8. J. GARRIDO, *Ion. Rev. Espan. Quim. Aplic.* **11** (1951) 206.
9. *Idem, ibid* **11** (1951) 453.
10. M. C. BALL and H. F. W. TAYLOR, *Min. Mag.* **32** (1961) 754.
11. J. F. GOODMAN, *Proc. Roy. Soc. A* **247** (1958) 346.
12. G. W. BRINDLEY, *Prog. Ceram. Sci.* 3 (1963) 7.
13. P. J. ANDERSON, R. F. MORLOCK and J. F. OLIVER, *Trans. Faraday Soc.* **61** (1965) 2754.
14. S. MALINOWSKI, S. SZCZEPANSKA and J. SLOCZYNSKI, *J. Catalysis* 7 (1967) 67.
15. T. H. NIELSON and M. H. LEIPOLD, *J. Amer. Ceram. Soc.* **49** (1966) 626.
16. S. STOTZ and C. WAGNER, *Ber. Bunsenges. Phys. Chem.* **70** (1966) 781.
17. J. W. MEYER and J. YANG, *Amer. J. Sci.* **260** (1962) 707.

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Formation and structure of striations on the fracture surface of glassy polystyrene

In glassy amorphous polymers the fracture surface produced by tensile or bend loading often consists of a smooth mirror zone at the onset of fracture and of a rough striation zone in the region of rapid crack propagation (Fig. 1) [1]. Kusy *et al.* recently investigated these characteristic markings under different aspects of fracture in PMMA [2, 3]. Their observations agree with many of the results which we have obtained on PS (PS 168 N, BASF) [4]. The purpose of this work is to describe further details of the band structure. An energy criterion will be used to explain the formation of the bands, and together with the crack propagation model established by Doyle [5], it can be used for a step towards complete explanation of the crack propagation process in glassy amorphous polymers.

The mean width of the striations in PS decreased strongly in the temperature range 20 to −196° C. In PMMA the differences in band width are dependent principally on molecular weight. There is only a slight increase in band width with increasing temperatures (−196 to 77° C), and no essential influence of the extension rate on the band width was observed.

At higher magnifications in the SEM, all bands

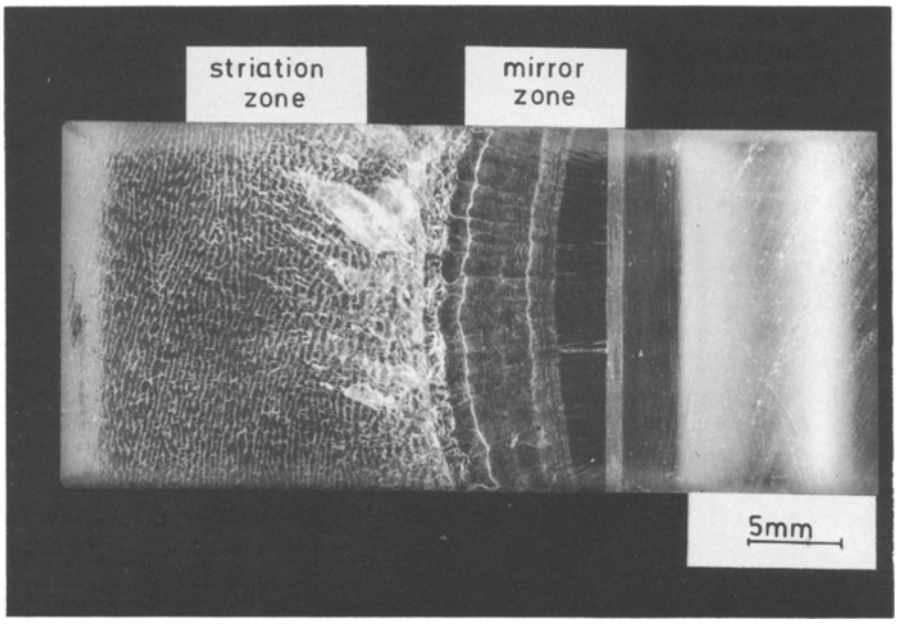

Figure 1 Complete fracture surface of a compact tension specimen of glassy polystyrene produced at room temperature under cyclic loading (mirror region) until fracture occurred by unstable crack propagation (striation zone).

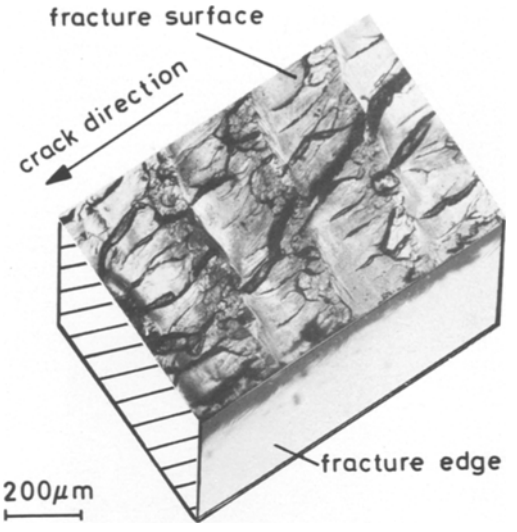

Figure 2 Relationship between striations and markings on adjacent side after failure. The four craze bundles indicate that the crack proceeded from right to left.

in PS as well as in PMMA showed a rough, cleft appearance at the origin, changing into a smooth area in the crack direction. It was noticeable that at the fracture edges on the surface of ruptured specimens, every striation was comprised of a curved cluster of crazes mostly originating from the onset of the rough region (Fig. 2).

This sequence of branching sites combined with a sequence of bands on the fracture surface can be explained by an energy criterion, which was also used to explain the macroscopic crack bifurcation in PS [4]. The crack continues to propagate as two or more branches, as soon as the specific stored elastic energy of the crack, G, is greater than or equal to the two-fold critical specific surface and deformation energy at the crack tip, G_c:

$$G \geqslant 2G_c.$$

In the individual crack branches characterized by a striation structure on the fracture surface, the stored elastic fracture energy, G, is always somewhat greater than the critical value, G_c. As the crack propagates in these branches a periodic change of fracture mechanism occurs, providing a basis for alternative retardation and acceleration of the crack tip, as proposed by Doyle [5]. During the accelerated propagation of the crack into a craze wedge, the crack tip becomes much sharper, with the result that the local stress ahead of the crack tip increases. At the moment when a craze cluster is formed in the region around the tip, G becomes greater than $2G_c$. Fracture can now be initiated at several sites of the craze bundle. This branching, in turn, will relieve the stress and hence $G_c < G < 2G_c$ is reached. Individual cracks unite to a common crack front by bending of the crazes in connection with a blunting and deceleration of the crack tip. The crack front then slowly proceeds into the new craze wedge ahead of it, and is newly accelerated and sharpened as the stress is restored. The process of crack branching and retardation is then repeated, generating a sequence of craze bundles, i.e. a sequence of striations on the fracture surface (cf. Fig. 8 in [2]).

The decreasing band width at lower temperatures can be attributed to the fact that the increase in stress leading to the formation of the craze cluster occurs after a shorter path of the crack. This is due to the greater rigidity of the molecular chains (high Young's modulus). On the other hand, the loading speed has no influence in the region of rapid crack propagation. Under these conditions, the actual crack velocity is close to a limiting velocity which is much higher than the loading rate and is determined by the elastic shear wave velocity in the material [6]. For PMMA this value was determined to be $700\,\mathrm{m\,sec^{-1}}$ [7]. The

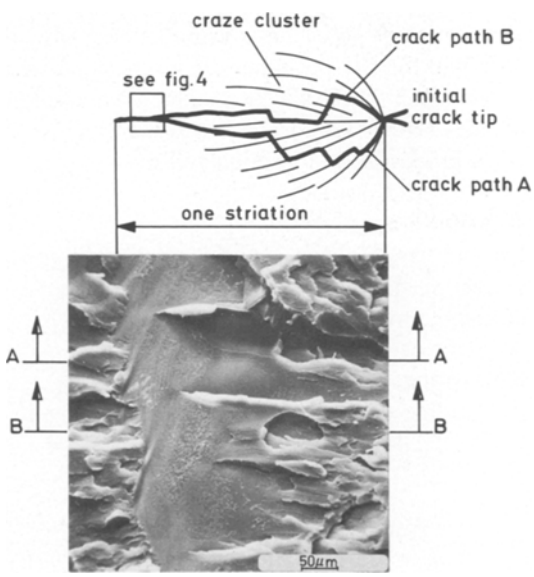

Figure 3 In a craze cluster (right) two possible crack levels are indicated (A, B), which yield into a common fracture plane (centre).

elongation rate only influences the acceleration of the crack to its limiting value and thus the size of the mirror zone.

The path of the crack in every bundle of crazes can be followed with the help of features on the fracture surface. One example for this is shown in Fig. 3. In the rough initial part of a striation, where the crack has propagated in several branches, well marked steps are found. The individual crack paths (in the figure designated as A and B) have united to form a unique crack front along these steps. In the smooth regions of a band, where the crack has run into a craze wedge, a patchwork remains on the fracture surface. This was also observed by Doyle on PS [5] and Kusy on PMMA [8]. The specks are due to residual layers of the craze wedge which have scaled off at the craze edge. They consist of fields of formerly stretched filaments, which after having been torn off on one side of the craze wedge are re-attached on the other side in their original structure (Fig. 4). Similar observations have been made by Hull on thick PS foils [9].

In conclusion it can be stated that the existence of a special stress field and deformation mechanism in front of a crack tip is necessary for the formation of bands on the fracture surface of PS as well as PMMA. The features within the bands and at the crack edge indicate the existence of the same fracture mechanism in both materials. The criterion for the beginning of macroscopic crack branching in PS can also be used for the explanation of the band formation during the microscopic crack propagation in both polymers.

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References

1. J. J. BENBOW, *Proc. Phys. Soc.* 78 (1961) 970.

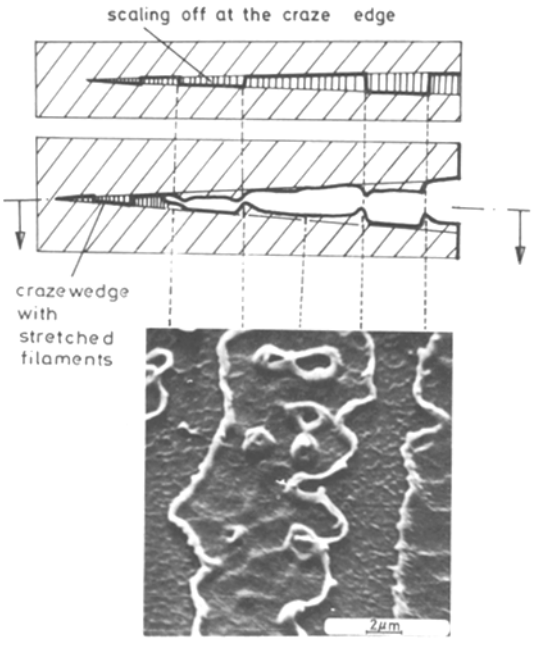

Figure 4 Further enlargement of the central zone of Fig. 3, showing the craze wedge after relaxation of the foil fibres which had been stretched before final rupture.

2. R. P. KUSY, H. B. LEE, D. T. TURNER, *J. Mater. Sci.* **11** (1976) 118.
3. R. P. KUSY, *ibid* **11** (1976) 1381.
4. K. FRIEDRICH, *Pract. Metallogr.* **12** (1975) 587.
5. M. DOYLE, *J. Mater. Sci.* **10** (1975) 159.
6. A. B. J. CLARK, G. R. IRVIN, *Exp. Mech.* **6** (1966) 321.
7. W. DÖLL, 3rd International Conference on Fracture, Vol. VII, No. VI (1973) p. 515.
8. R. P. KUSY, private communication (1 April 1976).
9. D. HULL, "Deformation and Fracture of High Polymers" (Plenum Press, New York, 1972) p. 171.

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