INTERACTION BETWEEN STRESS WAVES AND A GROWING CRACK

I. S. Guz'

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An experimental investigation is made of interaction between longitudinal and Rayleigh waves and a growing crack. It is shown that stress waves can be used effectively to change the direction of a growing crack and to slow it down. The change in the trajectory of the growth of the crack is due to changes in the state of stress at its apex. The angle of deviation of the crack depends on the angle of attack of the wave and on the state of stress at the apex. An expression is given for determining the angle of deviation of a crack.

The problem of the diffraction of stress waves at a straight cut similar to a crack has been solved by many authors. In [1, 2], the interaction between a flat shock wave and a cut, whose edges are either free or attached, was considered. Another solution to this problem is given in [3], where the sought displacements are expressed in terms of the values of some function $F_1(\theta)$, which is easily tabulated.

The authors of [4] investigated the effect of a transverse wave on a stationary crack. The diffraction of Rayleigh waves at a crack was experimentally determined in [5, 6]. It was shown that longitudinal and surface waves can stimulate the development of a crack; the trajectory of its growth is determined by the stressed state arising in the neighborhood of its apex. The fact of a change in the trajectory of the motion with the action of shock waves has been known for a long time [7, 8]. This has been applied successfully to determine the rate of development of a crack, but the equation of the trajectories itself was not discussed, although in [8] an analytical expression is given for determining the angle of deviation with shock compression and elongation. It will be shown below that the expression given is not confirmed experimentally.

Starting from the assumption that the dominating factor determining the trajectory and rate of growth of a crack is the stressed state at its apex, and that it can be effectively changed using stress waves, investigations were carried out to determine the possibility of controlling the trajectories of the motion of a crack using stress waves. A polarization-optical method was used in conjection with high-speed moving-picture photography.

The experiments were made on samples of Plexiglas in the form of plates measuring $350 \times 250 \times 10$ mm^3. Two types were prepared: one for studying the interaction between a crack and longitudinal waves (Fig. 1a), the second for interaction with Rayleigh waves (in Fig. 1b, the arrow shows the point of application of a dynamic load). The differences in the form of the samples are due to the special characteristics of the excitation and propagation of Rayleigh waves. To give a crack with a determined trajectory of the motion, notches were made in the middle of the samples to a depth of 50 mm and, to impart a maximal rate to the crack, the samples were extended using a special device. The start of a crack was initiated by the explosion of a microcharge, placed in the notch. With the propagation of a crack to a depth of 30-50 mm, where it enters into the region under investigation, longi-

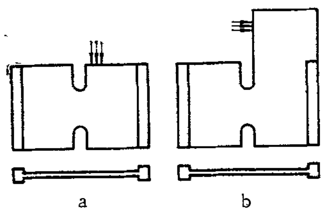

Fig. 1

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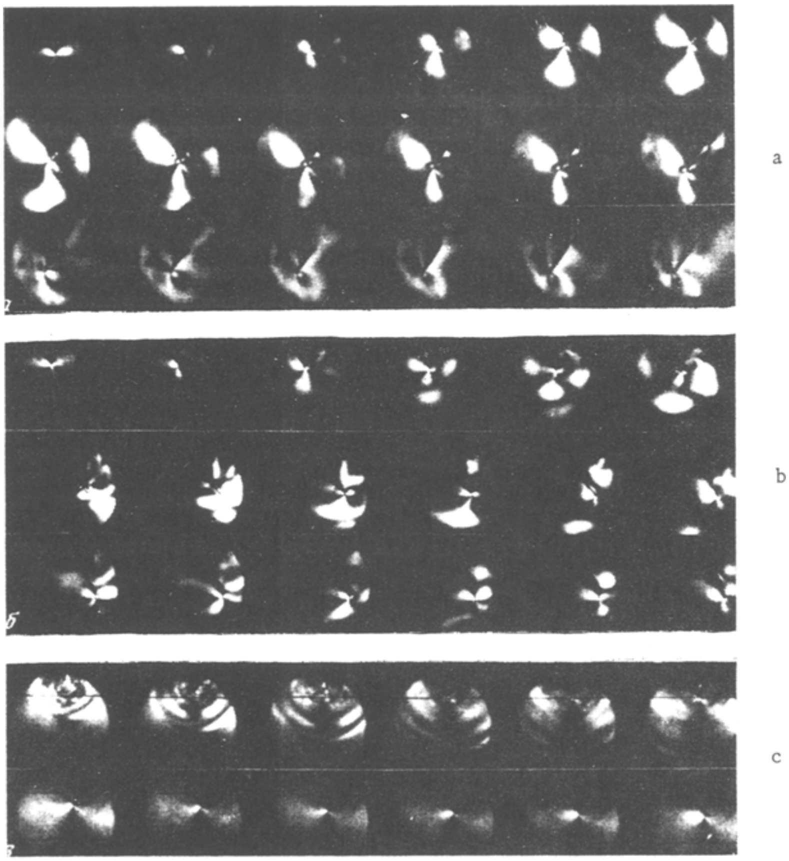

Fig. 2

tudinal or Rayleigh waves are excited at its edges. The longitudinal waves were excited by a method described in [5] and were transmitted along one of the sides of the crack.

The Rayleigh waves were produced by a concentrated explosion at the prolongation of one of the sides of the crack [6]. The distance from the point of the explosion to the apex of the growing crack was 150-170 mm. The moving-picture photography was done at a rate of 480, 000 frames/sec. Since the velocity of the crack did not remain constant from experiment to experiment, this was found to be one of the most complicated problems in the present investigation. This difficulty was overcome in the following manner: the samples were prepared with identical parameters of the notches, and were loaded up to an identical value of the stress concentration at the notch. A pulsed light source was switched on simultaneously with the start of the crack, while the stress waves were excited after 100 μsec. The moment of the photography was selected experimentally.

Moving-picture photos of the interaction of longitudinal and Rayleigh pulses with a growing crack are shown, respectively, in Fig. 2a, b, and the distribution of the stresses at its apex in the absence of interaction with stress waves, in Fig. 2c. An analysis of the photos shows that at the initial moment of the breaking of the continuity the velocity of the crack changes jumpwise from 0 to 300-400 m/sec in the course of 1-2 μsec, i.e., the acceleration of the crack is 2×10^8 m/sec^2. The rate of the fracture is then stabilized and amounts to 350-370 m/sec. The trajectory of the crack is rectilinear and lies in the plane of the most dangerous cross section. In the absence of the action of stress waves on the growing crack, a symmetrical stress field is formed at its apex.

Investigations of the zone of the microexplosion shows that the loaded region is characterized by several radial microcracks, at a rather large distance apart. The main crack is the one which is directed toward the side of the most dangerous cross section. The start of a crack under the action of an explosion takes place practically without a lag (the lag time is 2-3 μsec). Such a small time can hardly be connected with plastic deformation; it is rather due to the formation of a stressed state. The growth of the crack with increasing distance from the zone of the explosion takes place under the action of elastic energy, stored in the sample and the loading device.

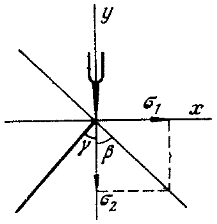

Fig. 3

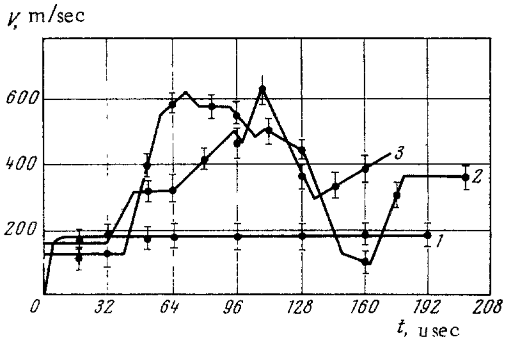

Fig. 4

Fig. 5

In the case of the action of longitudinal waves at the front of a developing crack (Fig. 2a), there is a redistribution of the stressed state at its apex; as a result of this, the gradient of the maximal tangential stresses is rotated by some angle γ with respect to the original direction. Since the velocity of elastic waves is considerably greater than the rate of growth of the crack, the process of interaction between waves and a growing crack can be regarded as the same as interaction with a stationary crack. Then, in accordance with [5], with the action of a wave at the apex of a crack, there arise dynamic elongation stresses, directed along a normal to the static stresses, as a result of which there is a redistribution of the stressed state which is visible on the moving-picture photos. Denoting by σ_1 the principal normal stresses, brought about by a static load, and by σ_2 those corresponding to a dynamic load, and assuming that the growth of the crack takes place under the action of normal elongational stresses, at an angle of 90° to the direction of their action, the angle of deviation of the crack can be expressed as $\gamma = 90° - \beta$, where β is the angle between the original direction of the growth of the crack and the direction of the equivalent normal stresses (Fig. 3).

It is shown in [5] that with a change in the entrance angle of the wave α the character of the distribution of the stresses (for small values of α) does not change, and only the value of the stresses changes. This means that a deformation directed along the crack is responsible for the formation of the stresses. With a rise in the value of α, its value decreases in accordance with a cosine law. Taking this into consideration, we can write

$$\gamma = 90° - \operatorname{arc\,tg}\frac{\sigma_1}{\sigma_2} = 90° - \operatorname{arc\,tg}\left(\frac{2\tau_{max}}{\sigma_2} - 1\right)$$

with α and σ_1 equal to zero, $\gamma \to 90°$, i.e., the value of γ depends on the entrance angle of the wave and the value of the static elongational stresses. This has been well confirmed experimentally. The expression for γ given in [8] is not confirmed experimentally (for the case discussed above, it gives the value $\gamma = 0$).

The results of moving-picture investigations make it possible to determine the time required for the formation of a stress field in the neighborhood of the apex of the crack, with the action of a stress wave on the crack. It is determined by the rate of propagation of shock waves and, in the material under investigation, amounts to 1-2 μsec. It is characteristic that a redistribution of the stressed state takes place even with very small amplitudes of the stress wave. This is explained by the participation of a small volume of material at the apex of the crack on the process of the redistribution. A special characteristic of the fracture under consideration is the high rate of the growth of the crack (700-800 m/sec) and its great acceleration. Figure 4 illustrates the change in the rate of growth of a crack with time: 1) in the absence of action; 2) with the action of a longitudinal wave; 3) with the action of a Rayleigh wave.

Such a high rate of growth of a crack with the action of a wave is explained by the fact that the influx of elastic energy into the zone of the fracture considerably exceeds the consumption of energy; the excess is expended for acceleration of the crack. It can be clearly seen on the moving-picture photos that there is a rise in the elastic energy at the apex of a crack with the action of a stress wave. The assertion that [7] the change in the stresses brought about by different shock waves has no appreciable effect on the growth of a crack is insufficiently justified.

A careful analysis of the kinetics of the interaction between a growing crack and Rayleigh waves shows that when they arrive at the apex of the crack there is at first formed a field of the stresses, analogous to the action of a longitudinal wave propagating along one of the sides of the crack. The gradient of the tangential stresses changes, as in the above-described case, but 4-6 μsec after the arrival of the wave at the apex, there is a repeated redistribution of the stressed state in its neighborhood. In this case, the gradient of the tangential stresses changes its direction by an angle of 100-120° with respect to the original direction. There is a synchronous change in the trajectory of the growth of the crack. This regularity in the change in the stress at the apex of the crack with the action of Rayleigh pulses is due to their inhomogeneity. The results obtained confirm the postulation that the running rosette in a Rayleigh pulse is connected with deformation along the half-space, while the main perturbation is connected with deformation along a normal to the half-space [6].

In carrying out the experiment it was also observed that under the effect of stress waves, during the process of the growth of the main crack, not one, but two or several, cracks are sometimes formed. In these cases, the rate of propagation of the forming cracks decreases sharply; in some cases, they stop altogether (Fig. 5). The recorded slowing down of the cracks can be explained as a partial coincidence of the trajectory of their motion and the direction of the applied stresses, as in the process of branching.

With the rotation of a crack under the action of a wave along the direction of the applied static stresses, in the absence of branching the retardation process is not observed, and, on the contrary, the motion of the crack is accelerated. The process of branching leads to a redistribution of the energy between the growing cracks (Fig. 5); therefore, there is an appreciable lowering of the velocity. The existing literature data is of a contradictory character: a number of authors note that the process of branching is not accompanied by a change in the rate of growth of a crack [7]; another group of investigators asserts the contrary [9].

Opinions as to the mechanism of this phenomenon are no less contradictory: according to [10] branching sets in with a rate of growth of a crack equal to 0.6-0.7 of the velocity of transverse waves in the given material; in the opinion of the authors of [11], this phenomenon occurs when the shearing stresses ahead of the crack and to the sides of it are found to be different. The branching observed in the present work is connected with the complex picture of the distribution of the stresses at the apex of the crack as a result of the action of Rayleigh waves, since the starting velocity of the main crack was considerably less than the velocity of the branching, i.e., 300-400 m/sec. It takes place at the moment of time when, at the apex, there is a stressed state with two sharply expressed gradients of the maximal tangential stresses and with the action of a wave of sufficient intensity. Such a stressed state is realized at the time of a change in the direction of the gradient of the tangential stresses.

In the case of the propagation of two cracks parallel to each other, the process of fracture exhibits certain special characteristics, consisting in the appearance of roughness of the surface of the break. This is explained by the action of stress waves, generated by the growing cracks, since, in the case of the propagation of a single crack, the fracture surfaces remain smooth.

Thus, the action of stress waves on the apex of a growing crack can be regarded as one method of control and slowing down in the supercritical stage of fracture.

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