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Failure of polystyrene in tensile and cyclic deformation

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The failure of polystyrene in cyclic deformation has been examined and compared with the fracture mechanisms involved in simple tension. The fatigue response can be divided into three discrete life ranges. In the short and intermediate life regions, fracture occurs by the processes of craze formation, craze growth, crack nucleation and crack propagation in a manner analogous to tensile failure. The primary influence of reversed straining is manifest as an acceleration of the crack formation stage of failure. In long life (low stress) fatigue, failure modes dissimilar to the documented craze breakdown pattern of crack nucleation are noted.

1. Introduction

The fatigue behaviour of amorphous glassy polymers has received scant attention relative to other mechanical properties, yet it is often the resistance of a material to cyclic stresses and strains that determines its usefulness in strength-related applications. The tensile fracture of amorphous polymers has been the subject of extensive investigations and, in particular, the role of crazing in fracture has been studied in detail [1–8]. A craze is a localized zone of plastic flow, and the breakdown of the craze structure to form a crack has been carefully documented in poly(methyl methacrylate) [2, 4, 5, 8] and polystyrene [2, 4–7].

In contrast to the detailed description of tensile fracture modes, no comparable data are available on fatigue failure. The present investigation on polystyrene was initiated as a first step in elucidating the specific role of crazing in cyclic deformation and fracture. Polystyrene is an ideal material in which to study crazing and the details of craze breakdown, because of its high propensity for craze formation and the large areal size of the crazes formed. The lack of significant bulk flow prior to fracture leads to the classification of polystyrene as a semi-brittle material [5], although on a local scale plastic deformation in the crazes is very extensive.

2. Experimental procedure

Cylindrical cross-section specimens with a reduced diameter of 0.25 in. and threaded ends were machined from commercially available (Foster Grant Co) 0.5 in. diameter isotropic polystyrene rod (number average molecular weight, Mn = 80000; $M_w/M_n = 3.2$). The specimen gauge lengths were carefully polished after machining using a cloth buffing wheel and stannic oxide as an abrasive.

All mechanical tests were performed in air at room temperature, in an electro-hydraulic MTS closed-loop test system. Details of the testing equipment and experimental arrangement have been given elsewhere [9]. Simple tensile tests to failure were executed at a constant strain-rate of 2×10^{-4} sec^{-1}. Fatigue tests were performed in fully reversed, uniaxial tension-compression using a triangular control cycle at a constant frequency of 0.1 Hz. To determine any thermal effects, samples instrumented with thermocouples on the exterior surface and in an internal cavity were cycled at various strain-rates with continuous monitoring of the sample temperature. At 0.1 Hz, the temperature rise was below 2°C.

In cycling between fixed (equal) strain limits (strain-controlled cycling) an Instron Strain Gauge Extensometer was affixed to the specimen to both measure and control specimen strain. However, because of the severe sensitivity of fracture to stress concentrations in polystyrene, premature cracks frequently developed under the extensometer knife edges. In a series of cyclic tests at short fatigue lives (high strain amplitudes) it was determined that the polystyrene stress-strain relation remain essentially unchanged during cycling prior to crack propagation. Thus, a strain-control limit could be converted directly to a stress-control limit via the elastic modulus with negligible error, i.e., the plastic strain at tensile fracture is very small (see Fig. 1). Taking advantage of this cyclic stability, most of the fatigue tests were executed in stress-control, thereby eliminating the necessity of affixing an extensometer to the specimen. It should be noted, however, that fully reversed stress-controlled cycling is not exactly equivalent to fully reversed strain-controlled cycling in polymers, because of the tension-compression strength differential characteristic of non-elastic deformation in most polymeric materials. In the present study, the strength-differential in polystyrene over the range of testing conditions (see Fig. 6) was on the order of 10%. Comparison of stress- and strain-controlled fatigue tests indicated no *measurable* effects of the control mode (stress or strain) on the fatigue response.

3. Results and discussion

3.1. Tensile behaviour

An evaluation of tensile deformation and fracture behaviour was made to provide a reference for interpretation of the cyclic deformation and fracture behaviour. Fig. 1 shows the tensile stress-strain relationship. Characteristic of the response of near semi-brittle materials [5], the flow stress for uniform non-elastic deformation was almost equal to the fracture strength, and the bulk response was largely elastic below about 5 ksi. The predominant mode of non-elastic deformation was in the form of crazes, which began to appear (visual examination) at about 6 ksi, and grew rapidly across the specimen cross-section. Craze development was so extensive that the rate of non-elastic strain (predominantly craze strain) quickly increased beyond the constant applied strain-rate at point B (Fig. 1), and the load began to decrease slowly. Catastrophic failure followed shortly on the load maximum. It is emphasized that the load maximum does not relate to the onset of extensive bulk ductility (as in, say, the cold-drawing of thermoplastics), but rather results from intense localized straining in the form of crazing. Similar observations have been made by Hoare and Hull [10] in compression-moulded polystyrene.

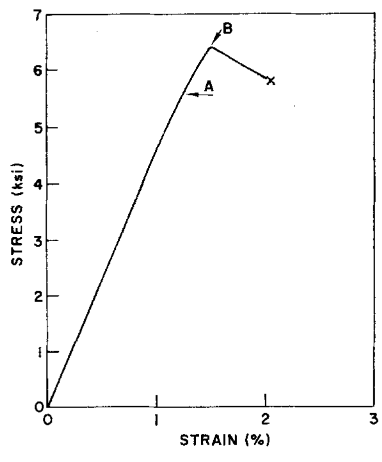

Figure 1 The stress-strain relation for polystyrene in tension at 298K. Point A marks the craze appearance stress (visual examination).

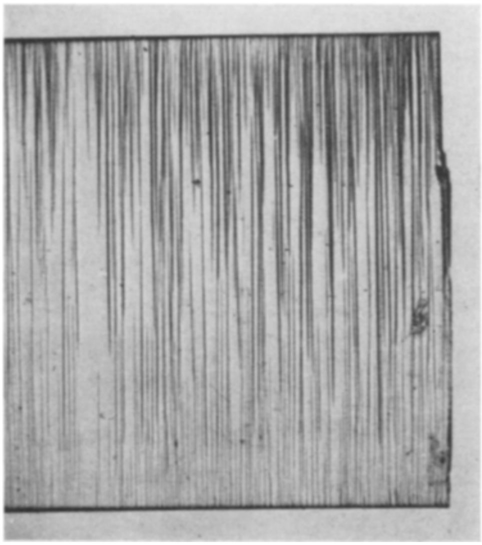

Figure 2 Longitudinal section through polystyrene sample fractured in tension. Viewed in transmitted light; stress axis horizontal.

The high density of crazing in tensile deformation is clearly revealed by examining a thin longitudinal section taken through the centre of the specimen [11], Fig. 2. Characteristically, each individual craze has developed to a large areal extent, in most cases traversing the entire specimen cross-section. Such crazes provide a lower energy path for crack propagation than the uncrazed matrix polymer, and thus act as a perferential fracture path [5, 12]. This can be seen on the tensile fracture surface shown in Fig. 3.

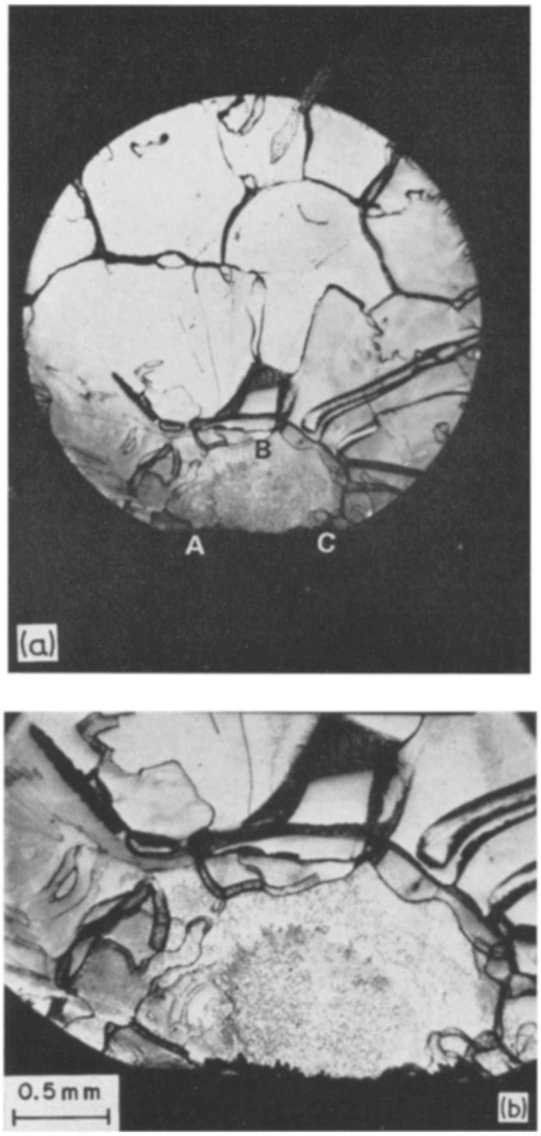

Figure 3 (a) Polystyrene fracture surface obtained in simple tension. (b) Higher magnification image of the slow crack growth region.

The striking mica-like appearance of the fracture surface is a direct consequence of crack propagation through pre-existing craze material, and can be attributed to several factors. First, the crack is channelled large distances through individual crazes; the planarity of craze growth in uniaxial tension thus gives rise to the planar fracture surface. Second, the molecules within the craze are stretched virtually to their maximum extensibility prior to the passage of the crack [4], so that very little plastic deformation is associated with the actual crack propagation. This results in a featureless fracture surface with high reflectivity. The details of the fracture process – involving an initial stage of slow crack growth and the continuous acceleration of the crack to high velocity (over the area ABC in Fig. 3), and catastrophic crack propagation – have been extensively discussed by Hull and co-workers [6, 7, 12, 13]. The microscopic details of fracture in the present experiments are in agreement with their observations.

The large area crazes develop as follows: a craze, as formed, effectively relieves the excess stresses surrounding the inhomogeneity originally responsible for craze nucleation; the driving force for subsequent craze growth is then the local stress associated with specific craze morphology [4, 5, 7, 14]. In the usual failure mode, the rate of areal craze growth greatly exceeds the rate of craze thickening (and hence crack nucleation [5]) so that large crazes develop prior to failure. Polystyrene is an extremely notch-sensitive material, however. If surface defects persist through specimen preparation, fracture can occur in a somewhat different manner. Typically, the stress concentration (defect) nucleates an isolated craze at a stress level below the general craze appearance stress. The craze is unable to fully relieve the large stress concentration, and craze breakdown in the vicinity of the defect occurs at a much higher rate relative to the concomitant craze areal growth than in normal craze growth. Fig. 4 shows the fracture surface that results (the different shape of the specimen is incidental and is not related to the difference in fracture topography). In this instance, crack propagation 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. This is in direct contrast to crack propagation through the static (in area) and fully developed craze characteristic of normal behaviour. Very little evidence of slow crack growth appears on the fracture surface and the extreme surface roughness reflects the considerable plastic deformation and crack bifurcation concomitant with crack propagation. A notable feature of the tensile fracture surface in Fig. 4 is the occurrence of coarse, striated markings. Since Murray and Hull [7, 12, 13] have discussed these features in detail, they are noted here simply to contrast their appearance with that of true fatigue-crack

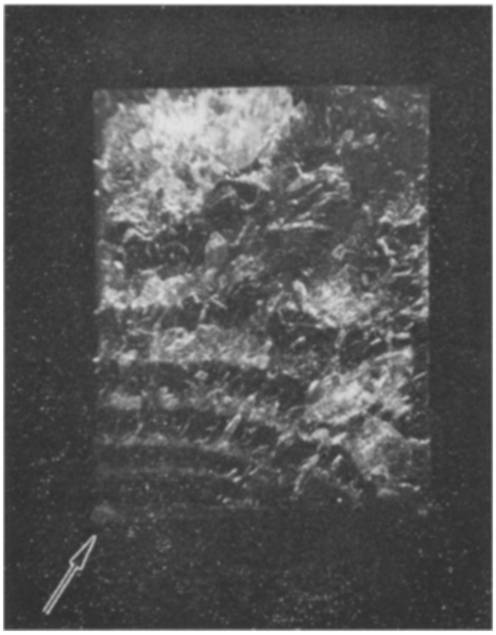

Figure 4 Polystyrene tensile fracture surface resulting from premature fracture at a stress below point A in Fig. 1.

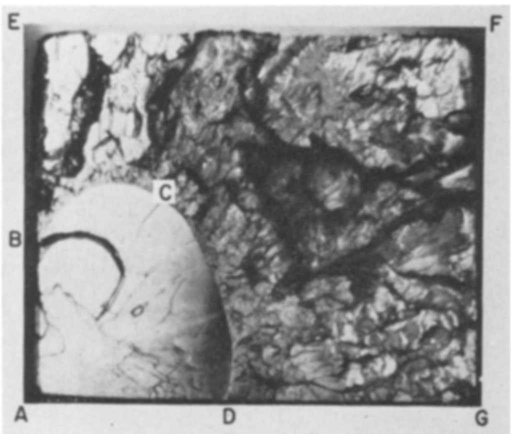

Figure 5 Polystyrene tensile fracture surface produced by interrupted constant-strain-rate unidirectional testing. See text for details.

arrest striae discussed below.

An additional experiment was performed to obtain the two types of crack propagation (Figs. 3 and 4) in one specimen, and to confirm the mechanism involved. A specimen was loaded in tension at constant strain-rate to 5 ksi, i.e. below the constant strain-rate craze appearance stress, and held at constant stress. After an incubation period, a few crazes developed and grew continuously. When the crazes had grown partway across the specimen cross-section, the constant strain-rate deformation was resumed to fracture. The resulting fracture surface is shown in Fig. 5. Over the region ABCD, the crack propagated through the pre-existing craze developed during creep. The fracture surface in this region is characteristically smooth and planar. After passing through the preformed craze, the crack then propagated (still at high velocity) through the remainder of the cross-sectional area BEFGDC, with the continued formation of new craze at its tip. The fracture surface in Fig. 5 is directly pertinent to the analysis of fatigue fracture in polystyrene. In particular, it provides the basis for evaluating the extent of areal craze development prior to catastrophic crack propagation in cyclic deformation.

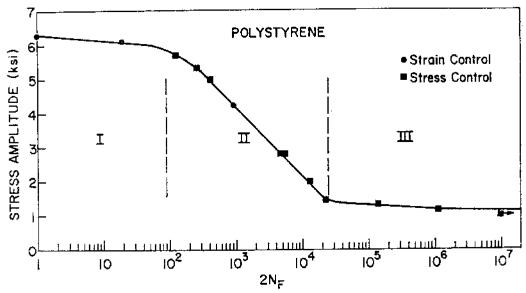

Figure 6 Polystyrene stress-fatigue life relation.

3.2. Cyclic behaviour

Fig. 6 summarizes the polystyrene fatigue data in a plot of peak stress amplitude against the logarithm of the number of reversals (twice the number of cycles) to failure. The data point at one reversal is tensile fracture. Experience with fatigue failure in metals [15–17] has emphasized the important roles of (1) stress or strain range (maximum to minimum), and (2) mean stress (maximum + minimum)/2. These same parameters are equally significant in the fatigue of polymers. In addition, the strong rate sensitivity of non-elastic deformation in most polymers introduces an important dependence on the time pattern of stress or strain application (i.e., sine wave versus triangular wave versus square wave). Since quantitative evaluation of the above effects has yet to be obtained in the fatigue failure of polymers, direct comparison of fatigue life data generated under different test configurations must be made with extreme caution. On the other hand, the mechanisms of fatigue failure appear to be less sensitive to variations in testing conditions. It is most beneficial, therefore, at the present understanding of polymer fatigue, to discuss phenomena and trends rather than to quantitatively correlate fatigue lives. The data in Fig. 6 are of prime interest, then, as a scaling reference for the discussion to follow.

The fatigue response of polystyrene is conveniently divided into three stages corresponding to regions of markedly different slopes on the plot in Fig. 6. 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 stresses encountered at these fatigue lives. The intermediate life region (II) can be well approximated by a linear relation between stress (or log strain) and log (life), and is common to most polymers; in fact, the slope of the fatigue life relation in region II is fairly constant from one polymer to another [18]. The long-life region (III) may be taken as an engineering fatigue endurance range.

Comparison of the data in Figs. 1 and 6 shows that the transition from region I to region II coincides with the constant strain-rate craze initiation stress (visual observation) in unidirectional testing. Thus, a clear distinction between region I and regions II and III can be drawn on the following basis: in region I, crazes form on the first tensile quarter cycle – the fatigue behaviour in the region is then essentially that of a pre-crazed sample; in regions II and III, on the other hand, crazes form as a consequence of cyclic deformation, so that the fatigue life reflects both craze initiation and crack nucleation and propagation. There are fractographic features typical of fatigue failure in each life region, and these provide a convenient characterization of the fatigue process. The cyclic stress-strain response in region II and III is common to a wide variety of polymers, and will be discussed first. Region I is particular to polymers that have a high propensity for crazing and will be considered later.

3.2.1. Fatigue failure in region II

Region II fatigue fracture in polystyrene follows the well characterized pattern of craze induced fracture described in [5]: craze nucleation, followed by craze growth and the deterioration of craze integrity, followed by crack formation, terminated by catastrophic crack propagation. The primary effect of reversals in the cyclic deformation is to accentuate certain stages in this process. Fig. 7a is a low-magnification microphotograph of a representative fatigue fracture surface in the intermediate life region (II). This particular sample failed after about 900 reversals at ± 4.2 ksi. A portion of the prominent annular ring on the fracture surface is shown in greater detail in Fig, 7b. Comparison of Figs. 7a and b with the tensile fracture surfaces shown in Figs.

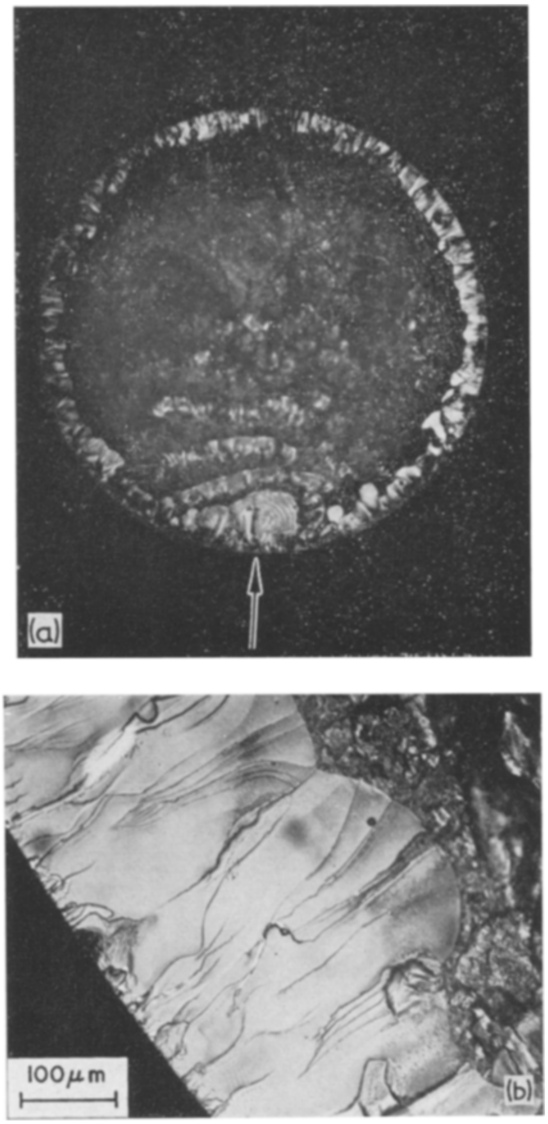

Figure 7 (a) Typical polystyrene fatigue fracture surface in region II. (b) Higher magnification image of a portion of the annular ring.

3, 4 and 5 allows several conclusions to be drawn. First, the annular ring marks the extent of areal craze growth – craze penetration – prior to catastrophic crack propagation; the mica-like appearance of the surface within the annulus is directly comparable to the fracture surfaces in Figs. 3 and 5. Second, the rough circular central region in Fig. 7a constitutes the portion of the fracture during which the crack was moving catastrophically through previously uncrazed bulk polymer (cf. Figs. 4 and 5). In particular, the coarse striae in this central region are not a consequence of incremental fatigue crack growth, but rather derive via the same mechanism as those shown in the tensile failure in Fig. 4. Finally, the extent of true fatigue crack growth is limited to the small semi-circular region at the bottom of Fig. 7a. This region is shown in greater detail in Figs. 8a and b, where a series of fatigue striae is clearly discernible.

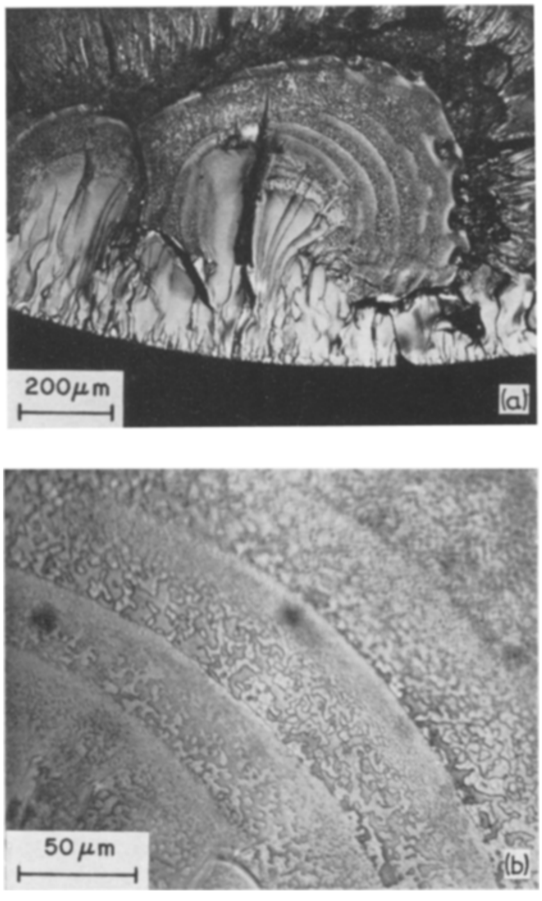

Figure 8 (a) The slow fatigue-crack growth region on the surface in Fig. 7a. (b) High magnification image of slow growth region showing detail of craze breakdown.

Consider first the *craze* nucleation stage in the failure process. As noted above, crazes do not appear on the first tensile quarter-cycle in region II, but develop with continued cycling. In a qualitative assessment, the number of cycles required to nucleate a craze (visual observation, i.e., low magnification (× 10) observation in a transmitted light-beam under dynamic testing conditions) decreases as the peak stress (or strain) increases. At any stress, crazes appear much earlier in the fatigue life than would be predicted on a simple extrapolation of time-under-load from creep experiments [18], even computing the cyclic time-under-load as the sum of the total times for each tension half-cycle. In this regard, an important effect of cyclic deformation is to localize non-elastic strain relative to the more homogeneous deformation characteristic of unidirectional testing at the same stress levels. This is analagous to the well-documented localization of plastic strain in fatigued metals [19]. It is suggested that in these more intensively strained regions, craze formation is easier than in the normal polymer. In support of this hypothesis, recent experiments [20] indicate that craze formation is governed by a critical value of the local strain or strain energy density. In addition, we have observed that cycling specimens of poly(methyl methacrylate) and polycarbonate under only compressive stresses results in a decrease in the craze appearance stress in subsequent tensile testing [18]. Thus, in the first stage of fatigue failure a true cyclic effect is manifest as an acceleration of craze initiation and craze growth – a necessary prerequisite to fracture in polystyrene in this stress range.

The effects of reversed straining are also evident in the crack nucleation stage. As in constant strain-rate and creep failure, crack nucleation in fatigue occurs via a process of craze breakdown closely tied to the rate and extent of craze thickness growth. The process of craze breakdown is one of strain localization in a small region of the craze and this occurs relatively independently of the areal growth of the remainder of the craze [5]. In the characteristic unidirectional fracture process in polystyrene, the rate of areal craze growth so exceeds the rate of crack formation within the craze, that crazes traverse the entire specimen cross-section prior to crack propagation (see, for example, Figs. 3 and 5). In fatigue, this strain localization within the craze is enhanced, resulting in a more rapid rate of crack nucleation relative to the rate of areal growth. Thus, comparison of Fig. 7 with Fig. 2 shows the limited extent of areal growth in region II fatigue relative to tensile fracture. In addition, creep tests under the range of stresses in region II produce total-cross-section crazing prior to crack nucleation (Fig. 11a) in much the same manner as in constant strain-rate deformation. It is clear that compared to tensile and tensile creep failure, the process of crack nucleation within the growing craze occurs more rapidly in cyclic deformation.

The crack nucleation event occurs in a submicroscopic volume of craze. The next stage in the failure process, be it unidirectional tension, tensile creep or fatigue, involves the slow growth of the crack nucleus to a size (determined by some modified Griffith criterion) at which unstable crack propagation occurs. It is this slow crack-growth process that is currently the best understood aspect of fracture in polystyrene, largely because of the comprehensive work of Hull and co-workers [6, 7] on tensile failures. Examination of the true fatigue-crack growth region in Fig. 8 reveals a surface texture similar to that observed in tensile fracture (Fig. 3) and extensively documented by Murray and Hull [6, 7]. The most prominent surface feature is an array of smooth patches. Murray and Hull have attributed this texture to the meandering course of the growing crack which, rather than channelling through the centre of the craze, travels first along one craze/polymer interface and then the other. They observed these patches to form at relatively high crack velocities, close to the maximum velocity in uncontrolled crack growth, but also noted [6, 7, 12] that the tendency to patch formation increased as the craze thickness decreased (above some minimum thickness).

In the present experiments, it has been emphasized that cycling accelerates craze breakdown relative to craze growth, and that crack growth occurs at lower craze thickness strains than in tensile tests. Thus, the patchy texture in Fig. 8 may derive at slower crack velocities, in thinner crazes, than encountered in tensile tests. The observations lead the present authors to conclude that the striae shown in Fig. 8b are evidence that the fatigue crack moved incrementally on each tension half cycle. Each striation delineates a point of crack arrest. Between the striae are regions (patchy texture) where the crack grew through the craze in a manner directly analagous to the meandering crack growth described above for simple tension (not necessarily at equivalent velocity). Examination of the detail in Fig. 8b indicates that within each striation the patchy texture is most prominent immediately at the start of each growth cycle, and peters out as the crack advances. Murray and Hull [6, 7] have noted that this profiled texture occurs when the craze ahead of the crack is tapered. The growing crack encounters craze of decreasing thickness; when the craze and crack tip dimensions are similar, no further patch formation occurs. A tapered thickness profile is generally associated with the newly formed craze material at the leading growth edge of the craze. Thus, it appears likely that craze growth also occurred incrementally on each tensile half-cycle; the fatigue-crack propagation was through newly formed craze ahead of the crack on each tensile stroke.

It is interesting to note that in the region beyond the slow fatigue-crack growth (Fig. 7a) a series of coarse bands similar to those in Fig. 4 are clearly visible. These bands are quite distinct in morphology and topography from the striae in the slow fatigue-crack growth region, and derive via some instability in catastrophic crack propagation. It is important to point out that the number of fatigue striae is very small compared to the number of cycles to failure. Thus, the slow crack-growth stage of fatigue failure constitutes a small fraction of the total fatigue life in polystyrene. The majority of the fatigue life of polystyrene is spent in crack nucleation.

Within region II there are several effects manifest with increasing fatigue life. As the peak stress amplitude decreases (increasing fatigue life) the extent of areal craze growth, i.e., the width of the annular ring, decreases. Conversely, the extent of slow crack-growth prior to catastrophic crack propagation increases with increasing life. The areal growth of crazes in fatigue appears to exert no direct influence on the extent of slow fatigue-crack growth. Rather, the size of the slow growth region is determined by the applied peak stress amplitude, in accord with previous observations relating to the size of the slow fatigue crack growth region to a Griffith type criterion [21, 22]. Finally, within the slow crack-growth region the number of striae increases, and the interstriation spacing decreases, as the life increases. This demonstrates the true fatigue nature of the slow crack-growth region. No attempt has been made to assess whether slow crack-growth occupies a greater or lesser fraction of the total fatigue life as the stress amplitude decreases through region II.

The final stage of fracture in region II is the rapid propagation of the crack across the remaining specimen cross-section. This aspect of fatigue fracture is no different than in tensile fracture. The transition in crack propagation mode from a crack moving through pre-crazed material (the annular ring), to a crack moving through previously uncrazed material is directly analogous to the fracture surface shown in Fig. 5, where a deliberately introduced transition from one mode to another is illustrated.

3.2.2. Fatigue failure in region III

The long-life region of fatigue (III) constitutes the so-called endurance limit range, where the slope of the fatigue-life relation is extremely shallow. Fig. 9 shows a typical region III fatigue fracture surface. Fractographically, the region II to region III transition is a gradual one. In region III, however, several distinct changes in the fracture process can be noted. First, the craze nucleation event is extremely rare, and requires a long cyclic incubation; ultimately, craze nucleation likely depends on a fortuitous perturbation in stress distribution. Secondly, craze areal growth, which appears to be directly related to peak stress amplitude, is severely restricted and there is no region corresponding to pre-existing (with respect to crack propagation) craze on the fracture surface. Third, most of the fatigue fracture in region III occurs in the slow crack growth mode. Unlike slow fatigue-crack growth in region II, however, slow growth in region III (ADEFCA in Fig. 9) occurs in two stages: the first stage appears as the very smooth, glassy region ABCA in Fig. 9, and is peculiar to region III fracture; the second stage, ADEFCBA is conventional slow fatigue-crack growth as seen in region II. The remainder of the fracture surface, DGFED, comprises the ultimate tensile separation of the specimen.

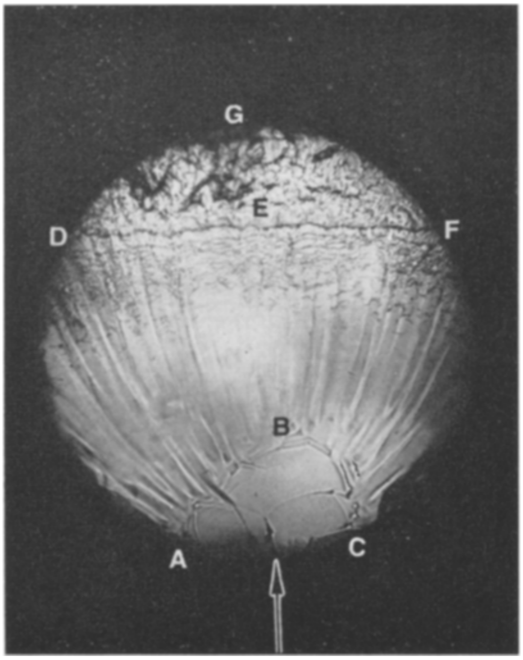

Figure 9 Typical polystyrene fatigue fracture surface in region III (long-life). The area ADEFCA is slow fatigue crack growth.

The earliest stage of fracture (ABCA) is not well understood. One important difference between fracture in long life fatigue and previously reported observations in tension and tensile creep is the extremely low stress level at which life fracture occurs. The only comparable data have been reported by Havlicek and Zilvar [22], who noted a region similar to ABCA in their long life, low stress tests. The region ABCA is featureless at the highest magnification available in visible light microscopy, with the exception of a faint but definite array of striae, Fig. 10a. On the assumption that the markings are crack arrest striae characteristic of fatigue-crack growth, the slow progress of the crack through this region is evidenced by the interstriation spacing on the order of 8 μm. There is no evidence of crazing on the fracture surface. This does not obviate the possibility, however, that crack growth still proceeded via the usual mechanism of craze breakdown. For example, if crack nucleation and growth occurred in a very thin craze, topographical relief on the fracture surface would be minimal. The postulate of low stress fracture in a thin craze goes counter to the relationship between increasing fracture stress and decreasing craze thickness noted by Murray and Hull [7]. However, the potency of reversed deformation in accelerating the craze breakdown process becomes increasingly strong as the peak stress level decreases; crack nucleation may thus occur within the craze at an early stage in its thickness growth. It is also possible that region ABCA derived

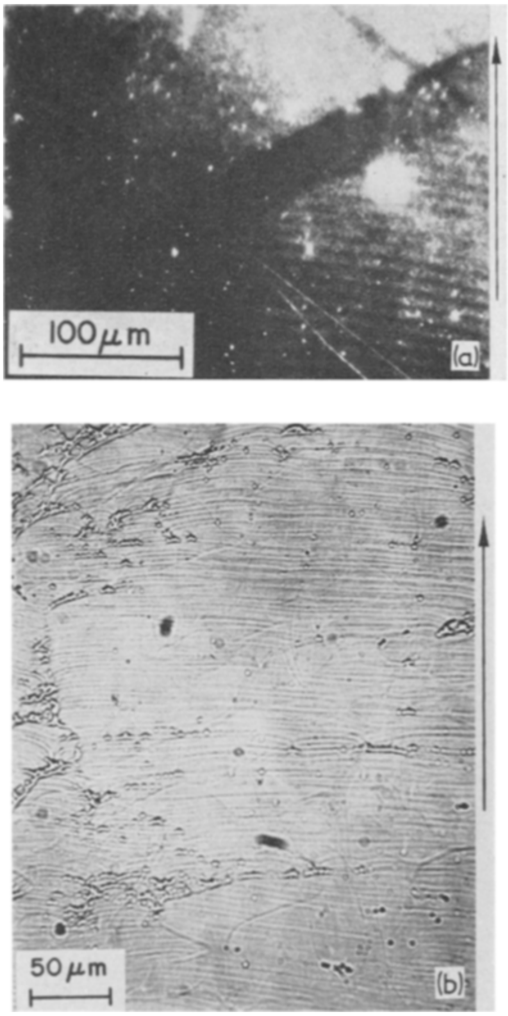

Figure 10 (a) Fatigue crack arrest striae in region ABCA in Fig. 9. The arrow indicates the crack growth direction. (b) Fatigue crack arrest striae in region ADEFCBA.

from crack propagation exclusively along one craze/normal polymer interface – at the low peak stresses in region III, the tendency for the crack to bifurcate or skip from one craze plane to another would be minimized. However, in this fracture mode, it would be expected that one of the matching fracture surfaces would show some evidence of residual craze structure and no such features were detected. Finally, it must also be considered that the early stages of crack propagation in long life fatigue occur with no craze participation, i.e., crack nucleation and propagation with no associated craze-type plastic deformation. Since crazing involves the dissipation of strain energy over some finite volume of material, the extreme localization of stress concentrations at the low fatigue stresses may preclude craze formation. In any case, the sharp transition along the boundary ABC is difficult to account for.

Region ADEFCBA results from a fatigue crack growth mechanism similar to that in region II type fracture – sequential craze formation, craze growth and craze breakdown, in a volume of material directly ahead of the slowly growing crack. This is particularly evident towards the latter stage of slow crack growth (approaching DEF in Fig. 9) where a patchy texture of "mackerel" markings, as noted by Hull and co-workers, can be seen. These markings are characteristic of "meandering" crack growth within a craze. Striations, assumed to be fatigue crack arrest markings, are discernible throughout the region ADEFCBA; Fig. 10b is a representative example, showing an interstriation spacing on the order of 10 μm.

3.2.3. Creep effects in regions II and III

In the discussion above, it has been emphasized that there is a true fatigue effect in the fracture process in regions II and III. The events tied to the strain localization associated with reversed deformation appear to control the fracture sequence, and are manifested primarily as an acceleration of processes that would otherwise similarly have been operative in constant load or constant strain-rate experiments. There is also some creep-type component, however small, to the deformation in regions II and III. Two additional experiments were performed to vary the amount of creep time at peak load, and assess the relative influence of this creep component on region II fracture. First, a specimen was crept at a stress of 5 ksi; the time to fracture was 16 min. In this failure mode, crazes grew completely across the specimen cross-section prior to crack propagation, resulting in the fracture surface shown in Fig. 11a. This creep fracture surface is identical to that obtained in constant strain-rate tensile fracture (Fig. 3) except for the detail of the initial crack growth region.

A second experiment involved the imposition of a low frequency tensile square wave function – i.e., a tensile creep stress of 5 ksi was interrupted every 2.5 sec by a rapid excursion to zero stress and back. The time to failure at 5 ksi in this mode was reduced to 3.6 min, that is, 88 cycles. The resulting fracture surface is shown in Fig.

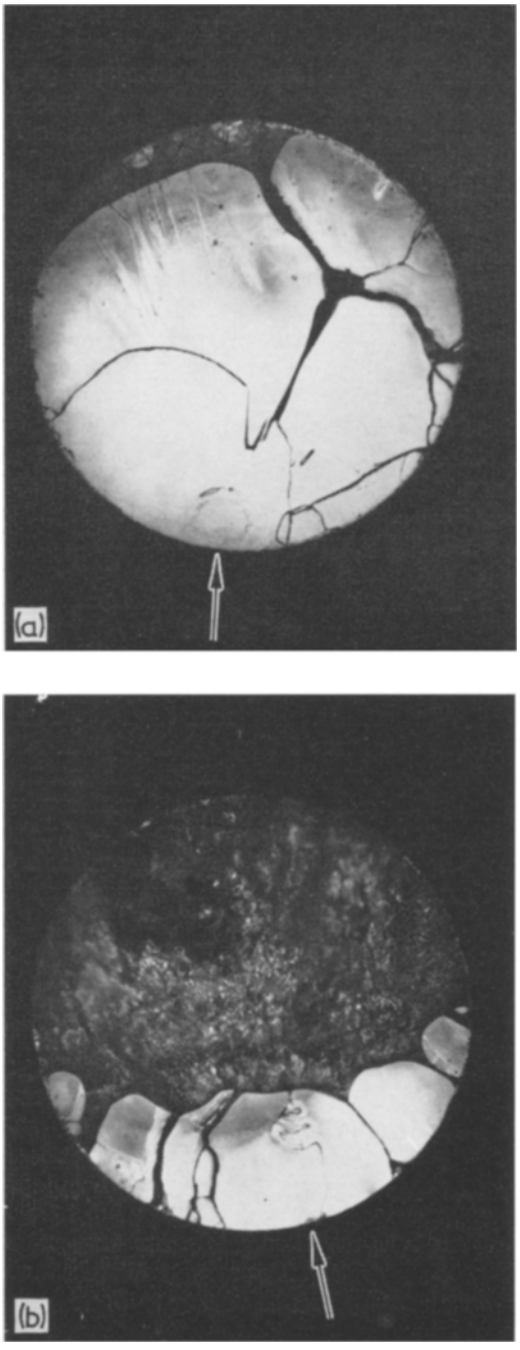

Figure 11 (a) Typical polystyrene tensile creep fracture surface in the stress range defined by region II in Fig. 6. (b) Fracture surface resulting from combined creep/ fatigue in stress range of region II.

11b. Several important points are noteworthy. The dramatic reduction in creep time in square-wave loading demonstrates the potent effect of reversed deformation on the craze breakdown process at constant stress, namely 16 min versus 3.6 min. On the other hand, the number of reversals to failure in the square wave experiment (176) is considerably less than the 420 reversals to failure in the conventional fatigue tests (Fig. 6); this illustrates the potential of the creep component in reducing fatigue life. Comparison of Figs. 11a and b with Fig. 7a shows that the extent of areal craze growth prior to crack propagation increases as the creep component in the failure process increases. Areal craze growth may, in fact, provide a sensitive indication of the relative amounts of creep and fatigue in any individual failure. On this basis, the creep component in the conventional fatigue tests, (cf. Fig. 7) is small, and decreases with increasing fatigue life through regions II and III. In contrast, with increasing peak stress amplitude – i.e., moving into region I – the creep component becomes increasingly important.

3.2.4. *Failure in region I*

As the peak cyclic stress amplitude is increased through region II, polystyrene experiences a rather abrupt deterioration in fatigue resistance as reflected by a sharp reduction in the slope of the fatigue life plot, Fig. 6. This abrupt transition occurs because the applied peak stress in region I exceeds the constant-strain-rate craze initiation stress; crazes are generated on the first tensile quarter cycle, and the entire fatigue life consists of craze growth and craze breakdown. The sharpness of the transition gives testimony to the potency of crazes as the sites and vehicles for crack initiation in thermoplastic polymers. With the elimination of the craze initiation part of fatigue in polystyrene, the fatigue life is drastically reduced from what would be predicted by an extrapolation to shorter lives of the cyclic response in region II. This abrupt transition, coincident with the critical crazing stress, is characteristic of all plastics which fail via craze nucleated fracture [18].

The fatigue fracture surface in region I reflects the large areal craze development and rapid crack propagation characteristic of high stress deformation. A typical region I fractograph is shown in Fig. 12. One conclusion that can be drawn from a comparison of Figs. 3, 11 and 12, is that creep plays a very significant part in the failure process in region I; areal craze growth prior to fracture is quite extensive. Unquestionably, reversed deformation also plays an import-

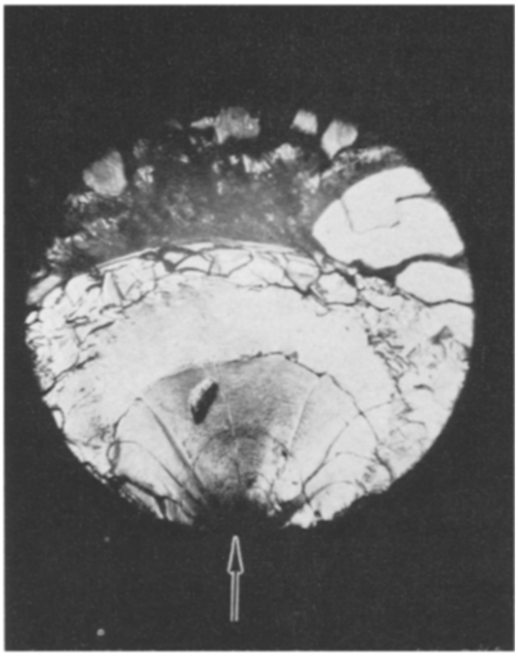

Figure 12 Typical polystyrene fatigue fracture surface in region I.

ant role in region I by accelerating the breakdown process so that the failure mechanism in region I is most properly described as combined creep/fatigue. Experimentally, region I failure is difficult to define because of the extreme stress sensitivity – i.e., the shallowness of the stress-life relation in Fig. 6 – but, small changes in peak stress amplitude can make marked changes in the appearance of the fatigue fracture.

The extent of areal craze growth prior to crack propagation decreases with decreasing stress. Under the high stress creep conditions that prevail on the portion of each tensile half-cycle above the constant strain-rate craze appearance stress, the rate of areal craze growth is a sensitive function of peak stress amplitude. In all but the unidirectional failure (1 reversal), there is insufficient stress/time to permit craze growth completely across the cross-section in one cycle. There is clear evidence in the fractograph in Fig. 12 that areal craze growth proceeds incrementally on each tensile half-cycle; craze arrest markings, quite analogous to the conventional fatigue crack arrest striae, are prominent. Such incremental craze growth is a characteristic feature of region I fatigue in thermoplastic polymers [18].

Virtually all of the fracture surface in Fig. 12 derived from catastrophic crack propagation, first through pre-existing craze and finally through previously uncrazed polymer. However, small patches of craze can be seen growing in from the periphery in the final fracture region, giving a combination rough/smooth texture. It is only towards the lower stress end of region I that visible manifestation of slow fatigue crack growth is resolvable prior to rapid crack propagation. Throughout region I the part of the fracture surface near the crack nucleus shows the patchy texture characteristic of craze induced fracture.

4. Conclusions

1. The topography of fracture in simple tension shows extensive areal craze growth prior to material separation.
2. The presence of significant stress concentrations can be detected by the absence of extensive areal craze development on the fracture surface.
3. The overall fatigue response of polystyrene can be separated into three regions, reflecting the relative influences of craze nucleation and crack nucleation on the fatigue life.
4. In the short and intermediate life regions, fatigue fracture occurs via the same mechanisms that have been well characterized in tensile fracture. The primary role of reversed deformation is an acceleration of the craze and crack nucleation events.
5. Long life fatigue fracture is less clearly understood, and may involve crack nucleation without associated crazing.

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