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Craze Distribution Around Cracks in Polystyrene

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The distribution of surface crazes in the vicinity of a stationary edge crack in a polystyrene sheet in tension is compared with the stress fields already investigated experimentally by Post. It is shown that the extent of crazing corresponds closely with the maximum principal stress contours determined experimentally and that the shapes of the crazes indicate that they grow along directions parallel to the minor principal stress axis.

1. Introduction

Recently Sternstein, Ongchin, and Silverman [1] have demonstrated convincingly that craze formation in polymers is governed primarily by the orientation of the major principal stress axis and the magnitude of the major principal stress at any point in a specimen. They analysed the distribution of crazes around a hole in a wide sheet, tested in tension, and compared this with the stress fields determined from linear elastic solutions. Quite good correlation was obtained between contours of maximum principal stress and the extent of the crazed volume of the specimen, indicating that there exists a minimum value of major principal stress which is required to propagate a craze. Crazes were not observed in regions where the major and minor principal stresses were nearly equal in magnitude, indicating that the formation of a craze requires a non-isotropic driving force, and therefore that a sufficiently high major principal stress is a necessary, but not a sufficient, condition for craze formation. Sternstein *et al* [1] also showed that craze growth occurs along a path such that the major principal stress always acts perpendicularly to the craze plane, that is, in this two dimensional experiment the crazes grow along minor principal stress trajectories.

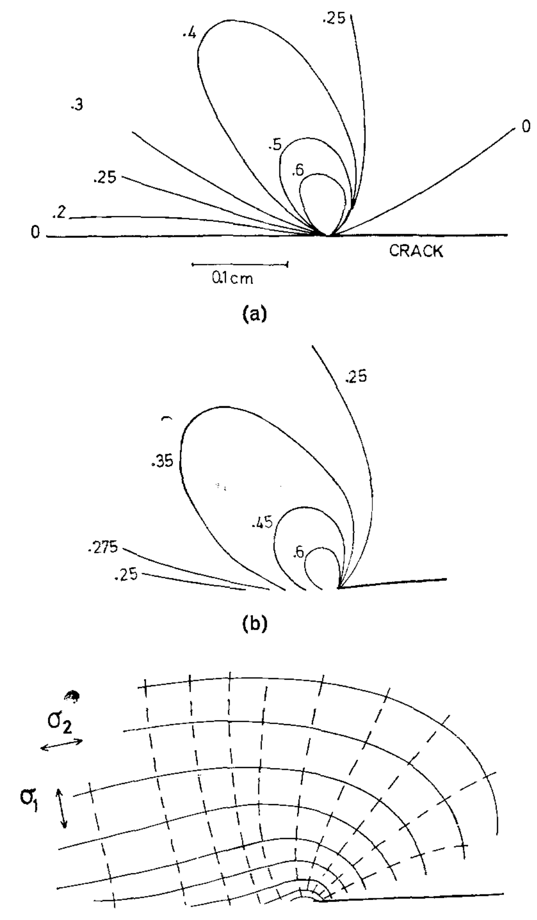
The stress field associated with a crack under tension provides a further and important stress system to test that craze formation is controlled by the principal stress criteria outlined above, and in this paper the distribution of surface crazes in the vicinity of a stationary edge crack in a polystyrene sheet in tension have been compared with the associated stress field, which has been investigated experimentally by Post [2].

This paper reports the initial investigations of a study aimed at furthering the understanding of the conditions required for the formation of crazes in the vicinity of a stress bias and of the fracture processes in materials which undergo plastic deformation by crazing (Hull [3]). The comparison between stress field and craze distribution is qualitative in that the craze distribution is not compared directly with a stress field determined under exactly the same conditions of loading and specimen dimensions. Standard experimental stress analysis techniques are currently being applied to this problem so that eventually it will be possible to carry out a quantitative comparison.

The main features of the elastic stress field in the vicinity of an edge crack in a thin sheet under tension as determined experimentally by Post [2], are described in section 2, the experimental procedures used for obtaining a distribution of crazes in the vicinity of an edge crack in a polystyrene specimen are described in section 3, and in section 4 the resultant distribution of crazes is compared with features of the stress field.

2. The Stress Distribution in the Vicinity of a Stationary Edge Crack in a Tensile Field

In a photoelastic stress analysis of a stationary edge crack in a tensile field, Post [2] obtained a complete experimental solution for the stress distribution around an edge crack by the independent determination of the sums (isopachic pattern) and differences (isochromatic pattern) of the major principal stress σ_1 and minor principal stress σ_2. Isoclinic curves were also determined experimentally and the major



Figures 1a, b and *c* Schematic diagrams of the isochromatic contours, major principal stress contours, and major and minor principal stress trajectories respectively in the vicinity of an edge crack under tension. In fig. 1c the major and minor principal stress trajectories are shown as broken and continuous curves respectively (× 12).

and minor principal stress trajectories determined from them; the tangent to a principal stress trajectory at any point on the trajectory is parallel to the related principal stress axis at that point. The experiments were made with thin sheets of photoelastic material so that the stress distribution corresponded to one of generalised plane stress. The crack length was significantly less than one half of the width of the specimen so that the external boundaries had a negligible influence on the stress pattern in the vicinity of the base of the crack, and in the experiments loading was always small enough to prevent additional fracture at the base of the crack.

A schematic diagram of the isochromatic pattern obtained by Post [2] is shown in fig. 1a. The scale mark has been included to give an indication of the variation of the stress field with distance from the crack tip for a crack approximately 0.8 cm long. The major principal stress contours in the vicinity of the crack, as determined from the data presented by Post [2], are shown in fig. 1b. In both figs. 1a and b the stress contours are multiples of an arbitrary stress value. The major and minor principal stress trajectories in the vicinity of the crack are shown in fig. 1c, where the major and minor principal stress trajectories are shown as broken and continuous curves respectively. The variables which will be used to describe the main features of the stress field are indicated in fig. 2. The

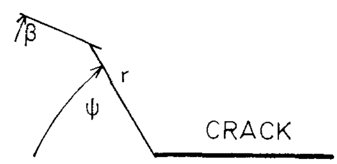


Figure 2 The variables used to describe the main features of the stress field within the vicinity of an edge crack.

variables r and ψ are self-explanatory and the angle β is the angle between the plane of the crack and the plane which is normal to the major principal stress axis at a particular point. It is clear from fig. 1b that the largest major principal stress at a given distance from the crack tip occurs at about $\psi = 65°$. The line of action of the principal stresses for $\psi \simeq 65°$ is very nearly perpendicular to the crack, that is $\beta \simeq 0$, as indicated by fig. 1c. Fig. 1a indicates that the major and minor principal stresses are approximately equal for small angles ψ.

3. Experimental Determination of the Distribution of Crazes around a Stationary Crack

In the most general sense crazing is a yielding phenomena and only occurs at relatively high stresses. Crazes will form locally in the region of a stress concentration, and because crazing is a time dependent phenomenon the amount of crazing will increase with time. Two important conditions must be satisfied for a proper comparison of the experimental distribution of the crazes with the elastic stress fields described in section 2. Firstly, the formation and growth of the crazes in the material around the cracks must not perturb the elastic stress field and secondly

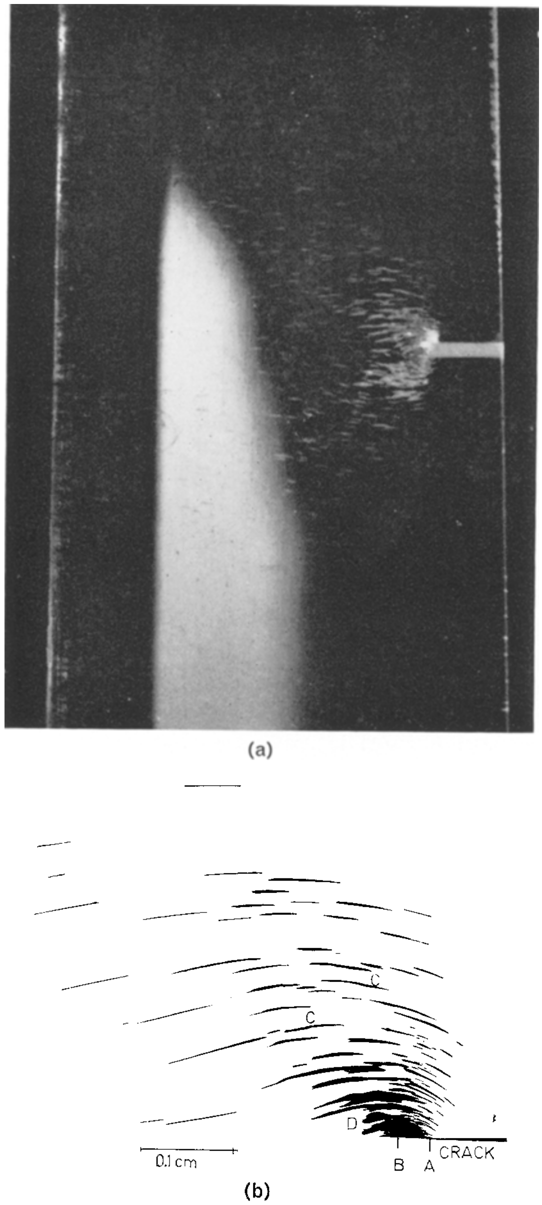


Figure 3 (a) Micrograph showing the craze distribution within the vicinity of an edge crack in a polystyrene specimen under tension. (b) Composite micrograph showing detail of the upper half of fig. 3a (× 12).

the crack must not grow during the period in which the crazes are growing.

The first condition can never be entirely satisfied because crazing involves yield. However, the total volume of craze which forms is extremely small; crazes in polystyrene are typically less than a micron thick and the density of crazes, even close to the crack tip, is never very large. Thus there will only be a small change in the elastic field and the observed agreement between theory and experiment described in the next section supports this. It should be noted that in some grades of polystyrene, craze formation is limited to a thin zone in the plane of the crack as described by Van den Boogaart [4] in PMMA and in this situation it will be necessary to take account of the plastic zone in defining the effective position of the crack tip.

The second condition is self evident and can be checked directly during the experiment. It does, however, raise a serious experimental problem. To produce a wide distribution of crazes around the crack requires a large applied stress, which must remain constant for a long time. Under these conditions it is difficult to avoid slow crack growth. A number of different materials were tested and it was found that the optimum conditions were relatively low stress, long time, constant load tests on a general purpose grade polystyrene, $Mv = 2.03 \times 10^5$. The crack was introduced into a 2.5 cm. wide specimen using the wedge technique described by Berry [5]. The edge of the sheet was ground away to remove the damage produced by the wedge and the final width was 2.0 cm. The craze distribution around a crack 0.3 cm long is shown in fig. 3a and the details on one side of the crack in fig. 3b. The specimen was a 0.3 cm sheet and the crazes started at the surface close to the crack tip. The crazes eventually spread outwards and grew in from the surface. During the constant load testing the crack grew about 0.034 cm; the initial and final positions of the crack front are marked on fig. 3b. The markings on the fracture surface show two distinct boundaries corresponding to A and B indicating that the crack grew relatively quickly between these two positions.

4. Discussion

The crazes illustrated in fig. 3b are surface crazes which developed under a plane stress condition and their distribution may be compared with the general features of the stress field determined experimentally by Post [2]. To confirm that the criteria for craze formation discussed in section 1 are operative it is necessary to show the following:
(*a*) That crazes follow paths defined by minor principal stress trajectories.
(*b*) The extent of the craze pattern is defined by a maximum principal stress contour.
(*c*) For a given maximum principal stress contour there should be a reduction in craze population

in regions where the minor and major principal stresses tend to be equal in magnitude.

Assuming that the crack grew quickly between A and B, two distinct craze patterns are to be expected in fig. 3b corresponding to crack tip positions A and B respectively. The minor principal stress trajectories of fig. 1c can be fitted exactly to the craze distributions of fig. 3b and the trajectories indicated by broken lines and continuous lines in fig. 4 correspond to crack tip positions A and B respectively. The agreement between the stress trajectories in fig. 4 and the craze pattern of fig. 3b confirm that criterion (*a*) is operative in the growth of crazes. Superposition of the minor principal stress trajectories as illustrated in fig. 4 also enables examination of the way in which a craze will propagate in a changing stress field. For example, a craze at position C in fig. 4 would propagate along C^1 as a result of the change in stress field associated with crack propagation from position A to position B. The craze morphology which results from the change in stress field is shown as a bold line at $C - C^1$ in fig. 4. Other examples of the expected morphologies are shown in fig. 4 and these correspond very closely to the morphologies of some of the crazes in fig. 3b. Crazes indicated by a C in fig. 3b are particularly clear examples of crazes which have grown partly in the stress field associated with crack position A and partly in the stress field associated with crack position B. These examples further confirm criterion (*a*) and also show that crazes respond to a change in stress field by changing their direction of propagation, to grow in a direction parallel to the minor principal stress axis. In regions of high major principal stress some crazes may even branch as a result of a changing stress field, as indicated by the crazes in region D in fig. 3b.

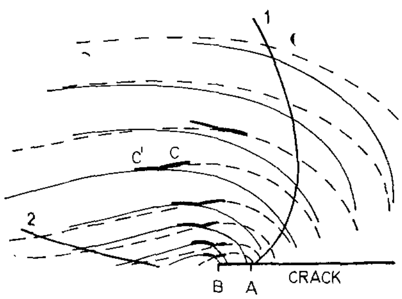


Figure 4 The minor principal stress trajectories of fig. 1c as fitted to the craze distribution of fig. 3b. The trajectories indicated by broken and continuous lines correspond to crack tip positions A and B of fig. 3b respectively (× 12).

The maximum principal stress contours which correspond most closely to the extent of the craze pattern in fig. 3b are indicated by bold lines in fig. 4. Contour 1 is the maximum principal stress contour for ψ in the range 90 to 180° and is associated with crack position A. Contour 2 is the maximum principal stress contour for small values of ψ and is associated with crack position B. Contour 1 is a very good description of the extent of the craze pattern. However, contour 2 does not correspond to the extent of the craze pattern and the main reason for this discrepancy is probably as follows. The criterion (*c*) would indicate an expected reduction in craze volume in regions where $\sigma_1 \simeq \sigma_2$. These regions are defined by small values of ψ so that if the criterion (*c*) is operative the contour 2 would not be expected to describe in a definitive way the extent of the craze pattern. In fig. 3a there is a quite noticeable decrease in craze population with decreasing ψ thus confirming criterion (*c*) and possibly explaining the discrepancy between contour 2 and the extent of the craze pattern. The craze distribution in fig. 3a confirms the observations of Sternstein *et al* [1] in that criterion (*a*), and to a lesser extent criteria (*b*) and (*c*), are operative in determining craze distributions in the vicinity of a stress bias.

It is also worth noting that some general features of the craze distribution in fig. 3a are consistent with previous observations reviewed by Andrews [6]. In regions of high stress the craze population is generally greater than the population in the low stress regions. The craze lengths tend to increase with decreasing stress level. A qualification of both of these properties is that for any particular major principal stress contour the craze population and craze length will tend to increase and decrease respectively with increasing difference in the major and minor principal stresses along the contour.

Acknowledgement

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