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Some features of behavior of solid dielectrics under high pressure combined with shear stress

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Abstract. The paper presents the results of experimental research of behavior of solid dielectrics under high pressure combined with high shear stresses with emphasis on specificities of explosion of this solids under such conditions, which is known as reological explosion. Revealed the dependence of shear deformation, which is necessary for explosion on pressure, speed of product of explosion was measured, mechanism of appearance of hard radiation which arising during the explosion was established.

1. Introduction

Reological explosion of solid state bodies is the specific form of destruction of said bodies under very high pressure and shear stresses. This phenomenon described first by P.W. Bridgman in his classical work [1]. He considered the explosions of the samples, which occurred from time to time during experiments, as a kind of disturbing factors and paid no attention for study of this phenomenon. Moreover, his apparatus with two pairs of anvils gave no possibility for such studies. The investigators, which were followed him later [2-4], emphasized on study of some concrete occurrences of the explosions, such as radio radiation, chemical reactions, etc. Just all of them gave many propositions on the nature of explosion, without complete experimental study of phenomenon [5, 6]. Such study was done by V. Shienok and T.Gorazdovsky [7-9], which introduced first the term «reological explosion» in this works. M. Yaroslavsky participated in some experiments and reported about achievement of comprehensive pressure as high as hundreds of thousands kilobars and many other very interesting results [10].

2. Experimental Procedure

The studies of this phenomenon were carried out with the apparatus (figure1) included one pair of Bridgman's anvils one of which were fixed at the ram of 100 tons hydraulic press and another at the shaft of mechanical reductor, which were mounted at this press. The reductor allowed to rotate said anvil around the axis, passed through the centers of both anvils. The angle of rotation was measured with accuracy of $\pm 0{,}2\ ℃$ and was unlimited. Speed of rotation was constant with valuation about $1\ ℃/sec$.

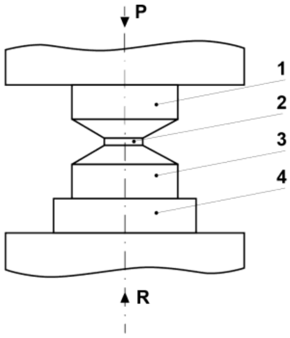

Figure 1. Scheme of the apparatus (1-upper anvil, 2-sample, 3-lower anvil, 4-shaft of redactor)

The anvils had a form of truncated cones made of alloy steel forced up HRC60, or of cemented carbide with 8 % of cobalt. The working surfaces of anvils had a square of 2-3 cm^2 and were grinded for roughness of a few of microns. The objects of investigations were polycrystalline dielectrics such as various forms of $CaCO_3$, coal, brick, salts, boric acid, etc. Chalk was the most convenient from them.

Pressure was valuated as average force to square of working surface of anvils because it was not hydrostatic with maximum in the center. Moreover, gradient of pressure was changing during deformation. Thus exact measuring of pressure was useless. Deformation valued as the angle of rotation of anvil because it was different in different points of the sample and exact measuring was useless too. The samples exploded when pressure and deformation achieved some values, individual for each material.

3. Results and Discussions

It was estimated, that explosion occurred only when pressure was higher, then some initial, which marked as P_0. The explosion never occurred below this value independently on deformation. The explosions, which were observed under pressures higher, then P_0 had a force depended on the value of pressure, namely: higher a pressure – strongly a force of explosion. The value of deformation, which was necessary for explosion (α), depended on the value of pressure. The form of this dependence one can see at the figure 2.

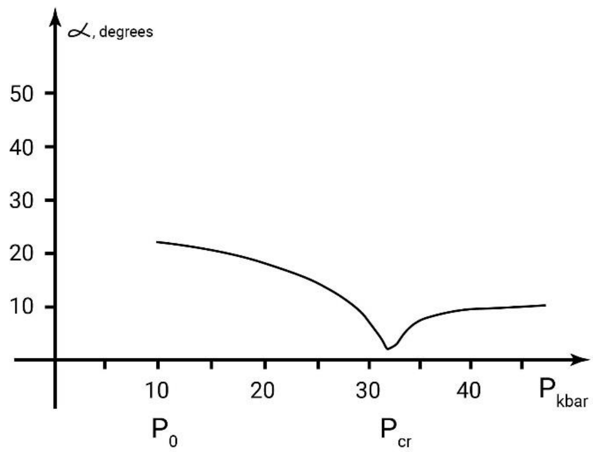

Figure 2. Dependence of rotation angle of anvil, which is necessary for explosion on pressure

The curve have a minimum, which is sharp enough and which is different for different materials. The value of pressure, corresponding to this minimum, is marked as P critical (P_{cr}). The value of α under P_{cr} is as small, as 1-3 degrees. The value of α is changing from tens of degrees at pressure P_0 to 1-3 degrees at P_{cr} and then it is increasing slowly with pressure to the value of about 10 degrees. The scatter of values of α is changing from tens of percents at pressures near P_0 to some percents at pressure P_{cr} and higher. Finding of this dependence was very useful, because the field of experiments became wider.

A tablet there was formed of material, which had been pressed between the anvils, under the pressure about P_0 and higher. The tablets were not formed under lower pressures – material was cracked only. Residual tablet remained between the anvil after explosion. The thickness of tablets depends on the sort of material and on the value of pressure and was about a few millimeters. The thickness and mass of residual tablets was less than the thickness and mass of tablets before the explosion. The tablets lost from a few percents to about 50 % of mass after explosion. The value of this loss depended on pressure and changed from minimum at P_0 to 50 % at P_{cr}. This loss just not changed at pressures higher, than P_{cr}. The density of the tablets after explosion was some percents higher, than before explosion.

The structure of the tablets differed drastically after explosion and before it. There are a lot of layers, which are laying under ±45° to the axis of symmetry of the tablets. This layers were similar to the cleavage surfaces in crystals, because its were the surfaces of destruction, when the tablets were crashed. The metal flakes were formed in the residual tablets, when the material was doped with metal powder. The orientation of this flakes was same, as orientation of said layers.

The material, which is flied out at the explosion have a form of dust. This dust have very special spectrum of particles dimensions and forms. Most of the particles (about 90 %) have dimensions of 1-2 microns and are just isotropic. The fracture surfaces were covered with a lot of this particles, which could not be removed by a flow of air.

The working surface of anvils obtained specific damages after explosion. There were two types of damages: «ripple» and scratches. This damages were observed both at the steel and hard alloy anvils. The «ripple» had «wave length» about a few millimeters and amplitude about some tenths of millimeter. The «wave length» was just independent on material of anvils, but amplitude was greater at steel anvils than at hard alloy anvils. The orientation of «ripple» was similar to orientation of ordinary ripple at the surface of water after stone drop.

The scratches had a length from some tenths of millimeter up to 2-3 millimeters, depth and width up to some tenths of millimeter. The forms of a scratches were very manifold and it's width and depth were changed along one scratch. The directions of a scratches was just chaotic at the central part of working surface of anvils, but this directions became radial at the peripheral part. It is necessary to note, that a hardness of all exploded materials and hardness of inclusions was noticeably less, then that of materials of anvils.

One more specificity of reological explosion was discovered. This specificity is named «related explosion», and it's nature is following: the material under the pressure higher than P_{cr} which is subjected to the deformation less, that is necessary for explosion, can remain in this state indefinite time and explode when the pressure decreased. The explosion under such conditions occurred when the pressure dropped to a value about P_{cr} and had full force. Thus we are observing a metastable state of solid body, which is existing due to potential barrier of definite magnitude by way of the pressure and is rupturing when the barrier drops below this magnitude. This metastable state is rupturing in the time less than 10^{-5} sec. Discovering of this phenomenon allowed to do a lot of useful experiments, such as high-speed filming of explosion, which is shown at the figure 3 and, which were unreal without «related explosion» experimental technique.

Dropping of electrical resistance of material in the moment of explosion was observed, but detailed investigation of this effect was not done.

The reological explosion is following with some interesting effects. One of such effects is a hard radiation, which is observing during an explosion and after it. The radiation was researched with the apparatus which had the high sensitive scintillation detector and computing device. The radiation, which appeared in the moment of explosion, and first had been observed [11], was electromagnetic and had upper energetic threshold of 10-12 keV. The number of registered particles depended on the

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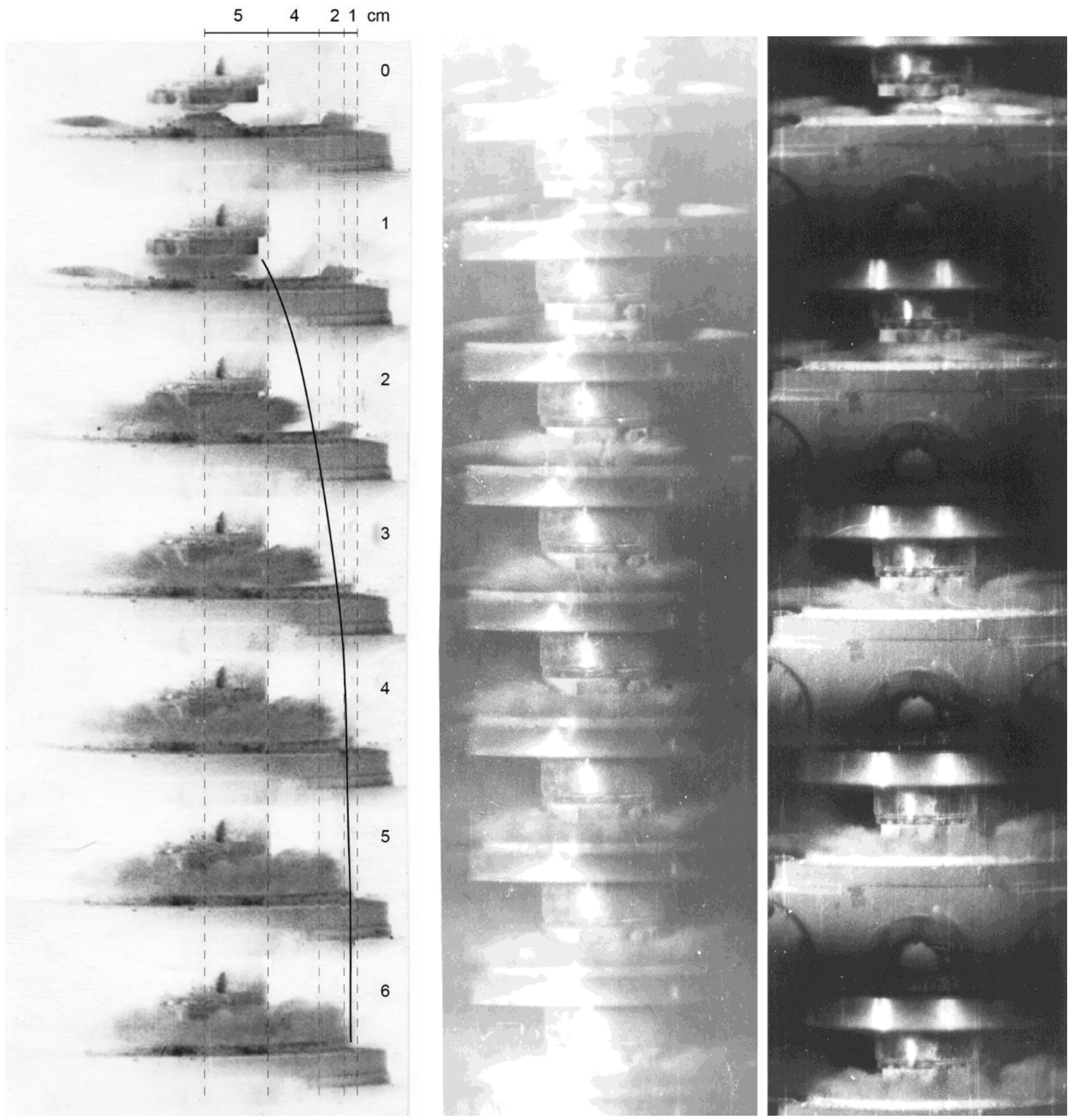
energy so, that it decreased quickly above this threshold and increased below it. The spectrum of energies of the particles was continuous below the threshold.



a b c

Figure 3. High-speed film of reological explosion speed of filming 10.000 (a, b) 5.000 (c) frames/sec. The curve at the frames 1-6 – dependence of speed of particles on time (a), frame 0 – last before explosion. The beginning of explosion: frame 1 (a), 3(b), 2(c).

The comparison of this results with the results of researching of other specificities of reological explosion made it possible to explain the nature of described radiation.

It was established with ballistic pendulum technique [10], that the speed of products of explosion was about 500-1000 m/sec at 5-10 cm from the center of exploding sample. The product of explosion of chalk under 30 kbar was dust with basic dimension of particles about 1,5 μm.

There was calculated the loss of speed of the particle, when it moves through air. The calculations, based at aerodynamics have many limitations of ranges of values of parameters, such as speed, dimensions, density, temperature etc. which are leading to incorrectness out of limitations. There was used method of direct calculation of loss of speed of the particle after collisions with air molecules to avoid possible mistakes. There was supposed, that air molecules have the mass, average between the mass of nitrogen and oxygen molecules, that molecules are motionless and collisions are elastic.

The particle with initial speed V_p^0 will have speed V_p^1 after one collision with air molecule in accordance to the laws of saving of energy and impulse:

$$V_p^1 = \left(\frac{m_p - m_a}{m_p + m_a}\right) \times V_p^0$$

where m_p – is the mass of particle and m_a – is the mass of air molecule.

After second collision the particle will have speed V_p^2:

$$V_p^2 = \left(\frac{m_p - m_a}{m_p + m_a}\right) \times V_p^1 = \left(\frac{m_p - m_a}{m_p + m_a}\right)^2 \times V_p^0$$

After i-collisions the particle will have speed V_p^i:

$$V_p^i = \left(\frac{m_p - m_a}{m_p + m_a}\right)^i \times V_p^0$$

Supposing that a particle have a spherical form, so it's mass is:

$$m_p = \rho\, 4/3\pi R^3$$

where ρ – density 3 g/cm^3 and R – is radius of particle 0,75μm.
So:
$m_p = 3 \times 4/3\pi(0{,}75 \times 10^{-4})^3 = 5{,}2 \times 10^{-12}\ g$
$m_a = m_{g-m}/N = 29/6 \times 10^{23} \approx 5 \times 10^{23}\ g$
where m_{g-m} – the mass of gram-molecule, *N* – Avogadro's number.

There was calculated the number of collisions of the particle and molecules of air at the distance of 1cm. This number (n) is equal to the number of molecules of air in the cylinder, having base area: $\pi R^2 = 1{,}75 \times 10^{-8}\ cm^2$ and generatrix – 1cm, i.e. in the volume $V_c = 1{,}75 \times 10^{-8}\ cm^3$

$$n = \frac{N}{V_0} \times V_c$$

where: *N* - is Avogadro's number, V_0 – is the volume of gram-molecule.
Thus:

$$n = \frac{6 \times 10^{23} \times 1{,}75 \times 10^{-8}}{22{,}4 \times 10^3} \cong 5{,}25 \times 10^{11}$$

The total mass of this molecules is:

$$m_a \times n = m_n = 5 \times 10^{-23} \times 5{,}25 \times 10^{11} \approx 2{,}610^{-11}\ (g),$$

i.e. at the distance of 1cm the particle impacts with a mass ≈ 20 times as much as it's mass and loses just all it's speed.

The speed of the products of explosion, as it is mentioned above, is 500 – 1000 m/sec at the distance of 5 – 10 cm from the center of exploding sample. It means, that even the particle loses only half of speed at 1 cm, V_p^0 have a value about 100-300 km/sec.

In accordance to this results, it became possible to make the assumption on the mechanism of appearance of radiation in process of reological explosion.

It is known from quantum mechanics, that excitation of atoms can occur as a result of collision of a bodies – «impact or shock excitation».

The probability of excitation (*W*) up the energy, which corresponds to the frequency ω is:

$$W = 2(\omega_{exc}/\omega_{km})^2$$

where:

$\omega_{exc} = 2\pi(V/d)$;
ω_{km} – is specific frequency of atom;
V – speed of impaction;
d – lattice constant of impacting material.

Calculation of a value of speed of collision of a nitrogen molecule with a particle of chalk, which is necessary for excitation and following radiation up energy of 10 keV gives (in assumption of full transformation of kinetic energy to energy of radiation):

$$mV^2/2 = 10\ keV = 1{,}6 \times 10^{-8}\ erg$$

$$V = \sqrt{\frac{2 \times 1{,}6 \times 10^{-8}}{5 \times 10^{-23}}}\ cm/sec \cong 250\ \ km/sec$$

Analysis of high-speed films of explosion gives the same results. There is a curve of speed dependence of particles on time at the figure 3,a. Extrapolation of this curve to the moment of origin of explosion leads to the value of initial speed of some hundreds km/sec/. Results of measuring of average speed of particles with ballistic pendulum, mentioned above may be used as independent reference point.

The comparison of this results with the results of experiments leads to conclusion: the hard radiation in process of reological explosion is a result of inhibition of high speed particles of exploding material in air. The upper energetic threshold of radiation corresponds to maximal speed of particles. The origin of some kind of damages of the surfaces of anvils became clear too – the objects, having speed of hundreds km/sec can damage the materials with hardness significally higher than that of such objects.

4. Conclusion

Revealed the dependence of shear deformation, which is necessary for explosion on pressure. It was established, that the speed of products of explosion can reach about 250 km/sec. The mechanism of appearance of hard radiation which arising during the explosion was established: it is arising due to collisions of high-speed products of explosion with the molecules of air.

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