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Calculation analysis of magnetic-pulse compaction of explosively formed high-velocity metal elements used for meteoroid protection testing

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ABSTRACT

Accumulation of microdamages as a result of intensive plastic deformation leads to a decrease in the average density of the high-velocity elements that are formed at the explosive collapse of the special shape metal liners. For compaction of such elements in tests of their spacecraft meteoroid protection reliability, the use of magnetic-field action on the produced elements during their movement trajectory before interaction with a target is proposed. On the basis of numerical modeling within the one-dimensional axisymmetric problem of continuum mechanics and electrodynamics, the physical processes occurring in the porous conducting elastoplastic cylinder placed in a magnetic field are investigated. Using this model, the parameters of the magnetic-pulse action necessary for the compaction of the steel and aluminum elements are determined.

1. Introduction

1.1. Need for spacecraft meteoroid protection

Collisions of spacecraft with solid bodies of natural and man-made origin are among the major factors leading to damage and destruction of the spacecraft [1]. At the initial stages of space exploration, only the possibility of collisions of spacecraft with meteoric matter was considered. However, by the end of the 1970s, it became obvious that as a result of large-scale space activity, the near-earth space was littered with a large number of objects of man-made origin that are not carrying out any useful functions (details and fragments of the last stages of carrier rockets, emergency and fulfilled the term spacecraft) [2–4]. The results of research in Russia, the USA, France, Germany and Japan indicate the progressive characteristic of the process of near-earth space contamination. By different estimates of low Earth orbits, up to heights of 1.5–2 thousand km, approximately 5000 t of technogenic objects have thus far accumulated, and the total number of fragments with a diameter of more than 1 cm (such fragments and larger sizes constitute the most serious danger) is not amenable to exact calculation and can significantly exceed 100 thousand. From them, only a small part (several percent) is found and tracked by land radar and optical means. In August 2014, in the Russian catalog of space debris fragments, there were 15.8 thousand objects, and there were more than 17.1 thousand objects in Earth's orbit (including operating satellites). Approximately 6% of the tracked objects are functioning, approximately 22% of the objects have stopped functioning, 17% represent the fulfilled top stages and accelerating blocks of carrier rockets, and approximately 55% are waste, technological elements accompanying starts and fragments of destructed spacecraft.

It is possible to reduce the damage from the collisions of spacecraft with fragments of space debris and meteoric substances of less than 1 cm in size, increasing the protection of the most important units and constructive elements [5–15]. The impacts on solid materials [8] and pressurized structural elements [9–11] follow different scenarios. Laboratory study of the hypervelocity impact scenario requires different types of accelerators [12–14].

1.2. Explosive formation of high-velocity elements for carrying out meteoroid protection tests

Modeling of the meteoric impact on the protective structures of spacecraft at a stage of their development and testing requires production of high-velocity compact metal elements (taking into account that the space debris composition impact strength of protective shields is generally determined in relation to steel and aluminum impactors) [16,17]. Possible solutions of this problem can be connected with the use of various launching devices, e.g., light-gas guns, electromagnetic launchers, and explosive devices [18,19]. In the case of the choice of launching device type, in addition to impactor parameters provided by this device, the use of the overall dimensions of the device (its "bulkiness"), its complexity and the labor input of carrying out

Abbreviations: PE, porous element; HC, hemisphere-cylinder

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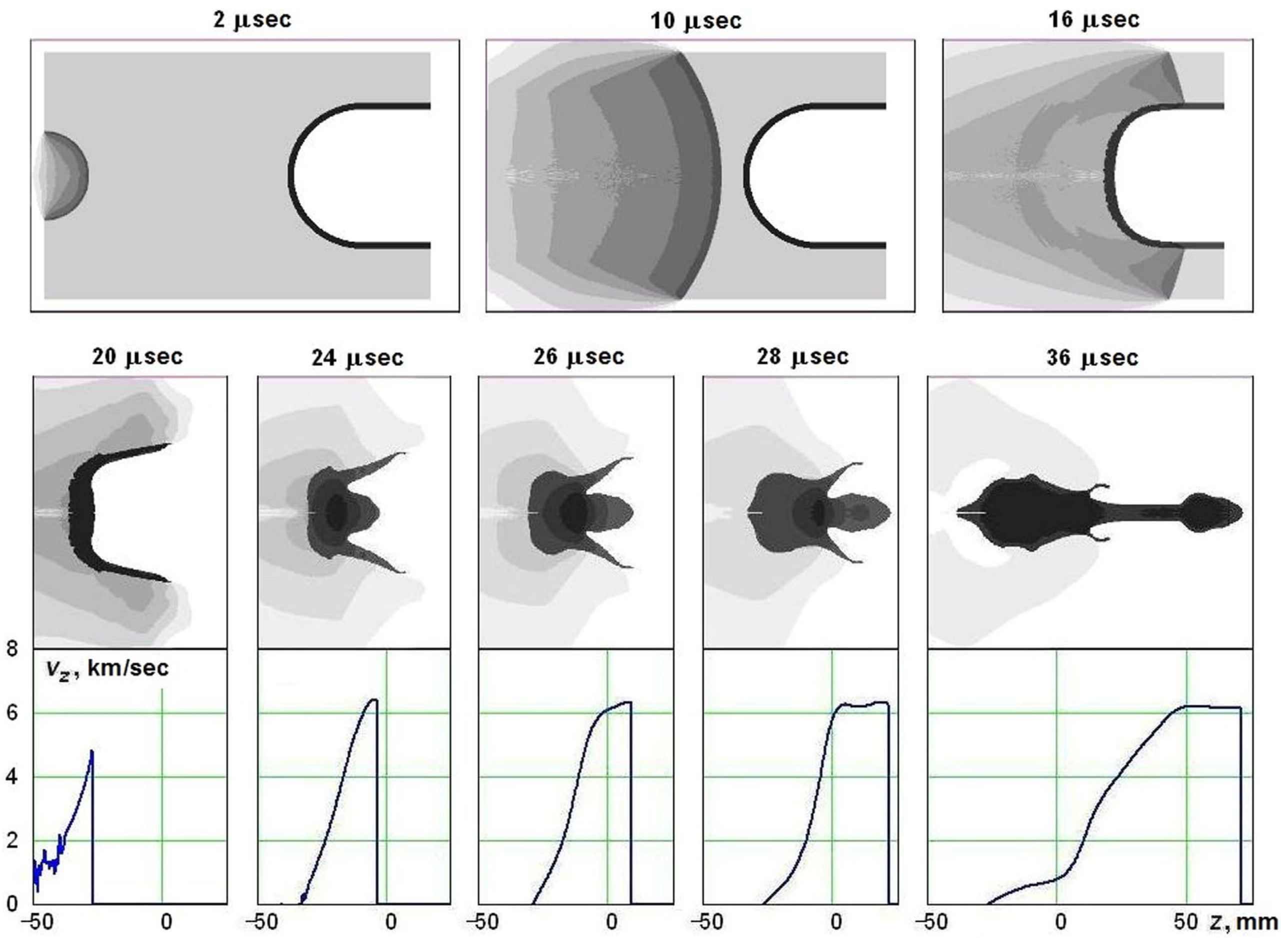

Fig. 1. Formation of a high-velocity compact element from the explosion of a charge with a liner of the combined hemisphere-cylinder shape.

experiments with this type of devices are also important. In this respect, explosive launching devices have an advantage. Explosive launching devices have been widely used due to their high efficiency, relative ease of operation, adaptability to laboratory conditions, low cost, and ease of changing the dimensions of the accelerators and projectiles. In turn, designs of the explosive launching devices that accelerate materials due to energy of a chemical explosive charge also differ in rather broad ways [20]. However, the dominant position among them in the reached parameters of high-velocity impactors (their mass and velocity) belongs to the axisymmetric shaped charges, which have one end of their specially shaped cavity lined with the profiled metal layer [21–24]. The charge with liner of the combined hemisphere-cylinder (HC) shape is among similar shaped charges. According to the available data [23,24], the application of HC liners has allowed for the development of a system of geometrically similar charges that steadily produce compact steel elements with a velocity of approximately 6 km/s and mass from 17 to 100 g.

In Fig. 1, on the basis of the results of numerical modeling [25] within a two-dimensional axisymmetric problem of continuum mechanics, the explosive formation of a high-velocity compact element via the use of HC liners is illustrated (the diameter of a shaped charge is 100 mm). It is visible that the distinguishing feature of the compact element formation process with HC liner use is its two-stage characteristic. In the first stage, at a liner, a hemispherical part collapses, and the jet flow is formed; in the second stage, the collapsing cylindrical part cuts the head site; continuing after that is further movement as a high-velocity compact body. The axial velocity on the cut site is constant at slightly more than 6 km/s. The thin jet of liner material moving after the produced element (see Fig. 1) by data of X-ray investigations [23,24] destructs on small particles due to the axial velocity gradient existing in the jet, and it gradually dissipates in the radial direction.

1.3. Problem of "loosening" of high-velocity elements from the explosive formation

As the production of high-velocity compact elements from shaped charges results from intensive plastic deformation of the liner material, numerous microdamages (microcracks, micropores, etc.) can arise and accumulate in the produced element. Reduction of its average density in comparison with the density of the initial liner material is a consequence of that. In this respect, in the case of explosive collapse of HC liner, the moment of cut-off of the jet flow head site by the collapsing liner cylindrical part is the most critical (see Fig. 1). The shock impact on the cut site has a consequence, i.e., distribution of a compression wave in it with the subsequent unloading from a free surface, during which there is a tension of comprehensive stretching in the material of the produced high-velocity element, creating powerful prerequisites for material "loosening".

According to estimates [23], the density of the steel elements produced in experiments by a shaped charge with HC liner and having the velocity of 5.8 km/s was lower than the density of the liner material (7.8 g/cm^3) and was between 4.1 and 6.1 g/cm^3. The nature of the target damage at high velocity depends on the density of the impactor material to an essential degree [26–29]. Therefore, for creation of the modeling conditions that are adequately similar to the real conditions of spacecraft collision with "monolithic" metal debris in an orbit, there is a problem of compaction of the porous elements (PEs) produced by the explosion at a stage of their movement before interaction with a target.