Numerical simulation of the high-speed interaction of a spherical impactor with a system of spaced heterogeneous plates

A E Kraus\textsuperscript{1,2}, E I Kraus\textsuperscript{1} and I I Shabalin\textsuperscript{1}

\textsuperscript{1} Novosibirsk State Technical University, 20 K. Marksa av., Novosibirsk, 630073, Russia
\textsuperscript{2} Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 4/1 Institutskaya st., Novosibirsk, 630090, Russia

kraus@itam.nsc.ru

Abstract. A 3D non-stationary problem of the interaction of space debris spherical particle and spaced protective screens is considered. To verify the 3D code, a series of calculations was performed of the impact of a spherical impactor made of ShKh15 steel at speed of 3.02 km/s with a spaced barrier consisting of three homogeneous plates, the first two made of AMg6 alloy and the third one made of steel 10. Comparison of the results of numerical calculations for hole diameters with experimental data showed (2-5)\% compliance. The collisions of steel spheres with AMg6 plates were calculated at an angle to the normal. To compare the resistance of the protective system, homogeneous screens were replaced by plates of heterogeneous material AMg6+B\textsubscript{4}C. It was shown that with the same mass characteristics, a heterogeneous system of screens had increased resistance compared to a homogeneous system.

1. Introduction
The protection of spacecraft is an important problem at present. Collision with cosmic dust or debris is a serious hazard to spacecraft.

The duration of flights increases and, thereby, increases the likelihood of meeting this danger. The issues of protection of spacecraft have arisen since the birth of the ideas of space exploration [1] and are relevant to this day. To protect the spacecraft from man-made space debris, screens are used consisting of several metal plates, usually about 0.5 mm thick, causing the disintegration of potentially dangerous objects into smaller fragments before they collide with the spacecraft’s body directly [2]. All such questions come down to the study of the high-speed interaction of a striking body with spaced plates. In [3], a series of experiments was carried out and numerical simulation of the effect of debris particles weighing from 0.7 to 20.0 g on screen protection was performed. The critical speeds were obtained for aluminum and steel plates at speeds of 0.5-6.5 km/s.

In [4], a numerical simulation of the effect of long rods on layered spaced barriers was considered. The probabilistic approach and the numerical technique proposed in the work in the most complete (from the physical point of view) three-dimensional formulation allow reproducing with high accuracy the processes of breaking through multilayered and spaced barriers by high-speed rod elements. In [5–7], based on REACTOR software package, it was managed to simulate the processes of high-speed loading of complex technical objects, for example, a tubular heat exchanger, which is a part of the...
spacecraft thermal regime support system. The numerical solution was brought until the “end”, i.e. until the reserves of kinetic energy of the incident debris particles were exhausted.

2. The purpose of the work and problem statement
The purpose of this work is to conduct a comparative analysis in the spatial case of the resistance of spaced protection systems made of homogeneous materials (two plates of aluminum alloy AMg6 and plates of steel 10) with a system of equally weighted heterogeneous material (two plates of AMg6+B,4C and a steel plate) at high speed loading.

A series of 3D non-stationary problems on the interaction of a uniform projectile with an obstacle in the form of spaced plates at angles of the meeting 0, 30, 45, 60 degrees to the normal was solved. The mathematical formulation of the problems was considered in detail in [8,9]. The calculations were performed with REACTOR software package [10,11], which implements numerical algorithms for solving balance equations using an explicit difference scheme, taking into account the deformation and fracture of materials and the fulfillment of boundary conditions.

3. Simulation of the experiment with a spaced barrier
Let a spherical impactor made of steel ShKh15 hit normally a system of spaced plates, the first two of alloy AMg6 and the third one of steel 10 at speed of 3.02 km/s. The geometry of the problem is shown in figure 1, the sphere is made of ShKh15 steel with diameter of 1.35 cm. The plates of AMg6 alloy 1.5 cm thick are located at distance of 3.0 cm from each other, and the plate of steel 10 with thickness of 1.0 cm is located at distance of 15.0 cm from the plates, as was done in the experiment in [12].

As a result of the calculations, the diameters of the holes were obtained; their values are given in table 1. The spherical impactor pierces both plates of AMg6, but does not pierce the third plate of steel (see figure 2). The following notation is introduced in table 1: \( d_1 \) is the diameter of the hole in the first plate, \( d_2 \) is the diameter of the hole in the second plate, \( h \) is the depth of the crater in the third plate, and \( \delta_i \) is the error of the author’s calculation relative to the experiment.

| Table 1. Comparative data of numerical experiment 1. |
|-----------------|-----------------|-----------------|-----------------|
| Experiment [12] | Simulation [12] | The authors’ simulation | \( \delta_i \), % |
| \( d_1 \), mm   | 35              | 38              | 34              | 2.8            |
| \( d_2 \), mm   | 40              | 44              | 40              | 0              |
| \( h \), mm     | \( \sim 2 \)    | 3 – 4           | 2.5             | 25             |
Figure 2. Visualization of the simulation results of experiment 1 with spaced plates.

Based on the series of calculations and comparison with experimental data [12], parameters were found for the equation of state of all materials [13,14], which were used below, see Table 2.

| Material  | $\alpha$, km/s | $S$ | $\mu$ | $\rho$, g/cm$^3$ | $G$, GPa | $K_s$, GPa | $Y$, GPa |
|-----------|----------------|-----|-------|------------------|----------|-----------|----------|
| Steel     | 4.90           | 1.288 | 0.29  | 8.01             | 93.92    | 192.32    | 0.80     |
| AMg6      | 5.46           | 1.310 | 0.33  | 2.63             | 26.49    | 73.95     | 0.42     |
| ShKh15    | 4.90           | 1.288 | 0.29  | 8.01             | 93.92    | 192.32    | 2.00     |

where $\alpha$ is the volume velocity of sound, $S$ is the slope of the generalized straight line in coordinates $D=a + SU$ for the shock adiabat, $\mu$ is the Poisson coefficient, $\rho$ is the initial density, $G$ is the shear modulus, $K_s$ is the bulk expansion modulus, and $Y$ is the yield strength.

In numerical experiment 2, a series of problems was solved on the interaction of a spherical impactor with a system of plates at the meeting angle of 30, 45, and 60 degrees to the normal. Figure 3 shows the geometric statement of the problem, in particular for angle of 30 degrees. It is necessary to determine the approach angle, at which the system of AMg6 plates will provide protection for the object located behind it.
Figure 3. Geometric model with angle of 30 degrees to the normal.

Figure 4 shows the results of numerical calculations and the shape of the holes obtained in the first screen after interaction. As the angle of meeting increased relative to the normal, the size of the punched hole also increased. The largest hole in the first plate was formed at the meeting angle of 60 degree relative to the normal. After breaking through the first plate, the striker collapsed, creating a cloud of fragments with particles of the plate broken off. The cloud of fragments of both materials after interaction with the second plate left a crater on the surface of the plate. The deepest crater was formed in the second plate at the meeting angle of 30 degrees, with the smallest hole in the first plate. After that, a cloud of destroyed particles changed the ejection direction vector perpendicular to the normal direction.
Figure 4. Visualization of the calculation results for meeting angles of 30°, 45°, 60°.

The calculation results for all meeting angles are summarized in Table 3. Since the holes at an angle different from the normal form the shape of the hole close to oval, the table shows the hole width $d_{11}$, the hole height $d_{12}$, the crater depth $h$, the plate serial number $n$. As can be seen from the data obtained, the AMg6 screen system provides a spherical impactor ricochet upon impact at angle of 60 degrees.

Table 3. The sizes of the holes after the impact at an angle.

| Angle | 30   | 45   | 60   |
|-------|------|------|------|
| $d_{11}$; $d_{12}$, mm | 26.8; 37.1 | 30.4; 42.0 | 37.3; 56.6 |
| $d_{21}$; $d_{22}$; $h$, mm | 36.9; 49.9; 140.0 | 33.6; 57.8; 76.0 | ricochet |
4. Simulation of the impact processes with a spaced heterogeneous barrier

Similarly to the formulation of numerical experiment 1, we consider the problem of the interaction of a spherical impactor made of ShKh15 steel with three spaced plates, the first two of heterogeneous materials (a mixture of AMg6 alloy and B₄C ceramics), and the third one of steel 10, a normal impact with initial velocity of 3.02 km/s. The description of the heterogeneous material was carried out according to the procedure [11,15,16], the volume fraction of ceramics in the heterogeneous barrier was 25%. The geometric formulation of the problem is presented in figure 5.

![Figure 5. Geometric model with heterogeneous plates.](image)

![Figure 6. Impact loss of the striker. The red line corresponds to the screen of heterogeneous material, the dashed line corresponds to the screen of homogeneous material.](image)
Comparisons of the ballistic resistance of homogeneous and heterogeneous barriers will be carried out with equal mass values. Since the density of AMg6 alloy does not differ significantly from the density of B4C ceramics, the equivalent thickness of the heterogeneous plate, at a volume concentration of 25%, is less by 1 mm.

| Table 4. The diameters of the holes in the heterogeneous plates. |
|-------------------|------------------|
| d1, mm            | 32               |
| d2, mm            | 37               |
| h, mm             | 0                |

From the graphs of momentum loss of the spherical impactor (figure 6), it can be seen that the model with heterogeneous obstacle has increased ballistic resistance and, in contrast to the homogeneous obstacle of AMg6, withstands the impact.

Figure 7. Visualization of the simulation results of the experiment with spaced heterogeneous plates.

The diameters of the holes in the first heterogeneous plate are smaller than in the homogeneous barrier (see figures 2 and 7). The results on the size of the holes in the heterogeneous barrier are summarized in table 4 with the designations similar to those in table 1.

5. Conclusions

- The parameters for the equation of state of the materials used in the calculation are determined.
- A screen of spaced plates made of homogeneous AMg6 material does not withstand the impact of the ShKh15 steel spherical impactor at interaction speed of 3.02 km/s.
- A screen of spaced plates made of homogeneous AMg6 material provides ricocheting of the spherical impactor at interaction speed of 3.02 km/s and the approach angle of 60 degrees.
- The screen of spaced heterogeneous AMg6+B4C plates with similar mass characteristics and ceramics volume fraction of 25% has increased ballistic resistance and withstands the impact of the ShKh15 steel striker at a similar interaction speed.

Acknowledgments
The work was supported by the Russian Foundation for Basic Research (project No. 19-08-00906).
References

[1] Whipple F L 1947 Meteorites and space travel. Astron. J. 52 131
[2] Gerasimov A V., Dobritsa D B, Pashkov S V and Khristenko Y F 2016 Cosm. Res. 54 118–26
[3] Bashurov V V., Bebenin G V., Belov G V., Bukharev Y N, Zhukov V I, Ioilev A G, Lapichev N V., Mikhailov A L, Smirnov G S, Fateev Y A and Schlyapnikov G P 1997 Int. J. Impact Eng. 20 69–78
[4] Gerasimov A V and Pashkov S V 2017 Procedia Engineering 204 284–91
[5] Fedorov M Y, Kraus E I and Shabalin I I 2018 AIP Conf. Proc. 2027 030177
[6] Fedorov M Y, Kraus E I, Fomin V M and Shabalin I I 2009 Bull. MAI 16 49–53
[7] Kraus E I and Shabalin I I 2016 Res. Sci. City 6–11
[8] Wilkins M L 1999 Computer Simulation of Dynamic Phenomena (Berlin, Heidelberg: Springer Berlin Heidelberg)
[9] Fomin V M and Kiselev S P 1997 Elastic-Plastic Waves in Porous Materials High-Pressure Shock Compression of Solids IV: Response of Highly Porous Solids to Shock Loading ed L Davison, Y Horie and M Shahinpoo (New York, NY: Springer New York) pp 205–32
[10] Kraus E I and Shabalin I I 2016 AIP Conf. Proc. 1770 030092
[11] Kraus E I, Melnikov A Y, Fomin V M and Shabalin I I 2019 J. Appl. Mech. Tech. Phys. 60 526–32
[12] Bashurov V V, Bukharev Yu N, Tereshin A I and Tverskov A V 2003 Modern methods for designing and testing rocket and artillery weapons 1 23–33
[13] Kraus E I and Shabalin I I 2016 J. Phys. Conf. Ser. 774 012009
[14] Kraus E I and Shabalin I I 2015 J. Phys. Conf. Ser. 653 012085
[15] Kraus E I, Shabalin I I and Shabalin T I 2017 AIP Conf. Proc. 1893 030130
[16] Kraus A E, Kraus E I and Shabalin I I 2019 AIP Conf. Proc. 2125 030067