Letters

Discontinuous fatigue crack growth in polycarbonate

A discontinuous crack growth (DCG) stage of fatigue crack propagation has been reported to occur in polycarbonate [1–3] and a number of other glassy polymers [2, 3]. In this stage the crack is arrested during most of the load cycles with discontinuous crack jumps occuring periodically. The nature of the DCG fatigue fracture process has previously been discussed in terms of a craze breakdown model [1–3]. Observations recently made indicate that such a model does not adequately describe the DCG process in polycarbonate.

BPA-polycarbonate tensile bars with rectangular cross-sections were machined from Lexan* polycarbonate extruded sheet (0.32 cm thick) and polished to a roughness of 0.05 micrometres. They were then fatigued to failure under (sinusoidal) load control at 5 Hertz in tension–tension with a maximum stress of 38 $MN\,m^{-2}$ and a minimum-to-maximum load ratio of 0.1. The fracture surface was examined by scanning electron microscopy. The subsurface region was studied by polarized transmission light microscopy. For this purpose, a grinding and polishing procedure [4] was utilized to produce thin sections, the planes of which included the loading direction and the crack propagation direction.

Fig. 1 is a scanning electron micrograph (SEM) showing part of a fatigue crack surface produced by discontinuous crack growth. The crack arrest bands (three are shown in Fig. 1) are sharply demarcated. The centre of the arrest band is raised above the adjacent portions. Between each pair of arrest bands is a nodular region, the nodules attaining maximum size about midway between the bands. Nodules of this kind are not evident within the arrest band.

Fig. 2 is a polarized light micrograph of a thin section which shows a DCG portion of one of the incomplete fatigue cracks co-existing in this specimen (crack plane normal to the photograph). Emanating from each crack surface is a periodic set of sharply delineated shear bands. A comparison of SEM and light micrographs shows that the base of each shear band is associated with a fracture surface arrest band. Both the size and spacing of the shear bands increase linearly with crack length. The shear bands are nearly normal to the crack plane at their base, then curve forward and asymptotically orient approximately 45° to the crack direction. The base of each shear band lies near a line connecting the tips of the preceding bands.

At higher magnification the bases of each pair of shear bands are seen to be separated somewhat on their trailing sides (Fig. 3). This spacing divided by twice the shear-band width equals the residual shear strain in the band at the fracture surface

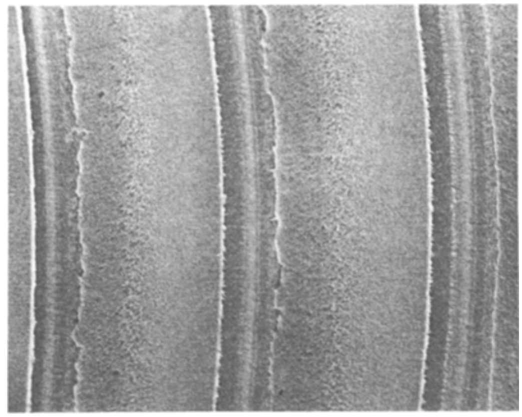

Figure 1 Scanning electron micrograph of DCG region showing several crack arrest bands. Band spacing ≈ 65 micrometres. (Crack growth direction left to right.)

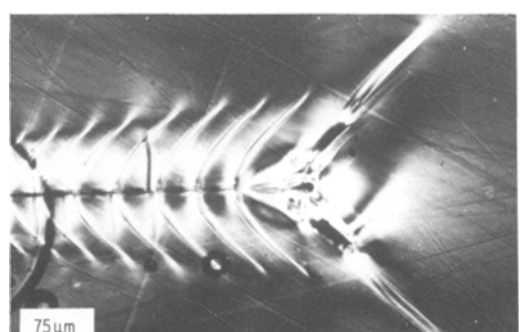

Figure 2 Polarized transmission light micrograph of a thin section of a fatigue crack interrupted soon after the DCG crack propagation stage terminated. The DCG process terminates with a pair of much larger shear bands, each of which contains a partial crack. Note: The bubbles and the partial ring to the left are artifacts of the sample preparation. (Crack growth direction, left to right.)

*Lexan is a trade mark.

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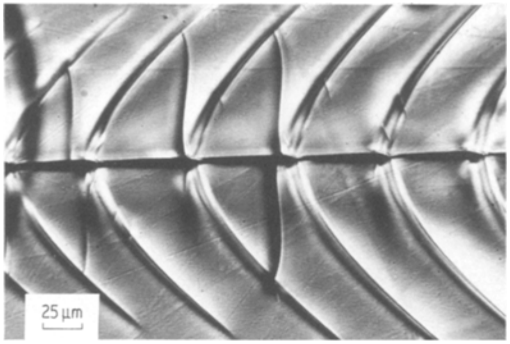

Figure 3 Higher magnification of DCG region of Fig. 2 showing detail of crack profile. (Crack growth direction, left to right.)

(approximately 30%). Diffuse yielding is also evident in the region between the discrete shear bands.

One thin section was lifted gently from its embedding epoxy after soaking in water. The section was mounted in a stressing jig on the microscope stage and the DCG crack tips examined as the specimen was being stressed. The stress bi-refringence that developed appeared to be concentrated just ahead of the base of the most advanced shear band pair.

In many of the fatigue cracks, the DCG stage of fatigue crack propagation terminates with a much larger pair of shear bands than the preceding bands. Each band in this ultimate pair often contains a separate crack growing at approximately 45° to the loading direction (see Fig. 2). If the fatigue fracture process had not been interrupted by fracture elsewhere, the primary fatigue crack would have merged with one of these partial cracks.

Other features observable in the thin sections (Fig. 3), such as the vertical crazes/cracks (parallel to the loading direction), are not thought to be central to the DCG growth mechanisms.

These observations indicate that the DCG crack-tip plastic zone for BPA-polycarbonate consists of a pair of discrete shear bands and a craze, which together approximate the letter "epsilon" in profile. Fig. 4 shows a fatigue crack which has just generated its first DCG "epsilon" plastic zone.

The plastic zone which develops in response to the intensification of stresses at a sharp crack tip is often modeled either in terms of tensile yielding or slip on discrete surfaces emanating from the crack tip [5]. The DCG "epsilon" plastic zone combines both of these plastic flow mechanisms: the tensile yielding occurring in a craze ahead of the crack tip and the slip occurring along two sharply delineated shear bands.

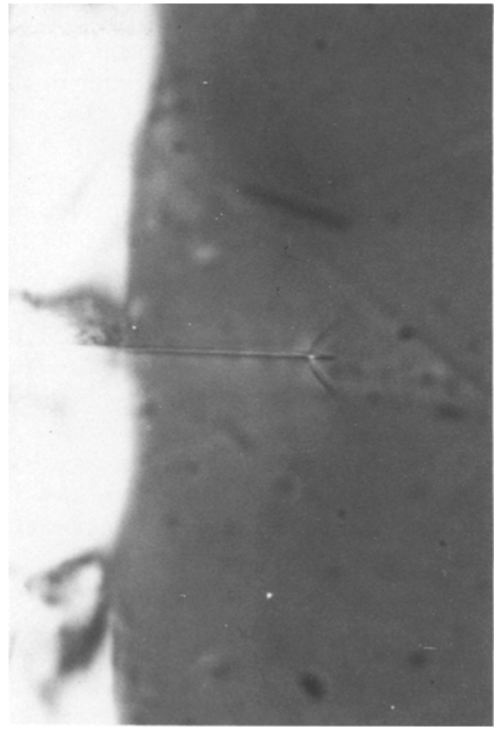

Figure 4 "Epsilon" plastic zone ahead of crack tip. Crack length ≈ 60 micrometres, craze length ≈ 5 micrometres. (Crack growth direction, left to right.)

Small-scale yielding crack analysis [6] predicts the initial path of the shear bands to be nearly normal to the crack direction, which is what is observed. Thus, early in their growth, the shear bands offer little protection to the region directly ahead of the crack tip where maximum hydrostatic stresses exist and craze initiation and growth are most favoured.

Under further cyclic loading, the shear bands grow and curve forward. The forward growth of the shear bands tends to reduce the stress on the base of the craze (i.e. the section of it close to the shear band base). The shear band itself grows in contour length and also thickens at its base by the incorporation of new material (including, presumably, pre-existing craze material). As the shear band grows the shear strain in the element at the trailing end of the shear band (at the crack tip) increases to its ultimate level (approximately 30%) and this element fails: hence, a flat ramp from the rear edge to the central ridge of the crack surface arrest band is produced by a succession of element elongations and ruptures.

This process of shear zone growth/failure might well continue indefinitely were it not for craze break-down. Bearing in mind the locus of maximum coarseness on the fracture surface (Fig. 1) and the reduction of crack-plane stress level caused by the shear bands, it is reasonable to assume that the craze structure fatigues most rapidly (i.e. the stress amplitude is greatest) at a position well ahead of the shear band base. After continued load cycling the crack jumps through the "epsilon" plastic zone by one of at least two plausible mechanisms.

In the first, a secondary crack initiates in the weakest portion of the craze (location of maximum surface nodular coarseness) and spreads backwards toward the advancing shear band crack as well as forward toward the craze tip. The merger of primary and secondary cracks then causes a sudden rise in stress on the foremost section of craze causing its immediate failure. Thus, the primary/secondary crack linkage triggers the crack jumping process.

In the second mechanism, the shear zone growth/failure process continues under cyclic loading. The crack tip thus gradually advances through the craze by a shear fracture process at the base of the thickening shear band. Eventually, the crack tip encounters a portion of craze sufficiently weakened that an instability develops and the crack jumps through the remaining craze.

The reason why the crack then stops at the tip of the pre-existing craze or just beyond is not known. It is tempting to suggest that the crack arrest relates to the inability of crazes in polycarbonate to grow rapidly under uniaxial loading so that the sudden overload results in the start of a new pair of shear bands instead. Countering this argument however, is the knowledge that rapid plane-strain crack advance under monotonic loading is known to lead to unstable, high-speed fracture at very low fracture energies [7].

Preliminary fatigue studies of unnotched samples of several other amorphous polymers, including polystyrene, polyvinyl chloride and poly (2,6-dimethyl-1,4-phenylene oxide), have not yet revealed similar crack tip plastic zones. The existence of an "epsilon" plastic zone in polycarbonate may thus account for the relative ease in producing stable DCG regions in the fatigue of unnotched samples of this resin. Clearly the process of understanding the nature of discontinuous fatigue crack growth has just begun.

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M. T. TAKEMORI
R. P. KAMBOUR
General Electric Company,
Corporate Research and Development Centre,
Schenectady, New York,
USA