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STUDY ON EXPLOSION IN DIFFERENT CROSS-SECTIONAL SHAPE CHARGE CAVITY IN TENSILE STRESS FIELD

Purpose. To study nature and patterns of main cracks development in a solid medium during an explosion of explosive charge in charge cavity with longitudinal symmetrical incision and various cross-sectional shapes

Methodology. Experimental methods were used to study process dynamics, nature and direction of cracks development during the explosion of explosive charge of various shapes and their transformation into a clear optical image under the influence of a focused laser beam through an optical system – the method of caustics. Study on stress field changes under the combined effect of static and dynamic loading on fracture medium by polarisation-optical method. Based on correlation analysis methods, study results are analysed.

Findings. It is experimentally proved that changing angle from 0 to 45° between longitudinal cut and plane jointly affected by tensile stresses and explosion action promotes opening of main cracks both parallel and perpendicular to cut direction. Dependences of propagation of main cracks caused by an explosion in model under different loading conditions are constructed. Calculations of stress intensity coefficients in medium under explosion and tensile stresses were performed.

Originality. Improved research methodology for establishing the mechanism of explosive loading of solid media by explosion of explosive charge of different cross-sectional shapes is proposed. Physical mechanism of main cracks formation and propagation in blast cavity under action of explosive charge of different shapes under different conditions of dynamic loading is revealed. Dimensions of symmetrical longitudinal incision and spatial location of crack along direction of tensile stresses are substantiated. Also, an idea of using a directed explosion to form a protective strip in the rock mass was further developed.

Practical value. The research results received can be necessary for developing new technical solutions to provide additional protective measures in the field of environmental and seismic safety of protected civil and industrial facilities during blasting operations in quarries and mines.

Keywords: *borehole, explosion, solid medium, caustic method, crack, tensile stress*

Introduction. Improving intensity of rock crushing using explosive energy is a topical issue. Solving this problem is inseparably connected with increase in explosive energy transformed into destructible part of the rock mass. Application in practice of the new destruction methods of strong rocks, which are implemented by using new designs of charges with different shape of inner surface of blasting cavity (for example, symmetric annular and longitudinal notches, simulating the top of formed crack; having triangular or square shape in section) will improve quality and efficiency of blasting operations with reduction of dynamic and seismic impact on buildings (structures), rock mass around the blasting borehole. These methods are widely used in directional blasting of buildings (structures) in demolition [1], solving complex engineering problems at destruction of strong rocks, for example, at opening, preparation and extraction of minerals at deep horizons of mines (mines), construction of underground structures of various technological purposes in conditions of stress-strain state (SSS) [2]. Therefore, consideration of this factor in initial phase of the explosion on the change in stressed state of medium around explosive cavity comes down to application of such design of charge which will change direction of spreading and formed cracks that improve effectiveness of the explosion. Consequently, the explosion mechanism in a charge cavity having, for example, a symmetrical longitudinal notch will contribute to concentration at the top of maximum stresses from the explosion action to tangential plane of rupture [3].

Progress in computer technology has provided effective analytical simulation tools: finite [4] and discrete element methods [5], allowing researchers to study action of directional blast loading mechanism of solid medium in notch prepared along length of borehole in initial static stress field (for example, numerical calculation by finite element method for elastic-dynamic problem) by multiple simulation [6]. At the same time, numerical solution on stress field distribution in rock mass from an explosion of explosive charge of different shape: round, square and triangular [7] allowed confirming efficiency of explosion energy transfer and degree of media crushing on sample models [8].

Considering the above, as well as the identified problems, whose solution without use of modern theoretical and experimental research methods does not provide sufficient reliability, convergence of research results and can not serve as a basis for their implementation in practice. On this basis, study on behaviour and propagation of crack in apex of notch along the length of a borehole (well), caused by the explosion, under initial tensile stress should be applied combined method of research: method of theoretical analysis and physical simulation on samples of solid media under their dynamic loading, which can serve as a basis for development of recommendations on conducting of drilling and blasting operations, application in complex mining-geological conditions of minerals production and construction of underground structures.

Literature review. Domestic and foreign scientists have carried out a number of studies which have produced interesting results. So, in the middle of the 60's, Drukovan M. F., in the late 70's Fourni, Chernikov A. G., and in the middle of 80's Efremov E. I., Avdeev G. F. and other researchers have firstly conducted series of experiments on models to study crack behavior and proved that changing of explosive cavity (borehole, well) shape along its length can effectively control direction of crack formation in rock. The theoretical studies allowed the authors to describe deformations of nonlinear elastic anisotropic body with a crack normal detachment, and at its apex [9], where there is a zone of pre-fracture taking into account the flat stress state [10]. Developing models of rock mass behavior under explosive loads, Kuznetsov V. M. (1977) proposed an original model of crack behavior as applied to anisotropic rock mass under dynamic loading (explosion).

To verify possibility of further application of Fourni method and their implementation in practice, explosions of borehole charges with longitudinal notches were carried out, which allowed establishing that presence of notch along borehole length can minimize formation of cracks around explosive boreholes and degree of their spreading beyond boundaries of formed cracks at the tops of longitudinal notch. For example, the authors of [11] used high-pressure waterjet cutting method for preparation of blast cavities with longitudinal notches as a cutting device during tunneling of large cross-section using drilling and blasting operations.

Stockwell and other researchers [12] have proven that using incised explosive charge structures during blasting contributes to effective transfer of blast energy to destroyed rock masses and reduction of burrs and overhangs on tunnel (excavation) surface during fracture propagation during construction of underground structures.

In [13], Liu, et al. outlined experimental results and their analysis in fracture of rock samples with an explosive charge having a circular, square and symmetrical notch in cross-section, using caustic method. They observed crack propagation behavior caused by an explosive explosion in a cavity with an incision and found that such cracks formed during specimen loading do not attenuate, which created the background for theoretical description of the assumed form of directional cracking in an explosive cavity (borehole). This is confirmed by numerical simulation of the explosion action at the initial stage of fracturing, given in [14]. It was found that the use of a longitudinal notch in the borehole (well) during the blast allows one to control energy transfer to the rock mass and reduce excessively large fracture area in the vicinity of the explosive cavity (borehole, well), which has a positive effect on the efficiency of rock failure. However, as noted in the above research results, we are talking only about the propagation and behavior of cracks under the influence of the stress wave caused by the explosion, without taking into account the influence of the initial static stress field. Consequently, the analysis of scientific research results has made it possible to formulate the main conclusions which recommend developing only engineering solutions to improve blasting in complex mining and geological conditions.

Researches have shown that the presence of an initial static stress field has a great influence on the efficiency of the explosion action. So, authors [15] researched possibility of using blasting method for tunneling, laid under the sea bed. They found out that the pressure of big mass of overhead sea water column promotes the formation of NAM of rock mass, having big negative effect both on tunneling process and stability of tunnel's lateral walls. In this case, as stated by Jahn [16], studying behavior of fractures at blasting, having symmetric longitudinal notches along the length of explosive cavity, considering initial static compressive stress under dynamic loading of solid media, it is established that the character of stress field formation around explosive cavity is also affected by gaseous detonation products (GDP). This applies to massifs of ejection-prone rocks (ejection-prone sandstone), dangerous for methane gas explosion, which leads to release of large volume of rock at its explosion. Such behavior of the stress-strain rock massif significantly worsens explosion efficiency, as confirmed in his work and Konicek [17], and in [18] the effectiveness of applied DBO technology for unloading rock massif over an extended span of built deep tunnel proposed an interesting technical solution in terms of content. The idea is to reverse the initiation of explosives contained in a sealed cartridge and placed in an explosive cavity drilled in the tunnel roof, which provides maximum unloading from the static compressive stress of the overlying rocks.

The processes of explosive fracture of rocks in stress-strain state during deep tunneling were evaluated numerically by simulation using LS-DYNA software [19]. The modeling results have shown that rock massif SSS has significant resistance to rock fracture in radial direction with respect to tunneling direction as well as to restraint of rock plastic deformation zone formation during its fracture around longitudinal symmetric notch. A similar mechanism of rock failure was found in soil of tunnel excavation by blasting, which significantly influenced the speed of tunneling [20].

The above research studies on rock destruction by blasting under the action of initial static compressive stress field showed the reduction of their destruction efficiency while using traditional methods of blasting. However, study on the mechanism of action of directional explosion in the destruction of rocks, which is formed in explosive cavities having longitudinal symmetrical notches and being in a state of initial static tensile stress, remain unstudied.

Application in practice of Fourni's method (1981) in difficult mining and geological conditions in the process of sinking works and unloading of rock mass, these actions contribute to redistribution of stresses in the vicinity of excavation under the action of tensile stresses in the rock mass.

Therefore, research results presented in this work will make it possible to eliminate drawbacks of previously obtained experimental data about the influence of longitudinal symmetrical notches in explosive cavities on propagation and behaviour of fractures caused by the explosion in the massif under initial static tensile stress and this paper is devoted to this problem.

The purpose of paper is to study the character and patterns of main fracture development in a solid medium during the explosion in a charge cavity with a longitudinal symmetrical notch and different cross-sectional shape.

Methodology, materials, equipment, presentation and discussion of research results. Considering difficulty of rock sampling and impossibility to estimate the mechanism of different cross-sectional shape explosive charge during development of process dynamics, nature and direction of crack development, the caustic method proposed by Fourni (1981) and Kutter (1971) has been applied for research, photoelasticity was firstly described by Brewster (1815) in his study on stress field development of optically active materials under loading, which assumed properties of birefringent optically anisotropic crystals. Later, photoelasticity effect was developed and realized in polarization-optical method developed, tested, and proposed for investigations by V. M. Komir (1972), I. F. Vanyagin and I. P. Sukharev (1990) with respective modification.

Caustic method was developed on the basis of experimental mechanics and is used to measure singular material parameters and transform them in the area of high stress and strain concentration into a clear optical image by exposing the material to a family of enveloping beams (special lines or surfaces) not converging in one point, near which the intensity of light field increases dramatically [21].

One of directions for studying singular material parameters is the use of optical quantum generators (OQG) – lasers and optical systems (OS) with required parameters.

For studying crack propagation in solid media by explosive charge with symmetrical notches on surface of explosive cavity, results of research on models made of optically active material – organic glass (polymethylmethacrylate – PMMA), with analogous properties of brittle fracture inherent to rock are worth attention.

By the research methodology, *two series of experiments were planned* on flat models under the same dynamic loading conditions.

For the *first series*, samples have flat models 200 × 200 × × 15 mm in the center of which explosive cavities 5–6 mm in diameter were prepared, with a symmetrical notch on the lateral surface 2 mm deep and opening angle φ equal to 60°, respectively. In each group of specimens (two specimens in each group) formed notches on the surface of the explosive cavity at an angle β: the *1st* – 90° to the horizontal plane of the model; the *2nd* – 45° relative to the axis of the explosive cavity. The *1st* group of models was destructed without tensile static stresses equal to 0 MPa, and the *2nd* group with a tensile load equal to 5.0 MPa.

During the *second series* of experiments, flat models with 150 × 150 × 15 mm dimensions with the following blast parameters were used: the *1st* group with a cylindrical blast cavity; the *2nd* group with an incision at angle β equal to 90° to the horizontal model plane; the *3rd* group with an incision at angle β equal to 45° relative to axis of blast cavity; the *4th* group with an incision parallel to horizontal model plane; the 5^{th} group with triangular and the 6^{th} group with square cross-sectional shapes respectively. Conditions of models' dynamic loading are similar to those for the first series of experiments, but without influence of static tensile stresses on the destructible medium.

According to the caustic method, experimental models to study the nature of crack propagation by explosion with an incision were carried out on the developed experimental stand of Dnipro University of Technology in conditions of "State Enterprise Scientific and Production Association Pavlohrad Chemical Plant" on the platform of mixed dynamic-static loading system, which includes a testing machine MTS, OCG – AMPHOS laser, with the following characteristics:

- output power up to 1000 W; pulse energy 20 mJ; pulse duration 1 ps, threshold voltage U_{thr} = 1400 V; threshold pump energy E_{thr} = 105 J; generation energy E_g = 0.17 J and with variable beam diameter d = 2-4-10-3 cm, high-speed video camera i-SPEED7 with video recording speed up to 1 million frames/s and optical system (OS) shown in Fig. 1.

Before experiments are carried out, one end of the sample is the PMMA model, fixed rigidly to stationary platen through a punch and the other end is fixed to the moving platen of the testing machine. The load and strain values of PMMA specimen during the whole testing process are recorded and transferred to PC. Dynamic (explosive) loading of the PMMA specimen is carried out by detonation of high-breezing explosive charge of 100 mg of PETN placed in an explosive cavity drilled in the model centre. Transmission of initiation pulse to explosive substance is carried out by a waveguide of non-electric initiation system (NIS), one end of which is placed in an explosive cavity, and the other end is connected to a detonator, connected to high voltage line of the PIV100M. A pulse generated by the explosive device is applied to detonator's glow bridge transmitted through the NSI waveguide to explosive charge.

Theoretical studies. During explosion the walls of charge cavity are subjected to detonation and shock wave at insignificant initial static stress with formation of crack system on the cavity surface [22]. We will use physical model of main crack propagation in a rock mass caused by explosion in cylindrical explosive cavity with longitudinal symmetric sharp-angled notch, which was described earlier in [23] and is shown in Fig. 2.

The model suggests that, under the action of detonation and shock wave pressure pulses caused by the explosion, a stress wave moves inside the notch behind their front. Reaching its inner lateral surface and reflecting from it caused the excitation of a strong dynamic shock with formation of intensive crushing zone (plastic deformations) on the surface and at apex of notch. Moreover, minimum values of compressive stresses near notch apex became basis for formation of tangential and minor tensile stress zone, which resulted in decrease in crack growth rate and, finally, crack bursting in places of initiation. Meanwhile, the stress wave concentration in direction of notch apex promoted formation of microcrack system up to borders, where the beginning of main crack nucleation was detected.

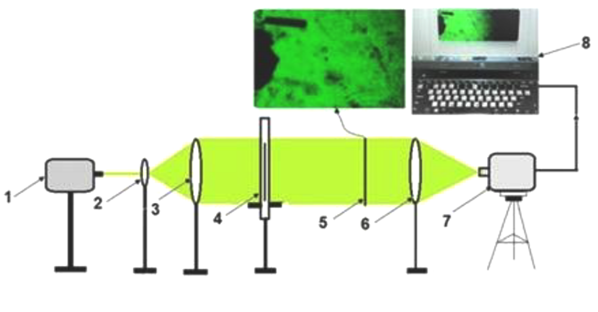


Fig. 1. Schematic diagram of experimental stand:

1 – laser; 2 - beam expander; 3, 6 – focusing lenses; 4 – platform of the MTS testing machine with the model; 5 – process image; 7 – high-speed video camera; 8 – computer

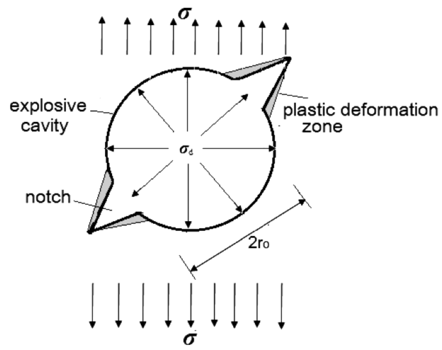


Fig. 2. Physical model of main crack propagation in an explosive cavity with a notch under blast action

To describe the stages of crack formation in an explosive cavity with a longitudinal symmetrical sharp-angled notch, according to the above model, consider another physical model in the form of an extended rock mass with an explosive cavity in the center (radius r_0) with formation of main cracks caused by explosive charge [23].

Let us assume that rock mass located in the field of vertical uniformly distributed tensile stress σ and having in explosive cavity notch with angle β with the direction of applied tensile stress field, which is subjected to explosion energy. In such an arrangement of charge cavity elements (longitudinal notch), with respect to the direction of applied tensile stress field, the action of stress wave promoted crack growth at the notch apex, which was subsequently amplified by the action of penetrating GDP due to weakening of stress wave action caused by the explosion.

The main stages of crack generation in an explosion-induced cylindrical cavity with a longitudinal symmetrical sharp-angled notch are shown in Fig. 3.

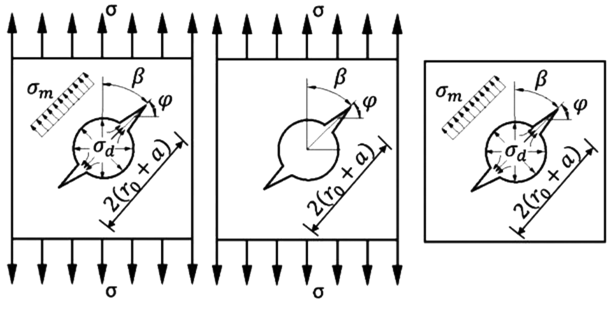
Assuming that crack propagation length is $2a$, then to simplify the calculation of quasi-static pressure parameters σ_m caused by increased volume of penetrating GDP and action of σ_d on the blast cavity (borehole) wall, it has been found that its propagation character is close to linear.

The action of initial tensile stress σ on sample is shown in Fig. 3, *b*. The loading intensity at the apex of the crack can be represented as

$$K_{\mathrm{I}}^{c} = \sigma\sqrt{\pi(r_o + a)}\sin^2\beta;$$
$$K_{\mathrm{II}}^{c} = \sigma\sqrt{\pi(r_o + a)}\sin\beta\cos\beta,$$

where K_{I}^{c} and K_{II}^{c} are static stress intensities in models under different loading conditions (loading conditions of Variant I and Variant II, respectively) under the action of initial tensile stress.

Under the action of quasi-static pressure σ_m of explosive gases (Fig. 3, *b*) stress intensity factor at crack apex can be de-



a *b* *c*

Fig. 3. Explosive physical model of the basic stages of crack formation in explosion cavity with a longitudinal symmetrical sharp-angled notch

termined under the following condition, according to the approach proposed by Zorin S. A. and Korneev V. M.

$$K_{\mathrm{I}}^{d} = \sigma_m F\sqrt{\pi(r_o + a)}; \quad K_{\mathrm{II}}^{d} = 0,$$

where K_{I}^{d} and K_{II}^{d} are stress intensity coefficients under explosive gases, for loading conditions I and II, respectively; F is a correction coefficient for stress intensity.

Using the superposition principle by combining applied loads, the following expressions were obtained

$$K_{\mathrm{I}} = K_{\mathrm{I}}^{c} + K_{\mathrm{I}}^{d} = \sigma_m F + \sigma \sin^2\beta\sqrt{\pi(r_o + a)};$$

$$K_{\mathrm{II}} = K_{\mathrm{II}}^{c} + K_{\mathrm{II}}^{d} = \sigma\sqrt{\pi(r_o + a)}\sin\beta\cos\beta.$$

Considering the maximum tensile stress from explosion during fracture formation, we get the following expression

$$(\sigma \sin^2\beta + \sigma_m F)\sin\varphi + \sigma \sin\beta \cos\beta(3\cos\varphi - 1) = 0,$$

where φ is a crack initiation angle.

Provided $F = 1$ and $\sigma_m = n_\sigma$, then the above formula may be written as follows

$$(\sin^2\beta + n)\sin\varphi + \sin\beta\cos\beta(3\cos\varphi - 1) = 0.$$

Therefore, according to the performed calculations, providing that the crack nucleation angle φ and inclination angle β varied in range $0 \le \beta \le 90°$ with a fixed value, there is no stable relationship between the joint action of GDP and initial tensile stress on crack formation process.

Study on explosion action inside a toothed notch in tensile stress field. Light flux of parallel beams generated by OCG – laser *1* (Fig. 1) after passing through lens *3* and hitting the sample *4* obtains image *5*, which enters the field of lens *6* (objective lens), is focused and transmitted to high-speed video camera *7*. Recorded by high-speed video camera *7*, the whole process of crack apex movement in the form of dark spots is digitally recorded on a magnetic carrier.

By the high-speed video camera *7*, the position of the crack apex (dark spots in image *5*) was evaluated by the dynamic stress intensity coefficient, according to the expression

$$K_{\mathrm{I}} = \frac{2\sqrt{2\pi}}{3g^{5/2} z_o c d_{sam} \lambda_m^{3/2}} D_{\max}^{5/2}; \quad K_{\mathrm{II}} = \mu K_{\mathrm{I}},$$

where K_{I} and K_{II} are dynamic stress intensity coefficients for medium loading conditions I and II, respectively; $D_{\max}$ is the maximum diameter of causticity spectrum in the direction of crack formation; g is the numerical coefficient; μ is the stress intensity proportionality factor; z_o is the distance from reference plate to the sample; c is optical constant of sample material (model); d_{sam} is sample thickness.

According to the methodology developed by Dnipro University of Technology and State Enterprise Scientific and Production Association Pavlohrad Chemical Plant [24], as an example let us consider the dynamics of crack propagation in the model (the first series of experiments) in the process of fracture by explosion. In specimens series C1-1 an explosive cavity was formed in which the notch was made at an angle of 90° in direction perpendicular to applied initial tensile stress, and in specimens series C1-2 – parallel to tensile stress. In another group of specimens, C2-1 and C2-2, at an angle of 45° in direction perpendicular and parallel to applied tensile stress, respectively. Models in each series were blasted under two loading conditions: I without tensile stress and II with 5.0 MPa stress. Fracture movies recorded by a high-speed video camera were produced based on blasting results. As an example Fig. 4 shows the dynamics of crack propagation (dark points on image – caustic pots at top of crack) from explosive cavity with a longitudinal symmetric sharp-angled incision at an angle of 90° to the horizontal plane model.

Under the action of stress wave (20 μks, Fig. 4) caused by the explosion, the dark spots in sample C1-1 series moved in a straight line without any obvious change in its direction (60 μs, Fig. 4). Over time, the diameter of dark caustic spots gradually increased until crack growth stopped. Process dynamics shows that maximum deflection angle (47°) of crack appeared by time of 180 μks followed by moving to boundaries of specimen reaching maximum angle and length of 153 mm by time of 220 μks. And for specimens of C1-2 series, which were subjected to joint loading from action of the explosion and tensile stress, crack trace with dark spots of caustic crack took enveloping form in the direction perpendicular to the initial tensile stress, at which the main crack began to branch into secondary cracks. At the same conditions for specimens of C2 group, the diameter of caustic spots gradually decreased with attenuation of crack growth.

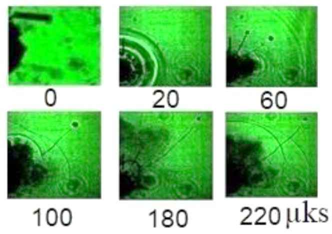


Fig. 4. Dynamics of explosive fracture propagation in explosive cavity with a 90° notch to horizontal plane model

According to the results, dependences of variation of main crack propagation length in time caused by the explosion in group C1 and C2 specimens are shown in Figs. 5 and 6.

The dependencies obtained were processed by correlation analysis with the derivation of the regression equation and the coefficient of determination. They showed high convergence with the experimental data.

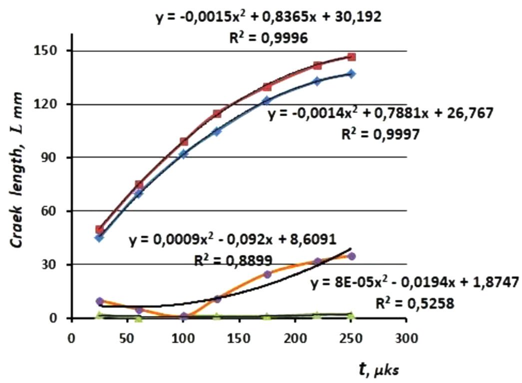


Fig. 5. Explosion induced main crack propagation curves in model group C1:

1– model C1-2 (//); 2 – model C1-1 (//); 3 – model C1-2 (⊥); 4 – model C1-1 (⊥)

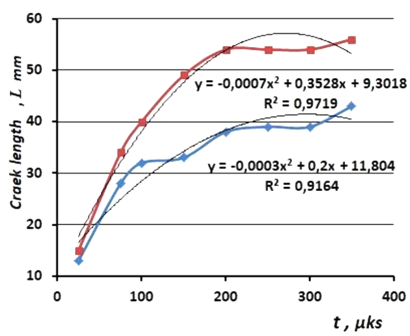


Fig. 6. Explosion induced main crack propagation curves in model group C2:

1– model C2-1; 2 – model C2-2

In order to establish nature and length of the main crack propagation in a sharp-angled notch, a designation was applied to determine direction of load application in the model: parallel and perpendicular to L|| and L⊥, respectively. During the entire loading process of the models, the crack propagation length L|| parallel to the sharp-angled notch for specimens group C1-1 and C1-2 reached their maximum values by the time equal to 240 μks (144 and 153 mm, respectively). These values had minimal difference, indicating that the initial tensile stress had little effect, as well as the attenuation of the stress wave caused by the action of the explosion. In summary, experimental results showed that, with angle enclosed between the sharp-angled notch and direction of initial tensile stress application equal to 45°, the applied stress has little effect on main crack propagation when it is directed parallel to sharp-angled notch and with maximum main crack deflection when applied stress is perpendicular to direction of sharp-angled notch.

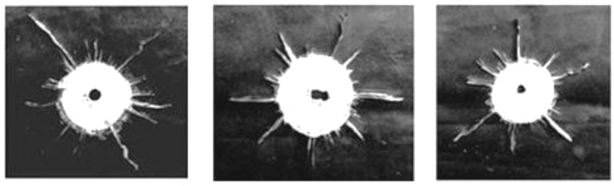
The nature of crack propagation in the model under different loading conditions was evaluated by the dynamic stress intensity coefficient K_I and K_{II} for different loading conditions. The results are given in Table.

Analysis of calculated data of dynamic stress intensity coefficient versus time at explosive fracture of model groups C1 and C2 (Table) revealed that the intensity of crack development for a series of C1 specimens (Fig. 5) was higher than that for samples C1-2. So, maximum values were 1.21 and 0.75 MPa · m$^{1/2}$ respectively. At the same time, change in the angle up to 45° between the direction of applied initial tensile stress perpendicular to sharp-angled notch promotes growth of primary and secondary cracks around charging cavity, and their damping when load is applied in parallel. This mode of loading activates growth of primary cracks with an increase in stress intensity coefficient at crack apex.

Study on blast action in a model with different cross-section blast cavity shapes outside of tensile stress field. Experimental explosions in models with different shapes of explosive cavity cross-section were carried out, according to the method [7]. Figs. 7 and 8 show photos of flat models destroyed by the explosion of high-breezing explosive charge – PETN with different shape of explosive cavity and with a longitudinal symmetric sharp-angled notch.

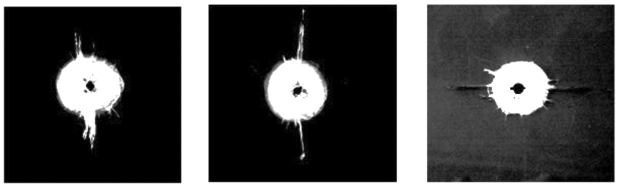
The photos of models (Fig. 7) destroyed by explosive charges of different cross-sectional shapes show that around the charge cavity there is an irregular distribution of different types of deformation, which depend on shape of charge cross-section.

For example, with circular shape (Fig. 7, *a*), there is a uniformly distributed grid of radial cracks, which extend to boundaries of model. Main and auxiliary cracks also propagate uniformly from the axis of the charge to all sides. When a triangular shaped charge is detonated (Fig. 7, *c*), a fracture pattern of the model is slightly different than when a cylindrical shaped charge is applied. In this case the nature of crack distribution in the model has a clearly expressed asymmetry.



a b c

Fig. 7. Photo of a flat model destroyed by concentrated explosive charge of cylindrical (a), square (b) and triangular (c) cross-sectional shapes



a b c

Fig. 8. Photo of a flat model destroyed by concentrated explosive charge with longitudinal symmetrical sharp-angled notch at 90° (a), 45° (b) and parallel (c) to horizontal plane of model

So, maximum stresses are concentrated in triangle tips (charge contour), which contribute to formation of both densely branched network of cracks and main cracks in these zones towards model boundaries. Analysis of the character of such cracks propagation (their maximal length) has shown that vector of maximum energy flux density of the explosion in such construction of a charge, is directed perpendicularly to prism faces, forming intensive network of cracks around charging cavity with radius 5–10 r_o (r_o – radius of charge). Formed multigradient stress field creates in the model an advanced network of cracks oriented perpendicularly both to charge cavity faces in shape of triangular prism, and in corners – prism tops – main radially directed cracks.

When a square-shaped charge destroys the model, radial cracks (Fig. 7, *b*) formed during the explosion are also characterized by well-defined directionality. Their greatest length with maximum opening up to model boundaries is observed in places of maximum stress concentration, i.e. in corners and perpendicular to lateral surface of square-shaped charging cavity. In this case the zone of plastic deformation is insignificant and amounts to only 2–3 r_o, and the zone of overstrain is 3–5 r_o.

Analyzing the configuration of the fracture zone with a square-shaped charge, we should note that its shape coincides with fracture zone of cylindrical shaped charge.

Table

Calculation of dynamic stress intensity factor for blast fracture of model groups C1 and C2

Indicators	Stress intensity factor, K^d, MPa · m$^{1/2}$	Model loading time, μs					
		25	50	100	150	200	250
Model of group C1-1	$K^d{}_I$	0.1	0.51	0.6	0.45	0.75	0.3
	$K^d{}_{II}$	0.0	0.05	0.05	0.08	0.1	0.15
Model of group C1-2	$K^d{}_I$	1.0	1.21	1.18	0.85	0.78	0.98
	$K^d{}_{II}$	0.3	0.5	0.6	0.3	0.2	0.6
Model of group C2-1	$K^d{}_I$	1.8	1.4	0.2	1.0	0.15	0.2
Model of group C2-2	$K^d{}_I$	1.25	1.6	0.25	1.15	0.2	0.2

Crack distribution in the model during the explosion with a longitudinal symmetric sharp-angled notch is shown in Fig. 8, without application of an initial tensile stress, with: *a* – the model in which longitudinal notch is directed at angle of 90°; *b* – 45° and *c* – parallel to horizontal plane of the model, respectively.

So, the zone of overgrinding and plastic deformation was formed around an explosive cavity in the radius equal to 3–5 r_o. Both main and secondary cracks were propagated around this zone in direction of notch. It was found that the depth of main cracks propagation in the samples of all series was 40–60 mm with a small angle of deviation from notch direction, and length of secondary cracks behind the zone of overgrinding and plastic deformation was not more than 10–15 mm.

Conclusions.

1. It has been established that initial static tensile stress changed the character of stress distribution around longitudinal sharp-angled notch and, as a consequence, influenced the character of crack propagation in the blast-induced model.

2. When the angle between longitudinal sharp-angled notch and plane of applied tensile stress is equal to 45°, under the action of explosion propagation of major cracks is promoted, both parallel and perpendicular to notch direction.

3. Stress intensity coefficients during the formation of main cracks increase under the action of tensile stress, and maximum deflection of the main crack is possible only when a sharp-angled notch is directed perpendicular to tensile stress, which leads to an increase in efficiency of a directional explosion.

4. It has been established that with the placed sharp-angled notch parallel to tensile stress, the main crack caused by the explosion has a linear character of propagation along sharp-angled notch, which leads to formation of secondary cracks on both sides of the explosive cavity and reduction of stress intensity coefficient in the main crack's apex.

5. It has been experimentally proved that during an explosion of charges with both triangular and square cross-sections, the vector of maximum energy flux density of the explosion is directed perpendicularly to prism faces, forming intensive network of cracks around the charging cavity with radius of 5–10 r_o.

Achieved scientific results may serve as a basis for the development of new technical solutions to improve technology of tunnelling large cross-section mine workings (underground tunnels, railway tunnels) in complex mining and geological conditions in hard rocks of a complex structure and provide additional protective measures in the field of environmental and seismic safety of infrastructure facilities for industrial and civil purposes. The developed technological parameters of drilling and blasting operations will be tested during construction of underground tunnels (Dnipro city) and at other sites during construction of underground structures for various technological purposes.

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Дослідження дії вибуху в зарядній порожнині різної форми перерізу в полі напружень розтягання

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Мета. Дослідити характер і закономірності розвитку магістральних тріщин у твердому середовищі під час дії вибуху заряду вибухової речовини (ВР) у зарядній порожнині з поздовжнім симетричним надрізом і різної форми поперечного перерізу.

Методика. Використана експериментальна методика з вивчення розвитку динаміки процесу, характеру й напрямку розвитку тріщин при вибуху заряду ВР різної форми та їх перетворення в чітке оптичне зображення під впливом фокусованого лазерного променю через оптичну систему – метод каустики. Дослідження зміни полів напружень при спільному впливі статичного й динамічного навантаження на середовище, що руйнується, здійснене поляризаційно-оптичним методом. Методами кореляційного аналізу проаналізовані результати досліджень.

Результати. Експериментально доведено, що зміна кута від 0 до 45° між поздовжнім надрізом і площиною, на яку спільно впливають напруження розтягання та дія вибуху, сприяє розкриттю основних тріщин як паралельно, так і перпендикулярно напрямку надрізу. Побудовані залежності поширення основних тріщин, викликаних вибухом, у моделі за різних умов навантаження. Виконані розрахунки коефіцієнтів інтенсивності напружень у середовищі під дією вибуху та напружень розтягання.

Наукова новизна. Запропонована вдосконалена методика досліджень зі встановлення механізму вибухового навантаження твердих середовищ вибухом заряду ВР різної форми поперечного перерізу. Розкрито фізичний механізм формування й поширення основних тріщин у вибуховій порожнині під дією вибуху заряду ВР різної форми за різних умов їх динамічного навантаження. Обгрунтовані розміри симетричного поздовжнього надрізу та його просторове розташування по відношенню до напрямку наведення напружень розтягання. Отримала подальший розвиток ідея використання направленого вибуху для формування захисної смуги в масиві гірських порід.

Практична значимість. Отримані результати наукових досліджень можуть стати необхідною умовою для розробки нових технічних рішень із забезпечення додаткових охоронних заходів в області екологічної та сейсмічної безпеки об'єктів цивільного та промислового призначення, що знаходяться під охороною, при проведенні вибухових робіт на кар'єрах і рудниках.

Ключові слова: *шпур, вибух, тверде середовище, метод каустики, тріщина, напруження розтягання*

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