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USING METHOD OF ORTHOGONAL X-RAY PULSING SHOOTING FOR EXPERIMENTAL RESEARCH OF INFLUENCE OF THE ANGLE OF THE NUTATION ON PENETRATING ABILITY OF LONG PROJECTILES

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ABSTRACT

In the paper the results of an experimental research and numerical modeling of high velocity interaction of rod projectiles with targets at various angles of nutation are submitted. The experiments were carried out on ballistic stands at velocities of a throwing of projectiles up to 2 km/s . The angle of nutation of a projectile at approach to a target was registered by a method of orthogonal X-ray pulse shooting. At numerical modeling of processes of shock interaction the physical and mathematical model is used. The model is described by compressed elastic-plastic medium and take into account development and evolution of micro damages at dynamic loading.

Keywords: projectile, target, high velocity impact, deformation, destruction, physical experiment, mathematical modeling

For ensuring of the normal approach of a projectile to a target, when its axis coincides with a vector of velocity, the various devices of stabilization are applied which in practice should provide a deviation of a vector of velocity from a longitudinal axis not exceeding size 3 - 5 degrees. However there is a number of practical tasks, for example, the protection against meteoric bodies and dust, in conditions, when the projectiles fly up to object chaotically. It is important in these conditions to establish the influence of an angle of nutation (of an angle between a vector to velocity and a longitudinal axis of a projectile) on integrated parameters of penetration. It is necessary for forecasting consequences of influence of projectiles for concrete designs.

The difficulties of research of processes of high velocity interaction of projectiles with targets at a wide variation of angles of nutation consist in complexity of registration of evolution of process and in the analysis of results of physical experiment with reference to change of mechanisms of destruction of targets. The computer modeling of such complex phenomena should be carried out in three-dimensional spatial statement. It creates significant difficulties of computing character. Besides the given problem is connected to the phenomena of loss of dynamic stability of rod projectiles in process penetration, which is especially brightly shown in conditions of impact of rods with targets at angles of nutation.

Analysis of experimental data shows that at face impact the depth of penetration is characterized by velocity of interaction and length of a projectile. At lateral impact (flat wise impact) the degree of destruction of a target is determined in shock wave parameters and in the greater degree is characterized by spall destructions. The penetrating ability of projectiles at intermediate angles of nutation should be between these by two limiting condition, therefore it is necessary to take into account simultaneous course of several mechanisms of destruction and their interaction.

The physical modeling of interaction of projectiles with targets at various angles of nutation was carried out on the fulfilled techniques of a throwing of projectiles on the ballistic stand at asymmetrical branch of segments of the pallet of a special design, which provided a variation of angles of nutation at approach to a target from 0^o (face impact) up to 90^o (flat wise impact).

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The experimental stand for physical modeling of tasks of high velocity impact is equipped with the pulse x-ray equipment with duration of radiation in nanosecond range. X-ray tubes are placed in the fixed sections of a line in mutual - perpendicular planes and can freely move along a line of flight of a projectile. The angle of nutation of a projectile at a target was registered by a method orthogonal X-ray pulse of shooting and paid off on the developed techniques. The technique of registration of a spatial situation of a rod projectile at a target is based on registration of the angular characteristics of its shadow image on X-ray photo at X-ray pulse shooting in two planes in the simultaneously coordinated moment of time. Characteristic X-ray photo of a spatial situation of a projectile at a target in the initial moment impact are given in a fig. 1.

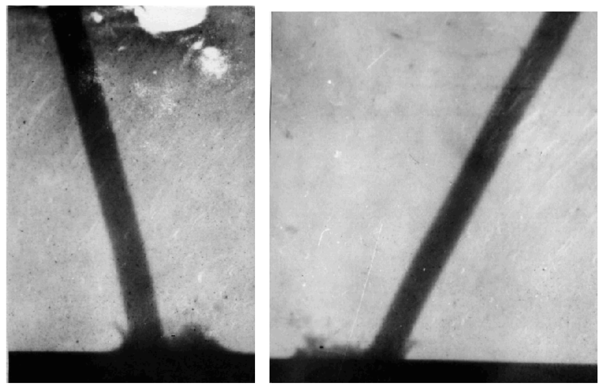


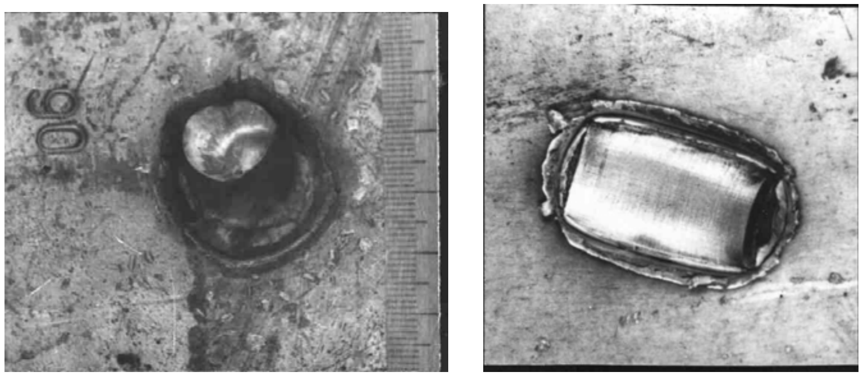
Fig. 1. X-ray photo of registration of an angle of nutation in two orthogonal planes at the approach of a rod to a target

In experiences the sizes of a zone of deformation and destruction in targets, sizes and form of the rests of projectiles after interaction and other parameters were registered. In experiment the cylindrical rods from steel 60C2A and heavy alloy were used. Targets are disks or plates from various alloys of aluminum and steel.

The analysis of experimental data shows that damage of a target is determined by a combination of several mechanisms of the destruction. The change of mechanisms of destruction is traced in an aluminum plate by thickness of 20 mm at impact by an aluminum projectile by a diameter of 16 mm and height 38 mm with initial velocity Vo = 970 м/c at different angles of nutation. With increase of velocity impact the process of destruction of a target is complicated by back spall. Numerical modeling of destruction of plates at face impact shows that the ring zone of adiabatic shift is distributed from an obverse surface to back, and it results in loss of durability of a material on perimeter of a projectile on all thickness of a plate, as shown in the work by Gorelski et al. (1988).

In case of impact with an intermediate angle of nutation the destruction of a plate is characterized by different mechanisms. So, at an angle of nutation 40^O through punching of a plate there is absent, a projectile is imbedded in it (fig. 2). On a back surface of a plate the shift crack on length on half of diameter of the deformed head part of a projectile is formed. At impact under an angle 90^O (flat wise impact) the process plastic deformation of materials proceeds on an obverse surface of a plate, the oval crater by depth of 7-8 mm (fig. 2-A) is formed, and on a back surface of a target is observed only weak protruding.

The parametrical researches are carried out and the dependences of depth penetration in thick steel targets of various hardness of projectiles from steel 60C2A by a diameter of 6,7 mm and length 134 mm of hardness HRC 53 … 55 are established. The results of researches are submitted in a fig. 3 as dependence of relative depth of a crater on an angle of nutation at velocities of impact of V_O = 780 m/s – curve 1, and V_O = 1040 m/s – curve 2. At small velocities of impact the linear reduction of depth penetration with increase of an angle of nutation and nonlinear gain with increase of velocity of impact is



A) B)

Fig. 2. Penetration of a projectile into the plate under an angle of nutation 40^{O} (at the left) and 90^{O} (on the right)

characteristic. Dependencies of relative depth of a crater in targets from high-strength steel (HB 300 … 320) from an angle of nutation for projectiles from steel 60C2A (lo = 85 mm, do = 6.7 mm) and from an heavy alloy (lo = 60 mm, do = 6 mm) at velocities of impact V^{O} = 1950 m/s are submitted on figure by curves 3 and 4 accordingly. They reflect characteristic sharp reduction of depth of craters at angles of nutation from 0 up to 50 degrees from normal and weak change at the large angles of nutation.

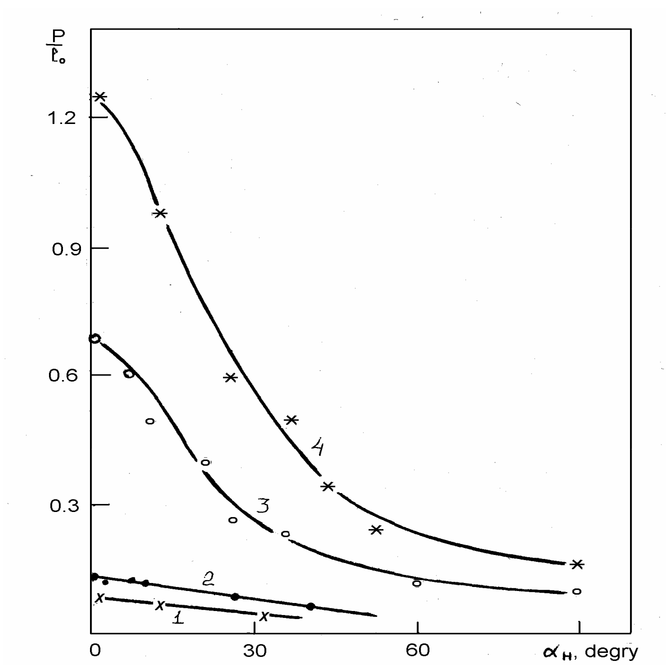
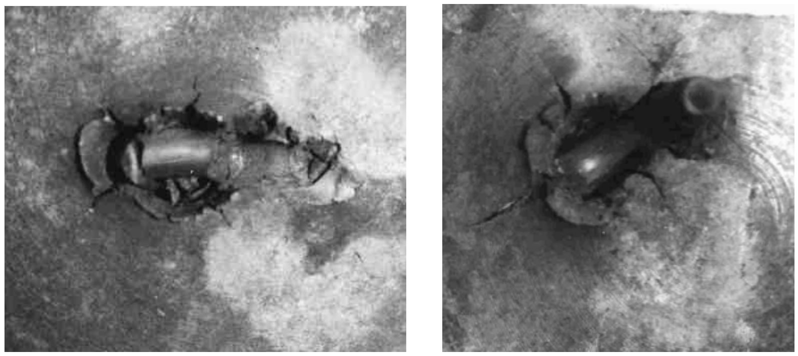


Fig. 3. Dependences of depth penetration of projectiles in steel targets from an angle of nutation

The sharp reduction of depth of a crater with increase of an angle of nutation is caused by destruction of projectiles or loss of dynamic stability. The destruction of projectiles of a shear type in several sections in a plane of a vector of velocity (fig. 4-A) is characteristic for rods from materials with high durability – for steel with hardness HRC 55 … 60.



A) B)

Fig. 4. Photos, characteristic for shear (at the left) and for bend (on the right) of rods during interaction with a steel target at the approach with a various angle of nutation

In these cases at impact of splinters of the rod on a target the series of additional craters is formed. The additional craters depth can be compared to depth of the main crater. The process of destruction of rods is characteristic for angles of nutation 30 … 60^{O} and at velocities of meeting of the order 1000 m/s. For rods from more plastic materials (the steel HRC 26 … 28) is observed their intensive bend. The characteristic kind of a rod after experience is illustrated by a photo given in a fig. 4-B.

The mathematical modeling of high velocity interaction of the lengthened projectiles with targets is carried out. In computations the model of damaged medium described in the work by Gorelski (2002) is used. Average density of damaged medium is defined by ratio $\rho = \rho_c (W_c/W)$, where W_c – volume of matrix medium, W – complete volume of medium. The system of the equations describing plastic deformation of compressed medium consists of the equations of movement, energy and change of specific volume of cracks:

$$\partial\rho/\partial t + \mathrm{div}(\rho\upsilon) = 0; \quad (1)$$

$$\rho\, \mathrm{d}\upsilon_i/\mathrm{d}t = \sigma_{ij,j}; \quad (2)$$

$$\mathrm{d}E/\mathrm{d}t = (1/\rho)\sigma_{ij}\varepsilon_{ij}; \quad (3)$$

$$\frac{dV_T}{dt} = \begin{cases} 0 \text{ при } |\mathrm{P_c}| \le P^* \text{ или } \mathrm{P}_c > \mathrm{P}^* \text{ и } \mathrm{V_T} = 0 \\ -\mathrm{sgn}(\mathrm{P_c}) K_4 \left(|\mathrm{P_c}| - \mathrm{P}^* \right)(\mathrm{V}_2 + V_T) \\ \text{при } \mathrm{P_c} < -\mathrm{P}^* \text{ или } \mathrm{P_c} > \mathrm{P}^* \text{ и } \mathrm{V_T} > 0, \end{cases} \quad (4)$$

where $\mathrm{p}^* = p_k V_1/(V_1+V_T)$, ρ — density, υ_i — components of a vector of velocity, E — specific internal energy, ε_{ij} - components of tensor of velocities of deformations, $\sigma_{ij} = -(P + Q)\,\delta_{ij} + S_{ij}$ — components stress tensor, S_{ij} — components of stress deviator, P_c — pressure in a continuous component of substance, $P = P_c (\rho/\rho_c)$ — average pressure, Q — artificial viscosity, V_1, V_2, P_k, K_4 — experimentally determined constants of a material. In the formulas for product of tensors, written down in the index form, the summation on repeating indexes is supposed.

The modeling of destructions will be carried out with the help kinetic of model of destruction of an active type. Growth of micro cracks continuously varies property of a material and causing relaxation of pressure. The pressure in the intact substance is function of specific volume, specific internal energy, of specific volume of cracks and in all a range of conditions of a loading is defined with the help of the equation of state according to the formula:

$$P_{-} = \rho_0 a^2 \mu + \rho_0 a^2 \left[1 - \gamma_0/2 + 2(b-1)\right]\mu^2 + \rho_0 a^2 \left[2(1-\gamma_0/2)(b-1) + 3(b-1)^2\right]\mu^3 + \gamma_0 \rho_0 E, \quad \mu = V_0 \big/ (V - V_T) - 1, \tag{5}$$

where V_0 and V — initial and current specific volumes, a and b — constant from linear ratio: $D = a + bu_m$, where D — velocity of a shock wave, u_m — mass velocity of substance behind front of a shock wave.

Deviator components of tensor of stress are determined by the formula:

$$2G\left(\varepsilon_{ij} - \frac{1}{3}\varepsilon_{kk}\delta_{ij}\right) = \frac{\mathrm{d}S_{ij}^0}{\mathrm{d}t} + \lambda S_{ij}\,; \tag{6}$$

where $\mathrm{d}S_{ij}^0 \big/ \mathrm{d}t$ – is determined by :

$$\frac{\mathrm{d}S_{ij}^0}{\mathrm{d}t} = \frac{\mathrm{d}S_{ij}}{\mathrm{d}t} - S_{ik}W_{jk} - S_{jk}W_{ik}\,, \tag{7}$$

and $2W_{ij} = \partial v_i/\partial x_j - \partial v_j/\partial x_i$.

Parameter l is equal 0 at elastic deformation and at presence plastic limit is determined with the help of a condition:

$$S_{ij}S_{ij} = \frac{2}{3}\sigma^2\,. \tag{8}$$

In the above mentioned formulas: G – module of shift, σ – dynamic limit of flow, which are determined through constants, according to experimental data. The numerical modeling was carried out by method of finite elements Gorelski *et al.* (1989), and Gorelski *et al.* (1994).

For revealing of destruction and temperature effects at impact the projectiles interaction of the steel cylinder by a diameter of 5.7 mm and height 85 mm with a steel plate by thickness of 60 mm was numerically simulated. The target from steel had parameters: ρ_0 = 7750 kg/m^3 , σ_0=1.01 GPa, G_0=81.8 GPa,, and material of a projectile was characterized in the following parameters: ρ_0=7850 kg/m^3, σ_0=2.1 GPa , Go=79 GPa.. The calculations are executed for angles of nutation in a range up to 30^{O} . In a fig. 5 the configurations of cooperating bodies are submitted at initial velocity of impact 1950 м/с at an angle of nutation 30^{O} in the various moments of time.

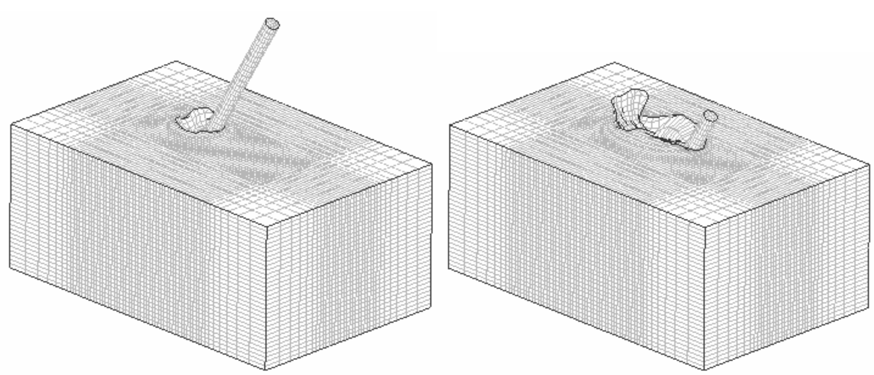


Fig. 5. Chronograms of process of impact at the moments of time 10 and 30 mks at velocity of impact 1950 m/s and angle of nutation 30^{O}

The dependences of change of relative depth of penetration from time are given in a fig. 6. It is shown that at the first stage the average velocity of projectiles at various angles of nutation fall approximately equally. At the second stage of process the additional resistance to penetration at angles nutation 15^O and 30^O caused by increase of the area of a contact surface results in faster fall of average velocity of penetration of projectiles.

Thus, the angle of nutation of a projectile at approach to a target was registered by a method of orthogonal X-ray pulse shooting. It is established, that the angle of nutation of a projectile renders essential influence on its penetrating efficiency, and this influence amplifies with increase of an angle of nutation and velocity of impact. The depth of penetration rod projectiles sharply decreases with increase of an angle of nutation in a range 0 … 50 degrees and is characterized by weak change at increase of angles of nutation more than 50 degrees. By a method of numerical modeling it is revealed that temperature effects and destructions in a projectile and target are brightly expressed at velocities more than 2000 m/s and at angles of nutation more than 30 degrees.

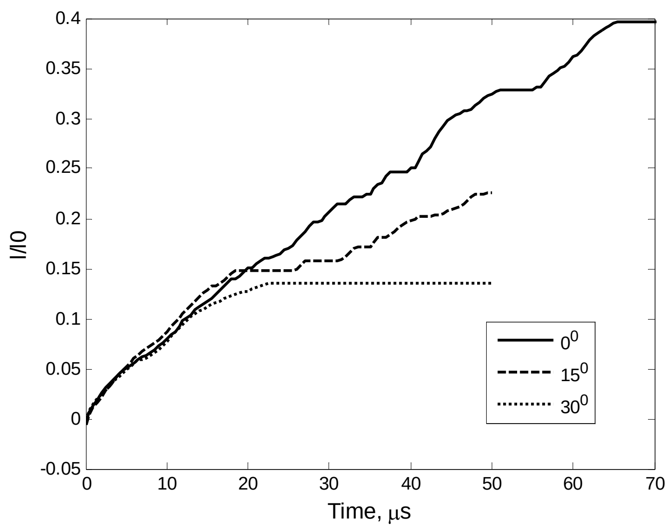


Fig. 6. Dependence of depth penetration from time for various angles of nutation

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