INTERACTION OF A GROWING CRACK WITH THE BOUNDARY IN A BICRYSTAL

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UDC 539.375

Dynamic photoelasticity has been used in conjunction with selective etching on lithium fluoride bicrystals to examine the interaction of a growing crack with inclined boundaries; it is found that the stresses at the head of the crack alter as the boundary is approached. The speed of the crack is related to the angle of incidence on the boundary and the angular disorientation of the latter. The change in crack speed is related to the change in state of stress at the vertex. Analytical and experimental distributions are presented for the stresses ahead of a growing crack.

It is known that the structure of a material has a certain effect on the growth of slow cracks [1-5].

A study has been made [6] of growing cracks breaking through boundaries in crystals; the change in growth kinetics for fast cracks was ascribed to the effects of the material structure. This result is only hypothetical in the absence of recordings of the load wave form and the change in the state of stress at the vertex of the crack.

We have examined the interaction of a growing crack with an inclined boundary in lithium fluoride bicrystals with disorientation angles from 1 to 25°; the measurements were made by dynamic photoelasticity on specimens $5\times40\times60$ mm, with dynamic breakage by a knife, a small explosion being initiated at the upper edge of the knife. The pulse duration was about 20 μsec. We recorded the progress of the crack with an SFR-1M camera (2.5 million frames/sec), using circularly polarized light.

To determine the effects of the boundary on the stress distribution at the vertex of the growing crack, we examined the state of stress near that point before approach to the boundary and from passage through it; we recorded frames for the crack growth for single crystals and bicrystals. Figure 1a shows the crack growth in dynamic loading for a single crystal. To transfer from the interference effects seen on the frames to the τ_{max}, one can use the results of [7] on the assumption of a quasistatic state of stress at the mouth of the growing crack. Then we have as follows for an anisotropically loaded body:

$$\delta = d_0 (B_1 - B_2)(\bar{\sigma}_x - \bar{\sigma}_y) \tag{1}$$

Here δ is the wave path difference set up in the specimen, d_0 is specimen thickness, and $\bar{\sigma}_x$ and $\bar{\sigma}_y$ are the normal stresses averaged over the thickness of the specimen, which are applied to areas perpendicular to the principal axes of the optical ellipsoid:

$$B_1 - B_2 = \frac{\varkappa (C_{11} - C_{12}) C_{44}}{\sqrt{C_{44}^2 \cos^2 2\beta + (C_{11} - C_{12})^2 \sin 2\beta}}$$

where c_{11}, c_{12}, c_{44} are optical constants, β is the angle between the principal axis of the ellipsoid and the [100] direction, and $\varkappa$ is a constant of the material for LiF.

The values of the optical constants have been published [7]; the theory of elasticity gives

Novokuznetsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 138-143, July-August, 1973. Original article submitted October 24, 1972.

$$\bar{\sigma}_x - \bar{\sigma}_y = (\sigma_1 - \sigma_2)\cos 2\alpha \tag{2}$$

where σ_1 and σ_2 are the principal normal stresses, and α is the angle between the principal axes of the optical ellipsoid and the stress ellipsoid.

From (1) and (2) we have

$$\tau_{max} = \frac{\sigma_1 - \sigma_2}{2} = \frac{\delta}{2d_0(B_1 - B_2)\cos 2\alpha} \tag{3}$$

In these experiments, the fringe fraction obtained did not exceed 0.5, so we used

$$\delta = \frac{\lambda}{\pi}\arcsin\sqrt{\frac{I - I_0}{I_{max}}} \tag{4}$$

where λ is the wavelength (5500 Å), I is the intensity transmitted by the analyzer, I_0 is the intensity with the polaroids crossed, and I_{max} is the intensity with the polaroids parallel minus I_0. It can be shown that

$$\cos 2\alpha = \frac{C_{11}\cos^2 2\beta + (C_{11} - C_{12})\sin^2 2\beta}{C_{11}^2\cos^2 2\beta + (C_{11} - C_{12})^2\sin^2 2\beta} \tag{5}$$

From (3) and (4) we find that I and β need to be known in order to determine τ_{max}; all the other quantities are either constants (d_0 and λ) or else are related to β (α, $B_1 - B_2$). The intensity was estimated from the density of the film as measured with an MF-2 microphotometer.

One determines β from the distribution of the isoclines; for this purpose, we set up five polarizing systems in the recorded region on the path of the crack: one circular one and four planar ones. The planar polaroscopes were set to record simultaneously isoclines with parameters of 0, 22.5, 45, and 60°. The τ_{max} were calculated from (3) and (4), which gave the following stress distribution at the vertex of a fast crack (Fig. 2). This shows that the largest maximal tangential stresses τ_{max} act in four planes passing through the vertex of the crack; these form a characteristic array.

Similar stress arrays at the vertices of stationary cracks have been described previously [8], but there they had a strictly symmetrical form of a regular cross turned at 45° in the direction of the crack. A certain asymmetry is seen in dynamic loading (Fig. 2), which is undoubtedly due to the dynamic character of the process.

The observed stress distribution ahead of the growing crack was compared with that calculated by the method of [9], the calculation being for velocities corresponding to those found by experiment. The following is a comparison of the analytical and experimental results:

r, mm	0.35	0.5	1	1.5	2	3	4	5	6
τ_{max}, kg/cm² experimental	50	40	31	28.5	26.2	24.8	24.5	23.5	20
τ_{max}, kg/cm² calculated	46	37.6	28.9	26.5	24.8	23.2	24.5	23.5	20

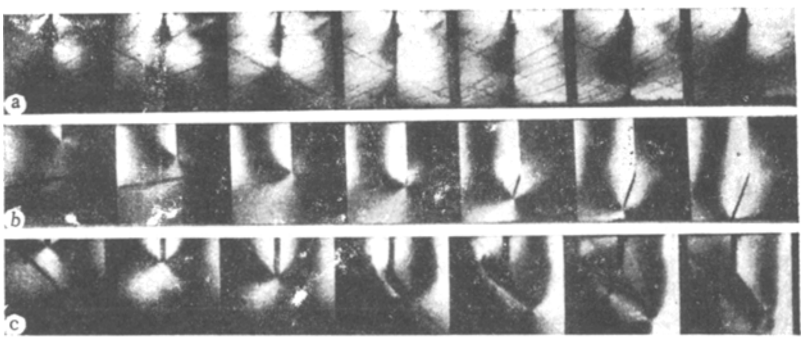

Fig. 1

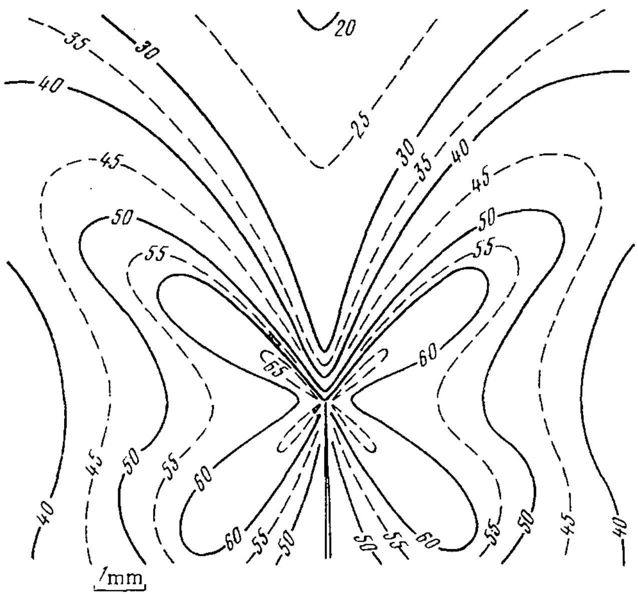

Fig. 2

This shows that there is good agreement for $r \geq 4$ mm from the vertex of the crack, although at lesser distances there is a discrepancy, which may be assigned either to errors in the experimental processing or to inaccurate description of the phenomena. Then one can describe quasibrittle failure to a first approximation via the basic concepts of the theory of elasticity.

Figure 1 shows characteristic patterns for cracks and crystals; it is clear that a crack propagating into a single crystal (Fig. 1a) produces a characteristic distribution at the vertex indicating stress concentration; there is no change in the intensity when a crack moves within the limits of a frame, so there is no change in the stress pattern at the vertex at least over a distance of 15 mm (size of the field photograph). When a crack propagates in a bicrystal with an inclined boundary (Fig. 1b), the transmission at the vertex is as for a single crystal (Fig. 1a) so the stress distribution is similar to that in Fig. 2; however, the intensity falls on passage through the boundary, and the effect is substantially dependent on the mutual orientation of the grains in the bicrystal, i.e., the disorientation angle θ and the angle of incidence φ on the boundary (φ is the angle between the crack and the normal to the boundary). When a crack passes through a boundary with $\theta \leq 4°$, there is practically no change in the intensity, no matter what φ may be. The reduction in the stress at the vertex on passage through a boundary in a bicrystal increases with θ for $\theta > 4°$ and also with φ.

These results on the birefringence are confirmed by an analysis of the crack speeds; the crack growth speed in dynamic loading is dependent on the load at the vertex, so the crack speed can be used to judge the stress.

To determine the crack speeds we measured the lengths of the growing cracks frame by frame; to obtain improved accuracy, we took into account some displacement of the field of view from one frame to another, which occurs to some extent in the SFR-1M. We calculated the mean velocities before and after transition through a boundary, which gave the relative velocity change

$$\Delta v/v = (v_0 - v')/v_0$$

where v_0 is the mean velocity before passage through the boundary and v' is the same afterwards.

The following are the relative velocity changes for bicrystals with various values of θ:

$\theta°$	4	6	8	11	15	19	22	24	25
$\Delta v/v_0$	0.22	0.235	0.24	0.26	0.295	0.342	0.42	0.48	0.538

It is clear that the velocity change increases with θ; this agrees well with observations on the intensity in the frames (Fig. 1), which indicates stress reduction at the vertex on passage through the boundary.

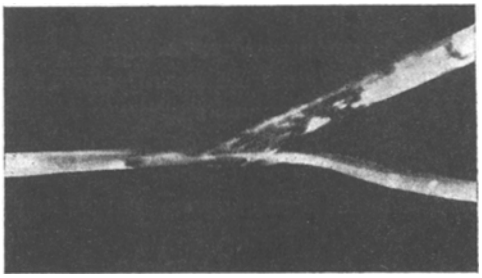

Fig. 3

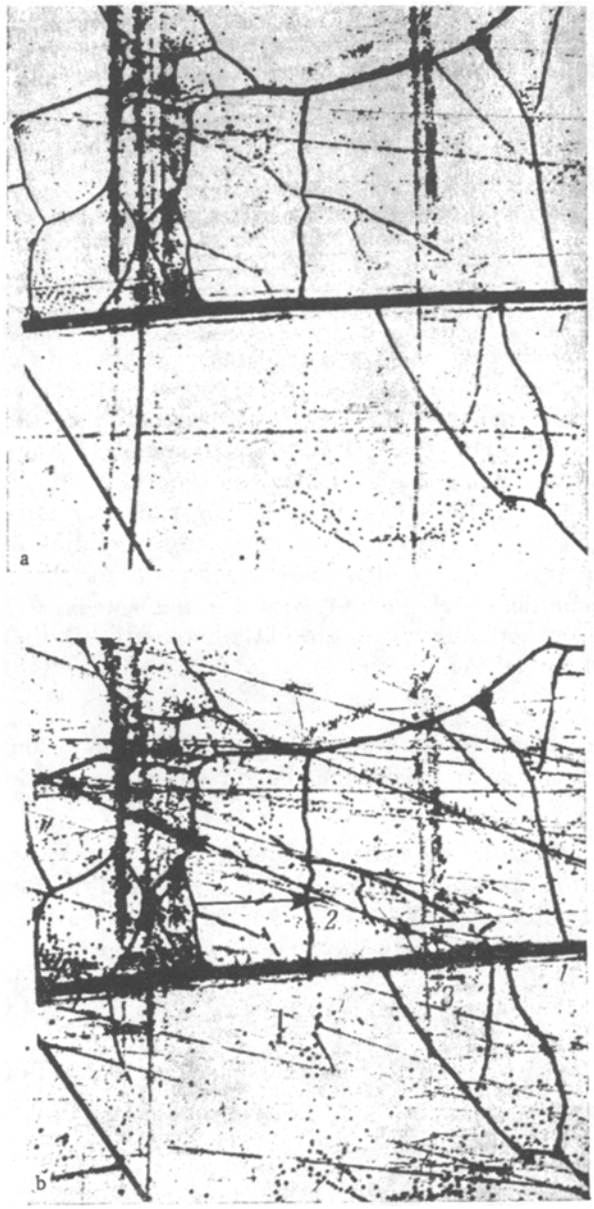

Fig. 4

The following is the relative velocity change on passage through a boundary as a function of angle of incidence:

Degree	19	15	18	25	30	35	40	43
$\Delta v\ (\theta = 4°)$	0.246	0.246	0.246	0.246	0.246	0.246	0.246	0.246
$v_0\ (\theta = 24°30')$	0.252	0.42	0.53	0.62	0.72	0.82	0.92	1

It is clear that at high φ there is a considerable change in the velocity when θ is large, but hardly any change for $\theta \leq 4°$; when the angle of incidence is large, the crack may stop completely at the boundary and produce a separation within the plane of the boundary itself. Figure 1c shows frames for this case, while Fig. 3 gives the external appearance of the crystal at the point where the crack passes into the plane of the boundary. In essence, in this case we get a transition from the transcrystallite type.

It has been stated [6, 8] that plastic stress relaxation occurs when a crack is slowed up at any form of barrier; in our case, we estimated the plastic deformation at the boundary from the change in the dislocation structure.

Figure 4 shows patterns built up from photomicrographs of the surface, which illustrate the change in dislocation structure when a crack is retarded at a boundary in a bicrystal (1 is the boundary, 2 is the trace of the crack, and 3 are the bands from slip in the second crystallite arising on deceleration of the crack). The etch figures show a certain increase in the dislocation density in the region where the crack is slowed at the boundary. The increase in dislocation density is due to a plastic deformation on account of local increase in stress where the crack halts. If the crack encounters an obstacle, one finds at the sides an increase in the depth of the zone of plastic deformation, which is revealed by the dislocation structure. An interesting feature is that slip bands disposed in the [100] cleavage plane are produced in the adjacent crystallite when a crack halts at the boundary. Repeated loading in this direction causes the crack to develop. These slip bands are the result of microplastic deformation preceding failure.

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