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Shear and craze development in the fatigue of ductile amorphous polymers

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The competitive interplay between shear and craze deformation in the fatigue of ductile amorphous polymers leads to the formation of intricate fatigue crack shapes and stable crack growth. The craze/shear dual deformation mode is expressed in a unique crack tip plastic zone, which has been observed in polycarbonate, polysulfone, a polyarylate block copolymer and a polyestercarbonate copolymer. The fatigue crack growth resistance in these polymers is high, and factors which affect the relative ease of shear flow and crazing are expected to affect their fatigue endurance.

1. Introduction

Polymers generally deform by crazing or shear flow. In most cases, one of these two mechanisms usually dominates the deformation behaviour. There are specific situations, however, where both mechanisms occur simultaneously on a nearly equal level. For thin samples, plane stress conditions near the free surfaces often lead to shear flow and shear lip formation, whereas the plane strain condition in the interior favours craze formation. This bulk response is primarily a geometric effect with the two processes widely separated in space and, in many ways, relatively independent of each other. On the other hand, a dual deformation response on a more local scale has been observed in some amorphous polymers under fatigue loading. For these situations, the competitive interplay of the crazing and shear flow process can be seen in the development of the epsilon crack tip plastic zone, which is composed of distinct planes of shear and craze formation arranged with a cross-sectional profile of the Greek letter epsilon [1]. Overall, this craze and shear competition can lead to the development of some extraordinary fatigue crack shapes, two of which are shown in Fig. 1. This note will characterize the growth behaviour of these fatigue cracks and attempt to rationalize the roles of the two principle deformation mechanisms in the fatigue crack development process.

As reported in a recent survey [2], epsilon plastic zones have been thus far observed in four amorphous polymers, two of which (polycarbonate and polysulfone) develop a single clam-shell-shaped crack profile (Fig. 2) when viewed normal to the crack plane. The two other polymers, a polyarylate block copolymer and a polyestercarbonate copolymer, exhibit intricate crack shapes (Fig. 1). The fatigue cracks referred to here and throughout this paper are surface-initiated cracks in the early stages of fatigue crack development, i.e. the cracks are (generally) small and slowly propagating. Furthermore, the crack propagation mode is discontinuous, requiring multiple load cycles between crack jumps. The resultant fracture surface markings have been referred [3] to as "discontinuous growth bands", as opposed to the single cycle advance fatigue "striations".

Although the discontinuous crack mode is common to most polymers during early crack development, the polymers with no epsilon plastic zone development exhibit much smaller discontinuous growth zones (< 1% of total fracture surface area) which are often barely discernable and ill-defined [2]. The polycarbonate and polysulfone cracks may extend up to 5% while the polyarylate and polyestercarbonate copolymer cracks often span 20% of the total fracture surface area. Beyond the discontinuous zone, single cycle

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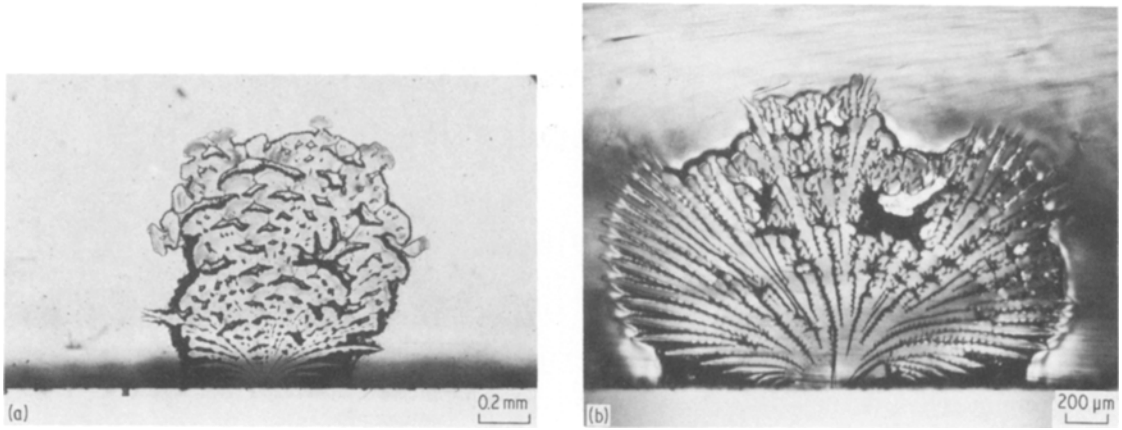


Figure 1 Optical micrographs of typical fatigue cracks in the polyarylate (a) and polyestercarbonate (b) copolymers. The load direction is perpendicular to the plane of the micrograph. (Reproduced by the permission of © 1984 Annual Reviews Inc [7].

crack advance occurs; this behaviour reflects the constant load amplitude fatigue testing of smooth bar samples. Generally, as crack shape complexity increases (as well as relative sizes of the discontinuous growth zones), crack growth rate decreases and overall fatigue lifetime increases. Since the crack shape complexity is a direct consequence of the dual deformation response to fatigue loading, knowledge of the effects of the competitive interaction between shearing and crazing at the crack tip could be instrumental towards understanding the mechanism of fatigue crack growth resistance in these polymers.

2. Observations

In polycarbonate (PC) and Union Carbide Radel polysulfone (PSF), the dual deformation epsilon growth region is contained within a single well-defined region, with the epsilon crack tip plastic zone developing along the entire crack front (Fig. 2). At the flanks near the sample free surface, the craze disappears and the narrow plane strain shear band pair transforms into plane stress shear zones which occupy a wedge-shaped region with sides running roughly ± 45° to the crack plane. On the free surface the characteristic shear zones [4] can be seen emanating from the tips of the crack opening. The disappearance of the craze at the flanks where plane stress shear flow occurs has a similar origin to the geometry (stress state) induced shear lip formation discussed earlier in the Introduction. Along the crack front, the epsilon zone process repeats itself with each discontinuous jump until some critical time when the forward craze stops growing while the final pair of shear bands extend unabatedly. ± 45° shear fatigue fracture occurs in this last pair of oversized shear bands. Crack growth during this interval is very slow with much of the crack lifetime spent here.

In a small proportion of the cracks, the forward craze becomes unstable and the crack advances through the craze on each load cycle. Although the crack advance on each cycle may be much shorter than the previous discontinuous crack jump lengths, the average rate per cycle is greater. The shear deformation at the crack tip is shorter, broader and more diffuse than the narrow, crisp epsilon shear bands.

The primary feature of PC and PSF fatigue cracks is that the epsilon region is confined to a single, large (up to 1 mm in diameter) region, which is usually terminated by shear fatigue fracture induced by the unabated growth of the final pair of plane strain shear bands.

For Union Carbide Ardel D100 polyarylate (PAR) and an experimental polyestercarbonate (PEC), however, a large intricate crack with many interconnected epsilon regions distinguishes the discontinuous growth regime. This complex crack growth behaviour can be separated into two basic growth processes: (i) the localization and near-termination of the epsilon process in small regions, and (ii) the repeated regeneration of these slow growth zones. Unlike PC or PSF, the unabated growth of the terminal pair of shear bands occurs "prematurely" for these two copolymers and creates much smaller epsilon regions, typically of the order of 25 and 150 μm

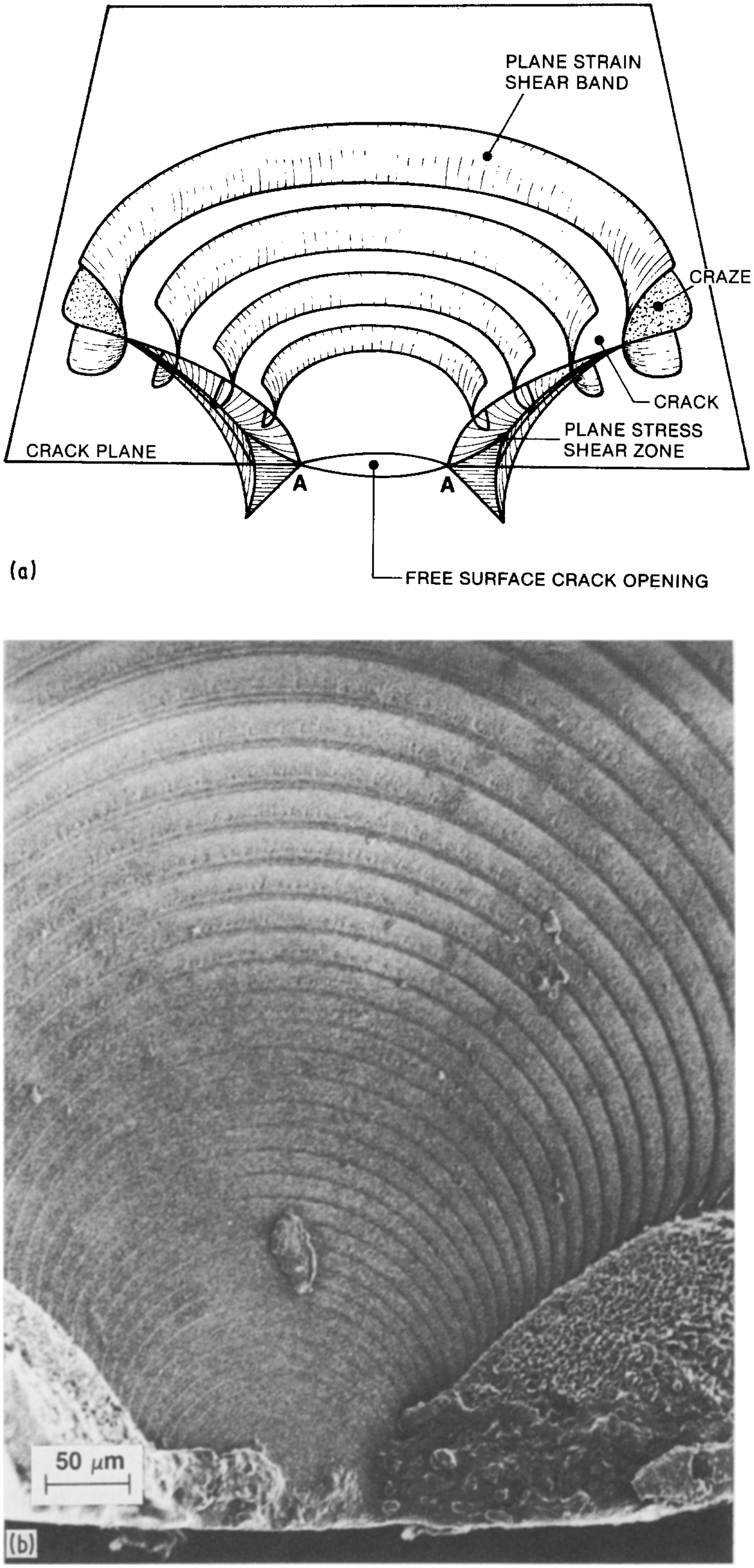


Figure 2 (a) Schematic view of epsilon crack growth region for polycarbonate and polysulfone. The plane stress shear zones occur near the surface on either side of the crack opening (AA). (b) Fracture surface view of a polycarbonate fatigue crack.

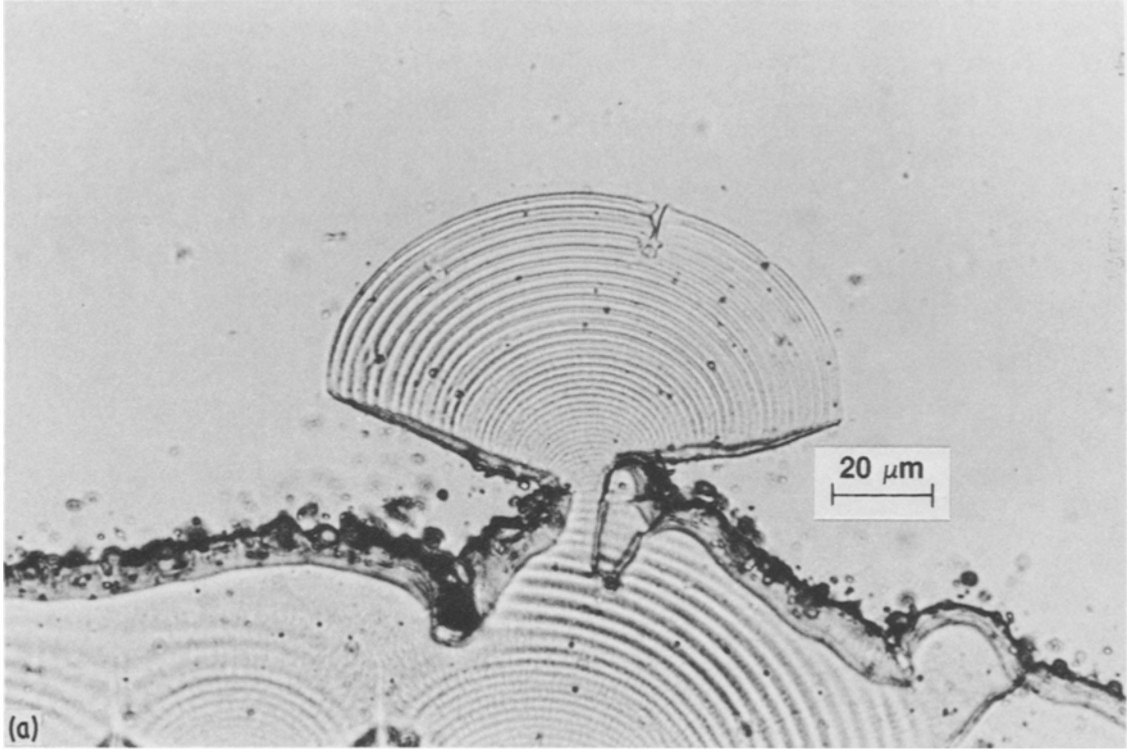


Figure 3 Localized epsilon growth regions in polyarylate (a) and polyestercarbonate (b, c). Crack arrest bands can be seen in (a) and (c), and are present in (b) although not visible in this optical micrograph. In (b), the irregular lines at the tips of the finger-like regions are due to moisture in the cracks. A faint convex craze profile can be seen at the extreme tips. (a) and (b) reproduced by the permission of © 1984 Annual Reviews Inc [7].

across. These localized regions take on various shapes, from clams, to fingers, to oscillatory regions (Fig. 3). The small clam-shell-shapes are miniature versions of the large zones found in PC and PSF.

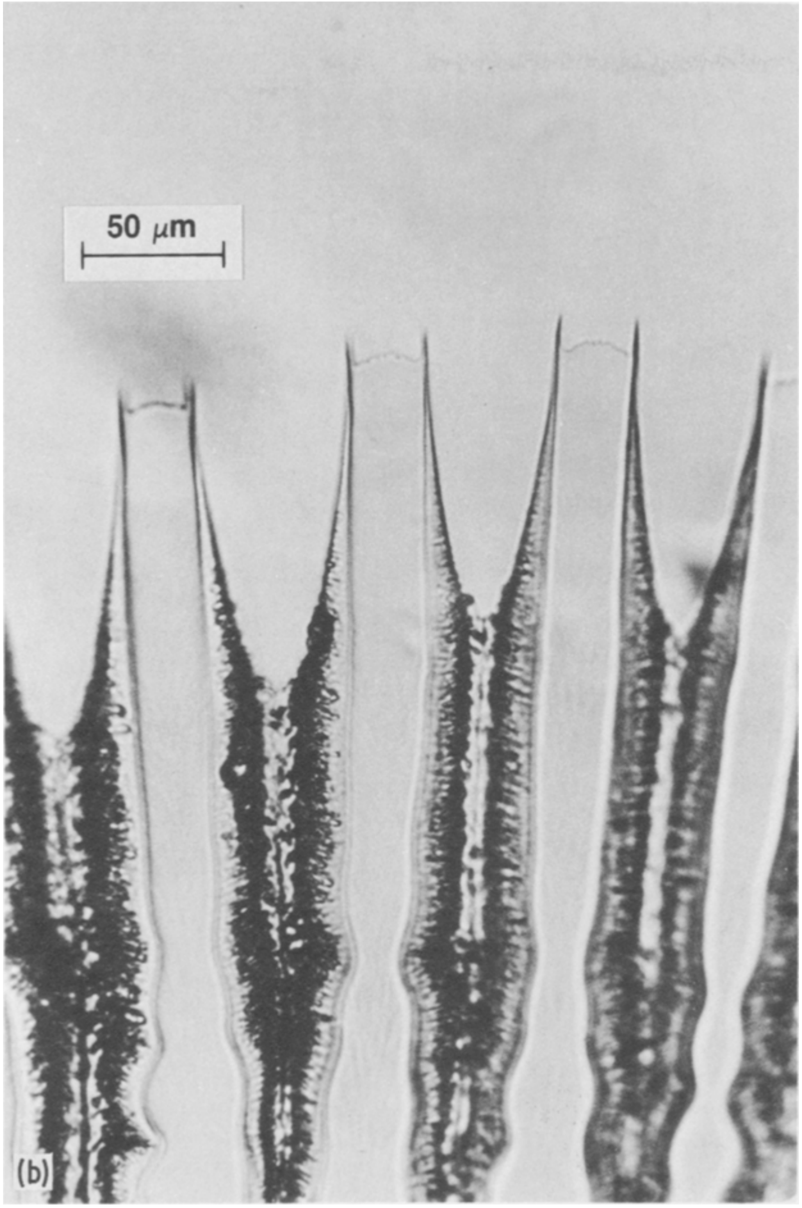
Although considerable time is spent in the continued development of the near terminal shear band pair, "leaks" develop before shear fracture takes place. New epsilon regions regenerate along the crack front and the process repeats itself. The successive growth, termination and regeneration of localized epsilon regions produces complex crack shapes as shown in Fig. 1, as well as very long fatigue crack lifetimes. To accomodate the expanding crack front as the crack grows deeper into the sample, branching and zig-zag growth occur (with the crack sometimes growing back *towards* the free surface (Fig. 4).

3. Discussion

Perhaps the most intriguing aspect of these epsilon producing cracks is the interplay of shearing and crazing. When crazing dominates, no epsilons form. When shear flow becomes more favourable, epsilon zones may form, but if shear flow becomes too favourable, the discontinuous growth behaviour may be suppressed and shear fracture may develop. The secondary interplay between shear fracture and craze leaks determines whether a single epsilon region or a multiple crack develops.

For the PAR and PEC copolymers, the complex crack growth behaviour can be explained by a relative ease of plane strain shear flow compared to craze growth. Large epsilon regions, such as found in PC, require a balance between craze and shear band development. Any preference for plane strain shear flow would accelerate the transition to shear fatigue and keep the epsilon regions small. Furthermore, a shear predominance would prevent the crack front from expanding, thus encouraging more tightly closed epsilon growth regions, such as fingers (Fig. 3b). The presence of oscillatory regions (Fig. 3c) attests to the competitive balance between these deformation modes.

The reasons for the continuous regeneration of



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new epsilon regions is somewhat more perplexing. Large plain strain shear bands which terminate epsilon growth occur quite readily in PEC and PAR. They have been observed to grow quite large and consume a considerable portion of the lifetime, yet they are quite resistant to fracture. This may be due to a relatively high plane strain shear fracture toughness. Thus, before shear fracture occurs and the shear fatigue crack growth process can dominate, craze growth may initiate somewhere along the crack front and produce a leak which regenerates the epsilon process beyond the near-terminal enlarged shear band pair.

Factors which affect the ease of shear flow and crazing, such as temperature, frequency and stress state are thus expected to affect the development of these fatigue cracks. Preliminary tests on the PEC copolymer at different temperatures and stress amplitudes are in accord with this idea. At − 20° C for example, the surface crack shown in Fig. 5 initially grew in a single large clam-shell-shape, which is reminiscent of those seen in PC at room temperature. The single large clam-shell is consistent with a greater tendency towards crazing at lower temperatures, whereas complex crack shapes are favoured at higher temperatures, where

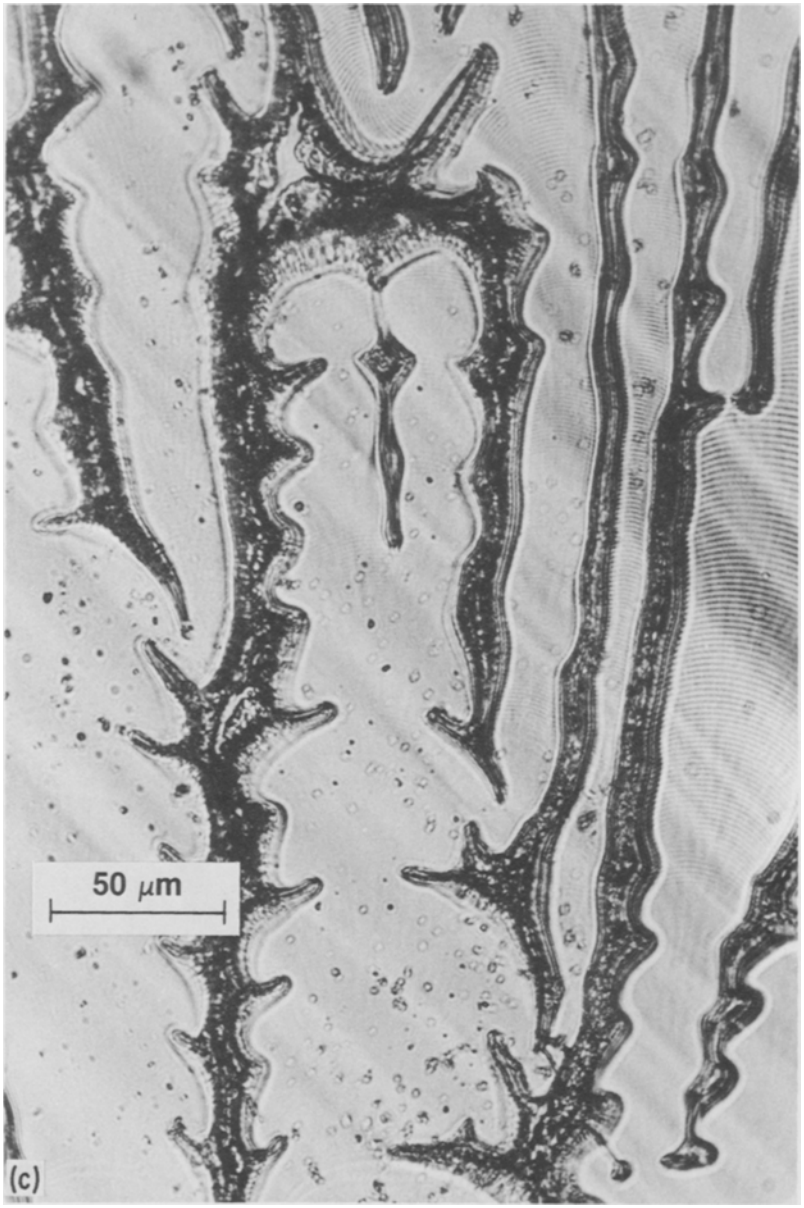

Figure 3 Continued.

enhanced shear flow is commonly observed in polymers. (This observation is to be contrasted with the results from ultra-thin sub-micron films where the reverse is apparently true, lower temperatures favouring craze growth and higher temperatures, shear deformation zones [5].) Subsequently, this crack transformed into many smaller localized epsilon regions, more typical of the room temperature behaviour. This transition may have been caused by (i) heating at the crack tip, hence leading to behaviour more indicative of higher temperatures, or (ii) higher crack tip stress for the lengthened crack, which could possibly favour shear flow.

One of the guideposts for the experimental search for epsilon crack development was a craze–shear correlation for amorphous polymers developed by Kambour [6]. In this correlation, the ratio ϵ_c/σ_y (where ϵ_c = craze initiation strain and σ_y = the tensile yield stress) reflects the ease of craze initiation relative to shear flow. A high value indicates a propensity towards shear flow, which is necessary for shear band development at a crack tip. This correlation proved to be quite useful as

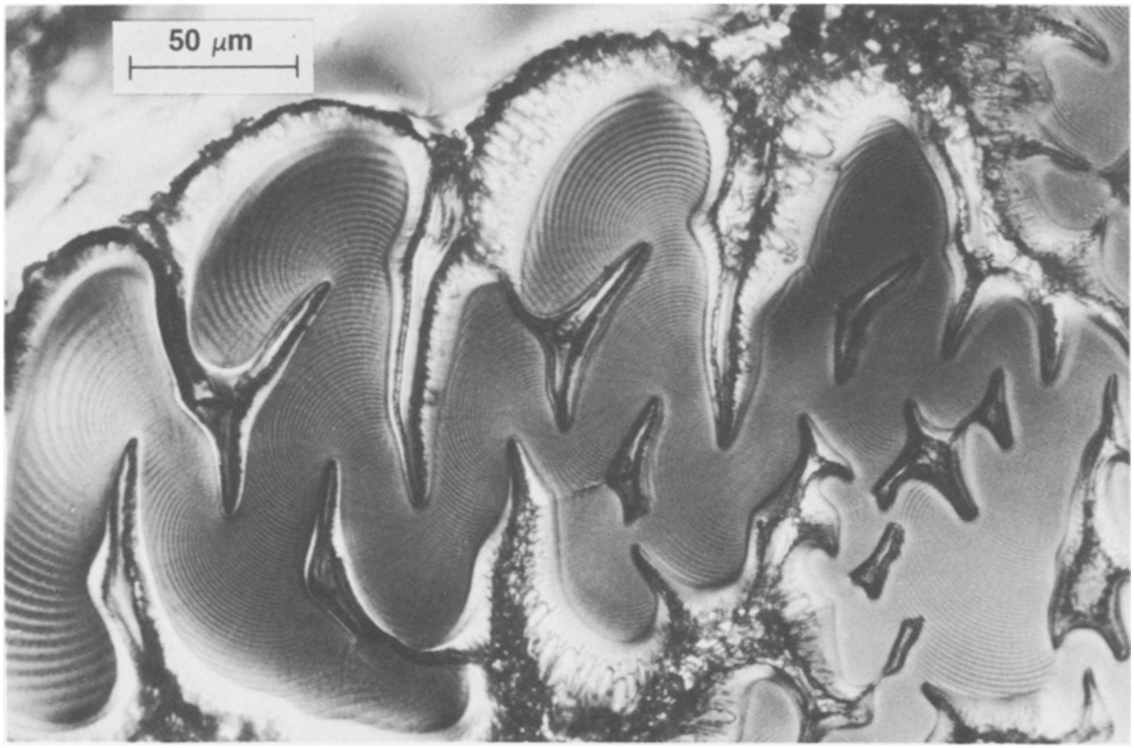

Figure 4 Optical micrographs of polyestercarbonate fatigue crack showing snake-like path to accommodate expanding crack front. 180° changes in crack growth directions can be seen.

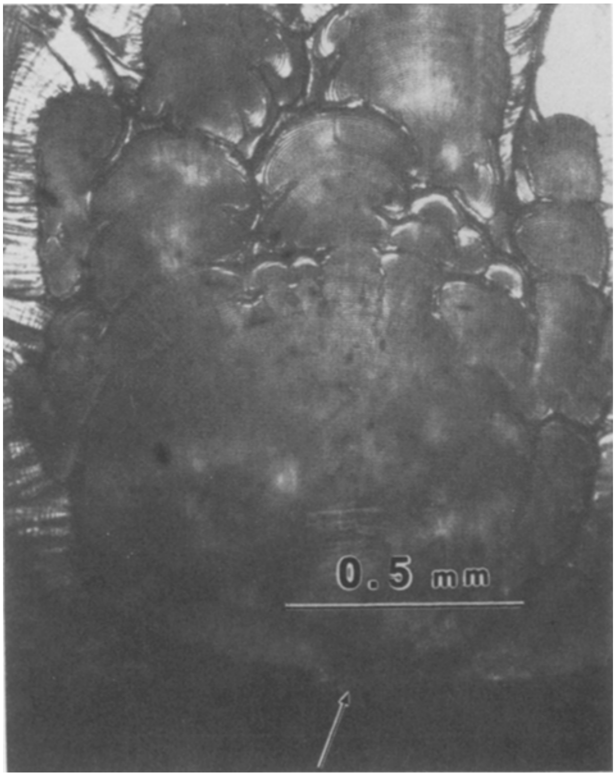

Figure 5 Polyestercarbonate fatigue crack grown at −20° C at 10 Hz between 6.7 and 67 MPa tensile stresses. The initial single large clam-shell epsilon zone transitioned into many smaller epsilon zones.

the four polymers discovered to exhibit epsilon development exhibited high ϵ_c/σ_y ratios. Other polymers showed high ratios and failed to produce epsilon zones, indicating that this correlation was approximate at best.

It appears likely that modified versions of the Kambour craze–shear correlation may be useful for understanding fatigue behaviour of these ductile amorphous polymers. The ratio of the stress intensity for craze growth to the plane strain shear yield stress may be more appropriate for epsilon development, with a high ratio emphasizing strong crazes and ease of shear flow, hence epsilon growth. Similary, a high value for the ratio of the stress intensity for craze initiation to the plane strain shear fracture stress may favour a transition to shear cracks, thus leading to a single epsilon clam-shell region rather than a multiple epsilon crack.

The epsilon crack growth process can thus be used as a measure of the interplay between crazing and shear flow tendencies in these amorphous polymers. The ability to undergo epsilon shear deformation can contribute to enhanced fatigue crack lifetimes by extending this slow crack growth/epsilon regime over a wider fracture surface area or by inducing a transformation to shear fatigue fracture. The resultant increase in fatigue toughness is a compelling reason for the continued study of this deformation phenomenon.

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