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Effect of Crazes on the Propagation of Cracks in Polystyrene

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A study of the fracture surfaces of polystyrene has revealed a direct connection between the fracture path and the shape and distribution of crazes. The effect is demonstrated by two examples; firstly, the propagation of a crack through initially uncrazed material and, secondly, the propagation of a crack through material containing an array of planar crazes parallel to the plane of propagation. It is shown that cracks propagate preferentially along crazes and that the formation of crazes in the stress field of a propagating crack results in the "hackle" surface normally associated with the propagation of cracks at high velocities.

1. Introduction

A casual observation of the fracture surface of polymers leads to the conclusion that the fracture process is extremely complex and that there are few features which can be regarded as meaningful. A more detailed study shows that each feature of the fracture surface can be related to the processes which accompany crack propagation. These processes are, in turn, related to the primary characteristics of the polymer, so that a complete description of fracture is a complex problem. There are many features of the fracture surface, which at first sight appear unique to a particular polymer tested under one set of conditions, which are really facets of a much wider phenomenon common to many polymeric materials. Polystyrene is a particularly suitable material for the study of fracture characteristics. It is expected that a detailed description of phenomena in this material will provide a basis for the interpretation of effects in materials which are less amenable to experimental examination.

Previous studies of polystyrene [1–3] have shown that under a wide range of conditions, craze-formation precedes fracture in tensile tests, and that crack nucleation occurs within the craze. In the early stages of growth the crack propagates along or through the craze and produces the so called "mirror" area of fracture. This is followed by a much rougher surface usually called "hackle" which is associated with bifurcation and branching of the crack. It is usually assumed that these processes are due to the crack propagating at velocities close to the limiting velocity. In this paper some of the mechanisms associated with these processes are considered. In the course of our studies numerous observations on hackle surfaces, many of which are complex, have been made. For convenience and clarity two simple examples of the phenomena have been selected. Some more general aspects of the processes involved are considered at the end of the paper.

2. Propagation of a Crack through a Craze

Murray and Hull [2] have shown that when a crack propagates in a preformed craze two processes may be involved: (i) cavitation of the craze and final separation by tearing of the material in the craze layer; (ii) splitting of the material along the interface between the craze and the uncrazed material. These two processes are illustrated schematically in fig. 1. The first

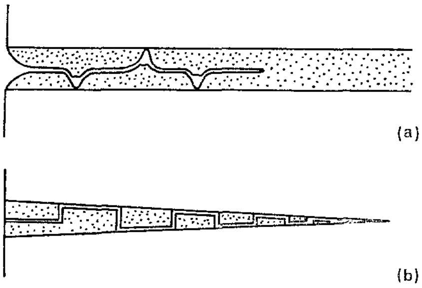

Figure 1 Schematic representation of mechanisms of crack propagation in a craze.

mechanism of propagation produces a surface made up of an initiation region formed from the coalescence of cavities, which is surrounded by a striated surface with secondary fracture features. The latter is normally associated with slow crack-propagation in thick crazes.

The second mechanism, fig. 1b, produces islands of craze layer which stick to one or other of the fracture surfaces. It occurs in thin crazes when the crack is propagating at a high velocity. Since the craze normally tapers to a very thin section, the size of the craze layer islands becomes finer as the crack approaches the tip of the craze. An example of this effect is shown in fig. 2. A variant of this island structure is the Mackerel pattern [4], but this is normally associated with large areas of a craze which is approximately uniform in thickness.

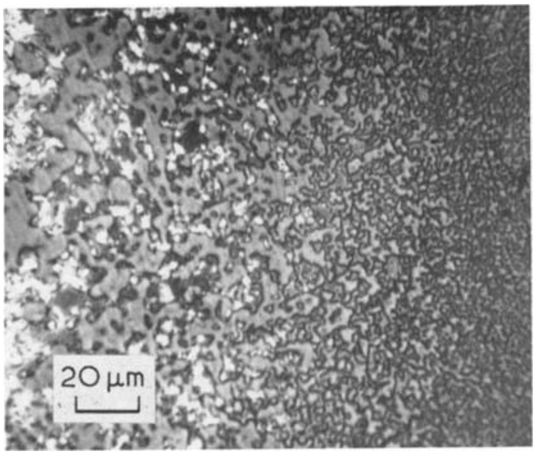

Figure 2 Fracture surface typical of a crack which has propagated by the mechanism shown in fig. 1b; optical micrograph, reflected light.

The crazes described here have formed in the tensile stress field prior to the nucleation of a crack. In a simple tensile test the stress field produces a parallel array of crazes lying normal to the tensile axis. The propagation of a crack associated with these crazes is, therefore, normal to the tensile axis also. However, the presence of a crack modifies the stress field. Bevis and Hull [5] have shown that in a specimen with a preformed crack the application of a tensile stress produces crazes which form along curved surfaces which are normal to the maximum principal stress at each point on the surface. The distribution of crazes produced in the stress field of a stationary edge crack tested in tension is illustrated schematically in fig. 3. Some interesting observations on the strain field around cracks have also been made recently by Vincent [6]. The same considerations apply to a moving crack, but the stresses are transitory and the formation of crazes will depend on the stress magnification and the crack velocity. In the two examples considered below evidence is given for the development of crazes during crack-propagation. Experimental details will be kept to a minimum because the features described can be observed in many grades of polystyrene, although the specific details may vary considerably.

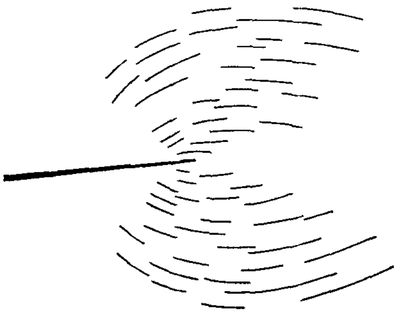

Figure 3 Distribution of crazes around an edge-crack.

3. Crack Propagation through a Region Free from Pre-Introduced Crazes

Specimens 5 in.* long and 1 in. wide were cut from $\frac{1}{8}$ in. thick sheet and the edges were ground and polished. A sharp crack was introduced at right angles to the axis of the specimen in the centre of the gauge length by pressing a sharp razor blade slowly into the edge. The slight

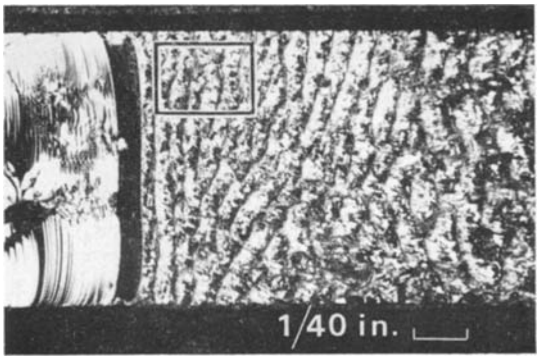

Figure 4 Optical micrograph of the fracture surface of a precracked specimen showing banded structure ahead of precrack. 1/40 in. = 0.063 cm.

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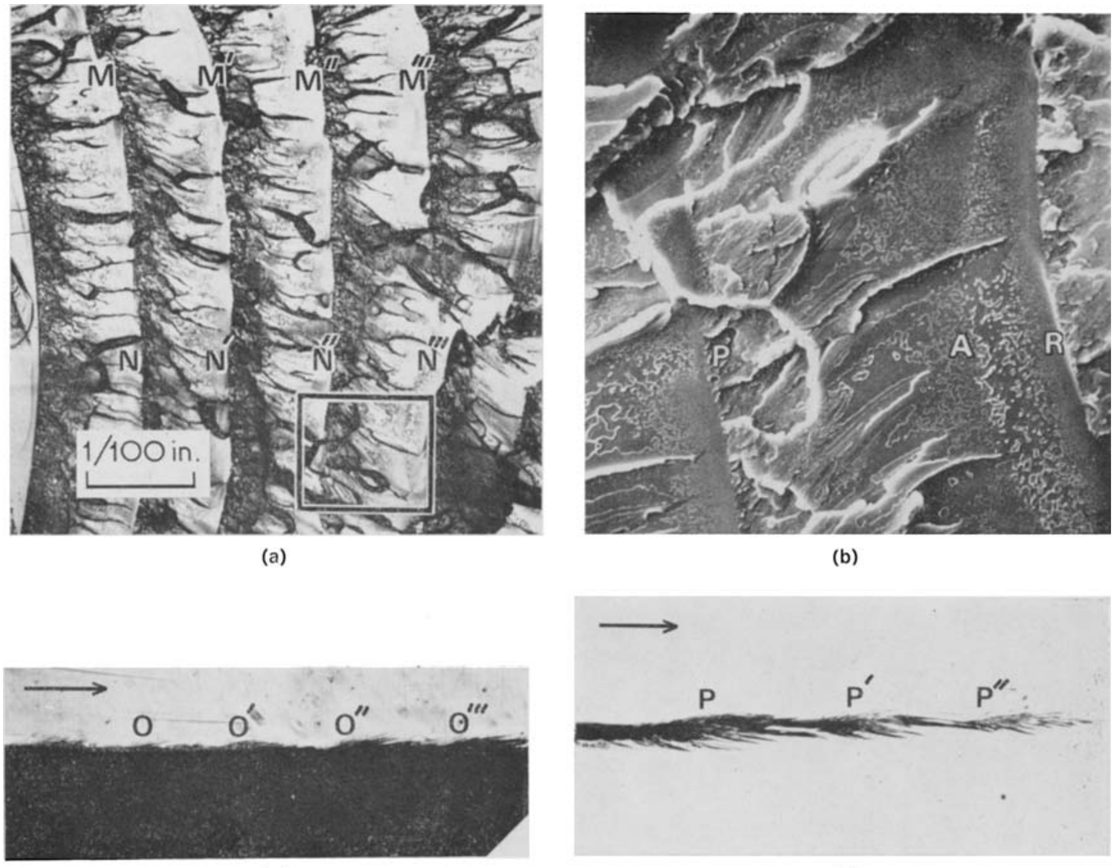
*1 in. = 2.54 cm.

wedging action of the blade produced a crack ahead of the razor edge. The specimens were then tested in tension at a strain rate of 10^{-4} sec^{-1} at 293° K. The general apperance of the fracture surface is shown in fig. 4. In the traditional sense the fracture was completely brittle. The "mirror" area at the left hand side is associated with the preformed crack which formed along planar crazes. The region examined in detail is outlined in fig. 5 and corresponds to the early stages of hackle fracture.

Various features of the selected area are shown in fig. 5. Opposite faces of the fracture surface were almost identical and differed only in the fine detail. Fig. 5a was taken in transmitted light to minimise scatter and the surfaces appear rather flat. The Stereoscan micrograph in fig. 5b gives a better impression of the irregular character of the fracture. The structure is readily interpreted in terms of a crack which has propagated along one of a bundle of crazes which forms in the stress field of the crack. The fine structure on the fracture surface in a region such as A (see fig. 5b) is analogous to the structure shown in fig. 2. The mottled appearance corresponds to patches of crazes and a similar interpretation is applicable. The sizes and distribution of the patches show that the crack has propagated from the edge at P, in fig. 5b, into a craze which has become progressively thinner towards the end of the craze at R. A large array of these small crack surfaces defines the position of the main crack front denoted by MN in fig. 5a and the crack has clearly moved in jumps, MN to M′N′ to M″N″.

Fig. 5c is a section normal to the fracture



(a) (b)

(c) (d)

Figure 5 (a) Detail of part of fig. 4, optical micrograph; transmitted light. 1/100 in. = 0.025 cm. (b) Detail of part of fig. 5a; Stereoscan micrograph. (c) Section normal to fracture surface parallel to direction of crack-propagation, indicated by arrow; optical micrograph, transmitted light. (d) Secondary crack which was parallel to main crack showing crazes formed along the crack path.

surface and parallel to the direction of crack propagation. An identification mark was used to arrange the photographs so that figs. 5a and c coincide. The fracture surface appears slightly cusped and the peaks at O, O′ and O″ coincide with the crack front boundaries at M, M′ and M″. Below the fracture surface a set of curved crazes has formed, spreading out from the region of the cusp. The shape and distribution of the crazes is similar to those observed around static cracks, fig. 3. Similar crazes can be seen around cracks which have stopped inside the sheet specimen as shown in fig. 5d; positions along the crack in fig. 5d equivalent to O, O′, O″ in fig. 5c have been marked P, P′, P″.

4. Crack Propagation through a Region Containing a Set of Preformed Crazes Parallel to the Plane of the Crack

The specimens for these experiments were the same shape and size as those described above (except that they were not so wide). The specimens were first loaded in tension and held at constant load to produce an array of crazes normal to the tensile axis, By selection of a suitable strain rate and holding load an array of closely spaced long crazes was formed. The crazes extended completely across the cross-section of the specimen. In most specimens the crazes started at the surface and grew inwards until they overlapped crazes growing from the opposite face. The stress was then increased until a crack nucleated in a craze and final fracture separation occurred.

The general appearance of the fracture surface is shown in fig. 6. Fracture has occurred entirely within the large crazes and the majority of the surface is identical to the type described previously, and shown in fig. 2, and corresponds to "mirror" fracture surface. The dark bands in

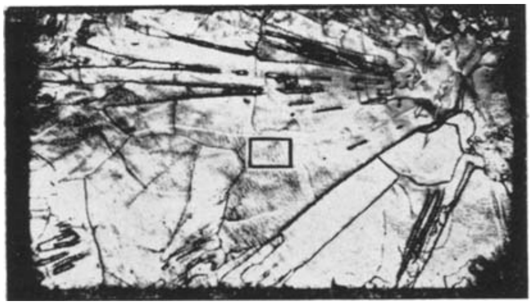
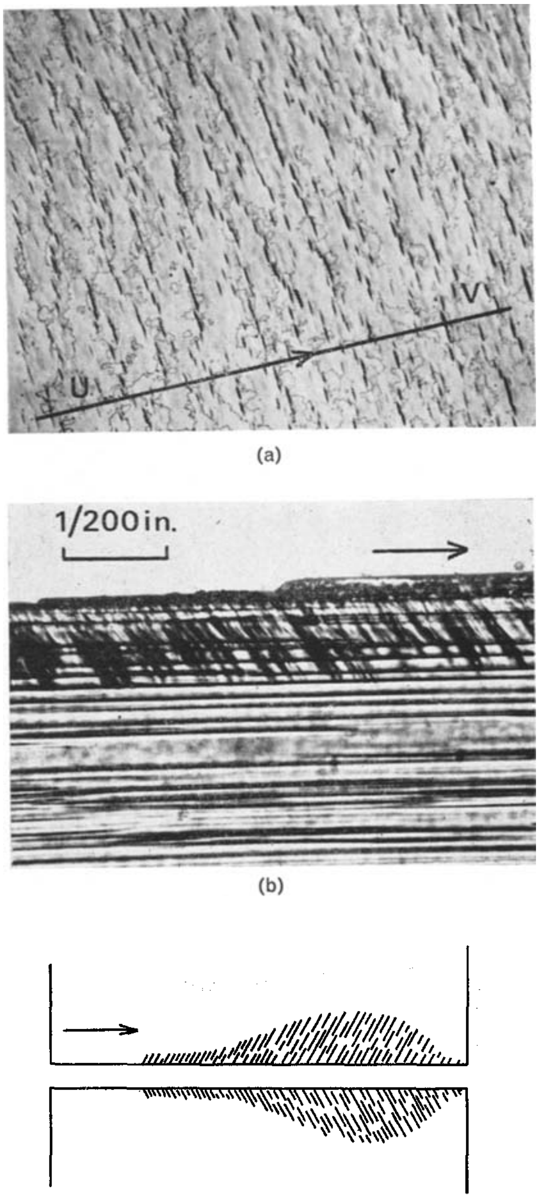


Figure 6 Optical micrograph of the fracture surface of a specimen with a preformed array of crazes parallel to plane of crack propagation; reflected light.



(a)

(b)

(c)

Figure 7 (a) Detail of part of fig. 6 showing patch effect and fine crazes. (b) Typical section normal to fracture surface of fig. 7a parallel to UV; optical micrograph, transmitted light. 1/200 in. = 0.013 cm. (c) Schematic representation of distribution of crazes along the path of fracture typical of specimen with preformed, closely spaced, parallel crazes.

fig. 6 are boundaries where the crack has jumped from one large craze to another.

The surface is covered with the patch effect of fig. 2 and in addition fine markings can be seen which map out concentric rings. These rings outline the shape of the crack front as it propagates through the craze and coincide with the shape of the bands in the Mackerel pattern [4] when it occurs. Details are shown in fig. 7. The patch effect is very fine and the lighting conditions were chosen so that the fine markings were not masked by the patches of craze. Comparison of opposite fracture surfaces showed that the fine markings did not coincide exactly although they had the same general shape and distribution. By focusing the microscope below the fracture surface it was possible to determine the distribution of the fine markings in three dimensions. The distribution can be seen more clearly in a section at right angles to the fracture surface cut along the direction of crack propagation – such as UV in fig. 7a. A typical section is shown in fig. 7b. The steps result from the crack jumping from one craze plane to another. The markings parallel to the edge of the fracture are crazes which formed before the nucleation of the crack and the markings at an angle to the edge are crazes which formed during crack propagation. The latter correspond to the fine markings on the fracture surface. The crazes form at an angle of 60° ± 2° to the plane of the crack and lie on a slightly curved surface following the shape of the crack front in the plane of crack propagation. The step on the fracture surface in fig. 7b makes approximately the same angle with the fracture surface, indicating that the fracture path probably followed a 60° craze formed on the opposite side of the main crack.

The depth of penetration of the crazes along the crack path increased as the length of the crack increased, as sketched in 7c. In addition it will be noted in fig. 7b that the length of the short crazes tends to be limited by the crazes parallel to the crack. The effect of crazes as barriers to other crazes is an interesting phenomenon which is readily demonstrated by bending a sheet of polystyrene in one direction and then in another direction, fig. 8. A set of primary crazes develop with the first bend and then a shorter set of crazes form with the second bend. This effect is presently being studied in some detail.

Figure 8 Primary and secondary crazes formed by bending; optical micrograph, transmitted light.

5. Discussion and Conclusions

In the first example it is clear that the crack has nucleated a set of crazes close to its tip and has then propagated along one of these crazes. A sketch of the crack propagation is shown in fig. 9. The banded structure on the fracture surface is generated because the crack moved in jumps. Similar fracture surface structures have been observed on other polymers – see [7] and [8] for examples. Andrews [8] refers to the effect as "slip-stick" behaviour although the actual mechanism is not described, except in terms of crack forking. From the present work it would seem that the length of the jump will be determined by the stress level and the length of the crazes. As the crack propagates rapidly along the craze the stress will be relaxed locally and the crack will slow down. This allows time for new crazes to form at the new position of the crack tip and as the stress builds up again the crack

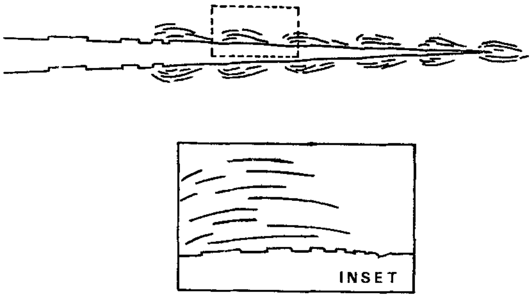
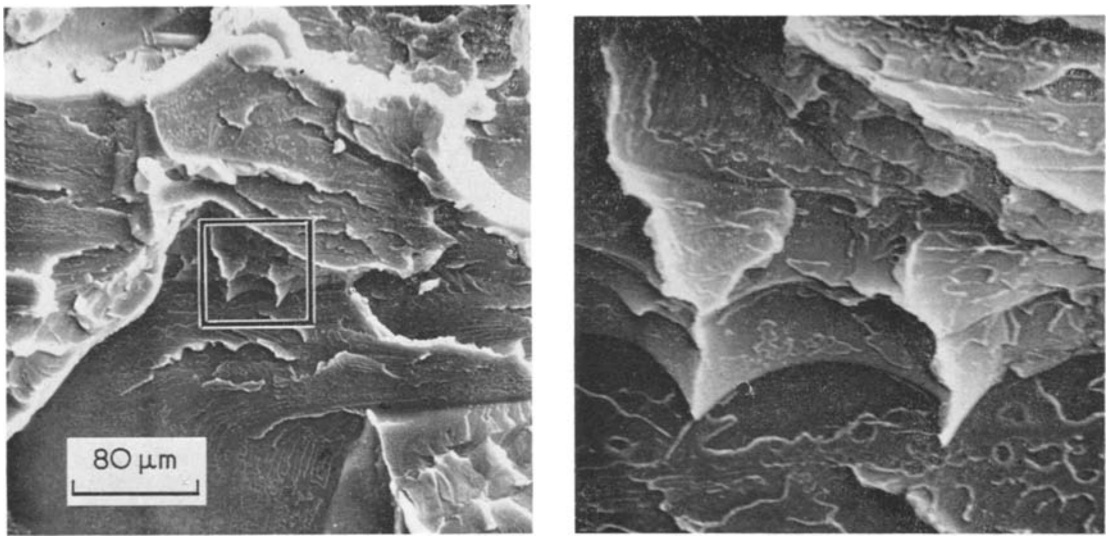


Figure 9 Schematic representation of the distribution of crazes along a crack propagating into undeformed material.

jumps along one of the new crazes. In the example described the movement of the crack appears to be relatively well-controlled. As the crack increases in length the stress around the tip will increase and this is accompanied by more irregular crack propagation. The same mechanism is involved, in that crazes are still associated with crack propagation, and the fracture surface has the same general features. Figs. 10a and b are Stereoscan micrographs of a very rough area.The mottled patchy surface indicates that fracture occurred along a craze in exactly the same way as in the more planar fracture surfaces. It is important to note, as emphasised by Beardmore and Fellers [9] from observations on polymethylmethacrylate and Beardmore and Hull [10] from work on tungsten, that the stress at which fracture occurs is far more significant than temperature in determining the surface structure of brittle-type fractures. In the present work crazes were observed around "brittle" cracks even at 77° K and observations similar to that shown in fig. 5d have been made at this temperature.

If this model is correct the spacing of the bands on the fracture surface will depend on those parameters which are related to the kinetics of craze growth in a given polymer and on the nature of the applied stress. Thus in a polymer where craze formation is restricted to very short distances by, for example, crystalline regions, intersecting crazes, and second phase particles, the frequency of crack jumping will be very high. Again, in a specimen subjected to alternating stresses the jump distance could be determined by the extent of crazing which occurs ahead of the crack during each cycle. A good example of the banded structure developed in the fatigue of polymethylmethacrylate has been reported by McEvily, Boettner and Johnston [11], although it should be emphasised that the interpretation of this effect in fatigue has not been given.

In the second example the normal distribution of crazes around the crack, cf. fig. 3, has been modified by the presence of a pre-existing array of parallel crazes. These crazes will allow considerable relaxation of the elastic stress field of the crack but will not allow total relaxation because the strain is restricted to a direction normal to the crack. Further relaxation occurs by craze formation at approximately 60° to the plane of the crack. An analytical solution of this relaxation geometry is at present being undertaken. It appears that the crack prefers to propagate along the pre-existing crazes than along the crazes which it generates as it moves except when it jumps from one craze to another. A schematic representation of crazes formed during crack propagation is shown in fig. 7c. No secondary crazes formed when the propagating



(a) (b)

Figure 10 (a) Stereoscan micrograph of a rough area of fracture surface showing the same patch effect observed on smooth fracture surfaces. (b) Detail of fig. 9a.

crack was short, but as the crack increased in length the stress intensity increased and secondary crazes were nucleated. In contrast to these observations it was found that in specimens with widely spaced primary parallel crazes, hackle surface developed. This is readily interpreted in terms of the relaxation of the stress field of the crack. With widely spaced crazes the stress field will not be relaxed close to the crack-tip and bundles of crazes similar to those shown in figs. 5c and d will be produced.

These observations imply that the occurrence of hackle-type fracture cannot be correlated directly with crack velocity. Although the velocity has not been measured in these experiments it would seem that in the second example where the crack was planar, the velocity of crack propagation would be higher than in the first example. This is contrary to the prediction that hackle occurs when the velocity reaches a critical value close to the limiting velocity.

The mechanism of relaxing of the stress field of the crack, described in this paper, support many of the observations made by Vincent [6], and could have a profound effect on the measurements which are made of fracture energy. There is clearly a large amount of deformation preceding fracture which will modify the structure of a pre-introduced crack as well as contributing to the work done in propagating the crack.

Finally, by way of conclusion, the effect of crazes on crack propagation can be demonstrated very clearly by introducing a set of crazes into a specimen and then propagating a crack through this array at a small angle to the plane of the crazes. Fig. 11 shows the effect produced. The crazes were introduced into one edge of the sheet by bending. The arrow shows the general direction of crack propagation and this occurs by a step-wise movement along the primary crazes at P and the secondary crazes at S.

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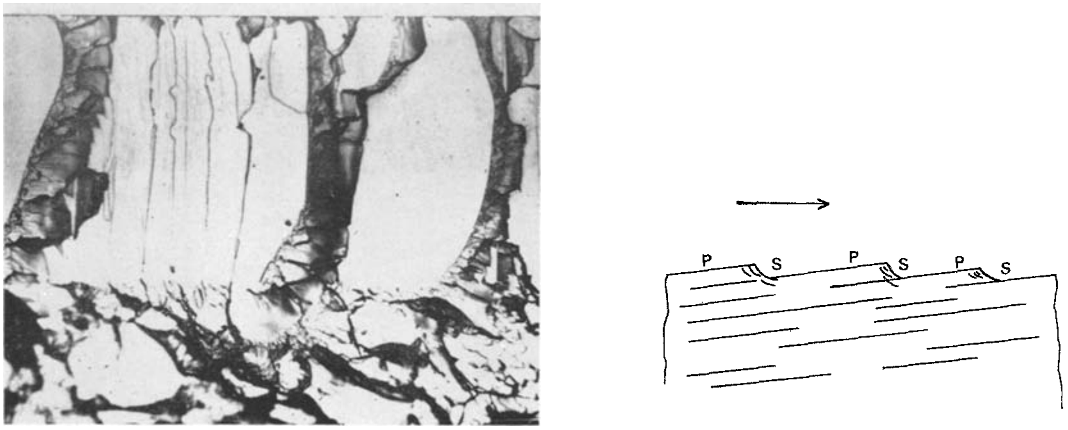

(a)

(b)

Figure 11 (a) Fracture surface of a specimen with preformed array of parallel edge-crazes at an angle of 10° to the direction of crack propagation; optical micrograph. (b) Schematic representation of a section through specimen in fig. 11a parallel to direction of crack propagation.