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SPALLING FAILURE IN A POLYMER CYLINDER ON UNSYMMETRICAL PULSE LOADING

A. V. Ostrik and V. P. Petrovskii

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Polymer materials are widely used. Components formed from highly filled rubber-type materials work under a great variety of conditions involving wide ranges in strain rate, including the rate range characteristic of shock-wave loading.

A description has been given [1] of how the strain rate affects the strength of a polymer consisting in the main of cellulose. In [2], there is a discussion of the behavior of filled elastomers (rubber) on strong pulsed loading. In [3], conditions for spalling failure in a fuel mixture based on polyurethane rubber were examined. In [2, 3], the studies concerned spalling due to reflection of stress waves from planar boundaries, with the main emphasis on failure associated with tensile stresses arising either from the reflection of a single front or from the interaction of two or more reflected fronts. There has been virtually no study on failure in elastomers due to interference between stress waves arising from reflection from curved surfaces. Interest attaches to how the properties of a highly filled elastomer and the geometry affect the spalling failure on strong pulsed loading.

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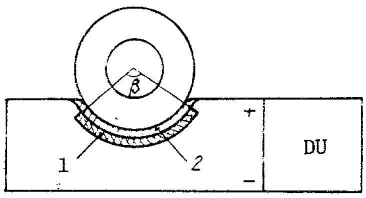

Fig. 1

TABLE 1

Foil explosion conditions	DU voltage, kV	
	20	25
	I_g, MPa·sec	
Without supporting plate	0.00008	0,00012
Support polyethylene film, δ = 220 μm	0.00034	0,0005
Support lucite, δ = 1000 μm	0.00062	0,0015

Specimens were used with outside diameter 4 cm and length 6 cm. The dimensions and shape of the internal channel varied. The measured density was 1.8 g/cm^3, while the speed of sound at atmospheric pressure was 1.7 km/sec. Tests were done on the elastomers in uniaxial stretching with strain rates in the range from 10^{-6} to 10^3 sec^{-1}, which were done with a tester at the Mechanics Institute, Moscow University [4]; these showed that the deformation behavior was very much dependent on the strain rate. With static strain rates of $\dot{\varepsilon} = 10^{-6}$-$10^1$ sec^{-1}, the elastomer behaves as a typical viscoelastic material with maximum failure stress up to 5 MPa, while with $10^3 > \dot{\varepsilon} > 10^2$ sec^{-1}, the dynamic vitrification effect occurs, and the specimens fail elastically at stresses of 30-50 MPa.

The shock waves in the cylinders were produced by an electrically exploding foil in direct contact with the loading surface. The foil was exploded by a discharge unit DU. Figure 1 shows the scheme. The DU had the following parameters: capacitor bank C = 18 μF, maximum voltage applied to foil U = 35 kV, and stored energy E = 11 kJ. The appropriate pulse intensity was provided by choice of the tension in the supporting plate 1 and the parameters of the foil 2 (material, thickness, and area). The dimensions of the loading region were determined by the angle β for a fixed foil width. Most of the tests were done with A5 aluminum foil 20 μm thick, width 2 cm and total area 15 cm^2 at U = 20 kV.

Experiments involving foil explosion are accompanied by substantial electrical interference, and it was difficult to measure the parameters of the wave by traditional electromagnetic or piezoelectric methods. The loading parameters were determined by means of special experiments and numerical calculations. Preliminary experiments with measuring plates gave the specific pressure pulses in relation to foil explosion conditions. The measuring-plate method is as follows. A thin plate with a known mass is placed in direct contact with the foil and is impelled by exploding the latter. The motion of the plate is recorded by a ZhLV-2 high-speed camera. This gave the mean speed of the plate, from which the specific pressure pulse was calculated from

$$I_g = Pv/gS,$$

in which P is the weight of the plate, v the average velocity, g the acceleration due to gravity, and S area. Table 1 gives measured I_g in relation to foil explosion conditions.

Calculations were performed by the [5] method on the pressure profile and pulses in electrical foil explosion for conditions analogous to those in the experiment (Fig. 2). The difference in the I_g from experiment was not more than 15%.

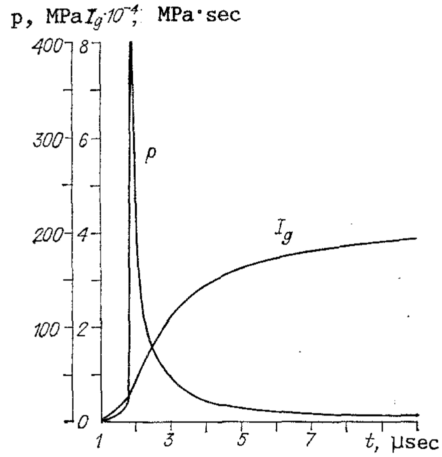

Fig. 2

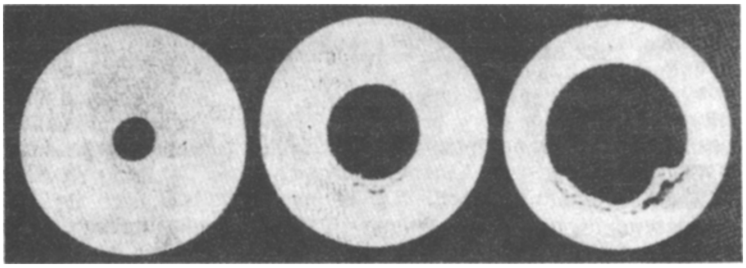

Fig. 3

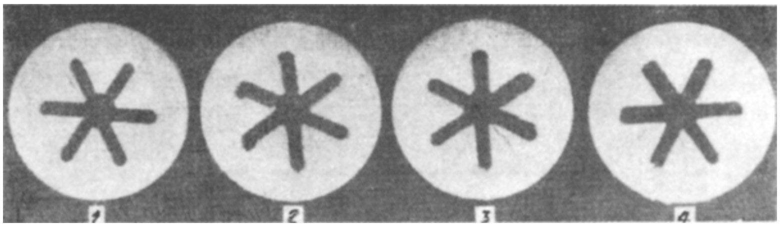

Fig. 4

Figure 3 shows cross sections of cylindrical specimens after loading at I_g = 0.00034 MPa·sec and the Fig. 2 pressure profile, which qualitatively demonstrates the effects from loading asymmetry, geometry, and specimen properties on the type and dimensions of the damage. A characteristic sickle shape applies for the damage to a specimen containing a cylindrical channel. The volume of damaged material decreases as the internal diameter of the channel falls. Such features are due to damping and geometrical cumulation of the stress waves, whose amplitude increases as $r^{-1/2}$ [6].

A different failrue pattern occurs with the star-shaped internal channels on Fig. 4. The loading angles β (Fig. 1) in these experiments were 30, 60, 90, and 120° (pictures 1-4). The characteristic zones are accompanied by damage features near the free surface related to crack growth between the rays. The rays and their orientation relative to the loading center have substantial effects on the mode of failure. The main fraction of the tension-wave energy is concentrated in the regions between the rays even when such a region does not lie directly under the loading center. The energy concentration in the space between rays is due to interference between the waves reflected from the sides of the rays and the inner part of the channel.

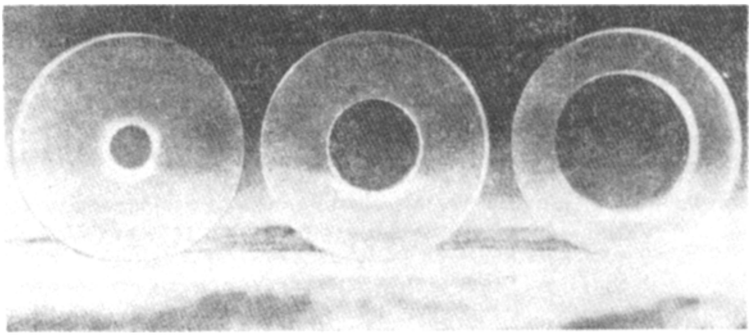

Fig. 5

A series of experiments were performed with geometrically similar cylindrical plexiglas specimens to compare the results and establish some quantitative conditions for spalling. That material has been researched the most extensively and is particularly convenient because of its good transparency.

Figure 5 shows sections of specimens after testing at I_g = 0.00034 MPa·sec with the Fig. 2 pressure profile. The damage is similar in form and volume to the spalling obtained with the elastomer. Plexiglas specimens begins to fail at 100-110 MPa in accordance with the [7, 8] results for $\dot{\varepsilon} = 10^4$-10^5, and at 170 MPa, failure sets in with the separation of a spalling layer, so in that strain range, the elastomer specimens fail under conditions close to those for plexiglas. This conclusion is confirmed to a certain extent by the [2] results, where it was shown that Poisson's ratio for rubber decreases from the 0.5 typical of an elastomer to 0.36 as the shock compression pressure increases, with the latter value characteristic of solids. High pressures in shock-wave deformation produce dynamic vitrification in the elastomer, and the mechanical characteristics increase, with the elastomer becoming similar to plexiglas in properties.

These results on failure in cylindrical polymers containing circular and six-ray star-shaped channels show that there are two main forms of damage: sickle-shaped in reflection from the cylindrical surface and as radial cracks between the rays. The shape and characteristic dimensions of the spalling are similar for the elastomer and plexiglas and occur with similar pulse parameters.

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