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Micromechanisms of fatigue-crack advance in PVC

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The fatigue-crack propagation characteristics in poly(vinyl chloride) (PVC) are examined in terms of fracture mechanics concepts where the crack growth rate is related to the applied stress intensity factor range. The microscopic details of fatigue crack extension are examined with the aid of light optical, scanning and transmission electron microscopes. The mechanism of crack advance is found to be that of void coalescence through craze material generated in advance of the crack tip. While the craze is shown to grow continuously with cyclic loading, the crack is found to grow discontinuously in several hundred cycle increments.

1. Introduction

In recent investigations, Elinck *et al* [1] and Faulkner and Atkinson [2] showed that fatigue-crack propagation in PVC could be related to fracture mechanics concepts. In addition, Elinck *et al* reported the appearance of interesting morphological features on the fracture surfaces – in particular, crack arrest lines whose spacings were approximatelly equal to the crack tip plastic zone size as defined by the Dugdale-Muskhelishvili model [3]. Furthermore, they concluded that the plastic zone size was formed during one cycle but that subsequent crack advance through the plastic zone occurred in a discontinuous manner; thus, their data indicated that increments of crack extension occurred in discrete bursts equal to the arrest line spacing with no further crack growth for several hundred cycles thereafter until the next discrete crack advance step. The discontinuous nature of crack advance as suggested in PVC is most surprising in view of the overwhelming weight of literature in metal alloys indicating fatigue-crack propagation to be a continuous process. For example, on a microscopic level, Forsyth and Ryder [4] showed clearly that the number of loading cycles was equal to the number of fatigue striations seen on the fracture surface. Similar observations have been made for polymers such as polycarbonate [5]. By comparing these observations with that of Elinck *et al* one must conclude that the arrest lines seen on the fracture surface in PVC are not fatigue striations in the normal use of that term.

The objective of this investigation was then to explore the micromechanisms of fatigue-crack propagation extension in PVC with particular attention to the continuous or discontinuous nature of plastic zone formation and crack advance.

2. Experimental procedures

Single-edge-notch fatigue tests were performed on rigid PVC (Cadillac Plastics Company) in laboratory air on an MTS electrohydraulic closed loop fatigue test machine at a cyclic frequency of 10 Hz. Specimen width, length and thickness were 7.62, 30.48, and 3.25 cm, respectively. Other tests were conducted on PVC at lower frequencies and the results reported elsewhere [6]. During each fatigue test, crack, length and associated number of cycle data were recorded. From such information the fatigue crack growth rate, $\mathrm{d}a/\mathrm{d}n$, was related to $\triangle K$, the prevailing stress intensity factor range, where

$$\triangle K = \frac{Y \triangle P \sqrt{a}}{BW}$$

where Y = geometrical correction factor $= -1.99 - 0.41\,(a/W) + 18.70\,(a/W)^2 - 38.48\,(a/W)^3 + 53.85\,(a/W)^4$. B = specimen thickness; W = specimen width; a = crack length; $\triangle P$ = load range. All tests were conducted with a minimum-to-maximum load ratio of 0.1.

Fracture surface markings were examined with an Etec Scanning Electron Microscope and from polyacrylic acid replicas examined in a Philips 300 Microscope. Additional light microscope studies of crack tip details were performed on a single edge notched sample which was cycled in an Instron testing machine at 0.4 Hz.

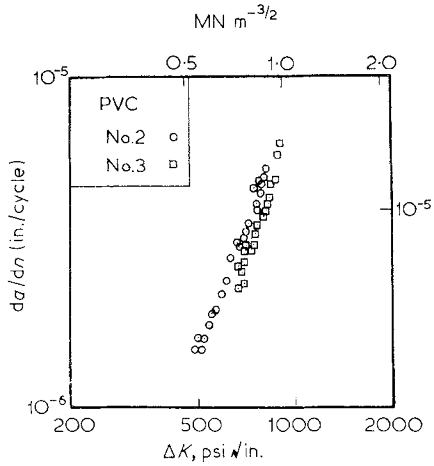

Figure 1 Fatigue-crack propagation rate versus stress intensity factor range in PVC at 10 Hz.

3. Experimental results and discussion

The fatigue crack growth rate for PVC as a function of the stress intensity factor range is shown in Fig. 1. The correlation of these data support the validity of fracture mechanics concepts with respect to description of the fatigue behaviour of polymeric materials such as PVC. In particular, an exponential dependence of crack growth rate on $\triangle K$ is observed with PVC, as has been noted previously for PVC [2] and for other polymers [7, 8].

Many arrest markings similar to those found by Elinck *et al* [1] were seen on the fracture surface, as shown in Fig. 2. Initially it was thought that these lines might be owing to creep effects resulting from test interruptions for crack length measurements. An additional test was, therefore, conducted wherein the test was interrupted only three times; well over one hundred arrest lines were seen on the surface.

The nature of crack advance as seen on the surface of the test panel was examined for a specimen pre-cracked at 10 Hz and then subjected to further cycling at 0.4 Hz. Fig. 3a shows the crack tip after the pre-cracking operation. In addition to the crack (crack tip indicated by arrow), two crazes are observed to extend ahead of the crack tip. After 100 loading cycles at a stress intensity factor range of 900 MN m$^{-3/2}$ the sample was rephotographed. Fig. 3b shows that the crack (denoted by the rumpled mating surfaces) did not grow; however, the two crazes extended further from the crack tip. Two additional 100 cycle increments resulted in further craze growth while the crack tip remained unchanged as shown in Fig. 3c and d. With another 150 cycle loading increment, the crack was seen to jump to a new position approximating the total length of the craze preceding the point of crack instability (Fig. 3e). This process of continuous craze growth but discontinuous crack extension was verified for additional loading increments and associated metallographic observations.

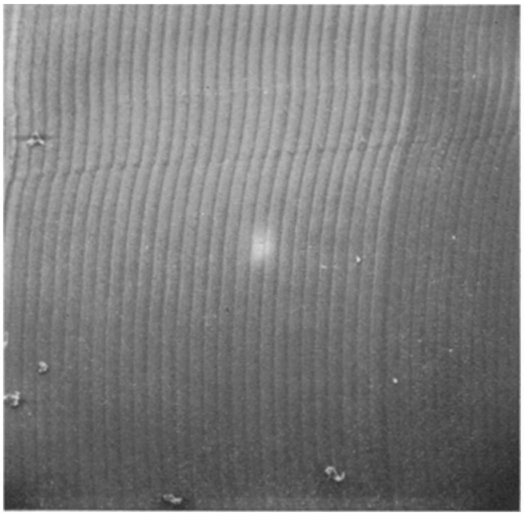

Figure 2 Arrest lines in PVC resulting from fatigue-crack propagation. Crack direction = right to left × 35.

On the basis of the information provided in Fig. 3 one may conclude that plastic zone formation as envisioned by Elinck *et al* [1] entails the formation of craze material at the crack tip and its immediate surroundings. Interestingly, the occurrence of crazing in PVC has been implied before [9] but not found in investigations reported by Kambour [10]. In any case, we observe the craze growth process to be continuous, though characterized by a decreasing rate with increasing craze length. This may be seen by comparing the craze length in the sequential photographs of Fig 3. Observations of decreasing craze growth rate with increasing craze length has been reported previously

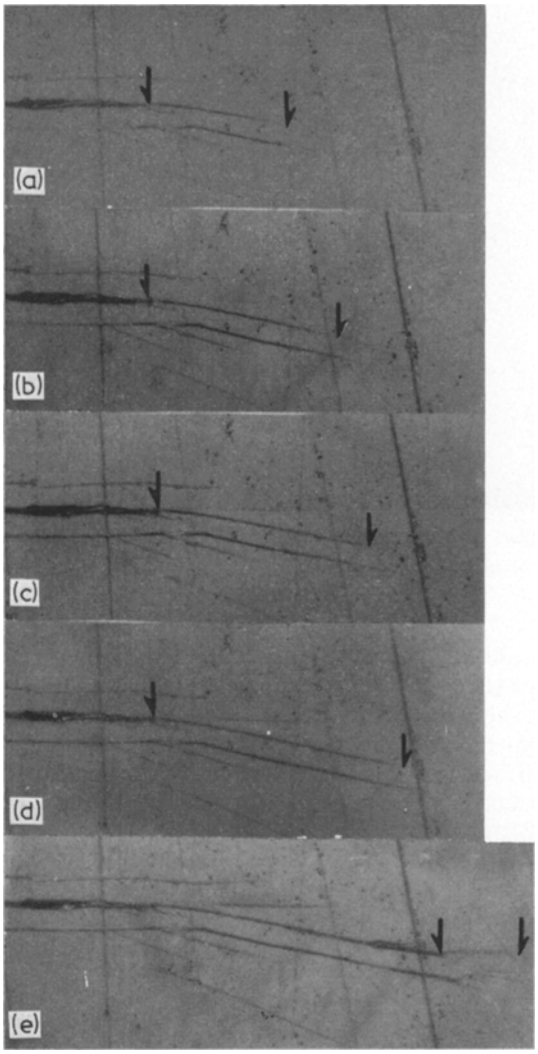

Figure 3 Composite micrograph revealing position of craze (↘) and crack (√) tip after fixed cyclic increments in PVC. (a) $N_1 = 0$; (b) $N_2 = N_1 + 100$; (c) $N_3 = N_2 + 100$; (d) $N_4 = N_3 + 100$; (e) $N_5 = N_4 + 150$ × 370.

by Marshall *et al* [11] and attributed to end controlled growth in the case of craze development in PMMA. As such, our finding of continuous craze growth rate is at odds with the conclusions reached by Elinck *et al* [1]. However, in agreement with the latter investigators, the crack was found to advance discontinuously over a distance comparable to the extent of craze development at the crack tip before the point of instability.

The continuous nature of craze growth coupled with discontinuous crack advance was found to be consistent with electron fractographic observations, which also provide support for the conclusion that crazing does, in fact, occur. Examination of polyacrylic acid replicas revealed the following morphological features: (a) the large light bands seen in Fig. 2 consist of equiaxed dimples which decrease in size with increasing crack length (Fig. 4a and b); (b) the narrow dark bands in Fig. 2 represent regions of narrow elongated dimples which are seen to point back towards the crack origin as shown in Fig. 4c. The entire sequence of fractographic events is shown together in Fig. 4d.

Based upon these observations the following crack extension model is postulated. Long thin crazes are formed at the crack tip and grow under the cyclic loading conditions. During this time interval, voids are formed throughout the craze and grow as a result of cyclic loading conditions. Since the number of loading cycles experienced by the crazed matter decreases rapidly with increasing distance from the crack tip, it is reasonable to expect a variation in microvoid size; large voids should exist near the crack tip while small voids should be developing near the tip. At some point, the craze reaches a critical size and crack propagation progresses rapidly (probably in one cycle) throughout the craze. While the rapid propagation of the crack through the crazed material would probably produce additional microvoid nucleation and allow for some growth of existing voids, change in the void size distribution in the craze as a function of distance from the crack tip would not be expected. Therefore, the observation of a decreasing dimple size with increasing crack length should reflect the void size distribution along the craze at the point prior to the instability of the crack. On the other hand, were the crack to propagate continuously through an ever-lengthening craze, a uniform microvoid size would be developed. Such was the case for continuous fatigue crack growth in an aluminium alloy where the same void size was seen over a two decade crack growth range [12]. Obviously, this is not the case in fatigue of PVC. Finally, when the crack reaches the end of the craze it will be arrested, with the crack tip being blunted by a stretching process of tear dimple formation (Beachem [13] has shown that these tear dimples would point back toward the crack origin). With further cycling new craze growth occurs and the sequence repeated again. From this pattern of craze-crack development the fracture

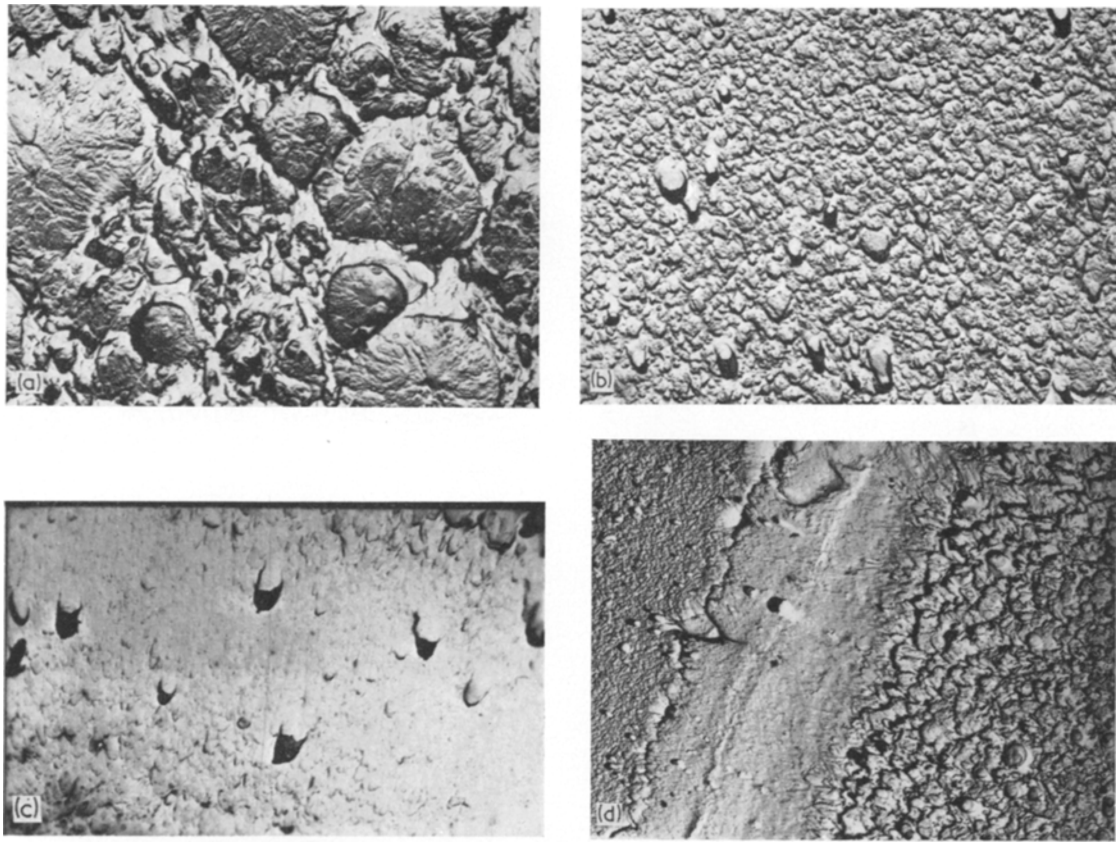

Figure 4 Microvoid appearance of fatigue growth bands in PVC. (a) Initial portion of growth bands containing large "equiaxed dimples" ×4650, (b) final portion of same growth band as in (a) containing small "equiaxed dimples" ×4650; (c) arrest line between adjacent growth bands revealing tear dimples pointing toward crack origin ×4500; (d) arrest line between adjacent growth bands, crack growth rate from left to right, ×1300.

Figure 5 Region of final failure. Crack growth from right to left ×920.

surface morphology associated with ultimate crack instability for the entire specimen should reveal a final band of dimples of decreasing size with increasing crack length followed by unstable crack extension markings rather than by the presence of an instability point midway through the large band of equiaxed dimples. The region shown in Fig. 5 supports this contention and the model as outlined above.

4. Conclusions

1. The stress intensity factor range is seen to correlate fatigue crack propagation data in PVC.

2. Crazing appears to occur in PVC, as well as in other polymers, and appears to precede crack extension under fatigue loading.

3. Craze development occurs at the advancing fatigue crack tip and progresses continuously with cycling though at a decreasing rate with increasing craze length.

4. Crack advance occurs discontinuously, and over a length comparable to the craze length existing at the time of the instability.

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