FRACTURE OF CONSTRUCTIONAL MATERIALS WITH HVOF COVERING AT DYNAMIC LOADS

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Abstract. In work features of deformation and material fracture with a multilayered covering at high-velocity impact interaction are investigated. The boundary dynamic problem in three-dimensional statement is solved by numerical method of finite elements. The multilayered covering is set in calculations obviously. When modeling of mechanical reaction of a steel substrate, the projectile and a covering intermediate layer made from NiAl ratios of Prandtl-Reuss and the condition equation in the form of Mi-Gruneisen are used. The coat layer from WC-Co shows elastic and fragile behavior. For the description of fracture of materials of a multilayered barrier Hoffman's criterion which includes various strength on tension and compression is used. It is shown that existence of a multilayered covering promotes increase of dynamic strength of a steel basis. It is established that reduction of penetration of the projectile, connected with covering existence, depends on velocity of interaction not linearly.

Introduction. The high-velocity (supersonic) gas-flame spraying (HVOF) is rather recent addition to family of processes of a gas-thermal spraying. This technique proves to be the most modern among technologies of a spraying. In the states of Europe and North America HVOF almost exclude a galvanic and methods of a vacuum spraying in many branches. Because of low velocity of particles at gas-thermal spraying the surface of particles has time to be oxidized that leads to low density of formation of coverings. The increase in velocity of particles as their temperature is lower allows to lower level of an oxidation of particles and to increase density of a powder covering. In powder sprays of HVOF of the first and second generations the cylindrical nozzle was used, whereas in the third generation Laval's extending profile nozzles are used. At such approach the velocity of a gas stream to exceed 2000m/s, and velocities of particles of a powder 800m/s. At HVOF technique the high adhesion is achieved, and porosity of a covering doesn't exceed 1 % [1].

Recently many results concerning elastic and strength properties of the multilayered coverings received by a method of a supersonic gas-flame spraying [2–4] are received. But the main part of works about research of the coverings received by the HVOF method, is devoted to research of their intense and deformable condition at static loadings. The analysis of deformation and fracture of similar environments at dynamic loadings is difficult and demands, as a rule, a three-dimensional approach and adequate models of behavior of not only each separate coat layer, but also a substrate.

In this work the behavior of a multilayered covering towards a steel substrate at dynamic loading of a design by the projectile at various velocities of interaction is investigated. The task was solved numerically by a method of finite elements with use of obvious finite-difference schemes by G. Johnson [5].

Basic equations of mathematical model. The system of the equations describing non-stationary adiabatic movements of the compressed media in the Cartesian coordinate system XYZ, includes following equations:

– continuity equation

$$\dot{\rho} + \operatorname{div} \rho \vec{\upsilon} = 0; \tag{1}$$

– motion equation

$$\begin{aligned} \rho \dot{u} &= \sigma_{xx,x} + \sigma_{xy,y} + \sigma_{xz,z} \\ \rho \dot{\upsilon} &= \sigma_{yx,x} + \sigma_{yy,y} + \sigma_{yz,z}; \\ \rho \dot{w} &= \sigma_{zx,x} + \sigma_{zy,y} + \sigma_{zz,z} \end{aligned} \tag{2}$$

– energy equation

$$\dot{E} = \frac{1}{\rho} \sigma_{ij} e_{ij}; \quad i, j = x, y, z. \tag{3}$$

Here ρ – density of media; $\vec{\upsilon}$ – velocity vector, u, υ, w – components of velocity vector on axes x, y, z accordingly; σ_{ij} – components of a symmetric stress tensor; E – specific internal energy; e_{ij} – components of a symmetric strain rate tensor; the point over a symbol means a time derivative; a comma after a symbol – a derivative on corresponding coordinate.

The behavior of the aluminum cylinder, and layers of NiAl and 316L at high-velocity impact is described by elastic-plastic media, in which communication between components of strain velocity tensor and components of stress deviator are defined by Prandtl-Reuss equation:

$$2G\left(e_{ij} - \frac{1}{3} e_{kk} \delta_{ij}\right) = \frac{DS^{ij}}{Dt} + \lambda S^{ij}, \ (\lambda \geq 0); \quad \frac{DS^{ij}}{Dt} = \frac{dS^{ij}}{dt} - S^{ik} \omega_{jk} - S^{jk} \omega_{ik}, \tag{4}$$

where $\omega_{ij} = \frac{1}{2}\left(\nabla_i \upsilon_j - \nabla_j \upsilon_i\right)$, G – shear modulus. Parameter $\lambda = 0$ at elastic deformation, and at elastic ($\lambda > 0$) is defined by means of a Mises condition:

$$S^{ij} S_{ij} = \frac{2}{3} \sigma_d^2, \tag{5}$$

where σ_d – dynamic yield point. The ball part of stress tensor (pressure) is calculated on the Mi-Gruneisen equation as function of specific internal energy E and density ρ:

$$P = \sum_{n=1}^{3} K_n \left(\frac{V_0}{V} - 1\right)^n \left[\frac{1 - K_0\left(\frac{V_0}{V} - 1\right)}{2}\right] + K_0 \rho E, \tag{6}$$

where $K_0,\ K_1,\ K_2,\ K_3$ – constants of material.

The behavior of WC-Co layer is described within the limits of elastic-fragile model. Before fracture components of a stress tensor in a target material were defined from equations of the generalized Hooke's law which have been written down in terms of strain rate:

$$\dot{\sigma}_{\mathrm{ij}} = C_{ijkl} e_{kl}\,, \tag{7}$$

where C_{ijkl} – elastic constants.

Fracture of an anisotropic material is described within the limits of model with use of Hoffman fracture criterion with various ultimate strengths of pressure and tension. This criterion, which has been written down by scalar functions from components of a stress tensor, has the following appearance:

$$\begin{gathered} C_1\left(\sigma_{22}-\sigma_{33}\right)^2 + C_2\left(\sigma_{33}-\sigma_{11}\right)^2 + C_3\left(\sigma_{11}-\sigma_{22}\right)^2 + \\ + C_4\sigma_{11} + C_5\sigma_{22} + C_6\sigma_{33} + C_7\sigma_{12}^2 + C_8\sigma_{23}^2 + C_9\sigma_{31}^2 \ge 1 \end{gathered}, \tag{8}$$

where C_i – constants of material.

It is supposed that fracture of anisotropic materials in the conditions of intensive dynamic loads occurs as follows:

– if strength criterion is violated in the conditions of pressure $\left(e_{kk} \le 0\right)$, the material loses anisotropy of properties, and its behaviour is described by hydrodynamic model, thus the material keeps its strength only on pressure; the stress tensor becomes in this case spherical ($\sigma_{ij} = -P$);

– if the criterion is violated in the conditions of tension $\left(e_{kk} > 0\right)$, the material is considered completely fractured, and components of a stress tensor are appropriate to be equal to zero ($\sigma_{ij} = 0$).

Pressure in orthotropic materials of targets is calculated by means of the equation of a condition:

$$P = \left[\exp\left(4\beta\frac{V_0 - V}{V_0}\right) - 1\right]\frac{\rho_0\alpha^2}{4\beta}. \tag{9}$$

Here ρ_0 is initial density of a material; V_0, V – relative initial and current volumes. Coefficients of the given equation are calculated from a shock adiabat: $D = \alpha + \beta u$, where α =1400 m/s, β =2.25, and u – mass velocity.

Initial and boundary conditions. The interaction (Fig. 1) of compact cylindrical steel projectile with multi-layer barrier is considered. The diameter of the projectile is equal to the length and equal to 2 mm. The material of projectile is Steel of mark St3. We study two types of targets. In the first type of barrier top layer applied by HVOF and contains 87% WC and 13% Co, the thickness of this layer is 0.25 mm. The second layer of thickness 0.205 mm – an alloy of 95% Ni and 5% Al. The third layer with a thickness of 1.5 mm – the substrate of steel 316L, consisting of 0.03% C, 1% Si, 2% Mn, 0.045% P, 0.03% S, 16–18% Cr, 2–3% Mo and 10–14% Ni.

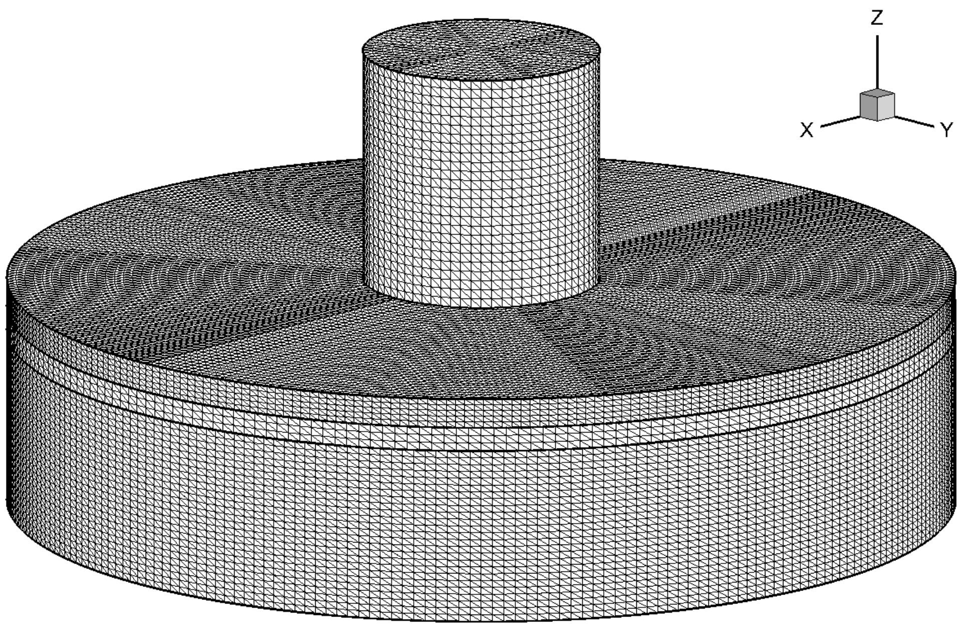

Fig. 1. The scheme of interaction of the projectile with the target. Computational mesh.

The second type of barrier – a barrier of single-layer monolithic from steel 316L. The thickness of the first and second barrier is the same – 1.955 mm. The thicknesses of the layers in the calculations for the first barriers were set on the basis of experimental data obtained with a scanning electron microscope [6]. Mechanical characteristics of the materials used are given in Table 1. The initial velocity of projectile ranged from 50 to 400 m/s. The angle of the meeting (the angle between the normal to the longitudinal axis of the projectile and the barrier) is $\alpha = 0°$ (normal impact).

Table 1. Mechanical properties of materials.

	Steel St3	316L	NiAl	WC-Co
Density, kg/m^3	7850	8031	5900	13900
Young modulus, GPa	204	200,38	169	398
Poisson's ratio	0,3	0,29	0,32	0,25
Yield strength, MPa	1010	262	1453	–
Tensile strength, MPa	–	–	–	4500

Initial conditions ($t = 0$):

$$\begin{aligned} &\sigma_{ij} = E = u = v = 0, \quad w = \upsilon_0, \quad i, j = x, y, z, \quad x, y, z \in D_1 \\ &\sigma_{ij} = E = u = v = w = 0, \quad i, j = x, y, z, \quad x, y, z \in D_2, D_3, D_4 \\ &\rho = \rho_i, \quad x, y, z \in D_i, \quad i = 1, 2, 3, 4 \end{aligned} \qquad (11)$$

Boundary conditions:
On free surfaces conditions of free border are realized:

$$\overline{T}_{nn} = \overline{T}_{n\tau 1} = \overline{T}_{n\tau 2} = 0. \qquad (12)$$

On contact surface sliding condition without a friction is realized:

$$\overline{T}^{+}_{nn} = \overline{T}^{-}_{nn}, \quad \overline{T}^{+}_{n\tau} = \overline{T}^{-}_{n\tau} = \overline{T}^{+}_{ns} = \overline{T}^{-}_{ns} = 0, \quad \overline{\upsilon}^{+}_{n} = \overline{\upsilon}^{-}_{n}. \tag{13}$$

Here $\overline{n}$ – a unit vector of a normal to a surface in a considered point, $\overline{\tau}$ и $\overline{s}$ – unit vectors, tangents to a surface in this point, $\overline{T}_n$ – a force vector on a platform with a normal $\overline{n}$, $\overline{\upsilon}$ – a velocity vector. The subscripts at vectors $\overline{T}_n$ and $\overline{\upsilon}$ also mean projections on corresponding basis vectors; the badge plus "+" characterizes value of parameters in a material on the top border of a contact surface, a badge a minus "–" – on bottom.

Discussion of the results. On Fig. 2 the settlement configuration of the projectile and the barrier of the first type to initial velocity 200 m/s at the moment of time 3 μsec is given. In section of ZX areas of the fracture which are realizing in the top layer received by the HVOF method are presented by gradations of gray color. Level of fracture is characterized by relative volume – the relation of volume of the fractured material in a final element (V_p) to total amount of the element (V_0). The value $V_p/V_0 = 1$ corresponds to total fracture of a material.

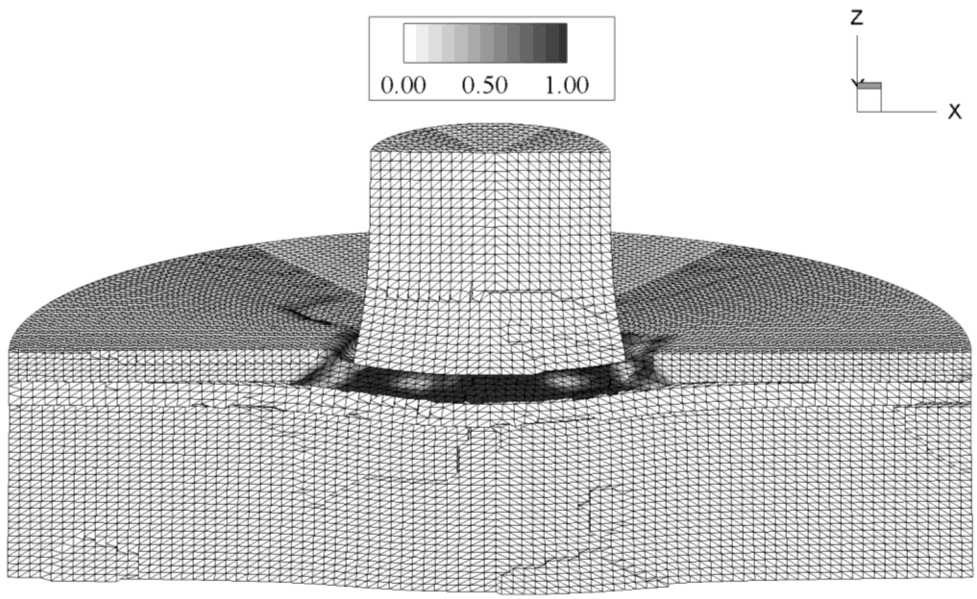

Fig. 2. Computational mesh. t=3 μsec.

To 3 μsec fracture of a material of the top layer of a barrier on all its thickness is observed, diameter of the fractured zone slightly exceeds diameter of the projectile. Fracture of the top layer occurs because of development in it of stretching tensions arising as a result of the influence of unloading waves and projectile introduction.

Development of wave processes in barriers can be tracked according to schedules on Fig. 3 and Fig. 4 where distributions during the various moments of time of tension σ_z on a symmetry axis on thickness of layered and monolithic barriers respectively, are presented. At the moment of impact on barriers pressure waves start to extend, and in a multilayered barrier the amplitude of a pressure wave for 17 % is higher, than in monolithic (curves 1). It is caused by higher elastic characteristics of WC-Co in comparison with steel 316L.

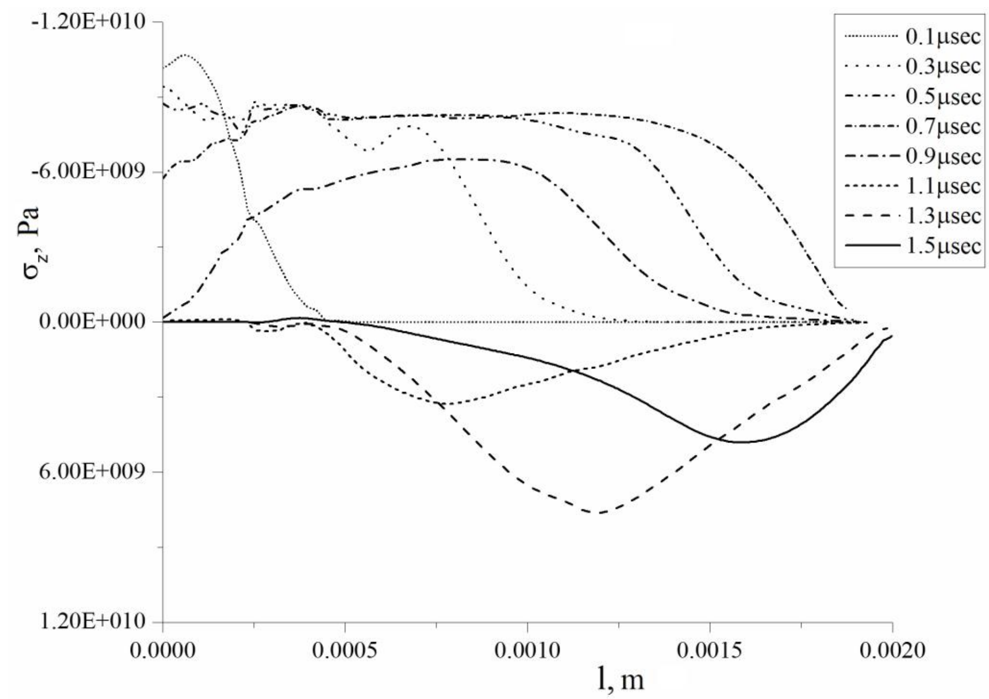

Fig. 3. The stress distribution over the thickness of a layered barrier.

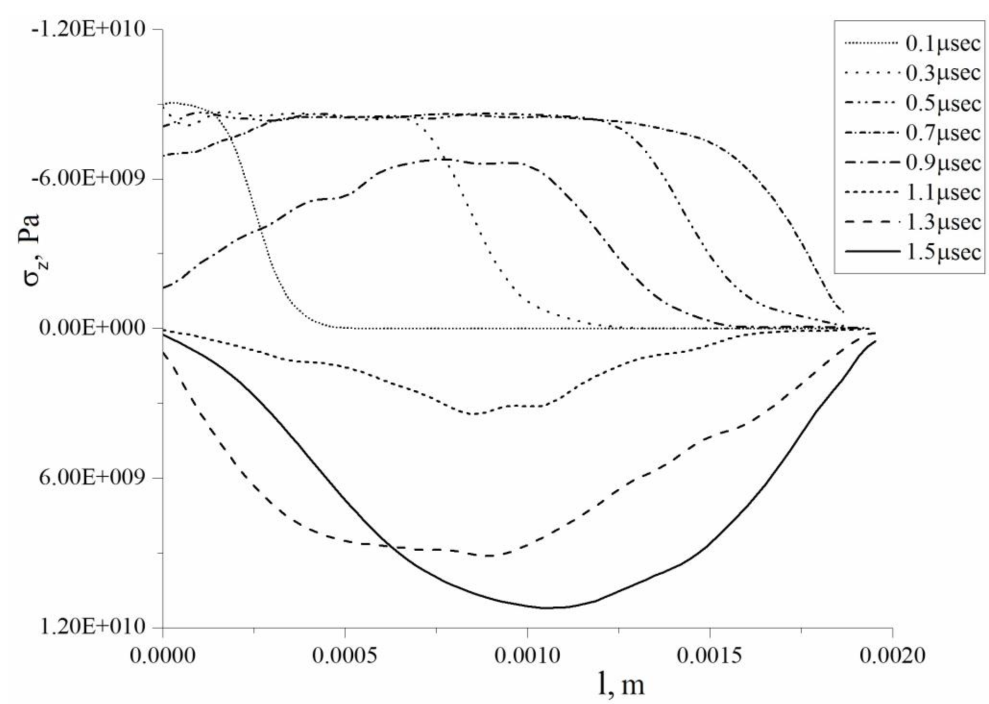

Fig. 4. The stress distribution over the thickness of a monolithic barrier.

Then unloading waves which were formed as a result of reflection of a compression wave from a lateral and back surface of the projectile come to a zone of contact of the projectile with a barrier.

These unloading waves extend on a barrier in the direction to a back surface, lowering stress behind a compression wave. And removal of compressing tensions in a multilayered barrier is accompanied by fracture of the top layer from WC-Co and as a result weakening of unloading wave. It is illustrated by curves 5–8 on Fig. 3 – to 1.1 μsec tensions are equal to zero on all thickness of the top layer. Therefore the maximum stretching tensions which arise in a substrate in a zone of an interference of unloading waves extending from lateral and back surfaces of the projectile and a back surface of a barrier, in a layered barrier they are less for 33%, than in the monolithic. It essentially reduces probability of emergence of splitting fractures in a steel substrate.

On Fig. 5 curves describing changes in time of depth of the projectile introduction into layered and monolithic barriers at various initial velocities of interaction are given. The received results testify that in the considered range of velocities the depth of the projectile introduction is less in case of a layered barrier. For example, to 3 μsec the difference in the heart of a crater for a layered and monolithic barrier makes: for initial velocity 100m/s – 57%, for 200m/s – 21%, for 400m/s – 18%.

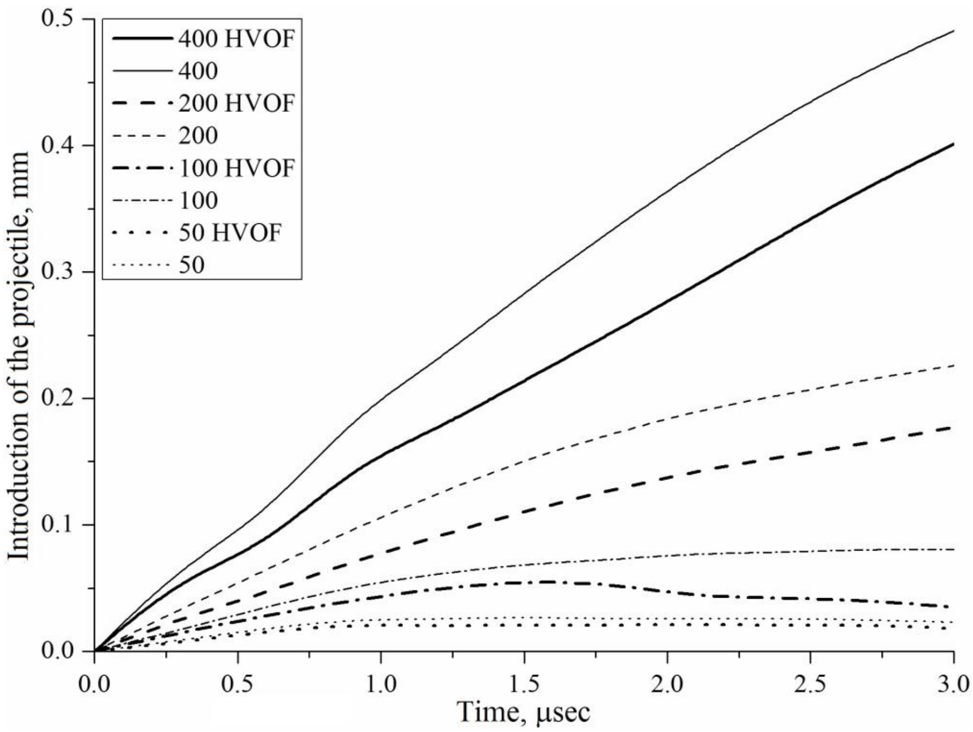

Fig. 5. Depth of penetration of projectile into a monolithic and layered barriers.

The relative difference in the depth of penetration of projectile into a monolithic and layered barrier is determined by the wave pattern in the target and depends on the initial velocity of interaction (Fig. 6).

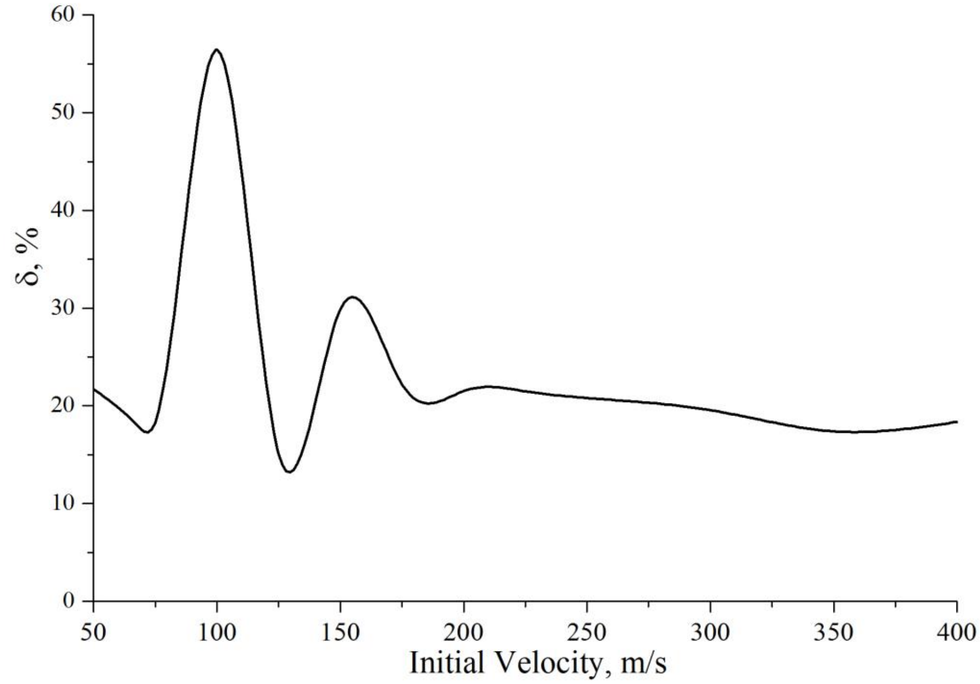

Fig. 6. The difference in the penetrating ability of a projectile for a layered and monolithic barriers depending on the initial velocity of interaction.

Conclusion. In this work the comparative analysis of penetration power of the projectile into a steel monolithic barrier and a barrier with multilayered NiAl – WC-Co covering is carried out. Research showed that existence of the high-strength layer received by the HVOF method, increases resistance to design fracture at impact loading. Increase of durability isn't proportional to a ratio of volumes of a covering and a barrier, and is reached because of change of nature of wave processes development and because of the decrease in level of stretching tensions in a zone of a probable splitting off connected with it. As a result there is more intensive braking and projectile deformation at an initial stage of process that leads to reduction of its penetration power. This effect is most strongly pronounced for low and average velocities of the projectile.

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