UDC 537.523

https://doi.org/10.33271/nvngu/2021-6/049

V. V. Sobolev[1],
orcid.org/0000-0003-1351-6674,
O. V. Skobenko[1],
orcid.org/0000-0003-4606-4889,
I. I. Usyk[1],
orcid.org/0000-0003-0824-5099,
V. V. Kulivar[1],
orcid.org/0000-0002-7817-9878,
A. V. Kurliak[2],
orcid.org/0000-0002-9928-0406

1 – Dnipro University of Technology, Dnipro, Ukraine, e-mail: velo1947@ukr.net
2 – Research-Industrial Complex "Pavlohrad Chemical Plant", Pavlohrad, Dniproperovsk Region, Ukraine

FORMATION OF CONVERGING CYLINDRICAL DETONATION FRONT

Purpose. To develop a laser method for initiating a converging cylindrical front of a detonation wave and a method for calculating the kinematic parameters of the cylindrical shell walls, accelerated by the pressure of the detonation products of an external explosive charge.

Methodology. An experimental technology for the manufacture of a photosensitive explosive composite and an experimental technique for igniting the surface of its layer with an extended laser beam without the use of a fiber-optic cable are used. The results of simulation modeling – the Monte Carlo method – were used to study the effect of illumination on the process of ignition of explosives by laser pulsed radiation. For the selected type of photosensitive explosive composite, its explosive and optical characteristics, the distance from the surface of the explosive charge to the lens scattering the laser beam, and taking into account the total area of the expanded beam, the regularities of the distribution of the radiation energy density over the vertical and horizontal sections of the laser beam were studied.

Findings. The analysis of the scientific and technical level of methods of shock-wave processing of materials in the region of ultrahigh pressures from the point of view of the fundamental value of the cumulation of energy in the waves of a converging cylindrical detonation and shock front is carried out. Physicomathematical modeling was carried out and the regularities of pressure increase in the wave front were established in the process of approaching the shell walls to the axis. The scientific results of modeling converging cylindrical shells under the influence of the pressure of the explosion products have been analyzed. A method for laser initiation of a converging cylindrical front of a detonation wave has been developed, and a method for calculating the kinematic parameters of the converging walls of a cylindrical shell has been proposed.

Originality. A technique has been developed for determining the energy characteristics of an expanded laser beam, calculating the laser radiation energy required to initiate detonation simultaneously on the entire lateral cylindrical surface of a photosensitive explosive composite. The idea of technical implementation of the cumulation of converging cylindrical detonation and shock waves was developed further. A technique has been developed for the numerical determination of the change in the internal average compression rate of the shell during the movement of its walls towards the axis for various ratios of its external radius to the wall thickness and taking into account the increase in pressure in the converging detonation front.

Practical value. For the first time, a method for laser initiation of a converging cylindrical front of a detonation wave was developed and a device was tested that forms a converging cylindrical front of a detonation wave and a corresponding shock front in the material under study by the impact of a metal shell converging to the axis. The core of the device is a laser explosive initiation system that uses light-sensitive explosive composites to initiate an explosive charge.

Keywords: *cylindrical shell, explosive, laser, initiation, detonation, kinematic parameters*

Introduction and literature review. Research interest in converging detonation and shock waves arose in the 1940s. In 1942, Guderley proposed a physical and mathematical model of a converging shock front in gas, which is still a time-tested tool for understanding the behavior of converging shock waves. In 1945, L. D. Landau and K. P. Stanyukovich, regardless of the results obtained by Guderley, found that when approaching the axis of the cylindrical front of the detonation wave, the pressure increases asymptotically. K. P. Stanyukovich presented the results of this work in the monograph [1]. In 1959, Ya. B. Zel'dovich considered the beginning of the convergence process and the mechanism of amplification of the cylindrical front of the detonation wave [2]. Self-similar solutions to the problem of the shock wave converging to the axis or center showed [3] that at the moment of focusing, such parameters as the speed of the converging wave, pressure and temperature at the wave front increase indefinitely, except for the density of the substance, which remains limited.

In recent decades, the problem of convergence of cylindrical shock and detonation waves has been investigated by various approximate analytical and numerical methods, for example, in [3–5]. The main results of the work consisted in determining the value of a quantity in a cylindrical coordinate system. Evidence of the relevance of the effect of unlimited local growth of gas-dynamic parameters is shown, for exam-

---

ple, by theoretical studies on the laws governing the convergence of cylindrical and spherical shock waves in a gas [6, 7], the study on the mechanisms of the onset of cumulation of hydrodynamic flows in plasma [8, 9]. In the study on some practical problems [8, 10, 11] in the field of gas-dynamic cumulative flows characteristic of converging cylindrical and spherical shock waves, wedge-shaped [12] and conical [13, 14] cavities, respectively, are often used. Estimates of thermodynamic parameters and characteristics of shock-compressed matter make it possible to understand the evolution of flows, especially in the vicinity of the top of a cone (center of the sphere) or edge of a wedge (axis of the cylinder), the tendency of the development of the process of convergence of shock waves and arising physical effects [15–17]. It has been experimentally established for the first time [18, 19] that the entry of a metal striker (piston) into the cavity of the cone at a supersonic speed is accompanied by the emergence of two axisymmetric gas jets in the region of the apex directed along the axis of the cone in opposite directions. In all experiments, the jets burned through the metal body of the cone and the striker, indicating that one jet was directed towards the moving striker filling the cavity, and the other toward the top of the cone. Perhaps this effect is associated with irregular reflection of the shock front from the surface of the conical notch [20, 21]. The second effect is associated with an anomalously high value of the manganese concentration at the interface between the metal and the cavity formed by the action of the jets. The estimate of the jet temperature is $1.1 \cdot 10^6$ K, the jet density is about 12 g/cm^3.

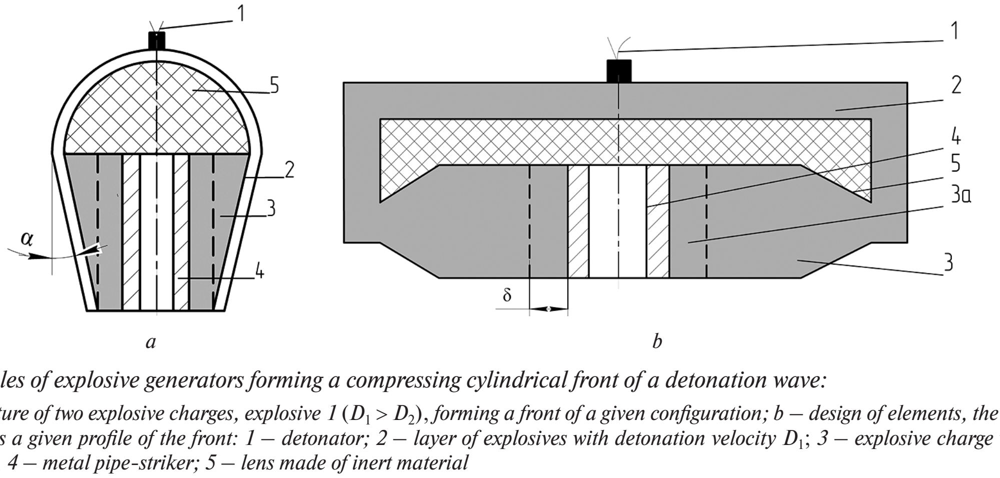
As a practical application, the phenomenon of cumulation of shock wave energy is used in military affairs, in materials science, mechanical engineering, physics and chemistry of plasma, laser physics, in studies on extreme states of matter, and so on. Shock waves are used with a wave front profile corresponding to the profile of the detonation wave front or the surface to be treated, on which a layer of explosive is applied [22, 23]. The front of the detonation wave can be linear, flat, in the form of a cone, ring [24], cylinder [25], a sphere, and their combinations. Depending on the method of initiation of the explosive charge, the last three types of complex wave profiles can be formed in the form of both converging and diverging fronts [26]. In practice, profiled waves are used mainly in mechanical engineering (processing of metals by explosion, synthesis of superhard materials, and so on) [27], military science, when carrying-out experimental research in the field of physics of high energy densities [28, 29] and performing special types of explosive works [29–31]. However, the formation of detonation and shock waves of a complex profile requires the construction of special explosive generators [32].

As an example, Fig. 1 shows diagrams of two explosive generators forming a converging cylindrical front of a detonation wave in an explosive charge. Fig. 1, *a* shows a device consisting of two different explosives: an initiating layer 2 with a detonation velocity D_1 and an auxiliary explosive 3 with a detonation velocity D_2. In practice, as a rule, the ratio $D_1/D_2 = 1.25–2.0$ is chosen. The angle α is found from the expression $\sin\alpha = D_2/D_1$. Obviously, with an increase in the angle α in the device, the mass of the auxiliary explosive increases, which can exceed the mass of the main charge 4 with a detonation velocity D_2. The ratio of the explosive mass to the shell mass along the length of the shell depends on the thickness of the auxiliary explosive layer. In the second type of generator (Fig. 1, *b*), an explosive charge is used, which conventionally consists of an initiating layer 2, an auxiliary charge 3 and a basic charge 4 adjacent to the outer surface of a cylindrical shell 4.

One of the known methods for forming a converging cylindrical front of a detonation wave is multipoint initiation of the lateral surface of a cylindrical explosive charge [33], which shows satisfactory results. In this work, the authors showed that the curvature of the detonation wave front for various explosives and for a limited thickness of the charge “depends only on the distance to the initiation point”. The method of forming a converging cylindrical wave by initiating the surface of the charge with an exploding wire, like the previous methods, has essential faults. One of them consists in the limited use of the mass of the explosive charge, since an increase in it requires large expenditures of energy for the evaporation of the wire (Japanese patent 48-32517).

The main disadvantage of devices initiating a converging cylindrical front of a detonation wave is the method of blasting. When constructing explosive generators, an additional mass of explosives is used, which sometimes exceeds the minimum required by several times, which leads to significant deviations of the shock compression parameters from the specified values. This situation is due to objective reasons associated mainly with the discrepancy between the physicochemical and explosive characteristics of standard blasting explosives and means of initiation to the conditions of the experiment. Compression of cylindrical shells by the pressure of explosion products, especially in the case of using the scheme in Fig. 1, *a* with decreasing mass of the explosive along the height of the shell leads to a proportional decrease in the ratio of the mass of the explosive to the mass of the shell $\rho\rho_{\exp} h_{\exp}/\rho_{sh} h_{sh}(m_{\exp 1}/m_{sh})$, where $\rho_{\exp}$ is the density of the explosive; $h_{\exp}$ is the thickness of the explosive layer; ρ_{sh} and h_{sh} are the density of the material and the thickness of the walls of the shell, respectively. Thus, the calculations of the kinematic parameters of the projectile shells will differ due to the increased content of explosives, which will lead to gross errors in thermobaric characteristics and ambiguous interpretation of the results of material processing.

The most attractive way to excite the detonation of a cylindrical charge can be the initiation of the lateral surface of the



a *b*

Fig. 1. Examples of explosive generators forming a compressing cylindrical front of a detonation wave:

a – a structure of two explosive charges, explosive 1 ($D_1 > D_2$), forming a front of a given configuration; b – design of elements, the arrangement of which forms a given profile of the front: 1 – detonator; 2 – layer of explosives with detonation velocity D_1; 3 – explosive charge with detonation velocity D_2; 4 – metal pipe-striker; 5 – lens made of inert material charge by laser pulsed radiation by analogy with the method for processing solid materials with plane detonation waves [26, 27].

A number of significant disadvantages, the main one of which is that the mass of the used explosive charge is several times higher than the calculated mass of the charge required to complete the task, characterizes each of the methods for exciting a converging cylindrical detonation front. In general, an increase in the mass of the exploded charge limits the use of generators of profiled detonation (and shock waves) [32, 34]. For example, with increasing the height H of a cylindrical explosive charge by n times, the mass of the charge m will increase by n^3 times.

An analysis of the existing methods for the formation of shock waves of a given profile and the results of experimental studies [35, 36], found that the main reason for the above disadvantages is the means of detonation, which excite the point initiation of explosive charges, and directly the explosive characteristics of standard explosives. For explosive generators, including multipoint initiation, the disadvantage is the impossibility of precision initiation of detonation simultaneously on the entire lateral surface of the cylindrical explosive charge. The use of generators of a converging cylindrical detonation wave (Fig. 1) leads, in particular, to the compression of the shell by the action of a pressure pulse of different magnitude along the formed cylindrical explosive charge (Fig. 1, *a*). An ideal method for the formation of a converging cylindrical front of a detonation wave can be the excitation of detonation simultaneously on the entire lateral surface of the explosive charge.

The purpose of the work is to develop a laser method for initiating a converging cylindrical front of a detonation wave and a method for calculating the kinematic parameters of the walls of a cylindrical shell accelerated by the pressure of detonation products of an external explosive charge.

Materials and research methods. The scheme of detonation initiation simultaneously for the entire lateral surface of the explosive 2 layer is shown in Fig. 2. Taking into account the faults of the known designs of generators of cylindrical detonation waves (Fig. 1) and methods for initiation of explosive charges, the energy of laser monopulse radiation is used [11, 22].

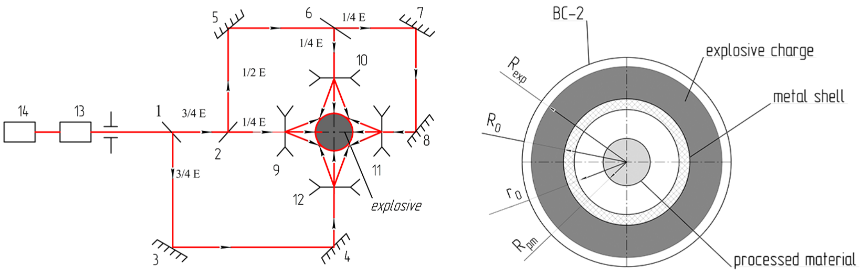
A thin layer (several millimeters) of a photosensitive explosive composite (PSEC), a substance of high sensitivity to the action of laser pulsed radiation, is applied to the surface of the explosive charge 1 [37, 38]. Radiation, acting on a cylindrical explosive charge from four sides at an angle of 90°, simultaneously excites detonation of the entire surface of the initiating layer of the PSEC. As a result of the explosion of the PSEC layer in the explosive charge 1, a cylindrical converging detonation front is formed. The layer of the charge of the PSEC is blasted with a monopulse radiation of a laser on the neodymium glass (the radiation wavelength is 1.06 μm; the exposure time at half-height of the laser monopulse is 11 ns; the delay time of the explosion from the beginning of the action of radiation to the flash of the PSEC is not more than 10 μs). The laser beam illumination of the entire lateral surface is carried out using mirrors 4, 5, 7 and 8, scattering lenses 9–12 and dividing plates 1, 2 and 6 with a certain radiation transmittance. The beam is expanded by scattering lenses, so that the diameter of the expanded beam exceeds by (5–10) % the length of the diagonal in the section of the explosive charge 1 along the axis (Fig. 2, *b*). The distance of the scattering lenses from the explosive charge is selected depending on the mass of the explosive charge and the features of the explosive characteristics of the PSEC, the minimum distance is 20–25 m or more.

The alignment of the device elements and the laser beam path is carried out using a laser diode (the color of the beam is red or green), whose beam is passed directly through a neodymium laser. The energy of monopulse radiation required to initiate detonation of the surface of the PSEC layer can be estimated using the expression $E = 3.14 \times D_2 \times E_0$, where D is the diameter of the expanded laser beam (cm); E_0 is the critical initiation energy density (mJ/cm^2) for the selected PSEC brand, taking into account the diameter of the unexpanded laser beam and the concentration of the PSEC binder [38].

The explosive charge is made of a TNT/hexogen 50/50 alloy, a layer of a photosensitive explosive composite is made of BC2 [37]. The steel pipe is installed in the axial hole of the explosive charge (Fig. 2, *b*).

Fig. 2, *a* shows a diagram of the laser beam path, in accordance with which radiation completely covers the side surface of the cylindrical explosive charge. Therefore, the outgoing laser beam with the radiation energy E falls on the dividing plate 1 with a certain transmittance γ_1. Part of the radiation with energy $E(1/4)$ is reflected from plate 1. A beam with energy $E(1/4)$, reflected from mirrors 3 and 4, passes through lens 12, expands and illuminates part of the lateral surface of the cylindrical explosive charge. The second beam with energy $E_{12}(3/4)$, passing through plate 1, hits plate 2. In this case, part of the radiation with energy $E(1/2)$, reflected from mirror 5, goes to plate 6, and the second ray with $E_9(1/4)$, passing through lens 9, expands, illuminating the side surface of the explosive charge. On plate 6, the beam with the energy $E(1/2)$ is divided into two more: one passes through the plate with the energy $E_{11}(1/4)$, then it is reflected sequentially from the mirrors 7, 8 and, passing through the lens 11, expands and illuminates the lateral surface of the charge. The rest of the surface of the charge is illuminated by a beam with an energy of $E_{10}(1/4)$, expanded by a lens 10. Thus, the condition of a uniform distribution of the energy density on the lateral surface of the cylinder is satisfied: $E_9 = E_{10} = E_{11} = E_{12}$. The reflection and transmission coefficients of plates 1, 2, and 4 are calculated so that the illumination of the lateral surface of the cylindrical charge is relatively uniform [25]. Explosive charge 1 is made of TNT/hexogen 50/50; an initiating layer of a photosensitive explosive composite BC2 [38] with a thickness of 3–4 mm was applied to the lateral surface of the explosive charge of explosive 1.

Basic device parameters. When the cylindrical front of the detonation wave converges to the axis of the explosive charge, the pressure increases according to a power law as $r^{-0.47}$ [2] (the adiabatic exponent n was taken equal to 3). According to Ya. Zel'dovich, as the radius decreases, the pressure increase at the wave front increases due to the transition



a *b*

Fig. 2. Diagram of the formation of a converging cylindrical detonation wave:
a – layout of the device elements; b – elements of the explosive charge

of detonation from the normal to the overcompressed mode. However, the onset of such a transition in a cylindrical explosive charge depends on its radius: the larger the radius is, the larger the layer of the explosive charge is within which the detonation wave can be characterized as normal with parameters corresponding to the Jouguet point. The increase in pressure is especially strong in the front of the detonation wave closer to the axis of the charge [2]. The choice of explosive, metal for the shell (striker), wall thickness, shell and external radius of the explosive charge 1 is made on the basis of the specified final shock-wave parameters, starting with preliminary calculations of the elements of the optical network and the features of the distribution of the energy density of laser radiation on the lateral surface of the explosive charge. It was found that the energy density distribution in the laser beam is in satisfactory agreement with the Gaussian distribution [39, 40].

Fig. 3 shows the energy density distribution over the vertical and horizontal sections of the laser beam. The presented information was obtained using an analyzer Silicon Camera Model LBA 1000A. The unevenness of the intensity of energy distribution does not exceed 30 %.

We assume that when the laser beam expands, the Gaussian distribution is retained over the area of the expanded beam. The dispersion σ^2 depends on the distance between the lens and the surface at which the energy level is determined. Using the diagram in Fig. 4, it is easy find the diameter of the expanded laser beam

$$2r_p = d \times R/F,$$

where d is a diaphragm diameter (m); F is lens focal length (m); R is a distance from the focus of the lens to the lateral surface of the cylinder (m).

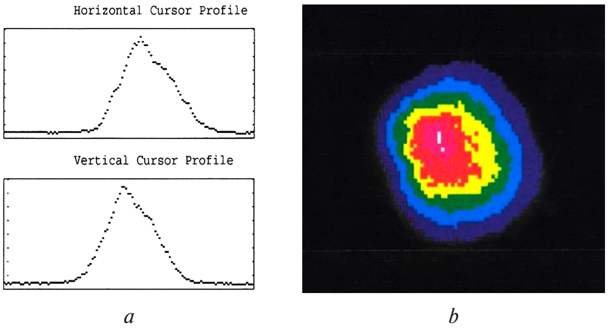
A laser beam expanded to a diameter of $2r_p$ should illuminate the lateral surface of the cylinder, visible from the side of the lens that scattered this beam. For reliable initiation of the layer of the photosensitive composite, the diameter must be greater than the diagonal of the axial section of the cylindrical charge with height H and diameter $2r$

$$2r_p > (1.05 - 1.0) \cdot [H^2 + (2r)^2]^{1/2}.$$

From experience with a laser system for initiating surfaces, it is sufficient to expand the laser beam to a diameter that is 10 % larger than the diagonal of the explosive charge.

In practice, the following device dimensions have been adopted. Charge radius $r = 0.12$ m, height $H = 0.4$ m; the initial diameter of the laser beam was 0.5 cm, the diaphragm diameter was 0.35 cm. After expansion on the lateral surface of the charge, the beam diameter was 0.512 m. The distance between the scattering lens and the surface of the explosive charge was 25 m, each (of four) laser beam was expanded by 0.204 m^2 (total area 0.816 m^2).

As an example, demonstrating the efficiency of the proposed method for the formation of converging cylindrical shock waves in Fig. 5 shows the initial placement of the container with the test material inside the explosive charge and the container after blasting.



a *b*

Fig. 3. Distribution of the energy density of laser radiation:

a – in the vertical and horizontal sections of the beam; b – in the irradiation spot

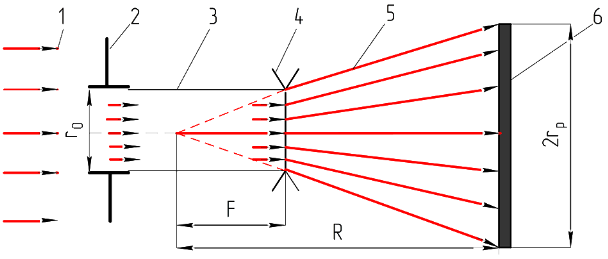
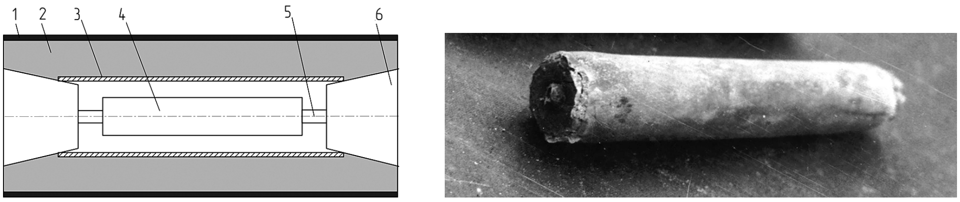


Fig. 4. Illustration of the expansion of the laser beam by the lens:

1 – the laser beam is not limited by the diaphragm; 2 – diaphragm; 3 – a laser beam limited by a diaphragm; 4 – diffusing lens; 5 – extended beam; 6 – surface illuminated by an expanded laser beam

For BC2, the critical energy density is $E = 5$ mJ/cm^2 [41]. We denote the total energy in the pulse as W. Then $W/4 = E(\theta, r_p)/E_s$, where $E(\theta, r_p)$ is the radiation energy density on the lateral surface of the cylindrical explosive charge; E_s is the distribution function of the energy density on the lateral surface of the charge; θ is a sector on the lateral surface of the charge, which is illuminated by two adjacent beams, denoted as θmin and θmax. Using the method for calculating the energy parameters [39], the physicochemical and explosive characteristics of the selected photosensitive explosive composite [42], the regularities of illumination in the volume of the PSEK [40], the minimum value of the distribution function of the laser energy density was determined at θmin $E_s = 1.831 \times 10^{-4}$ cm^{-2}. Then $W = 4 \cdot 5 \cdot 10^{-3}/1.831 \cdot 10^{-4} = 109$ J. The energy of this magnitude is quite real for pulsed radiation ($\tau = 2 \cdot 10^{-8}$ s). The detonation delay time of this photosensitive composite BC2 from the beginning of radiation generation does not exceed 5 µs.

Kinematic parameters of the shell. In the general case, the mathematical problem of throwing a plate of finite dimensions by detonation products of an explosive charge is three-dimensional and unsteady. However, in practice, calculations are used according to simplified models, which, as shown by spe-



a *b*

Fig. 5. A device for processing materials by a cylindrical shock wave front:

a – a diagram of the device; b – appearance of the container after treatment with a shock wave: 1 – photosensitive explosive composite BC2; 2 – explosive charge; 3 – metal shell (striker); 4 – container with the test material; 5 – centering rings; 6 – the core of the container cial experiments, give quite acceptable results. In many problems of throwing plates or cylindrical shells, the initial period of motion of the shell accelerated by the detonation products formed during the explosion of the explosive charge is considered. This means that the front of the detonation wave falls normally to the surface of the shell; the inertial motion of the shell after the expansion of the detonation products is not considered and is not taken into account. This formulation corresponds to the modes of explosion welding, in which the movement of the shell wall does not exceed 1.0–1.5 of its thickness, while the expansion of detonation products does not end until the moment of impact. The advantage of the viscous incompressible fluid model for the shell material is that it was the first to explain [43] the reason for the shell stopping when the inner surface reaches a certain radius not equal to zero, the dynamic loss of stability of the shell due to the action of viscous forces, the rapid transition of the entire kinetic energy of the shell into warmth, and so on.

In real conditions, to obtain shock compression pressures in the range of 50–100 GPa, the shell acceleration is carried out in a gap equal to 2.5–5.0 shell wall thickness $\delta = R_0 – r_0$ (Fig. 2, *b*), the ratio of the shell radius to the wall thickness was chosen within 5–10 units. Taking into account the results obtained in [2], the calculated values of the pressure of the detonation products on the shell walls are increased by 10 %. The model of an incompressible fluid, which is the basis for calculations for a compressible shell, can satisfy the set practical problems. It is believed that, due to the large values of the applied loads, the shell behaves like an ideal incompressible fluid. This position is confirmed experimentally [44].

Error limits of the hydrodynamic approximation in the model of an incompressible fluid exist due to the lack of consideration of the plasticity of the shell material. The estimation of the error of the hydrodynamic approximation for collapsing shells by the method of a computational experiment shows the following features. First, at pressures of detonation products on the outer surface of the shell in the range of 6–10 GPa and during acceleration of the shell in a gap equal to 2.5 of its wall thickness, the obtained dependences have error limits in the speed of movement of the shells, reaching 3–5 %. With an increase in pressure on the shell surface to 10–15 GPa, the percentage of error decreases to 3 %, and already at pressures of 20 GPa or more, it decreases to almost zero. In real conditions, a pressure of 6 to 20 GPa acts on the outer surface of the cylindrical shell. Therefore, in the calculations, it is possible to accept the hydrodynamic model with sufficient accuracy [31, 45]. When specifying the shell speed, a recalculation should be made taking into account the reduced error limit.

The one-dimensional motion of a cylindrical shell made of an ideal incompressible liquid collapsing under the action of gaseous products of instantaneous detonation is described by a differential equation of the form

$$\frac{du_H}{dt} = \frac{1}{R\ln\frac{R}{r}}\left\{\frac{u_H^2}{2}\left[\left(\frac{R}{r}\right)^2 - 1\right] - u_H^2 \ln\frac{R}{r} - \frac{P}{\rho_{st}}\right\}, \qquad (1)$$

where u_H is speed of movement of the outer surface of the shell; R is the outer radius of the shell or striker; r is the inner radius of striker; ρ_{st} is shell material density; P is pressure of detonation products on the outer surface of the striker. The pressure inside the shell can be neglected. In this case, the values of the parameters that determine the motion of the shell on its outer surface give the boundary conditions for integrating the system of differential equations describing the expansion of the detonation products.

A hyperbolic system of partial differential equations describing the one-dimensional motion of a gas with cylindrical symmetry

$$\begin{aligned} &\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{1}{\rho}\frac{\partial P}{\partial r} = 0; \\ &\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial r} + \frac{\rho u}{r} = 0 \end{aligned} \qquad (2)$$

can be represented using the well-known transformations in the form of a characteristic system of differential equations with derivatives taken along the characteristic directions. For the case of adiabatic gas flow (*k* is the adiabatic index), this system has the form:

- along the P-characteristic $dr/dt = u + c$

$$dP = d\left(u + \frac{r}{k+1}\tilde{n}\right) = -\frac{uc}{r}dt; \qquad (3)$$

- along the N-characteristic $dr/dt = u - c$

$$dP = d\left(u - \frac{r}{k+1}c\right) = -\frac{uc}{r}dt.$$

The numerical solution method is based on the approximation of system (3) on the characteristic mesh. If the initial conditions are given on a spatially similar line, then it is possible to calculate the field of values of u, c in the region of gas motion, i. e. obtain a numerical solution to the Cauchy problem.

For the convenience of writing the calculation scheme, equations (1, 3) should be converted to dimensionless parameters according to the transition formulas

$$\bar{R} = \frac{R}{R_0}; \quad \bar{r} = \frac{r}{R_0}; \quad \bar{c} = \frac{c}{c_0}; \quad \bar{u} = \frac{u}{c_0}; \quad \tau = c_0\frac{t}{R}, \qquad (4)$$

where R_0 is the value of the outer radius of the striker at the initial moment of time; c_0 is speed of sound in resting detonation products; *t* is time.

When substituting the values of dimensionless coordinates into system (3), the system will not change its form; the sign "~" is further omitted.

Using the formulas for the adiabatic flow

$$P = A\rho^k; \quad c^2 = k\frac{P}{\rho}; \quad \frac{P}{P_0} = \left(\frac{c}{c_0}\right)^{\frac{2k}{k-1}}, \qquad (5)$$

the last term in equation (1) can be represented as

$$\frac{P}{\rho_{st}} = c_0^2\left[\frac{q}{k}\left(\frac{c}{c_0}\right)^{\frac{2k}{k-1}}\right],$$

where the parameter $q = \rho_{exp}/\rho_{st}$ denotes the ratio of the densities of the explosive and the material of the striker. In the approximation of instantaneous detonation, the initial density of detonation products ρ_0 is assumed to be ρ_{exp}. After that, equation (1) in dimensionless variables takes the form

$$\frac{du_H}{dt} = \left(R\ln\frac{R}{r}\right)^{-1}\left\{\frac{u_H^2}{2}\left(\frac{R^2}{r^2} - 1\right) - u_H^2\ln\frac{R}{r} - c_0^2\left[\frac{q}{k}\left(\frac{c}{c_0}\right)^{\frac{2k}{k-1}}\right]\right\}. \qquad (6)$$

The diagram of the process under consideration is shown in Fig. 6 (solid lines – graphs of displacement of interfaces; dashed lines – *P*- and *N*-characteristics). Curves $R(\tau)$ and $r(\tau)$ are graphs of movement of the outer and inner surfaces of the striker, respectively. The convergence of the striker walls begins at the moment $\tau_0 = 0$ ($R = 1$). The boundary of the rarefaction wave $M(\tau)$ moves to the right along the resting gas. Thus, a region of moving gas is enclosed between *R* and *M*.

Approximation of equations (3, 4) consists in replacing differentials by finite differences. Let the flow parameters (τ, u, c) at points A_i, $I = 1, 2, 3, \ldots$ have already been calculated on the

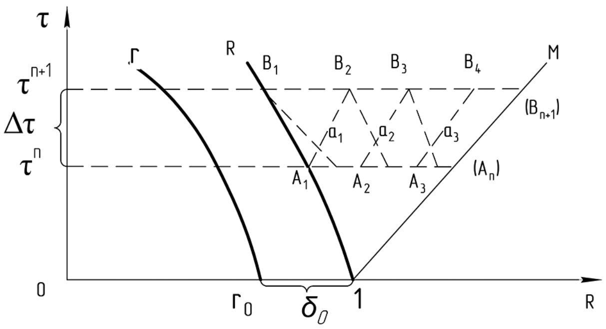


Fig. 6. Diagram of the compression process of a cylindrical shell, $\delta_0 = 1 - \upsilon_0$ is the initial thickness of the shell wall

time layer τ^n (in what follows, the designations of the points are identified with their spatial coordinates). It is required to calculate the parameters on the layer $\tau^{n+1} = \tau^n + \Delta\tau$. The distribution of parameters between points A_i is assumed to be linear. The increment of the parameter values during the transition to a new layer occurs along the characteristics and is determined by their values on the previous layer in accordance with the equations of system (3).

The calculation begins with the determination of the coordinate of the boundary point B_1, calculated on the assumption that the speed of the striker during the period of time ($\Delta\tau$) remains constant

$$B_1 = A_1 + u(A_1)\Delta\tau. \tag{7}$$

The corresponding value of the inner radius r is found by the formula

$$r = \sqrt{R^2 - R_{00}^2}, \tag{8}$$

where $R_{00} = \sqrt{R_0^2 - r_0^2}$ is the parameter characterizing the mass of the striker (cross-sectional area); R_0 and r_0 are the outer and inner initial radii, respectively. Speed $u_H = u(B)$ is found using the equations (4, 5)

$$u(B_1) = u(A_1) + \frac{\Delta\tau}{A_1 \ln\frac{A_1}{r}} \left\{ \frac{u_H(A_1)}{2}\left[\left(\frac{A_1}{r}\right)^2 - 1\right] - \right.$$
$$\left. - u^2(A_1)\ln\frac{A_1}{r} - \frac{q}{k} c^{\frac{2k}{k-1}}(A_1) \right\}. \tag{9}$$

The speed of sound at point B_1 is calculated by the formula

$$c(B_1) = \frac{k-1}{2}[u(B_1) - N(B_1)], \tag{10}$$

which requires a preliminary calculation of $N(B_1)$. To find the increment ΔN along the N-characteristic coming to B_1 from some point a_1 on the τ^n-layer, it is necessary to determine the coordinate a_1. The latter can be done using linear interpolation between the points A_i, which leads to the following algebraic expression

$$a_1 = \frac{B_1(A_2 - A_1) - \Delta\tau(A_2 - A_1)\left[c(A_1) - u(A_1)\right]}{(A_2 - A_1) - \Delta\tau\left\{\left[c(A_1) - u(A_1)\right] - \left[c(A_2) - u(A_2)\right]\right\}} -$$
$$- \frac{\Delta\tau A_i\left\{\left[c(A_1) - u(A_1)\right] - \left[c(A_2) - u(A_2)\right]\right\}}{(A_2 - A_1) - \Delta\tau\left\{\left[c(A_1) - u(A_1)\right] - \left[c(A_2) - u(A_2)\right]\right\}}. \tag{11}$$

After that, the value $N(B_1)$ is found

$$N(B_1) = N(a_1) + \frac{u(a_1)c(c_1)}{a}\Delta\tau. \tag{12}$$

The flow parameters at the remaining points B_{i+1}, $I = 1, 2, 3, \ldots$ on the τ^{n+1}-layer are calculated in the following order. First, the coordinate values and the values of the function P are determined

$$B_{i+1} = A_1 + \Delta\tau[u(A_i) + c(A_i)];$$
$$P(B_{i+1}) = P(A_i) - \frac{u(A_i)c(A_i)}{A_i}\Delta\tau. \tag{13}$$

As well as for point B_1, the points for each B_{i+1} are found and the values of N in them are determined

$$N(B_{i+1}) = N(a_{i+1}) + \frac{u(a_{i+1})c(a_{i+1})}{a_{i+1}}\Delta\tau. \tag{14}$$

The values of the mass velocity and the speed of sound at points B_{i+1} can be calculated if the parameters of the quantities P and N are known

$$u(B_{i+1}) = \frac{1}{2}\left[P(B_{i+1}) + N(B_{i+1})\right]; \tag{15}$$
$$c(B_{i+1}) = \frac{k-1}{4}\left[P(B_{i+1}) - N(B_{i+1})\right],$$

where u and c are mass velocity and speed of sound in detonation products. Each time for point B_1 the value of the velocity of the inner surface of the striker is calculated

$$u_B = u_H R/r. \tag{16}$$

When passing from τ^n to τ^{n+1}, the number of calculated points increases by one and the entire calculation process is repeated until the moment when r reaches the specified value $r_{00} \geq 0$, i.e. until the process of convergence of the striker is completed in the considered range of variation of the radius.

The values r_{00}, R_{00}, k, q are set as initial parameters for the program operation. The values of the flow parameters at points B_1 for each moment of time are printed. In this case, it is necessary to set parameters of the flow at some initial moment of time as the initial ones. Usually three points are given on τ^n, they can be taken from the analytical solution for the plane case. The step size Aτ after a series of tests and in accordance with the data by S.A. Kinelovsky, et al. (1970) was chosen equal to 0.1. As r_{00} tends to zero, the curves of the internal velocity u_B increase indefinitely, and the velocity of the outer surface u_H, on the contrary, begins to decrease from a certain moment in time, i.e. the kinetic energy of the collapsing striker is increasingly concentrated around its inner surface, which is consistent with the data of [43]. The maximum heat release is observed at $r/r_0 = 0.4$, where r and r_0 are the current and initial internal radii of the shell, respectively. At the moment the striker stops, all of its kinetic energy is converted into heat.

To characterize the dynamics of the striker as a whole, the average velocity u_c was calculated from the condition of conservation of the impulse of the striker

$$u_c = \frac{2Ru_H(R - r)}{R_{00}^2}. \tag{17}$$

The graphs of the velocities u_c after the initial section of acceleration almost do not increase, stabilizing at a certain saturation value characteristic of a given striker.

Fig. 7 shows the results of calculating the velocity of the walls of a cylindrical shell (striker) according to the above method. The ratios of the densities of the explosive and the material of the striker $\rho_{exp}/\rho_{st} = q$ and the thickness of the walls of the impactor $R_0 = 1 - r_0$, where r_0 is the initial value of the inner radius of the shell.

The value of the outer initial radius is taken as the unit of length measurement. In fact, in the program, the thickness of the striker wall was specified by the value of the parameter R_{00}, which is the value of the outer radius of the shell for the case of its complete compression. The graphs of the speed of movement of the inner wall of the striker in cases 1–9 and the corresponding average speeds u_c were printed. The adiabatic

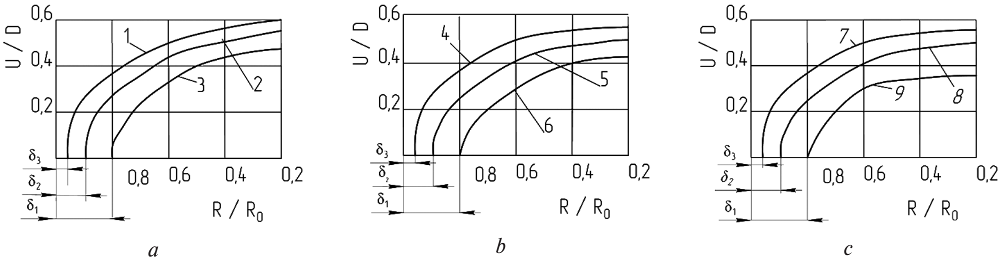


Fig. 7. Graphs of the internal average compression rate of the shell during the movement of its walls towards the axis at the initial shell thickness $\delta_1 = R_0/20$; $\delta_2 = R_0/10$; $\delta_3 = R_0/5$:

a – 1, 2, 3 ($q = 0.340$, $\rho_{\exp} = 1.0$ *g/cm*^{3}, $\rho_{st} = 2.9$ *g/cm*^{3}); *b – 4, 5, 6* – ($q = 0.127$, $\rho_{\exp} = 1.0$ *g/cm*^{3}, $\rho_{st} = 7.85$ *g/cm*^{3}); *c – 7, 8, 9* – ($q = 0.230$, $\rho_{\exp} = 1.73$ *g/cm*^{3}, $\rho_{st} = 7.5$ *g/cm*^{3})

index of the detonation products was taken equal to three ($k = 3$).

Conclusions. The laser method of detonation excitation of the initiating layer of a photosensitive explosive composite makes it possible in the future to standardize physical experiments on the effect of shock waves of a given profile on a substance. The disadvantage of the devices is the need to adjust the laser path and align the beam with the surface of the explosive charge before each explosion. Creation of explosive composites that are photosensitive to laser pulsed radiation and new means of blasting stimulates the further development of the physics of megabar pressures. It allows studying changes in the properties of materials of various classes under the action of extreme values of density, pressure and temperature, cumulation of magnetic field energy, study on mechanisms of redistribution of the self-energy of plasma flows, and so on. The method of laser initiation of converging detonation and shock waves can be used in materials science, mechanical engineering, power engineering and military affairs.

The developed method of excitation of the converging detonation front, the recipe composition of the photosensitive explosive composite and the technology of its synthesis, as well as the method for calculating the elements of the device, the energy and physical parameters of the optical module contain elements of "know-how". The device is intended for solving various scientific and practical problems in the field of physics and chemistry of megabar pressures. To ensure high efficiency of a device that forms converging detonation (and shock) waves by laser initiation, an initial high accuracy of symmetry of the device elements is required.

Acknowledgement. We wish to express our gratitude to colleagues who made an invaluable contribution to the development of research on laser initiation of explosives and the creation of photosensitive explosive composites: M. Ilyushin, A. Chernay, N. Zhitnik, I. Tselinsky, I. Shugalei, A. Sudarikov, A. Smirnov, A. Ivanov, A. Baranovsky, Yu. Kuchugurny, A. Dlugashek, K. Yah, Jan Ovsik and many other remarkable engineers and scientists.

The research was carried out by order and with the financial support of the Ministry of Science and Education of Ukraine, partly by the Committee on Science of the Republic of Poland and the joint program of European countries in the field of scientific research and experimental development "Eureka".

References.

1. Stanyukovich, K. P. (1971). *Unsteady motions of a continuous medium: monograph*. Moscow: Nauka.

2. Nakai, S., & Takabe, H. (1996). Principles of inertial confinement fusion – physics of implosion and the concept of inertial fusion energy. *Reports on progress in physics*, *59*, 1071-1131. https://doi.org/10.1063/5.0023100.

3. Sedov, L. I. (1987). *Similarity and Dimensional Methods in Mechanics: monograph*. Moscow: Nauka.

4. Nakamura, Y. (1983). Analysis of self-similar problems of imploding shock waves by the method of characteristics. *Physics of Fluids*, *26*, 1234. https://doi.org/10.1063/1.864273.

5. Zababakhin, Ye. I., & Zababakhin, I. Ye. (1988). *Phenomena of unlimited cumulation*: *monograph*. Moscow: Nauka.

6. Yusupaliyev, U., Sysoyev, N. N., Shuteyev, S. A., & Yelenskiy, V. G. (2015). The law of convergence of strong cylindrical and spherical shock waves in a gas with a uniform density. *Pis'ma v Zhurnal eksperimental'noy i teoreticheskoy fiziki*, *101*(9), 683-686.

7. Yusupaliev, U., Sysoev, N. N., Shuteev, S. A., & Belyakin, S. T. (2017). The self-similarity index of the convergence of strong cylindrical shock waves in a gas with a uniform/density. *Moscow University Physics Bulletin, 72*(6), 539-543.

8. Sokolov, I. V. (1990). Hydrodynamic cumulative processes in plasma physics. *Uspekhi fizicheskikh nauk*, *160*(11), 140-166.

9. Trishin, Yu. A. (2000). On certain physical problems of cumulation. *Prikladnaya mekhanika i tekhnicheskaya fizika*, *1*(5), 10-17.

10. Ben-Dor, G. (2017). *Shock Wave Reflection Phenomena*. Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3-540-71382-1.

11. Konovalov, N. A., Pilipenko, O. V., Skorik, A. D., Kovalenko, V. I., Semenchuk, D. V., & Mikhaylov, S. P. (2015). Development and full-scale testing of small arms shot oppressors with spherical baffle elements. *Tekhnicheskaya mekhanika*, (1), 3-14.

12. Konovalov, N. A., Pilipenko, O. V., & Skorik, A. D. (2014). Small arms shot oppressors with a barrel expansion chamber. *Tekhnicheskaya mekhanika*, (3), 3-14.

13. Derentowicz, H., Kaliski, S., Wolski, J., & Ziolkowski, Z. (1977). Generation of Thermonuclear Fusion Neutrons by Means of a Pure Explosion. *Bull. Academie Polonaise des Sciences, Serie Sciences Techniques*, *25*, 897-905.

14. Sobolev, V., Cabana, E. C., Howaniec, N., & Dychkovskyi, R. (2020). Estimation of Dense Plasma Temperature Formed under Shock Wave Cumulation. *Materials*, *13*(21), 1-9, 4923. https://doi.org/10.3390/ma13214923.

15. Stamov, L. I., & Tyurenkova, V. V. (2018). Simulation of reflection and focusing of shock waves in a conical cavity in a chemically reacting gas. *Matematicheskoye modelirovaniye*, *30*(3), 3-18.

16. Ndebele, B., & Skews, W. (2018). The reflection of cylindrical shock wave segments on cylindrical concave wall segments. *Shock waves*, *28*(6), 1185.

17. Kheyfets, A. E., Zel'dovich, V. I., & Frolova, N. Yu. (2017). Temperature-deformation effects during convergence of a steel cylindrical shell. In *Zababakhinskiye nauchnyye chteniya: collection of materials of the XIII International Conference,* (pp. 54-55). Snezhinsk: Izdatelstvo RFYATS – VNIITF. Retrieved from http://irbiscorp.spsl.nsc.ru/fulltext/WORKS/2017/%D0%97%D0%9D%D0%A7-2017_%D0%A2%D0%B5%D0%B7%D0%B8%D1%81%D1%8B.pdf.

18. Romanov, G. S., & Urban, V. V. (1982). Numerical simulation of an explosive plasma generator taking into account the transfer of radiation energy and evaporation of the walls. *Inzhenerno-fizicheskiy zhurnal*, *43*(6), 1012-1019.

19. Teslenko, A. G., Gubenko, S. I., Sobolev, V. V., & Slobodskoy, V. Ya. (1987). On the emergence of gas jets during explosive processing and their effect on the structure of iron alloys. *Izvestiya vuzov. Chornaya metallurgiya*, (12), 84-89.

20. Glass, I. I. (1977). *Shock waves and the man: monograph*. Moscow: Mir.

21. Rubidge, S., & Skews, B. (2014) Shear-layer instability in the Mach reflection of shock waves. *Shock Waves, 24*(5), 479-488. https://doi.org/10.1007/s00193-014-0515-6.

22. Chernai, A. V., Sobolev, V. V., Ilyushin, M. A., & Zhitnik, N. E. (1994). Generating mechanical pulses by the laser blasting of explosive coating. *Combustion, Explosion, and Shock Waves*, *30*(2), 239-242.

23. Chernai, A. V., Sobolev, V. V., Ilyushin, M. A., Zhitnev, N. E., & Petrova, N. A. (1996). On the mechanism of ignition of energetic materials by a laser pulse. *Chemical Physics Reports*, *15*(3), 457-462.

24. Chernai, A. V., Sobolev, V. V., Chernaj, V. A., Ilyushin, M. A., & Dlugashek, A. (2003). Laser initiation of charges on the basis of di-(3-hydrazino-4-amino-1,2,3-triazol)-copper (II) perchlorate. *Fizika Goreniya i Vzryva*, *39*(3), 105-110. Retrieved from https://www.scopus.com/authid/detail.uri?authorId=7202818072.

25. Sobolev, V. V., Shiman, L. N., Nalisko, N. N., & Kirichenko, A. L. (2017). Computational modeling in research of ignition mechanism of explosives by laser radiation. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (6), 53-60.

26. Sobolev, V. V., & Chernay, A. V. (2009). Explosion processing of materials using laser initiation of explosive charges. In *High Energy Material Processing: Collection of Scientific Papers,* (pp. 173-181). Dnepropetrovsk: Art-Press.

27. Chernay, V. A., Bunchuk, Yu. P., & Pakhomov, S. N. (2003). Welding of heat exchanger tubes using optical initiation of explosive charges. *Collection of scientific papers of the National Mining University*, (18), 56-62.

28. Kal'diroly, P., & Knopfel, G. (Eds.) (1974). *High energy density physics*. Moscow: Mir.

29. Al'tshuler, L. V., Krupnikov, K. K., Fortov, V. Ye., & Funtikov, A. I. (2004). The elements of physics of megabar pressures. *Vestnik Rossiyskoy akademii nauk*, *74*(11), 1011-1022.

30. Trunin, R. F. (Eds.) (1992). *Properties of condensed substances at high pressures and temperatures*. Sarov: VNIIEF.

31. Danilenko, V. V. (2010). *Explosion: physics, engineering, technology: monograph*. Moscow: Energoatomizdat.

32. Stanyukovich, K. P., Baum, F. A., & Shekhter, B. I. (2013). *Explosion physics: monograph*. Moscow: Ripol klassik.

33. Dudin, S. V., Sosikov, V. A., & Torunov, S. I. (2019). Laboratory explosive system for cylindrical compression. *Combustion, Explosion, and Shock Waves*, *55*(4), 507-511. https://doi.org/10.15372/FGV20190419.

34. Kanel', G. I., Razorenov, S. V., Utkin, A. I., & Fortov, V. Ye. (1996). *Shock-wave phenomena in condensed media: monograph*. Moscow: Yanus-K.

35. Ilyushin, M. A., Smirnov, A. V., Sudarikov, A. M., Tselinskiy, I. V., Chernay, A. V., & Shugaley, I. V. (2010). *Metal complexes in high-energy compositions: monograph*. Sankt Peterburg: LGU im. A. S. Pushkina.

36. Chernaj, A. V., Sobolev, V. V., Ilyushin, M. A., & Zhitnik, N. E. (1994). The method of obtaining mechanical loading pulses based on a laser initiation of explosion of explosive coatings. *Fizika Goreniya i Vzryva*, *0*(2), 106-111. Retrieved from https://www.researchgate.net/publication/292548581.

37. Soboliev, V., Bilan, N., & Kirichenko, O. (2014). Mechanism of additional noxious fumes formation when conducting blasting operations in rock mass. *Progressive Technologies of Coal, Coalbed Methane, and Ores Mining,* 471-477. https://doi.org/10.1201/b17547.

38. Chernai, A. V., Sobolev, V. V., Chernaj, V. A., Ilyushin, M. A., & Dlugashek, A. (2003). Laser ignition of explosive compositions based on di-(3-hydrazino-4-amino-1,2,3-triazole)-copper(II) perchlorate. *Combustion, Explosion and Shock*, *39*(3), 335-339.

39. Sobolev, V. V., Kulyvar, V. V., Kyrychenko, A. L., & Zazymko, V. I. (2018). Method of forming converging cylindrical shock waves. In *Prospects for the development of alarm technologies,* (pp. 136-141). Dnipro: Natsionalnyi Tekhnichnyi Universytet. Retrieved from http://ir.nmu.org.ua/handle/123456789/152337.

40. Sobolev, V. V., & Chernay, A. V. (2013). Use of the Monte Carlo method to solve the problem of detonation excitation in an explosive charge by a laser monopulse. *Informatsionnyy byulleten' Ukrainskogo soyuza inzhenerov-vzryvnikov*, (1), 3-8.

41. Ilyushin, M., Shugaley, I., & Sudarikov, A. (2017). *High-energy metal complexes: synthesis, properties, applications*. Saarbrucken: Lap Lambert academic publishing GmbH&CO.KG.

42. Ilyushin, M. A., Tselinskiy, I. V., & Sudarikov, A. M. (2006). *Developing components for high-energy compositions*. Saint Petersburg: Leningradskiy gosudarstvennyy universitet im. A. S. Pushkina.

43. Matyushkin, N. I., & Trishin, Yu. A. (1978). On some effects arising from explosive compression of a viscous cylindrical shell. *Prikladnaya matematika i tekhnicheskaya fizika*, (3), 99-112.

44. Mikhaylov, A. N., Gordopolov, Yu. A., & Dromin, A. N. (1974). Collapse of thin-walled pipes under explosive loading. *Fizika goreniya i vzryva*, (2), 277-284.

45. Kashirskiy, A. V., Korovin, Yu. V., Odintsov, V. A., & Chudov, P. A. (1972). Numerical solution of a two-dimensional non-stationary problem of shell motion under the action of detonation products. *Prikladnaya matematika i tekhnicheskaya fizika*, (4), 76-79.

Формування збіжного циліндричного фронту детонаційної хвилі

В. В. Соболєв[1], *О. В. Скобенко*[1], *І. І. Усик*[1],
В. В. Кулівар[1], *А. В. Курляк*[2]

1 – Національний технічний університет «Дніпровська політехніка», м. Дніпро, Україна, e-mail: velo1947@ukr.net

2 – Державне підприємство «Науково виробниче об'єднання «Павлоградський хімічний завод», м. Павлоград, Дніпропетровська обл., Україна

Мета. Розробка лазерного способу ініціювання циліндричного фронту детонаційної хвилі, що сходиться, і методики обчислення кінематичних параметрів стінок циліндричної оболонки, розігнаної тиском продуктів детонації зовнішнього заряду вибухової речовини.

Методика. Використана дослідна технологія виготовлення світлочутливого вибухового композиту та експериментальна методика запалювання поверхні його шару розширеним лазерним променем без застосування оптоволоконного кабелю. Використані результати імітаційного моделювання – метод Монте Карло – в дослідженнях впливу освітленості на процес запалювання вибухових речовин лазерним імпульсним випромінюванням. Для обраного типу світлочутливого вибухового композиту, його вибухових і оптичних характеристик, відстані від поверхні заряду вибухової речовини до лінзи, що розсіює лазерний промінь, і з урахуванням загальної площі розширеного променю, вивчалися закономірності розподілу щільності енергії випромінювання у вертикальному й горизонтальному перерізі лазерного променю.

Результати. Проведено аналіз науково-технічного рівня методів ударно-хвильової обробки матеріалів в області надвисокого тиску з точки зору фундаментального значення кумуляції енергії у хвилях збіжного циліндричного детонаційного та ударного фронту Проведено фізико-математичне моделювання та встановлені закономірності збільшення тиску у фронті хвилі у процесі зближення стінок оболонки до осі. Проаналізовані наукові результати моделювання циліндричних оболонок, що сходяться під дією тиску продуктів вибуху. Розроблено спосіб лазерної ініціації циліндричного фронту детонаційної хвилі, що сходиться, запропонована методика обчислення кінематичних параметрів стінок циліндричної оболонки, що сходяться.

Наукова новизна. Розроблена методика визначення енергетичних характеристик розширеного лазерного променю, розрахунку енергії лазерного випромінювання, що необхідна для ініціювання детонації одночасно всієї бічної циліндричної поверхні світлочутливого вибухової композиту. Отримала розвиток ідея технічної реалізації кумуляції циліндричних детонаційних і ударних хвиль, що сходяться. Розроблена методика чисельного визначення зміни внутрішньої середньої швидкості стиснення оболонки під час руху її стінок до осі для різних співвідношень її зовнішнього радіуса до товщини стінки та з урахуванням збільшення тиску у фронті детонації.

Практична значимість. Уперше розроблено спосіб лазерного ініціювання збіжного циліндричного фронту детонаційної хвилі та апробовано пристрій, що формує збіжний циліндричний фронт детонаційної хвилі та відповідний фронт ударної хвилі у дослідному матеріалі ударом циліндричної металевої оболонки, що збігається до осі. Основою пристрою є лазерна система ініціювання вибухових речовин, що використовує світлочутливі вибухові композити, призначені для ініціювання зарядів вибухових речовин.

Ключові слова: *циліндрична оболонка, вибухова речовина, лазер, ініціювання, детонація, кінематичні параметри*

The manuscript was submitted 29.12.20.