Experimental studying and predicting the consequences of high-velocity impact of rod projectiles with layered and spaced targets

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Abstract. The paper represents the experimental study and mathematical modeling of the shock resistance of composite spaced targets subjected to the high-velocity impact of steel and tungsten rod projectiles. The results of the study indicate a significant effect of the spacing and thickness of the steel target plates on the penetration process, leading, at high impact velocities, to a decrease in the total penetration depth in comparison with the depth in a monolithic target. An explanation of this effect is proposed, which consists in the fracture of the head of the projectile beyond each plate of the assembly due to tensile stresses. One of the possible approaches for evaluating the penetration depth and the number of spaced plates can be the proposed approximate (engineering) method, which takes into account the dynamic strength characteristics of the materials of interacting bodies. The geometrical and kinematic parameters of the projectile beyond the plates of the assembly are obtained considering the fracture of the material by the mixed mechanism “adiabatic shear - spalling”. The calculations performed by the proposed method are in good qualitative and quantitative agreement with the experimental data.

1. Introduction

Interest in the problems of high-velocity interaction of deformable bodies is stimulated by both fundamental problems of high-pressure physics and materials science and the expansion of the range of applied problems [1-5]. Studying the high-velocity interaction of axisymmetric rod projectiles of various lengths with single targets and structures representing a set of simple targets (layered, shielded and spaced) from different materials (metals, alloys, ceramics and plastics) occupies a special place in solving the complex problem of high-velocity impact of multi-scale solids. The database on high-velocity impact of bodies from homogeneous and composite materials is constantly expanding [4-10]. Nevertheless, the selection of effective structural materials for complex protective structures and projectiles is still an urgent problem.

Complete perforation of multilayered spaced targets is characterized by specific features, such as high deformation rate, shear and spall fracture, physics and mechanical and strength properties of plate material, etc. Systematic combined experimental and theoretical studies of damage and perforation of finite thickness targets show that changing the initial conditions of interaction (increasing the velocity of interacting bodies, choosing the material of the target and projectile, its geometry, angle of impact, etc.) significantly changes the mechanisms of fracture of the material [4-8].

Traditional methods for studying the impact of solids are large-scale model and full-scale parametric experiments conducted to determine studied characteristics as a function of initial parameters of interacting bodies. In addition, the number of fractured spaced targets, the nature and size of fracture in fractured plates, the condition of high-velocity fragments captured by special devices [5, 10-13] are recorded.

The most promising experimental design techniques are the creation of a semi-empirical complex of computational methods, which would include simple models, empirical constants obtained from an experimental database, and a set of actual criteria for transferring the results of physical modeling to
nature. A number of engineering techniques have been developed for predicting the consequences of high-velocity impact [13-17].

Due to the extremely short duration of the high-velocity impact of bodies, an important source that gives certain information directly from the zone of deformation and fracture is numerical simulation, which “freezes” the interaction process at any stage of its development, shows the level of deformation, structure and areas of fracture, studies the dynamics of the process, as well as analyzes in steps the fracture mechanism of different materials. Depending on the velocity of the projectile, the material of interacting bodies can be in a fragmented, molten, or vaporized condition [1-5]. A model of a porous elastoplastic medium is widely used as an effective tool in computer modeling of these processes. This model considers a separated fracture to be a process of growth and merging of microdefects (microcracks) due to isotropic tensile stress [4-8].

This work is devoted to experimental studying the features of the impact interaction of cylindrical rods with multi-layered spaced targets in the range of impact velocities up to 4 km/s. The presented model of high-velocity interaction of solids was used to predict impact consequences, including the kinematic and geometric parameters of the projectile beyond a plate and the entire structure. Section 2 provides the experimental data on the limiting thickness of penetration into steel plates and spaced assemblies at the normal and 60-degree impact of rod projectiles made of WNF-90 alloy in the interaction velocity range of 1 ... 3 km/s. Section 3 provides a numerical (engineering) model for calculating the kinematic and geometric parameters of a projectile deformed during interaction with the plates of the assembly. The calculations of some interaction parameters for solving specific problems of high-velocity impact are presented in section 4.

2. Experimental procedure and test results

The physical processes of high-velocity interaction of projectiles with targets were modelled on test benches, which included three main elements such as a ballistic installation, a ballistic path with recording and synchronizing equipment, and a target [18,19]. The projectile was accelerated by a powder or two-stage light-gas gun with a caliber of 8 mm and 23 mm [20]. The setup and the principle of operation of such setups are known, for example [5]. The velocity of accelerated bodies was measured by an electromagnetic displacement sensor with an accuracy of about 0.5%. The experiments were conducted in the range of impact velocities up to 5 km/s. Steel 60C2A (ρ=7.85 g/sm³) and WNF-90 alloy rod projectiles with a diameter of 4...7 mm and an elongation (length to diameter ratio) from 8 to 20 were used in the experiments. Targets are steel plates with a hardness of HB 260...320 and fiber-glass reinforced plastic STEF and STKT grades.

The measuring bench is used to record space-time parameters of the projectile in flight (velocity, spatial orientation, angle of incidence to the target, etc.), kinematic characteristics of interaction of the projectile with the target after penetration (the velocity of the projectile during penetration into and beyond the target, dynamics of a fragment stream beyond the target, fragment scattering angles, etc.).

The dynamics of high-velocity interaction of the projectile with the target and their fracture are characterized by very small-time intervals. Single-frame orthogonal X-ray flash photography is one of the most effective tools to study such processes and currently remains relevant. In the general case, kinematic and angular parameters of an individual fragment in a stream beyond the target are determined by recording its spatial coordinates at discrete time intervals. Orthogonal X-ray flash photography was used in the experiment. The method of decoding X-ray diffraction patterns is based on the spatial-coordinate binding of a separately fixed fragment in the "reference" system according to the corresponding parameters of its shadow image.

Figure 1 shows an X-ray diffraction pattern for the impact of a 10 mm thick steel plate with a WNF-90 projectile with a diameter of 4 mm and a length of 40 mm at an initial impact velocity of 2672 m/s. The X-ray diffraction pattern shows that by the time 20 μs, the projectile maintains the symmetry of flight in the direction of impact and, as the results show, decreases in length during interaction with the target.
The fracture of the plate takes place as follows. A shock wave is formed at the initial stage of impact and propagates into the plate along the material [21]. After the shock wave exits onto the rear surface of the target and is reflected from it as an unloading wave, the accumulation of microdamages in the target takes place. At the same time, a region of high pressures is formed in the zone of contact with the projectile, and the material of the target is fractured by a shear mechanism. Figure 1 shows this fact in the form of a stream of different size fragments located around the projectile. At the same time, microdamages continue to accumulate, and a zone of spalling (separation) fracture is formed near the rear surface of the target. This process ends with the separation of the spall layer from the rear surface of the target. This moment is shown in the X-ray diffraction pattern in the form of a “plate” of darkening located near the rear surface of the target and parallel to it. Thus, the target is fractured by the shear and separation (spall) mechanism [22, 23].

![Figure 1](image1.jpg)

**Figure 1.** X-ray diffraction pattern of the stream of fragments beyond a 6 mm thick steel plate upon normal impact with a 4x40 WNF-90 rod at a velocity of 2670 m/s.

Figure 2 demonstrates a characteristic X-ray diffraction pattern of the interaction dynamics of a WNF-90 rod projectile with a 6 mm thick steel plate at an incidence angle of 60°. It can be seen that under these interaction conditions, the projectile is broken into pieces along the length. At the same time, it indicates that the remaining part of the projectile occupies a leading position. The fragments on the front surface of the target are mainly grouped in the direction normal to the flight line of the projectile, and the angle of fragment scattering beyond the target is between the impact line and the normal to the plate.

![Figure 2](image2.jpg)

**Figure 2.** X-ray diffraction pattern of the impact of a 6 mm thick steel plate with a WNF-90 rod at a velocity of 2674 m/s and an angle of 60.
Figure 3 shows two X-ray diffraction patterns of penetration of a WNF-90 alloy projectile into an spaced three-layer structure consisting of a set of steel plates (HB 340) with a thickness of 10 mm and 10 mm spacing. A characteristic type of plate fracture in a system of the spaced target is a rear spall fracture of the first plates and a “perforation” of the spall layer. Other plates demonstrate the fracture in the form of cutting the “plug” [23]. Due to the high density of the interacting materials, the position of the projectile in the system of spaced plates is not visible in the X-ray diffraction pattern.

Figure 3. X-ray diffraction pattern of the penetration of a WNF-90 alloy rod into a three-layer spaced target from steel plates at a velocity of 2016 m/s at 29 μs [13].

High-velocity interaction of rod projectiles with monolithic, shielded, layered, spaced and layered-spaced structures was experimentally studied. The experiments were conducted in the impact velocity range of 1…3 km/s using assemblies representing a set of armor plates with alternating plates of composite materials mechanically bonded to each other for various thickness combinations.

Figure 4 shows the summarized results for the impact of different targets with WNF-90 alloy rod projectiles in the impact velocity range of 1.5…3.0 km/s and at incidence angles of 0° and 60° in the “maximum equivalent penetration thickness – impact velocity” coordinates. Curve 1 describes the thickness of a monolithic steel plate at the maximum impact velocity, which is selected as the base one. Curve 2 corresponds to the total perforation thickness of spaced targets, and curve 3 corresponds to the equivalent thickness (weight per unit area) of layered (data are indicated by squares) and shielded structures. The maximum thicknesses of the fractured spaced and layered targets at an impact angle of 60° is described by a single curve 4, which indicates a weak effect of the layered structure on the limiting penetration velocity at large impact angles between the projectile and the target.

Figure 4. Relative maximum thickness of perforation of combined targets by WNF-90 alloy projectiles.
The presented dependences indicate that the variety of initial impact conditions in the studied impact velocity range significantly affects the penetration of rod projectiles made of heavy alloys. Analysis of these experiments leads to the conclusion that in the studied range of normal impact velocities, the layered structure is more effective than the monolithic one by 20 ... 25% and spaced by 10 ... 15%. The obtained data on the shielded structure are in good agreement with the data on the layered one and are equal to \( \sigma = 2 \cdot 10^{-3} \text{ m} \) for the studied values with a 0.9 confidence interval.

3. Engineering model

The penetration depth of rod impactors into metal targets semi-infinite in thickness was evaluated by a simulation model with allowance for the shock compressibility of the projectile material. The governing equations expressing the laws of conservation of mass, momentum and energy, taking into account the hydrodynamic approximations [14, 15], are given in the form:

\[
\begin{align*}
\frac{dV}{dt} &= -\sigma^d / \rho_p, \\
\frac{dl}{dt} &= -(V - U), \\
\frac{dl_k}{dt} &= Ud_t, \\
0.5Ap_p(V - U)^2 + \sigma^d &= 0.5p_hU^2 + H_0, \\
A &= (c_0 + su) / (c_0 + (s - 1)u),
\end{align*}
\]

where: \( \rho_p \) and \( \rho_t \) - density of the material rod and target; \( V \) is the velocity of the free end of the projectile; \( U \) is the penetration velocity; \( l \) is the current length of the projectile; \( L_k \) is the penetration depth; \( \sigma^d \) is the dynamic yield stress of the projectile material; \( H_0 \) is the dynamic hardness of the target material. The linear equation of shock adiabat \( D = c_0 + su \) for metals includes \( c_0 \) and \( s \) projectile material constants used to determine the coefficient \( A \) [2].

The dynamic yield strength is determined by the relation:

\[
\sigma^d = (1 - 2\gamma) / (1 - \gamma) \cdot \sigma_{HEL},
\]

where: \( \gamma \) is the Poisson's constant, \( \sigma_{HEL} \) is the Hugoniot elastic limit.

In the first approximation the value \( H_0 \) for steel armor plates was estimated by comparing the calculated values with the experimental data at an impact velocity of about 1000 m/s (in one experiment).

The moment of knocking out the “plug” is determined by the equality of the force applied to the contact surface and the force necessary to shift material according to the height and diameter of the plug. An empirical relation is used to evaluate the deformation of the rear surface of the target. The diameter of the crater was calculated by the law of conservation of energy in the element of the projectile \( dl = Vdt \), with allowance for the plastic deformation of the element and target \( dL = Ud_t \).

\[
dm(V^2 - V_{lim}^2) / 2 = (\Delta E)_p + (\Delta E)_t.
\]

The limiting velocity \( V_{lim} \) characterizes the state when the kinetic energy of the projectile element is not sufficient for plastic radial deformation of the target material and is determined by the relation [24]:

\[
V_{lim}^2 = 3\sqrt{3} c_0 / (\rho_p / \rho_t) (\sigma' / E)_t,
\]

where: \( \sigma' \) is the yield strength; \( E \) is the elastic modulus of the target material.

The model was tested by the penetration depth of rod projectiles with a density of 2.7 ... 19.3 g/cm\(^3\) into aluminum and steel targets Correcting constants in the model were selected according to experimental data. The calculation results were in good agreement with experimental data in the impact velocity range of 1...5 km/s. Figure 5 shows the calculated and experimental data on the penetration depth of tungsten (1); WNF-90 alloy (2); and 60C2A steel (3) rods into a steel target. The calculations were in good agreement with the experimental data [24].
4. Calculation results

The residual velocity of the projectile beyond the target was calculated taking into account the kinetic energy loss for the work performed to knock out and accelerate the “plug” on the rear surface of the target. For the spaced target consisting of several separate plates, the kinematic parameters of the remainder of the projectile beyond the previous plate were taken as the initial impact conditions for the subsequent plate. This condition was established analyzing a series of X-ray diffraction patterns of rod projectiles penetrating into spaced structures, for example, a three-layer spaced structure shown in figure 3.

Figure 6 shows the calculations of the residual velocity and length of the rods beyond the monolithic target in relative coordinates. Curve 1 describes the change in the velocity of the WNF-90 rod with a diameter of 6 mm and an elongation of 10 mm beyond the target, and curve 2 is for a 60C2A steel rod with a diameter of 9.7 mm and an elongation of 10 mm. The impact velocity is 2 km/s. The corresponding changes in the length of the rod beyond the target, indicated by a dash, are also shown here. The obtained velocities are in satisfactory agreement with the experimental data obtained in the tests.
The presented engineering model was used to predict the consequences of high-velocity impact of rod projectiles with layered spaced targets in experiments.

The geometric and kinematic parameters of rod WNF-90 alloy projectiles 60 mm in length moving with a velocity of 2800 m/s were evaluated upon impact with a spaced target consisting of a set of steel plates with a HB 320 hardness, a thickness of 10 mm and a 10 mm gap between them. Table 1 shows the calculations, and figure 7 presents a graphical representation.

**Table 1.** Parameters of the projectile beyond the steel plates of the spaced target.

| No of plate | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-------------|---|---|---|---|---|---|---|---|---|
| \(l_{\text{resid}}\), mm | 60 | 54 | 48 | 42 | 35 | 28 | 20 | 10 | \(L_k = 1.3\) mm |
| \(V_{\text{resid}}\), m/s | 2800 | 2720 | 2570 | 2350 | 2060 | 1720 | 1310 | 81 | 0 |

![Figure 7](image)

**Figure 7.** Velocity (1) and length (2) of the WNF-90 rod beyond the plates of the spaced target.

(velocity beyond the target / projectile length / number of plates).

The effect of the material hardness on the number of steel plates perforated by a 60 mm long WNF-90 rod in a spaced target is presented in Table 2, where \(L_c\) corresponds to the penetration depth into the unperforated plate.

**Table 2.** The number of perforated steel plates in a spaced target, elongation 10.

| \(V_0\), m/s | \(H_D\), GPa | No | \(L_k\), mm | \(H_D\), GPa | No | \(L_k\), mm |
|-------------|-------------|---|------------|-------------|---|------------|
| 1700        | 5           | 0.2 | 4          | 3.4         |
| 2200        | 6           | 1.1 | 5          | 7.8         |
| 2500        | 3.0         | 6   | 9.4        | 4.0         | 6 | 3.9         |
| 2800        | 7           | 1.3 | 7          | 0.1         |
| 3100        | 7           | 5.8 | 7          | 2.0         |

No – number of the plate
Predicting the perforation of natural targets and structures is of practical interest. Calculations were performed to evaluate the perforation of steel plates (HB 320) 750 mm in thickness by WNF-90 alloy rod projectile with a weight of 8 kg. In the calculations the diameter was varied from 21.5 mm to 3.42 mm, which corresponded to a variation in elongation from 15 to 60 calibers. The calculated limiting penetration velocity of plates is shown in figure 8. At the same time, the calculations showed that uranium and tungsten projectiles of the same mass (m = 5 kg) with an elongation of 10 and an impact velocity of 1900 m/s perforated a 600 mm thick steel plate, but at a velocity of 1750 m/s, only uranium projectiles perforated this plate in contrast to tungsten ones.

![Figure 8. Maximum velocity of penetration into a monolithic steel target versus the elongation of the WNF-90 rod.](image)

Similar calculations were performed for a wide class of materials: projectiles - steel, tantalum, WNF-90, tungsten; targets - steel of different hardness, titanium alloys, aluminum alloys. Analysis of the data obtained indicates that ability of projectiles made of high-density materials to penetrate into layered structures is lower compared with semi-infinite blocks of the same material, and the final result of penetration into targets is determined by the thickness of the plates and the alternation of plates of different materials in the assembly.

5. Conclusion
The penetration of rod projectiles made of steel, tungsten and WNF-90 alloy into layered spaced targets was experimentally studied. The perforation of targets occurred through viscous spreading of the material in the contact zone and in the rear spall fracture zone. The time required for the development of rear spall fracture is comparable with the time when the projectile penetrates into the target, and as a consequence, the spall layer is broken into fragments.

It was established that upon the impact of WNF-90 alloy rods in the velocity range of 1.5 ... 4.0 km/s, the layered structure in mass equivalent per unit area was more effective than the spaced one by 10 ... 15% and the monolithic one by 20 ... 25%. Upon the oblique impact, the projectile was broken into pieces. Upon the normal impact with the target of finite thickness, the field of fragments beyond the target was symmetrical with respect to the projectile, and upon the oblique impact, fragments were located between the impact line and normal to the rear surface of the target.

An engineering method was proposed for evaluating the parameters of interaction of rod projectiles with combined targets, based on a modified hydrodynamic model which includes the dynamic compressibility of the projectile material in the contact zone. The numerical algorithm can estimate the maximum penetration velocity of a projectile into targets of finite thickness upon the normal and oblique impact, the velocity and length of the projectile beyond the layered spaced target. Examples of solving a number of problems on perforation of combined targets by high-density material rods (density is 7.8 ... 19 g/cm³) with an elongation up to 20 in the impact velocity range up to 5 km/s were given. The calculations were in good agreement with the experimental data.
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**Abbreviations**

- HB 300 – Brinell hardness, 300 MPa (kgf/mm²)
- WNF-90 alloy – tungsten-nickel-iron alloy, density of $\rho = 17.2$ g/cm³
- 60C2A – grade of steel, density of $\rho = 7.83$ g/cm³, HB 320.
- STEF – grade of fiber-glass reinforced plastic, density of $\rho = 1.95$ g/cm³
- STKT – grade of fiber-glass reinforced plastic, density of $\rho = 1.76$ g/cm³

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