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PECULIARITIES OF BRITLLE AND DUCTILE MATERIALS DESTRUCTION AND DEFORMATION DURING THE EXPLOSION OF INDUSTRIAL SHAPED CHARGES

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ОСОБЛИВОСТІ РУЙНУВАННЯ ТА ДЕФОРМУВАННЯ КРИХКИХ І ПЛАСТИЧНИХ МАТЕРІАЛІВ ПРИ ВИБУХУ ПРОМИСЛОВИХ КУМУЛЯТИВНИХ ЗАРЯДІВ

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ABSTRACT

Purpose. To study the laws of deformation and destruction of brittle and ductile rocks and concretes under explosion of industrial shaped charges.

Methods. In experiments, the following methods of investigation were used: method of contact sensors for determination of jet velocity; determination of the ultrasonic wave velocity in the concrete samples; methods of optical and electronic microscopy; X-ray phase analysis; measuring and visual analysis of the dimensions and nature of deformation and destruction zones.

Findings. The work describes the experimental data on the destruction of barriers made of concrete, granite, steel ST 3, AMC-n alloy, and zinc by the explosions of shaped charges of serial production with porous liners. Calculation formulas for estimating the radius of a destruction zone of geomaterials and rocks in case of a semi-infinite barrier are suggested. The calculation method is based on the estimation of energy impact on the rock by jet penetration velocity into the barrier. Jet velocities are determined experimentally and by engineering methods. The reasons for deviations in the hole shape and deflection of the destruction zone from the symmetry axis were determined.

Originality. The modes of penetration of shaped jets into rocks of different porosity, the size of the fracture zone around the hole and the causes and mechanisms of the deviations of the hole shape from the symmetric one are established.

Practical implications. The results of the research will be used to design blasting-and-perforation operations in geotechnological wells and can be used to design initiating devices for borehole charges.

Keywords: *shaped charge, shaped liner, shaped jet, deformation, destruction*

1. INTRODUCTION

Until the early 90s of the last century, shaped liners (SL) (in literature – liners) from solid metal were used in shaped devices. Starting from the 90s up to the present time, powdered SL manufactured either by cold compression or compression with additional sintering, have been used in the industrial charges for geological survey, oil and gas industries.

Advantages of porous liners produced by powder metallurgy method, over solid SL are proved experimentally and boil down to the following factors (Trishin & Kinelovskii, 2000; Voitenko, Goshovskii, Drachuk, &

Bugaets, 2013; Youmard, Roduner, Santschi, & Wister, 2001; Voytenko & Bugaets, 2016):

– technological simplicity in manufacturing of intricately shaped SL from the materials with necessary engineering properties;

– since the shaped charge jet is in fact a flow of porous material, and the penetration rate in the condensed media is higher than the sound speed in the material of the shaped charge jet (SCJ), there appears an attached shock wave, which is located near the point of contact with a barrier (Voytenko & Bugaets, 2016). As a result, the degree of substance heating in the porous SCJ is significantly higher than the similar indicator for solid SCJ, causing reduction of its viscosity and increase in the depth of penetration into barriers;

– amount of energy in the zone of interaction between SCJ and the barrier, is increased by adding Al powder (Voytenko & Bugaets, 2016) into the liner composition, containing copper, nickel and other metals with a melting point ≤ 3000°.

Depending on the physical and mechanical properties of the barrier's and liner's material, various modes of penetration of solid bodies and shaped charge jets into plastic and brittle materials, as well as the physical effects of the shock action amplification, connected with the collapse of pores (Balankin, 1988a; Balankin, 1988b), may take place. Results of the research into rock micro-destruction caused by the penetration of single and contiguous paired SCJ, are described in the work (Merkulov, 2016). It is shown that during the explosion of single charges micro cracks appear around the hole, while in case of explosions of contiguous paired charges in the concrete samples with the strength of 53 MPa and the speed of longitudinal sound waves of 4046 – 4586 m/s, a crack between the holes is formed. The authors assume that a similar pattern of destruction will also take place in a semi-infinite barrier – sandstone of the pay. Insufficient attention was paid to the research of the micro- and macro-destruction during penetration of SCJ, as well as to the peculiarities of deformation of barrier's plastic materials during the explosions of the industrial charges.

The destruction of oversized fractions by gas shaped charges (GSC) from ammonite 6 JV is investigated in the work (Poplavskyi, 2007). The paper argues that GSC are more efficient in crushing than mud caps, under the following conditions:

– GSC is installed directly on the rock (contact explosion);

– the angle of concavity is $2\alpha = 40 - 60°$, its diameter is not less than 0.8 d_{ch} (d_{ch} – charge diameter), the thickness of explosives layer is no less than critical. It should be noted that the relevance of explosive crushing of oversize fraction has significantly decreased recently due to the successful application of other technical means.

During the explosion of the shaped charges (SC) with liners in the form of spherical segments and cones with blunt angles, the penetrator cores (in literature – compact elements (CE)) are formed in the top. The typical size of the penetrator core is $\sim 10^{-2} - 10^{-1}$ m (Timoshenko & Chepkov, 2011). The entire mass of the liner goes into the penetrator core, and its speed is about 2.2 – 3.5 km/s depending on the properties of the explosive material and the liner density (Merkulov, 2016). In the case of the liner shaped as an elongated ellipsoid of variable thickness, the CE speed is up to 7.5 – 10 km/s, which is comparable with the SCJ speed (Fedorov, Bayanova, & Ladov, 2015). The energy of the penetrator core is an order of magnitude more than the energy of SCJ in the charge of the same caliber.

Shaped charge jets with a characteristic size of $\sim 10^{-3}$ m. are formed during the explosion of shaped charges with conical liners and acute apex or charges of similar shape. The speed of the SCJ leading part is about 6 – 12 km/s (depending on the explosive properties and density of the liner material), the mass of SCJ ~ 0.1 – 0.2 of the liner mass (Timoshenko & Chepkov, 2011). The problem of choosing between penetrator core and SCJ for crushing or softening of rocks during shaped explosions does not have any trivial solution and requires energy assessment, as well as experimental or theoretical research. It is known that in military practice, the penetrator cores are used for destruction of lightly armored targets, including the spalls of barriers, while for destruction of heavy armored targets SCJs are used.

The purpose of this work is to determine characteristics of deformation and destruction of brittle and ductile rock during explosions of industrial shaped charges.

2. METHODS OF EXPERIMENTS

From the literature (Held, 2001) and numerous patents it is known that in terms of the parameter $V_{j0\max}\sqrt{\rho_j}$ (where $V_{j0\max}$ – the initial velocity of the jet head, $\sqrt{\rho_j}$ – density of its material) more preferred materials for the jet are W, Mo, Ni, and Cu. Three of them were used in our experiments (W, Ni, Cu). Furthermore, Pb powder was used as a plasticizer in the liner composition, and Al served as an energy supplement. Main charge calibers are presented in this paper by the charges with explosive mass of 10 g and an angle at the liner apex (2α) 70° and 55°/60°, explosive mass of 18 g and an angle at the liner apex (2α) 44°/48°, explosive mass of 23 – 24 g and an angle at the liner apex 43°/45°. To evaluate the effect of SCJ on metal barriers, direct measurements of linear dimensions of the channels and methods of optical and electronic microscopy were used. To measure the speed of copper SCJ from a porous liner in free flight, we used the method of contact sensors described in the paper (Voitenko, Goshovskii, Drachuk, & Bugaets, 2013). For the measurement of the longitudinal wave velocity in concrete samples, a standard method using the UK-10PMS device was used. Products of interaction between shaped jets and metal barriers were studied using the microprobe and X-ray phase analysis methods.

Experiments on concrete destruction by explosion with shaped charges were carried out on specimens in the shape of columns 70 × 70 × 700 mm, placed in a plaster shell, which in turn was placed in a demountable steel tube 0.14 m in diameter with a wall thickness of 0.015 m. This allowed reducing influence of the reflected wave of tension on the formation of cracks in the concrete. Study of crushing intensity depending on the speed of SCJ motion in the target was investigated on free concrete cylindrical targets 130 mm in diameter and rock samples. A steel plate 5 mm thick was set between the charge and the concrete or rock sample. Furthermore, some material deformation and destruction characteristics during penetration of SCJ were examined on metal targets in the form of a set of plates made of steel ST 3 aluminum alloy AMC-n and zinc.

3. FEATURES OF BRITTLE ROCKS AND GEOMATERIALS DESTRUCTION

With the penetration of jets, as well as of the solid or porous striking pins into rock, the size of the fracturing area that occurs around the formed channel is meaningful for practical applications. At the same time, the destruction is determined by the mode of SCJ movement in the barrier's material: subsonic, transonic and supersonic.

The speed of solid copper SCJ with a velocity gradient from 6.5 km/s ($V_{j0\max}$) to 1.5 km/s in fragile media (glass and sitall) is 4 km/s and 3.6 km/s ($u \approx (0.55 - 0.62)\ V_{j0\max}$) in metal barriers (M1 copper, steel ST 40, VT6 titanium) – $u \approx 0.46 - 0.51\ V_{j0\max}$ (Rumyantsev, 2011). Note that we are talking about the initial hydrodynamic stage of penetration. During penetration of SCJ from the porous powder liner (W – Cu – Sn – C – CH composite) into aluminum alloy 6061 – T6 at a speed of the head part 6.4 km/s, the calculated penetration velocity at the initial stage was ≈ 4 km/s ($V_{j0\max} \approx 0.63\ V_{j0\max}$), and then it gradually decreased (Glenn, 1998). It is important that the above SCJ speed value (Glenn, 1998) is close to the value, obtained in the work (Voitenko, Goshovskii, Drachuk, & Bugaets, 2013) (6.6 – 7.0 km/s), which is explained by the congruence of explosives properties, also by composition and porosity of the liner material. During penetration of the same jet into the concrete through two metal plates modeling perforator body and well casing pipe, the initial penetration speed was ≈ 2.54 – 3.4 km/s (Glenn, 1998). During subsonic penetration of SCJ into limited-size samples of brittle material (BM), the compression wave passes through BM with sound velocity c1, or there occurs a two-wave configuration – elastic precursor with the speed of sound and a compression wave propagating at a slower rate. When it exceeds the yield stress and with the advent of the lateral wave of unloading, the material is destroyed. The same thing happens during a supersonic penetration of SCJ. The compression wave in this case is a ballistic shock wave moving in front of the contact boundary "SCJ – rock" at a speed greater than c_1. A similar pattern holds for explosion of mud caps. It differs from the destruction by shaped explosion in that the primary system of cracks develops in the sample from the contact surface "explosive – rock", and when unloading waves approach these cracks propagate over the entire sample, causing its crushing.

Our experiments with copper liner on the charge of small caliber yielded the value of $V_{j0\max} = 7.5 - 8.0$ km/s. For the aluminum liner this value was 9.5 – 9.8 km/s. Calculation of the copper SCJ head part speed by the Trishin – Kinelovski method for a charge of small caliber $2\alpha = 55°$ and $2\alpha = 70°$, the detonation velocity 8100 km/s and a relative porosity of the liner material $m = 1.2 - 1.4$ ($m = \rho_0 / \rho_{00}$; ρ_0, ρ_{00} – density of monolithic and porous material) yields the following values: $V_{j0\max} = 6.91 - 7.98$ km/s. For the composite (W – Cu – Pb) liner the value $V_{j0\max} = 5.36 - 6.19$ km/s (Drachuk, Hoshovskyi, & Voitenko, 2007). Calculation of speed for SCJ made of A1 and Cu – Al (85 – 15% and 91 – 9% mass) mixture was conducted by the L.P. Orlenko method, as the porosity of the liner made of A1 (8 – 16%) and mixtures Cu – Al is approximately 2 – 2.3 times less than that of copper (Drachuk, Hoshovskyi, & Voitenko, 2007). Therefore L.P. Orlenko engineering method is quite acceptable for Al and mixtures, because the accuracy of the calculation by this method increases with decreasing of porosity. Calculation yields the following values $V_{j0\max} = 9.098$ km/s for Al, and 8.275 km/s and 8.608 km/s for Cu – Al mixtures correspondingly. Detonation velocity in this variant of calculation is equal to 8100 km/s. The porosity, based on the experimental data, was changing according to the linear law from the cone apex (8%) to its base (16%) (Drachuk, Hoshovskyi, & Voitenko, 2007).

Since in the rocks with medium or high porosity (Ks ~ 10 – 30%), the maximum speed of sound is $c_l = 2400 - 3650$ m/s, nearly all shaped jets, including the heavy ones, based on W at the initial stage penetrate into such rocks with supersonic velocity $u > c_1$. The shock wave arises not only in the shaped jet, but also in the rock.

In dense low porosity rocks ($k_n \leq 5 - 7$), depending on the density of the base material, the sound velocity is about 3400 – 4200 m/s in dry rocks and ~ 4100 – 4900 m/s – in water saturated rocks. Therefore, some of the shaped jets in such rocks will be moving at supersonic speeds, and some – in the subsonic mode. At a late stage of penetration, the majority of the shaped jets will move at a subsonic speed.

The size of fracturing area is determined by the shock wave (SW) intensity in the rock and the radial inertial displacement of the cavern walls, like during the explosion of the elongated charge (Trishin, 1999). The unloading wave in the semi-infinite barriers is absent.

In accordance with the results of the work (Trishin, 1999), the penetration of the shaped jet, deformation and destruction of the porous medium is equal to the explosion of elongated charge with heat input, which is determined by the speed of the jet U_0 in porous medium:

$$E = \rho_{00} U_0^2 \frac{\pi d^2}{4}\ ; \tag{1}$$

for the flow around a cylinder with a flat end.

The force acting on the hemispherical end, is (Trishin, 1999):

$$X = \frac{1}{2}\rho_{00} U_0^2 \pi r_0^2 - \frac{1}{2}\rho_{00} U_0^2 \frac{\pi d^2}{4}\ . \tag{2}$$

The amplitude of the pressure attenuation at the shockwave p_f front for one-dimensional motion with distance is described by the well-known formula (Mikhalyuk, 1980; Vakhnenko, Nagornyy, Denisyuk, & Mishchenko, 2003):

$$p_f = A\left(\frac{Q^{1/\nu}}{r}\right)^{\mu}, \tag{3}$$

where:

Q – the energy of the explosion;

v – the symmetry of one-dimensional flow;

$v = 1$ – plane symmetry;

$v = 2$ – cylindrical;

$v = 3$ – spherical;

μ – constant;

A – dimensional coefficient that depends on the properties of the medium and explosives (Mikhalyuk, 1980).

Work (Vakhnenko, Nagornyy, Denisyuk, & Mishchenko, 2003) provides theoretical substantiation of the ratio, obtained in a number of experimental works, connecting the energy of the explosion Q to the size of the destruction zone r_f:

$$r_f = RQ^{1/v}, \tag{4}$$

where dimensional constant R satisfies the equation:

$$\frac{R^{2(1+\mu-v)}}{2\alpha R^2 + \left(BR^{\beta}\right)} = \frac{\gamma_v}{H}. \tag{5}$$

In this equation, γ_v – the energy of cracks formation per volume unit; α – the coefficient of shock wave attenuation due to the rock energy absorption; B – dimension factor; β – Index showing the dependence of the wave load impact time on the distance r and the explosion energy Q in case of zero energy loss (Vakhnenko, Nagornyy, Denisyuk, & Mishchenko, 2003).

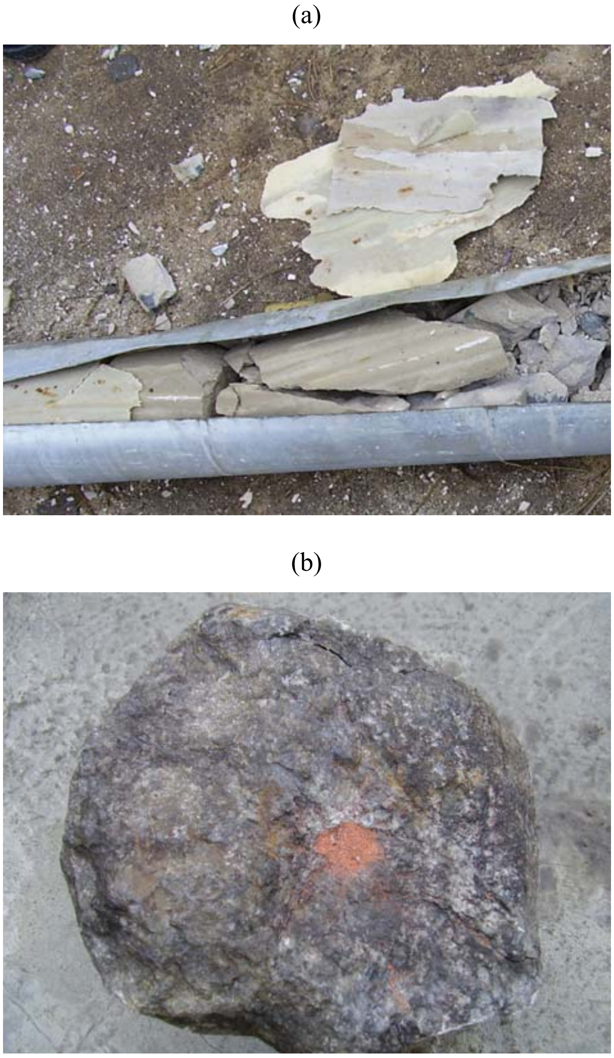
To determine all of the above values, it is necessary to carry out experiments, while for many rocks these constants are defined. According to the conclusions of the work (Vakhnenko, Nagornyy, Denisyuk, & Mishchenko, 2003), it is enough to perform several experiments for getting statistical sampling, and to obtain a direct dependence (4). The constant R is easily derived from it. From formula (5) we can determine the energy of cracks formation, if all other constants are known.

Since the information about the velocity of shaped jet penetration is often not available, the availability of experimental data concerning the size of the destruction area around the crater, allows estimating the speed of penetration. Calculation for copper porous liner and semi-infinite concrete barrier with a compressive strength 27 MPa shows that the radius of the destruction zone around the canal on the plot of the hydrodynamic stage of penetration can be estimated as ≈ (9 – 11)*d*. In the calculations, the following parameters were used for the initial assessment: $d = 2.1 \cdot 10^{-3}$ m; $U = 3500$ m/c; $\rho_{00} = 6500$ kg/m^3; dynamic strength of the barrier material (ST 3) $\sigma = 3$ GPa; density of the target material $\rho_t = 7800$ kg/m^3; density of the shaped jet material – $\rho_j = 6500$ kg/m^3; diameter of the channel in the target (ST 3) $D = 9 \cdot 10^{-3}$ m. The calculation of the shaped jet diameter was carried out by the well-known formula (Andreev et al., 2004):

$$d = D\frac{1}{V_{j0\max}}\sqrt{\frac{2\sigma}{\lambda}\frac{\sqrt{\rho_T}+\sqrt{\rho_j}}{\sqrt{\rho_T\rho_j}}}. \tag{6}$$

In calculations, the value of constant λ was assumed equal to one. To evaluate the destruction zone radius, experimental data for concrete were used (Vakhnenko, Nagornyy, Denisyuk, & Mishchenko, 2003), according to which it is equal to 24 r_{ch} (r_{ch} – charge radius). In the absence of the outer shells, the destruction of a cylindrical sample of concrete with a diameter of 0.13 m in a thin metal shell occurred along the entire channel with cross-cutting radial cracks. In the presence of an outer shell of steel and plaster, cracks do not extend beyond the concrete specimen. In this case, the depth of the channel during the explosion of the charge of 10 g mass on target ST 3 – concrete number 1 with composite (W – Cu – Pb) conical porous lining was ($2\alpha = 70°$) – 199 mm ($2\alpha = 55°/60°$) – 295 mm. Concrete was intensely crushed to the depth of 100 – 110 mm at maximum, and likely supersonic, penetration velocity, of has occurred, and while deeper penetration at a lower speed – crushing intensity decreases to two – three radial cracks (Fig. 1a). The speed of longitudinal sound waves in concrete No 1 was 3791 m/s; density – 2399 kg/m^3; the porosity – 12.5%. The longitudinal wave velocity of sound in concrete No 2 – 1051.1 m/s; density – 1867 kg/m^3; porosity – 9%. With the explosion of the charge of greater caliber weighing 23 – 24 g with a composite liner (W – Cu – Pb, 50 – 40 – 10%, by weight) on the concrete sample (concrete No 1) with water (15 mm) and steel (10 mm) barriers, the depth of penetration of the shaped jet was 600 – 700 mm. The intensity of the crushing decreased with the depth of penetration. At the end of the penetration, the sample was sometimes destroyed by a single radial crack on the base of 150 – 200 mm. Decrease in crushing degree along the penetration speed reduction in some sense simulates a decrease in the crushing action of the downhole charge while reducing the velocity of detonation. Samples from the foamed concrete where completely destroyed on the plot of shaped jet (Al) penetration, with a longitudinal crack on the plot free from penetrating impact of the shaped jet.

In more dense and durable materials penetration occurs at subsonic speeds and is accompanied by decrease in channel sizes and number of cracks (Fig. 1b). The volume of the channel in the sample is shown in Figure 1b and is about 2.8 cm^3. This is approximately 9% lower than in steel, 3.2 times less than in zinc and 3.8 less than in AMC-n (Voytenko & Bugaets, 2016). It is also confirmed by the pictures of destruction and weakening of barriers made of porous copper under high speed penetration of steel ball into them (Merzhievskii & Chistyakov, 2014). The dependence of the channel depth in rocks on the porosity for the case of shaped penetration in the first approximation, is linear (Voitenko & Shukurov, 2016), as well as for porous metals at high velocity impact of a steel ball (Merzhievskii & Chistyakov, 2014). Apparently, this is a common regularity for porous media and high-speed impact. The size of destruction zone of the porous copper with a porosity of 40.4% under the impact of the steel ball with a diameter d at a rate commensurate with the rate of the shaped jet, is ≈ (9 – 13)*d*.


(a)

(b)

Figure 1. Destruction of concrete with composite shaped jet (W – Cu – Pb) (a) and of granite with homogeneous shaped jet (Al), (the channel in granite is filled with copper powder (b))

4. FEATURES OF DEFORMATION AND DESTRUCTION OF PLASTIC MATERIALS

A whole class of rocks that are involved into development of deposits according to downhole geotechnology methods, have pronounced plastic properties. This refers to shale, argillaceous sandstones and limestones, mudstones. Therefore, the shaped penetration of plastic materials is of direct practical interest.

Experiments on the combined target ST 3 – AMC-n allowed to establish a linear decrease in the depth of penetration with a simultaneous increase of the cavern diameter with increasing content of Al for composites Cu – Al and W – Al without changing the geometric shape of the liner. Same regularity, though weaker due to the proximity of the mixture components density, characterizes the composite W – Pb (Fig. 2).

Shapes of the craters formed during the penetration of powder shaped jets of Cu – Pb, W – Cu – Pb, W – Cu – Pb – Al correspond to modern concepts of the nature of crater formation during high speed penetration of gradient shaped jets into plastic materials.

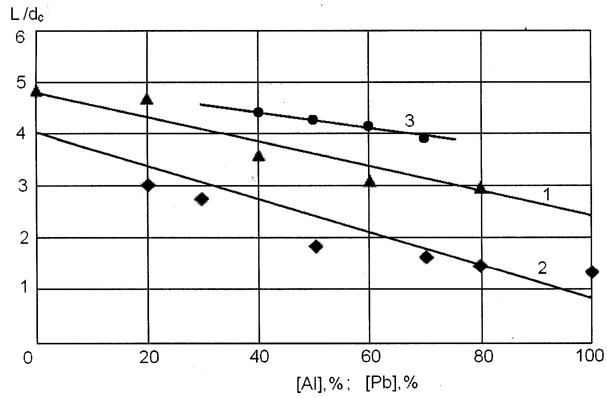
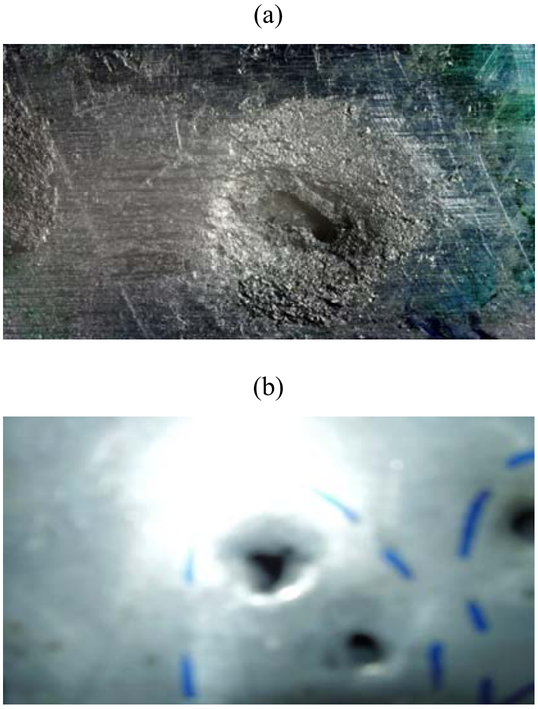


Figure 2. The dependence of the channel depth in the ST 3 on the content of Al and Pb in composites W – Al (1), Cu – Al (2), W – Pb (3)

Usually, these are channels of approximately conical shape with decreasing diameter. Reducing diameter indicates a gradual decrease in jet velocity (Andreev et al., 2004). At the end of penetration, the crater's shape often deviates from the round. The hole becomes oval or even irregularly shaped, with different deviations from the axial symmetry, up to the formation of two holes instead of one (Fig. 3b). Almost in 30 – 40% of experiments, the hole has increased in diameter 2 – 3 times at the final stage of penetration. Apparently, under the conditions where the rate of penetration is close to critical, the rear parts of shaped jets, having a larger diameter due to radial diffusion, are coming up, and their impact on the barrier results in "pasting" of the shaped jet material, increase in channel diameter and material radial ejection onto the back side of the penultimate plate. Often the channel end is clogged by the tail parts of the shaped jet.


(a)

(b)

Figure 3. Types of holes in the AMC-n barrier when the penetration of composite shaped jets (Cu – Al) (a) and (W – Cu – Pb) (b)

Improper form of a channel in the cut is related to local in-homogeneities of the material density in the moving shaped flow. This is especially typical for mixed powder materials (Cu – Al – Pb, W – Cu – Pb, W – Cu – Pb – Al), and to a lesser extent for the quasi-homogeneous ones (Cu – 90%, Pb – 10%). However, only part of the substance in the jet cross cut is sufficiently dense to pierce the barriers, while the remaining part is a low-density material – the result of the radial dissipation of the shaped jet. Numerous small caverns on the barrier around the punched hole result from the action of this part of the jet on the barrier (Fig. 3a). The formation of two holes is associated with the presence of two dense inhomogeneities in a moving jet.

It is interesting to note the feature characterizing the destruction of zinc barriers, formed from the zinc battery plates, which were previously put in an acidic medium. Apparently, there is a connection between this fact and formation of cracks of longitudinal scabbing, which is observed in the plates under the bottom of cavern (Fig. 4), where the shaped penetration has already ended.

Figure 4. Cracks with longitudinal chipping in the rear zinc plate

Cracking was observed only in zinc targets. It was absent in steel and aluminum barriers and is, apparently, associated with the formation of the surface initial effects under the influence of acid, which had developed into the cracks with longitudinal scabbing under the dynamic loading.

Sometimes during the works in the wells, we had observed the formation of the shaped jets, moving at an angle different from ~ 90°. The mechanisms of such shaped jets formation are proposed in work (Andreev et al., 2004) and boil down to initiating the process of liner collapsing by oblique asymmetrical detonation wave with the deflection of initiation point from the axis of symmetry, and, may be associated with a different density and different wall thickness of the liner. In experiments on targets of ST 3, it has been ascertained that the deviation from the axial symmetry begins after the appearance of hair cracks and signs of plastic deformation on the press – tool and the punch in the area, forming the top of the liner and the central part of the charge. Also, the asymmetrical compaction is possible not only in the main explosive slab, but also in the lower highly dispersed initiating part of the explosive (hexogen). This means that the initiating impulse, due to the presence of local inhomogeneities in the density and porosity of the explosive, will be asymmetrical, which leads to a deflection of the shaped jet from the symmetry axis.

In some industrial experiments, we had observed the formation of three instead of one shaped jets, along the symmetry axis (Fig. 5).

Figure 5. Three entry holes in the lid instead of one after the explosion of 18 g charge with a composite liner (W – Cu – Pb)

One shaped jet has formed on one axis of symmetry and two – at an angle of about 35 – 45° to the symmetry axis approximately along the line of detonation propagation in the linear initiator.

In many technological experiments, the shape of the entry hole was different from the circular, it was asymmetrical, including ones with a broken and ragged edges. The main reason for this phenomenon is a longitudinal-transverse instability of the detonation wave (DW). The reasons for this phenomenon are formulated in the monograph (Andreev et al., 2004):

– frontal instability during the transition of an initiating shock wave (ISW) into the detonation;

– structural and geological inhomogeneity of the charge, and, consequently, of the energy release also;

– amplitude and temporal characteristics of the detonation initiation;

– the emergence of explosives desensitization areas;

– an abrupt change in the direction of DW motion (“the angle effect”) in conditions close to the limit of detonation propagation.

Structural inhomogeneity behind the front of DW acting on the liner resulted in occurrence of asynchronous SW leading to the distortion of the flyer liner surface, asymmetrical collapse of liner elements and, consequently, to the formation of jets with noncircular cross sections, leading to the formation of holes of different shapes with broken and ragged edges in metallic barriers, which are often observed in the experiments conducted in the air (Fig. 3). Perhaps this is also the reason for formation of several jets instead of one. The asymmetry of the liner collapse resulting from the structural inhomogeneity behind the front of DW is intensified by the structure of the liner composite material containing local inhomogeneities (Fig. 6).

Properties of explosives in industrial charges and experimental parties, especially porosity and density, are determined by properties of the original conversional explosive and technology of its processing. Technology of processing products from explosives, usually of military application, involves grinding of the slab, washing and re-pressing in the shaped charges or other civilian products. This technological chain inevitably leads to local inhomogeneities in the explosive material. Even if pure product with the addition of phlegmatizer was used for the manufacture of individual batches, the formation of local inhomogeneities can also take place due to the unequal distribution of phlegmatizer.

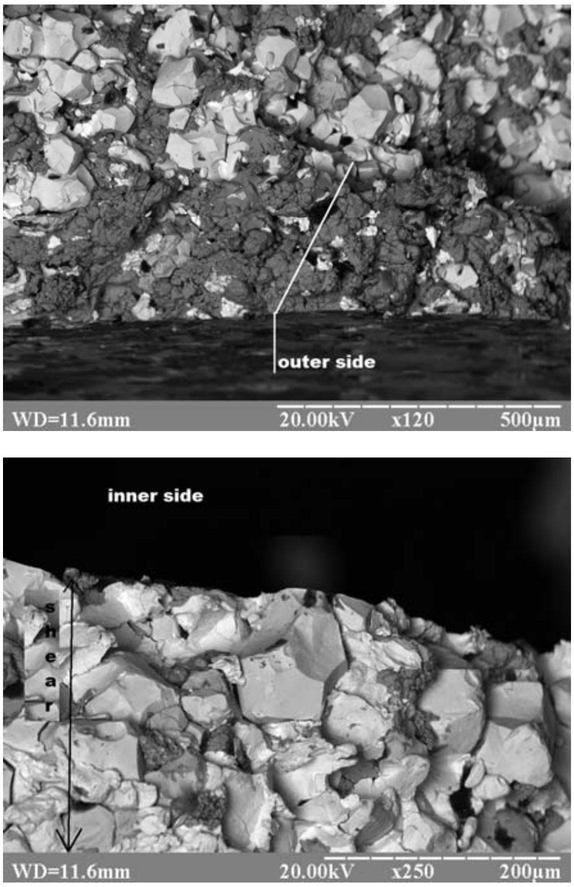


Figure 6. Distribution of components W, Pb (light gray) and Cu (dark gray) in the liner

The study of interaction products of shaped jet from porous liner (Cu – Al) and steel barrier by microprobe analysis, has showed the presence of separate composite (Fe – Cu – Al, Al – Fe – Cu, Fe – Si – Al in ascending order of quantity) particles of perfect spherical shape with diameter ~ 1.0 – 2.5 mkm, indicative of partial evaporation and the subsequent condensation of iron, copper and aluminum and admixtures (Si, K and others) (Fig. 7). This makes it possible to estimate the temperature in the zone of interaction value ~ 2735°C (the evaporation temperature of iron) and 2877°C (the evaporation temperature of copper).

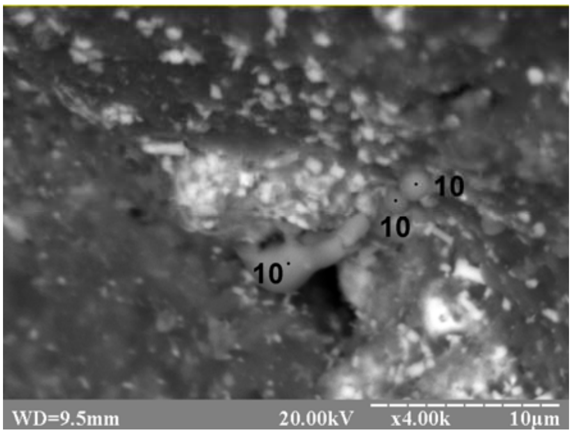


Figure 7. The morphology of the material ejected from the crater (10 – Fe – Cu – Al) (in order of decreasing of component amount)

Figure 8 shows the diffractogram of composite jet Cu – Al (80 – 20% wt.) products interaction with the barrier of AMC-n, which confirms the presence of $CuAl_2$ intermetallic compound in the composition of these products. Moreover, other unidentifiable phases of Cu_x-Al_y were found. During the formation of $CuAl_2$ the heat in the amount of ~ 330 kJ/mol is released.

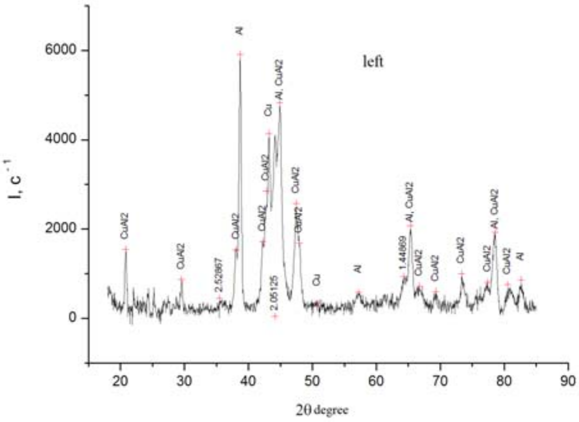


Figure 8. Diffractogram of the material formed during the interaction of the jet from Cu – Al and the barrier from AMC-n

The additional energy release during the penetration of cumulative jets of the porous liners containing Al, leads to an increase in the degree of plastic deformation, greater release of the barrier material from the crater and increase of its volume (Fig. 9).

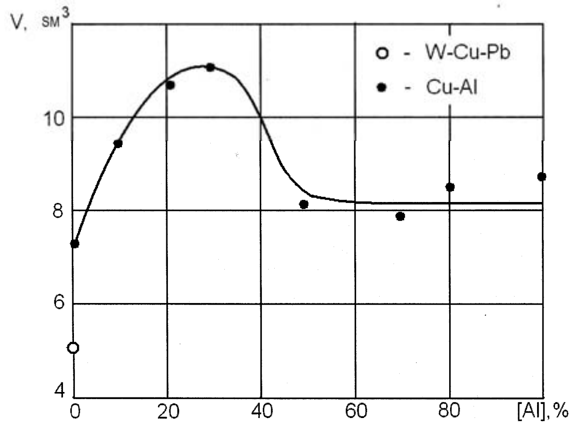


Figure 9. The dependence of the crater volume in the barrier from ST 3 – AMC-n from the Al content in the composite Cu – Al

Considering that with an increase of the amount of Al in the liner, containing copper, nickel and other metals, the energy in the zone of interaction between the shaped jet and the barrier increases, it should be expected that the intensity of rocks and other brittle materials destruction will increase with the penetration of composite jets, containing Al and metals with a melting point of ≤ 3000°.

In conclusion, we would like to note, that if the mechanisms of asymmetrical shaped jets formation are clear enough, the mechanism underlying formation of the three holes in the charge cover with a conical liner remains open and requires further research.

5. CONCLUSIONS

1. The penetration of shaped jets of industrial shaped charges into rocks with high and medium porosity at the initial stage $l_1 \sim (0.3 - 0.5)L$ (L – length of the channel) occurs in a supersonic mode with the formation of cracks around the formed channel and the intense fragmentation of free samples. Further the penetration occurs at a subsonic speed, and several radial cracks are formed around the channel.

2. Radius of the crack formation zone during penetration of copper shaped jets into concrete and sandstone of medium porosity and strength, in the case of a semi-infinite barrier, is estimated to be $\sim (9 - 11)d$ (d – diameter of the jet).

3. By adding Al into the copper liner, channel volume and rock destruction zone are increased. With increasing of density and rock strength, we can observe a decrease in the size of perforation channel and in number of forming cracks.

4. All kinds of deviations in the shape of the holes and in the area of destruction from the axial symmetry during explosions of industrial shaped charges are primarily connected with the heterogeneity of composite materials of the liner and longitudinal-transverse instability of DW.

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ABSTRACT (IN UKRAINIAN)

Мета. Дослідження закономірностей деформування й руйнування крихких і пластичних гірських порід та бетонів при вибуху промислових кумулятивних зарядів.

Методика. Метод контактних датчиків для визначення швидкості струменя; визначення швидкості ультразвукових хвиль у зразках бетону; оптична та електронна мікроскопія; рентгенофазний аналіз; вимірювання й візуальний аналіз розмірів та характеру зон деформування і руйнування.

Результати. В роботі описані експериментальні дані про деформацію та руйнування перешкод з бетону, граніту, пінобетону, сталі Ст 3, сплаву АМЦ-н і цинку вибухами кумулятивних зарядів серійного виробництва з пористим облицюванням. Запропоновано розрахункові формули для оцінки радіусу зони руйнування геоматеріалів і гірських порід у разі напівнескінченної перешкоди. Визначено причини відхилень форми отвору і зони руйнування від осі симетрії.

Наукова новизна. Визначено режими проникнення кумулятивних струменів у породи різної пористості, розміри зони руйнування навколо отвору, а також причини і механізми відхилення форми отвору від симетричної.

Практична значимість. Результати досліджень будуть використані для проектування вибухопрострілочних робіт у геотехнологічних свердловинах і можуть бути використані для конструювання ініціюючих пристроїв свердловинних зарядів.

Ключові слова: *кумулятивний заряд, кумулятивне облицювання, кумулятивний струмінь, деформування, руйнування*

ABSTRACT (IN RUSSIAN)

Цель. Исследование закономерностей деформирования и разрушения хрупких и пластичных горных пород и бетонов при взрыве промышленных кумулятивных зарядов.

Методика. Метод контактных датчиков для определения скорости струи; определение скорости ультразвуковых волн в образцах бетона; оптическая и электронная микроскопия; рентгенофазный анализ; измерение и визуальный анализ размеров и характера зон деформирования и разрушения.

Результаты. В работе описаны экспериментальные данные о деформировании и разрушении преград из бетона, гранита, пенобетона, стали Ст 3, сплава АМЦ-н и цинка взрывами кумулятивных зарядов серийного производства с пористыми облицовками. Предложены расчетные формулы для оценки радиуса зоны разрушения геоматериалов и горных пород в случае полубесконечной преграды. Определены причины отклонений формы отверстия и зоны разрушения от оси симметрии.

Научная новизна. Определены режимы проникания кумулятивных струй в породы различной пористости, размеры зоны разрушения вокруг отверстия, а также причины и механизмы отклонения формы отверстия от симметричной.

Практическая значимость. Результаты исследований будут использованы для проектирования взрывопрострелочных работ в геотехнологических скважинах и могут быть использованы для конструирования инициирующих устройств скважинных зарядов.

Ключевые слова: *кумулятивный заряд, кумулятивная облицовка, кумулятивная струя, деформирование, разрушение*

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