EXPERIMENTAL INVESTIGATION OF THE DYNAMICS OF GROWTH OF BRITTLE FRACTURES

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In investigating dynamic processes which give rise to fracture, a necessary part of the experiment is the measurement of the rate of growth of a crack. The best known methods of measurement are as follows: a) the method of bonding fine wires or other sensitive elements over a crack; b) the method of high-speed photography; c) the method of modulation by ultrasound of a fixed frequency; d) the method of measuring the electric potential; e) the method of measuring the electric resistance of bonded foils, conducting paper, adhesives, etc.

The methods of bonding fine wires, photography, and modulation by ultrasound are essentially discrete; and their use requires certain a priori information on the course of the process being studied. Shortening the quantization time generally leads to fewer readings. This fact and the complexity, the high cost, and the cumbersome nature of the apparatus make these methods less than ideally suited to a detailed study of such rapid and complex processes as the development of cracks. In addition, in the method of ultrasound modulation additional energy is introduced into the region at the tip of the crack, and this obviously can affect the nature of its motion.

Measurements of electric potential and electric resistance can be performed so that the change in length of the crack gives a discrete or analog electric signal. To obtain more complete information on the rate of development of a crack it is obviously desirable to obtain a signal in analog form. The disadvantage of the electric potential method is that the measurements can be performed only on conducting materials, and requiring increased sensitivity forces the use of a high current density, which leads to a change in the physical and mechanical state of the material at the tip of the crack and affects its growth in time. The method of measuring the electric resistance of bonded sensitive elements can give the desired results, but its greatest disadvantage is the uncontrollable delay of the rupture of the sensitive element relative to the tip of the crack. This stems from the fact that the sensitive material is several orders of magnitude thicker than the width of the crack at the tip, which is a few tenths of an angstrom unit.

In order to eliminate these deficiencies we used as a sensitive element an ultrathin film of an electrically conducting material evaporated in vacuum onto the surface of the sample under study. The distance from the evaporator to the surface was chosen so as to obtain a film of uniform thickness.

The thickness h of the film was measured with an interferometer and was chosen so as to satisfy the condition $h_1 < h < h_2$, where h_1 is the minimum thickness for which the evaporated layer retains the properties of a continuum (for copper, $h_1 \approx (50-100)\ 10^{-8}$ cm [1]); h_2 is the maximum thickness for which plastic deformation of the evaporated layer can be neglected. Experimental estimates showed that in our case $h_2 \approx 600 \cdot 10^{-8}$ cm. After evaporating onto the sample 1 and checking the film thickness, the film was cut in two symmetric halves (Fig. 1). One half forms the working element 4 and the other, a calibration element 3. Figure 1 shows the connections of the elements in the bridge circuit 5. During the motion of the crack the unbalance signal U(t), where U is the electric potential and t is the time, is fed into the storage oscillograph 7, which can be triggered both externally by the rupture of a special evaporated strip and internally by the signal under study. Before the experiment was started the amplitude and duration of the oscillograph sweep were calibrated by using a type G5-15 oscillator 8. A type F-4202 digital voltmeter 6 was used to obtain the calibration curve. The whole circuit was shielded against interference by the screen 2. The resistors R_k, made of the film itself, are used to correct the characteristics of the sensitive elements.

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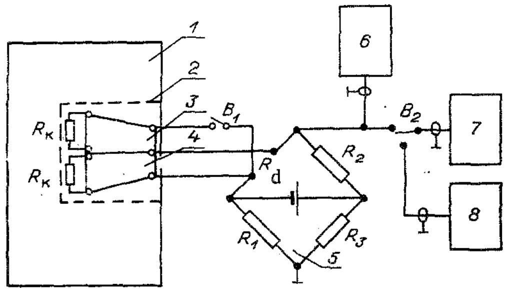

Fig. 1

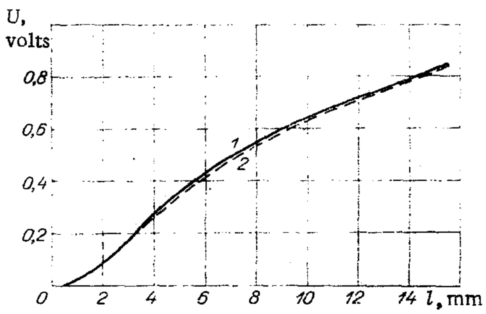

Fig. 2

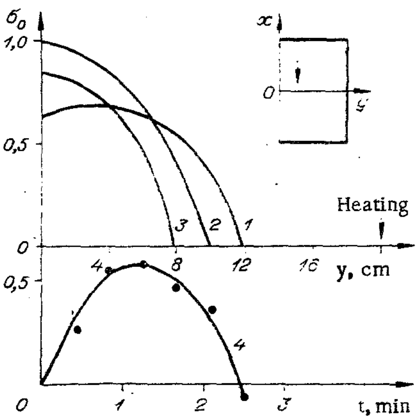

Fig. 3

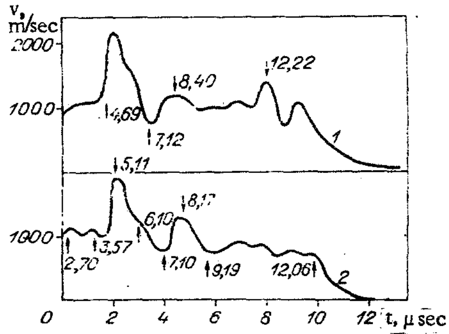

Fig. 4

The calibration curve $U(l)$, where l is the length of the crack, obtained for element 3 by cutting the evaporated layer, is used to calculate l (t) and v(t), the rate of growth of the crack. Curves 1 and 2 of Fig. 2 were obtained with the calibrating and working elements respectively. The maximum relative error is $\pm 1\%$. The advantages of the method described for measuring crack speed are its remarkable simplicity, accuracy, and the possibility of a detailed study of any stage of the fracture process by selecting the sweep time, the level of sensitivity, and the triggering level of the oscillograph.

The samples used in the investigation were $14 \times 9 \times 0.14$ cm glass plates. A notch 0.15 cm deep with a radius of curvature of 0.01 cm at the tip was made in the center of one edge. The plate was stressed thermally by heating a spot 0.15 cm in diameter from both sides by heating elements placed 0.05 cm from the surfaces. The temperature of the glass in the region of the heating elements was 50°C. As a result of thermal stresses and their concentration at the tip of the notch a rectilinear macroscopic crack grew from the notch to the heated area where it stopped. It required about 3 min of heating to obtain a shock. By varying the position of the heating elements the crack lengths could be varied by an order of magnitude. The sample as a whole obviously does not experience any rotations or displacements in this method of stressing. A characteristic feature of the method is the complex character of the thermoelastic stress field. Curves 1, 2, and 3 of Fig. 3 show the stress $\sigma_0 = \sigma_* / \sigma_{*\max}$ normal to the axis of the crack at times t=1, 2, and 3 min, respectively. The stresses were calculated by equations given in [2] which take account of the effect of the edge of the plate in introducing a fictitious heat source of the same strength located symmetrically with respect to the edge. Curve 4 of Fig. 3 shows the time dependence of σ_0 measured at a distance of 8 mm from the edge. The stresses were determined with KTD-1 silicon strain gages with a 2.5 mm base. The effect of heating the gages on the magnitude of the signal was taken into account in the measurement.

Using the procedure described, we performed more than 10 measurements of the crack speed v. Typical graphs of v(t) are shown in Fig. 4. Here time is counted from the beginning of the sweep of the beam. The value of the quantization time $\tau = 0.5$ μsec taken in the processing of the experimental analog curve is not the limit. For a more detailed investigation of the process τ can be decreased. In addition, analog methods of processing the signal can be used. Our measured values of crack speed differ somewhat from traditional values (e.g., [3, 4]) primarily in the very pronounced stepwise nature of its growth. Figure 4 shows that a change in crack speed by a factor of two occurs in less than 0.5 μsec. The maximum value of the speed observed in all the experiments is $0.4c_1$, where c_1 is the speed of longitudinal vibrations. For our test material $c_1 = 5.1$ mm/μsec. Experimental proofs of the pulsation of crack speed have appeared in the literature [5, 6] based on a comparison of adjacent frames of motion-picture film.

The causes of the stepwise crack growth in our experiments remain unexplained. A simple calculation eliminated the effect of waves reflected from the side faces of the plate parallel to the line of fracture. The most realistic causes may be the following: a) the nonuniformity of the static field of thermoelastic stresses preceding the beginning of the growth of a crack and its dynamic rearrangement; b) a dependence of the fracture energy γ_{eff} on the crack speed of the form shown, for example, in [7].

It can be seen from Fig. 4 that the absolute maximum speed (points 4.69 and 5.11, where the numbers indicate the crack length in mm from the tip of the notch) occurs in the region of tensile stresses. The decrease in speed is related to the transition of the tip into the region of compressive stresses (curve 3 of Fig. 3). Calculations show that the further increase in speed (points 7.12 and 7.10) is related to the arrival of the Rayleigh wave c_R from the corner of the plate. The value of c_R was taken as $0.55c_1$. The 1.5 mm depth of the initial notch was taken into account in the calculations. Further crack growth occurs in a region of compressive stresses with insignificant fluctuations of speed which in the final stage is 50–100 m/sec. In this case the growth mechanism may be thermal fluctuation processes occurring at the tip.

Fractograms of the fracture surface were studied to check qualitatively on the quasistable crack growth and speed measurements. The fractography was done in two ways: by a direct study of the surface through an MIM-7 optical microscope using a magnification of 100, and with an LG-75 He–Ne laser beam reflected from the surface of the crack onto a screen. The first method was used to study the initial phase of quasistable crack growth, and the second to find the characteristic domains and points during the dynamic part of the motion up to the end. This procedure is based on the dependence of the curvature of the fracture surface on the crack speed, with the curvature varying both in the direction of crack growth and over the thickness of the plate. Figure 5 is a schematic diagram of the experiment. The laser beam 1 passes through the cylindrical lens 2 and falls on the fracture surface 6 of half the sample 3. The reflected beam falls on the screen 4. Using a micrometer gauge a screen with a rectangular slit 5 of width 0.5 mm is moved along the surface. In this way a rectangular portion on the surface of the crack cut out by the slit is reflected into a certain line determined by the curvature of this part.

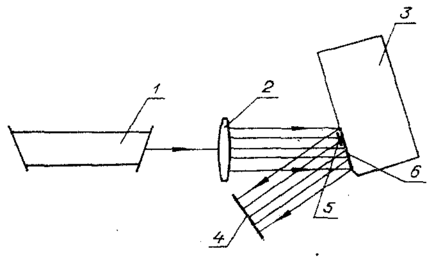

Fig. 5

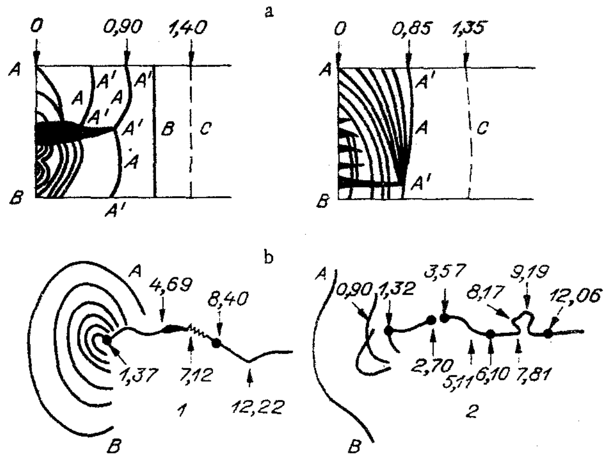

Fig. 6

Figure 6a shows fractograms made with the MIM-7 optical microscope. The figure represents a stage of subcritical growth of a crack. It is clear that growth begins from initial defects of the medium (dark regions) which can be produced, for example, in cutting the glass. The advance of the crack front (curve A) is restrained by the points of attachment A' on the free surface. This may be produced by the plastic deformation of surface layers of the material. After the crack front is rectified its motion occurs in individual noticeable jumps, lines B and C, where line C is less distinct than the others. Observations with a microscope at a large distance from the notch did not help to show any other characteristic features of the fracture surface indicating the beginning of the dynamic growth of a crack.

The results of the fractography obtained by the second method by using a laser are shown in Fig. 6b. Here curves 1 and 2 corresponding to curves 1 and 2 of Fig. 4 are images on a screen of a light beam from the fracture surface. The numbers denote the distance in millimeters of the line cut by the slit 5 (Fig. 5) on the surface from the tip of the notch. Curve AB corresponds to the leading edge of this surface. The narrowing of the reflected light beam is related to the decrease in curvature of the surface and the transition from "viscous" to "brittle" fracture (points 1.37 and 1.32). These data agree with observations under a microscope (lines C whose distances from the tip of the notch are 1.40 and 1.35 mm).

On the fractogram corresponding to the dynamic motion of the crack there are portions of increased brightness of the light pattern (marked by points on curves 1 and 2 of Fig. 6), parts of disruption of the beam, and parts of bending its trajectory. The first is related to the change in curvature of the surface in the direction of motion of the crack in such a way that there is focussing of the beam to a point – a break in the form of a plane lune. In the second case a pattern opposite to the first is observed. The curvature of the trajectory of the light beam is related to the rotation of the vector normal to the surface in a plane perpendicular to the crack velocity. On curves 1 and 2 of Fig. 4 the characteristic points on the fractogram are indicated by arrows. Here it is clear that the results of the fractography qualitatively reflect the characteristics of crack growth measured by the method described above.

Thus, the investigation performed can be considered proof of the possibility of pulsations of the rate of crack growth. The method of stressing the samples and measuring the speed can be used in future experimental studies of processes related to the brittle fracture of materials.

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INTERACTION BETWEEN CRACKS POSITIONED AT AN ANGLE

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The interaction between cracks in an elastic plane weakened by a system of cracks has, as a rule, been investigated in the case of collinear cracks only. More complex configurations were analyzed in [1, 2], in the first of which four slits placed symmetrically about their common center were studied by using Fourier transforms; in the other, a periodic system of lengthwise–crosswise cracks was studied. In [3] singular integral equations were produced for a system of arbitrarily oriented cracks; numerical results were obtained only for collinear cracks oriented at the same angle to loading direction. In the case of brittle failure the investigation of the interaction between two arbitrarily directed cracks is of interest, this being the subject of the present article.

Let there be two cuts L_1 and L_2 in the xOy plane (Fig. 1) whose parametric equations are (k = 1, 2).

$$L_k\colon x(t) = a_k t,\ y(t) = b_k t,\ 0 < t_k \leqslant t \leqslant t_{k+2}$$
$$(a_k = \cos\alpha_k,\ b_k = \sin\alpha_k).$$

The boundaries of the cuts are assumed to be stress-free, and at infinity the applied forces are

$$\sigma_x^\infty = \sigma_1,\quad \sigma_y^\infty = \sigma_2,\quad \tau_{xy}^\infty = 0. \tag{1}$$

The following representation [2] of the stress function U is employed:

$$U(x, y) = \frac{1}{2}(\sigma_1 y^2 + \sigma_2 x^2) + \sum_{k=1}^{2} \frac{1}{2\pi} \int_{t_k}^{t_{k+2}} [f_1(t) r_{1k} + f_2(t) r_{2k}] \ln(r_{1k}^2 + r_{2k}^2)\, dt, \tag{2}$$

where

$$r_{1k} = a_k x + b_k y - t;\ r_{2k} = -b_k x + a_k y.$$

The function (2) must satisfy the conditions (1). The conditions on the boundaries of the cracks L_k are

$$(\sigma_y + \sigma_x) + (\sigma_y - \sigma_x)\cos 2\alpha_k - 2\tau_{xy}\sin 2\alpha_k = 0,$$
$$(\sigma_y - \sigma_x)\sin 2\alpha_k + 2\tau_{xy}\cos 2\alpha_k = 0,$$

where

$$\sigma_x = \partial^2 U/\partial y^2;\ \sigma_y = \partial^2 U/\partial x^2;\ \tau_{xy} = -\partial^2 U/\partial x \partial y,$$

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