CYCLIC DEFORMATION AND CRAZE GROWTH IN POLYCARBONATE

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INTRODUCTION

The role of crazing in the fracture of amorphous polymers is one of the most widely studied aspects of fracture in polymers, and has been the subject of two recent reviews [1, 2]. The importance of crazing in cyclic deformation is not well documented, primarily due to the lack of mechanistic fatigue studies in amorphous polymers. In a previous investigation, the present authors determined the fatigue properties of polystyrene at room temperature [3], with particular emphasis on the crazing aspects of cyclic deformation and fracture. The present study on polycarbonate was undertaken as part of a continuing theme of developing an understanding of cyclic deformation in polymers. The primary purpose of this work was to determine the generality of the conclusions drawn from the polystyrene study with regard to the interplay of crazing and fatigue failure mechanisms.

EXPERIMENTAL PROCEDURE

Cylindrical cross-section specimens with a reduced diameter of 3.18mm and threaded ends were machined from commercially available polycarbonate rod. The gage length of the specimens was carefully polished after machining. All mechanical tests were performed on an Instron machine, with the specimen immersed in liquid nitrogen at 78K. (Immersion in contact with liquid nitrogen promotes the crazing tendency [4].) A constant strain rate of 10^{-2} sec^{-1} was maintained for all tests. Fatigue tests were performed in fully reversed, uniaxial tension-compression between fixed, equal strain limits. The strain controlled cycling was achieved by affixing LVDT extensometers to the shoulders of the specimen; these extensometers were used to both measure and control specimen strain.

RESULTS AND DISCUSSION

Tensile Behaviour

The tensile behaviour of polycarbonate in liquid nitrogen was determined initially to provide baseline data for comparison with the cyclic deformation and fracture behaviour. The tensile deformation and fracture response is shown by the stress-strain curve in Figure 1. Bulk flow and craze formation occur simultaneously, and the characteristic pattern of craze growth, craze breakdown to form a crack, and subsequent crack propagation pre-empts the continued development of more homogeneous flow and the polymer fails prematurely [1]. This semi-ductile [1] type of behaviour differs from the semi-brittle [1, 3] behaviour of polystyrene in

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which no bulk flow occurs and all the non-elastic strain prior to fracture is accommodated in the crazes.

The penetration of the craze into the sample can be clearly seen on the tensile fracture surface as shown in Figure 2. The annular ring delineates the areal extent of craze growth (growing in from the surface) prior to crack propagation. The appearance of the annular ring is characteristic of crack propagation through pre-existing craze material [1, 3]. The circular, central portion of the sample represents catastrophic crack propagation through previously uncrazed material. It should be noted that in this portion of the fracture, crack propagation probably still involves the formation and breakdown of a craze, but the craze participation in fracture is dynamic and the crack and craze tip velocities are essentially equal.

The overall conclusion to be drawn from Figure 2 is that the craze had grown to the area delineated by the annular ring before the formation of a crack within the craze. The crack then grew slowly, at a continuously accelerating rate, in the nucleus area indicated by the arrow in Figure 2. Subsequently, catastrophic crack propagation occurred over the remainder of the cross-section. As in polystyrene [3, 5, 6], there is a marked difference between the details of slow crack growth through pre-existing craze and catastrophic crack propagation through pre-existing craze (annular ring in Figure 2).

Cyclic Behaviour

The fatigue response of polycarbonate at 78K in contact with liquid nitrogen is shown in Figure 3. The point at one reversal refers to tensile failure. There are two distinctly separate regimes of fatigue response; the separation is indicated by the distinct change in slope at $2 N_F \approx 30$. The short life region (I) is characteristic of a wide variety of amorphous thermoplastics, and is directly related to the copious crazing which develops at the high tensile strains (stresses) involved in this life range [3]. The intermediate life region (II) is common to most polymers. Normally, there is a transition to a third, long life region as for polystyrene [3]. In the present tests on polycarbonate, data in the long life region were not developed, partly because of the experimental difficulties of long life tests in liquid nitrogen, and partly because stage III was not of prime interest in this study. Nevertheless, it is anticipated that a region III (equivalent to a fatigue limit) will exist in a manner directly analogous to that in polystyrene [3].

Typical fracture faces characteristic of the short life region [1] fatigue failure are shown in Figure 4. The depth of penetration of crazes (areal extent) increases with increasing life as evidenced by the increasing areas of the smooth annulus until craze growth has occurred totally through the cross-section of $2N_f = 23$. Confirmation that the smooth area corresponds to pre-existing craze prior to crack propagation can be obtained by observation of thin, longitudinal sections. The depth of craze growth from the surface into the specimen is plotted in Figure 5 as a function of fatigue life. Cycling promotes areal craze growth in region I, an effect somewhat different to that observed in polystyrene [3] where craze areal extent diminished slightly with number of cycles to failure through region I. The interplay between the effect of reversed stresses (strains) on craze growth as opposed to the effect on craze breakdown into a crack may well be a function of the inherent crazing characteristics of the polymer. In the case of polycarbonate at 78K, cycling in the stress range of region I certainly accelerates both the craze growth kinetics and the

craze breakdown process. For this polymer, the craze growth is apparently affected to a greater extent than the breakdown process. By contrast, in polystyrene [3] the craze breakdown is promoted to the greater extent.

Fatigue crack growth occurred over only a very small fraction of the cross-sectional area in all the fracture faces in Figure 4. For example, the incremental fatigue crack growth area is shown in more detail in Figure 6 where a crack arrest marking (ABC) typical of incremental crack growth is clearly evident. The majority of the cross section of the fracture faces in Figure 4 reflects catastrophic fracture and the particular features represent the results of interaction between the rapidly propagating crack and the pre-existing material state.

The incremental nature of craze growth can be deduced from the markings on the fracture face, Figure 4(b) and 4(c) [7]. A series of concentric ring-shaped markings covers the fracture surface, Figure 4(c). The markings resulted from the intersection of the fracture plane with crazes oriented parallel to the applied stress axis. Detailed examination of longitudinal sections confirmed this conclusion. A mechanism for the formation of the annular, longitudinal crazes has been suggested previously [7]. The concentric markings, Figure 4, delineated the craze-front arrest points during incremental growth under cyclic stress.

In a manner directly analogous to polystyrene [3], the annular region corresponding to craze growth decreases with increasing fatigue life (decreasing stress amplitude) in the intermediate life region II. No evidence of an annular ring is visible, and longitudinal sectioning of the specimens confirmed the absence of crazing under these testing conditions. The areal extent of craze growth (penetration from the surface) in region II is shown in Figure 5. In this fatigue life region, the decreasing craze size with increasing life concurs with the observations on polystyrene [3]. Region II is distinct from region I with regard to the craze formation in that the stress levels of region I are high enough to nucleate crazes on the first tensile stress application. Subsequent cycling promotes growth of the crazes. In contrast, in region II the stress level is insufficient to nucleate crazes immediately and the initial cycles are spent in promoting craze nucleation as opposed to growth. This difference between region I and II is reflected in the lower density of crazes in region II as well as the more limited areal growth.

The extent of slow fatigue crack growth prior to catastrophic crack propagation increases with increasing life in region II. In the low cycle regime of region II, the slow growth region is crescent shaped similar to that in Figure 4(b) and Figure 6. With increasing life in region II, the slow fatigue crack growth region changes in shape, to a semi-circular type. At still longer lives, the slow crack growth region assumes a more linear growth front. In the final stage of fracture in region II, rapid propagation of the crack through regions of the specimen free of preformed craze occurs. The general topography of this region is sensitive to the applied stress level and can vary from markedly irregular to a fairly smooth type of surface.

Concurrently with the change in slow crack growth geometry as a function of fatigue life in region II, the number of crack arrest striae increases and the interstriation spacing decreases with increasing life. Again, these observations correlate directly with those on polystyrene [3] and can be regarded as generally characteristic of fatigue in amorphous polymers with a high crazing propensity.

CONCLUSIONS

The fatigue of polycarbonate in liquid nitrogen follows a similar pheno-
menological pattern to the fatigue of polystyrene [3]. The overall effect
of cyclic stresses (strains) in all polymers which craze can, therefore,
be generally concluded to be an enhancement of both craze growth and craze
breakdown. The relative degree to which the two processes are accelerated
will be dependent upon the crazing propensity of the particular polymer
being studied. In addition, there is a commonality of fractographic
feature which can be used as a basis for identification and analysis of
polymeric failures.

ACKNOWLEDGEMENTS

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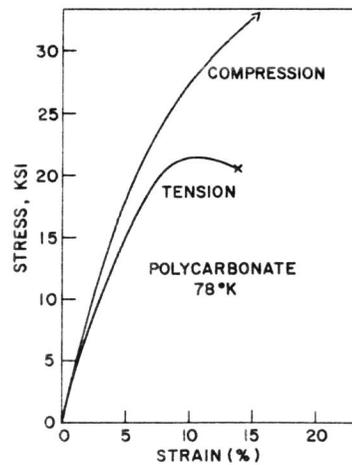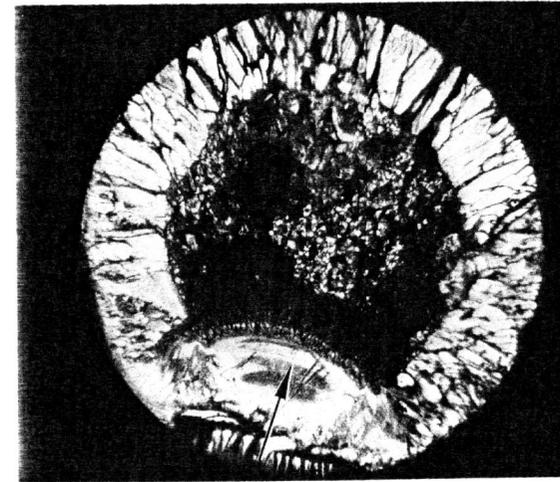7. BEARDMORE, P. and RABINOWITZ, S., J. Mats. Sci., 7, 1972, 720.

Figure 2 Typical Tensile Fracture of Polycarbonate in Liquid Nitrogen
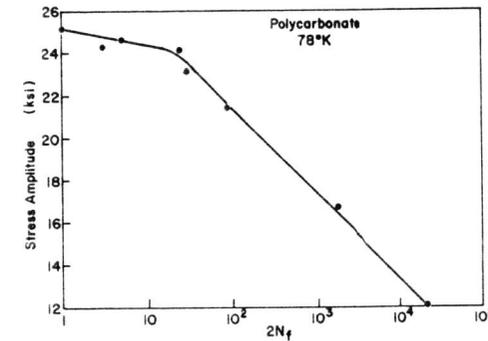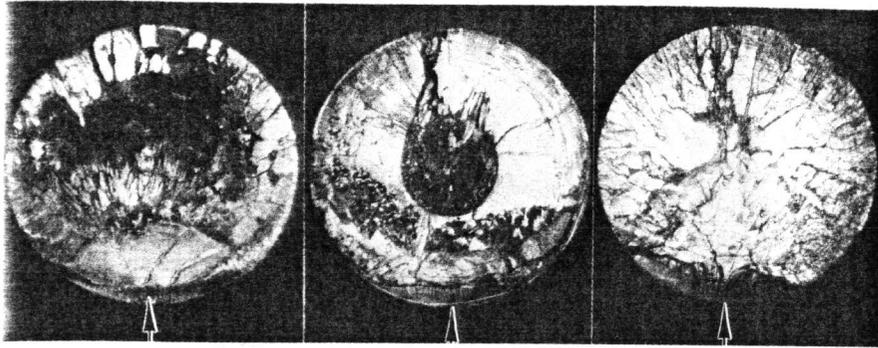

Figure 3 Stress Amplitude versus Number of Reversals to Failure. The
Distinct Change in Slope Separates the Short Life Region (I) from
the Intermediate Life Region (II)

Figure 1 Stress-Strain Curves of Polycarbonate in Liquid Nitrogen

(a)   (b)   (c)

Figure 4   Typical Fatigue Fractures in the Short Life Region (I):
           (a) $2N_F = 3$,   (b) $2N_F = 5$, and   (c) $2N_F = 23$
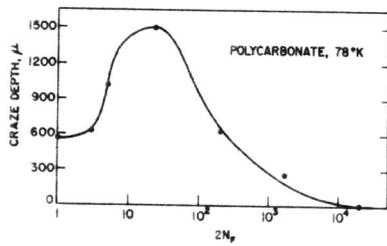

Figure 5   Craze Penetration from Surface of Specimen as a Function of
           Reversals to Failure
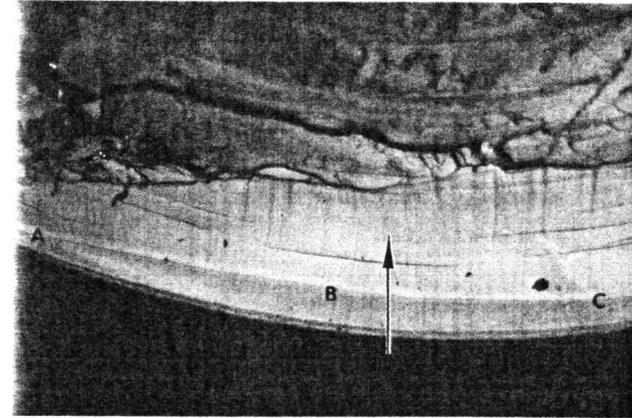
Figure 6   High Magnification Micrograph of Slow Fatigue Crack Growth
           Region of Figure 5. The ABC Line is a Fatigue Crack Arrest
           Striation