JOURNAL OF MATERIALS SCIENCE 33 (1998) 1699–1702

Fractographic study of high-density polyethylene pipe

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High-density polyethylene (HDPE) pipe is now being used as an alternative to medium-density polyethylene (MDPE) for gas, water, sewage and waste-water distribution systems. Laboratory tests appear to show that HDPE is more able to suppress rapid crack propagation (RCP), whilst remaining sufficient resistance under the operational circumstances that lead to the type of slow crack growth observed in service failures. There have been many fractographic studies on MDPE pipe materials, actual pipe and fittings, but little on HDPE. A fractographic study of the type of HDPE pipe in current production has been undertaken. For these tests, whole pipe sections were subjected to either static or dynamic internal (water) pressurization fatigue loading. Failure mechanisms are discussed based on the fracture morphologies resulting from these tests. A further argument for good resistance of HDPE pipe to RCP is suggested. © *1998 Chapman & Hall*

1. Introduction

Since the 1960s polyethylenes (PEs) have gained wide acceptance in the application of pipe systems for conveying gas, water, sewage and waste water. Medium-density polyethylene (MDPE) has excellent long-term strength properties and was first used for gas distribution in the UK in 1969 [1]. In recent years there has been extensive studies of the possibility of rapid crack propagation RCP occurring in MDPE pipe systems. Concern over this potentially dangerous, though highly improbable, failure mode has lead to publications related to the (critical) pressure necessary for RCP to occur in PE pipes [1–4]. A finding of this work is that high-density polyethylene (HDPE) pipe materials are better in this respect than those of MDPE.

At present it is still not possible to predict RCP performance in PE pipe [4]. Besides the concern over the possibility of RCP failure in PE pipe, there is also the problem of finding an accelerated test method to predict the long-term performance of these improved PE pipe materials. It takes years for these materials to fail under static fatigue test. Currently, dynamic fatigue tests are used as accelerated methods to generate failure within a few days. There are reports on the dynamic fatigue tests and subsequent fractographic studies on MDPE pipe material and whole pipe [5–10]. However, there is a lack of similar studies on HDPE pipe. The present work attempts to examine the failure performance of a recent HDPE pipe through a fractographic study of the fracture morphology from both static and dynamic fatigue tests. In one study, HDPE pipe was shown to be more ductile than MDPE pipe material [11] which could explain why the recent HDPE pipes appears more resistant to RCP, but there is no definitive explanation.

2. Experimental procedure

HDPE pipes with an external diameter of 90 mm and Standard dimention ratio (SDR) 17.6 were extruded by a manufacturer using Solvay pipe grade resin (Eltex TUB 124) from Solvay Chemicals Ltd. The preparation of the test specimens was according to British Gas Specification [12]. Sections of 410 mm long pipe were cut and a notch was introduced externally on each specimen by using a milling cutter. Both ends of each test piece were subsequently capped and immersed in water maintained at 80 °C. The test was started after soaking the specimens for 2 h. For a static test, the internal water pressure was maintained constant at 5.5 bar. A sine wave of 5.5 ± 4 bar pressure with a frequency of 0.4 Hz was used for the dynamic fatigue test. Upon failure of the specimens, they were removed and dried in air. The section immediately around the failed notched region was removed. This was then cracked open with a sharp blow to one free edge to expose the fracture surface.

The fractured surfaces were analysed macroscopically by using a video microscope (Microvision MV2100, from Findlay Vision Co. Ltd). Microscopic analysis of the actual surface was possible by using a low-vacuum scanning electron microscope (Jeol JSM 5300LV). Thin sections of the specimen were microtomed from the transverse side to the fractured surface. They were then examined under the video microscope.

3. Results

Fig. 1 shows three distinct bands of microstriations on the fractured surface that had failed in the static test. Band A, that is immediately next to the notch, appears to be smooth. Band B shows many voids, and in band C, larger and fewer voids together with long drawn fibres are seen. The orientation of these fibres appears to align with the crack propagation direction.

Fig. 2 show the three bands at higher magnification. Band A (as shown in Fig. 3) is a fragmented membrane of fibres which extends from the edge of the notch and overhangs on to band B. Band B consists of short drawn fibres pointing generally towards the crack propagation direction. It has been reported that this band is the result of slow crack growth and is normally considered to be a brittle failure [6], but the actual surface is more complex and three-dimensional [9]. Fig. 4 shows a higher magnification view of band C. The fibres are, in fact, highly drawn and oriented towards the crack propagation direction as suggested above. The ends of the fibres are pulled down from the material matrix. This highly deformed area is reported to be caused by the accelerated crack propagation before the final catastrophic rupture of the material [13]. The final yielding of the remaining material suggests a ductile failure that commonly occurs when PE is under tension.

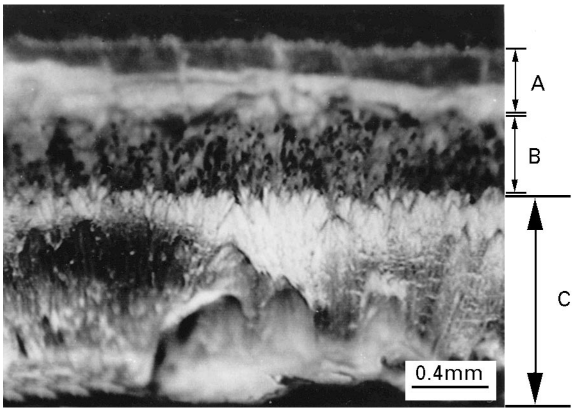

Figure 1 Video microscopic view of the static fatigue fractured surface. Bands A, B and C are shown as indicated. The edge of the notch is at the upper boundary of band A. Crack propagation direction is from top to bottom.

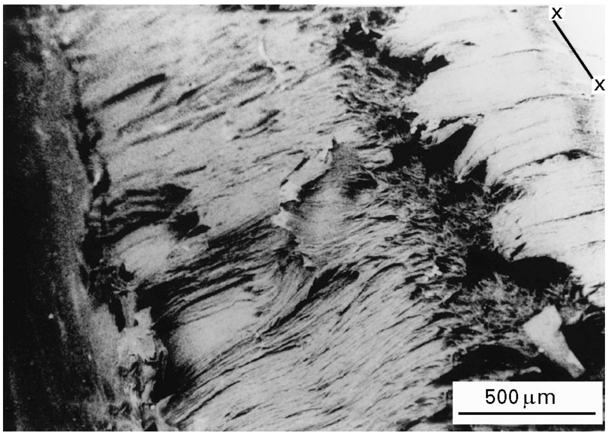

Figure 2 Scanning electron micrograph showing bands A, B and C. Crack propagation direction is from top right to the left. The notch edge is indicated by line X–X.

Figure 3 Scanning electron micrograph showing bands A and B at higher magnification.

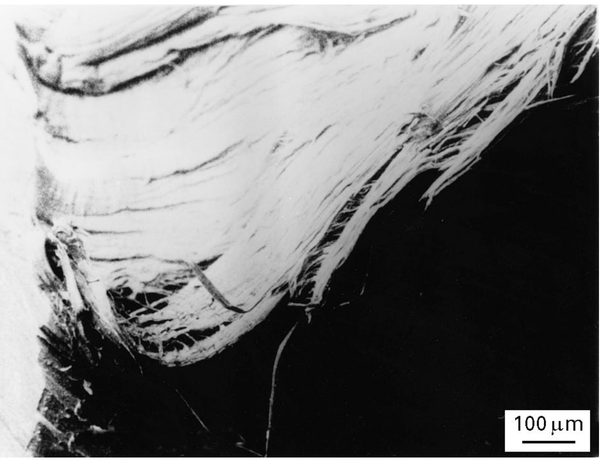

Figure 4 A higher magnification view of band C showing the highly drawn fibres with their ends pulled out of the material matrix.

For the dynamic fatigue fractured surface, three bands or macrostriations are also observed (as shown in Fig. 5). Band a appears to be smooth, like band A above. Band b shows dimples and crevices, whereas larger and fewer crevices are observed in band c. Microstriations are also observed on bands b and c. The surface appears smoother than the static fatigue fracture surface.

Fig. 6 shows bands a and b at a higher magnification. Sheets of fibres can be seen that were compounded upon each other. In this instance, the microstriations were more regularly spaced as reported by White and Teh [14]. Band a appears to be a sheet of fibres that has been compressed and laid over band b (Fig. 7). The microstriations appear to be very fine, shallow and closely spaced. In band b, sheets of fibres appear to be crushed in layers and at irregular intervals, creating microstriations that are deeper and more widely spaced than those of band a (Fig. 8). Fig. 9 shows band c at a higher magnification. A bundle of fibres is seen to have been dislodged from its otherwise layered position at the edge of the fractured surface (Fig. 10). This clearly shows that the microstriations are actually sites at which sheets of fibres were bent, compounded and then layered into the material matrix.

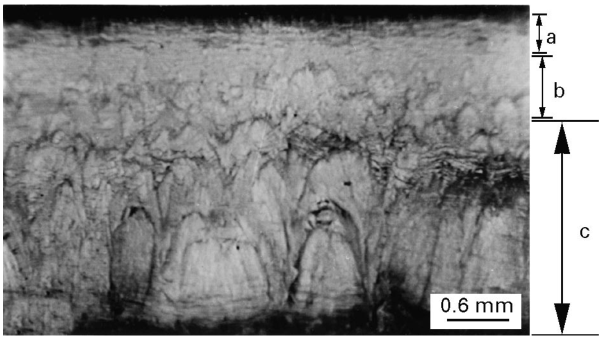

Figure 5 Video microscopic view of the dynamic fatigue fractured surface. Bands a, b and c are shown as indicated. The edge of the notch is at the end of band a. The crack propagation direction is from top to bottom.

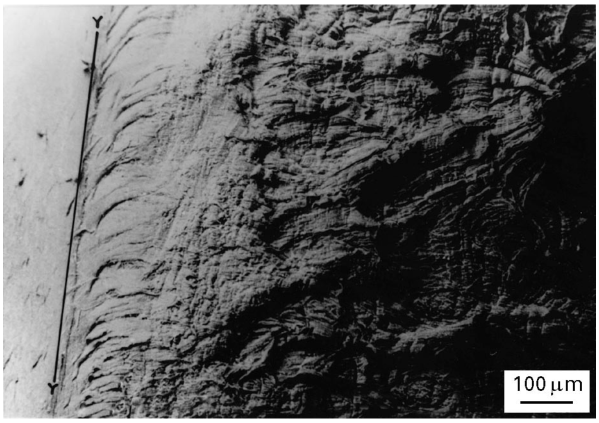

Figure 6 Scanning electron micrograph showing bands a and b. The crack propagation direction is from left to right. The notch edge is indicated by line Y–Y.

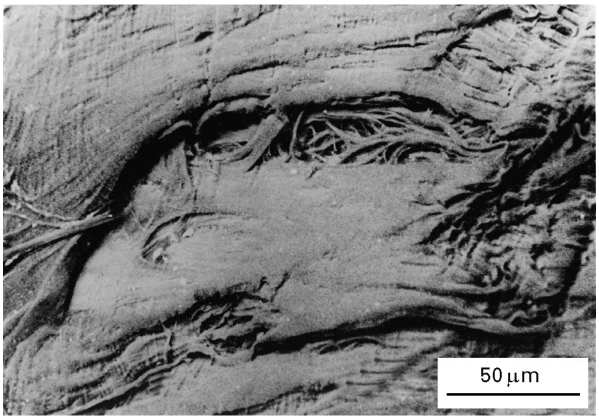

Figure 7 Scanning electron micrograph shows band a to be a sheet of fibres that has been compressed and laid over band b. Band b is on the far right.

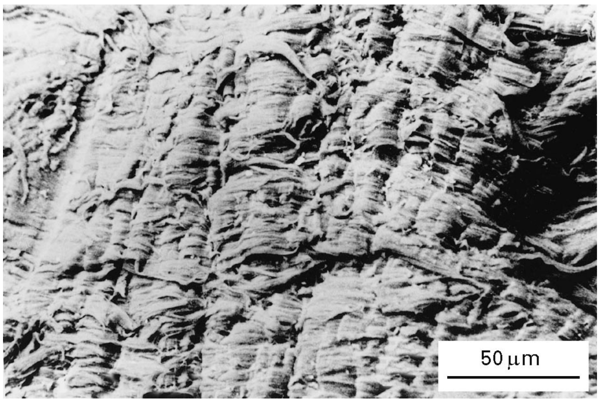

Figure 8 A higher magnification view of band b showing microstriations that are irregularly spaced.

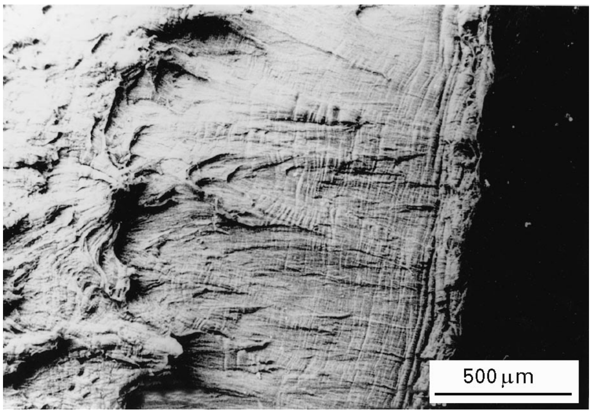

Figure 9 Scanning electron micrograph showing a higher magnification view of band c. There are larger and fewer crevices in band c than in band b.

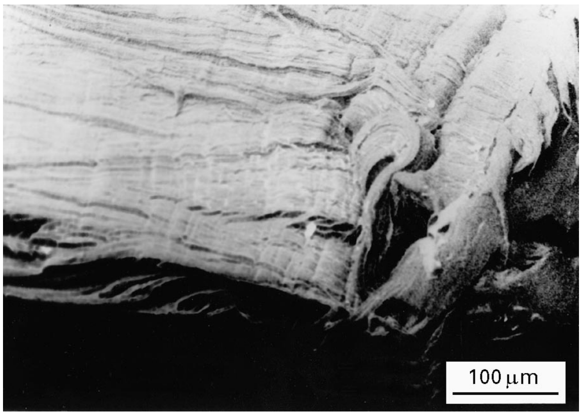

Figure 10 Scanning electron micrograph showing a bundle of fibres that has been dislodged from its "tucked-in" position.

Fig. 11 shows a thin section of a dynamic fatigue failure that has been cut perpendicular or transversely to the fractured surface. A similar view was also obtained from the static fatigue sample. For both cases, no side crazes were observed branching out from the edge of the fracture surface.

4. Discussion

There have been many postulations with respect to the nature of the mechanisms of brittle-type fracture of the form discussed above; however, a strong indication may be obtained from an analysis of the fracture morphology. Under constant internal hydromechanical pressure, a craze was formed initially at the notch tip. Over a period of time, the voids in the craze coalesced and formed larger voids which eventually initiated a crack. At the crack base near to the notch, a fibrous membrane was formed which was able to withstand the fracture load while the crack within the craze propagated. This fibrous membrane has been reported by Lu and Brown [6] and Strebel and Moet

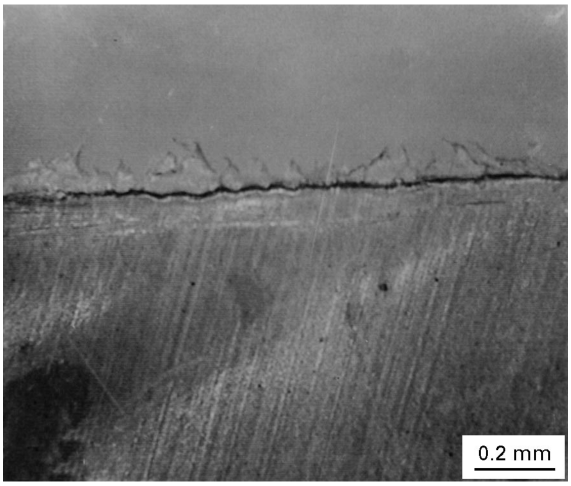

Figure 11 Video microscopic view showing no side crazes branching out from the edge of the fractured surface.

[7]. Lu and Brown [6] suggested that the membrane was formed under plane stress conditions because it was not fragmented by the localized stress which was acting within the craze. However, as the crack propagation continued, the fibrous membrane was eventually fragmented as an accelerated and catastrophic failure occurred at the final remaining ligament of the material (as shown in band C).

It has been reported by Gedde *et al.* [11] that under a similar test with MDPE pipe specimen, brittle failure was observed at a stress level at and below 5 MPa. This observation differs from what has been observed on HDPE. There is a distinct discontinuity which occurs at the transition from slow crack growth or brittle failure (band B) to the final yielding of the remaining material or ductile failure (band C) mode on the fractured surface. The HDPE pipe was subjected to a stress level of 4.6 MPa, which is below the stress level (5 MPa) reported to exhibit brittle failure in the MDPE pipe. This suggests that the current HDPE pipe material is more ductile than the MDPE. RCP failure exhibits a brittle failure mode [1], and may be the reason why, under experimental conditions, RCP is possible at comparatively higher temperatures in MDPE.

For the dynamic fatigue test, based on the fractographic observations, the above failure mechanism applies, with the addition of the loading and unloading cycle on the specimen. As reported by Zhou and Brown [15], the unloading part of the square wave that they used caused bending and crushing of the fibres. As shown in this study, it is evident that the microstriation formation is due to the fibre bending and compounding, resulting from the relaxation half of the (sinusoidal) cycle they employed. Microstriations do not appear to be fracture lines between clusters of lamellae as reported by White and Teh [14]. Fig. 7 shows that the microstriations on the fibrous membrane at the crack base are shallower than those on the rest of the surface. This suggests the possibility that the fibrous membrane might be the final site of failure before the material ruptured.

As shown in Fig. 11, there are no observable side crazes branching out of the crack arrest sites at 45°, as reported by the other researchers [6–10]. They attributed the presence of such crazes to the relaxation of local stress at the crack-arrest sites [6, 7] or the cause of plastic yield of the material [9]. This suggests the HDPE samples used in these tests show no localized plastic yielding of the material. This may also be a contributing factor to the greater resistance of HDPE to RCP.

5. Conclusion

This study has shown that the HDPE pipe material used, was more *and not less* ductile than MDPE, and that localized stress was not exerted at the crack-arrest sites. These may be the reasons why HDPE was reported to perform better in the RCP tests [4]. The failure mechanism is found to be similar in both static and dynamic fatigue tests, apart from the additional effect due to the bending and crushing of the unloading part of the sine wave used.

Acknowledgements

The authors thank Jeol (UK) Ltd., for the use of the Low-Vacuum Scanning Electron Microscope and in particular Mr Andrew Yarwood for his assistance in obtaining the micrographs.

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Received 11 September
and accepted 3 October 1996