Fatigue Fracture Behavior of Single-Edge-Notched Specimens Prepared From Polyethylene Pipes

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This paper presents a comparative analysis of crack propagation behavior of single-edge-notched (SEN) specimens prepared from high density polyethylene (HDPE) and medium density polyethylene (MDPE) gas grade pipes tested under fatigue loading conditions. The rate of crack growth was found to be influenced by the morphology in the pipe. The crack propagation behavior was governed by the plasticity at the crack tip which in turn was linked to the sample crystallinity. The effect of oven aging on fatigue life was also addressed. Oven aging was found to increase the crystallinity which resulted in lowering the fatigue life.

INTRODUCTION

The long term properties of plastic pipeline systems are in general evaluated by hydrostatic testing at elevated temperature. In the case of polyethylene (PE), the short term test involves the pipe withstanding a hydrostatic pressure at 80°C for 165 hours. The long term test requires the generation of hydrostatic test data at 80°C for 10,000 hours (1). The latter test is very time consuming and expensive to conduct. Therefore, there is significant attraction in developing a reliable and rapid test method to evaluate the integrity of PE pipes. At present, there is a need to understand the aging behavior of PE pipes as a function of aging temperature. Furthermore, it is also necessary to understand the effect of aging on the long term durability of PE pipeline systems.

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Chaos et al. (2) examined crack propagation behavior under creep conditions in SEN specimens prepared from MDPE pipe. Their investigation suggested that the crack growth behavior was dependent on the location of the notch with reference to the pipe wall. They found that the morphology ahead of the notch influenced the rate of crack propagation. The variation in the morphology across the pipe wall (surface to the bore) is a consequence of the processing and cooling conditions which were used during the extrusion of the pipe. This results in a density gradient in the pipe, with the surface exhibiting a lower crystallinity content compared to the bore. Crack growth in PE pipes has been investigated extensively by Brown et al. (3). They suggested that the resistance to slow crack growth was governed by the crystalline and not by the amorphous regions. A study on the effect of crystalline morphology on the fatigue crack propagation in PE was undertaken by Runt et al. (4). They found that a larger spherulite size and crystallinity content appeared to have a deleterious effect on fatigue properties. Egan et al. (5) established that both the fracture toughness and the crack growth rates to be strongly dependent on the molecular weight and molecular weight distribution of the resin. Furthermore, when variations in molecular weight were minimal, it was found that increasing the short branch content improved the fracture performance.

In this study, the effect of oven-aging on the crack propagation behavior for two types of PE resins was investigated under fatigue loading conditions. The influence of the location of the notch in relation to the pipe wall was also investigated.

EXPERIMENTAL

The SEN specimens were produced by cutting 180mm OD SDR11 gas grade HDPE and MDPE pipes into longitudinal strips using a custom made pipe-cutting machine. The SEN specimens were designed to produce plane strain fracture over 75% of the fracture surface. The machine utilized a twin cutter arrangement and a specially designed clamping fixture to hold a section of a pipe, 200mm in length, firmly in position while cutting. The dimensions of the strips were 200mm (length) x 14mm (width) x pipe wall thickness, approximately, 17mm. The twin cutters arrangement provided a reproducible sample width. Prior to testing, the SEN specimens were notched by pressing a fresh (sharp) razor into the strips at a rate of 1mm/min. The blade was held in a specially designed clamp to ensure a notch depth of 3mm for all the SEN samples. A commercially available notching machine was also used as a comparison. The two pipe resin samples were also aged in an air-circulating oven for one year at 80°C. Compression-molded plaques were used as the reference material.

The fatigue tests were carried out on an Instron 8032 servo-hydraulic machine under constant loading rate of 2kN/sec with a stress ratio of 0.1 and a peak stress of 8MPa. An environmental chamber was used to maintain the sample temperature at 30°C. An extensometer was mounted on the SEN specimens to monitor crack opening displacement as a function of fatigue cycles.

RESULTS AND DISCUSSION

Figure 1 illustrates the influence of the notching Tool-Tip on the resultant notch profile. Figure 1(a) represents the case where a commercially available blade was used to create a pre-notch. This was then ‘sharpened’ using a microtome blade (0.8mm thickness). The notch symmetry and the associated damage is readily apparent as whitened areas, see Figure 1(a). Figure 1(b) represents the case where the custom made notch device was used to introduce the notch. The thickness of the blade was 0.25mm. Fatigue tests carried out using the two notching methods gave a significant variations in the fatigue life-times. A 35% reduction in the fatigue life was observed for samples with the sharper notch (Figure 1(b)). Brown et al. (6) have carried out a detailed study on issues relating to the method of notching and the subsequent consequences of this on fracture behavior in PE resins.

Two predominant failure modes were observed in the fatigue tested SEN specimens. One characteristic failure mode was a ductile failure which was seen to occur by a yielding process at high stress levels. The other was a ductile-brittle type failure mode, see Figure 2. With reference to Figure 2, the light areas represents an apparent brittle type failure in a SEN sample. The darker regions were identified as regions corresponding to ductile crack arrest. The arrow indicates the direction of the fracture. A higher magnification view of the ductile-brittle fracture is shown in Figure 3. Figure 3(a) represent the brittle region and Figure 3(b) represent the ductile region. The difference in the failure modes for the two regions are readily apparent. Figure 4 shows a fracture surface of PE pipe sample which failed on-site. Here the extent of the ductility is significantly reduced and it shows some resemblance to that shown in Figure 3(a). The implication here is that the laboratory-based fatigue test can be designed to give failure modes which resembles those seen in pipe samples which failed under site conditions.

The relative fatigue performance of the MDPE and HDPE pipe samples are shown in Figure 5. With reference to Figure 5, the crack opening displacement measurement was plotted as a function of cycle for both the pipe resins. The initial stage of the curves was identified as that due to nonrecoverable creep at the notch tip, promoting a ductile crack arrest. The fatigue life was found to be longer for the HDPE samples. However, when the two pipes were aged in an air-circulating oven for one year at 80°C, the fatigue life for HDPE drooped significantly to a level lower than that observed for the aged MDPE pipe, see Figure 5. The crystallinity content in both pipes were measured and was found to increase considerably throughout the pipe wall after aging. This was attributed to thermal annealing of the polymer at 80°C. This phenomenon was studied extensively by Rueda et al. (7). They suggested a lamellar diffusion mechanism to occur at elevated temperatures which in turn was said to lead to the increase in the crystallinity. The increase in crystallinity is proposed as a possible reason to account for the observed fatigue results for the aged pipes. The rate of crystallinity increase was found to be higher in the case of HDPE resin.

In order to gain an insight into the failure mechanism under fatigue loading, the fatigue test was suspended for the unaged HDPE and MDPE SEN specimens at approximately 60% of their respective fatigue life. The crack regions were microtomed and inspected under a polarized optical microscope, see Figure 6(a) MDPE and (b) HDPE. With reference to Figure 6(a), the crack growth was seen to be accompanied with secondary fracture at approximately 45° to the primary crack front.

As mentioned previously, the PE pipes have a morphology-gradients throughout the wall thickness. The effect of this was studied by plotting the crack opening displacement as a function of cycle using three different notch locations: (a) outer surface notch; (b) inner surface notch; and (c) side notch. It is clear from Figure 7 that that the rate of crack growth is influenced by the level of crystallinity ahead of the notch tip.

The fracture behavior at the crack tip could be described as follows: when the crack opening reaches a maximum, strengthening of the fibrils ahead of the crack due to the orientation of the fibrils in that region. Damage mechanisms responsible for the crack propagation were found to be the formation of voids and yielding, see Figure 8(a). Therefore, the crack growth was observed to occur with an accompanying layer of damage ahead of the crack tip. Figure 8(b) illustrates a similar failure process to that shown in Figure 8(a).

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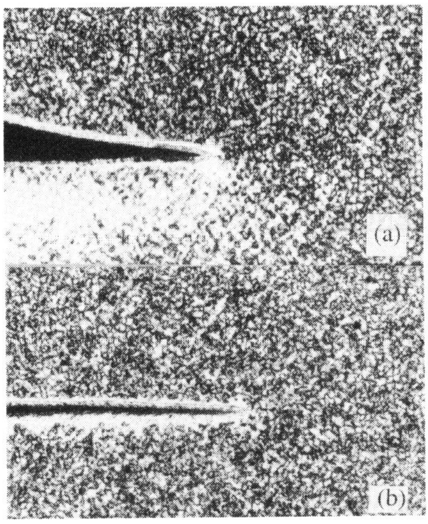

Figure 1. The effect of the method of notching on the microstructure.

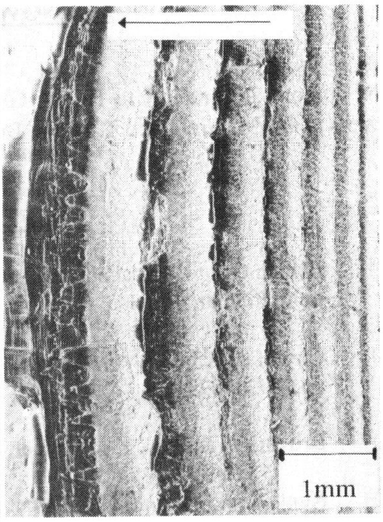

Figure 2. Ductile-brittle fracture surface.

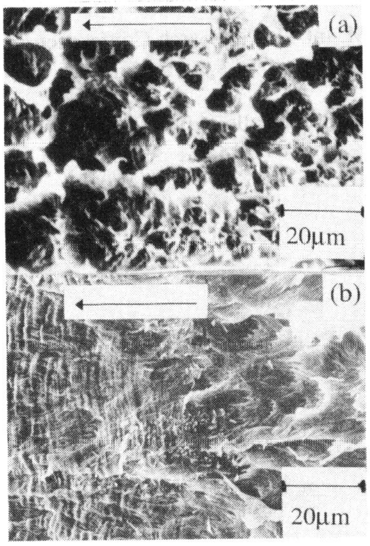

Figure 3. High magnification of the ductile -brittle failure (a) brittle (b) ductile.

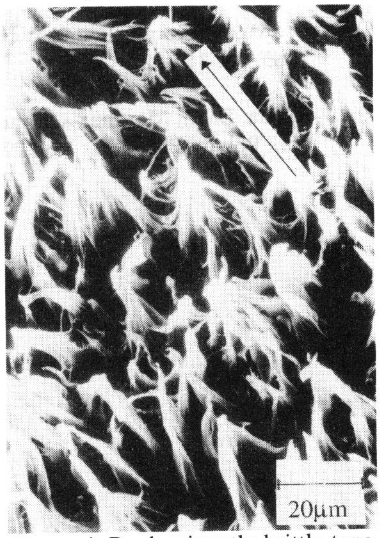

Figure 4. Predominantly brittle type fracture observed in a PE pipe sample which failed on site.

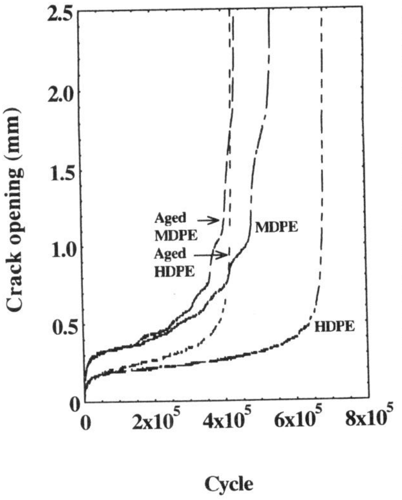

Figure 5. Crack opening as a function of fatigue cycles for aged and unaged pipes.

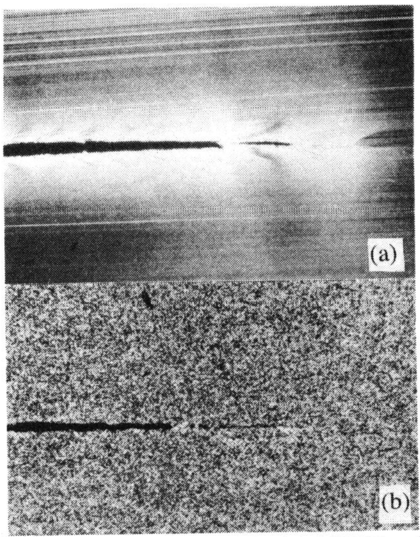

Figure 6. Crack growth in (a) MDPE and (b) HDPE.

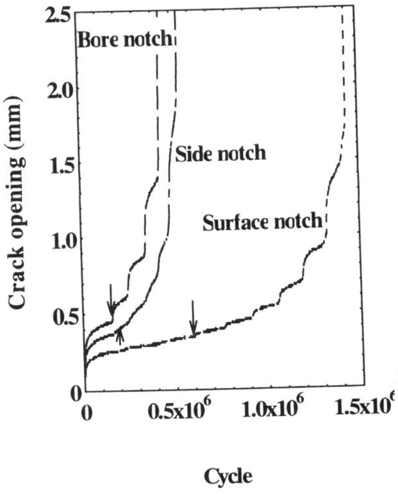

Figure 7. Crack opening as a function of fatigue cycle for different notch location.

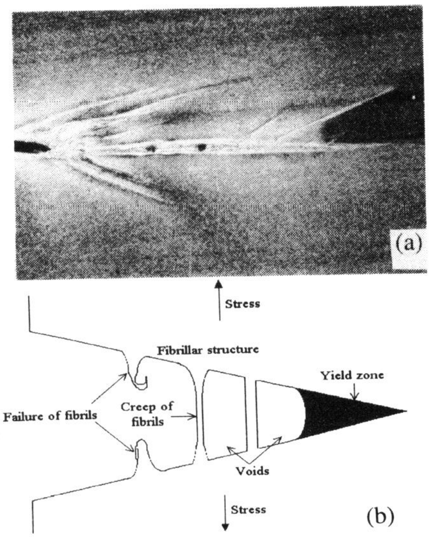

Figure 8. Crack growth mechanism.