# SPONTANEOUS PROPAGATION OF CRACKS IN LITHIUM FLUORIDE SINGLE CRYSTALS

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One of the main problems arising in the investigation of fracture is the problem of interaction between the processes of fracture and plastic deformation. In recent years a number of papers have been published on the interaction between cracks and dislocations. In [1] Gilman showed that a crack, growing slowly in a lithium fluoride single crystal, produces dislocation loops near its tip. In [2] the relationship between this phenomenon and the spontaneous propagation of a crack in lithium fluoride was demonstrated. The same phenomenon was observed in alkali-halide crystals by M. P. Shaskol'skaya, Wang Yang Wen and Ku Shu-chao [3], and in bismuth single crystals by Kosevich [4] and Finkel, Kutkin, Savel'ev, Zraichenko, Zuev, and Kositsina [5]. The authors of [2] attribute this effect to the generation of self-oscillations in the wedge–cracked body system. On the basis of this explanation, the authors of [6, 7] developed a theory of self-oscillations in the splitting of brittle bodies, which, in certain conditions, makes possible an experimental determination of the ratio of specific surface energies of fracture for a stationary and a moving crack. Below we give some results of experiments carried out on these lines.

## DESCRIPTION OF EXPERIMENT

Lithium fluoride crystals were used as specimens. Their mechanical properties were determined in compression at room temperature. These compression tests were performed on a Dubov–Regel machine [8] in the (100) crystallographic direction at a speed of $0.4 \times 10^{-5}$ sec$^{-1}$.

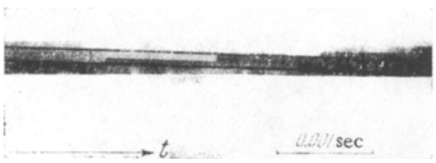


Fig. 1

The yield point was 340 g/mm$^2$, the strain at which the formation of visible cracks started was approximately 2%. During an attempt to deform the crystals at a speed of about $10^{-3}$ sec$^{-1}$ almost immediate cracking was observed.

The rectangular parallelepiped specimens (4 × 4 mm$^2$ base, length about 50 mm) were made by splitting the material along the cleavage planes. The initial crack was produced by a slight knock with a chisel with its sharp edge directed along the center line of the base; the length of this crack was usually 15–20 mm. The cracked specimens were heated together with the furnace to 800° C, held at this temperature for 5 hr and subsequently cooled, again with the furnace. After annealing no double refraction was observed when the specimens were examined under a polarization microscope with crossed nicols. The dislocation density in annealed crystals remained approximately $3 \times 10^4$ cm$^{-2}$ (not counting the dislocations in block boundaries). The dislocations were exposed by selective etching ($10^{-4}$ molar solution of ferric chloride in water [9]).

The specimens were split with a wedge of uniform thickness moving at constant speed. This was made from a 0.1-mm thick razor blade. The cleavage rates, i.e., the velocity of the wedge with respect to the specimen, were 0.007, 0.07, 0.7, 20, 40, 490, and 960 mm/sec.

The speed of propagation of the crack was measured by means of PSK-24 and SKS-1M motion-picture cameras as a function of the cleavage rate. The image of the crack was projected on the film by means of an optical system capable of magnifying or reducing the image several times. The wedge was stationary with respect to the camera, while the specimen moved. This arrangement made the finding of the crack in the field of view of the camera easier. The speed with which the motion-pictures were taken varied from 1 to 4000 frames per second according to the cleavage rate. In some cases the SKS-1M camera was used with a remote compensation prism for photorecording by the method described in [10]. In this manner it became possible to improve the time resolution, which then reached 10 μsec. In this method of filming, the crack image was continuously projected on moving film (without optical compensation of the image shift) with the crack and the film moving in mutually perpendicular directions. As a result the film showed the time dependence of the crack tip coordinate (Fig. 1).

After splitting, one of the halves of the specimen was broken, by a hard blow with the chisel, into two halves along a plane parallel to the long side of the specimen and normal to the plane of previous splitting. After exposure of the dislocations on the quarter of the specimen thus obtained, their distribution was investigated under a metallographic microscope on the cleavage plane and on the plane normal to it. A total of about 100 specimens was investigated.

## EXPERIMENTAL RESULTS AND DISCUSSION

Investigation revealed that the propagation of the crack tip was discontinuous. For a certain time the crack tip remained stationary and then suddenly moved to a different position.

Let us consider the existing explanation for the discontinuous motion of the crack [2, 6, 7]. According to the theory of quasibrittle fracture, the following relation applies to the splitting off of a thin strip of width b from a uniform isotropic elastic material with Young's modulus E by means of a rigid wedge of thickness h:

$$l_0^4 = \frac{3Eh^2b^3}{64T(0)}. \qquad (1)$$

Here, $l_0$ is the length of the stationary equilibrium crack in front of the wedge, and T(0) is the density of surface energy of fracture for the stationary crack. From the assumption that T(0) is a decreasing function of the crack tip speed, we arrive, ignoring the property of inertia of the material of the strip, at the conclusion that after starting to move the crack tip instantaneously reaches another position such that

$$(l_0 + \Delta l)^4 = \frac{3Eh^2b^3}{64T(v_*)},$$

where $\Delta l$ is the length of the jump, and $T(v_*)$ is the density of surface energy of fracture for a crack moving at speed $v_*$, $v_*$ being the speed at which the density of surface energy of fracture is a minimum. Thereupon the crack tip remains stationary until the wedge again approaches to a distance $l_0$. Hence

$$\frac{T(0)}{T(v_*)} = \left(1 + \frac{\Delta l}{l_0}\right)^4. \qquad (2)$$

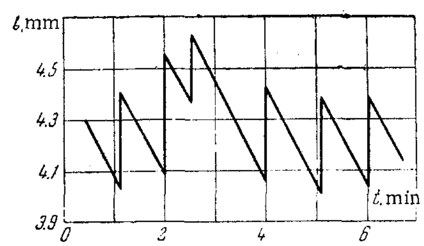


Fig. 2

A direct conclusion to be drawn from this explanation is that the average speed of the crack is equal to that of the wedge; the curve representing the dependence of the crack length on time must be a periodic curve consisting of a succession of triangular pulses, the front of each pulse being a vertical straight line.

Roughly speaking, this behavior of the crack was observed at splitting rates of 0.007, 0.07, and 0.7 mm/sec. Figures 2 and 3 show the dependence of the crack length on time, for specimens split at 0.007 and 0.7 mm/sec, respectively. Figures 4 and 5 give the corresponding photomicrographs of the plane (×70) normal to the cleavage plane for these specimens. The photographs show the development of slip bands from the points where the crack stopped; in the first case the slip extended to a region extending over a distance between individual jumps; consequently, after the crack has passed through the entire specimen, the specimen remains plastically deformed. In the second case the plastic deformation remains localized in two slip planes. At a splitting rate of 0.07 mm/sec the slip distribution is intermediate between these two cases.

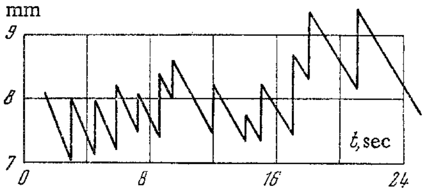


Fig. 3

Thus, the motion of the wedge causes plastic deformation of the specimen. If at time t the length of the crack in front of the wedge is $l$, then the deformation of the material on one side of the crack, in the section between the wedge and the crack tip, is $h/2l$ (h is the wedge thickness). At time $t_1$ the deformation is $h/2l_1$, where $l_1$ is the length of the crack at time $t_1$. The average rate of strain at time $t_1 - t$ is

$$\frac{h}{2}\left(\frac{1}{l_1}-\frac{1}{l}\right)\frac{1}{t_1-t},$$

and as $t_1 \to t$ this expression changes to

$$\frac{h}{2}\frac{d}{dt}\left(\frac{1}{l}\right)=\frac{h}{2}\left(-\frac{1}{l^2}\right)\frac{dl}{dt}=\frac{h}{2}\left(-\frac{1}{l^2}\right)V, \qquad (3)$$

where V is the splitting rate. The substitution of h = 0.1 mm, V = = 0.007 mm/sec, $l$ = 4 mm into (3) gives a strain rate of $2.2 \times 10^{-5}$ $sec^{-1}$. At a splitting rate of 0.7 mm/sec the strain rate is of the order of $10^{-3}$ $sec^{-1}$. Thus, at a strain rate of about $10^{-5}$ $sec^{-1}$ the slip bands widen until strain hardening stops the process. This occurs at a strain of the order of $h = 2\,l_0 = 1.25\%$. An increase of the strain rate to $10^{-3}$ $sec^{-1}$ excludes this process, and the crack begins to spread before the slip bands have time to widen appreciably. The rates of strain are of the same order of magnitude as during the compression test. Consequently, the process of widening of the slip band (multiple cross slip [11]) has its own typical, quite considerable duration. Nothing more definite can be said about it on the basis of experimental data, since the shear stress acting in the slip band is not known.

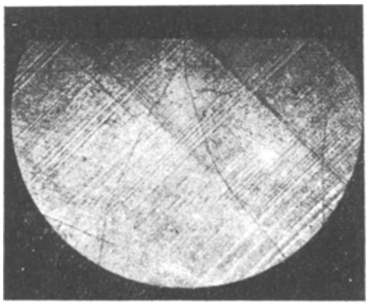

Fig. 4

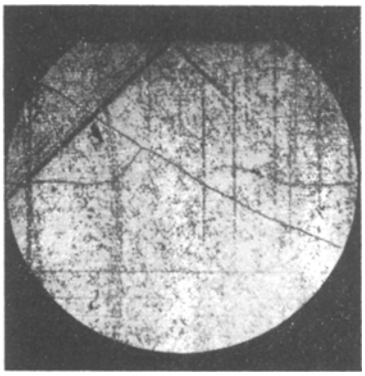

Fig. 5

Well-developed plastic flow precludes the use of Eq. (1) for determining T(0), since the plastic strain affects not only the stress in the region of the tip but also reduces the cleavage force with which the wedge acts on the specimen [12] because the displacement of the crack sides caused by the wedge are not purely elastic. For this reason h in Eq. (1) is unknown. However, in (2) h is eliminated; using this ratio we can find the ratio of specific surface energies of fracture for the stationary and moving cracks $T(0)/T(v_*)$. We give below the average values for $\Delta l$ at all the splitting rates V used, together with the average values of the crack lengths in front of the wedge $l_0$, and values of the ratio of surface energy densities for the stationary and the moving crack $T(0)/T(v_*)$ for some splitting rates.

| $V$ | 0.007 | 0.07 | 0.7 | 20 | 40 | 490 | 960 mm/sec |
|---|---|---|---|---|---|---|---|
| $\Delta l$ | 0.5 | 1.0 | 1.8 | 2.4 | 2.8 | 3.9 | 4.1 mm |
| $l_0$ | 4.3 | 6.0 | 8.0 | — | — | — | — mm |
| $T(0)/T(v_*)$ | 1.5 | 1.8 | 2.2 | — | — | — | — |

Thus, in lithium fluoride the density of surface energy of fracture in the presence of plastic strain is of the same order of magnitude as in the absence of plastic strain (i.e., during the jump). It should be noted that according to the literature data the values for metals differ by three orders [13].

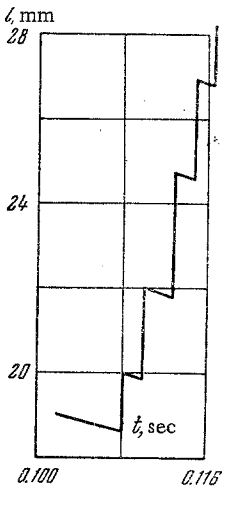


Fig. 6

Beginning at a splitting rate of 20 mm/sec the dependence of the crack length on time (Fig. 6) becomes incompatible with the theory of quasibrittle fracture. The crack grows in jumps and its average speed is not equal to the wedge speed but exceeds it several times (from three to fifteen times on different specimens). This can be seen from Fig. 1, remembering that the wedge is stationary with respect to the motion-picture camera. The photomicrograph (×4) of the cleavage plane of one of the specimens is given in Fig. 7 (splitting rate 40 mm/sec). A feature of splitting at high speeds is "second-order jumps," which can be observed under a microscope. The experimental technique used did not permit the reliable interpretation of these "jumps"; however, in some cases the film suggests that the "first-order jumps," i.e., the jumps considered above, decay in the course of time into "second-order jumps." The dislocation loops corresponding to "second-order jumps" are located near the surface and, in contrast to first-order jumps, do not form slip bands. The use of the photorecording method made possible the measurement of jump speed. It was found to be 35–80 m/sec for different jumps, which is in good agreement with the result obtained in [2] where a speed of 60 m/sec was measured for crack propagation with formation of a similar microstructure. The error in determining the speed was ±8 m/sec.

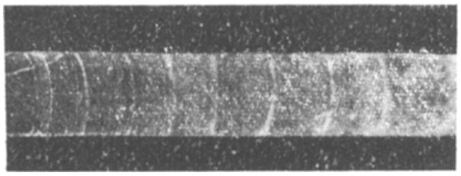

Fig. 7

The described "breakaway" of the crack from the wedge definitely suggests that the explanation of discontinuous crack propagation given in [2] on the basis of the theory of quasibrittle fracture is inadequate in the present case. It is possible that this behavior can be explained after a detailed examination of the structure of the tip zone, i.e., examination of the behavior of the crack in the stress field of the dislocations it produces. Given such an approach the source of the force moving the crack will be plastic flow in the crack tip caused by the wedge, rather than the wedge itself. The structure of the tip zone of the crack is of no significance when the stress field produced by the cohesion forces practically vanishes at distances much smaller than any of the characteristic dimensions of the problem. In this case the cohesion forces are characterized by an integral quantity, the surface energy [14]. This is the case when the cohesion forces are molecular in nature and rapidly decrease with increasing distance. In the presence of plastic strain this can be explained in a different way. Although the dimensions of the zone in which the plastic flow occurs are small compared with the crack length, they are still commensurable with the length of the jump. It should be pointed out that the possibility of the production of cracks by dislocations has been frequently discussed theoretically, but in relation to other types of stress states [13].

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