NATURE OF EXPLOSIONS OF COMPRESSIBLE THIN LAYERS

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Bridgman [1] first described the explosions of thin layers of materials under the effect of pressure and shear. Later the circle of materials in which this phenomenon was observed was broadened [2-5]. Several hypotheses were expressed on the nature of the phenomenon. According to [2], the explosion is brittle fracture of the specimen, and according to [3, 4, 6] a chemical reaction. However, no quantitative investigation of the phenomenon was performed and, consequently, there should be agreement with the opinion of the authors of [5] that the reasons for the explosive phenomena cannot possibly be considered clarified.

Explosions of thin layers are not only of theoretical interest. There is a foundation for assuming that such occur in energy-stressed mills during the grinding of powders. Thus, explosions resulting in the destruction of 30 cm in diameter beams [7] have been observed during the milling of powders.

Explosions of thin compressible layers are studied experimentally in this paper. A model is proposed for the phenomenon, on whose basis an explanation is given for the data obtained and some in the literature.

Methodology of the Tests

The tests were conducted by the Bridgman method. The material being investigated was compressed between flat anvils, one of which could be rotated at a rate of 0.13 deg/sec under pressure.

The angle of possible misalignment of the anvils did not exceed 0.2°. The friction coefficient for the materials utilized was not less than 0.1. Correspondingly, the angle of friction was greater than 6°, which significantly exceeds 0.2°, and hence, the influence of the possible misalignment could be neglected. Anvils of 7 mm diameter from tempered ShKh15 steels were used. The compressive force F was recorded during the tests with $\pm 1.3 \cdot 10^3$ N accuracy, the specimen thickness with $\pm 2 \cdot 10^{-3}$ mm accuracy (the compression diagram was constructed from these data) and the torque M with ± 0.7 Nm accuracy. The rate of application of the compressive force is $2 \cdot 10^2$ N/sec, and the unloading rate is 10^5 N/sec. The tests were conducted with powdery materials. A storage oscillograph was used to record the elastic waves occurring during the explosion. The signal was taken off by a strain-gauge sensor fastened to one of the rods of the press or from a piezoelectric sensor mounted on the anvil. The change in material structure was studied by means of an x-ray survey with a diffraction pattern record.

Test Results

Explosions can occur during loading, during anvil rotation under load, during holding under load, and during unloading. The phenomenology of the event is identical in all cases. The explosion is accompanied by a jump diminution in M, F and h (the first drop in Fig. 1, a test with ZnSb), a sharp sound, decomposition of the material, sometimes destruction of the anvils (a system of radial cracks), and sparking for materials with a melting point above 1000 K. A film of about 1 μm thick remains on the anvil surface after an explosion. Near the site of the explosion it is continuous with a smooth surface (Fig. 2a, magnification ×5.4). The film continuity is spoiled with distance from the site of the explosion. The boundaries of the discontinuities have smooth outlines. Solidified passes (shown by the arrow and drops of spherical shape can be observed (Fig. 2b, magnification ×200). The film adheres strongly to the anvil. This indicates that the material being discarded is partially melted. In tests with those materials in which explosions occur,

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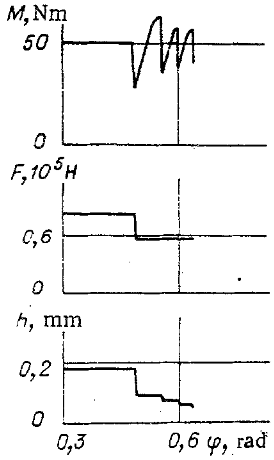

Fig. 1

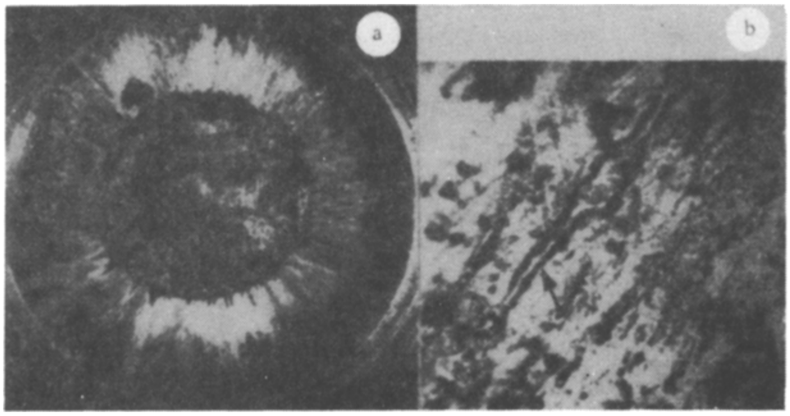

Fig. 2

clicks occur during anvil rotation under pressure; they are accompanied by the same phenomena as the explosions but in smaller scales (Fig. 1).

Initially the capability of different substances to explosion during an identical action (loading to a 2 GPa pressure, rotation for 3 min, unloading) was studied. The explosion of substances with a covalent bond (9 elements and compounds), crystal-hydrates (11 compounds), metals, 5 alkali-halide compounds, as well as K_2SO_4, N_2SO_4, $CasO_4$, KNO_3, $NaNO_3$ was successfully caused here.

Typical kinds of compression patterns are represented in Fig. 3. The compression pattern of plates of plastic materials 3 consists of two sections, hanging, on which the layer thickness does not change as the compressive force grows; and extrusion, on which the thickness decreases. There is also a hanging section ac on the compression patterns of powders of brittle materials. As the compression force increases, the hanging is either spoiled by the explosion 2 or goes over into plastic extrusion 1.

A dependence between the critical compressive force (at whose attainment during loading an explosion will occur) on the layer thickness is found for a number of substances (Figs. 4 and 5). The points in Fig. 5 are 1) V_2O_5, 2) S, 3) Ge, 4) Si, 5) glass. The dependence of the duration of the holding prior to explosion on the pressure and the diffraction patterns of aluminum alums before and after the holding under pressure is represented in Figs. 6 and 7.

A study of the signals from the strain-gauge sensor and the piezoelectric sensor showed that an unloading impulse first passes over the elastic system at the time of the explosion.

DISCUSSION AND RESULTS

Since the films of the congealed material (see Fig. 2a) and the cracks in the ruptured anvils are located symmetrically relative to the center of the anvils, the misalignments of

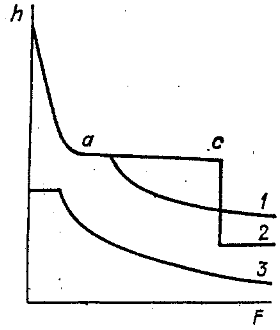

Fig. 3

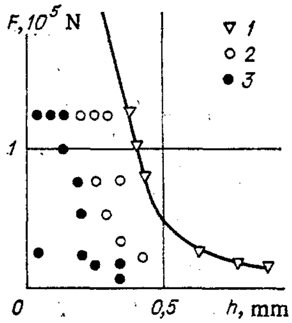

Fig. 4

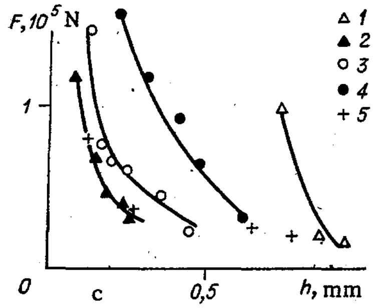

Fig. 5

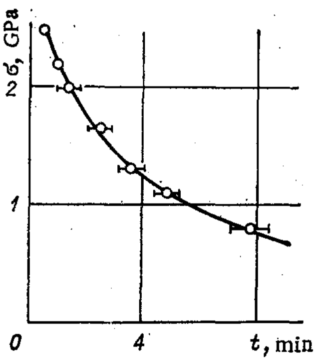

Fig. 6

the anvils are therefore not the reason for the explosion. The relation between the capability to explode and the brittleness of the materials (see Fig. 3) and the unloading nature of the first impulse generated by the explosion confirm the hypothesis of the explosion as a brittle fracture process that develops because of spoilage of the mechanical stability. Since the critical force is independent of the strengthening characteristics of the materials (see Fig. 5), the stability of the layer is evidently determined by the friction forces acting on the contact surface of the specimen and the anvils, and more exactly, by the relationship between the displacing action of the compressive force and the retentivity of the friction. The retentive effect predominates in the hanging mode. As the compressive force increases the displacing action grows and becomes predominant, and hanging is replaced by plastic displacement of explosion. It is natural to assume that the relationship between the displacing and retaining actions is determined by the pressure distribution over the anvil radius, i.e., by the kind of function $\sigma(r)$.

Let us consider the change in $\sigma(r)$ during compression of plates of a plastic material. If the layer of material is thin and in the elastic state, then $\sigma(r)$ is similar to the pressure distribution during the contact interaction of elastic bodies [8]. Indeed, changes associated with the presence of the layer are due to the elastic deformation of the layer. This deformation is proportional to the pressure, i.e., where the pressure is greater, the compression of the layer is greater; consequently, the pressure gradients in the presence of a layer will be less but the nature of the distribution is conserved. In this case the greatest pressures act on the anvil edges [9], and at the center of the anvils for the plastic state of the layer [10, 11]. The passage from the elastic to the plastic state as the compression force grows will start with the flow of material at the layer edges, and then the boundary of the plastic and elastic zones moves to the center. Since the pressure gradient is negative in the plastic zone, and positive in the elastic zone, the domain of greatest pressures is located on the zone boundary and is also shifted towards the center. A change in the form of $\sigma(r)$ results in the fact that clamping of the layer in the edge part and, therefore, the retentivity attenuates, and the displacing action grows as a distribution with negative gradient is set up. In plastic materials and in materials acquiring plastic properties under pressure [12], the pressure redistribution and then the layer extrusion also occur gradually.

The pressure redistribution in brittle layers can result in an explosion-like ejection. Displacement of the edge parts of the layer is accompanied by their fracture. The carrying

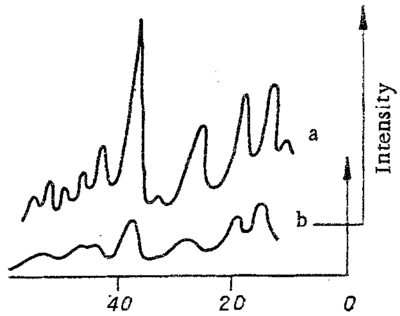

Fig. 7

capacity of the fractured material and the side support, which it exerted on the neighbor located closer to the center of the material, are reduced. This material can be fractured, than that next to it is fractured, etc. The process is self-sustaining in nature. Therefore, shifting of the domain of greatest pressure to the center causes an explosion-like fracture of the whole layer. However, not each chipping of the layers that is constantly observed during pressing of brittle materials results in an explosion. This means that satisfaction of another condition, spoilage of the stability of the layer as a whole, is required for the development of an explosion.

We use the stability treatment [13] for a quantitative description of the conditions for the onset of explosions. We neglect the energy expended in layer deformation by considering this small for brittle fracture during ejection. The stability is spoiled if the work of the compressive force δ_A exceeds the work of the friction force δA_T for a small closure of the anvils by δh. The energy δA_T is converted into heat, and the energy $(\delta A - \delta A_T)$ into the kinetic energy of the ejected material.

For the critical state

$$\delta A = \delta A_{\text{т}} = F\delta h; \tag{1}$$

$$\delta A_{\text{т}} = 2\int_0^R 2\pi r k\sigma(r)\,\delta r dr \tag{2}$$

(k is the friction coefficient and r is the layer radius).

Let us examine the form of $\sigma(r)$ in powder layers. In contrast to the monolithic, in powder layers there is a fabricated system of internal discontinuities and, hence, they possess the capability for plastic deformation [12. The authors of [14, 15] arrive at the deduction about the plastic behavior during the compression of thin powder layers on the basis of a comparison between the experimental data on the pressure distribution in powder and monolithic layers. It is assumed in the computations that there are two zones in powder layers, just as for plastic materials: a plastic at the edges and an elastic at the center with a pressure distribution in the plastic zone as in [10, 11].

The pressure diminishes to the center in the elastic zone of monolithic specimens. In powder layes this distribution changes because of compression of the powders. Compression of the powders is the capacity to residual deformation in the axial compression direction. Because of the high compression of the material in the domain of higher pressures, the maximum of $\sigma(r)$ at the edge of the elastic zone is flattened out and the pressure at the center is elevated. Consequently, σ = const is taken for the elastic zone, which is confirmed by the following. The pressure is uniform in the elastic zone according to computations [11]. The difference between this result and [9] is due to the fact that the anvils are considered stiff in [11]. Such an assumption is acceptable in tests with powders since the elastic deformation of the anvils can be negelcted in comparison with the deformation of the layer. Moreover, it is detected experimentally in [14, 16] that if the width of the edge-sustaining ring exceeds half the anvil radius, then the pressure in the central zone (filled with powdered quartz in [14]) is uniform. As computations showed, the width of the plastic zone is greater than half the radius at the critical compressive force in our tests, and a necessary condition for stability is the existence of a zone at the center of

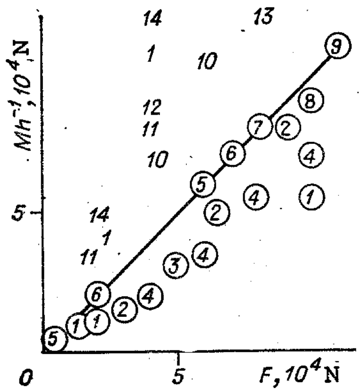

Fig. 8

the anvils in which the pressure does, at least, not grow towards the center. This result is in agreement with the assumption about an elastic zone with uniform pressure.

Neglecting the change in layer density at the initial instant of ejection, we have from the volume conservation conditions

$$\pi r^2 h = \text{const}, \ \delta r = r\delta h/2h. \tag{3}$$

Utilizing (1) as well as the expressions

$$F = \int_0^R 2\pi r\sigma(r)dr; \tag{4}$$

$$M = \int_0^R 2\pi rk\sigma(r)\, rdr, \tag{5}$$

we obtain a series of algebraic systems of three transcendental equations with four unknowns, r the radius of the plastic and elastic zone boundary, τ_s the critical shear stress of the material, k a constant, and h, for a number of values of the critical forces. Computations show that the interval of possible values of k for which the systems have a solution and the variables take on physically real values is narrow and comprises several hundred. The computed dependence $F_k(h)$ for ZnSb with k = 0.15 is in satisfactory agreement with the test results [see Fig. 4, where 1) explosions are obtained during loading; 2) during rotation under load; 3) it is impossible to obtain an explosion; solid line is the result of computations].

Substituting (3) and (5) into (2) and using (1), we find $F = Mh^{-1}$. Since the measured times are determined by the friction forces of the motion, which is less than the rest friction force, then the inequality $F_k > Mh^{-1}$ should be satisfied for explosions under loading. The test results conform to this inequality [Fig. 8, where the numbers correspond to the test conditions and the numbers in the circles correspond to conditions under which explosions occur: 1) V_2O_5; 2) Si; 3) Ge; 4) ZnSb; 5) S; 6) InSb; 7) $AlNH_4(SO_4)_2 \cdot 12H_2O$; 8) $NaMoO_4 \cdot 2H_2O$; 9) $FeSO_4 \cdot 7H_2O$; 10) CaF; 11) SiO_2; 12) Fe_2O_3; 13) CuO; 14) Al_2O_3].

The representations developed permit clarification of a number of observations. Anvil rotation because of the lowering of the friction coefficient (see Fig. 4), and holding under load because of creep, result in broadening of the plastic zone, buckling, and explosion. Clicks evidently occur because of the instability of just the edge annular zone rather than of the whole layer.

The material displaced after spoilage of stability under the effect of friction is warmed up because of the elastic energy of the loading system delivered to it. A computation of the energy balance with the heat elimination through the anvil taken into account shows that the ejected material is partially melted. The time of process development is $2 \cdot 10^{-4}$ sec, which agrees with the oscilloscope data. The velocity of the ejected particles, calculated from both the condition of combined motion of the anvils and the layer material as well as data on the magnitude of the flight path of the powders in air, is in agreement and equals 10^2 m/sec.

Cases of the explosions of metal–sulfur mixtures [3], which possess plastic properties because of the presence of metals, seemingly contradict the brittle-fracture hypothesis. However, tests showed that explosions in such and similar mixtures of elements, for instance, zinc or cadmium with sulfur, occur after preliminary plastic deformtions that occur upon rotation of one of the anvils. During this deformation brittle compounds are formed in the mixtures, and explosion is the process of destruction of these compounds. The formation of intermediate compounds during the combined plastic deformation of mixtures of elements was observed in [3] and studied in [17].

Distortion of the structure of aluminum alums $AlNH_4(SO_4)_2 \cdot 12H_2O$ because of holding under a 1 GPa pressure (a: 1 min, b: 30 min), recorded by the lowering and broadening of the diffusion peaks (see Fig. 7), cannot possibly be explained by plastic deformation, which at least takes place during shifting of the plastic zone boundary to the center, but is quite small. There remains to assume that processes resulting in structure distortion are developed in the material itself. Dehydration apparently proceeds in alums since the water molecules are retained most weakly in the compounds. Since the pressure increases the stability of the hydrate modes [18], the motive force of the process is related to the inhomogeneity of the pressure in the plastic zone. Such a dissociation process under the effect of a pressure gradient was observed in [19] in silver iodide with halogen molecules being formed in the low pressure region. The free water molecules reduce the friction, resulting in explosions.

Thus, explosions in thin compressible layers are developed because of losses by the mechanical stability system, which can occur because of chemical processes.

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GROWTH OF A MAIN CRACK UNDER THE INFLUENCE OF GAS MOVING INSIDE IT

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The motion of a gas or liquid in a growing main crack is examined in connection with the problem of the hydraulic fracture of an oil-bearing bed [1, 2] and evaluation of the quantity of gaseous products escaping from the cavity formed by the underground explosion into the atmosphere by way of the crack [3]. The studies [1, 2] formulated and solved a problem on the quasisteady propagation of an axisymmetric crack in rock under the influence of an incompressible fluid pumped into the crack. An exact solution was obtained in [4] to the problem of the hydraulic fracture of an oil-bearing bed with a constant pressure along the crack. The Biot consolidation theory was used as the basis in [5] for an examination of the growth of a disk-shaped crack associated with hydraulic fracture of a porous bed saturated with fluid. A numerical solution to a similarity problem on the motion of a compressible gas in a plane crack was obtained in [6]. Here we examine the problem of the propagation of a main crack (plane and axisymmetric) under the influence of a gasmoving away from an underground cavity.

1. <u>Formulation of the Problem</u>. The motion of an isothermal gas in a main crack is described by the system of equations [6]

$$\frac{\partial}{\partial t}(\rho w) + \frac{1}{r^n}\frac{\partial}{\partial r}(r^n u \rho w) = 0, \qquad (1.1)$$

$$\frac{\partial}{\partial r}p + 12\mu w^{-2}u = 0, \quad p = c^2\rho,$$

where ρ is density; u is velocity; p is the gas pressure; c is the isothermal sonic velocity; μ is the gas velocity; n is a geometrical parameter ($n = 0$ for planar symmetry and $n = 1$ for axial symmetry); w is the opening of the crack; r is a coordinate; t is time.

Since the velocity of the crack under the influence of the gas moving inside it is much lower than the velocity of Rayleigh waves, then the opening of the crack is connected with the rock pressure and the gas pressure by the expression [7]

$$w(r, t) = \frac{4(1-\nu)}{\pi G} L(t) \int_{\xi}^{1}\int_{g(t)}^{\theta} \frac{[p(\eta, t) - p_\gamma]\,\eta^n d\eta\,\theta^{1-n} d\theta}{\sqrt{\theta^2-\eta^2}\sqrt{\theta^2-\xi^2}}. \qquad (1.2)$$

Here, $\xi = r/L(t)$; $L(t)$ is the length of the crack at the moment of time t; $g(t) = r_0/L(t)$; r_0 is the radius of the underground cavity; p_γ is the rock pressure; ν is the Poisson's ratio; G is the shear modulus.

System (1.1)-(1.2) is closed by the condition of finiteness of the stresses on the contour of the crack [4], which determines the length (radius) of the crack:

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