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Dynamic Fracture of Ductile Materials

Interaction of structural elements of space vehicles with high-velocity projectiles

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Abstract

The paper represents the study concerning the high-velocity interaction of textolite and glass with aluminum and steel particles which simulate technogenic space debris, as well as with ice and granite particles which simulate natural materials of natural space bodies.

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Keywords: High-velocity impact; fracture; fragmentation; space debris; space vehicles;

1. Introduction

Providing the strength of textolite and glass elements for space vehicles is an important practical problem. Textolite (fabric-phenolic resin laminate) is a structural material, a laminate based on a fabric of fibers and a polymeric binder (for example, bakelite, polyester resin, epoxy resin). These materials are used as structural elements of space vehicles: windows, glass in optical instruments, heat shields, etc.

There is a need to investigate the interaction of glass and textolite with the flows of technogenic and natural space debris to maintain the integrity of space vehicles exposed to the impact by large fragments and to reduce the erosion of structural elements exposed to the flow of ultrafine particles.

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Therefore, the theoretical and experimental determination of maximum strength for the structural elements of space vehicles exposed to high-velocity particles is an urgent problem from a practical point of view. This work represents the theoretical and experimental study concerning the interaction of high-velocity compact projectiles with the glass and textolite targets of finite thickness. The paper considers the impact with aluminum and steel particles which simulate space debris, as well as with ice and granite particles which simulate natural particles of space bodies.

To study the high-velocity interaction processes, an experimental stand was developed, manufactured and installed. This stand includes a universal base frame that can be used for fixing of any available accelerators at SRI AMM (T-29, 23/8 PPH, 34/8 PPH, 34/23/8 PPH, 50/23 GDI), as well as a new three-stage light-gas installation (RF patent, No. 2490580) and an evacuated chamber. The stand is equipped with units for the measurement of dynamic pressure in barrels, as well as with the sensors of the muzzle and trajectory velocity of models and projectiles, including original sensors (RF patent, No. 2193207).

The stand allows the various studies of high-velocity impact to be conducted at velocities up to 8 km/s and higher. The uniqueness of the stand is that the base frame for the fixing of the accelerator and the evacuated chamber are mounted on a single platform suspended. This eliminates the negative influence of shot on the foundation of the building. To calculate elastoplastic flows used technique implemented on tetrahedral cells and based on the combined use of the Wilkins method [1] for calculation of internal body points and Johnson method [2] for calculating contact interactions. The most common way to protect objects is to use materials with high physical and mechanical properties, such as ceramics and composites based on it. Layered barrier enable prevent damage and destruction of protected structures or stretching of the pressure pulse in the layered system due to multiple reflection of waves from layers with different acoustic impedances, or pressure pulse energy dissipation during plastic deformation of highly porous layers or fragmentation of ceramic materials.

The second possible way to counter high-velocity projectiles is to throw groups of spaced plates and rods from conventional and composite materials towards projectiles. As a result of the dynamic interaction and intense deformation occurs the partial destruction of the projectiles or the deviation projectiles from the line of collision. Consequently, the projectiles can rebound from the surface barrier, or deviate from the object to be protected and do not interact with the barrier. All these factors reduce the penetration of projectiles into the protected object. In this work numerical simulation of the interaction of high - velocity projectiles with groups of spaced rods and plates is carried out.

2. Equations describing the motion of a compressible elastoplastic body with an allowance for probabilistic fracture

The equations describing spatial adiabatic motion of a solid compressible medium are differential consequences of the fundamental laws of conservation mass, pulse and energy. In general they have the forms [1-5].

To equations we must add the equations taking into account relevant thermodynamic effects associated with adiabatic compression and strength of the medium. In general case, under the influence of the forces on the solid-deformable body, both volume (density) and the shape of the body are changed by different dependencies. Therefore, stress tensor is the sum of spherical tensor and the stress tensor deviator. The equation of a solid state was chosen in the form of Mie –Grüneisen.

In addition, the two fracture mechanisms can be implemented during the high-velocity interaction, namely the shear and spall mechanisms. The criterion of critical equivalent plastic strain [6] was used as a criterion for the shear fracture.

For the computation of the plastic material fracture (aluminum, steel), the Johnson - Cook relation was also used [7]. For the computation of the brittle material fracture (glass, ice, granite), the Johnson - Holmquist relation was used (JH2) [8].

Three-dimensional simulation for the interaction of targets with high-velocity projectiles is based on the equations which describe the spatial adiabatic motion of a solid compressible medium and are the differential consequences of the fundamental laws, such as the conservation of mass, momentum and energy. To compute elastoplastic flows, the tetrahedral cells are used to apply a technique that is based on combined using the Wilkins method for the calculation of internal body points and the Johnson method for the calculation of contact interactions [1-5]. The discretization of the three-dimensional area into tetrahedrons is conducted gradually using the automatic generation of mesh. The fracture process of glass, ice, and granite was considered to be the fracture process of brittle material, without the section of plastic deformation that is typical for the deformation of metals.

The variant of the SPH method is also used in the work [9]. The numerical method is based on the use of the weak variational formulation. The smoothing parameter is considered to be a hidden state variable and takes into account its effect on physical processes: the change of the smoothing parameter for separate nodes is equivalent to the change of the corresponding relative volume, which influences on the stress-strain state of material, and as a result, is a specific form of deformation that is considered in the computation. The computation for the acceleration of nodes is based on the definition of summarized forces which are determined by estimating the effect of the node movement on the strain field in the neighborhood of nodes (instead of the direct differentiation of the stress field).

In real materials the fracture process is always determined by the internal structure of the medium, the presence of inhomogeneities usually caused by the different orientation of grains in polycrystalline material or inhomogeneities in composite materials, the difference in microstrength inside grains and on the grain boundary or the interface boundary. Therefore, to improve the adequacy of the numerically simulated process, there is a need to add a disturbance to the experimental data, namely in the physical and mechanical characteristics of the fractured medium, i.e., the random distribution of the factors determining the mechanical properties of material. The introduction of information on the polycrystalline structure of material to the calculation procedure requires a large amount of experimental data and the high demands for computing capacity, which confines the implementation and application of this approach.

In this connection, a simplified version of simulation is used for the probabilistic failure mechanism. The physical and mechanical characteristics of the medium which are responsible for the strength are considered to be randomly distributed over the volume of material. The density of the probable distribution for these parameters is taken in the form of different distribution laws generally dependent on the table (average) value of the distributed parameter, the variable dispersion of the parameter distribution, and other characteristics of the medium.

The parameters, such as yield stress, tensile strength, maximum strain and other constants which determine the time of fracture in various strength theories and fracture criteria are directly dependent on the number and size of defects and should be randomly distributed over the volume with dispersion depending on the homogeneity of material. The probability density of random variables was taken in the form of normal Gaussian distribution with the average number equal to the tabulated value and the variable dispersion. The ideology and procedure of the probabilistic approach used to solve the problem of solid fracture are shown in detail in [5].

To solve three-dimensional problems, there is a need to consider the natural heterogeneity of the real material structure that influences on the distribution of physical and mechanical characteristics over the volume of structural elements and is one of the factors determining the behavior of fracture. This factor can be considered in the equations of deformable solid mechanics by using the probabilistic distribution laws of physical and mechanical characteristics over the volume of construction. Natural fragmentation of projectiles and targets is computed by introducing the probabilistic distribution mechanism of initial defects in the structure of material. The initial inhomogeneities of material are computed by the probabilistic distribution of the fracture criterion in the cells of the computational region, using a modified random number generator that provides a random variable obeying the chosen distribution law.

2. Experimental studies. Test computations

The effect of cosmic dust on the windows of space vehicles was studied using a three-stage pneumatic ballistic light-gas installation(pneumatic LGI). The three-stage LGI with the use of compressed gas was chosen for the experiments on the test stand (SRI AMM TSU) [5].

Fig.1. Three-stage pneumatic light-gas.

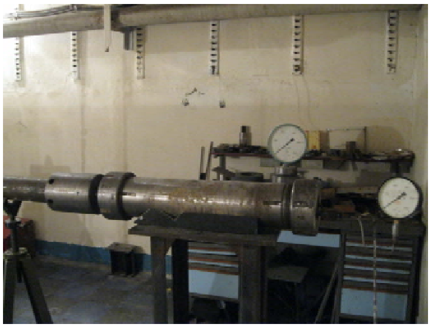

Fig.2. First pneumo stage.ballistic installation.

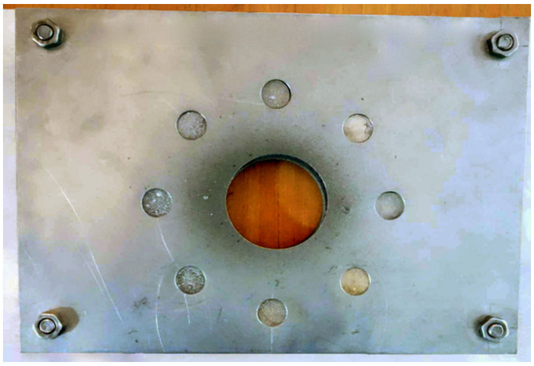

Fig.3. Target for comparative tests.

Fig.4. Results of tests (50 micron Fe powder).

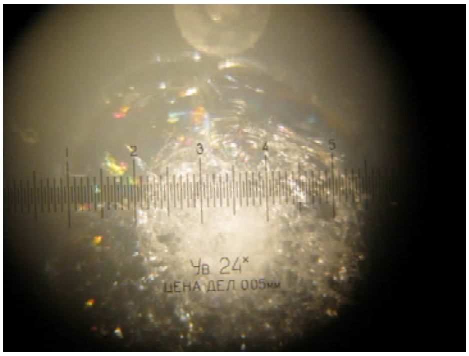

Fig.5. Interaction of the K8 glass plate with a soft particle the density of which is 1 g/cm^3 (simulation of silica gel ball).

Test computation. The dimensions of the plate were 0.3×0.3×0.3 mm, the ball diameter was 50 microns, the impact velocity was equal to 1, 2, 3 km/s. For the velocity of 1 km/s, the computation results are shown in Fig. 6 [10].

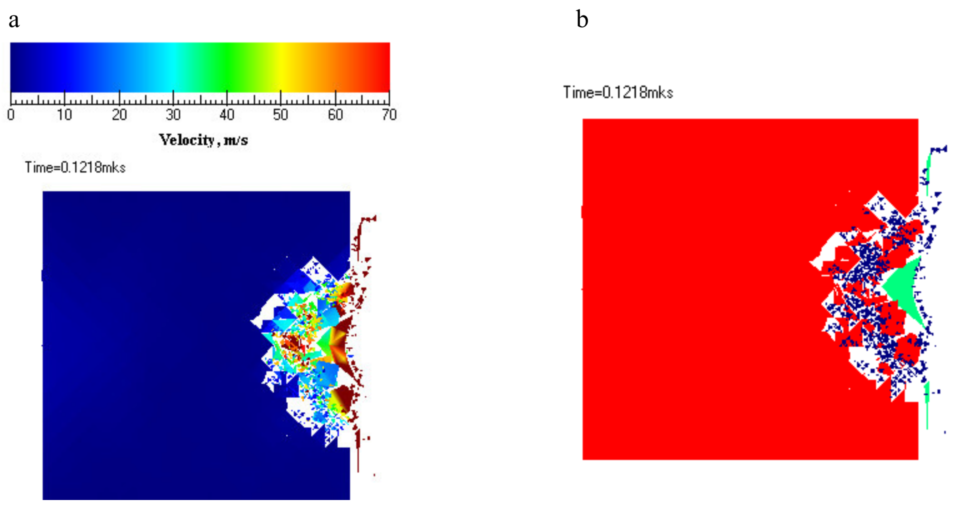

Fig.6.(a) 2-D cross sectional view of the system «plate-ball» for the impact velocity of 1 km/s, the time t = 0.12 μs, the velocity distribution in the system; (b) is the phase diagram.

The results of calculating the depth and diameter of the craters in the glass gave a difference in the results of about 5-7% compared with the experiment.

Comparison of experimental and computed values. The impact of the two-layer target (textolite ST-HT, thickness of 8.0 mm + AMg6, thickness of 5.0 mm) with a projectile (100Cr6, diameter of 12.7 mm) at an angle of 30° to the normal line was investigated for the velocities of 741 m/s and 962 m/s. The computations of the projectile velocities after penetration of the target are shown in Table 1, where the computations are compared with the experimental data [11]. For textolite, the error is not more than 5%. See Table 1.

Table 1. Comparison of experimental and computed values for the projectile velocities after penetration of the target.

$V_{н}$, m/s	$V_{к}$, m/s, experiment	$V_{к}$, m/s, computation
741	516	490
962	723	700

3. Results of numerical simulation

The impact of high-velocity aluminum particles (density ρ_0 = 2.64 g/cm) with steel (density ρ_0 = 7.7 g/cm) was considered for the velocity of 3000 m/s to simulate space debris, the impact of ice particles (density ρ_0 = 0.92 g/cm) with granite (density ρ_0 = 2.6 g/cm) was considered to simulate natural micrometeorites. Glass (density ρ_0 = 2.53 g/cm) and textolite (density ρ_0 = 1.59 g/cm) were used as the target. The dimensions of the glass target were 0.25 cm in thickness and 0.6 cm in diameter. The dimensions of the textolite target were 0.5 cm in thickness and 1.3 cm in diameter. In the first case, the ball was 0.1 cm in diameter and 0.2 cm in the second case.

Figs. 7-10 demonstrate the results of computations for the impact of the glass plate with different high-velocity particles. The results of computations for the impact of the glass plate with a steel ball are shown in Fig. 7.

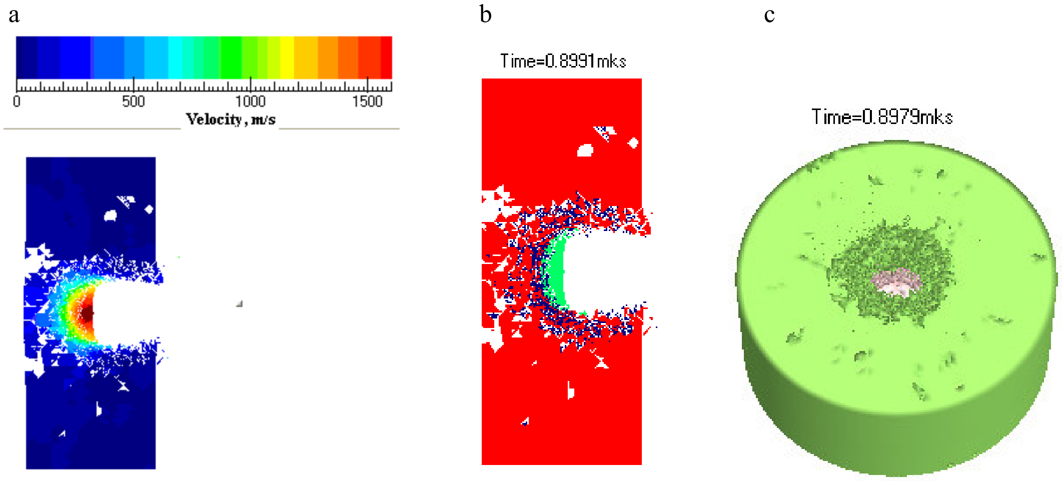

Fig.7.(a) 2-D cross sectional view of the system «glass plate-steel ball» for the impact velocity of 3000 m/s for the time t = 0.898 µs, the velocity distribution in the system; (b) is the phase diagram; (c) is the 3D picture of impact.

The impact of an aluminum particle with a glass plate is shown in Fig. 8.

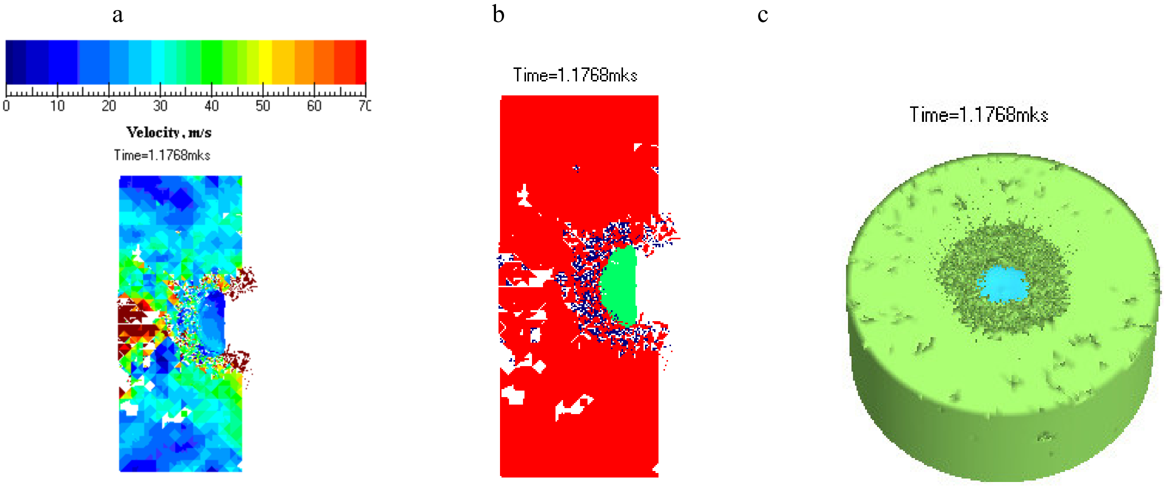

Fig.8. (a) 2-D cross sectional view of the system «glass plate-aluminum ball» for the impact velocity of 3000 m/s and the time t = 1.768 µs, the velocity distribution in the system; (b) is the phase diagram; (c) is the 3D picture of impact.

Fig. 9 shows the results of computations for the impact of the glass plate with a granite ball.

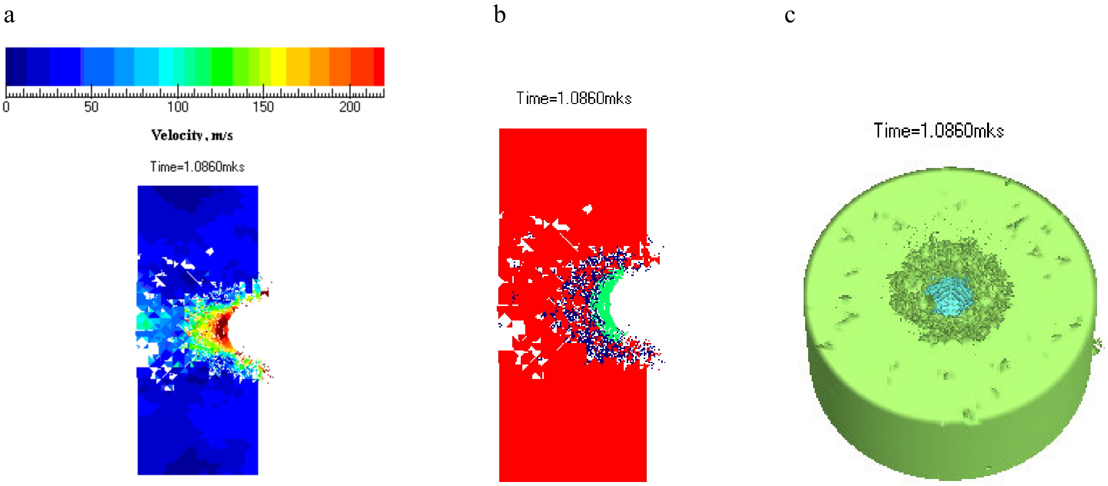

Fig.9. (a) 2-D cross sectional view of the system «glass plate-granite ball» for the impact velocity of 3000 m/s and the time t = 1.086 μs, the velocity distribution in the system; (b) is the phase diagram; (c) is the 3D picture of impact.

The impact of an ice fragment with the glass plate is shown in Fig. 10.

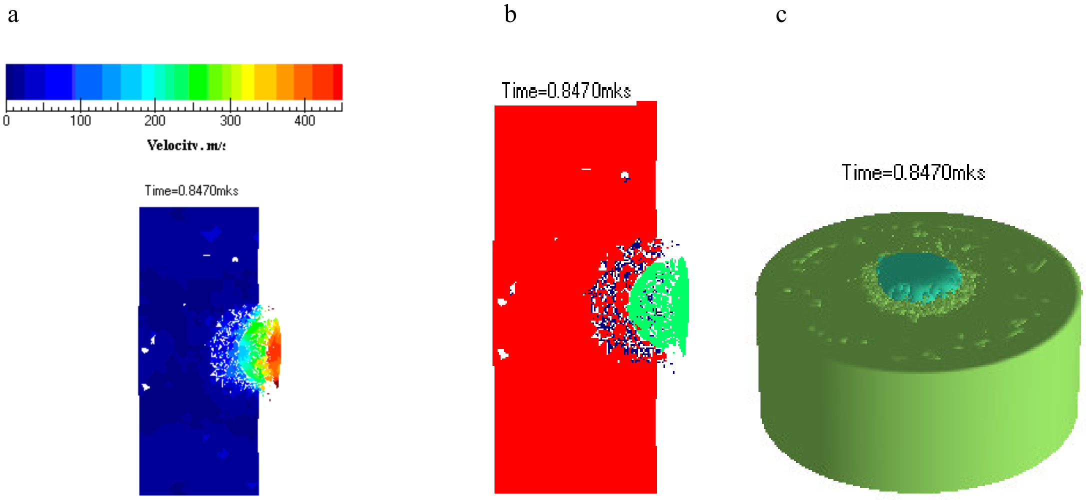

Fig.10. (a) 2-D cross sectional view of the system «glass plate-ice ball» for the impact velocity of 3000 m/s and the time t = 0.847 μs, the velocity distribution in the system; (b) is the phase diagram; (c) is the 3D picture of impact.

Figs. 11-12 demonstrate the results of computations for the impact of the textolite plate with different high-velocity particles. The computation for the impact of the textolite plate with the aluminum ball is shown in Fig. 11.

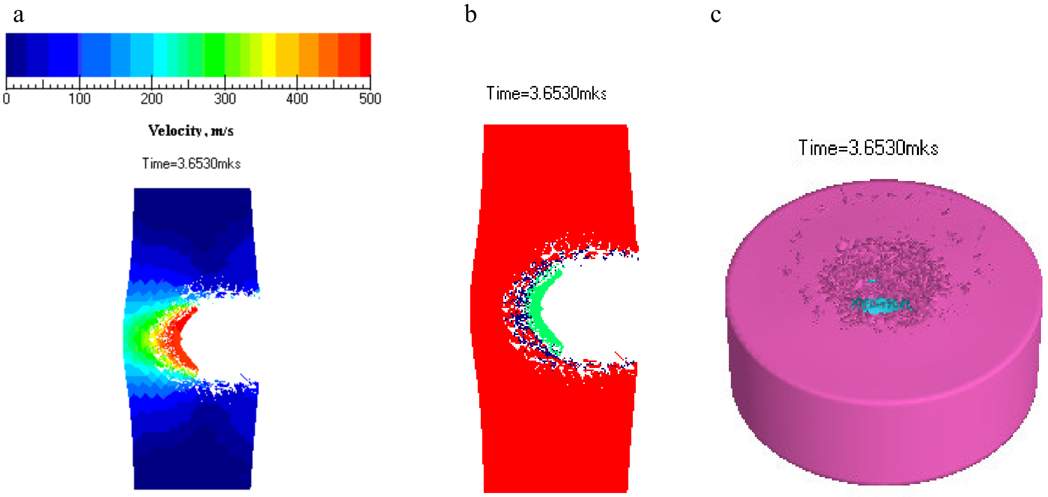

Fig.11. (a) 2-D cross sectional view of the system «textolite plate-aluminum ball» for the impact velocity of 3000 m/s and the time t = 3.653 µs, is the velocity distribution in the system; (b) is the phase diagram;(c) is the 3D picture of impact.

The impact of the ice fragment with the textolite plate is shown in Fig. 12.

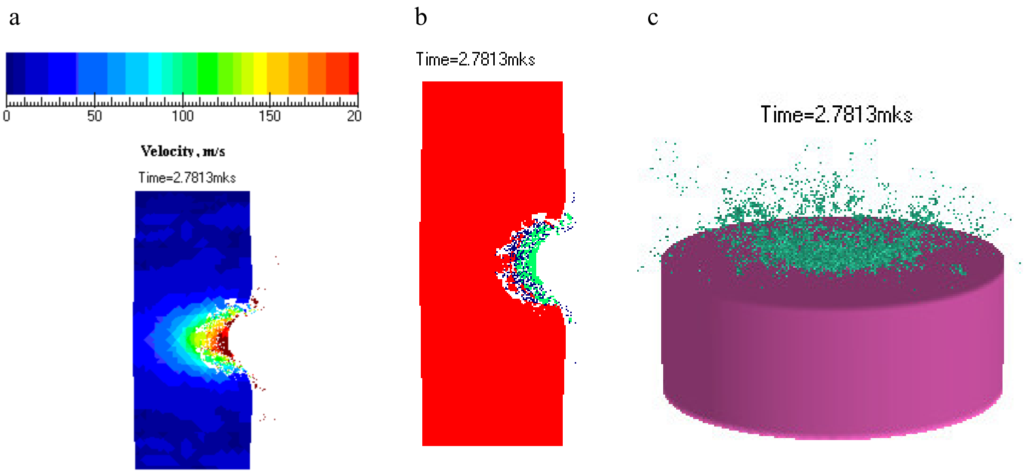

Fig.12. (a) 2-D cross sectional view of the system «textolite plate-ice ball» for the impact velocity of 3000 m/s and the time t = 2.7813 µs, the velocity distribution in the system; (b) is the phase diagram ; (c) is the 3D picture of impact.

The phase diagrams given above show the velocity distribution inside the plate and the remnants of the ball, where the plate is represented by the red color, the remnants of the ball are represented by the green color and the microfragments of interacting bodies are represented by the blue color. The impact leads to the brittle fracture of glass and the formation of the fragment cloud with partial emission outside the crater. The spall fracture is observed on the rear surface of the glass plate. The fracture of balls depends on the properties of ball materials: brittle or elastoplastic materials.

The finite difference method and the SPH method were used to simulate the impact of the group of seven steel spherical particles with a glass surface. The radius of particles is r = 0.5 mm, the particles are arranged in a circle with a diameter D_1 = 4.0 mm. The diameter of the glass plates was D_2 = 20.0 mm, the thickness of the plates was h = 1.0 mm. In the SPH method the distance between the plates was 0.2 mm, in the finite - difference method the distance between the plates was 0 mm. The initial velocity of the particles was v = 1.0 km/s. The Mi-Grüneisen equation of state was used in the computations. To simulate the metal particles, the elastoplastic model was used.

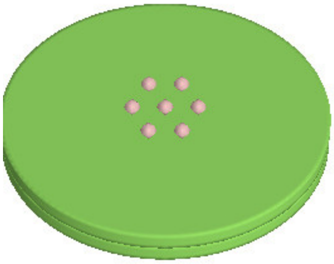

Fig.13. computational scheme.

The problem was solved in the three-dimensional formulation, using the SPH method. To simulate the top plate, 40,000 nodes were used and 10,000 nodes were used for the simulation of the lower plate. To simulate spherical particles, 72 nodes per spherical particle were used.

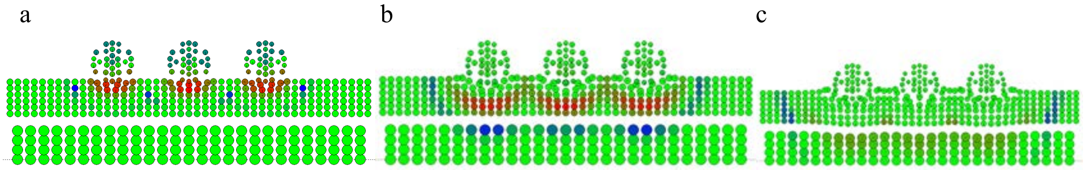

Fig.14. (a) stress computed by the SPH method. The 2D cross-section of the computational region for the different moments of time t = 15 µs; (b) t = 25 µs; (c) t = 35 µs. The area of the glass material fracture is separated.

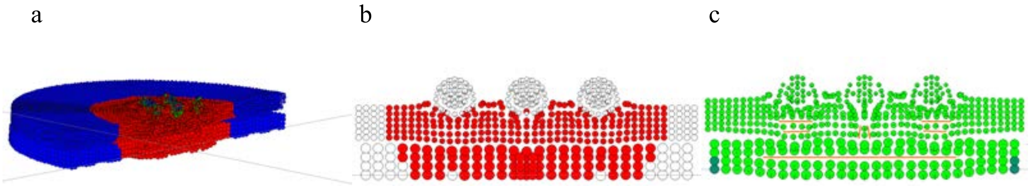

Fig.15. (a) computations of fracture conducted by the SPH method, the 3D configuration with an area of fracture; (b) is the 2D cross section of the computational fractured region; ()c is the beginning of fragmentation (t = 50 µs).

a b

Fig.16. (a) computations conducted by the mesh method (time t = 1.7 μs), the 3D configuration; b is the 2D cross-section of the computational region.

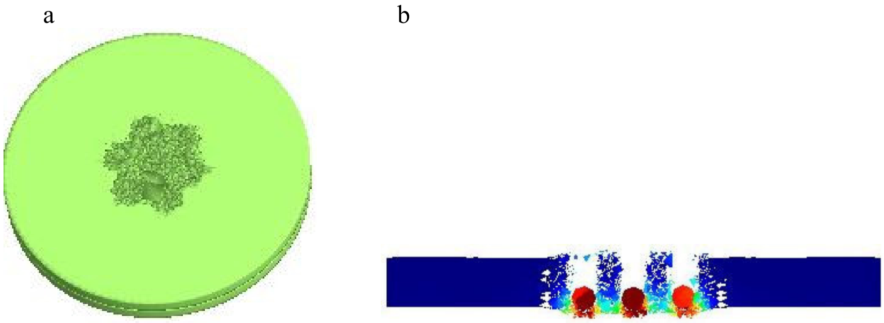

Fig.17. (a) computations conducted by the mesh method (time t = 3.57 μs), the 3D configuration; (b) is the 2D cross-section of the computational region.

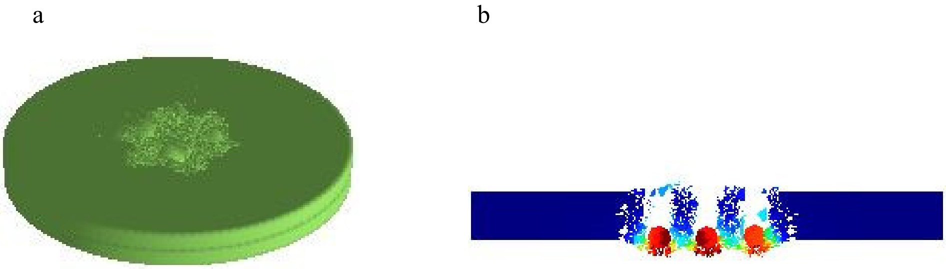

Fig.18. (a) computations conducted by the mesh method (time t = 4.2 μs), the 3D configuration; (b) is the 2D cross-section of the computational region.

It should be noted that the mesh method [5] using a probabilistic approach to the description of the fracture process of bodies exposed to impact allows the area of damaged and fractured material to be computed more accurate during impact (Figs.16-18) compared with the SPH method (Figs. 14-15). The mesh method is also more accurate in the computations for the formation of fractured target fragments and allows the interaction of fractured target fragments to be taken into account more precisely.

Conclusion

Providing the strength of textolite and glass elements for space vehicles is an important practical problem. There is a need to investigate the interaction of glass and textolite with the flows of technogenic and natural fragments to maintain the integrity of space vehicles exposed to the impact by large fragments and reduce the erosion of structural elements exposed to the flow of ultrafine particles. Therefore, the theoretical and experimental determination of maximum strength for the structural elements of space vehicles exposed to high-velocity particles is an urgent problem from a practical point of view.

The processes of deformation and fracture of the glass and textolite space vehicles elements exposed to high-velocity particles of natural and technogenic origin were the objects of the study in this work. In the experiments, the light-gas installation was used to accelerate microparticles with a velocity up to 7 km/s, and the mathematical models were developed to simulate the impact of particles with different targets. The efficiency of the studies was determined by the presence of the unique installations for the high-velocity acceleration of solid bodies and the complex numerical simulation of investigated phenomena.

The approaches proposed to simulate the interaction of space debris and the elements of space vehicles allow the stress-strain state, fracture and fragmentation of glass and textolite space vehicle elements to be computed in the three-dimensional formulation under high-intensity loading.

It should be noted that the mesh method using a probabilistic approach to the description of the fracture process of bodies exposed to impact allows the area of damaged and fractured material to be computed more accurate during impact compared with the SPH method. The mesh method is also more accurate in the computations for the formation of fractured target fragments and allows the interaction of fractured target fragments to be taken into account more precisely.

Acknowledgements

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