Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Impact interaction of shells and structural elements of spacecrafts with the particles of space debris and micrometeoroids

To cite this article: A V Gerasimov *et al* 2017 *J. Phys.: Conf. Ser.* **894** 012018

Impact interaction of shells and structural elements of spacecrafts with the particles of space debris and micrometeoroids

A V Gerasimov[1], S V Pashkov[1] and Yu.F. Khristenko[1]

[1]Research Institute of Applied Mathematics and Mechanics by
Tomsk State University, Tomsk, Russia

E-mail: `ger@niipmm.tsu.ru`

Abstract. Space debris formed during the launch and operation of spacecrafts in the circumterrestrial space, and the flows of micrometeoroids from the depths of space pose a real threat to manned and automatic vehicles. Providing the fracture resistance of aluminum, glass and ceramic spacecraft elements is an important practical task. These materials are widely used in spacecraft elements such as bodies, tanks, windows, glass in optical devices, heat shields, etc.

1.Introduction

The Lagrangian approach that has well-known advantages for multi-contact interactions of bodies during impact, especially when solving three-dimensional problems, can be successfully used for high-velocity impact problems considering the fragmentation of solids under intensive dynamic loading. One of the factors determining the fracture behavior of real materials is the natural heterogeneity of the material structure that influences the distribution of physical and mechanical material characteristics over the volume of the body under study. This factor can be considered in the equations for the mechanics of deformable solids by using the random distribution for the initial deviations of strength properties from the nominal value (simulation of initial defect material structures). Solving three-dimensional problems considers the natural heterogeneous real material structure that has an effect on the distribution of physical and mechanical material characteristics over the volume of structural elements and is one of the main factors determining the fracture behavior of real materials. Therefore, in order for the numerically simulated process to be in good agreement with experimental data, it is necessary to introduce disturbances into the physical and mechanical characteristics of the medium to be fractured, i.e. to specify a random distribution of the factors which determine the strength properties of the material.

2.Governing equations

The problems are solved using 3D formulation, considering a natural heterogeneous material structure that influences the distribution of physical and mechanical characteristics over the volume of structural elements and is one of the factors determining the fracture behavior.

The equations describing the spatial adiabatic motion of a solid compressible medium comprise the equation of mass conservation, the momentum equation and the energy equation [1-3].

The equations which consider the corresponding thermodynamic effects connected with adiabatic compression and the strength of a medium should be added to these equations. In the general case, when forces act on a deformed solid, there is a change in the volume (density) and the shape of the solid for different dependencies. Therefore, the stress tensor is the sum of the spherical tensor and deviator of the stress tensor.

To describe the shear strength of a body, the Prandtl - Reuss equations and the von Mises yield condition were used [1]. The state equation of the solid was chosen in the form of Mi-Grüneisen [1]. The criterion of ultimate equivalent plastic strain was used as a shear fracture criterion [1]. The fracture of glass and ceramics was considered to be the fracture of a brittle material without a plastic strain zone that is typical for metal strain. The Johnson-Cook relations were used to simulate the fracture of ductile materials (aluminum, steel) [4]. The Johnson-Holmquist (JH2) relations were used to simulate the fracture of brittle materials (glass, ceramics) [5].

Solving three-dimensional problems considers the natural heterogeneous real material structure that has an effect on the distribution of physical and mechanical material characteristics over the volume of structural elements and is one of the main factors determining the fracture behavior of real materials. Therefore, in order for the numerically simulated process to be in good agreement with experimental data, it is necessary to introduce disturbances into the physical and mechanical characteristics of the medium to be fractured, i.e. to specify a random distribution of the factors which determine the strength properties of the material. The natural fragmentation of projectiles and a target is simulated by introducing a probabilistic mechanism for the distribution of initial defects in the structure of the material to describe the formation of cracks.

The computation technique uses tetrahedral cells and is based on the combination of the Wilkins method for the calculation of internal body points and the Johnson method for the calculation of contact interactions [2,7-8]. The ideology and methodology of a probabilistic approach applied to the solid fracture problems is given in detail in the monograph [9].

A new three-stage light-gas gun (RF patent No. 2490580) has been developed, manufactured and mounted to study the processes of high-velocity interaction. It allows different studies of high-velocity impact processes to be conducted at velocities of up to 8 km/s.

3.Test computations

The problem of the ring fracture [10] and the problem of the two-layered target (fiberglass ST-HT + alloy D16) fracture by a ball (G52986) were numerically simulated for the normal and oblique impact with the target surface at an impact velocity of 900 m/s as test computations [11]. The computations were in good agreement with the experimental data.

4.Computations

The main tasks which should be solved during the high-velocity impact of space objects with particles are to preserve the integrity of different spacecraft elements (bodies, tanks, solar panels, etc.) subjected to the impact of sufficiently large fragments and reduce erosion for the surface of structural elements exposed to the flows of small and ultrafine particles.

The first problem considers the impact of a cluster of six spherical elements with one and two targets at a different velocity and a different angle to the surface of the target. The impact angle is counted from the normal line to the face of the plate in the clockwise direction. The size of the plates was 5x5 cm, the thickness was 0.35 cm, and the material was aluminum. The material of the ball 0.56 cm in diameter was steel. The group of balls was placed in a circle with a diameter of 1.5 cm, and all the balls simultaneously interacted with the target. The target was fractured and a distinctive fragment of the target flew at a velocity of 400 m/s, which was less compared to the velocity of the projectile fragments (~ 450 m/s, Figure 1) at an impact velocity of 800 m/s. It can be concluded that the secondary flow of fragments can cause significant fracture to the second target.

Figure 1. Group impact of compact elements with a thin target at a velocity of 800 m/s: (a) - t = 10 μs; (b)-t = 75 μs.

The consequences of this impact are clearly observed with increasing the impact velocity. Figure 2 shows the interaction of the cluster of projectiles with a two-layered spaced target for the time t = 20, 50, 77 μs. The distance between the plates was 0.3 cm. The flow of the target fragments which are formed after the penetration of the first target differs in velocity. For the projectiles, the velocity is about 1100 m/s, and for the target fragments, the velocity is varied from 600 m/s to 430 m/s. After the penetration of the second target, the velocity of the projectile fragments is decreased to 650 m/s, and the velocity of the target fragments is a spectrum from 370 to 250 m/s. The formed powerful flow of fragments poses a great threat to the object protected by the target.

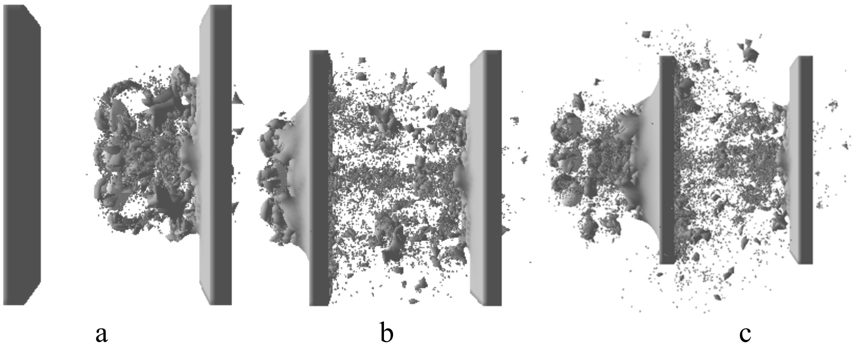


Figure 2. Group normal impact of compact elements with a thin target at a velocity of 1500 m/s: (a)-t = 20 μs; (b) - t = 50 μs; (c)-t = 77 μs.

The deviation of the impact angle by 60° does not significantly change the fracture behavior of the plate. For these and following computations, the size of the plates was 8x8 cm and the thickness was 0.5 cm. Here, as in the previous problems, a hole is formed, which is approximately equal to the diameter of the initial circle of the balls on the target, and also a multi-velocity flow of the projectile and target fragments is formed. Several stages of this process are shown in Figure 3 (time t = 10, 50, 130 μs).

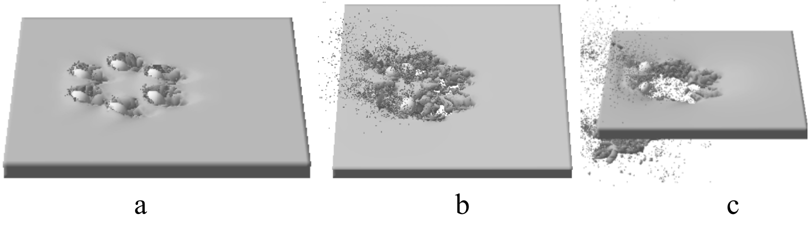
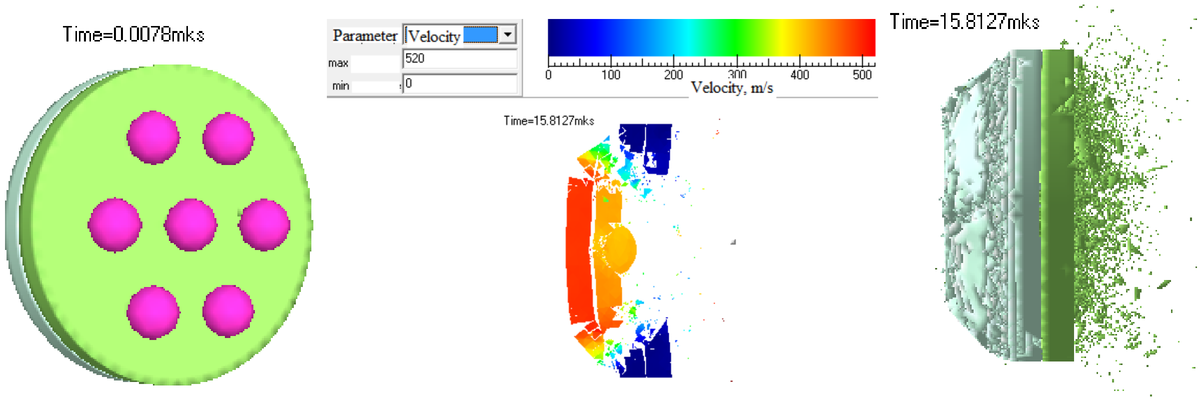


Figure 3. Group impact of compact elements with a thin target at an angle of 60° and a velocity of 1500 m/s: (a)-t = 10 μs; (b)-t = 50 μs; (c)-t = 130 μs.

The impact of a group of 7 tungsten projectiles 5 mm in diameter at a velocity of 1000 m/s with a two-layered glass and ceramic target is shown in Fig. 4. The radius of the circle along which the elements of the group were located was 8 mm. The diameter of the target was 3 cm, and the thickness of the layers was 3 mm.

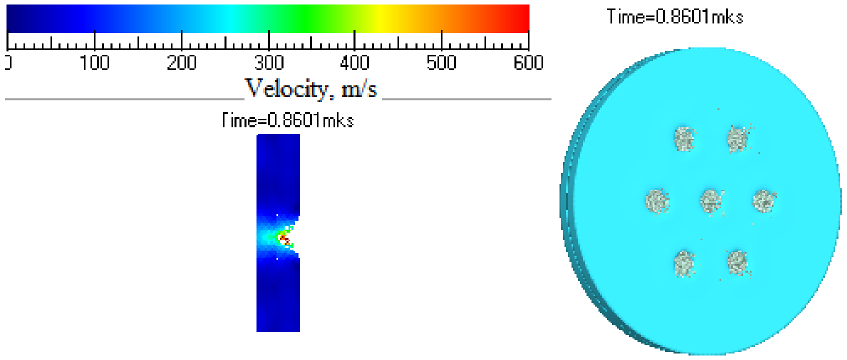


a b c

Figure 4. Group normal impact of 7 compact tungsten elements with a two-layer target (glass-ceramics) at a velocity of 1000 m/s: (a)-initial configuration; (b)-two-dimensional cross-section of the computational area; (c)-3D computations for the impact and fracture of the target; t = 15, 8127 μs.

During impact interaction, there is the intensive fragmentation of the first glass layer with its partial ejection from the front surface of the target, and a fragment in the form of a "plug" flies out of the second ceramic layer (Figure 4 (b)) at a residual velocity of 520 m/s.

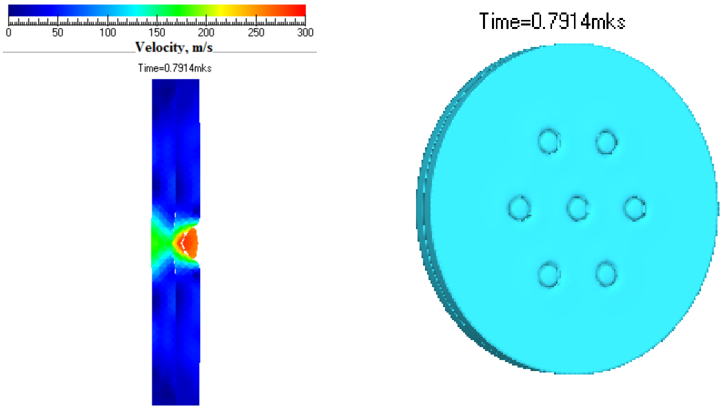
Figure 5 shows the computations for the impact of the group of 7 steel, aluminum and ceramic particles 1 mm in diameter at a velocity of 3000 m/s with two-layered aluminum, glass and ceramic targets. The radius of the circle along which the elements of the group were located was 4 mm. The diameter of the target was 2 cm, and the thickness of the layers was 1 mm.



a b

Figure 5. Group normal impact of 7 compact ceramic elements with a two-layer target (aluminum-aluminum) at a velocity of 3000 m/s: (a)-two-dimensional cross-section of the computational area; (b)-3D computations of the impact process; t = 0.86 μs.

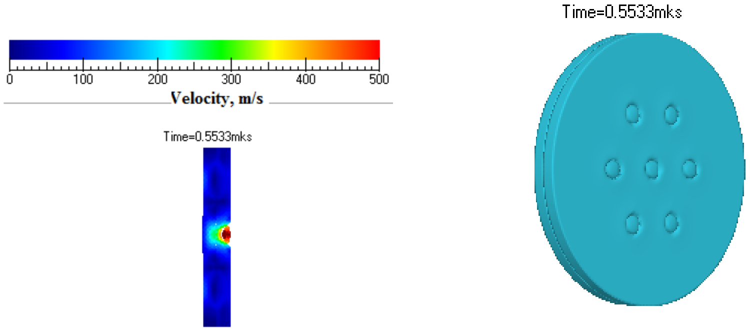
During the impact of ceramics with aluminum plates, there is the intensive fragmentation of ceramic projectiles and the reduction in the velocity of their fragments up to zero. The penetration of the target is not observed, but we can track the formation of craters, their depth and size on the front surface.



a b

Figure 6. Group normal impact of 7 compact aluminum elements with a two-layer target (aluminum-aluminum) at a velocity of 3000 m/s: (a)-two-dimensional cross-section of the computational area; (b)-3D computations of the impact process; t = 0.63 μs.

During the impact of an aluminum projectile with aluminum plates (Figure 6), there is the deformation of projectiles, an increase in the size of a crater and a reduction in the velocity of projectiles to zero. The penetration of the target is not observed, and there is no noticeable fracture of bodies. In contrast to the brittle fracture of ceramics, the plastic deformation of aluminum projectiles is observed.



a b

Figure 7. Group normal impact of 7 compact aluminum elements with a two-layer target (ceramics-glass) at a velocity of 3000 m/s: (a)-two-dimensional cross-section of the computational area; (b) -3D computations of the impact process; t = 0.5533 μs.

At present, there is a need in ceramic coatings to protect the glass elements of spacecrafts. Figure 7 shows the computations for the glass-ceramic system subjected to impact loading by an aluminum projectile. The results obtained allow the deformation of the glass-ceramic system to be qualitatively estimated and the dimensions of protective layers to be quantitatively analyzed for the different impact velocities and sizes of projectiles.

The results obtained show that the group impact of a cluster of high-velocity elements leads to the significant fracture of targets and the formation of a hole, the size of which exceeds the total area of projectiles in the plane projection of the target. The formed fragmentation field behind the first target leads to the fracture of the second protective plate and can cause irreparable damage to the main equipment. A decrease in the angle of impact leads to the ricochet of projectiles and a change in the deformation of an aluminum plate. For the small sizes of projectiles, the penetration of the first layer is observed in the construction and the integrity of the second layer is preserved.

Acknowledgments

This work was partially funded by the Russian Foundation for Basic Research, the grants No. 16-08-00037 A, No. 15-08-06689 and No. 15-08-02265 A.

References

[1] Stanyukovich K *et al* 1975 *Physics of Explosion* (Moscow: Nauka)
[2] Wilkins M 1967 *Computational Methods in Hydrodynamics* (Moscow: Mir)
[3] Wilkins M 1999 *Computer simulation of dynamic phenomena* (Berlin-Heidelberg-New-York: Springer)
[4] Kuzkin V and Mikhalyuk D 2010 *Computational Continuous Mechanics* **3** 32
[5] Egorova M and Parshikov A 2015 *Physico-Chemical Kinetics in Gas Dynamics* **16** 1
[6] Kreyenhagen K *et al* 1970 *AIAA Journal* **8** 2147
[7] Johnson G, Colby D and Vavrick D 1979 *Int. J. Numer. Methods Engng.* **14** 1865
[8] Johnson G 1981 *Trans. ASME. J. of Appl. Mech.* **48** 30
[9] Gerasimov A *et al* 2016 *High-velocity impact. Simulation and Experiment* (Tomsk: STL)
[10] Gerasimov A, Alexeev N, Mikhailov V and Pashkov S 2005 *AIP Conference Proceedings* **849** 57
[11] Gerasimov A, Pashkov S and Surkov V 2007 *Russian Physics Journal* **50** 46