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Simulation Of High-Speed Interaction Between Impactor And Layered-Spaced Design Involving Explosive

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Abstract. In this paper we present calculating and experimental study of high-speed interaction between explosive content, protected by layered-spaced design, and the cermet impactor in wide speed range. An experimental technique and mathematical model of during the behavior of explosives, protected by layer-spaced design, by with high-speed impact. The process of the interaction between the cermet impactor and element of the protective design is customized and depends on the materials of the interacting bodies, the speed and angle of impact.

INTRODUCTION

During the development of protective structures shielding the explosive charge it's needed to create prediction methods of high-speed impact various impactors on such structures. Generally the explosive protection is a set of layered-spaced plates made of various materials: light metals, plastics etc. Impactors can also be represented by different composites. Analysis and numerical simulation of high-speed impact process in such materials require the knowledge of their thermophysical properties in a wide range varying parameters [1]. This requires a abundant experimental data volume about these materials [2 - 5].

The experimental and theoretical formation of processes modeling due to the high-speed collision allows to obtain the most complete data for the design each of the protective structure and effective impactors, overcoming obstacles set in front of explosive with next initiation of explosive.

In order to rationally design and make demands to the strength characteristics of the materials it is important to develop the scientific basis of predicting the effects of high-speed impact, based on the physical and numerical modeling of high-speed interaction processes. Consequently, it becomes important to create the mathematical models and numerical methods, allowing in a wide range of the dynamic load parameters to describe the processes of deformation and fracture of materials laminated shell structures.

The object of this work is a stress-strain behavior and the protective structure destruction during the high-speed cermet impactor impact, as well as the detonation of explosives. The aim of the work is to develop models, methods and calculated programs of the interaction between cermet impactor and explosives, protected by layer-spaced design.

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MATHEMATICAL MODEL

Specific volume of the porous medium υ is given as a sum of matrix specific volume υ_m and pore specific volume υ_p. Porosity of material is characterized by the relative void volume $\xi = \upsilon/\upsilon_p$ or the parameter $\alpha = \upsilon/\upsilon_m$ called porosity, which are connected by the dependence $\alpha = 1/(1-\xi)$. The system of equations describing the motion of porous elasto-plastic medium is of the form:

$$\frac{d}{dt}\int_V \rho dV = 0, \frac{d}{dt}\int_V \rho \mathbf{u} dV = \int_S \mathbf{n}\cdot\boldsymbol{\sigma} dS, \frac{d}{dt}\int_V \rho E dV = \int_S \mathbf{n}\cdot\boldsymbol{\sigma}\cdot\mathbf{u} dS,$$
$$\mathbf{e} = \frac{\mathbf{s}^{CR}}{2\mu} + \lambda\mathbf{s}, \mathbf{s}:\mathbf{s} = \frac{2}{3}\sigma_T^2 \tag{1}$$

where t – the time; V – the integration volume; S – the surface of integration volume; $\mathbf{n}$ –the outer normal unit vector; ρ – the density; $\boldsymbol{\sigma} = -p\mathbf{g} + \mathbf{s}$ $\boldsymbol{\sigma} = -p\mathbf{g} + \mathbf{s}$ – the stress tensor; $\mathbf{s}$ – its deviator; p – the pressure; $\mathbf{g}$ – the metric tensor; $\mathbf{u}$ – the velocity vector; $E = \varepsilon + \mathbf{u}\cdot\mathbf{u}/2$ – the total specific energy; ε – the internal specific energy; $\mathbf{e} = \mathbf{d} - (\mathbf{d}:\mathbf{g})\mathbf{g}/3$ – the strain velocity deviator; $\mathbf{d} = (\nabla\mathbf{u} + \nabla\mathbf{u}^T)/2$ – the strain velocity tensor; $\mathbf{s}^{CR} = \mathbf{s} + \nabla\mathbf{u}\cdot\mathbf{s} + \mathbf{s}\cdot\nabla\mathbf{u}^T$ – the Kotter-Rivlinco rotational derivative; $\mu = \mu_{m0}(1-\xi)\left[1 - (6\rho_{m0}c_{m0}^2 + 12\mu_{m0})\xi/(9\rho_{m0}c_{m0}^2 + 8\mu_{m0})\right]$, $\sigma_T = \sigma_S/\alpha$, – the effective shear modulus and yield stress respectively; $\rho_{m0}, c_{m0}, \mu_{m0}$ – the initial density, volume sound velocity and shear modulus of matrix material; σ_S - the dynamic yield stress of matrix material. The parameter λ is eliminated by the Mises plasticity condition.

The system of equations is ended by the equation of state and relations describing the growth kinetics and pore flowing.

If the linear dependence of shock wave velocity Don mass velocity u for the matrix material $D = c_{m0} + qu$ is known, the equation of state of the porous material is of the form

$$p = \frac{\rho_{m0}}{\alpha}\left[\gamma_{m0}\varepsilon + \frac{c_{m0}^2\left(1 - \frac{\gamma_{m0}\eta}{2}\right)\eta}{(1-q\eta)^2}\right] \tag{2}$$

where $\eta = 1 - \rho_{m0}\frac{\upsilon}{\alpha}$, γ_{m0} – the Grüneisen coefficient of the matrix material.

Compaction of an initially porous material when compressing is described by the equation:

$$\frac{\rho_{m0}c_{m0}^2\left(1 - \frac{\gamma_{m0}}{2}\eta\right)\eta}{(1-S_{m0}\eta)^2} + \rho_{m0}\gamma_{m0}\varepsilon - \frac{2}{3}\sigma_s \ln\left(\frac{\alpha}{\alpha-1}\right) = 0 \tag{3}$$

The kinetics equation of pore compaction is used for determining the parameter α under the condition $p - \frac{2}{3}\frac{\sigma_s}{\alpha}\ln\left(\frac{\alpha}{\alpha-1}\right) > 0$, otherwise $\frac{d\alpha}{dt} = 0$. The growth of pores in the plastically deformed material when stretching is described by the equation:

$$\frac{\rho_{m0}c_{m0}^2\left(1 - \frac{\gamma_{m0}}{2}\eta\right)\eta}{(1-S_{m0}\eta)^2} + \rho_{m0}\gamma_{m0}\varepsilon + a_s \ln\left(\frac{\alpha}{\alpha-1}\right) = 0 \tag{4}$$

The kinetics equation of pore growth describes the evolution of the parameter α α in the range $1 < \alpha_{00} < \alpha \le \alpha_*$. It is used at

$$\alpha p + a_s \ln\left(\frac{\alpha}{\alpha - 1}\right) < 0 .$$

Otherwise $\frac{d\alpha}{dt} = 0$. The equation includes three easily determined parameters: $a_S, \alpha_{00}, \alpha_*$. $a_S = \frac{2}{3}\sigma_s$. α_{00} - there is dual porosity in the material, α_* – the critical value of porosity when destruction of the material occurs.

The parameters of equations of state c_{m0} and q of composite materials, which are multicomponent homogeneous mix, are determined in terms of shock adiabatic curves of mix components $D_i = c_{0i} + q_i u$ by graphic method using ratios in the front of the shock wave:

$$D = \upsilon_{m0}\sqrt{\frac{p_m}{\upsilon_{m0} - \upsilon_m(p_m)}},\ u = \sqrt{p_m(\upsilon_{m0} - \upsilon_m(p_m))} ,$$

where $\upsilon_{m0} = \frac{1}{\rho_{m0}} = \sum_{i=1}^{n} m_i \upsilon_{m0i}$ $\upsilon_{m0i} = \frac{1}{\rho_{m0i}}$ $m_i = v_i \frac{\rho_{m0i}}{\rho_{m0}}$ .The initial density, volume and mass concentration of the *i* mix component are designated by ρ_{m0} , v_i , m_i respectively.

Invariables (υ_m, p_m), the shock adiabatic curve of the matrix material of a composite has the form:

$$\upsilon_m(p_m) = \sum_{i=1}^{n}\left\{\upsilon_{m0i} - \frac{1}{p_m}\left[\frac{c_{0i}}{q_i}\sqrt{\frac{p_m q_i}{p_{m0i}c_{0i}^2} + \frac{1}{4}} - \frac{1}{2}\right]^2\right\} m_i \tag{5}$$

The shear modulus of the matrix material and yield stress are determined by shear moduli and yield stresses of components: $\mu_{m0}^{-1} = \sum_{i=1}^{n} v_i \mu_{m0i}^{-1}; \sigma_s = \sum_{i=1}^{n} m_i \sigma_{si}$.

To calculate the dynamic destruction of fragile composite materials of complex structure, it is reasonable to apply phenomenological approach [4] in which strength criteria are expressed through invariant connections between critical values of loading macro characteristics – stresses and deformations. In this case, in the process of dynamic loading before performance of criterion of durability, material is described as linearly elastic body. As a strength condition, the criterion offered in [5] is used:

$$3J_2 = [AI_1 + B]\left\{1 - (1 - C)\left[1 - \frac{J_3}{2}\left(\frac{J_2}{3}\right)^{-\frac{3}{2}}\right]\right\} \tag{6}$$

where I_1, J_2, J_3 – the first invariant of stress tensor, the second and third invariants of stress deviator respectively; $A = R_c - R_p$ $B = R_c R_p$ $C = \frac{3T_c^2}{R_c R_p}$ R_c R_p T_c – ultimate strengths under uniaxial compression, stretching and pure shear respectively.

The surface (6) for isotropic materials has to correspond to the convexity condition (according to the Drucker-Hill's postulates) which sets the following limits on the calculated parameters $0.530 \le \frac{T_c}{\sqrt{R_c R_p}} \le 0.577$ .Numerical values A , B , C are determined by the ultimate strengths of a composite in the process of stretching, compression and pure shear obtained under dynamic loading.

After completion of the strength criterion it is considered that material is damaged by cracks. Fragmentation of the damaged by cracks material which was affected by the stretching stresses occurs when the relative void volume reaches critical value $\xi_* = \frac{\alpha_* - 1}{\alpha_*}$,where α_* – the critical value of porosity when destruction of the material occurs.

If the material damaged by cracks is affected by the compressive stress, the fragmentation criterion is the limiting value of intensity of plastic deformations $e_u^* = \frac{\sqrt{2}}{3}\sqrt{3T_2 - T_1^2}$ where T_1 and T_2 - the first and second invariants of strain tensor.

The destroyed material is modeled by the granulated medium with standing the compressive loadings but not withstanding the stretching stresses. The numerical realization of mathematical model is carried out by the software package in full spatial design.

To assess the fulminate ability of explosives under shock-wave loading (when $p > P_{min}$) detonation fulminate criterion was used as:

$\int_{t_0}^{t} p^2 dt = K$, where K - material constants, p – explosive pressure,

$P_{min} = \frac{2\sigma_s}{3\alpha_{00}} \ln(\frac{\alpha_{00}}{\alpha_{00} - 1})$ - minimum pressure for the fulminate of detonation.

Numerical implementation of mathematical model occur by using software package in the total spatial statement [6]. (by the modified finite-element technique in the total spatial statement)

COMPUTATIONAL AND EXPERIMENTAL DATA

To identify the basic processes which has an impact on the behavior of materials, protecting explosive charge at high-speed impact, experimental studies was conduct by using smoothbore ballistic installation of 30 mm caliber. The impactor was placed in the guiding device, consisting of pushing textolite pallet. Figure 1 shows the appearance of hurled assembly (a), assembly (b) to be not deformed or destroyed during acceleration on the accelerator channel.

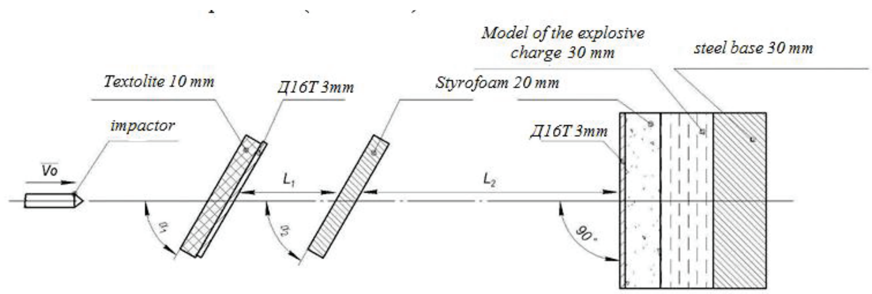
(a) (b)

FIGURE 1. Hurled assembly of projectile involving textolite (a) and assembly with the cermet impactor of 30 mm caliber (b) The cylindrical impactor is made from cermet material based on an alloy of tungsten-cobalt-nickel iron and it has a weight m_0 = 34 g, diameter d_0 = 9 mm. The impactor accelerated in a ballistic installation [7] up to velocity V_0 = 2761 m/s.

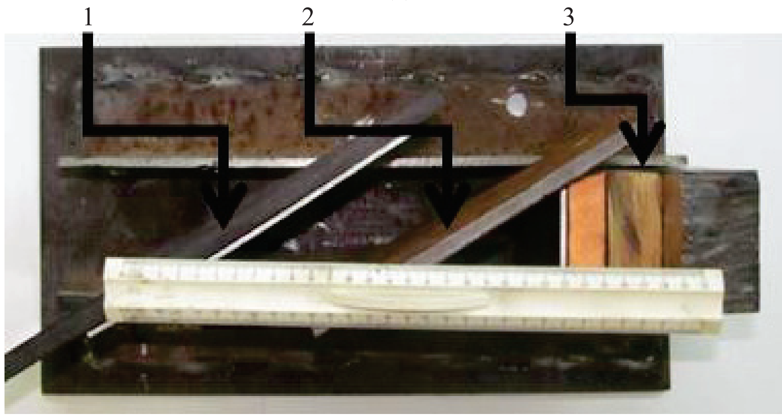
Figure 2 shows the model for the study as constructive and layout scheme of explosives protective structure. The scheme (a) and general arrangement (b) of physical model involve: 1 – the first obstacle that is a double-layer plate (carbon fiber-reinforced plastics 12 mm + aluminium alloy Д16Т 3 mm), 2 – the second obstacle (steel 10 mm), 3 – the third obstacle that is multi-layer assembly (aluminium alloy Д16Т 3 mm + styrofoam 20 mm + textolite, imitating the explosive, 30 mm), located on a steel substrate of thickness 45 mm).

The deflection angle of the first and second obstacles $\alpha_1 = \alpha_2 = 60°$. Distance L_1 = 95 mm, L_2 = 65 mm.

The result of interaction between impactor and protective structures is punching of all three obstacles. The steel substrate formed crater of deep 3.2 mm (Fig. 3).



(a)



(b)

FIGURE 2. The scheme (a) and general arrangement (b) of physical model
1 – the first obstacle (carbon fiber-reinforced plastics 12 mm + aluminium alloy Д16Т 3 mm), 2 – the second obstacle (steel 10 mm), 3 – the third obstacle (aluminium alloy Д16Т 3 mm + styrofoam 20 mm + textolite, imitating the explosive, 30 mm), located on a steel substrate of thickness 45 mm)

(a) (b) (c)

FIGURE 3. The result of the interaction between the impactor and the obstacles in the collision
a – the first obstacle (carbon fiber-reinforced plastics 12 mm + aluminium alloy Д16Т 3 mm), b – the second obstacle (steel 10 mm), c – the third obstacle (aluminium alloy Д16Т 3 mm + styrofoam 20 mm + textolite, imitating the explosive, 30 mm), located on a steel substrate of thickness 45 mm)

The obtained data were used to verify the mathematical model of the behavior of materials that protect the explosive charge during interaction with the impactor.

As follows the results of predictive calculations of collision at the impactor velocity of V_0 = 2000 m/s with obstacles. Mathematical modeling is conducted taking into account the possible detonation of explosives by the interaction. At the collision with the first obstacle the cermet impactor deformed and partially destroyed (Fig. 4). By 20 microseconds the impactor punches the first layer, and then the second layer of the screen by 40 microseconds.

By 50 microseconds the impactor residue of weigh 21 g has the velocity 1835 m/s, at this velocity it flies distance L_1 = 50 mm and communicates with the second screen (Fig. 5).

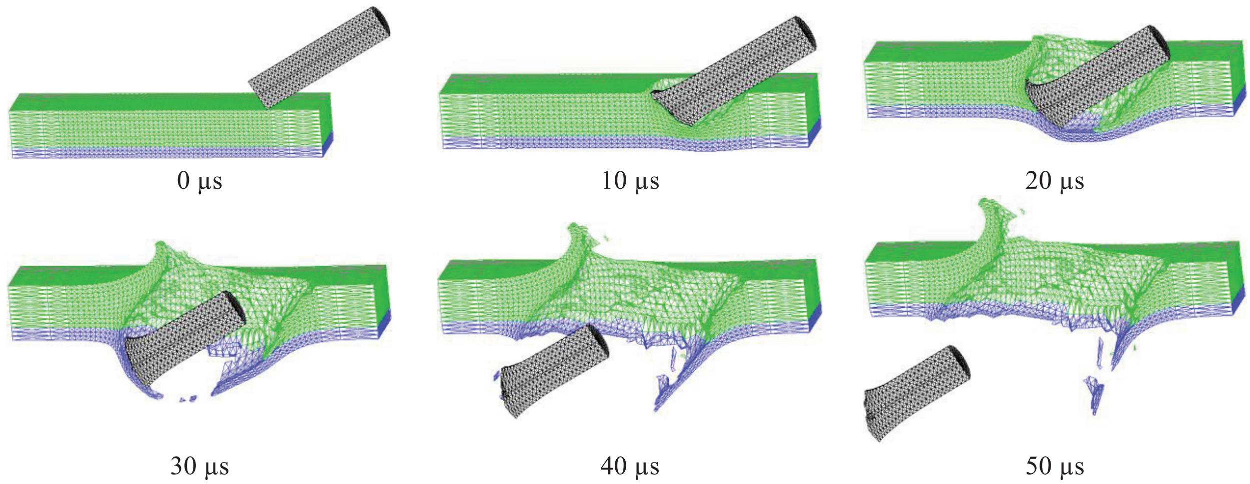


FIGURE 4. The interaction between the cermet impactor and the first obstacle at V_0 = 2000 m/s

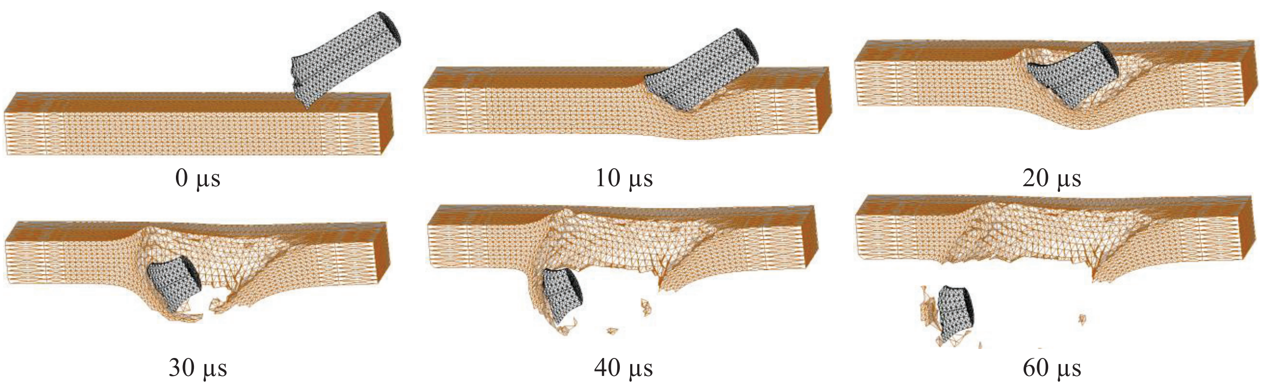


FIGURE 5. The interaction between the cermet impactor residue and the second obstacle (single-layer steel obstacle) screen at V = 1835 m/s

After punches through the second screen (process lasts 40 microseconds) impactor "produced" to a residue of weigh 5.66 g. At the same time its velocity decreases to V = 1086 m/s. With this velocity it flew the distance L_2 = 50 mm and interacted with the third obstacle including explosive (Fig. 6). The debris field (no image), acting on the obstacle, accompanies the impactor residue.

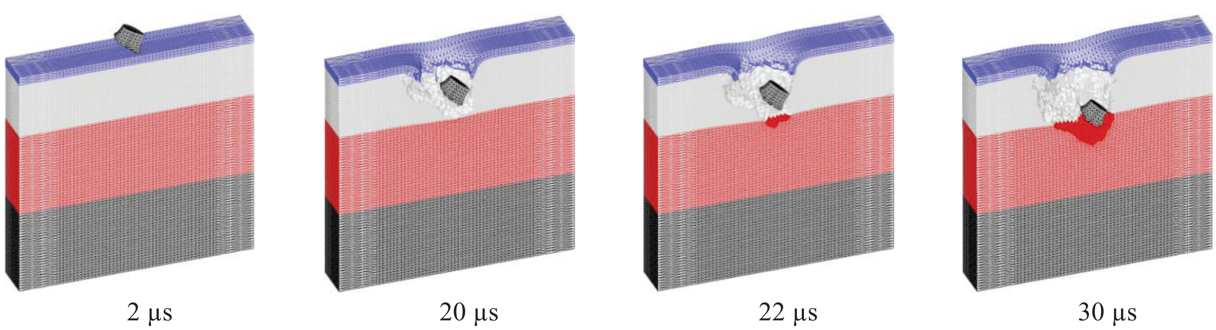


FIGURE 6. The interaction between the cermet impactor residue and the third obstacle at V = 1086 m/s

During the interaction between the cermet impact residue with the third obstacle the punching of the first protective layer occurs at 20 μs and of the second one occurs at 22 μs. At that moment the explosive detonation is evidenced. The explosive detonation criterion is fulfilled at the area indicated by dimout. At the 30 μs the cermet impactor interacts direct with explosive. The calculation stopped when the velocity of the cermet impactor is $V = 941$ m/s and the weight of the residue is 5.16 g.

Let's consider the collision of the cermet impactor with explosives protected by layered-spaced design at a velocity is 6000 m/s. Figures 7, 8 and 9 show the streak picture of interaction. During the collision of the cermet impactor with the first screen the impactor is deformed and partially destroyed. At the 4 μs it punches the first layer of screen, then the second one at the 12 μs. At the 18 μs the cermet impactor residue with the weight equal to 16.87 g has the velocity equal to 5877 m/s. The impactor with this velocity is flying the distance $L_1 = 50$ mm and interacts with the second screen (Fig. 8).

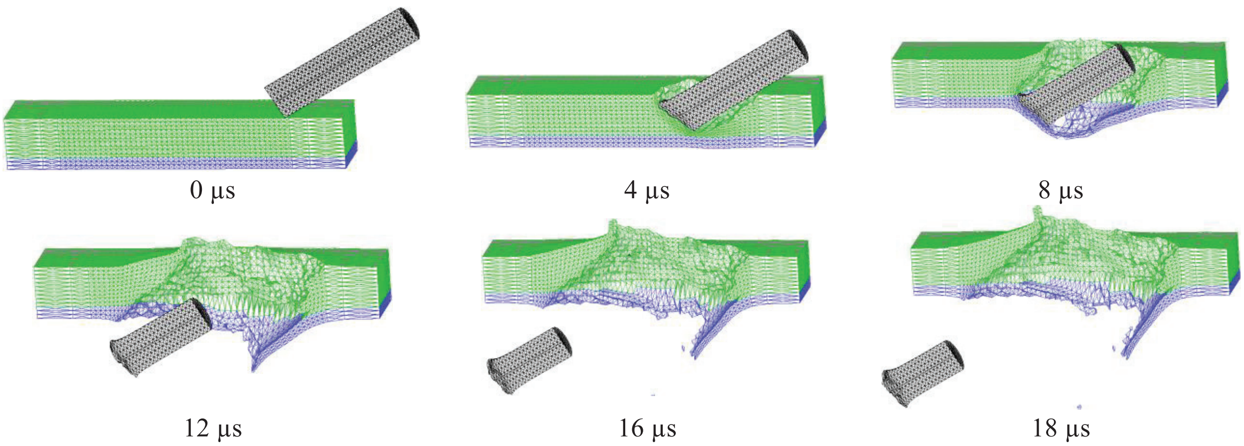


FIGURE 7. The interaction between the cermet impactor and the first obstacle at $V_0 = 6000$ m/s

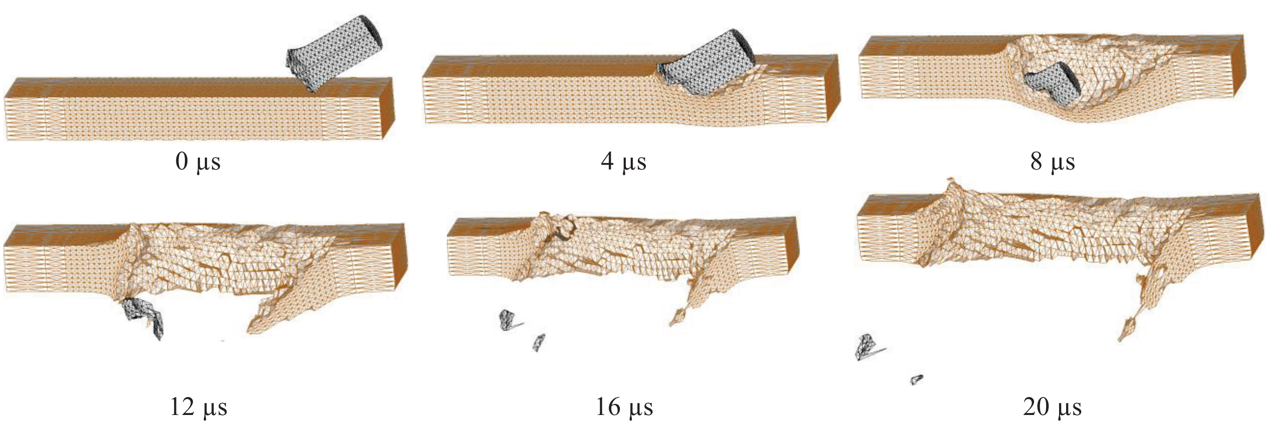


FIGURE 8. The interaction between the cermet impactor residue and the second obstacle (single-layer steel obstacle) screen at $V = 5877$ m/s

After the punching of the second screen per 20 μs the impactor is destroyed on several residue and the leading one is 0.66 g. In this case its velocity decreases to $V = 3866$ m/s. The cermet impactor residues interact with the third obstacle included explosive (Fig. 9). To 4 μs the leading residue punches the first layer of duralumin and stops in the styrofoam layer. It is evident that the impactor residues are completely destroyed to 8 μs. A perturbation doesn't reach the explosive layer. The explosive detonation doesn't occur.

Thus, the layered-spaced design, protected explosive, is subjected to mechanical damage by the high-speed residue (~ 6000 m/s), but the catastrophic consequences doesn't observed.

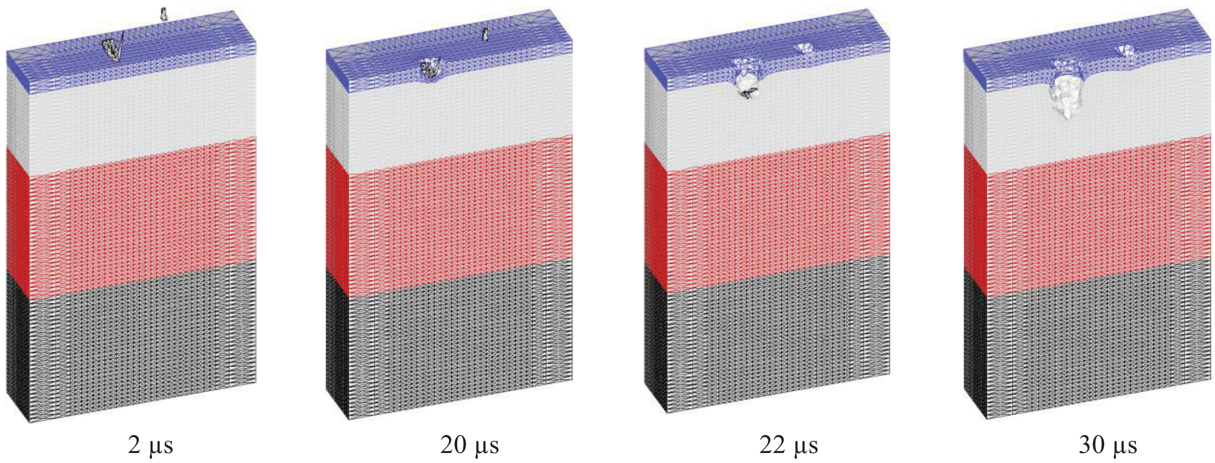


FIGURE 9. The interaction between the cermet impactor residue and the third obstacle at $V = 3866$ m/s

CONCLUSIONS

The experimental technique of research for the high-speed collision of the impactor with multilayer obstacles by using the ballistic installation of 30 mm caliber was developed.

The mathematical model and calculation method for research of the interaction of high-speed cermet impactor with the multilayer layered-spaced design, including explosives was developed.

In consequence of the experiment the cylindrical cermet impactor weighing 34 g, accelerated by the ballistic installation up to velocity $V_0 = 2761$ m/s, punches the protective structure and, as shown by calculations, leads to the detonation of the explosive charge.

During the increasing of impactor velosity to 6 km/s the layered-spaced design, protected explosive, is subjected to mechanical damage, but the explosive detonation doesn't occurs.

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