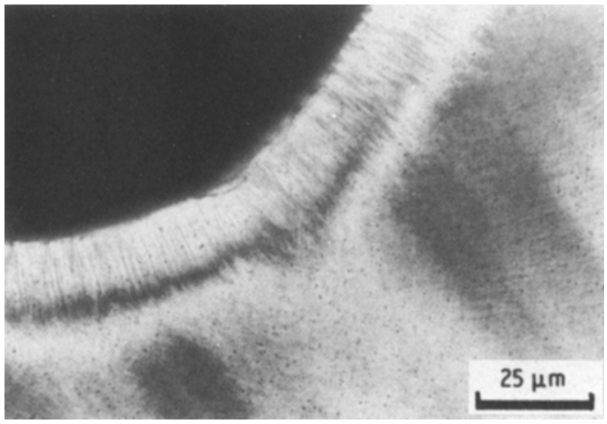

Figure 9 Detail of structure beneath the blunted notch root.

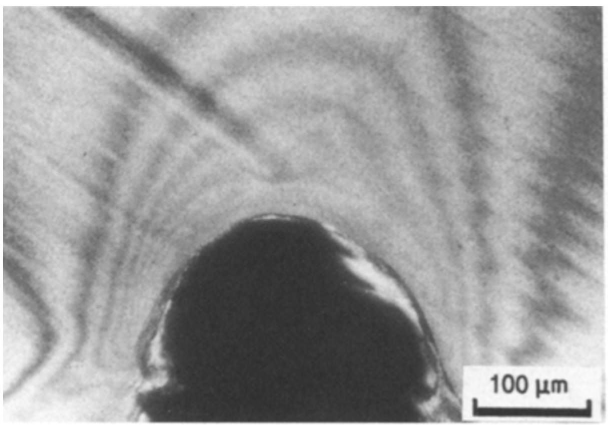

Figure 7 Microtomed sections of blunted notch root showing optical fringes (transmitted polarized light).

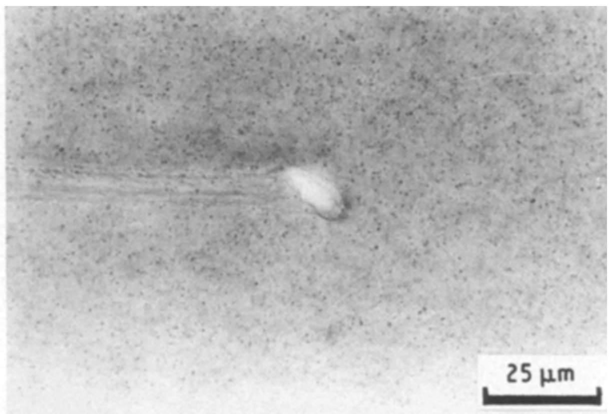

Figure 10 Discreet bands emanating from a void developing at the tip of a CLF (transmitted light).

fringes when stressed in the elastic range and viewed in transmitted polarized light. Discrete discontinuities can also be seen within the fringe patterns themselves.

Using a prestress cycle such as that shown in Fig. 19, the fatigue lifetime is extended many fold. The reason for this is evident in the scanning electron micrograph of Fig. 4 where the notch root is seen to be blunted. Figs 5 and 6 show views looking into the blunted notch root.

From these figures it is possible to identify micro-striations running along the base of the notch root. Also apparent from Fig. 5 is the development of fibrosity prior to the initiation of a region of tearing fracture.

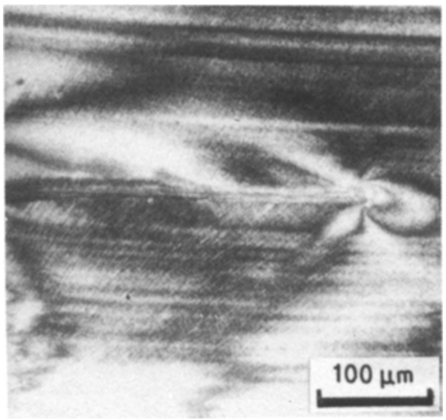

Figure 11 As Fig. 10, but using polarized light. (Tip of CLF, right).

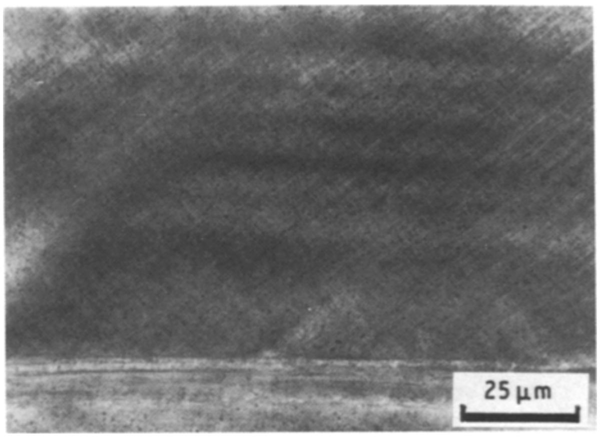

Figure 12 CLF with shear bands (note the possible initiation site of a BFF in the middle of the CLF).

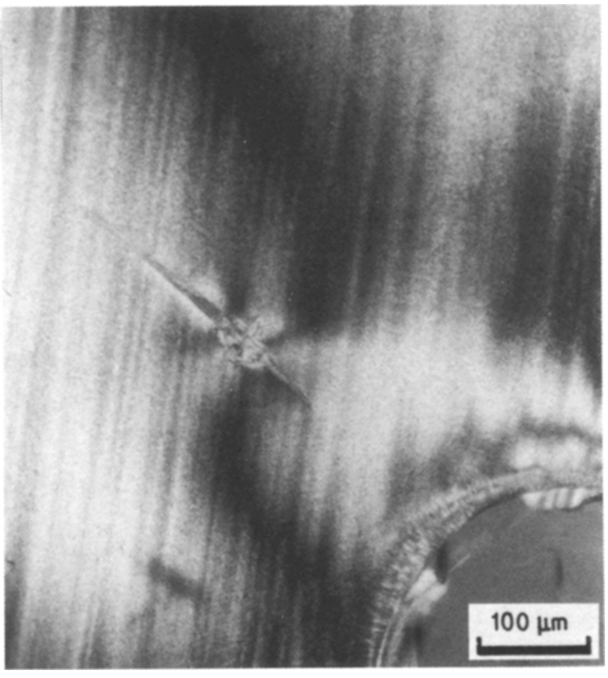

Figure 13 Craze initiation site away from blunting notch root.

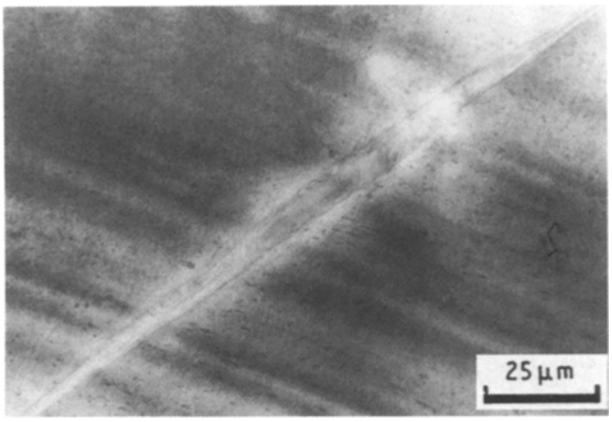

Figure 14 "Craze" initiation. Note the similarity to diamond cavities which occur in oriented materials.

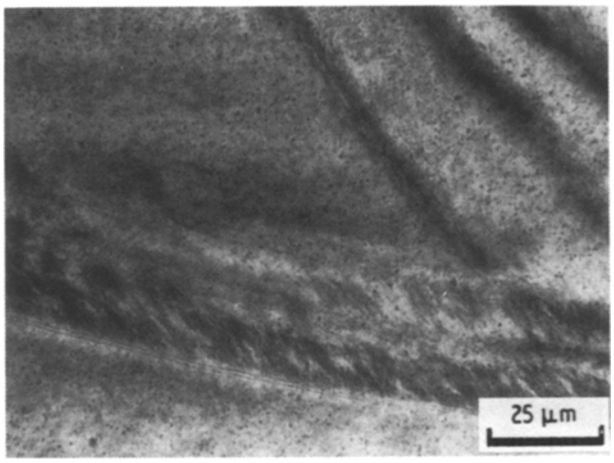

Figure 15 Branching crazes below a creep fracture surface.

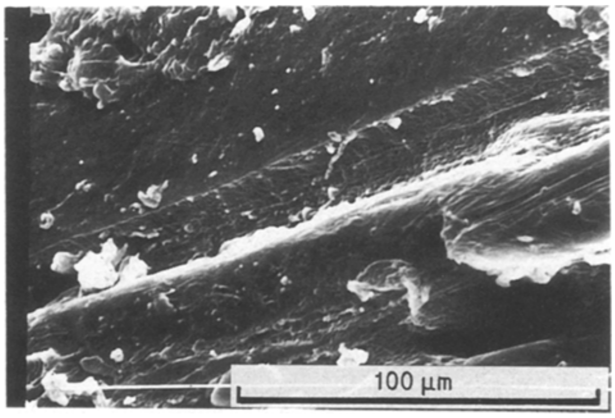

Figure 16 Transverse fracture through a CLF.

By taking microtomed sections, Figs 7–9, the origins of notch-tip blunting can be seen. As well as fringes, very fine discrete lines can be seen radiating in spirals from the notch root. Directly adjacent to the surface of the notch there appears to be a region of dense crazing and this underlies the microstriated and torn notch root.

The discrete lines seen amongst the fringes at the notch root reappear during the later stages of fracture and their presence becomes more marked. Fig. 10 shows the CLF at the crack tip at the late stage of fracture. Discrete bands can just be resolved radiating from a void which is developing at the tip. If polarized light is used, as in Fig. 11, then these lines become

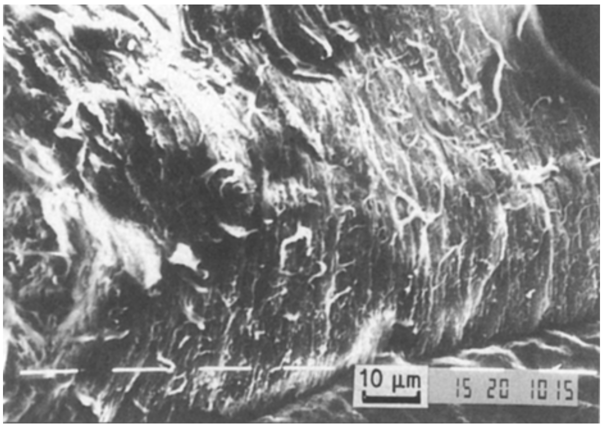

Figure 17 Scanning electron micrograph of a replica of a CLF. (Transverse fracture).

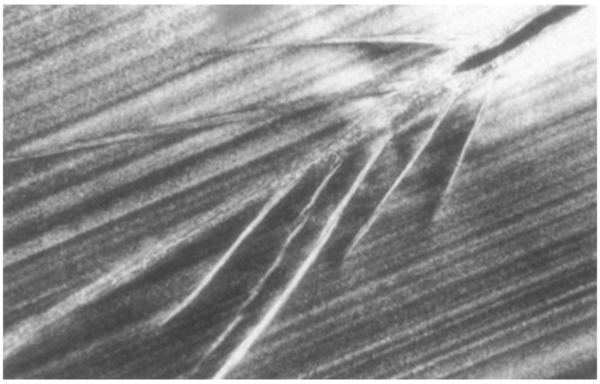

Figure 18 CLF and BFF at the tip of a fracture crack.

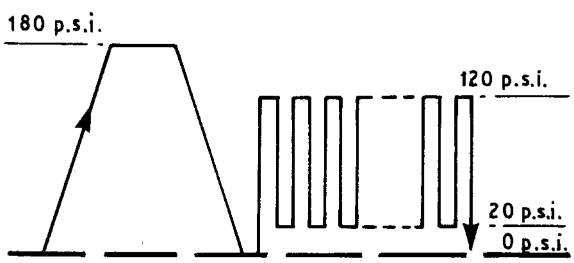

Figure 19 Square-wave load form with pre-stress. Pre-stress: 0–180 p.s.i. (10^3 p.s.i. ≡ 6.89 N mm^{-2}) in 10 s; hold time 10 s, 180–0 p.s.i. in 10 s.

more evident and are clearly directional. Also, as at the notch root, optical fringes become apparent and these are present over the same area as are the discrete bands. Particularly evident are bands concentrating above and below the CLF which appear to map the classical mode of formation of persistent slip bands in metals and also the bands seem particularly intense at the tip of the CLF in planes inclined forward above and below the CLF tip. In another specimen the nature of the discrete banding is clear. Fig. 12 shows a CLF at the tip of a fatigue fracture above which is seen two sets of discrete bands which are mutually perpendicular and which are both at approximately 45° to the plane of the main fatigue crack.

All of the above evidence suggests that the discrete bands are shear bands. By analogy to the work of Liu and Harrison [4] it is a possibility that the partly recoverable diffuse stress-whitening at the notch root in polyethylene as reported by Swapan *et al.* [12] is caused by the interaction of such shear bands.

In one specimen, which was prestressed in the same way as those shown in Figs 7–9, a CLF developed away from the notch root at the limit of the zone of shear bands (Figs 13 and 14). The mechanisms of formation of this CLF therefore appear to interact with the elastic/plastic boundary. There are other examples where CLFs (such as that shown in Fig. 15) are bounded by shear bands on one side, but not on the other. These shear bands must also map the elastic boundary.

It may not be a coincidence that CLFs form at the elastic/plastic boundary because this is where tensile hydrostatic components of stress are concentrated due to plastic constraint.

In the case of glassy polymers one may expect tensile hydrostatic stress to increase the propensity for crazing. However, the situation is not so simple with semi-crystalline (SC) polymers. For example Pae [13] suggested that SC polyolefines would yield under a purely hydrostatic stress, a contention reinforced by the work of Parry and Tabor [14]. Further, in the work of Rose and Meurer [4], it was shown that shear bands in oriented polyethylene intersect to cause intense strain concentrations.

The CLFs have a varied appearance, some lacking the gross cavitation typical of crazes in glassy polymers. Evidence for this is seen in Figs 15–17. Fig. 15 is a microtomed section showing branching crazes beneath the fracture plane of a creep failure. No gross cavitation is evident. Fig. 16 is a transverse fracture of the CLF (SEM). Fig. 17 is an SEM of a replica of a transverse fracture of the CLF. None of these figures show the gross cavitation which defines a craze. It is of interest to note that the CLFs form concave depressions on transverse fracture surfaces. These could be due to the transverse fracture relaxing the hydrostatic tension in the CLF. Similar "crazes" forming concave depressions have been shown in polypropylene by Harrison and Juska [15] but those crazes were cavitated. We believe that a possible reason for the "crazes" found by Harrison and Juska to be cavitated was most likely to be damage caused by the electron beam as CLF material is particularly sensitive to damage in this way.

4. Conclusions

Shear bands have been shown to be a mechanism of plastic yield in polyethylene gas-pipe materials. They are found in relation to crack-blunting mechanisms. Craze-like forms (CLFs) have been found which develop ahead of a blunting notch root. The proposed mechanism of formation of a CLF by the interaction of shear bands, provides an explanation for observations by others of a pre-formed crack existing behind the notch root during the early stages of fatigue crack growth [16]. There is evidence that CLFs develop in association with the elastic/plastic boundary if this is taken to be marked by the extent of shear bands. Branching fracture features formed in the later stages of failure are often associated with zones of intense shear. It is still not clear yet whether branching fracture features (BFF, e.g. Fig. 18) formed in the initial stages of the more brittle fatigue zones (less damaged zones) are shear bands, or are formed by a multiple crazing mechanism due to unstable crack propagation, especially as these processes need not be mutually exclusive. The CLFs have a variety of forms but need not contain the gross cavitation which defines a craze and may support the contention that the mechanism of CLF formation is fundamentally different from that of craze formation, if one considers that the plastic growth of voids or the initiation of voiding (on sufficient scale to overcome void stabilization) in a "rubbery" phase, are required to form a craze.

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