Agronomy Research **17**(6), 2445–2454, 2019
https://doi.org/10.15159/AR.19.213

Powder particle flow acceleration methods for simulation of interaction with materials used in spacecrafts

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Abstract. In recent decades, the role of satellites for monitoring the condition of agricultural land and forests, as well as in the study of natural resources, has especially increased. The amount of debris in near-Earth space is constantly increasing, which creates a real danger to the operation of satellites and other flying objects. The failures of satellites and spacecrafts increase the cost of their production and inhibit the development of the industry, lead to pollution of near-earth space by space debris. The U.S.-based Space Surveillance Network is currently tracking about 40,000 space objects- the vast majority of which are defunct satellites and fragments from collisions. It was estimated that there are more than 8,378 tons of junk around the Earth at speeds of up to 70 km h^{-1}, threatening functioning spacecrafts. Development of a new method for ground-based testing of protective materials, microchips and control systems will enable to avoid further pollution of near-Earth space.
This paper discusses methods for accelerating fine particles using explosive devices and an electromagnetic field and the possibility of using them to develop and research protective materials.

Key words: dynamic impact, shielding, protection, powder metallurgy, spacecraft, space dust, super-deep penetration.

INTRODUCTION

The interaction of hypervelocity particles with the surface of spacecrafts was in the focus of attention since the beginning of regular launches starting from first spacecrafts Vega-1 and Vega-2 and continuing by ESA spacecrafts Giotto and SPADUS. Zodiacal cloud observations and measurements made with a spaceborne dust detector indicate a daily mass input of interplanetary dust particles ranging from 100 to 300 tones (Bernhard et al., 1995; John M.C. Plane 2012; Belous et al., 2019). Thereto more than 5,000 launches since the start of the space age, each carrying satellites have resulted in space becoming increasingly congested and contested.

For a long time, all attention in the development of protective shells is paid to space debris ranging in size between millimetres to meters. However, in the last decade, researches have shown that the influence of space dust (micron-sized) dust has been seriously underestimated. Previous analysis of the state of solar panels the Mir space station, the Hubble Space Telescope and other spacecraft, showed that the layered structures of solar cells are very sensitive to streams of cosmic dust (Rival et al., 1997; Lorenz, 1998). The impact of a superfast microparticle with a velocity $v > 5$ km s^{-1} on a solid target causes mechanical and plasma processes. A crater, an ejection of plasma and steam are forming on the surface of the solar cells, and a shock wave propagates in the battery's layered structure.

The further experiments suggested that when microparticles collide with a spacecraft shield, it may cause not only a mechanical damage, but also causes an occurrence of plasma, which in turn leads to the appearance of electromagnetic radiation capable of disabling nearby electrical equipment (Maki et al., 2004; Fletcher & Close, 2017). Other research has shown that the flow of high-speed dust particles penetrates into metal barriers to depths up to centimetres (Aleksentseva & Krivchenko, 1998; Krestelev, 2014; Qi & Chen, 2014). Therefore, the existing protective shields of spacecraft do not provide reliable protection. Development of additional protection is required. An additional challenge is the carrying out full-scale tests to measure protective properties of various materials. Providing such experiments on spacecraft is costly and complex, so the computer simulation is often used, which is not always able to ensure full compliance.

The effect of super-deep penetration (SDP), demonstrating the possibility of penetration of high-speed flows of powder particles into barriers to depths of tens of centimeters, is capable of creating a ground-based method for testing the protective properties of materials. For this reason, it is necessary to analyze the capabilities of various particle acceleration methods.

SUPER-DEEP PENETRATION METHOD

Super-deep penetration (SDP) is a complex physical phenomenon, when in a split second bunch of powder particles with a fraction less than 200 microns, accelerated to speeds of 700–3,000 m s^{-1}, penetrates into the solid metal body at depth in tens, hundreds mm. At the same time the high and ultra-high pressure (0.2–20 GPa), intensive deformation, local heating, friction are occurred (Kheifets et al., 2004; Owsik et al., 2008).

Penetration depths depend on the material of obstacle as well as on the parameters of a dust cluster. Pressure level in zones of particles motion ensures dynamic phase transition. Material in a solid phase undergoes a transition into a quasi-liquid (dense plasma) state. Due to pulsation of channel elements (in a direction perpendicular to particle motion), plasma jets of opposite directions are formed in channel areas. Jets move inside a shell and ejected from it (Fig. 1). Intense interaction of dust clusters with a protective shell material leads in a closed volume to strong electric effects, which can initiate magnetic field oscillations. During the SDP process in the range of very short intervals flow of powder particles (strikers) move in a volume of the metal body. Behind the strikers in a dense 'quasi-liquid' plasma channel cavities are formed, which can slam under the effect of background pressures. In this case matrix crystal lattice is destroyed with high speed, and the matrix material changes from a solid state to a dense plasma, i.e. a dynamic phase transition is realize (Usherenko, Usherenko, and Yazdani 2017). A principal reason of making difficult detection of SDP on space stations is the absence of reach-through holes and, accordingly, absence of depressurization of the module with the equipment.

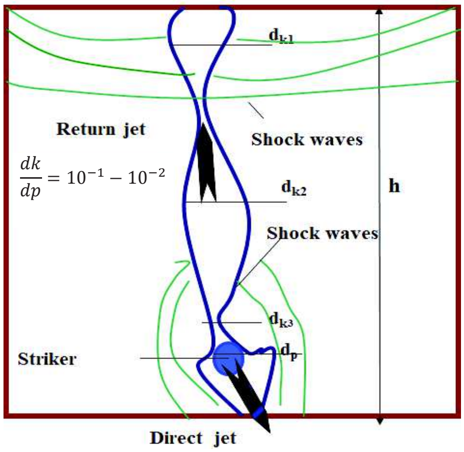

Figure 1. Scheme of channel element (dp – diameter of a striker (particle); dk – diameter of a channel, and h – channel depth).

Under the influence of all these factors, the structure of the matrix material in the areas of ultra-high pressure is ground up to complete amorphisation. These areas are intertwined with the areas of the matrix material, creating in a polycrystalline matrix reinforcing carcass and accordingly an anisotropic composite material (Usherenko et al., 2017). This physical phenomenon occurs only in a closed system.

To develop of new solutions for spacecrafts protection of high-speed dust particles it is necessary to investigate different dynamic load methods, which enable realization of the SDP process in the earth-based conditions.

POWDER PARTICLES ACCELERATION METHODS

Various sources of acceleration of small-sized particles in vacuum and various environments are used for initiation of high-speed movement. These methods can be subdivided into several groups: explosive, electromagnets, etc. Small-sized particles accelerators are subjected to a certain set of requirements, the main ones being simplicity, economy, reliability and safety. For an experimental study of the processes implemented in high-speed collisions, it is necessary to choose an appropriate accelerator providing acceleration of microparticles of a certain mass to given speeds.

A lot of methods are used for throwing bodies of small mass from less than a gram to tens and hundreds of grams. Throwing via resilient elements - strings, rods, curved plates does not provide high throwing speed, due to the complexity of the mechanical construction, and basically does not exceed the speed of sound.

Throwing with high pressure liquid media. The most commonly used is throwing compact bodies or a dispersed medium with water jets. Acceleration of bodies by this method is accompanied by moistening in the throwing medium, additional electrification, and also additional voltage from hydrodynamic flow around the medium (Aleksentseva, 2015; Ben-Dor et al., 2018).

The method of acceleration of micron-sized metallic charged particles using electrostatic accelerators is used for simulating the interaction of solar cells and other elements of a spacecraft with ultrahigh-speed micron particles (micrometeors) (Burchell et al., 1999; Hasegawa et al., 2001). This method provides the acceleration of metal particles with a mass 10^{-10}–10^{-16} g to speeds of tens of km s^{-1}. The disadvantage of this method is that the acceleration of the dielectric microparticles to such speeds is difficult, because charging in contact with a charged needle at the source of micron particles of the accelerator will be in several orders of magnitude lower than charging of metal particle of the same size and mass. Therefore, the speed of the accelerated dielectric particle will be significantly lower than of a metal particle.

In electromagnetic railguns, particles are accelerated by the interaction of induced eddy currents with a moving magnetic flux. With the additional use of explosive compression of the magnetic layer, it is possible to bring the speed of particles with a mass of 0.01 g to 10 km s^{-1} or more (Rashleigh & Marshall, 1978; Semkin et al., 2015). Disadvantages of such railguns are the occurrence of the arc discharge at the contacts, the frequent destruction of the accelerating coils and particles during the acceleration process.

To bring the useful payload into space, electrothermochemical and combined electrodynamic accelerators have been developed. Electrothermochemical accelerators provide speeds up to 2.5 km s^{-1}, electrodynamic accelerators in experiments provide speed about 7 km s^{-1}, but additionally consume energy of hundreds of MJ becoming very expensive equipment for industrial applications (Aleksentseva, 2015).

The magnetic-pulse method is widely used for throwing bodies with a mass of 0.1–500 g at speeds of 30–1,000 m s^{-1} (Mironov & Viba, 2007; Mironovs et al., 2013). The technology of magnetic-pulse processing of materials (MPPM) uses the principle of converting electrical energy stored in a storage device into a powerful pulsed magnetic field that affects the material being processed in a strictly metered form (Gafri et al., 2006; Mironov et al., 2019). For MPPM technological processes, it is necessary to create strong magnetic fields with a strength of 10^5–10^7 A m^{-1}. Such fields are formed in the working tool - inductor when the capacitive energy storage device is discharged onto it (Gluschenkov, 2013). A unit for magnetic-pulse treatment (MPU) generates pulse currents, the magnitude and duration of which can vary widely. The working range of the amplitude of current pulses is 10^4–10^6 A, the duration is 10–1,000 microseconds.

Magnetic pulse installation is a generator of single-multiple current pulses, which contains the energy storage. The stored energy in MPU is released in the inductor-workpiece system in the form of a magnetic field and heat, which are used to perform treatment. High rates of energy release and energy density are realized in pulse modes, which are not achievable in stationary modes, for example, in generators operating at a frequency of 50–1,000 Hz. In MPU during 1–10 seconds energy is accumulated at a relatively low power consumption from the power supply. Depending on the stored energy and efficiency, the average electricity consumption of the MPU from the power network is 0.5–3 kW h^{-1}.

Gas throwing is most widely used for all research purposes. The simplest method is to throw a piston pusher in a tube, which does not provide significant throwing speeds. Pressure P 'can vary in the range of 1–10 MPa. Throwing velocity is in a range of 0.1– 100 m s^{-1}. Two-stage light-gas guns, forming the gas phase in the first stage, provide throwing with a maximum velocity of up to ~7,000 m s^{-1}. The pressure in the gas front at the maximum is up to 1,000 MPa (Aleksentseva, 2015). The three-stage light-gas guns are capable to accelerate projectiles up to 9.5 km s^{-1} (Piekutowski & Poormon, 2006; Putzar & Schaefer, 2016).

Acceleration and throwing of compact bodies by products of explosive combustion. The speed range of explosive combustion is about 3–4.5 km s^{-1}, up to 9 km s^{-1}. The pressure at the front of P ″ can be 1–10 GPa. Explosive combustion is realized by initiating of the propelling charges of gunpowder, high-energy rocket fuels. Explosive methods are the most effective, providing acceleration of bodies due to the initiation of explosives with a detonation velocity D = 5–9 km s^{-1} and pressure P = 10–100 GPa (Huneault et al., 2011). At Fig. 2 a front pressure during throwing by gas discharge, explosive combustion and the shock wave of an explosive are shown (Aleksentseva, 2015).

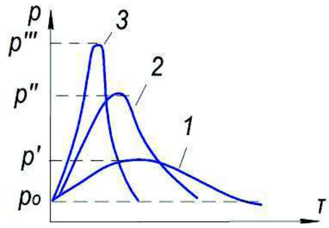

Figure 2. The front pressure (p) at throwing by gas discharge – 1; explosive combustion – 2; the shock wave of an explosive – 3.

Magnetic Pulse Accelerators

At the heart of the principle of MPU (Fig. 3) is used the method of direct conversion of electrical energy stored by the energy storage device into the electromagnetic field arising in the inductor.

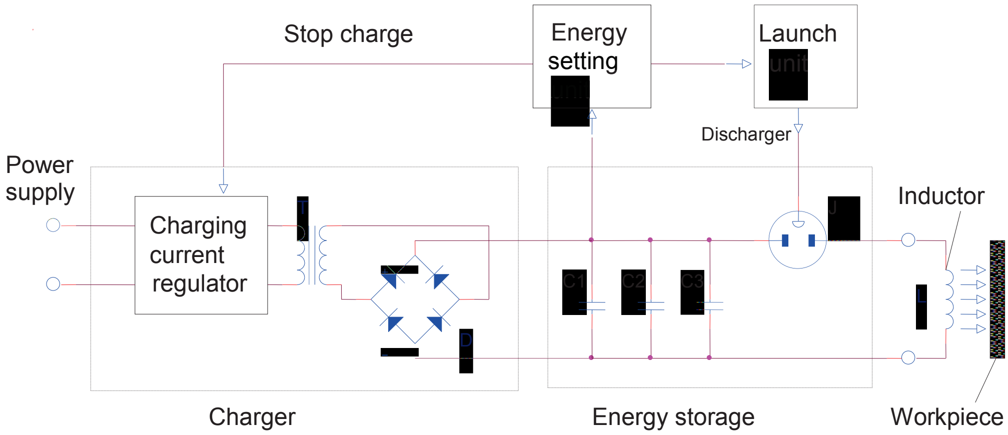

Figure 3. Block diagram of the MPU.

The energy storage device consists of a battery of pulse capacitors C1...C3. Capacitors are charged with direct current from a charger consisting of a high-voltage transformer T1 and rectifier D. The stored energy can be smoothly dosed by adjusting the charge voltage. When the voltage on the capacitors reaches a predetermined level, the energy setting unit stops the charge with the ‘Stop’ command and issues a discharge command. The start-up unit includes a discharger J, which discharges the capacitors of the energy storage to the inductor L.

In the process of discharge of the energy storage device, an electromagnetic field arises in the working zone of the inductor. The electromagnetic field induces eddy currents in a workpiece. The interaction of the electromagnetic field of the inductor and currents in the workpiece creates a pulse pressure, which leads to the work of deformation and pulse heating of the processed material (Lapkovskis, 2012; Lapkovskis & Mironovs, 2012). The processes of charge and discharge of energy storage in MPU are automated.

The technique features the use of capacitor banks with stored energy from 1 up to 100 kJ. The discharge of capacitors to the coil (working tool) initiates short pulsed electromagnetic field with intensity of 50–200 A m^{-1} and duration of few milliseconds (Fig. 3). The interaction time of flow of particles with a surface of the workpiece is about 2–6 μs. (Fig. 4).

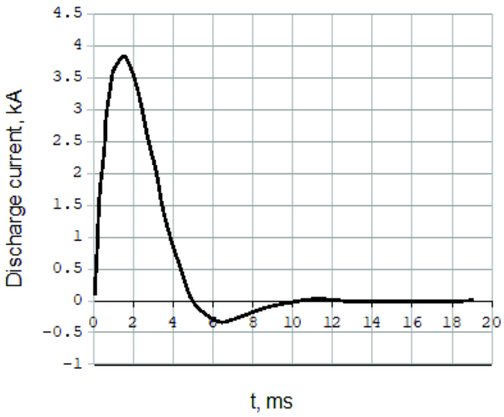

Figure 4. A typical impulse shape generated by impulse current source.

Explosive Accelerators

In accelerators of this type, particles are accelerated by the classical explosive method. There are explosive accelerators of the following types: accelerators with powerful explosives and shaped charges, devices with plasma acceleration and electrostatic accelerators.

Explosive accelerators are characterized by simplicity of design and low cost and are widely used in practice. Acceleration does not depend on the material of the accelerated jet (conductive, non-conductive). When using such accelerators, the flow of microparticles is formed due to the compression of the container with powder particles by the explosive charge (Belous et al., 2017).

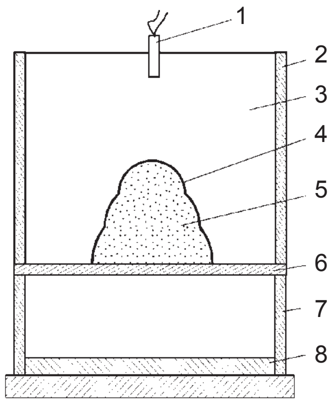

Figure 5. Outdoor explosive accelerator: 1 – initiator; 2 – facing; 3 – charge; 4 – cumulative lens; 5 – powder mixture 6 – plate-cartridge base; 7 – adjusting support; 8 – obstacle.

The device described in (Usherenko, 2013) can be the basis for creating an accelerator for conducting experiments on modeling and simulating the processes of high-speed collision of cosmic dust with spacecrafts. The equipment is based on the scheme of an explosive accelerator with a cumulative lens. The traditional scheme of the collision, formation and impact of a stream of discrete microparticles is shown in Fig. 5 (Usherenko, 2013). This scheme allows to use relatively small explosive charges

(≤ 0.3 kg), including those from recycled ammunition, with a low detonation velocity (≤ 4,000 m s^{-1}). The average speed of such stream of powder particles is usually ~1,000–3,000 m s^{-1}. The advantages of such scheme are a relatively large mass of the throwing bunch (~0.03–0.2 kg), the ability to control the cross section of the bunch (0.05–0.25 m) and the loading time at colliding with a metal barrier (~10–1,000 µs). At the same time, the high, energy flux has significant gradients of speeds (300–3,000 m s^{-1}) and densities (0.01–0.5$\rho_{theoret}$).

The second variant of the explosive scheme for obtaining the effect of SDP is shown in Fig. 5. In this case, when a gun accelerator is used as the basis, the loading parameters (speed and time) become more defined and constant comparing with a design of an explosive generator (Fig. 6). The speed of throwing the stream according to this scheme is 950–1,200 m s^{-1}. According to the pulse registration data on the oscilloscope during processing, the exposure time of the powder flow with the workpiece was determined (Fig. 7). The interaction time of the particle stream with a total mass of 1 g with the surface of the workpiece was about 10–12 µs. (Aleksentseva, 2015).

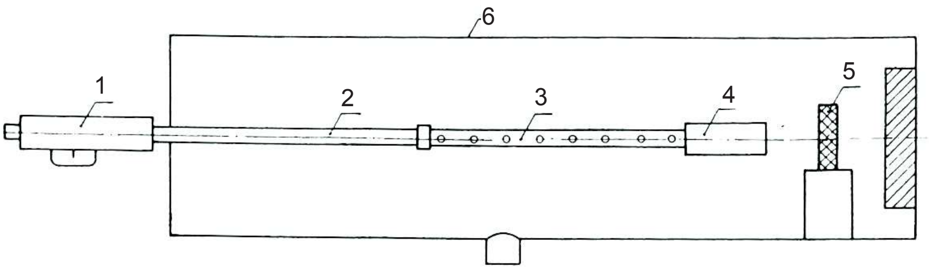

Figure 6. Ballistic accelerator: 1 – charging chamber; 2 – barrel with a diameter of 16 mm; 3 – chamber for depressurization of powder gases; 4 – speed meter; 5 – sample holder; 6 – vacuum chamber.

Explosive methods of throwing in SDP mode in order to ensure throwing velocities in 1.0–3.5 km s^{-1} are the most acceptable for industrial technologies. In addition, high pressures provide an intense impact of the shock wave on the workpiece material, which is a necessary part of the complex super-deep penetration method and to a small extent can be implemented by other methods of throwing. Depending on the goals and objectives, it is possible to apply the scattering of impactors with the necessary spreading radius, formation of a micro-body jet (based on the cumulative effect or a stream of various lengths for processing materials in SDP mode (Aleksentseva, 2015).

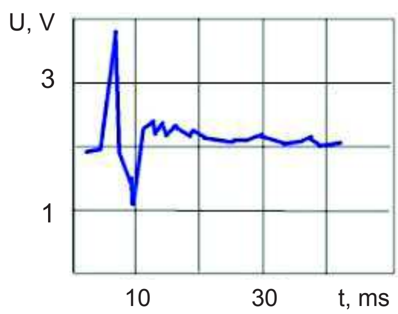

Figure 7. The type of pulse from the pressure sensor when exposed to flow on the workpiece.

The main parameters of explosive and magnetic pulse accelerators of powder particles are given in Table 1. The main advantages of the explosive acceleration method are the high acceleration velocities of the powder flows and amount of energy applied to the accelerated flow. The disadvantages are a small distance of movement and low number of pulses. The main advantages of the electromagnetic acceleration method are a wider range of particle sizes, longer distance of movement and a high number of pulses. A very important advantage of magnetic pulse accelerators is a higher level of staff safety.

Table 1. Parameters of powder particles accelerators

Type of accelerator	Amount of energy applied to the accelerated material (kJ kg^{-1})	Size of the moved particles (mm)	Distance of movement (m)	Velocity of movement (m s^{-1})	Number of pulses (min)
Explosive	150–3,000	0.001–0.5	0.01–0.2	300–3,000	1
Magnetic pulse	2–20	0.001–10.0	0.01–2.0	10–1,000	1–200

CONCLUSIONS

Failures of satellites and spacecrafts increase costs of their production and inhibits the development of the industry, lead to pollution of near, earth space by space debris. The lack of a test method does not allow to solve the problem.

Thus, the investigation of the interaction of high-speed flows of powder particles with a barrier is topical. Using the method of dynamic material loading with a high-speed flow of powder particles will provide an easy and effective way of testing the protective properties of materials and electronic systems in ground-based conditions.

SDP method ensures the penetration of powder particles in metal obstacles to depths of 60–300 mm. It exceeds the thickness of the protective shields of spacecraft. Ground-based materials testing technology developed on the basis of the SDP effect will allow to perform tests of protective properties of various materials using destructive testing tools.

The most promising methods of acceleration in the SDP mode are the magnetic-pulse and explosive methods. Explosive methods of acceleration in SDP mode in order to ensure throwing velocities in 1–3.5 km s^{-1} are the most acceptable for industrial technologies, and magnetic-pulse methods provide greater safety for the staff in laboratory conditions.

AKNOWLEDGEMENTS. This work has been supported by the European Regional Development Fund within the Activity 1.1.1.2 'Post-doctoral Research Aid' of the Specific Aid Objective 1.1.1 'To increase the research and innovative capacity of scientific institutions of Latvia and the ability to attract external financing, investing in human resources and infrastructure' of the Operational Programme 'Growth and Employment' (No. 1.1.1.2/VIAA/2/18/335).

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