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Competing fatigue mechanisms in BPA–polycarbonate

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A change in the mode of fatigue fracture in bisphenol-A–polycarbonate results in a large discontinuity in the fatigue lifetime of notched specimens. This discontinuity is such that the lifetime above the transition is at least an order of magnitude *greater* than the lifetime below the transition. In addition, prior creep-loading of the specimens at 7500 psi (52 MPa) for as little as 60 sec or fatiguing at 7500 psi for 500 cycles changes the subsequent fatigue fracture mechanism at 4000 psi (28 MPa) from discontinuous crack growth to plane-strain shear fracture (over most of the notch). The mechanism change also increases the lifetime at 4000 psi by two orders of magnitude. This indicates that the change in mechanism at the notch occurs very early in the fatigue lifetime and is not due to hysteretic heating.

1. Introduction

Changes in the mode of fatigue failure are common in polymers [1] and are usually reflected in a change in the slope of the fatigue stress against lifetime curve [2]. The large temperature rise at high stress levels due to hysteretic heating or structural rearrangement due to high strains can cause the polymer to bulk shear yield. This is in contrast to the localized, craze-dominated failure at low stress levels [3, 4]. The change in the lifetime curve is such that the failure of the sample is accelerated at high stresses.

In sharply notched specimens of bisphenol-A (BPA)–polycarbonate, there is a transition in fatigue mode as the stress is increased that is unlike the aforementioned mode change. This change in fatigue mechanism is from craze-dominated, discontinuous crack growth to plane-strain shear fracture. Because of the very different growth rates of the two mechanisms, the transition in failure mode causes a large discontinuity in the fatigue lifetime curve itself, such that the lifetime just above the transition stress is at least an order of magnitude *greater* than the lifetime below the transition. Unlike bulk shear yielding, the plane-strain shear fracture is localized and not due to hysteretic heating.

The transition in fatigue failure mechanisms occurs because of an intimate competition between crazing and shear banding at the crack tip of BPA–polycarbonate [3, 5]. This competition produces a unique plastic zone consisting of both a pair of shear bands and a leading craze at the crack tip and has been called the "epsilon plastic zone". As the stress level is increased, the balance between crazing and shear banding is shifted such that the fatigue fracture mechanism changes from discontinuous crack growth (craze initiated) to plane-strain, shear fatigue fracture. Because the plane-strain, shear fatigue crack growth is slower than the discontinuous crack growth, there occurs a large discontinuity in the fatigue lifetime curve.

2. Experiments and results

The fatigue tests were carried out in tensile load control in an Instron 1350 servohydraulic tester. The samples were injection-moulded into a dog-bone shaped geometry described in ASTM D638 (Type I). The minimum to maximum stress ratio was 1 : 10 and the tests were carried out at both 1 and 10 Hz.

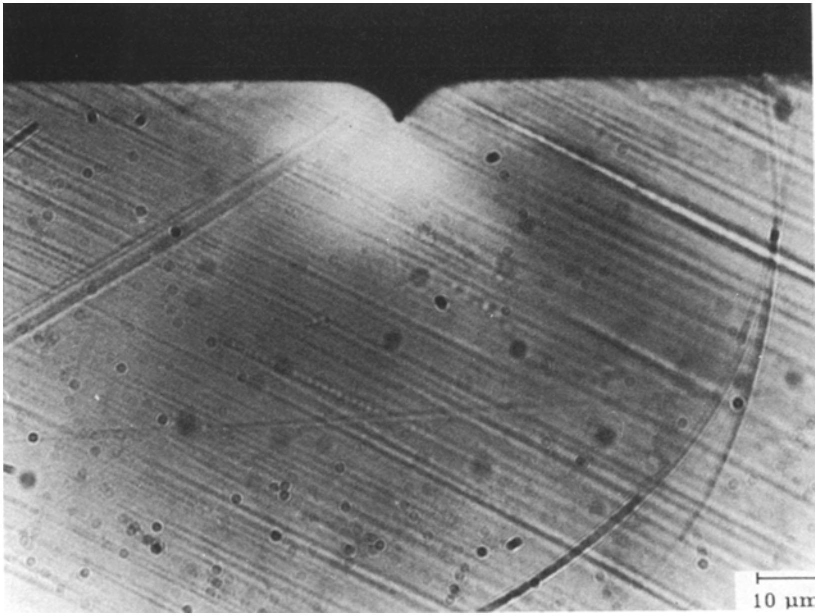

Figure 1 Thin-section profile of notch in BPA–polycarbonate knit-line specimens. Weakened area in front of notch extends the length of the precrack to approximately 25 μm.

The notch in the sample was made by filling the dog-bone mould from opposite ends of the sample (double-gated). The notch formed at the merging of the flow fronts (on the free surface) [6, 7] is shown in Fig. 1 and had a depth of approximately 10 μm uniformly around the perimeter of the gauge section. This notch proved to be a reproducible effect from which fatigue initiated.

The fatigue lifetime for the double-gated samples is shown in Fig. 2. As can be seen, there is a large discontinuity in the lifetime at approximately 6000 psi (41 MPa). At stresses below approximately 5500 psi (38 MPa), the samples fail in a craze-dominated manner, giving a lifetime shown by the filled triangles in Fig. 2. In this stress range, the cracks initiate over a large portion of the notch (Fig. 3). The fracture surface shows evidence of both discontinuous crack growth and single cycle growth (Figs. 4 and 9a below) indicating that the crack propagated through a leading craze. Unlike fatigue cracks initiated from small surface crazes, most samples did not make the transition from discontinuous crack growth to plane-strain, shear fatigue fracture.

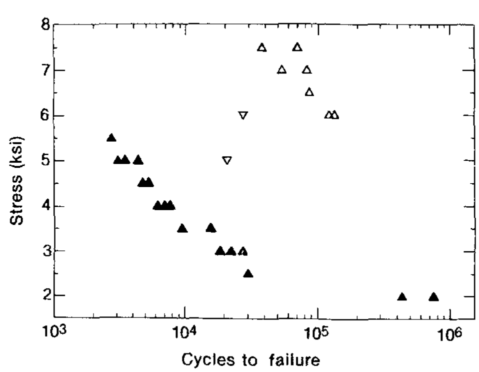

Figure 2 Fatigue lifetime variation of BPA–polycarbonate with (△) knit-line samples which failed by plane-strain shear fatigue fracture, (▲) failure by discontinuous crack growth, (▽) mixed-mode failure. 1 ksi = 1000 psi = 6.9 MPa.

At stresses above 6000 psi, both the fatigue lifetime and the appearance of the fracture surface are quite different. The fatigue lifetime shows an increase of at least an order of magnitude (symbols (△) in Fig. 2). In addition, the fracture surface shows a very ductile, "honeycombed" appearance (Fig. 5) and is oriented approximately $\pm 45°$ to the load direction. Unlike the craze-dominated failure at lower stress levels, the crack only propagates a short distance (25 μm) perpendicular to the load direction. The crack is then terminated by a pair of shear bands (Fig. 6) which prohibits a craze at the crack tip from developing. Failure occurs when voids within the shear band coalesce giving the honeycombed pattern common to plane-

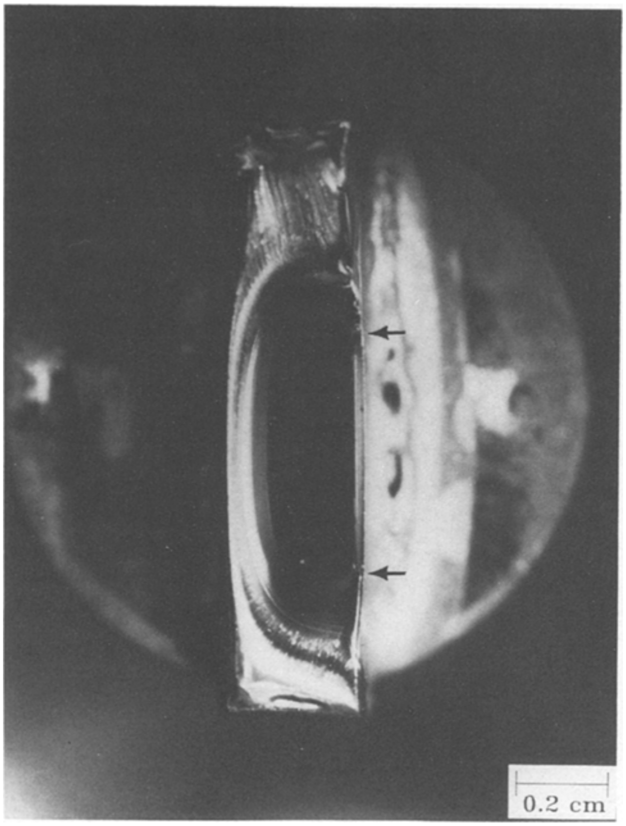

Figure 3 Fracture surface of typical craze-initiated fatigue failure at knit line. Unlike smooth specimens, the initiation site (between arrow) is over a large portion of the knit line.

strain shear fatigue failure. The large increase in the lifetime indicates that this process is much slower growing than the discontinuous crack growth.

Several things were done to ensure that the shift in the lifetime was not due to badly knitted material at the knit line. As in the work of Criens and Mosle [8], tensile yield tests gave the same

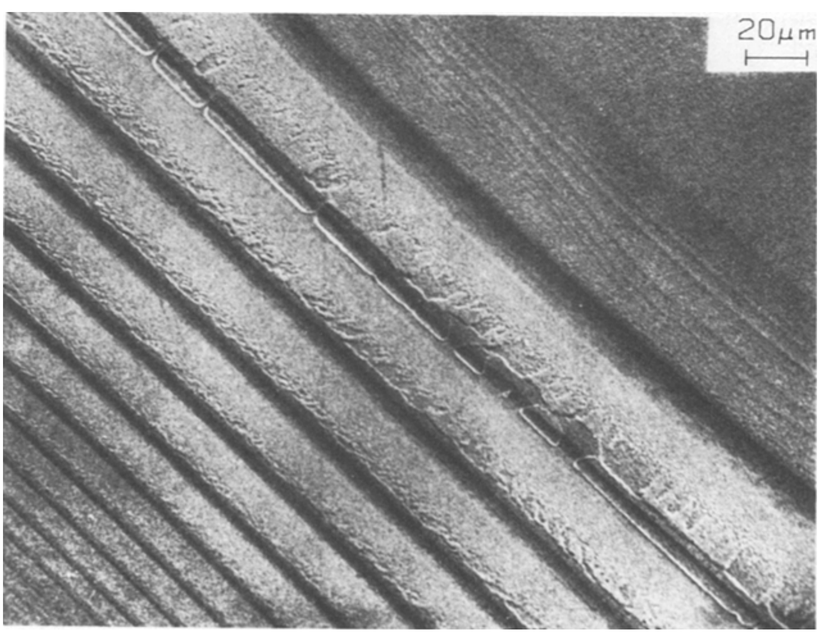

Figure 4 Scanning electron micrograph of fracture surface of craze-initiated, discontinuous crack growth in knit line specimen fatigued at 4500 psi (31 MPa). The fracture surface is perpendicular to the load direction.

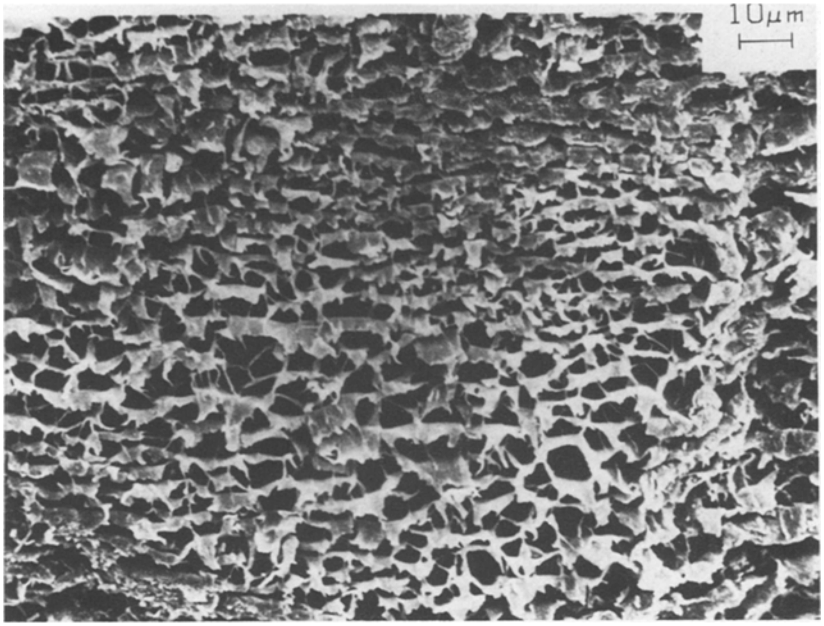

Figure 5 Plane-strain, shear fatigue fracture surface at initiation site of knit-line sample fatigued at 6500 psi (45 MPa). Fracture occurs through coalescence of voided areas within a shear band. The fracture surface is oriented approximately 45° to the load direction.

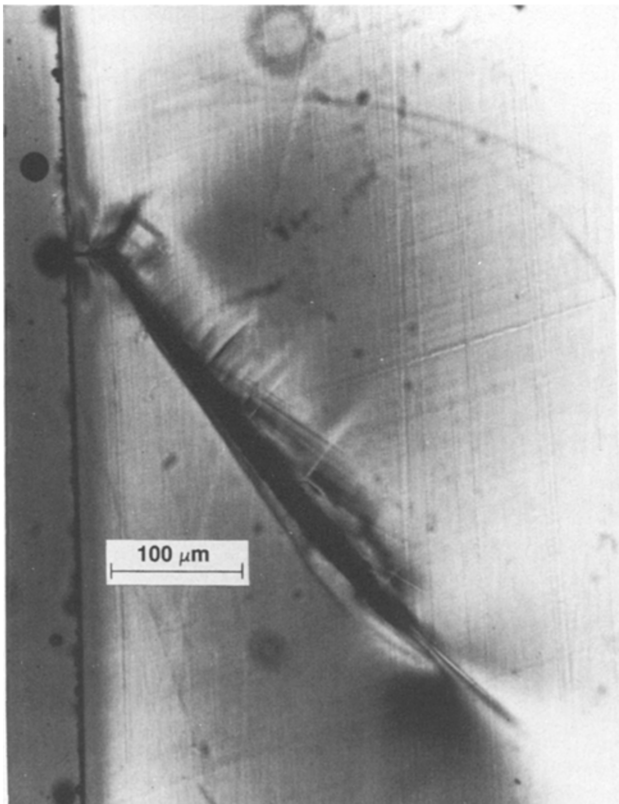

Figure 6 Thin section of partially fatigued knit-line sample showing the profile of plane-strain shear fatigue fracture.

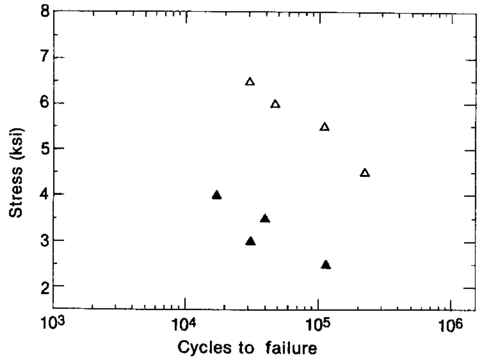

Figure 7 Fatigue lifetime of liquid-nitrogen razor-notched smooth-bar specimens of BPA–polycarbonate: (△) samples failing by plane-strain shear fracture (▲) samples failing by craze initiated, discontinuous crack growth.

yield stress as for samples injection-moulded from only one end (single-gated). The sample did not yield at the knit line but elsewhere in the gauge section.

To test the fatigue strength of the knit line without the notch, at least 25 μm of the surface of the sample was removed by polishing with various grades of silicon carbide paper and finally 1.0 to 0.3 μm alumina. Samples prepared in this manner were then fatigued at a variety of stress levels. Although these samples did not have as long a lifetime as the single-gated specimens, the samples did not show the transition and did not fail at the knit line. The cause of the early failure in these polished samples was the defects introduced by polishing, as well as removal of the compressive layer at the surface.

It should be pointed out that polishing away less than 25 μm of the surface was not enough to eliminate all signs of the notch. These samples still failed at the knit line when fatigued. Thus, there was most likely a region of weakened material in front of the notch (Fig. 1) which extends to a depth of 25 μm.

Finally, to show that the transition was not due to the knit line itself, qualitative attempts were made to re-create the notch by making a 0.3 mm deep razor scratch on a single-gated specimen. The scratch was made at liquid nitrogen temperatures in order to cut down on plastic deformation at the tip of the crack. Fig. 7 shows the fatigue lifetime results. Once again there is a transition in lifetime and mode of failure.

Experiments were also done to show that the transition was not due to hysteretic heating. Data taken at 1 Hz gave the same lifetime curve as tests at 10 Hz. In addition, unfatigued samples were creep-loaded at 7500 psi (52 MPa) for various lengths of time and then tested in fatigue at 4000 psi (28 MPa). Since there was no heating during the creep-loading, the effects shown were due only to the high stress level. As can be seen from Fig. 8, prior creep-loading for as little as 60 sec increased the subsequent lifetime by almost two orders of magnitude. These samples failed in a mixed mode with discontinuous crack growth from small sections of the notch, followed by plane-strain shear fatigue failure. This response was similar to the samples which failed in a mixed mode at higher stresses (symbols (▽) in Fig. 2).

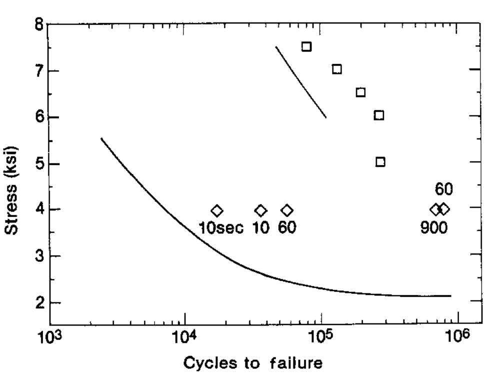

Figure 8 Comparison of fatigue lifetimes: (◇) knit-line samples creep-loaded at 7500 psi (52 MPa) for the indicated time and then fatigued at 4000 psi (28 MPa); (□) smooth-bar samples. The lines are the lifetime of knit-line samples shown in Fig. 2.

3. Discussion

Direct evidence for the transition in fatigue fracture mechanism as a function of stress in notched specimens of BPA–polycarbonate is given by the very different fracture surfaces (Figs. 4 and 5). At stresses below the transition stress of approximately 6000 psi (41 MPa), there exists additional evidence for the competition between crazing and plane-strain shear banding. Fig. 9a shows the discontinuous crack growth and single-cycle growth on the fracture surface of a sample tested at 5500 psi (38 MPa). The subsurface profile of the region (Fig. 9b) shows one half of the pair of shear bands associated with the epsilon plastic zone. There is a one-to-one correspondence between the shear bands and the discontinuous crack growth arrest bands

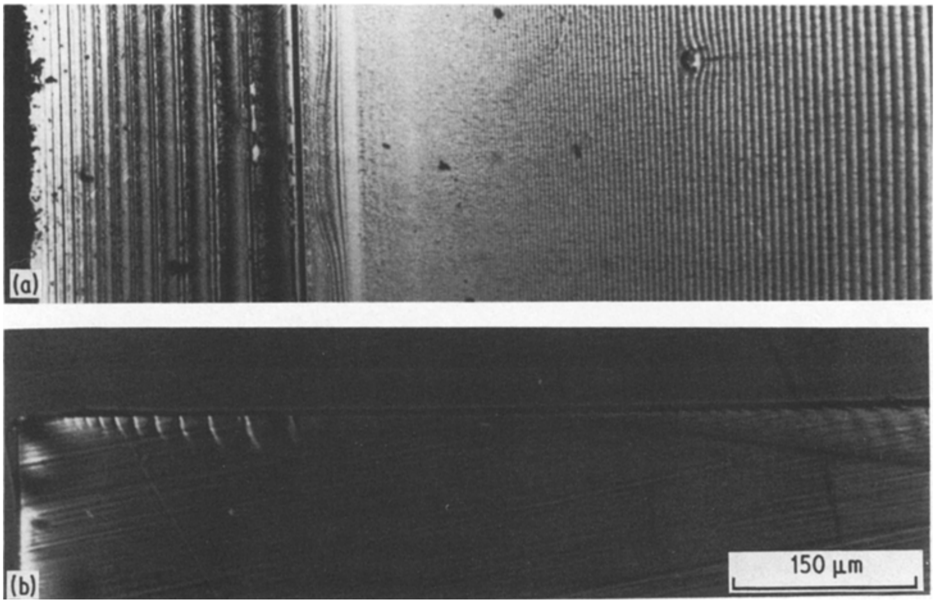

Figure 9 (a) Fracture surface of knit-line specimen fatigued at 5500 psi (38 MPa) showing discontinuous crack growth and single-cycle striations. (b) Subsurface view of (a) showing one half of the pair of shear bands of the "epsilon plastic zone".

on the fracture surface. Farther out along the crack, there are more diffuse shear bands associated with the single-cycle growth region.

The large discontinuity in the lifetime curve is a reflection of the fact that the two fatigue failure mechanisms have very different growth rates. Unlike unnotched specimens where the fatigue crack starts from a small surface craze, the notched specimens are essentially precracked. By partially fatiguing the notched samples just above and below the transition stress and making thin sections of the notch region, it has been found that the weakened area ahead of the notch (see Section 2) fractures after only 10 to 100 cycles. For samples just below the transition stress this leads to the growth of the epsilon plastic zone and subsequent discontinuous crack growth. For samples tested above the transition stress, only the shear bands grow. The sheared region in front of the crack is large enough to keep a craze from growing at the crack tip. Thus, the difference in lifetime is due to a change in the mechanism of failure.

The unnotched specimens (symbols (□) in Fig. 8) do not show the transition because of the time it takes to initiate the fatigue crack and because they exhibit both kinds of behaviour. The fatigue failure of the unnotched specimens initiates from a small surface craze. This surface craze grows into discontinuous crack growth with an epsilon plastic zone. However, unlike the notched specimens, the cracks are very small and form a distinctive "clam shell" shape on the fracture surface [3, 9]. The discontinuous growth in these specimens terminates with a pair of large shear bands and a transition is made to plane-strain shear fracture. Because unnotched specimens show both types of behaviour (similar to the mixed-mode samples in Fig. 2), they do not show the discontinuity in the fatigue lifetime.

It should be noted that at stress levels below 3500 psi (24 MPa) there is an additional transition in mechanism from epsilon crack growth to discontinuous crack growth without shear bands. Although the fracture surfaces appear similar at 3000 psi (21 MPa) and 3500 psi, thin sections of both fractured and partially fatigued samples show that the subsurface shear bands of the epsilon plastic zone appear at 3500 psi but do not exist for samples fatigued at 3000 psi. This change in mechanism does not have a large effect on the fatigue lifetime.

In conclusion, notched specimens of BPA–polycarbonate have shown a drastic change in fatigue failure mechanism from discontinuous crack growth to plane-strain shear fatigue fracture as the stress is increased. Because the samples are pre-cracked and exhibit either one mechanism or the other, the very different lifetimes are an indication of the different growth rates of the two mechanisms. Because polymers which exhibit the epsilon plastic zone [3, 9, 10, 11] have this competition between shear banding and crazing, there is always a possibility of making the transition from discontinuous crack growth to plane-strain shear fracture. Thus, the possibility exists that the fatigue lifetime can be increased by inducing the plane-strain shear fatigue process.

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