FRACTURE OF RODS UNDER THE ACTION OF STRESS WAVES

V. G. Zhurba

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The experiments were carried out on plastic rods. The impulse load was applied either by initiating an explosion at the end or by means of a metal striker ejected by an explosion. Moiré fringes were used to record displacements of the rod in the direction of its axis. The motion of these fringes and the fracture of the rods were recorded by high-speed photography (SFR apparatus).

The figure shows a few frames illustrating the motion of the fringes and the fracture process. The loaded end of the rod is just out of the field of view at the top of the photograph, while the free end is seen at the bottom. Numbers represent the time in microseconds after the explosion.

The Moiré fringes in the unstressed rod (first frame) are parallel to its longitudinal axis. When the stress wave passes down the rod the bands are displaced at right angles to the longitudinal axis and change their curvature. The displacement of a Moiré band at a given point in the rod is directly proportional to the displacement of the cross section passing through this point in the direction of the longitudinal axis. The angle between the fringe at a given point in the rod to its position prior to the arrival of the stress wave is proportional to the component of the deformation tensor in the direction of the longitudinal axis of the rod (for the sake of brevity, we shall refer to this as the longitudinal deformation or, simply, deformation) in the particular cross section.

Numerical differentiation of the displacements obtained by observation of the Moiré fringe pattern was used to deduce the deformations ε and mass velocities v for the stress wave, and hence the longitudinal-wave velocity c. The stress was determined from the formula

$$\sigma = \rho c v, \qquad (1)$$

where ρ is the density.

The static modulus of elasticity is $E_1 = 25.7 \cdot 10^3$ kg/cm^2. The limit of proportionality is 200 kg/cm^2 and the rupture strength is 470–550 kg/cm^2 for deformations of 0.023–0.030, respectively.

The dynamic modulus of elasticity was calculated from the formula

$$E_2 = \rho c^2.$$

It was found that E_2 lay in the range 55 000–65 000 kg/cm^2, i.e., it exceeded E_1 by a factor of more than two.

Let us use the experimental data to determine the basic factors responsible for the fracture of the rod. When an impulsive load is applied to the end of the rod, the material near the region of loading undergoes intensive fragmentation. A compression wave travels toward the free end (compression and extension waves are defined as stress pulses of a given sign in which the stresses at right angles to the wave front are, respectively, compressive and extensive).

The maximum longitudinal deformations in the compression wave near the loaded end of the rod are not more than 0.027–0.30. Increase of the load leads to an extension of the local fragmentation zone at the loaded end and to a more intensive fragmentation, but it does not increase the maximum deformation in the compressive wave propagating toward the free end of the rod. The plastic deformation zone near the region of impact behaves as a barrier for waves corresponding to longitudinal deformations exceeding a certain critical value which, for compression waves in plastic rods, is 0.027–0.030.

The loaded end of the rod is not fractured by stresses of 1300 kg/cm^2 in the immediate neighborhood of the impact area, the corresponding deformation being 0.022.

The velocity of propagation of the maximum deformations (0.027–0.030) is lower by 7–8% than the velocity of the leading edge of the wave front, showing the presence of plasticity during such deformations.

The maximum of the deformation wave is found to reduce during its motion, and the rate of this reduction decreases monotonically. For a sufficiently long rod, the maximum wave parameters may fall to values for which the free end of the rod does not fracture.

When the compression wave is reflected from the end it is transformed to an extension wave.

Experiments have shown that if the maximum deformation exceeds 0.022–0.023, which is the minimum necessary for fracture under static conditions, the extension wave gives rise to crack formation. Therefore, deformations of 0.022–0.023 can be regarded as critical deformations in the extension wave in plastic. If the maximum deformation in the extension wave is just greater than the critical value, the crack formation will take place when the compression wave is totally reflected at a distance from the free end which is not less than half the wavelength. This is in agreement with the results reported in [1, 2]. If the maximum deformation in the wave is greater than the critical value, then crack formation begins when the extension deformation exceeds the critical value, i.e., when the process of reflection of the compression wave is still continuing. In this case, crack formation begins at a distance less than half a wavelength from the free end.

According to the rupture theory put forward by Griffith [3], the crack formation centers are microcracks which are present even in the unstressed material.

The fracture theory put forward by Machinskii [4] proposes that the crack "nuclei" appear when the stress wave passes through "weak" regions in a rock.

Our results are in agreement with the theories of Griffith and Machinskii. For example, when the maximum deformation in the extension wave is just less than the critical value, no crack formation is observed. If, however, there is a defect on the surface of the rod (for example, a slight transverse scratch), even at a distance of a few wavelengths from the free end, this defect will act as a crack formation center, whereas at other points on the rod no cracks will be formed.

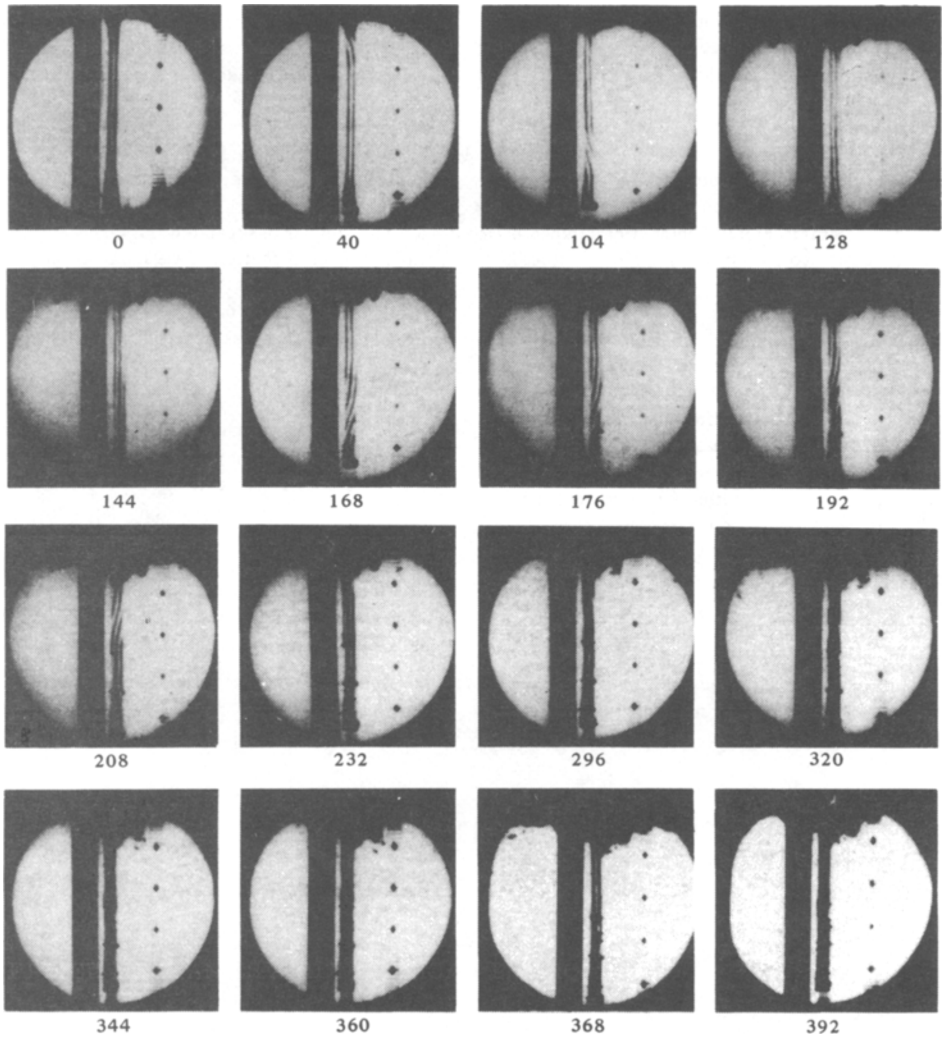
Cracks due to tension waves in rods, on the surface of which a grid of very fine transverse cracks has been introduced, will practically always appear at the points where the scratches are introduced.

The fact that fracture in rods under identical conditions does not take place in the same way is also in agreement with the theory of Griffith and Machinskii. This can be explained by the presence of weak points (microcracks, structural defects, etc.) which govern the nucleation of the cracks.

The presence of weak points prevents us from predicting with high accuracy the positions where the cracks will appear, because critical deformation depends on the type and size of defect (the greater the maximum deformation in the extension wave, the greater the probability that microcracks and defects will act as crack nuclei). Further development of the cracks is very dependent on the tension-wave transit time, even if the wave intensity is low. With crack development an unloading relief wave is propagated in the direction of wave motion from the newly formed surface along the rod.

The portion of the tension wave separated by the crack and "trapped" in the split-off fragment is reflected from the newly formed surface, and is therefore converted into a compression wave. When the trapped tension wave is reflected again, there is a relative displacement of the fragment from the remainder of the rod, i.e., an opening appears which is proportional to the impulse wave trapped in the fragment.

During the formation of cracks the fragments of pieces inside them receive angular momentum due to the reflection of the tension wave from the newly formed surface and the simultaneous transmission of another part of the wave through a region of the cross section which the crack has not yet reached. The angular momenta of the various



Motion of the Moiré bands, and the development of fracture under the action of an explosion.

pieces are equal and opposite, since the angular momentum of the rod as a whole is a constant.

The relief wave which propagates from the newly formed surface in the direction of motion of the extension wave prevents further development of cracks which have not developed appreciably. The length of the crack "damped" by the relief wave is proportional to the rate of its development and to the distance between the damped crack and a crack formed earlier, and is inversely proportional to the velocity of the relief wave. Rupture occurs when the crack succeeds in extending across the entire width of the rod before the relief wave arrives from a crack formed earlier. Therefore, for a single transit of the main tension wave, the length of the fragment cannot be less than a certain value for a given rate of development of cracks and given width of rod. This length is the minimum distance along the wave front between weak points at which crack formation can begin.

The compression wave propagating from the newly formed crack toward the free end will be reflected from a crack formed earlier, or from the free end, and will convert into a tension wave which, in spite of the fact that the maximum deformation in it is much less than the critical value, will lead to the further development of damped or undeveloped cracks and, therefore, to the further fragmentation of pieces split off earlier.

The intensity and wavelength of the tension wave expending a proportion of its energy in crack formation, deformation, and the motion of the individual fragments may fall to such an extent that further crack formation and development cannot take place. The length of the split-off pieces increases in the direction of the loaded end since, as the intensity of the wave decreases, the cracks can appear only at the weakest points.

The compression wave produced by the reflection of the tension wave from the loaded end can be partially transmitted by a through crack formed earlier if the opening is less than a certain value characteristic for the given impulse.

The various waves leaving the cracks are then reflected by other free surfaces and give rise to further development of cracks and crack nuclei initiated during the first transit of the tension wave, and this leads to the formation of new fragments and further fragmentation of existing fragments. There is an associated closing and opening of cracks, the compression waves pass from one fragment to another, and the collision of these fragments results in new compression waves.

The fraction of fragmentation due to the wave reflected from the loaded end of the rod is quite high.

Under the conditions of our experiments, fragmentation due to waves resulting from the second reflection from the loaded end was not observed.

Khanukaev [2] has found that the total length of the separating fragments is equal to one-half of the effective part of the compression wave.

Our data have shown that the total length of the separated fragments is greater than the total length of the wave, and much greater that the effective part of the wave. The number of separated fragments was determined by Khanukaev as a multiple of the maximum tensile stress divided by the rupture strength. However, our experiments have shown that the maximum possible tensile stress in plastic rods is less than 1600 kg/cm^2, the minimum value of the rupture strength is 1300–1400 kg/cm^2 and, therefore, the ratio of these quantities cannot be greater than 1.2.

The number of separated fragments is thus seen to depend on a large number of factors. If we consider only wave parameters, then we must conclude that the number of cracks resulting from the transit of this wave depends on the wave maximum, whereas the final length of each resulting crack depends on the length of the stress wave.

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