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FRACTURE OF SOLIDS BY WEAK BLASTS

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In this work, the results of different experiments on blasting rocks and model materials during combustion of powders, combustion and detonation of gas mixtures, and also in explosion of condensed HE charges in inert shells are generalized. Mechanisms of crack incipiency and conditions of crack propagation were determined and factors responsible for the increase in number of cracks with increasing load rate of chamber walls were elucidated. It is noted that the shape of initial cracks and the height of the loading zone of a cylindrical cavity have an effect on the fracture pattern. The kinetics of cracks in camouflet gas combustion is estimated. Attention is paid to the possibility of peripheral destruction of the crack edges in the intracrack gas detonation. Critical fracture surfaces are obtained for radial and disk-shaped cracks under quasistatic and dynamic loading of polymethylmethacrylate (*PMMA*).

Numerous works have been published on blasting of solids with either nuclear charges or chemical brisant explosives. Alternatively, much less attention has been paid to fracture of solids in combustion of powder charges, in explosion of charges in inert shells with low detonation velocities, and also in detonation of gas mixtures.

Theoretical investigations mostly consider the problems of propagation of main cracks under the action of pressure that appears in wells or bore-holes during explosion [1, 2] or under the action of gas flow in a crack [3]. The results of experimental modeling of fracture of solids during combustion of a powder charge in a bore-hole have shown that, in addition to kinetic peculiarities of a single crack, there exists a dependence of the number of cracks and of their geometry on the load rate of the well walls, on configuration of initial cracks or notchs, and on dimensions of the loading zone along the generating line of the well [4, 5]. The occurrence of several cracks at relatively low (10^{10}–10^{11} Pa/sec) rates of loading of the bore-hole wall is not entirely known [4, 5]. Although the present investigations were of applied character, they were also aimed at revealing some general rules for the fracture of solids during combustion of a powder charge in a well, and in combustion or detonation of a gas mixture in a camouflet cavity. Also, it was important to compare the mechanical effects of a powder charge, of a camouflet gas blast, and explosion of a condensed HE charge in an inert shell, and cracking mechanisms in fracture of solids by the above-mentioned agents.

ROCK BLASTING BY POWDER CHARGES

Experiments on fracture of compact homogeneous clays were carried out in vertical bore-holes 0.093 m in diameter and 1.5–3.5 m deep with charges in the form of blasting cartridges in polyethylene shells filled by black or pyroxylin (in rods) powder. The charges were symmetrically disposed in two combustion chambers of the device and were initiated by standard igniters. The loading density of the combustion chambers was varied within the 102–568 kg/m^3 range.

The width of the annular nozzle between the combustion chambers of the special device designed for localization of the loading region of the bore-hole along the generating line ranged from $2 \cdot 10^{-3}$ to $8 \cdot 10^{-3}$ m.

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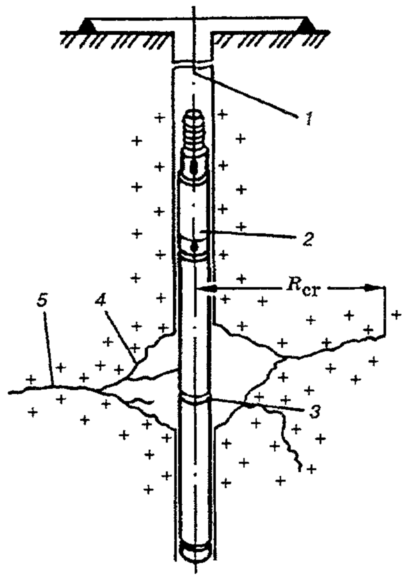

Fig. 1. Schematic placement of the device and character of fracture of massif: bore-hole (1), device (2), annular nozzle (3), cavity (4), crack (5).

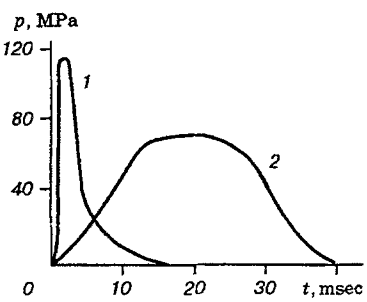

Fig. 2

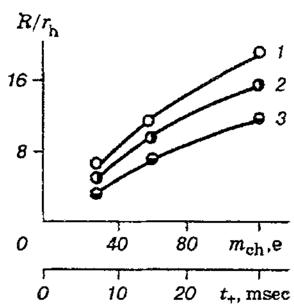

Fig. 3

Fig. 2. Profiles of combustion chamber pressure for combustion of different powders: (1) black powder, $\Delta = 387$ kg/m^3, $\delta = 1.25$ mm, (2) pyroxylin powder, $\Delta = 568$ kg/m^3, $\delta = 6$ mm.

Fig. 3. Radius of a main crack versus powder charge mass with a nozzle width of 2 (1), 4 (2), and 6 mm (3); hole diameter 93 mm.

This device was freely suspended by a cable within the bore-hole, without touching its face (see Fig. 1). The combustion chamber pressure in the device was measured by diaphragm strain gauges, which were screwed in the walls of the combustion chambers, and also by crusher pickups [6].

Figure 2 gives profiles of the blasting-chamber pressure in combustion of the black powder and pyroxylin charges, respectively. Outflow of the powder gases in air was recorded by a high-speed SKS-1M16 framing camera with a recording speed of 800–1000 frame/sec. The framing–camera sequences thus obtained showed that, during outflow, the jet expands axially with its further transformation into a spreading cloud of combustion products. The small cross-sectional dimension of the jet comparable with the hole diameter $2r_h$ predetermined the rock destruction by the same radial–circumferential crack in the flow plane, according to the results of [4]. The framing camera data show that the average outflow velocity of the jet from the $2 \cdot 10^{-3}$ m

TABLE 1

Intraballistic parameters of the device for the powder rupture of rocks

Test number	Δ, kg/м^3	p_{max}, MPa	δ, mm
1	102	20.2	6
2	204	43.0	6
3	221	58.5	6
4	416	75.5	6
5	102	22.4	4
6	204	49.0	4
7	416	83.0	4
8	387	115.5	1.25
9	568	67.8	6

nozzle was 160 and 285 m/sec when the loading density of the chambers was 102 and 204 kg/m^3, respectively.

The high-speed framing–camera data along with data of visual observation suggest that the observed outflow jet spreading and the great compressibility of the tested soft rocks are responsible for formation of a cavity in the near-fracture zone either in dry or water-containing holes. Both the height and diameter of the formed cavity and also the crack radius depend on the the powder charge mass m_{ch} and properties of the rock. As m_{ch} is increased, the continuos increase in dimensions of the cavity and the crack is observed. With large masses of charges, 3–4 other vertical cracks arise in the near-hole zone. They nucleate in the loading zone localized along the bore-hole height. This is related to an increase in the loading rate [4].

The data obtained were then processed by means of mathematical statistics. On the basis of the computation results, the radius R of the main radial–circumferential crack related to the bore-hole radius r_h was plotted versus the powder charge mass m_{ch} for different nozzle width δ (Fig. 3). The shape of the curves in Fig. 3 shows that the crack dimensions increase propotionally with an increase in the charge mass and that the coefficient of the proportionality decreases as the nozzle diameter increases.

Table 1 gives the maximal combustion chamber pressures p_{max} and the loading density p_{max} for black powder (tests 1–8) and pyroxylin charges (test 9). These data point to the natural dependence of p_{max} on Δ, and on δ. The outflow time for the gas jet at Δ = 102–204 kg/m^3 was found to be 10^{-2}–$1.5 \cdot 10^{-2}$ sec and to increase with increasing loading density (see Figs. 2 and 3). In combustion of an exposed powder charge without the use of device with combustion chambers, the clay massif was destroyed with vertical cracks.

If a radial crack is initially present in the bore-hole wall, fracture proceeds in the plane of this initial crack. This was shown both in tests with concrete blocks and in experiments with clay rocks.

FRACTURE OF PMMA IN CAMOUFLET GAS EXPLOSIONS

The fracture of solids during gas detonation in a cavity with an initial crack is characterized by the possibility of detonation or combustion of gas not only in the cavity but also in the crack.[1] In this case, a gas mixture optimal in composition can detonate even within the smallest cracks with an opening of the order of 10^{-4}–10^{-3} m [7].

The mechanics of fracture of solids in a camouflet gas explosion is virtually unknown. Only a few theoretical works are close in formulation to the problem of the development of a rupture crack during intracrack gas detonation. The propagation of a rupture crack in a solid under dynamic loading following the crack tip at a varying rate was considered in [8]. This problem is similar to the one formulated in [9]. The solution derived in [8] allows calculation of the crack propagation parameters at the moment of start under

[1]Experiments were carried out in cooperation with Drs. V. V. Zakharov, D. Kukshin, and P. A. Parshukov.

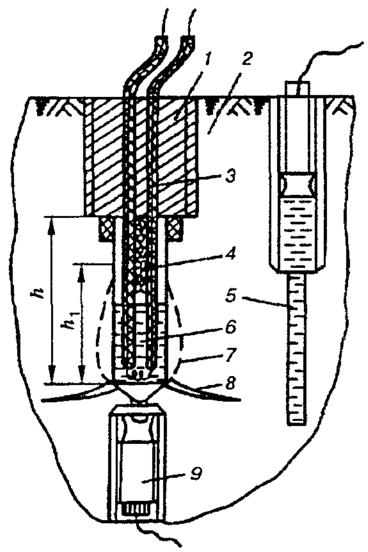

Fig. 4. Arrangement for loading of a PMMA specimen and recording of the average crack velocity in gas explosion.

instantaneous gas detonation in the crack. During actual detonation or fast combustion of gas inside a crack (which depends on the composition of the gas mixture and its initial pressure), dynamic disturbance in the form of the detonation or combustion wave front propagates along the crack edges and the condition for the crack start can be realized even before the wave front reaches the neighborhood of the crack tip. After the crack starts and the gas detonation is completed, the crack pressure falls, hence further crack motion can no longer be described by the analytical solutions obtained in [8].

Here, the approach suggested in [3] seems to be more adequate [3], provided that the wave processes in the gas and heat losses are neglected. When the detonation wave moves along the crack edge, compression and shear waves would propagate in the vicinity of or at a certain distance from the moving disturbance. But could either these stress waves or the moving load initiate the incipience of other cracks at the edges of the main one? To answer this question, more thorough investigations are required.

In our experiments, we used solid polymethylmethacrylate specimens 2 [4] (Fig. 4). The initial disk-shaped crack 8 with a radius of $(2\text{–}5.2)r_{\text{h}}$ in the vicinity of the bore-hole was produced by striking the liquid with a piston. Also, in some test series, we used specimens with two additional cracks 7 and 8, and one crack 8. After that, special piezotransducers were mounted at the opposite face of the specimens [4]. The bore-hole was filled with water and then corked 1 hermetically. Under the cork, calcium carbide 4 was placed between wires 3 so that it did not touch the water surface 6.

After hermetization of the hole, the specimen was turned over. The chemical reaction of calcium carbide with water lasted for 400–600 sec. The blast of the resulting gas mixture was initiated by a copper wire 10^{-4} m in diameter and from $3\cdot10^{-3}$ to $6\cdot10^{-3}$ m in length exploded electrically with the use of a capacitor discharge (capacitance 100 μF, initial voltage 2–2.5 kV, and electric explosion energy 0.1–0.2 kJ).

The average propagation speed of the main crack 8 was registered by the method of signal transducers 9 placed in water-filled holes 5 at distances of $11r_{\text{h}}$ and $18r_{\text{h}}$ from the central bore-hole (see Fig. 4). The distances were chosen such that the effect of additional holes on fracture of the specimen was completely excluded. In our tests, the dimension (height) of the loading interval h was varied from $3.6r_{\text{h}}$ to $10.6r_{\text{h}}$. In the fast combustion or detonation regime, the compression wave was reflected from the blast cavity end with a gradual increase in pressure in the subsequent reflections (Fig. 5a). The average velocity of the detonation or combustion wave was determined as the ratio $2h_1/\tau$ (see Fig. 4).

The physical processes occurring in the gas are covered in great detail in, e.g., [7, 10]. Therefore, in

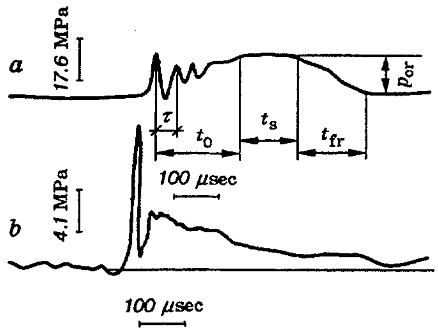

Fig. 5

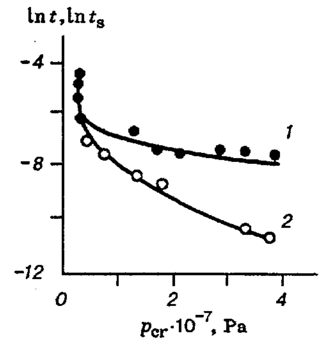

Fig. 6

Fig. 5. Pressure profiles: (a) in a blast cavity in explosion of a mixture of $148C_2H_2 + 1.4N_2 + 0.40O_2$, $p_0 = 2.1$ MPa; (b) near signal transducer in explosion of a mixture of $148C_2H_2 + 1.3N_2 + 0.3O_2$, $p_0 = 3.6$ MPa.

Fig. 6. Time delay of crack start versus critical cavity pressure (1) and curve of longevity of PMMA with a crack (2).

this work, we report only ranges for the basic parameters characteristic of the wave propagation in the gas and of fracture of PMMA. Also, we note several effects revealed in the experiment: the initial gas pressure in the cavity ranged from 1.9 to 7.5 MPa; the explosion pressure amplitude ranged from 12.7 to 225.0 MPa; the pressure pulse duration was $t = 4 \cdot 10^{-4}$–$9 \cdot 10^{-3}$ sec; the average rate of the pressure rise was 30–3500 GPa/sec; the wave propagation velocity for the combustion was 60–800 m/sec; and the detonation wave velocity was 1800–2000 m/sec.

The rear front of the pressure pulse, which characterizes the fracture regime, was almost linear in the complete fracture of the specimen and has a flattened shape in the partial fracture (Fig. 5b).

The average propagation velocity of a disk-shaped crack that stopped in the specimen was 113 ± 10 m/sec, as recorded by the transducers; the propagation velocity of the radial crack was 131 ± 10 m/sec in the complete destruction of the sample; and the average rate of pressure rise was 300 and 266 GPa/sec, respectively. Taking into account that in blasting of solids the crack propagation velocity subsides with increasing distance [11, 12], one should expect that in the near explosion region the crack velocity can be several times higher than the value obtained.

A specimen with an initial disk-shaped crack (height of the loading interval $h < (6\text{–}6.5)r_h$ and loading rate $\dot{p} \leqslant 10^{11}$ Pa/sec) was destroyed just by this disk-shaped crack. But, at $h > (6\text{–}6.5)r_h$, a radial crack occurs. As the loading rate is increased in going on to the detonation regime of blasting gas decomposition, the radial cracks increase in number to 2–4, and the total number of the cracks becomes 3–5. The possibility of incipience and development of radial cracks in specimens with an initial disk-shaped crack is accounted for by the delay time of the crack start (induction period) t_s. In this period, a high-stress region occurs at the tip of the initial macrocrack and different microfailures and discontinuities are accumulated [13]. Again, in this period, a high-stress region forms around the bore-hole where analogous destruction processes leading to incipience and development of microcracks occur. An analogous (precritical) stage was previously considered in the theory of spalling fracture [14]. Thus, this induction period along with the finite propagation speed of the initial disk-shaped crack and its inability to completely absorb the explosive products are responsible for formation of radial cracks around the bore-hole.

The assumption that there is a delay in the crack start was first made in [15]. The typical pressure profile $p(t)$ is either a gently-sloping or flange-shaped curve, where one can notice an interval with a nearly constant pressure at a critical stress level of a certain duration (see Fig. 5a), which supports this assumption. Our experiments have shown that this value depends on the loading rate or, what is the same, on the actual

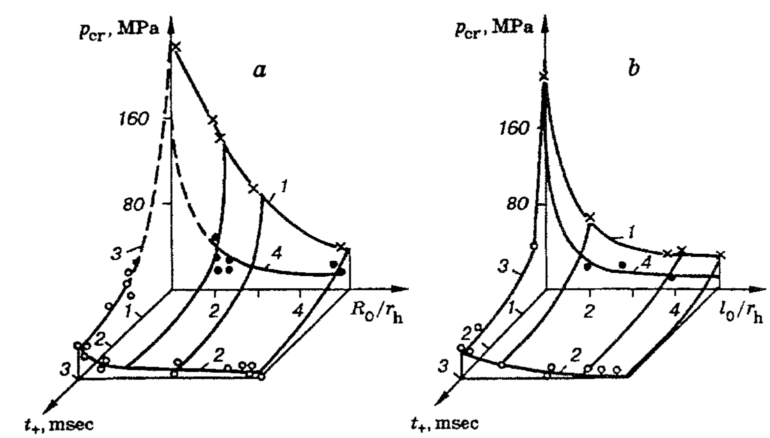

Fig. 7. Critical fracture surfaces in the space of loading pulse parameters for the criterion of the maximal coefficient of stress intensity. (1) $t_+ = 30$–15 μsec, (2) $t_+ = 3000$–200 μsec, (3) $R_0/r_h \to 1$, $l_0/r_h \to 1$, (4) $t_+ = 160$–20 (a) and 30–20 μsec (b).

pressure values. Figure 6 gives a plot of the delay time of the crack start t_s against the value of the critical fracture pressure on semilogarithmic coordinates. Here t is the time of existence of a specimen with a crack under loading. It is equal to the sum of the time required for the pressure to reach the critical level t_0, of the induction period t_s, and of the time of development of microcracks t_{fr} (duration of the postcritical stage of fracture). It is seen from Fig. 6 that the relationships considered are very similar.

Figure 7 shows critical surfaces in the space of loading pulse parameters for the criterion of the maximal coefficient of stress intensity. The graphs were plotted on the basis of results obtained in fracture tests of solid PMMA samples during gas explosion in a cavity with disk (Fig. 7a) or radial (Fig. 7b) interior cracks. When constructing these surfaces, we used data on the threshold pressure for the PMMA rupture obtained in hydraulic rupture tests [4], and also data obtained in different regime of gas combustion and detonation in a cavity. The graphs in Fig. 7 show that, as the loading rate is increased, the relationships between the threshold failure pressure p_{cr} and the initial crack size R_0/r_h and l_0/r_h becomes stronger. The critical surface $F_R(p_{cr}, t_+, R_0/r_h)$ is located above the critical surface $F_l(p_{cr}, t_+, l_0/r_h)$, which completely agrees with the relationships of the threshold pressure that are already known in the linear mechanics of failure for the cases of initial disk-shaped and one- or two-side radial cracks [16].

A comparison of the mechanical effects exerted by fast-burning black powder charges under loading localized with the use of the device described above and by explosion of a gas mixture in the indicated range of initial pressures shows that they are nearly equal.

When comparing time parameters for fracture by weak and strong explosions (in terms of the energy release rate), we can see that the time period during which the predestruction zone is formed around the cavity ranges from one to tens of milliseconds for quasistatic powder rupture to tens and hundreds of microseconds for explosion of a condensed HE charge [17, 18]. Thus, Konstandov et al. [17] showed that in the fracture of flat specimens by tensile waves the delay time for the crack start t_s from a notch was $2.8 \cdot 10^{-6}$ sec. Also, Efremov et al. [18] determined the starting moment of the cracking process in integral PMMA blocks depending on the size of the side air gap Δr for explosion of extended PETN charges: $t^* = 12$–21.6 sec.

The tendency to the shorter time of crack propagation in the precritical destruction stage with the higher stress level around the cavity is also in agreement with our consideration of the initial fracture period as a thermofluctuating process [19].

Under certain conditions, the mehanical effect of brisant HE charges in inert (damping) shells is similar to the effect of powder charges and gas explosions. Thus, a RDX charge with a mass of $0.15 \cdot 10^{-3}$ kg in a sand shell partially destroyed a PMMA block of the same dimensions by three radial cracks with a depth of

(5–7)r_h. However, a further increase in the charge mass and changeover from a sand shell to an air one leads to complete destruction of the block and an increase in number of cracks, which is apparently associated with compaction of microcracks in the predestruction zone [14].

CONCLUSION

1. The mechanical effect of camouflet gas explosion at $p_0 \leqslant 7$–7.5 MPa is similar to that of a fast-burning powder charge in the case of localization of loading along the cavity or to the mechanical effect of a brisant explosive in an inert (damping) shell.

2. The fracture of solids around the cavity cannot be determined only by the type of initial cracks, their orientation, and the energy release rate in gas blast, explosion or combustion of some condensed material, but also depends on the height of the application interval of dynamic loading.

3. The incipience of radial cracks around the cavity in specimens with either an initial disk-shaped crack or an annular notch, both perpendicular to the cavity axis, is believed to be due to a delay in the crack start, during which a predestruction zone forms at the crack tip and a predestruction zone for formation of radial cracks occurs in the vicinity of the cavity. The cracks grow in number with a rise in the loading rate of the cavity walls, which, in its turn, might be associated with increasing density of microcracks in the predestruction zone around the cavity.

4. The duration of this induction period for a rupture crack and the overall time of the precritical fracture stage increases with decreasing loading rate. The dependence of the induction period on the cavity pressure is similar in shape to the longevity curves.

5. The crack propagation speed in a camouflet gas explosion is intermediate between the velocity of slow cracks in quasistatic hydraulic rupture and fast cracks in explosive fracture of solids.

6. The critical surfaces in the space of loading parameters for the criterion of the maximal coefficient of stress intensity, indicates that the relationship between the threshold rupture pressure and the size of the initial radial or disk-shaped cracks increases with increasing loading rates.

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