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Simulation of a Group Impact on a Heterogeneous Target of Finite Thickness

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Abstract. Numerical simulation of the processes of high-speed loading of homogeneous and heterogeneous targets by single projectiles, as well as by a group of projectiles with the same parameters in mass and momentum, has been carried out. Based on a comparison of the numerical simulation results for loading targets with different sets of projectiles, it is found that a projectile in the form of a ring knocks out the maximum hole in the target in terms of geometric dimensions, while a set of seven small disks removes the maximum mass from the target. The ring impact forms a continuous spall plate, which outruns the cloud of fragments of the destroyed material. Adding more than 5% of ceramics to the aluminum target volume does not allow the projectiles to penetrate through.

Keywords: impact, heterogeneous media, numerical simulation

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Introduction

The work [1] investigates the collective action of solids (steel balls) on duralumin barriers at the collision speed of about 1 km/s. The fact of more efficient penetration of a group of balls into barriers in comparison with the penetration of a single ball was experimentally established, which indicated the mutual influence of bodies in the process of a multiple impact at a moderate collision speed. It was argued that further research was required to identify the mechanism of weakening the target material under multiple impacts.

In [2], a numerical study of the process of dynamic surface erosion caused by successive impacts of several particles was carried out. The particles flew in successively. The study showed that during multiple collisions of particles, the phenomenon of strain hardening was observed, which significantly influenced the impact process. The energy losses increased with increasing speed and angle of the impact. The volume of the eroded crater increased with the number of collisions. Plastic deformation and shear failure were identified as the main mechanisms of the erosion.

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The creation of a reliable system for protecting spacecraft from elongated fragments of space debris dictates the need to study the nature of the interaction of high-speed elongated projectiles with protected objects. Thus, in [3], the interaction of a group of projectiles with a system of spaced plates was considered. The simulation results showed a greater danger of the collision of a group of projectiles with the protected body of the spacecraft in comparison with the impact of a single projectile with the same velocity and mass equal to that of seven projectiles. The numerical technique developed in this work allows one to simulate the process of interaction of the spacecraft shell with long rods in a wide range of velocities and impact angles.

In continuation of the study of the spacecraft protection resistance, in [4], a group impact was considered as the impact interaction of the shells and structural elements of spacecraft with space debris particles. The effect of a group of spherical bodies on spaced plates was considered. The results obtained show that the group action of high-speed elements leads to significant destruction of the target and the formation of a hole, the size of which exceeds the total projection area of the particles [5]. The resulting debris cloud behind the first target destroys the second protective plate and can cause irreparable damage to the main equipment. An increase in the hitting angle leads to a ricochet of the projectile and a change in the deformations of the aluminum plate. At small particle sizes, penetration of the first layer of the structure is observed, while the integrity of the second layer is preserved.

The work [6] presents the results of a study of a high-speed interaction of natural and technogenic particles with targets of finite thickness made of aluminum, glass, and fiberglass. These materials are widely used as structural elements of spacecraft, such as spacecraft housings, reservoirs, windows, glass in optical devices, heat shields, etc. The projectiles made of aluminum, glass, and asbestos-reinforced laminate, particles of aluminum and steel represented the space debris, and particles of ice and granite represented the natural particles of space bodies. In this study, the nature of deformation, damage, and destruction of targets made of plastic and brittle materials was qualitatively and quantitatively assessed.

Continuing the work on a group impact, considered by us in [7] on the example of ice, let us investigate the reaction of a heterogeneous cermet medium to the impact of a high-speed group of bodies.

1. The problem statements

Following [8, 9], we use the model of a rigid deformable body. The model consists of equations of motion, mass balance, momentum, and energy, as well as the equations of state and elastic-plastic Prandtl–Reuss flow:

equations of trajectory of material particles motion

$$\dot{x}_i = u_i; \tag{1}$$

equation of medium continuity

$$V_0 \cdot \rho_0 = V \cdot \rho; \tag{2}$$

law of change of a material particle momentum

$$\rho \cdot \dot{u}_i = \sigma_{ij,j}; \tag{3}$$

change of internal energy of a particle

$$\rho \cdot \dot{e} = \sigma_{ij} \cdot \dot{\varepsilon}_{ij}; \tag{4}$$

the strain rate tensor is of the form

$$\dot{\varepsilon}_{ij} = 0,5 \cdot (u_{i,j} + u_{j,i}); \tag{5}$$

the stress tensor can be presented in the standard form

$$\sigma_{ij} = -\delta_{ij} \cdot P + s_{ij}, \tag{6}$$

where s_{ij} is deviator of the stress tensor, responsible for the reaction to shear deformation of the material particles; δ_{ij} is Kronecker delta; P is function of pressure in the form of Mie–Grüneisen.

The process equations are taken in the Prandtl–Reuss form

$$\hat{s}_{ij} + d\lambda' \cdot s_{ij} = 2 \cdot G \cdot \dot{\varepsilon}'_{ij}, \tag{7}$$

where $\dot{\varepsilon}'_{ij} = \dot{\varepsilon}_{ij} - \dot{\varepsilon}_{kk}/3$, provided Huber–von-Mises plasticity condition

$$s_{ij} \cdot s_{ij} \leqslant 2 \cdot Y_0^2/3, \tag{8}$$

where Y_0 is the dynamic yield strength, and scalar factor $d\lambda$‘ is determined by the known procedure of reducing to the yield circle. The above equations use the standard notation: each of indices i, j takes values of 1-3; the repeated indices assume summation; dot over a symbol is the time derivative; index after comma is derivative by the corresponding coordinate; x_i, u_i are components of vectors of the position and velocity of a particle, respectively; ρ is the current density; G is the shear modulus.

The initial conditions for the i-th body at $t = 0$ in domain $D(\boldsymbol{x},t)$ often have the form:

$$\rho^i(x,0) = \rho^{i0}(x), \quad u^i_j(x,0) = u^{i0}_j(x), \quad s_{ij} = P = e = 0, \tag{9}$$

where $\rho^{i0}(\boldsymbol{x})$, $u^{i0}{}_j(\boldsymbol{x})$ are specified initial distributions of the material density and the velocity vector throughout region $D(\boldsymbol{x},t)$.

The partial differential equations are transformed into an explicit difference scheme on a tetrahedral grid along the trajectory of each material particle (in this case, a cell of the difference grid). The difference grid in arbitrary multiply connected domains is constructed using the dynamic method [10].

To take into account the processes of destruction, the system is supplemented with relations linking the parameters of the stress-strain state with the limiting values of materials [9, 11]. As the equation of state, a thermodynamically complete low-parameter equation of state is used [12–15], almost all parameters of which are given in reference books. Parameters of the contact surfaces of interacting deformable solids are calculated according to the symmetric algorithm [9]. The models formulated above are implemented in the form of the REACTOR software package, which makes it possible to successfully solve the problems of mechanics of a deformable solid in a wide range of collision velocities [16, 17].

2. High-speed impact on a homogeneous target

Let a steel projectile (a group of projectiles) made of Steel4340 interact with a target made of aluminum alloy Al5083. It is required to determine which configuration of projectiles with equal kinetic energy (impact velocity and mass) provides a through hole of maximum diameter in a target with thickness $h_t = 4.5$ cm. Properties of the materials are shown in Tab. 1 [18, 19].

Table 1. Parameters of the materials

Material	ρ, kg/m^3	K, GPa	G, GPa	Y_0, GPa	σ_1^*, GPa	ϵ^*, %
Al5083	2720	69.01	26.4	0.358	0.477	0.12
Steel4340	7874	168.0	80.0	1.0	7.5	0.325

To solve the problem, similar to [7], the following steel projectiles of the same mass were chosen: (1) a single disk; (2) a ring (Fig. 1a); (3) seven cylinders; (4) seven spheres (Fig. 1b); (5) seven small disks. The geometric model of the three-dimensional problem is shown in Fig. 1. To reduce the numerical load on the problem, the possible movement of the target is limited by a massive guard casing.

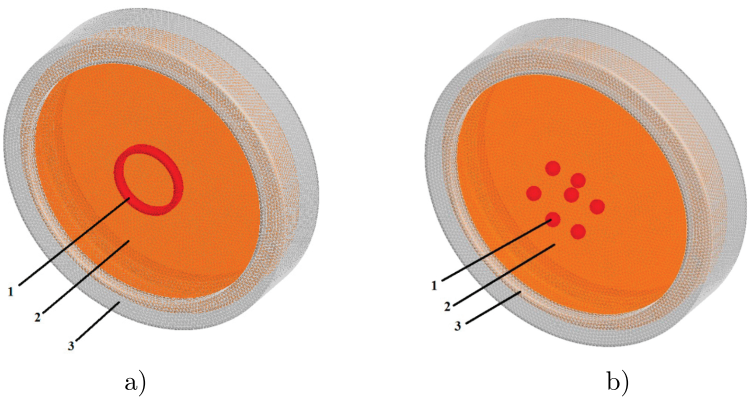


Fig. 1. The initial geometry of the problem on the collision of an aluminum target and a steel projectile; 1 – Steel4340, 2 – Al5083, 3 – guard casing

The impact velocity for all considered cases $U = 950$ m/s. The shapes and sizes of the projectiles and punched holes are shown in Tab. 2, where r, h are the radius and height of the projectiles, U_{res} is the residual velocity of the projectile, m is the mass of the knocked-out hole, R_{min}, R_{max} are the radii of the knocked-out hole in the narrowest and widest places.

Table 2. Shapes and sizes of the projectiles and punched holes

Shape of the projectile	r, cm	h, cm	U_{res}, m/s	Punched hole		
				m, g	R_{max}, cm	R_{min}, cm
Single disk	3.29	0.55	63	1565	12.05	8.23
Ring	4.5-3.8	1	35	2255	17.16	12.76
Cylinder (7 pcs)	0.675	1.85	126	1495	11.22	9.06
Sphere (7 pcs)	0.8685	-	67	2023	17.58	11.34
Small disk (7 pcs)	1.061	0.75	112	2902	14.06	11.66

Consider the process of knocking out a hole with a single steel disk. The result of 3D simulation of the penetration process is shown in Fig. 2. For clarity, a section along the axis of the hole is shown. The blow occurs from right to left. The projectile and target are colored according to the speed of movement. The particles of the destroyed projectile are colored red, those of the target are gray, the guard casing is not shown. The process of knocking out a hole begins as an impact of a plate on a massive obstacle, i.e. with a crater formation. Further, the impulse of the compression wave reaches the free rear surface, and unloading begins. The interaction of the two unloading waves, from the back and front surfaces, forms a tensile wave, which causes spalling (see Fig. 2, time moment t=10 μs). The disk continues to move, partially turning and collapsing, while carrying the destroyed aluminum barrier into the region beyond the barrier. In the process of destruction, a conical hole is knocked out, since the diameter of the crater formed at the initial stage of the impact is larger than the diameter of the rear hole.

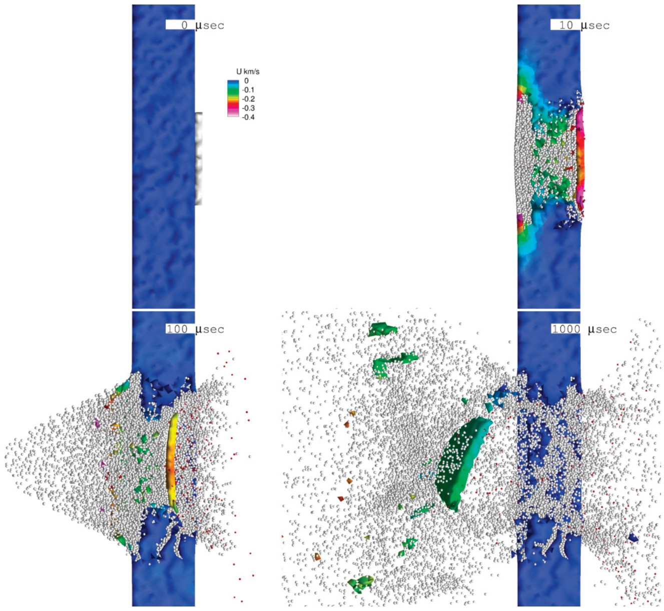


Fig. 2. 3D motion picture of the process of breaking through the barrier with a single steel disk

When the single steel ring hits the aluminum barrier, the destroyed aluminum is ejected in the form of a jet (see Fig. 3, 260 μs), the direction of which is opposite to the direction of the impact velocity. This phenomenon is caused by the formation of an annular crater, the ejection inside the ring is a converging flow of aluminum fragments, which leads to the formation of a jet flow opposite to the direction of impact. The unloading of the compression wave from the rear surface and the tensile waves from the reverse flow upon meeting form a rather complex surface of spall fracture, which significantly weakens the target. The spall plate, in an almost undisturbed form, continues to move ahead of the behind-the-barrier particle cloud. Moving the ring deep into the plate leads to the formation of a "plug" and almost complete deceleration of the ring.

The impact results with a group of 7 cylinders or 7 spheres, the dimensions of which are shown in Tab. 2, hardly differ. At the final stage of the penetration process, a group impact leads to the appearance of a common large hole, while the average speed of the projectiles behind the obstacle remains high enough, about U_{res}=120 m/s. In the process of penetration, projectiles undergo deformation and rotations around their mass center, since the destruction of the target material occurs in a complex stress-strain barrier (see Fig. 4).

When hitting with 7 small disks (the radius is greater than the thickness), the largest through

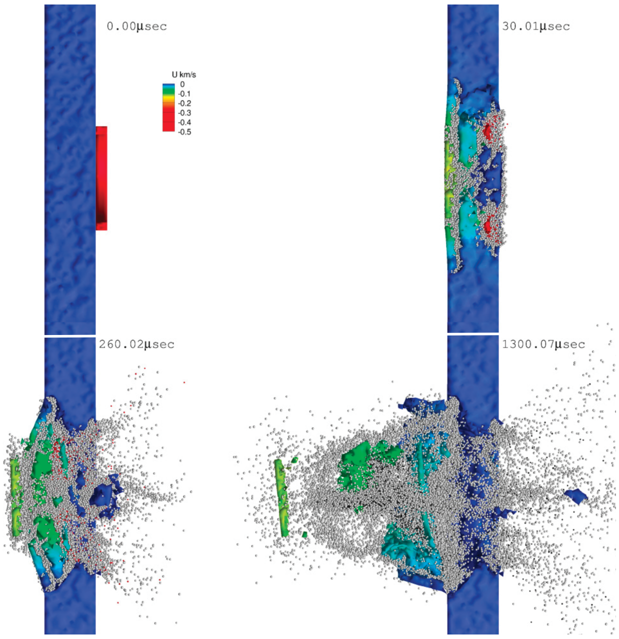


Fig. 3. 3D motion picture of the process of breaking through the barrier with a single steel ring

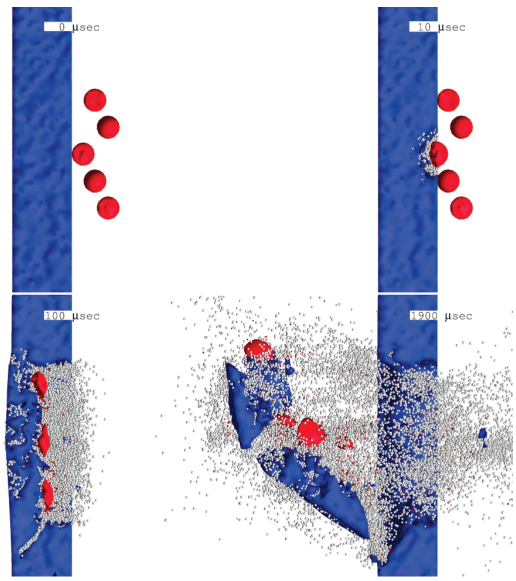


Fig. 4. 3D motion picture of the process of breaking through the barrier with a group of 7 spheres

hole is formed and the largest amount of the barrier mass is knocked out. Note that the unloading of the compression wave formed by the sum of the compression waves from each disk leads to the formation of spall fractures near the rear surface of the target. The small discs deform and rotate around their mass center as well. Radial through cavities merge along a part of their periphery and form a separate target fragment, which is carried out by the central disk, forming a large through hole.

The results of numerical simulation, presented in Tab. 2, show that the impact of a steel ring on a barrier of finite thickness leads to the formation of a hole in it of the largest size, while the residual speed of the ring is minimal for all considered cases, which means that the energy spent on destruction is maximum. Similar results were obtained for the impact of 7 small disks, but at the same time, the mass carried out beyond the barrier in this case is the greatest.

3. High-speed impact on a heterogeneous target

Let us consider the problem of penetrating heterogeneous targets by a group of projectiles to estimate the effect of ceramic inclusions on the armor resistance of the target. Heterogeneous targets are constructed of an aluminum alloy with a given volume fraction of ceramics Al_2O_3 or SiC. Since the group of projectiles in the form of small disks had knocked out the greatest mass from the target, and the group of projectiles in the form of 7 cylinders had had the highest residual velocity, we performed calculations with these forms of projectiles for heterogeneous targets as well. The initial collision velocity and geometrical parameters of the target are similar to the above calculations. The geometry of the problem for the cases under consideration is shown in Fig. 5. The region with the cermet heterogeneous composite is covered by a difference grid with the cells in the form of a tetrahedron, filling the space without gaps and overlaps. At that, a given volume of ceramic inclusions is randomly distributed over the volume of the matrix [17].

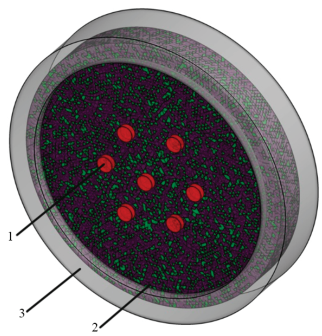


Fig. 5. The initial geometry of the problem on the collision of a heterogeneous target and a projectile of seven small disks: 1 — Steel4340, 2 — Al5083 + 25% Al_2O_3, 3 — guard casing

The simulation of the process of collision of a group of strikers with heterogeneous targets made of aluminum alloy with a volume fraction of SiC ceramics from 5% to 15% is carried out. Fig. 6 shows the process of interaction of a group of seven small disks with a heterogeneous target with ceramics volume fraction of 5%. Since the heterogeneous target, due to the inhomogeneity of neighboring areas, can receive significant damage, the small disks, due to the complexity of the stress-strain state, which causes the difference in forces on the disk surface, receive significant rotation. A continuous hole with a radius of about 8.5 cm is formed in the target, which is 3–4 cm smaller than the hole in the homogeneous target. The knocked-out mass in this case is 2750 grams, which is comparable to the result for a homogeneous target. However, it is necessary to take into account the difference in the initial masses of the homogeneous and heterogeneous targets, since the addition of ceramics increases the overall density of the target, because the density of ceramics $\rho_{SiC} = 3.18$ g/cm^3, $\rho_{Al_2O_3} = 3.7$ g/cm^3, which exceeds the density of the homogeneous target $\rho_{Al} = 2.7$ g/cm^3. In the case of a collision of the group of projectiles with a target containing 10% ceramics, no through penetration of the target occurs. A spall fracture is observed on the rear side of the target with the formation of a stream of particles of small mass.

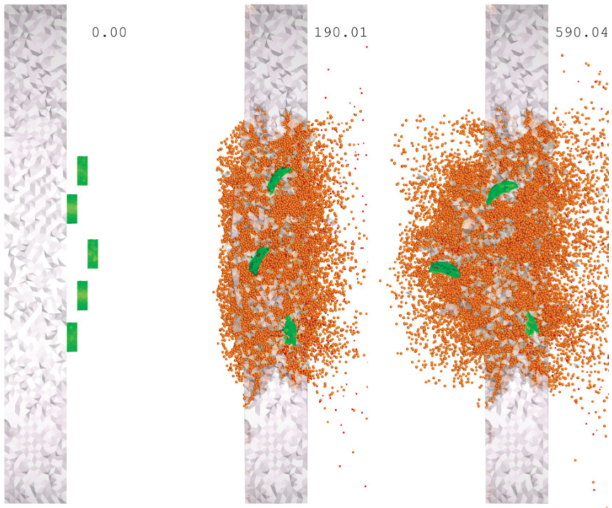


Fig. 6. 3D motion picture of the process of knocking out a hole from the target with a group of seven small disks. Target with 5% volume fraction of SiC

Let us consider the interaction of a group of disks with a heterogeneous target containing the volume fraction of Al_2O_3 ceramics from 5% to 15%. The calculation result for the target with the ceramics concentration of 5% is shown in Fig. 7.

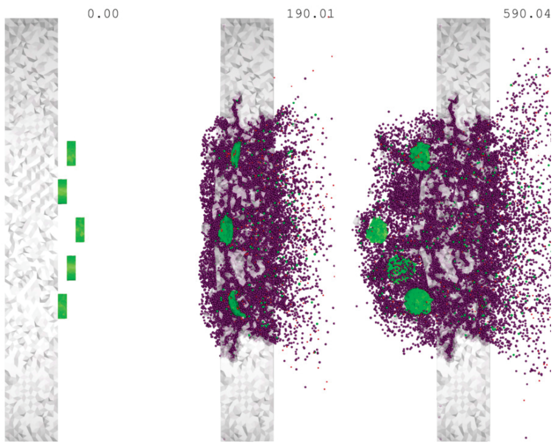
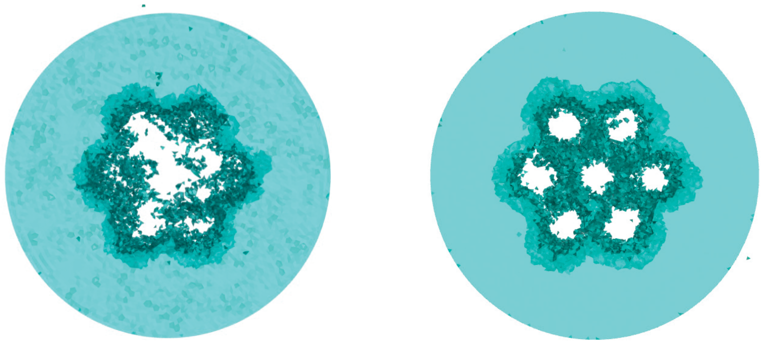


Fig. 7. 3D motion picture of the process of knocking out the plug from a target with 5% volume fraction of Al_2O_3 by a group of seven small disks

Seven non-intersecting holes are formed in the heterogeneous target, as shown in Fig. 8b. The hole for a target containing 5% of SiC ceramics is shown there as well, Fig. 8a. The strength characteristics of Al_2O_3 ceramics are lower than those of SiC ceramics [20], which ensures better penetration of small projectiles through a heterogeneous target based on Al_2O_3 ceramics. This is the reason for the lower velocity loss in the target based on Al_2O_3 ceramics.



a) b)

Fig. 8. Holes formed in a target with 5% volume fraction of ceramics: (a) SiC; (b) Al_2O_3

The collision of a group of seven cylinders with similar heterogeneous targets was simulated. A heterogeneous target containing 5% by volume of SiC ceramics did not receive a through hole. The cylinders were deformed in the course of interaction with the target, and virtually all destruction of the target occurred on the front surface. An increase in the volume fraction of SiC ceramics in the target to 10% did not change the fracture trend, and the mass knocked out by spalling did not exceed 500 grams.

When a group of seven cylinders collides with a target containing 5% by volume of Al_2O_3 ceramics, the central cylinder breaks through the target, while the rest of the cylinders stop, as shown in Fig. 9. The residual velocity of the piercing cylinder is 70 m/s. In this case, it can be said that the target with a fraction of Al_2O_3 has a lower resistance than the target with a fraction of SiC. When the volume fraction of Al_2O_3 ceramics in the target is 10%, no penetration occurs, similar to the case of 10% SiC. The knocked-out mass is about 700 grams.

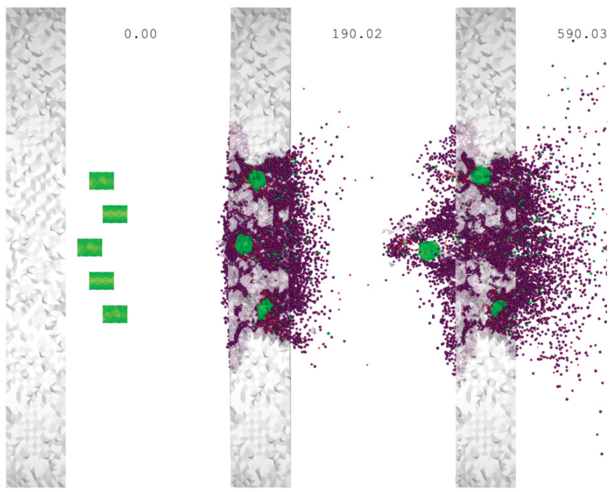


Fig. 9. 3D motion picture of the process of knocking out the plug from a target with 5% volume fraction of Al_2O_3 by a group of seven cylinders

All the results of calculations are summarized in Tab. 3. The largest mass is knocked out in the case of interaction of seven small disks and a target with 5% volume fraction of SiC ceramics. Heterogeneous targets with 15% volume fraction of Al_2O_3 and SiC ceramics at the given geometrical parameters and initial collision velocity were not penetrated by any of the above projectiles (groups of projectiles). Heterogeneous Al5083/SiC targets have better ballistic resistance compared to Al5083/Al_2O_3 targets.

Table 3. Knocked-out mass and residual velocity in a heterogeneous target

Projectile shape	Volume fraction and ceramic material	Punched hole			U_{res}, m/s
		m, g	R_{max}, cm	R_{min}, cm	
Small disk (7 pcs)	5%, SiC	2750	8.7	8.3	42
	10%, SiC	983	0	0	0
	15%, SiC	800	0	0	0
	5%, Al_2O_3	2543	-	-	73
	10%, Al_2O_3	2016	-	-	10
	15%, Al_2O_3	-	0	0	0
Cylinder (7 pcs)	5%, SiC	1415	0	0	0
	10%, SiC	409	0	0	0
	5%, Al_2O_3	1137	1.2	1	71
	10%, Al_2O_3	734	0	0	0

Conclusions

1. A projectile in the form of a ring knocks out a hole of maximum diameter in a homogeneous aluminum barrier, while a group of 7 small disks removes the maximum mass from the barrier.

2. The impact of a steel ring on a homogeneous aluminum barrier forms a solid spall plate, which outruns the cloud of destroyed material fragments.

3. A heterogeneous cermet barrier based on aluminum alloy 5083 with addition of Al_2O_3 ceramics is inferior in armor resistance to a heterogeneous barrier with the addition of SiC at the same concentration of ceramics.

4. Adding 5% or more of ceramics to the aluminum alloy 5083 volume at meeting speeds up to 950 m/s prevents through penetration of the heterogeneous barrier.

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Моделирование процессов группового удара по гетерогенной преграде конечной толщины

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Аннотация. Проведено численное моделирование процессов высокоскоростного нагружения гомогенных и гетерогенных мишеней одиночными ударниками, а также группой ударников с теми же параметрами по массе и импульсу. На основе сравнения результатов численного моделирования процессов нагружения мишеней разными наборами ударников обнаружено, что ударник в виде кольца выбивает в мишени максимальное отверстие по геометрическим размерам, тогда как набор из семи малых дисков удаляет из мишени максимальную массу, удар кольцом формирует сплошную откольную тарелочку, которая опережает в своем движении облако фрагментов разрушенного материала, внесение в алюминиевую мишень керамики более 5 % по объему не позволяет ударникам сквозного пробития.

Ключевые слова: удар, гетерогенная среда, численное моделирование.