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Study of the Efficiency of Corrugated Mesh Shields for Spacecraft Protection against Meteoroids and Manmade Space Debris

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Abstract—High collision velocities and mass restrictions impose serious requirements on the design of anti-meteoroid spacecraft protection. In this study, the high efficiency of corrugated mesh anti-meteoroid shields in comparison with conventional metal mesh shields is confirmed based on the results of numerical modeling.

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1. INTRODUCTION

Spacecraft design involves taking measures to shield the object or its individual systems from exposure to hypervelocity micrometeorites and space debris particles. An increase in the efficiency of anti-meteoroid protection is related to the optimization of its mass, since excessive weight of the spacecraft structure is generally unacceptable due to mass restrictions imposed during its design.

The primary purpose of the protective shield is to minimize the impact of hypervelocity particles on the main systems of the spacecraft. Upon impact with the shield, the colliding projectile particle is fragmented and destroyed completely or in part, subsequently turning into an expanding debris cloud; melting and evaporation of the projectile material is possible as well [1].

In general, the material strength characteristics of protective shields are not determinative of their performance given the high velocity of collision (the velocity of space debris lies in the range of 1–16 km/s; the velocity of micrometeorites is 11–72 km/s). The main task of the shield is to provide the maximum scatter of the debris cloud front. Taking the velocity distribution of particles into account [1], the range of 3–7 km/s is considered the most dangerous for the survivability of the spacecraft structure in low Earth orbits (where the flows of manmade debris are predominant), since at such interaction velocities, the debris cloud that passes through the protective shield is rather compact and has high enough velocity to damage the object.

The first protective shield (the so-called Whipple shield based on the use of a double wall), was proposed in 1947, even before the beginning of space flights [2]. Initially, relations that describe the performance of double-walled shields under the influence of meteor particles were developed [3]; later, the concepts of multilayer shields (Multishock) [1], as well as mesh double bumper (MDB) shields [4] appeared.

There are numerous examples of the use of metal mesh shields on spacecraft [5]. The high efficiency of protective mesh shields was shown in [4, 6–14].

An MDB shield that was intended for protection against the impacts of meteoroids and manmade debris is studied in [4]. This shield is designed as a set of four spaced layers, where a wire mesh is used as an outer bumper.

Adding a fine mesh as the front bumper and inserting a highly durable fabric layer between the second bumper and the rear wall make it possible to achieve a significant increase in efficiency. The wire mesh bumper efficiently splits the projectile into smaller fragments, which are subsequently destroyed by the second bumper. The mass concentration in the wire leads to a more energetic and focused impact against the projectile. This leads to a more intense fragmentation of the projectile, especially at the nodes of the mesh, and increases the momentum distribution front of the fragmented part. The ballistic properties of a protective shield with such a configuration can save 30–50% of mass as compared to a conventional Whipple shield (double wall); and in the case of an impact at an angle of 45°, the mass saving rises up to 70%, which is confirmed by test results in the velocity range of light-gas guns. This study presents equations that allow determining the geometric characteristics of the elements of the MDB shield in relation to the spacecraft; the angle of the particle impact was included in the parameters that determine the performance capability of the structure. Numerical simulation was used to expand the velocity range and estimate the energy and pressure parameters in the localized parts of the projectile impacting the mesh bumper.

Study [6] describes the results of comparative laboratory tests of solid single-layer aluminum shields and multilayer mesh shields for the capability to fracture and slow down projectiles of various materials in the range of collision velocities of 1–6 km/s. The parameters of multilayer mesh shields (the number of bumpers, wire thickness, and mesh pitch) varied; the total aerial density of the protective shield was 0.016–1.6 g/cm^2. The article experimentally confirms the higher efficiency of multilayer mesh shields and notes their higher resistance to repeated impacts due to the relatively lower mass loss than for solid shields.

In [7], hypervelocity impacts against metal meshes were studied. Based on X-ray images of the debris cloud produced in a hypervelocity collision, it was shown that in the case of a metal mesh bumper, the velocity of the center of gravity of the debris cloud was 65% of the initial impact velocity. The experiments were conducted with a two-stage light-gas gun. Steel and copper wire mesh and polycarbonate projectiles were used for the tests.

A hybrid solution was presented in [8]: a composite of an Al-6Mg alloy matrix reinforced with Ti–6Al–4V meshes fabricated by the pressure infiltration method was used as a shield. The tests were carried out at a velocity of 2.5 km/s; similar tests were also carried out on a target of Al-6Mg alloy for comparison. Internal damage was analyzed by means of ultrasound scanning. The main conclusion of the study is that the proposed composite target is more efficient and has better energy absorption than a target without the mesh.

In [9], the results of a theoretical and experimental study of protective mesh shields are presented. Experiments on hypervelocity impacts against structural elements of a spacecraft using powder and light-gas ballistic guns, as well as numerical modeling in a full three-dimensional formulation, are described. The experiments tested several variants of protective shields designed to protect typical spacecraft elements against the impact of hypervelocity meteoroids and manmade debris; the options included a double-mesh shield and a Whipple shield of equivalent mass. In the first variant, a stainless-steel woven mesh with parameters $a = 0.5$ mm and $d = 0.3$ mm (where a and d are the mesh pitch and wire diameter) was chosen; the second bumper was the same mesh with parameters $a = 0.3$ mm and $d = 0.2$ mm. A 2-mm-thick sheet of AMg6 alloy was used as the back wall (typical design of spacecraft). The distance between the outer and second bumpers was 15 mm; the distance between the second bumper and the rear wall was 35 mm.

Tests for the durability of this shield design against a hypervelocity impact of solid projectiles were carried out using launching devices: an 8-mm caliber powder gun and an 8-mm caliber MPH 23/8 light-gas gun. The test results showed a significant increase in the performance of the mesh shield compared with a conventional shield of a similar specific mass.

In [10], the effect of various combinations of aluminum mesh bumpers on the fragmentation of a hypervelocity projectile was studied with the following parameters: the impact velocity in the range of 2.2–6.2 km/s, impact along the normal to the barrier, and spherical aluminum projectiles with a diameter of 4 mm. The LS-DYNA software package (SPH method) was used as a research tool. The results showed that the pattern of the debris cloud, as well as the distribution of velocity and kinetic energy, varied with the impact position of the projectile. The distribution of the debris cloud was more uniform when the projectile hit the point of intersection of the mesh wires. These studies were also conducted to improve the efficiency of the protective structures of spacecraft under the action of space debris.

Paper [11] describes experimental studies of hypervelocity impacts of spherical aluminum projectiles with a diameter of 6.4 mm against multilayer combined shields with inclusion of aluminum and stainless-steel mesh bumpers. The projectiles were launched using two-stage light-gas guns at a speed of approximately 4 km/s. The character of fragmentation of hypervelocity particles was studied depending on the position of the mesh shield in the set, wire diameter, and mesh pitch. In a series of experiments, the protective structure in which the mesh shield was used as the inner bumper, i.e., immediately in front of the protected wall, turned out to be the most efficient, which is understandable. Considering that the maximum efficiency of the mesh shield is achieved under certain conditions (the projectile velocity corresponds to the fragmentation segment on the ballistic curve; the size of the projectile is comparable to the mesh pitch), the mesh shield can efficiently split the undamaged part of the projectile, which, after passing through several solid shields, approaches a flat shape.

The numerical simulation of hypervelocity impact against mesh barriers using LS-DYNA was carried out in [12], where a combined multilayer barrier with inclusion of a mesh screen was chosen as the object of study. Same as in [10], the influence of the projectile position during impact on the characteristics of the debris cloud was studied, and the simulation was compared with experimental results. The mesh and solid shields were made of aluminum alloys; the projectile was a 4-mm aluminum alloy sphere.

In [13], the results of a series of experiments on hypervelocity impacts were analyzed. The object of the study was the characteristics of a debris cloud formed during hypervelocity perforation of thin barriers that included steel meshes. Aluminum spherical projectiles with a diameter of 6.35 mm were used; the impact velocity varied from 1.95 to 3.52 km/s. The processing of the experimental results allowed a general assessment of the spatial distribution, as well as the mass and size distribution of ejecta particles produced in the impacts. As applied to the problem of reducing near-Earth space pollution, the authors argue against the use of aluminum plates as the first (outer) bumper in the configuration of the spacecraft protective shield.

Study [14] describes a numerical simulation of the impact of hypervelocity projectiles on an aluminum cellular container. Its resistance to meteor impacts was compared with the resistance of a flat aluminum sheet with a similar areal density. The main conclusion of the study is that the cellular container absorbs more energy from the debris and produces smaller debris after the impact. As a result, the mesh container can be used as one of the shields in a multilayer protective structure to increase the performance of the latter.

The results of an experimental study of the fragmentation of spherical aluminum projectiles with a diameter of 6.35 mm against two solid aluminum and two steel mesh shields at impact velocities from 6 to 7 km/s are presented in [15]. A heavier mesh showed the most intense fragmentation of the projectile with the formation of small fragments, the number of which is several times higher than the number of fragments for other barriers of lesser and similar weight. Integral distributions of crater volumes over the witness surface were found in all the experiments. A comparative analysis of the distribution of crater volumes for lightweight and heavy shields is given.

In general, it is currently obvious that mesh shields are more efficient than solid shields given equal specific mass, and their efficiency is most noticeable when the size of the projectile is comparable to the mesh pitch.

In this study, we propose the concept of a protective shield, which combines the advantages of mesh shields and inclined surfaces. The efficiency of the proposed concept of a protective mesh shield is investigated by means of numerical simulation in the maximally complete three-dimensional setting considering the contact interaction of debris. For all studies mentioned here that were performed after 2000, the numerical simulations of mesh barrier performance were carried out using the LS-DYNA software, with the exception of [9].

2. DESCRIPTION OF THE MODEL

The efficiency of an inclined protective mesh shield was studied using numerical simulation. The interaction of a mesh barrier with a compact projectile in the form of an aluminum ball similar in size and density to typical meteor particles capable of breaking through a protective screen is considered in the Lagrangian 3D formulation. A woven mesh shield is modeled by two layers of wires oriented in mutually perpendicular directions.

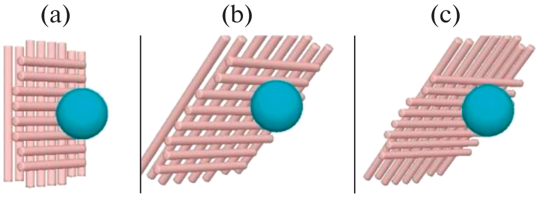

Fig. 1. Variants of a protective mesh shield with equal specific mass: (a) the shield is positioned along the normal; (b) the shield is positioned at an angle of 45° to the normal (mesh pitch is increased); (c) the shield is positioned at an angle of 45° to the normal (wire diameter is reduced).

To increase the range of effective particle capture, an inclined mesh barrier is considered. For the study, we selected variants for mesh shields with equal reduced (in the direction of impact) specific mass. The identical specific mass of the shield for different cases is achieved by changing one of the parameters of the basic mesh dimensions (a_0, d_0), where a_0 is the mesh pitch and d_0 is the wire diameter.

Figure 1 shows the variants of projectile impact against the mesh shields of equal reduced specific mass. In variant (a), the shield is perpendicular to the direction of movement of the projectile (basic mesh dimensions a_0, d_0). In variant (b), the shield is an inclined mesh (at an angle of 45° to the normal) with the mesh pitch increased by $\sqrt{2}$ times $\left(a_0/\cos\varphi, d_0\right)$. In option (c), the agreement of the specific mass between the direct and inclined screens is achieved by reducing the wire diameter by $2^{1/4}$ times $\left(a_0, d_0\sqrt{\cos\varphi}\right)$.

The following basic dimensions of the steel mesh were selected for numerical simulation: mesh pitch $a_0 = 0.5$ mm and wire diameter $d_0 = 0.32$ mm. The diameter of the aluminum projectile was 1.7 mm. The impact velocity in all the model experiments was 5 km/s.

The behavior of materials is described by a model of an ideal elastoplastic medium. The system of equations describing the mathematical model of the motion of a continuous medium is given in [16]. The motion of the medium is described in the Lagrangian approach. The system of equations based on the laws of conservation of mass, momentum, and energy is closed using the equations that consider the thermodynamic effects associated with the adiabatic compression of the medium and the material strength of the medium. Plastic deformations were described using the Prandtl–Reuss relations under the Huber–Mises condition of plasticity; the equations of state were taken in the Mie–Grüneisen form [17]. The model included the relations for strain hardening of materials [18].

As a criterion for failure under intense shear deformations, the equivalent plastic deformation reaching

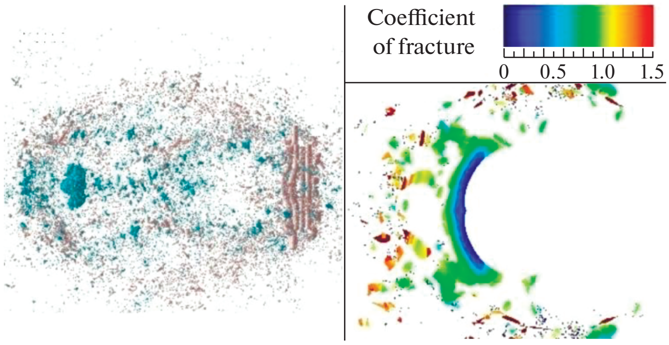

Fig. 2. Debris cloud and the degree of damage of the projectile upon impact along the normal (diagram in Fig. 1a). Time $t = 5$ μs.

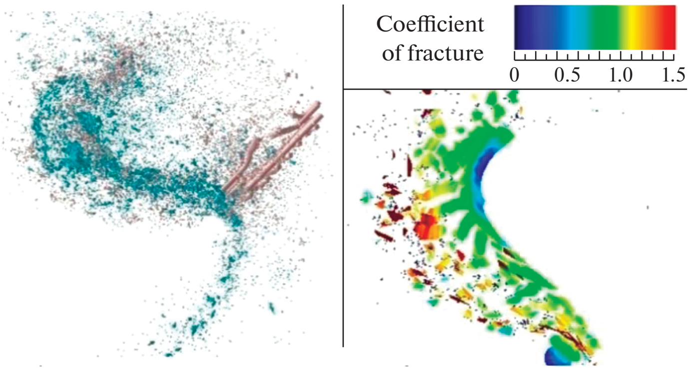

Fig. 3. Debris cloud and the degree of damage to the projectile upon impact at an angle of 45° with mesh pitch increased by $\sqrt{2}$ times (the diagram in Fig. 1b). Time $t = 5$ μs.

its limit value was used [19]. To describe the destruction, we used the method of splitting the difference mesh into nodes [16] and an explicit description of the destruction surface. The condition of perfect sliding and non-leakage along the normal was used in the interaction of the fragments and for the contact surfaces.

To calculate elastoplastic flows, we used a tetrahedral cell technique based on the methods of Wilkins [17] and Johnson [20, 21]. The difference scheme in three-dimensional implementation and its physical interpretation are given in [17, 22].

The initial inhomogeneities of the structure were modeled using a random distribution of initial deviations of the material strength properties (equivalent plastic deformation and yield strength of the material) from the nominal value. The probability densities of random variables were taken in the form of a normal Gaussian distribution. The basic principles of a probabilistic approach to modeling the strength properties of polycrystalline materials used in numerical modeling are described in [23].

3. RESULTS OF NUMERICAL SIMULATION

Figures 2–4 illustrate the simulation results for each of the three protective shield variants shown in Fig. 1.

Table 1 lists the parameters that allow us to compare the efficiency of the protective properties of shields of various configurations: residual velocity and degree of destruction of the projectile (mass of debris, i.e., the destroyed part of the projectile, as a percentage of its initial mass).

In the case of an impact along the normal (Fig. 2), the projectile was flattened upon passing the mesh but retained its integrity. In the calculations with the tilted protective shield (Figs. 3–4) the size of the compact undestroyed part of the projectile was much smaller than for the impact along the normal, while the level of accumulated damage was fairly high. There was a rebound of part of the debris during the process.

These results are fully consistent with the assumption that an inclined mesh barrier is more effective

Table 1. Values of some parameters obtained by numerical simulation

Parameter	Mesh variants		
	(a)	(b)	(c)
Residual velocity, %	56	55	58
Projectile fracture percentage	31	71	76

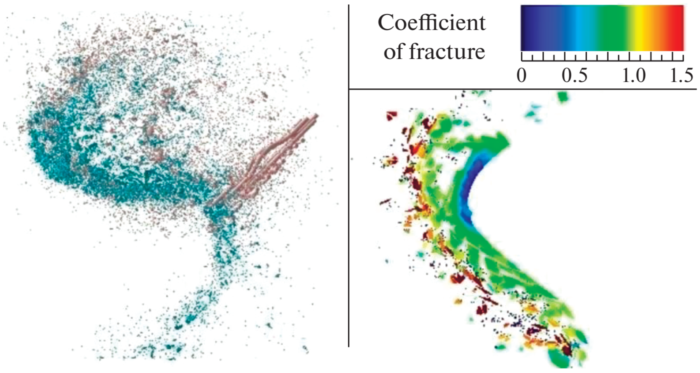

Fig. 4. Debris cloud and the degree of damage to the projectile upon impact at an angle of 45° with wire diameter decreased by $2^{1/4}$ times (the diagram in Fig. 1c). Time $t = 5$ µs.

than an upright mesh barrier (with equal reduced mass) for the entire range of sizes and velocities:

—For the vast majority of approach angles from the range under study, the probability of a significant change in the trajectory increases.

—The area and time of contact increase; therefore, the impulse transmitted to the shield also increases.

—The way the projectile interacts with the inclined mesh is similar to the “grater” effect, which leads to increased fragmentation and a decrease in the size of the undamaged part of the projectile.

—The preferential direction of the impact at an angle and the increase in the interval between interaction with individual wires (strings) facilitates the dispersal of the debris front of the destroyed part, which is the primary purpose of the protective anti-meteoroid shield.

—For an inclined mesh, the effective clearance is significantly reduced, which, given an equal specific mass, allows efficient capture of particles in a wider range of sizes.

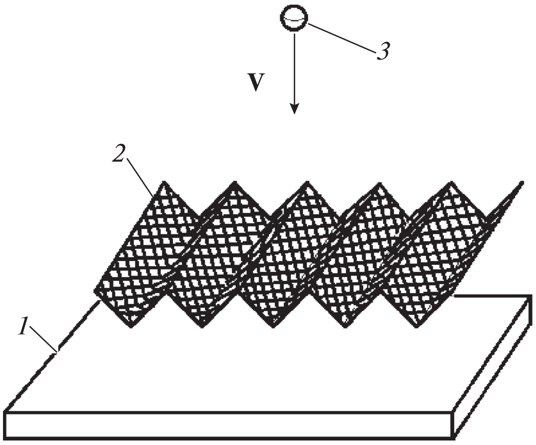

Fig. 5. Corrugated mesh shield: (*1*) wall of the spacecraft; (*2*) corrugated mesh; (*3*) micrometeoroid.

From a technological point of view, an inclined shield is certainly unfeasible; however, there are several design solutions that can be proposed to use this effect:

—Stamping or embossing (slight effect at minimal cost).

—Wavy mesh with a sinusoidal structure of the shield surface.

—Corrugated mesh (Fig. 5).

—Corrugated or wavy mesh enclosed between layers of thin foil or mesh with a minimum specific mass (this option is quite technological from the point of view of manufacturing and installation; the rigidity of this design will be sufficient to maintain its shape and will simplify mounting it on the spacecraft body).

—Corrugated or wavy mesh filled with foam, which provides technological rigidity of the shield.

—Two stacked layers of corrugated mesh (filled with foam) with mutually perpendicular corrugations that form a “sandwich,” which, similarly to plywood, will have an increased rigidity at maximum manufacturability (the orthogonality of the corrugation tilt will provide maximum scattering of the debris front).

Note that in all cases it is assumed that the width of the folds corresponds to several diameters $(4-6d)$ of the typically most dangerous particles affecting the protective structure (in the case of meteoroid and space debris impacts, the width is 8–12 mm).

CONCLUSIONS

The results of numerical simulations in the examples confirm that corrugated mesh shields are more effective than conventional meshes as an anti-meteoroid protection in all major parameters (effective gap, residual velocity, and fracture percentage) given the same specific mass. The design of protective shields based on corrugated metal mesh (Fig. 5) was patented by the authors [24]. It can be successfully used to protect critical elements of spacecraft against meteoroid and space debris impacts.

Combined protective shields made of corrugated mesh filled with foam and enclosed by bounding surfaces, in addition to increased durability, will be able to minimize the ejection of collision-produced debris into surrounding space, which is quite relevant from the point of view of the problem of near-Earth space pollution.

A promising direction of research is the study of the performance capability of multilayer spaced barriers with corrugated metal mesh (or a combination of meshes) as one of the layers.

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SPELL: OK