JOURNAL OF MATERIALS SCIENCE 12 (1977) 1383–1391

The fracture of notched tensile specimens of a transparent ABS polymer

R. W. TRUSS, G. A. CHADWICK
Department of Mining and Metallurgical Engineering, University of Queensland, St. Lucia, Queensland, Australia

The fracture of notched samples of a transparent ABS polymer has been studied. The role of crazing in the fracture of these samples has been investigated by examining transverse and longitudinal sections of the specimens before and after fracture, and by following crack growth with a 16 mm movie camera. The fracture surfaces have also been studied by SEM. A three-stage fracture process has been found. Initial crack growth has been observed through a craze in the craze bundle which formed at the notch, producing a highly whitened region on the fracture surface. The crack continually accelerated and, at a later stage in the fracture, was shown to jump between crazes in the craze bundle, leaving islands of whitened material on the fracture surface. When the crack appeared to catch up with the tip of the craze bundle, a third banded region has been observed on the fracture surface.

1. Introduction

The fracture of single phase glassy polymers has been the subject of considerable research, but very few investigations have centred on the fracture of two phase rubber-toughened polymers. For instance, the fracture processes of glassy polystyrene [1, 2, 3], polymethylmethcrylate [4] and styrene-acrylonitrile [5] have each been catalogued to varying degrees of detail. Kambour [6] has summarized the results of crazing and fracture of thermoplastics published prior to 1973. Apart from our own work, the only reference to the fracture behaviour of ABS in air is that of Hagerman [7] although the fracture of ABS in corrosive solvents has recently been reported by Mai [8], but in neither of these papers are the crazing and fracture processes investigated in detail.

As part of a continuing research programme on the deformation behaviour of ABS materials, we previously examined the fracture of unnotched tensile samples of ABS polymers. Various grades of pigmented ABS were investigated and the effects of strain rate, temperature and rubber content were reported [9]. Another report commented briefly on the fracture of an unnotched transparent ABS [10]. Although all the samples previously tested were highly crazed at the time of fracture, it could not be ascertained unequivocally that fracture occurred through the breakdown of a craze. This present work entailed an investigation of fracture in notched samples of the transparent ABS at a single strain rate, and in these samples, fracture proceeded through crazes which formed at the notch. The fracture surfaces and the associated crazing and stress whitening were studied to determine the mechanisms involved in fracture of these samples.

2. Experimental

The material used in this work was Cycolac CIT brand transparent ABS polymer supplied by Marbon Chemical (Pty.) Ltd. It contained approximately 30 wt % rubber, the rubber particles ranging in size from 500 to 1500 Å. (An electron micrograph of the microstructure of this material has been presented in a previous paper [10]). Specimens were cut from injection moulded 3.2 mm thick sheets to a size 30 mm × 65 mm × 3.2 mm and these specimens were then annealed at 353 K for 2 h; Notches were produced by pressing a razor blade into the edge of the specimen to a depth of approximately 0.5 mm.

Several specimens were fractured at room temperature on an Instron testing machine using a constant cross head speed of 0.5 mm min^{-1}. Initial growth of the craze and the crack from the notch was sufficiently slow to be observed with the unaided eye, but final fracture occurred too rapidly to observe the final failure. This period of rapid crack growth was recorded on 16 mm film at a filming rate of 200 frames per sec. Transverse and longitudinal sections of the specimens were examined by optical microscopy before and after fracture to establish the extend of crazing and stress whitening and their relationship to the fracture path. Fracture surfaces were studied by both optical and SEM.

3. Results

Several specimens were tested but the fracture behaviour of the different specimens was essentially the same. The notching process produced a short craze at the tip of the notch and on application of a load to the specimen, this craze moved slowly into the specimen. Many additional crazes nucleated either at the notch or a short distance from the notch, producing a bundle of crazes propagating on neighbouring parallel planes. These can be seen in Fig. 1 which is an oblique view of a well developed craze bundle at a notch. A plan view of this craze bundle revealed that the crazes made an approximately semicircular interface with the uncrazed polymer, and that river lines were present normal to this craze–polymer interface. River lines have been shown previously to result from slight variations in the plane of the craze [10] and are clearly evident in Fig. 1. This micrograph also indicates that the distance between the planes of the individual crazes at the tip of the craze bundle may be as large as 0.5 mm.

The growth of the craze bundle and the crack can be followed in Fig. 2, which are prints taken from the 16 mm film. The craze bundle grew to approximately 5 mm in length before appreciable crack growth was observed (Fig. 2a). Dark bands (actually bands of stress whitening) emanated at approximately 40° from the craze bundle and increased in size and intensity as the craze bundle grew and the crack began to propagate. Initial slow crack growth occurred from the notch through the craze bundle (Fig. 2b), and was associated with a broadening of the craze bundle (Fig. 2c), and a period of more rapid craze growth. This usually occurred by one or two crazes extending beyond the craze bundle (Fig. 2d). Final fracture of the specimen was extremely rapid. Fig. 2e is the last frame before complete fracture of the specimen (0.005 sec before complete fracture) and indicated that the crack was still propagating through the craze bundle and that a zone of crazed material was present above and below the plane of fracture. However, this zone of crazed material appeared to terminate at M in Fig. 2f and the crack path became irregular past this point.

The feature at N in Fig. 2f resulted from a crack which nucleated off the plane of the main crack. These secondary cracks occurred in a number of specimens and often resulted in a slight deviation of the main crack leaving parabolic markings on the fracture surface.

Measurements of craze and crack length were taken from the 16 mm film and are plotted against time before complete fracture in Fig. 3. (Craze growth occurring before ~ 40 sec before complete

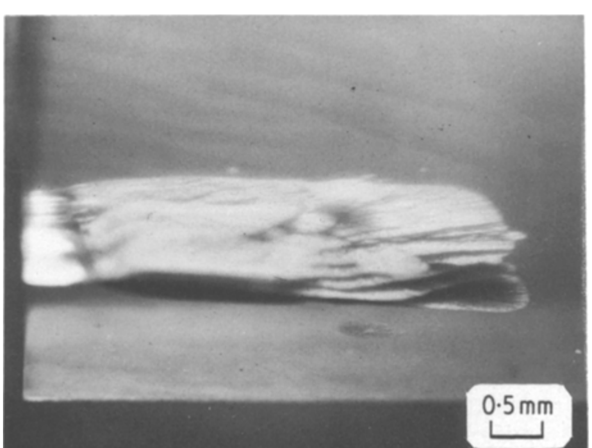

Figure 1 Oblique view of a well developed craze bundle at a notch. The crazes display a distinct river line pattern.

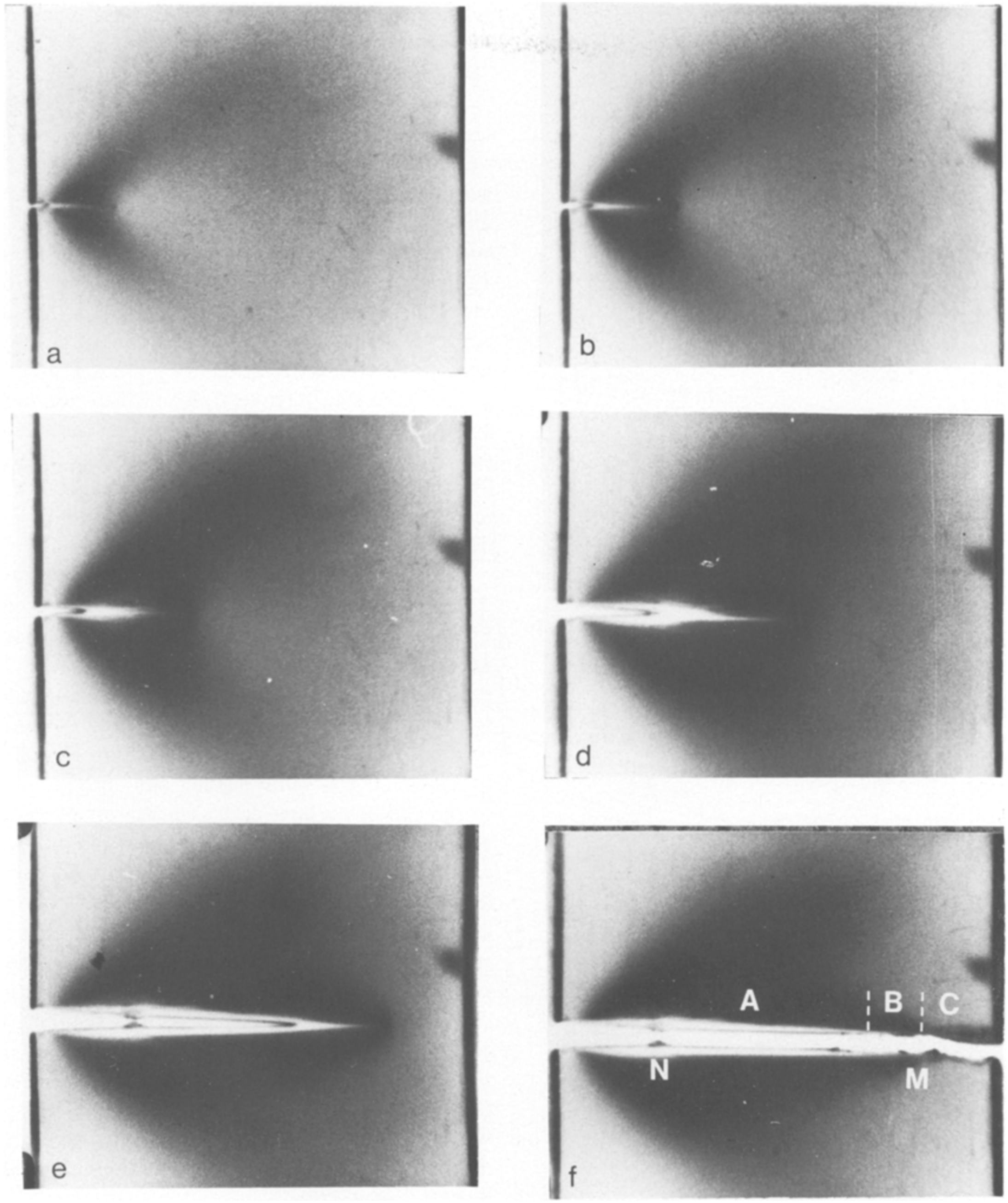

Figure 2 Prints taken from 16 mm film showing craze and crack growth from the notch at different times before final fracture (a) 13 sec, (b) 6 sec, (c) 3 sec, (d) 0.7 sec, (e) 0.005 sec, (f) fractured specimen.

fracture was not filmed). Initially the craze grew slowly before accelerating ahead of the growing crack. No appreciable crack growth occurred till ~ 25 sec before fracture. Then the crack grew slowly but accelerated continually to a final velocity $> 1\ \text{m sec}^{-1}$. The actual length of craze ahead of the crack was obtained by subtracting the crack length from the craze length and this is plotted in Fig. 4. The logarithm of the actual craze length increased linearly with time until ~ 5 sec before complete fracture, and the initial crack growth had no effect on this trend. When the crack length reached 2.75 mm, the length of craze ahead of the crack suddenly increased reaching a maximum

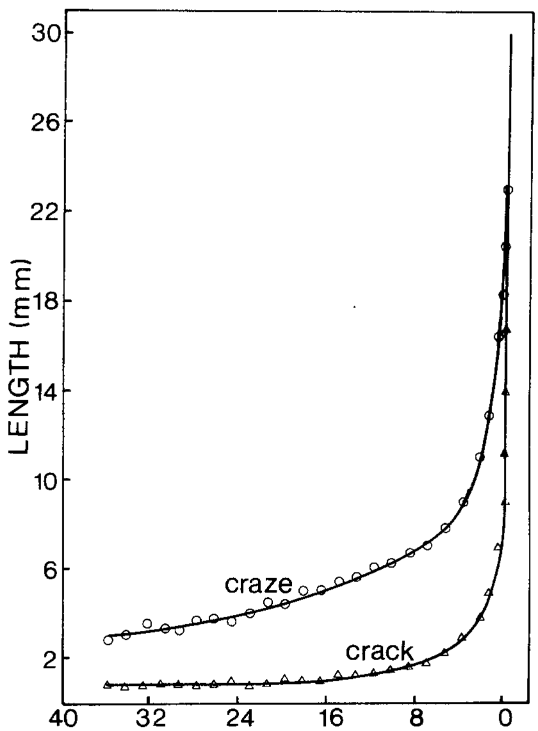

Figure 3 Distance of crack and craze tip from the edge of the specimen as a function of time before final fracture.

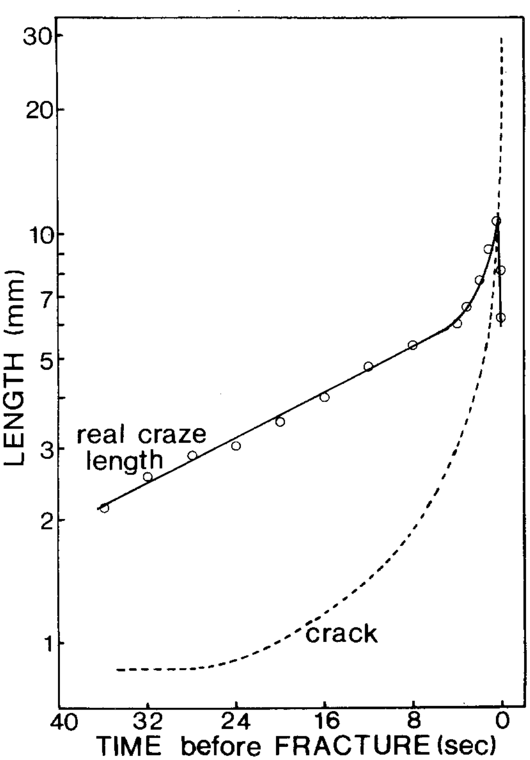

Figure 4 Actual length of craze ahead of the crack tip as a function of time before final fracture. The curve for crack length is superimposed on this curve.

when the crack length was 8 mm, whereupon the actual craze length decreased sharply as the crack length continued to rise rapidly.

Typical matching fracture surfaces resulting from fracture of these specimens are shown in Fig. 5a. Three regions can be identified on the fracture surface and these have been labelled Regions A, B and C. Fig. 5b shows the accompanying stress-whitening above and below these fracture surfaces. Large crazes parallel to the fracture surfaces can be seen in Regions A and B while Region C was accompanied by a pulsing of the stress-whitening with no large crazes present.

The extents of Regions A, B and C are also indicated in Fig. 2f and it can be seen that the extent of each region varied markedly between specimens. The reason for these variations is not known but may be related to the depth and sharpness of the initial notch.

The transition from Region A to Region B cannot be distinguished clearly in Fig. 5 as it is masked by the highly stress-whitened nature of both regions. However, after coating with aluminium in preparation for examination in the scanning electron microscope, this transition was clearly evident to the unaided eye. The transition from Region B to Region C was quite distinct and corresponded to the end of the large crazes which were observed to propagate initially from the notch. This observation, in conjunction with the measured rapid decrease in the actual craze length ahead of the crack as the Region B/Region C transition was approached (Fig. 4), suggested that this transition may have resulted from the crack tip overtaking the tip of the craze bundle and that the morphology of Region C resulted from the crack propagating rapidly beyond the large crazes which grew from the notch. However, crazing was still associated with crack propagation in Region C since considerable stress-whitening was still observed in this Region.

Each of the three regions on the fracture surface was studied in more detail by optical and scanning electron microscopy and a detailed description of the appearance of each region is presented in the remainder of this section. The associated crazing and stress-whitening was also examined and related to the fracture surface morphology, thus elucidating some of the fracture processes.

Region A appeared highly stress-whitened and almost featureless at low magnification except for some variations in the plane of fracture which can

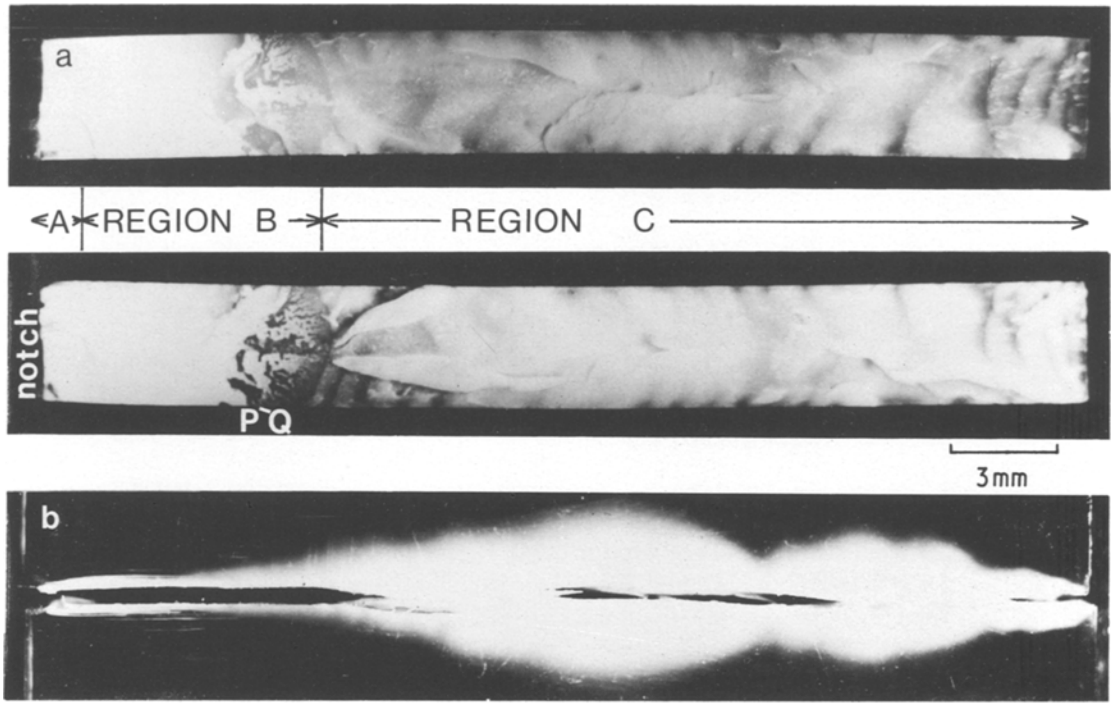

Figure 5 (a) Typical matching fracture surfaces showing the three regions on the fracture surface. (b) The fracture surfaces have been placed together to show the accompanying stress whitening above and below the fracture surfaces.

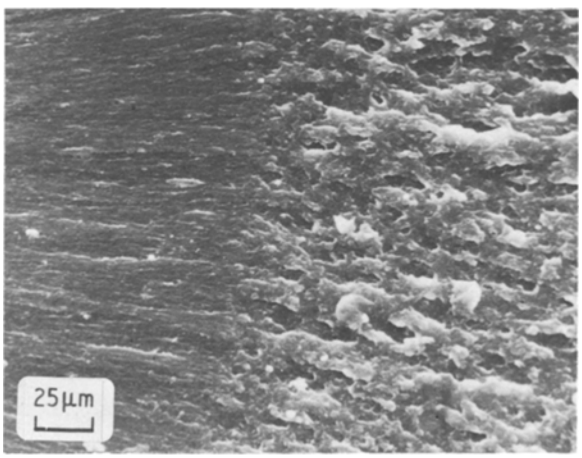

Figure 6 SEM of the transition from Region A to Region B.

be traced to irregularities of the notch (Fig. 5a). Fig. 6 is a scanning electron micrograph of the transition from Region A to Region B on the fracture surface. In Region A, slight variations in the plane of fracture can be seen, producing sharp steps on the surface aligned in the direction of crack propagation. The distance between these steps was of the same order of magnitude as the distance between the river lines of the crazes shown in Fig. 1. At higher magnification, this region had drawn "dimple" structure, similar to that reported for the slow crack growth region on the fracture surface of unnotched ABS samples [9]. The drawn fibrils between the dimples were orientated in the direction of crack growth which produced the apparent smoothness at low magnifications.

Near the boundary with Region A, Region B was also highly stress-whitened, but away from the boundary, this highly stress-whitened structure gave way to a morphology of islands of stress-whitened material protruding above a surface which displayed little whitening, Fig. 7. Comparison of

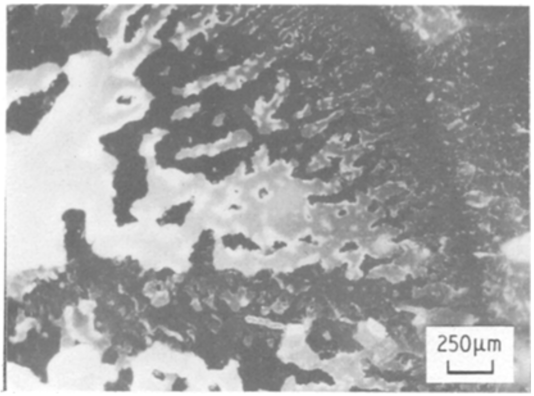

Figure 7 Islands of whitened material typical of Region B (Crossed polars).

matching fracture surfaces (Fig. 5a) revealed that where an island of whitened material was present on one surface, it was absent from the other. These islands of whitened material resulted from the crack oscillating between crazes in the craze bundle growing from the notch. In Fig. 8, a craze can be seen below the fracture surface, the crack having jumped into the plane of this craze between P and Q. The step at P corresponded with the start of the first unwhitened area of the fracture surface (P in Fig. 5a) while the step at Q corresponded to a small lightly whitened island of material which is faintly visible at Q in Fig. 5a. As the fracture jumped between crazes, a crack often continued along one craze for a short distance after the main crack jumped to the plane of a second craze. This tended to lift the edge of the whitened areas producing the bright rim on these areas when examined under polarized light. (Fig. 7). In general, all of the whitened areas were associated with features similar to that shown at P in Fig. 8. These islands of whitened material became smaller and thinner as the boundary with Region C was approached.

The finer variations in the plane of fracture associated with the river lines in Region A (Fig. 6) became discontinuous in Region B, but near the boundary with Region A, were still oriented in the direction of crack propagation. Fig. 9 is an SEM of an area similar to that shown in Fig. 7, the large feature across the centre being the edge of one of the islands of whitened material. The fine steps associated with the river lines were present on both the whitened and unwhitened areas of the fracture surface but they were no longer orientated in the crack propagation direction. A tendency existed for these fine steps to be radially orientated, such as at R, and this orientation would correspond with the river lines of an elliptical craze nucleated in the stress field of the notch.

Higher magnification examination of Region B (Fig. 10) revealed a flake like morphology with some evidence of a dimple structure caused by voiding around rubber particles similar to that observed in Region A. This structure was present over the whole Region B irrespective of the macroscopic features that were present.

Region C showed some quite large protrusions from the fracture surface but was characterized by a series of bands or ribs. There was no large variation in the plane of fracture across these ribs but the beginning of each rib was associated with a coarsening of the fracture surface morphology and and increase in the stress-whitening appearing on the surface. The surface morphology gradually

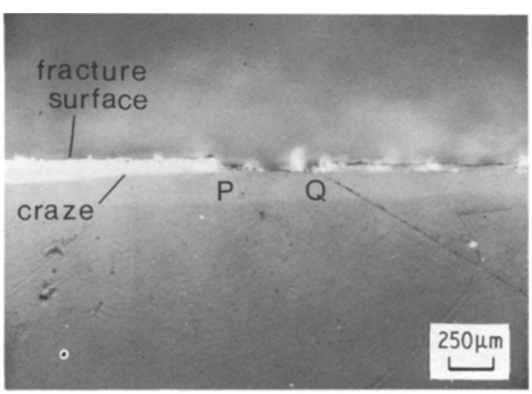

Figure 8 Jumping of the crack between crazes in the craze bundle.

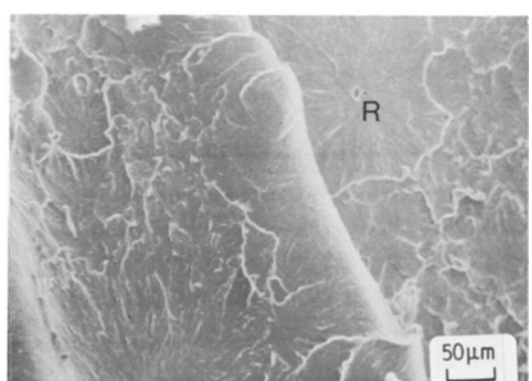

Figure 9 SEM of Region B at an area similar to that shown in Fig. 7.

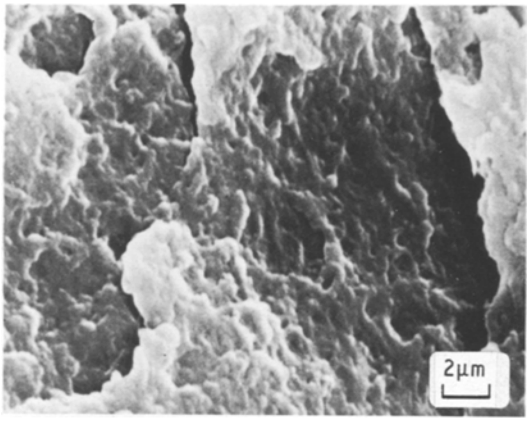

Figure 10 SEM of Region B at higher magnification.

became smoother towards the end of the rib with a corresponding decrease in the surface stress whitening. A similar pulsing occurred in the underlying stress-whitening, maximum whitening occurring at the beginning of a rib, tailing off to a minimal amount at the end of a rib. The ribs were mirrored on matching fracture surfaces, the beginning of a rib on one surface corresponded with the beginning of a rib on the matching fracture surface. The spacing between the ribs in most samples was variable (Fig. 5a) but was more regular in others (Fig. 12b). Despite variations in the rib spacing, the features present on the ribs were similar in all cases. The beginning of a rib can be seen in Fig. 11. Large irregular features are evident at the beginning of the rib in contrast to the finer features of the tail of the preceding rib. At higher magnification, a structure similar to that observed at high magnification on Region B (Fig. 10) was observed right across the rib.

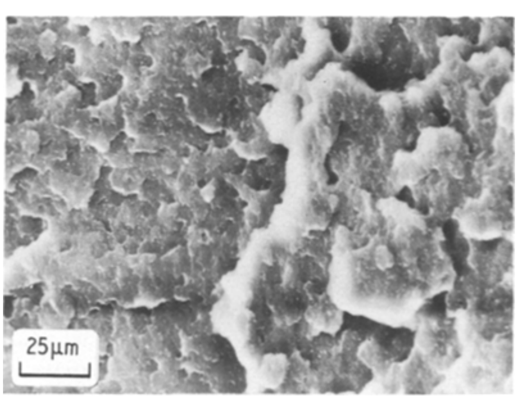

Figure 11 Variation in morphology at the end and beginning of a rib.

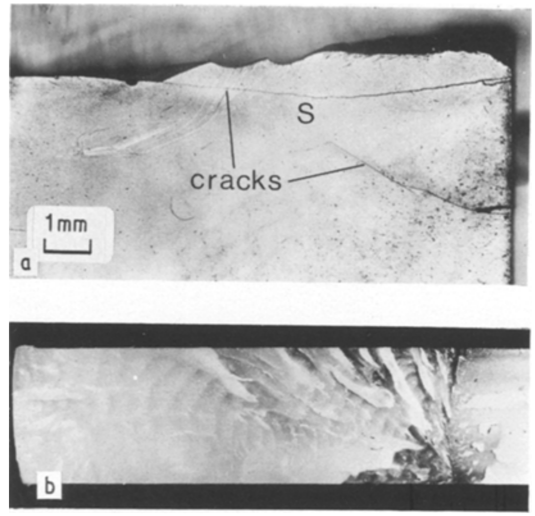

Figure 12 (a) Specimen in which the crack has branched (b) fracture surface.

The fracture mechanisms producing the rib structure were studied further in a specimen in which the rapidly propagating crack had branched. Complete separation of the surfaces had occurred on one of the crack branches but only partial separation on the other branches, Fig. 12a. The fracture surfaces produced by the completely separated crack branch displayed closely spaced ribs, Fig. 12b. The crack branches on which the surfaces had only partially separated could be studied in the reflection optical microscope. Oblique examination of these crack branches confirmed that ribs similar to those shown in Fig. 12b were also present on these branches.

Fig. 13 is a higher magnification micrograph of the unseparated crack in the vicinity of S in Fig. 12a. Approximately linear propagation of the crack occurred at T and T′ and these areas corresponded to the end of a rib seen in plan view. Between these regions considerable irregular cracking and crazing of the material surrounding the crack occurred. The typical morphology at the beginning of a rib was produced as the fracture front stepped irregularly between these smaller cracks on different planes. This produced large irregular features on both fracture surfaces. This process can be seen more clearly in Fig. 14 which is a view of the beginning of a rib at still higher magnification. Smaller

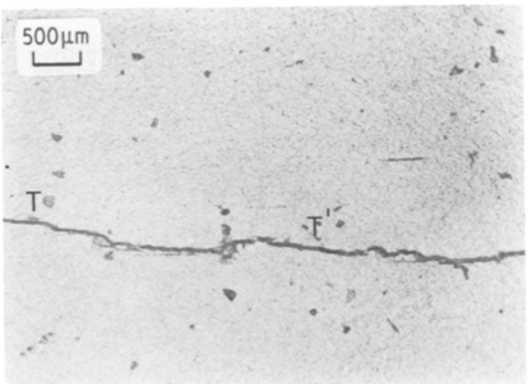

Figure 13 Higher magnification of the crack in the vicinity of S in Fig. 12.

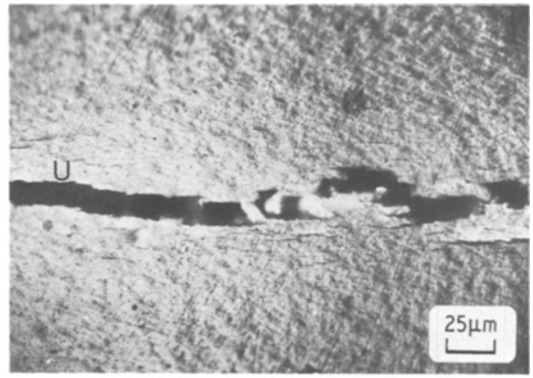

Figure 14 Optical micrograph of a crack at the beginning of a rib showing how the crack has jumped irregularly between smaller cracks.

variations of the plane of fracture can also be seen at U in Fig. 14 where the crack was propagating in and apparently planar fashion. These fine variations corresponded to the finer features present at the tail end of a rib and appeared to result from the fracture jumping between small cracks which were present along the periphery of the main crack. These small cracks may have resulted from a process of voiding around rubber particles [9] or from the fracturing of small crazes by the stress field of the main crack.

4. Comparison with unnotched samples

The unnotched samples displayed a two stage fracture surface; a double cone region with a drawn dimple morphology corresponding to a slow crack growth, and a rougher, though rounded, fast crack propagation region [10]. The slow crack growth Region A produced by a crack propagating through a craze in the notched samples had a surface morphology similar to that of the slow crack growth region of the unnotched samples. However, none of the macroscopic features such as the islands of crazed material and the banding characteristic of the fracture surface of the notched specimens were present on the fast crack growth region of the unnotched specimens. The large amount of crazing present in the unnotched samples at the time of fracture provided numerous paths for the rapidly propagating crack to follow, and this eliminated the macroscopic banding which occurred when no pre-fracture crazing was present. At higher magnification, the morphology of the fracture surface of both the notched and unnotched specimens when the crack was propagating rapidly was rough and irregular with evidence of voiding around rubber particles. The features were more rounded and the drawing around the rubber particle voids more severe in the unnotched samples than in the notched samples.

5. Comparison with glassy polymers

Some features observed on the fracture surface of this two phase rubber-toughened ABS polymer were similar to those observed in single phase glassy polymers. The banding in Region C of the fracture surface of ABS resembled the ribs reported on PMMA fracture surfaces [4]. Banding on a much finer scale has also been reported in polystyrene and has been attributed to the crack jumping between crazes in a craze bunch which forms ahead of the crack. Although the mechanisms involved in banding in polystyrene are not completely understood [2, 3], they may be comparable to those occurring in ABS.

On a superficial level, the islands of whitened material observed in Region B of this ABS material may be likened to the finer patch pattern found in polystyrene, however, no evidence of a mechanism described by Murray and Hull [1] for the production of this patch pattern in polystyrene by the fracture of the craze/polymer interface was found in this material. The large islands of whitened material present on Region B of the fracture surface of ABS were produced by a different mechanism of the crack jumping between crazes. The drawing of the polymer, especially that observed in Region A of this ABS material, is not nearly as apparent in glassy polymers.

6. Summary and conclusions

The following processes occurred in fracture of notched specimens of this transparent ABS polymer. Under a sufficiently high applied load, a bundle of crazes formed at the notch. Initial slow crack growth appeared to occur through one of these crazes, and produced a highly whitened yet macroscopically smooth fracture surface (Region A). The river lines observed in crazes were duplicated in slight variations in the plane of the fracture surface. At higher magnifications, this region of the fracture surface had a drawn dimple morphology.

The crack continually accelerated and its growth was initially confined to the craze bundle. At first, this craze bundle accelerated ahead of the crack but as the crack began to grow rapidly, the actual craze length ahead of the crack suddenly decreased. This decrease in the actual craze length ahead of the rapidly propagating crack was accompanied by the crack jumping between the crazes in the craze bundle producing the morphology of islands of whitened material typical of Region B.

The ribbed morphology of Region C appeared to result from the crack catching up with the tip of the craze bundle. The formation of these ribs was associated with a large amount of subsidiary cracking above and below the plane of the main crack, the coarser features on the fracture surface at the start of a rib resulting from the fracture jumping between these auxiliary cracks. The smoother morphology at the tail end of a rib resulted from the crack stepping between much smaller cracks many of which were present close to the main crack.

Acknowledgements

The polymeric material on which this research has been conducted was generously provided by Marbon Chemical (Australia) Pty. Ltd. RWT is grateful for the provision of a Commonwealth Postgraduate Research Award.

References

1. J. MURRAY and D. HULL, *Polymer* **10** (1969) 451.
2. P. BEAHAN, M. BEVIS and D. HULL, *Proc. Roy. Soc.* **A343** (1975) 525.
3. M. J. DOYLE, A. MARCANCI, E. OROWAN and S. T. STORK, *Proc. Roy. Soc.* **A329** (1972) 137.
4. R. P. KUSY, H. B. LEE and D. T. TURNER, *J. Mater. Sci.* **11** (1976) 118.
5. H. D. MOSKOWITZ and D. T. TURNER, *J. Mater. Sci.* **9** (1974) 861.
6. R. P. KAMBOUR, *J. Poly. Sci. Macromolecular Reviews* **7** (1973) 1.
7. E. M. HAGERMAN, *J. Appl. Polym. Sci.* **17** (1973) 2203.
8. Y. W. MAI, *J. Mater. Sci.* **11** (1976) 303.
9. R. W. TRUSS and G. A. CHADWICK, *J. Mater. Sci.* (in Press).
10. R. W. TRUSS and G. A. CHADWICK, *J. Mater. Sci.* **11** (1976) 1385.

Received 6 October and accepted 6 December 1976.