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ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ПАРАМЕТРОВ ФУНКЦИОНИРОВАНИЯ УДЛИНЕННЫХ ЗАРЯДОВ РАЗЛИЧНОЙ КОНФИГУРАЦИИ

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Аннотация: Работа проводилась с целью определения на основе экспериментальных данных параметров кумулятивной струи и распределения энергии в кумулятивной струе. Эксперименты проводились с помощью сверхскоростной кинокамеры СФР-2М и теневой установки ИАБ-451. Были исследованы параметры функционирования кумулятивных удлиненных зарядов с различной конфигурацией кумулятивной выемки. Определены параметры детонационных волн в зарядах различной конфигурации. Для зарядов типа УКЗ-7М, УКЗ-11М и УКЗ-13М было выявлено, что скорости детонации определяются плотностью запрессовки составов и составляют диапазон 8200÷9000 м/с. Установлены расчетные зависимости скоростей движения материала оболочки для различных конструкций с учетом и без учета прочности материала оболочки. Определены величины углов наклона фронта движения кумулятивной струи к боковой поверхности заряда. Разработанная математическая модель позволяет определять параметры системы «струя-пест» не только для начального момента формирования системы, но и для каждого последующего, вплоть до разрушения системы. В результате данного исследования предложено расширить область использования кумулятивных удлиненных зарядов в горном деле, в то время как такие заряды зачастую применяются только при проведении специальных взрывных работ.

Ключевые слова: взрывчатое вещество, кумуляция, удлиненные кумулятивные заряды, скорость детонации, кумулятивный нож, скорость разлета оболочки зарядов, численная модель, плотность энергии.

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Experimental studies on the performance parameters of elongated shaped charges of different configurations

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Abstract: The study was carried out in order to experimentally define parameters of the shaped charge jet and energy distribution in it. Experiments were performed using ultra-high-speed SFR-2M camera and shadow installation IAB-451. Performance parameters of elongated shaped charges with different cavity configurations were examined. Parameters of detonation waves in charges of different configurations were estimated. For charges of the ESC-7M, ESC-11M and ESC-13M types, it was found that the detonation velocities are determined by the density of the press-fitting of the compositions and range from 8200÷9000 m/s. Motion speed dependencies of charge shell material were established for different designs with and without taking into account material strength. Values of incidence angles between shaped charge jet front and lateral surface of the charge were identified. Developed mathematical model allows to determine parameters of the «jet-slug» system not only for the initial moment of system formation, but for each subsequent step up to system demolition. As a result of this study, it was proposed to expand the scope of the use of elongated shaped charges in mining, while such charges are often used only in special blasting.

Key words: explosive, cumulation, elongated shaped charges, detonation velocity, cumulative knife, expansion velocity of the charge shell, numerical model, energy density

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Introduction

Shaped charge effect, which is associated with the operation of charges of special design, is widely used in civil engineering. At the same time, a large number of studies is performed to extend the field of its application and to increase the performance of manufactured articles; the most rational designs of shaped charges are being developed, including elongated shaped charges (ESC). E.g., in paper [1] authors describe the application of ESC for handling metalwork, as well as the use of additive technologies for manufacturing geometrically precise objects. Results of research [2] display the details of successfully implementing cumulative cutting of large steel structures. Brian Burch in his thesis studied the use of shaped charges for underwater operations and estimated the variation in penetration depth of the cumulative knife for charges with different liner angles. Experiments demonstrated a significant decrease in the penetration capability of the charges, as compared to their use under normal conditions [3]. Paper [4] describes the application of numerical modeling in LS-DYNA in order to choose optimal parameters of the shaped charges; however, it does not provide any comparison with experimental data (motion speed of the jet and slug; jet and slug length, etc.).

Presently there are comprehensive studies on jet formation of axisymmetric shaped charges [5—8]. However, such processes, as cumulative knife formation in the ECS, the process of collapsing and parameters of liner closing have not been properly investigated, although their understanding is crucial for design and rational use of ESC. A specific feature of this research is the fact that obtained experimental results are considered not only as initial data for optimizing charge design parameters, but also as a basis for developing mathematical models of manufactured article operation.

Methods

The general approach, applied to the development of mathematical models, is a combined experimental and analytical research method.

Study on the parameters of detonation waves in charges of different configurations

In the present research we assume that detonation of considered elongated charges is characterized by a flat, non-smooth front.

From the theory of detonation wave it follows that, other conditions being equal, detonation velocity of the explosion system is primarily determined by specific chemical energy (explosion heat). However, detonation speed and other detonation parameters are also affected by physical characteristics of the charge: its diameter, density, state of matter, presence of charge shells, particle sizes. Some of the mentioned factors influence characteristics of the detonation process only in a certain variation range of the respective factor.

As we examine detonation parameters of elongated charges of different diameters, placed in a copper shell, let us consider the influence of these factors on detonation parameters of the studied charges in greater detail.

Dotrish, Cast and many other researchers [9—11] studied a dependency of detonation velocity on charge diameter. Basing on their works, it can be considered a proven fact that as the charge diameter increases, so does the detonation velocity, reaching its maximum under a certain limiting diameter d_{lim}. The general pattern of this dependency is displayed in Fig. 1.

Given that charge diameter is less than the limiting value, detonation velocity depends on the presence and characteristics of the charge shell, particle sizes of the explosive and its physical structure [12, 13]. Stationary distribution of detonation is only possible for charges with diameter $d >> d_{lim}$. With an increase of charge diameter above its critical value, detonation velocity also increases, approaching asymptotically to its limiting value. For low-density powder explosives the relative increase of detonation speed (D/D_{max}) is approximated by the ratio of charge diameters (d/d_{lim}). Thus, detonation velocity grows rapidly — with a minor increase in diameter — in the explosives with a small critical diameter.

As the studied charges contain HMX, which has a small critical diameter d_{cr} = = 1 mm and d_{lim} = 4 mm, a conclusion can be drawn that charges ESC-7M, ESC-11M and ESC-13M will have different detonation velocities, which will depend on charge density and under maximum density must not exceed 9.3 km/s. With increasing charge density, detonation velocity of explosives also increases, first rapidly, then more slowly, but its growth does not stop even under highest attainable densities. Numerous experimental data demonstrate that for explosives consisting of carbon, hydrogen, oxygen and nitrogen atoms and their compositions, optimal detonation velocity in charges with density above 1 g/cm^3 linearly depends on density.

Taking into account the above mentioned facts, the experiments were designed to estimate detonation parameters of the studied charges. In particular, such key parameter as velocity of charge detonation was calculated. Survey of the detonation initiation process was carried out using SFR-2M camera with IAB-451 shadow instrument [14, 15]. Slow-motion camera

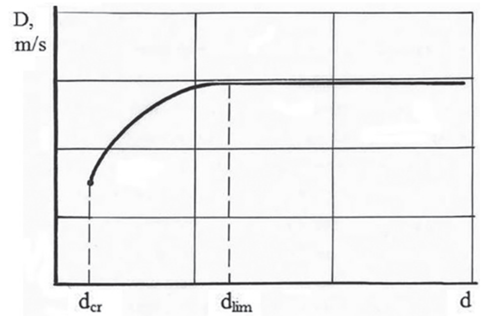


Fig. 1. Dependency between detonation velocity and charge diameter

Рис. 1. Зависимость скорости детонации от диаметра заряда

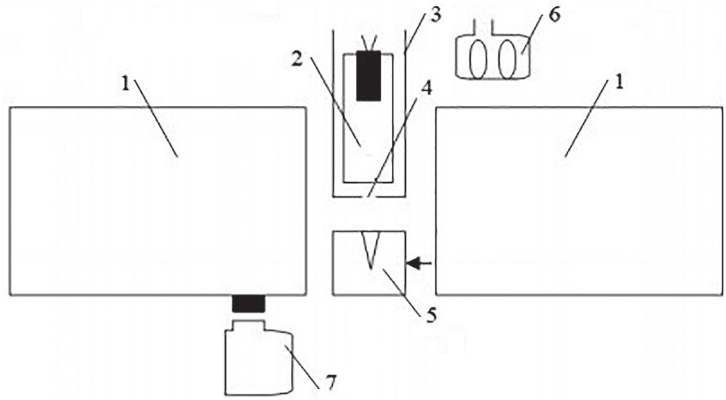


Fig. 2. Experimental facility arrangement
Рис. 2. Схема экспериментальной установки

mode was used. Initiation was performed by a relatively powerful detonator. Experiment survey was performed at camera speed of 106 frames per second. At first, the detonator was located immediately adjacent to the charge end-face, positioned perpendicular to the optical axis of IAB-451 instrument in such a way as to capture formation of the shock wave from the detonator and initiation of detonation in the charge (Fig. 2).

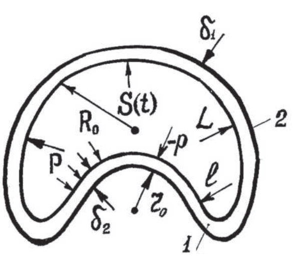
Estimation of charge shell expansion velocity for charges made of different materials

The process of cumulative knife formation and its impact on the target can be divided into a sequence of separate processes, which eventually define the efficiency of shaped charge performance. Such processes include:

- collapse of shaped charge liner, involving interaction of the detonation wave, sliding along the charge axis, with each section of the charge shell and liner and eventually defined by the velocity of charge shell motion and collapse velocity of elements in the section of a shaped charge liner;
- closure of shaped charge liner elements, resulting in the generation of shaped charge jets that form a cumulative knife;
- motion of cumulative knife to the target, associated with the elongation of jet elements due to velocity gradients along the jet, occurring in the process of its formation, and fragmentation of the jet, as its elements reach critical elongation;
- interaction between the cumulative knife and the target, which involves penetration of the knife into the medium and its depressurization.

Let us consider the first stage — the impact of the detonation wave on the charge shell and cumulative cavity. We assume that each section of the shaped charge, as the detonation wave reaches it, witnesses an instant detonation of the charge of unit length. Due to small diameter of the charge, the impact of shock release waves from the lateral side of the charge is neglected. Therefore, the pressure of detonation products is considered constant across the entire section of the charge. Under pressure the charge shell will expand, whereas the cumulative liner will shrink.

As a basis of mathematical model, describing this process, let us take the model of projecting plates, separated by a layer of explosive. Utilization of this model is reasonable for plastic materials of the charge shell, such as copper. In this case, charge shell and cumulative cavity are regarded as plates. The problem is solved



1 – cumulative cavity (first plate)
2 – charge shell (second plate)
δ_1, δ_2 – thicknesses of the first and second plates
L, l – surface lengths of first and second plates
P – pressure exerted on the first plate
p – pressure exerted on the second plate

Fig. 3. Shaped charge parameters for the calculation algorithm
Рис. 3. Параметры кумулятивного заряда для схемы расчета

basing on the laws of momentum and mass conservation. Material of the charge shell and the cumulative cavity is considered perfectly plastic medium. Expansion of detonation products obeys the isentropic law [16, 17]. Let us introduce key designations needed for the calculation of shaped charge parameters (Fig. 3).

The law of momentum conservation for this scheme can be written in the form of two equations, describing motion of the charge shell and the cumulative cavity as follows:

$$\begin{cases} M\dfrac{d^2R}{dt^2} = \alpha(\rho - \sigma_s) \\ m\dfrac{dr^2}{dt^2} = -l(\rho - \sigma_s) \end{cases}, \quad (1)$$

where σ_s is the dynamic yield strength of the shell material, regarded as backward pressure; M is the mass of the shell; m is the mass of cumulative cavity liner; r is the radius of cumulative cavity liner.

The minus sign in the second equation shows that the liner shrinks in the process of loading. The law of mass conservation can be written in the form:

$$\begin{cases} M = \alpha \cdot \rho \cdot \delta_2 = R \cdot \varphi_2 \cdot \rho \cdot \delta_2 = const \\ m = l \cdot \rho \cdot \delta_1 = \\ = (r_1 + \delta_1) \cdot \varphi_1 \cdot \rho \cdot \delta_1 = const \end{cases} \quad (2)$$

where ρ is the density of liner material; φ_1, φ_2 are the central rotation angles of the shall and the liner, respectively.

The change of pressure in time can be written as follows:

$$P(t) = \frac{\rho_{ex} \cdot D^2}{8}\left(\frac{S_o}{S(t)}\right)^3; \; S(t) = \frac{L^2 - l^2}{4\pi}, \quad (3)$$

Inserting (2, 3) into the set of equations (1), we obtain the expression:

$$\frac{d^2R}{dt^2} = \frac{R\varphi_2}{M} \cdot \left[\rho_{ex}D^2\left(\frac{S_o}{S(t)}\right)^3 - \sigma_s\right] = \tau_2(R,t)$$

$$\frac{d^2r_1}{dt^2} = -\frac{r_1\varphi_1}{m} \cdot \left[\rho_{ex}D^2\left(\frac{S_o}{S(t)}\right)^3 - \sigma_s\right] = \tau_1(r_1,t) \quad (4)$$

Initial conditions will take the form:

$$\left.\frac{dR}{dt}\right|_{t=0} = \left.\frac{dr_1}{dt}\right|_{t=0} = 0$$
$$\left.R\right|_{t=0} = R_0; \; \left.r_1\right|_{t=0} = r_{1,0} \quad (5)$$

Solution of the system (4) with initial conditions (5) was obtained numerically using Runge-Kutta method [18 – 20]. In this method, the function and its derivative are defined as follows:

$$\begin{cases} R_{k+1} = R_k + R_k'\Delta t + \dfrac{1}{6}(k_1' + k_2' + k_3')\Delta t \\ r_{1,k+1} = r_{1k} + r_{1k}'\Delta t + \dfrac{1}{6}(k_1 + k_2 + k_3)\Delta t \end{cases} \quad (6)$$

$$\begin{cases} \dfrac{dR_{k+1}}{dt} = R_{k+1}' = R_k' + \dfrac{1}{6}(k_1' + 2k_2' + 2k_3' + k_4') \\ \dfrac{dr_{1,k+1}}{dt} = r_{1,k+1}' = r_{1,k}' + \dfrac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \end{cases} \quad (7)$$

where k is the number of iteration step.

The system was solved with a time step (Δt = 0.01 μs). The calculation of cumulative liner motion was performed until the moment of its collapse (r).

Study on the process of shaped charge jet formation and energy distribution in the shaped charge jet

Under the influence of sliding detonation wave on the cumulative cavity liner, liner elements converge in the center of the cumulative cavity and form a solid compact mass — a slug [21, 22]. External and internal layers of metal in the slug are characterized by their velocity gradient that forms the jet, which attracts metal from internal layers of the lining and especially the slug.

At the initial stages, jet and slug motion should be regarded as a single process, as the «slug-jet» system breaks into separate masses only at the moment, when inertial forces in the metal overwhelm adhesive strength [23].

Fig. 4 presents a film record of the formation and motion of the shaped charge jet, taken from the end-face of the charge. As seen from the record, the only thing visible in the initial moments (up until t = 5 μs) is the motion of the charge shell. Within the same time period, formation of the shaped charge jet and slug takes place and they start to move together. Only after t = 5 μs the shaped charge jet emerges and leaves the moving shell behind. Note that the jet and the slug move together only during 10—15 μs after charge initiation, and then the jet breaks away from the slug.

Therefore, at early stages of shaped charge explosion it is reasonable to regard combined motion of the «jet-slug» system. As seen from Fig. 4, within this period the cumulative knife profile can be considered rectangular.

These assumptions allow to construct a mathematical model for the initial stage of jet motion and to estimate its kinematic energy [24—26]. Kinetic energy (E) and momentum (J), imparted to the shaped charge liner by the detonation wave can be defined as:

$$J = \int_0^m v(m)dm = m\int_0^{\varphi_0} v(\varphi)d\varphi$$
$$E = \frac{1}{2}\int_0^m v^2(m)dm = \frac{1}{2}m\int_0^{\varphi_0} v(\varphi)d\varphi \quad , (8)$$

where m is the mass of shaped charge liner; $v(\varphi)$ is the cross-section distribution of collapse velocity [27, 28]

$$v(\varphi) = v_m\left(\cos^{1.7}\varphi_0 + 0.12\cdot\sin^9\varphi_0\right), \quad (9)$$

where v_m is the collapse velocity of cumulative cavity apex; φ_0 is the rotation angle of cumulative cavity. In the studied shaped

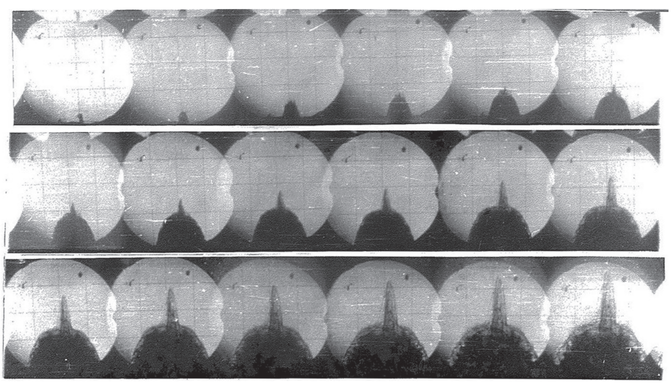


Fig. 4. Film record of the formation and motion process of the shaped charge jet
Рис. 4. Кинограмма процесса формирования и движения кумулятивной струи

charges, the angle φ_0 lies in the interval 135—145°, which corresponds to integral values in formula (8) $E = 0.8v_m$ and formula (9) $J = 0.72v_m$. The value v_m is defined as the maximum velocity of liner motion.

According to conducted research (9—11), velocity is distributed linearly along the shaped charge jet:

$$v = v_0 - (v_0 - v_n) \cdot \frac{x}{l}, \qquad (10)$$

where v is jet velocity in a certain point, located at the x distance from the jet head of length l; v_0, v_n are the velocities of jet head and jet tail, respectively. Hence, momentum and energy of the system «slug-shaped charge jet», considering their shape, can be written as follows:

$$J = \int_0^l v dm = \int_0^l \left[v_0 - (v_0 - v_m) \cdot \frac{x}{l} \right] r_1 \cdot \rho \cdot dx = \\ = \rho \cdot r_1 \cdot l \cdot \left(\frac{v_0 + v_n}{2} \right)$$

$$E = \frac{1}{2} \int_0^l v^2 dm = \int_0^l \left[v_0 - (v_0 - v_m) \cdot \frac{x}{l} \right] r_1 \cdot \rho \cdot dx = \\ = \frac{\rho \cdot r_1 \cdot l}{6} \cdot \left(v_0^2 + v_n \cdot v_0 + v_n^2 \right) \qquad (11)$$

where r_1 is the lateral size of the jet; ρ is the density of jet material.

Thus, a set of equations was obtained to estimate unknown parameters in the «slug-jet» system. The mass of the shaped charge jet itself can be derived from hydrodynamic theory of converging jets, under the assumption that liner elements collide under the angle φ, defined by central angle of each element. In this case, the mass of the shaped charge jet is defined by expression:

$$m_j = m \int_0^{\varphi_0} \sin^2 \varphi \cdot d\varphi, \qquad (12)$$

Knowing the jet mass and total length of the «jet-slug» system, let us derive the jet length from the ratio:

$$\frac{m_j}{m} = \frac{l_j}{l}, \qquad (13)$$

as well as velocity in the tail jet using equation 10.

Results and discussions

Results of experimental estimation of detonation parameters for charges of different types were obtained using film records. For example, Fig. 5 presents a record of the shock initiation process in the 110 mm long segment of the charge. In frame 3, initiation of charge detonation is clearly visible. In frame 4 detonation passes through the charge, in frame 6 the detonation ends. Analysis and statistical processing of the record demonstrates that for ESC-7M charges the detonation process occurs with the velocity of 8,125 m/s, for ESC-11M charges — 8,750 m/s and for ESC-13M charges — 9,200 m/s. Analysis of the film record also shows that the angle of charge shell expansion with respect to the charge axis from the side of the cumu-

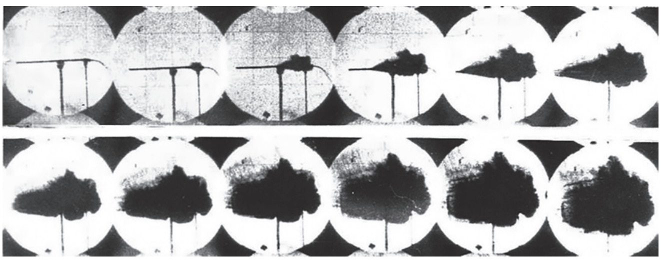


Fig. 5. Film record of detonation passing through the elongated charge after end-face initiation (time between frames is 4 μs)

Рис. 5. Кинограмма процесса прохождения детонации по удлиненному заряду при инициировании в торец заряда (время между кадрами 4 мкс)

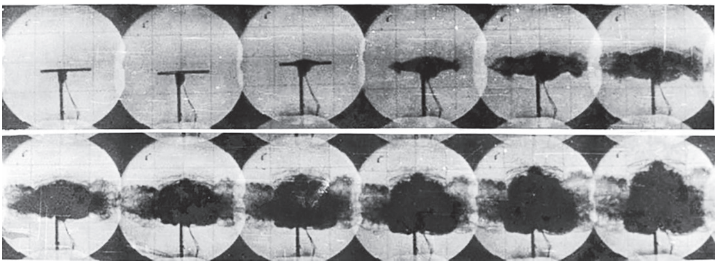


Fig. 6. Film record of detonation passing through the elongated charge after central initiation (time between frames is 4 μs)

Рис. 6. Кинограмма процесса прохождения детонации по удлиненному заряду при инициировании в центр заряда (время между кадрами 4 мкс)

lative cavity is different for all three types of charges and varies between 19° and 21°.

In the second set of experiments the charges were initiated using a detonator, located on the opposite side from the cumulative cavity, in the center of the charge (Fig. 6). Analyzing the film records, we discovered that initially the angle of charge shell expansion was smaller than in the previous experiment. However, as the detonation passed through the charge, it took on the same values as in earlier cases. Notably, the detonation spreads across the charge equally in both directions and adopts the same values, as in end-face initiation of the charge.

Estimation results of shell velocity expansion for charges made of different materials, obtained using described mathematical model for three ESC types, are presented in Fig. 7, 8. Dependency of charge shell and cavity liner velocity on time and different shell materials for ESC-7M is displayed in Fig. 9. Fig. 10 demonstrates a comparison between experimental and calculated velocity-time dependencies with and without taking into account the strength of shell material.

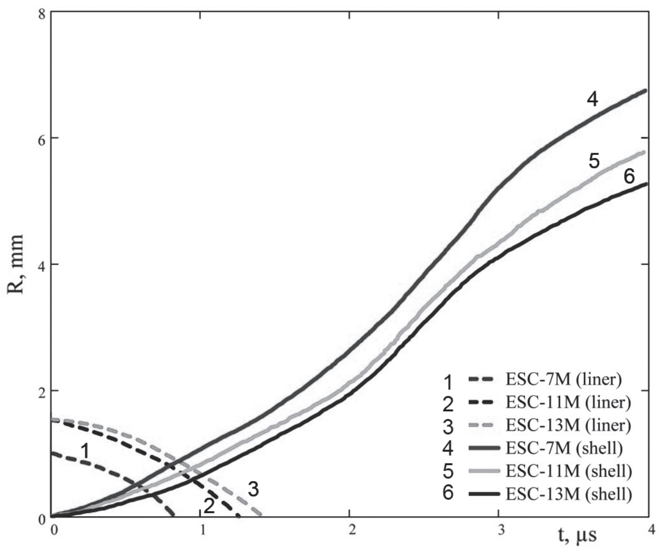


Fig. 7. Time variation of ESC shell and liner sizes

Рис. 7. Изменение размеров оболочки и облицовки УКЗ во времени

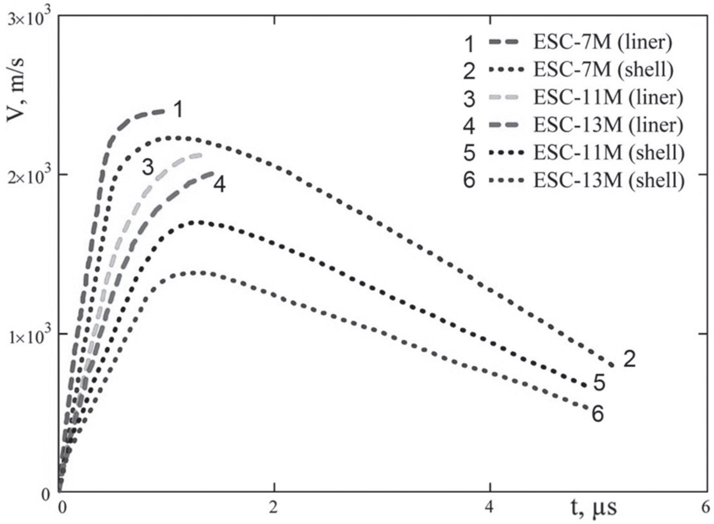


Fig. 8. Time variation of ESC shell and liner velocity taking into account material strength
Рис. 8. Изменение скорости движения оболочки и облицовки УКЗ во времени с учетом прочности материала

Analysis of results demonstrates that ESC-7M shell has the greatest velocity. This is explained by the fact that the shell and the cavity of this charge have the greatest mass. Collapse of the cumulative cavity occurs in the timespan from 0.8 µs (ESC-7M) to 1.5 µs (ESC-13M). The shell of the shaped charge continues to expand after that.

Comparison between experimental and calculated data shows that shell strength should not be taken into account, as shell velocity stays practically the same in the course of its motion. Calculated results, obtained without considering strength, are very close to experimental data and, hence, this calculation method can be used to describe shell motion. It should be noted that

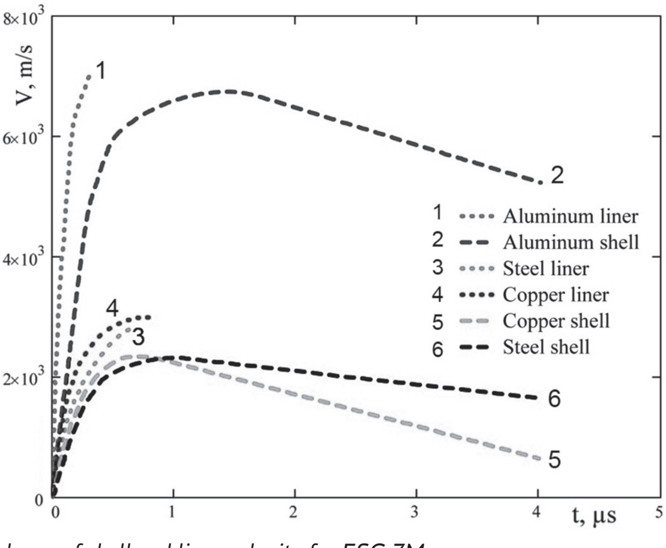


Fig. 9. Time dependency of shell and liner velocity for ESC-7M
Рис. 9. Зависимость скорости движения оболочки и облицовки УКЗ-7М во времени

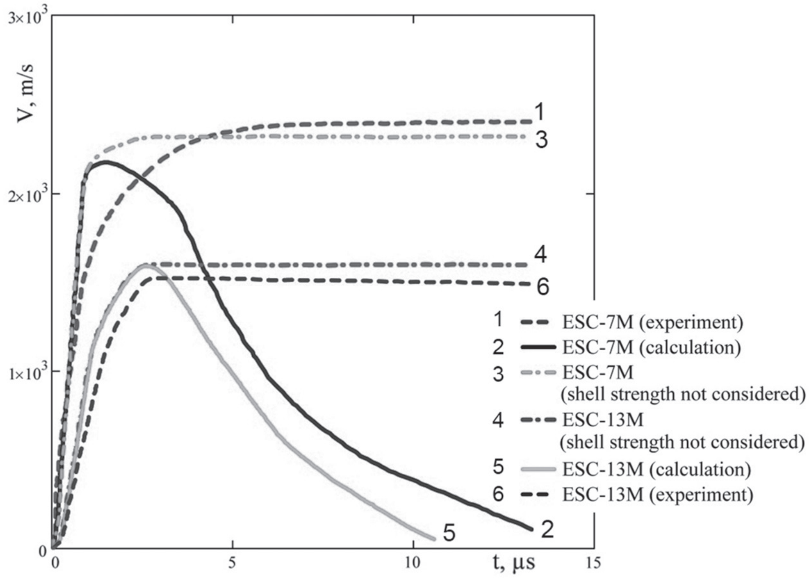


Fig. 10. Comparison between experimental and calculated dependencies of shell material velocities
Рис. 10. Сравнение экспериментальных и расчетных зависимостей скоростей движения материала оболочки

in actual experiments it takes the shell a slightly longer time to gain the velocity close to the maximum value, compared to the calculations. Therefore, liner collapse in the experiments also takes longer than calculated. This is explained by certain inertia of shaped charge material, which cannot immediately pass from standstill to the state of motion at maximum velocity.

Results of parameter estimation for the «jet-slug» system are presented in Table. Analysis of results, presented in the Table, demonstrates that the shaped charge jet carries the major share of energy in the «jet-slug» system. It should be noted that the separation of the «jet-slug» system into the jet and the slug is quite arbitrary. However, basing on the obtained results of shaped charge jet length, a conclusion can be made that the entire cumulative cavity contributes to the formation of jet length.

Velocities of the jet head, obtained in the processing of film records (Fig. 4) show a good agreement with calculation results. So, jet velocity of ESC-7M charge lies in the range 2,950 – 3,000 m/s, ESC-11M – 2,700 – 2,900 m/s, ESC-13M – 2,500 – 2,800 m/s.

Values of incidence angles between shaped charge jet front and lateral surface of the charge, estimated using the method described above – a ratio of jet head velocity to the velocity of charge detonation, lies in the interval 19 – 21° for ESC-13M,

Calculated values of parameters in the «jet-slug» system
Расчетные значения параметров системы «струя-пест»

Charge type	Velocities			*l*, mm	l_j, mm	m_j, g	r_1, mm	*E*, kg	E_j, kg	*J*, kg·m/s	J_j, kg·m/s
	V_0, m/s	V_n, m/s	V_c, m/s								
ESC-7M	3,10	720	2,50	3.5	0.9	1.5	0.2	1,962	1,015	0.624	0.882
ESC-11M	2,90	630	2,15	5.8	1.8	3.8	0.3	2,681	1,869	2.72	1.16
ESC-13M	2,60	580	1,80	6.31	2.02	4.5	0.32	2,900	1,900	2.98	1.31

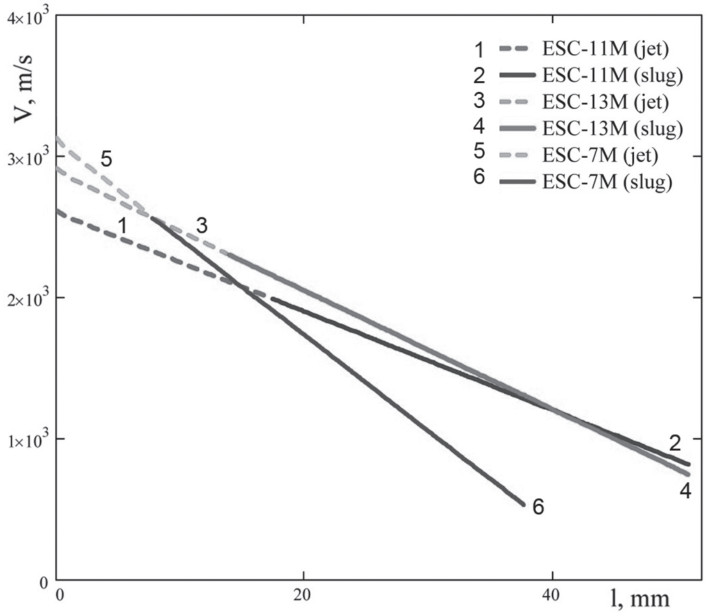


Fig. 11. Lengthwise distribution of velocity in the «jet-slug» system
Рис. 11. Распределение скорости системы «струя-пест» по ее длине

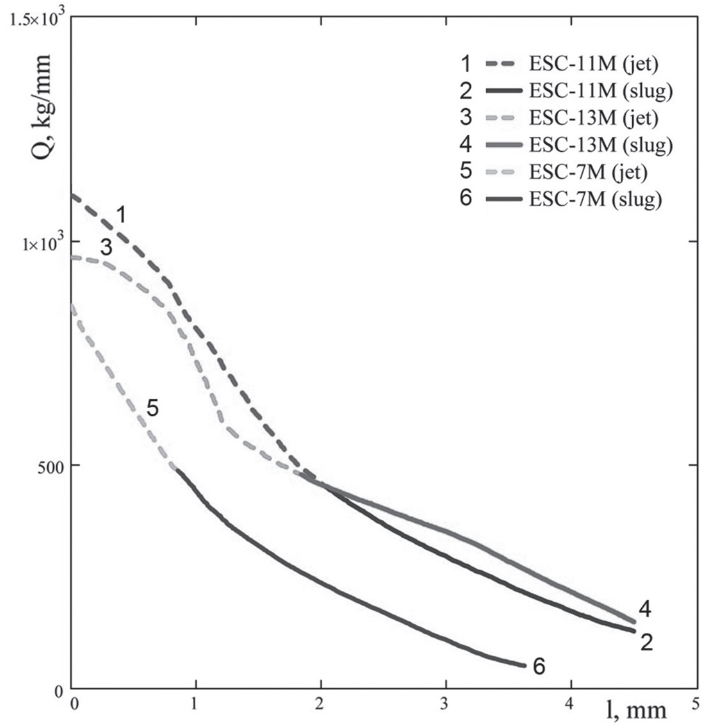


Fig. 12. Lengthwise distribution of energy density in the jet
Рис. 12. Распределение плотности энергии по длине струи

20 – 22° for ESC-11M and 23 – 24° for ESC-7M charges, which corresponds to ratio values, varying from 0.31 to 0.415.

Fig. 11, 12 display a lengthwise distribution of velocity and energy density for three types of shaped charges in the formed «jet-slug» system. It is visible from the charts that energy densities of ESC-11M and ESC-13M charges are close to each other and significantly exceed energy density of ESC-7M charge.

Integration of energy density curve (Fig. 11) over length allows to estimate the value of energy for separate elements of the «jet-slug» system [29, 30]. Developed mathematical model allows to determine parameters of the «jet-slug» system not only for the initial moment of system formation, but for each subsequent step up to system demolition.

Shaped charge effect, associated with exploding charges of special design, is widely used in specific blasting operations [31 – 33]. As a result of this study, it is proposed to extend the field of ESC application in the mining industry, particularly in the extraction of mineral resources [34, 35].

Conclusion

A suggestion to apply ESC in the mining industry is supported by the values of shaped charge parameters, obtained in this study. So, for charge types ESC-7M, ESC-11M and ESC-13M it was estimated that detonation velocities are determined by the density of explosive compaction and vary in the range 8,200÷9,000 m/s. The value of charge shell velocity affects such parameter of ESC functioning, as the incidence angle between the motion front of the shell, liner and, eventually, the cumulative knife, and the lateral surface of the charge.

We assume that subsequent research should be aimed at constructing mathematical models, which will describe interaction of these ESC types with the target, performing high-speed survey for a detailed study on cumulative knife penetration into the targets made of different materials, as well as carrying out industrial experiments. It is planned to examine the application of additive technologies in order to manufacture materials for ESC liners.

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