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Hypervelocity impact of mm-size plastic projectile on thin aluminum plate

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ABSTRACT

The experimental studies of the process of hypervelocity (up to 6 km/s) impact of a mm-size projectile on a thin aluminum plate is described. The numerical simulation of this process is presented. The data on the evolution, structure, and composition of the debris cloud formed as a result of the impact are reported. Basic specific features of the debris cloud formation are revealed.

1. Introduction

At the dawn of space exploration a major threat to space vehicles was considered to be their meeting with meteorites. At present the main threat is a collision with the objects formed in the near space as by-products of the human activity [1–6] and referred to as man-made space debris. These objects are the fragments resulting from destruction of rockets, out-of-service orbital stations and satellites, etc., and consisting of different materials, such as metals, ceramics, composites, and plastics. The fragments typically have irregular shapes and, therefore, the consequences of their impact differ from those of impacts of spherical particles. According to the estimates, the number of fragments of space debris with a size of 1–10 cm in the near-Earth space has reached $(2–2.5)\times10^5$ and the number of fragments 0.1–1 cm in size is $(80–100)\times10^6$ [7]. The speed of collision of the debris fragments with a space vehicle surface is 3–8 km/s. At present the hypervelocity collision of plastic projectiles with the metal from which the space vehicle surface is made is most poorly studied experimentally. Modern physical and mathematical models that describe the hypervelocity interaction between bodies and different obstacles are based on experimental results which remain the principal means of research into the physics of impact and its consequences. The main goal of our study was to demonstrate possibilities and advantages offered by the use of compact railguns developed at Ioffe Institute [8–11] for the investigation of hypervelocity impacts of mm-size bodies on different targets and to study the impact process of cubic plastic projectiles on thin aluminum plates.

2. Experimental

The compact railgun with a plasma piston [8] used in the experiments as an accelerator is capable of accelerating plastic projectiles (2-mm polycarbonate cubes) to high speeds of 5–6 km/s in air at atmospheric pressure. Fig. 1 shows an example of a flight and impact of a 2 mm cubic projectile on a 1.5 mm thick aluminum plate. The experiment was conducted in air at atmospheric pressure. The shock waves arising in air due to the projectile motion and also formation of debris clouds on both sides of the target plate are clearly seen in Fig. 1. The left side of the figure shows the gas ejected from the railgun channel together with the projectile.

For the experiment, a 1.2-m long ballistic range including a projectile accelerator (railgun), sensors for measuring the projectile speed, a device for determining the projectile orientation near the target, and the target itself were used. The setup was placed into a hermetic chamber. Before the experiment the air was pumped out, and helium was pumped in. This allowed us to carry out experiments at a lower gas density (in 7 times) of the surrounding medium as compared with air. This significantly reduced the debris cloud deceleration during its burst.

The diagnostics used in the experiment included: (i) measurements of the projectile speed before its impact on the target; (ii) registration of the projectile orientation in the flight before its impact; (iii) registration of the debris cloud evolution and its influence on the witness plate surface.

The target plate thickness was 0.5 mm or 1 mm. In the experiments the projectiles collided with the target at normal and tilted incidence angles. A 5 mm thick aluminum witness plate on which the imprints of the debris cloud were left was placed at a distance of 40–50 mm from

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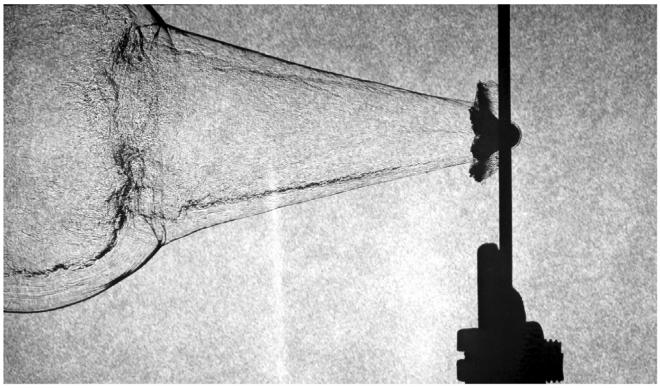

Fig. 1. Schlieren picture of a 2 mm plastic projectile impact on 1.5 mm thick aluminum plate at normal incidence.

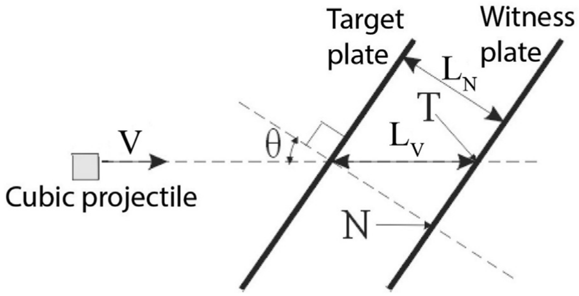

Fig. 2. Geometry of the experiment. L_V is the distance between the target and witness plates along the projectile velocity vector; L_N is the distance between the target and witness plates along the normal to the target plate; V is the cubic projectile velocity vector before the impact; θ is the angle between the velocity vector and the normal to the target plate, i.e., the incidence angle.

the target plate. The scheme of the projectile collision with the target is shown in Fig. 2. The witness plate is affected by the debris cloud, i.e., the cloud formed from fragments of the target and the projectile materials after the impact on the target plate. The experiments were conducted for different angles between the velocity vector and the normal vector to the target.

The projectiles in our experiments were cubic, so it could be expected that the impact process would depend on the projectile orientation at the moment of collision. To take into account this factor, the projectiles were photographed near the target in two projections. Conventional SLR cameras the shutters of which were opened just before the shot and remained open throughout the experiment were used. The exposure was provided by a single-pulse backlighting of two white scattering screens located near the projectile trajectory. As a light source, an electron-beam pumped semiconductor laser with a light pulse duration of 10 ns and wavelength of 632 nm was employed. Synchronization was provided by laser triggering by the signal of the first projectile speed sensor. To protect the cameras from extraneous light (railgun channel and flashes), the lenses of the cameras were equipped with optical filters having the bandwidth close to the spectral characteristic of the semiconductor laser. Since the ballistic range was filled with helium, there was no ignition of the hot fine particles ejected from the target plate at the moment of impact in the direction opposite to the cubic projectile motion.

Since measurements of high speeds ($V > 1–2$ km/s) of mm-size bodies is a complicated task, original thin-film sensors [12] were developed. As special experiments showed, these sensors affected only slightly the speed and orientation of rapidly moving ($V \approx 5$ km/s) plastic bodies of mm sizes. The projectile speed was measured by a pair of thin-film sensors located in the projectile trajectory. The first sensor was located at 140 mm from the railgun channel muzzle. In addition, four diaphragms with the apertures 6 mm in diameter were installed at regular intervals between the railgun muzzle and the first sensor. The diaphragms were needed to eliminate the gas ejected from the railgun channel together with the projectile. The second sensor was placed near the target or directly on it. The accuracy of speed measurements by these sensors was better than 1%.

To register the evolution of the debris cloud resulting from destruction of the target plate and projectile, two methods were used: (1) a superfast photographing of the debris cloud on the background of the luminous screen, and (2) Toepler shadow shooting using a pulsed laser as a light source. To get hypervelocity photographs of the debris cloud, the beginning of the shooting was synchronized with the moment of projectile impact on the target plate. To illuminate the screen with a reference grid (the cell size was 10×10 mm^2), a pulsed tubular lamp with a special reflector was used. The exposure time of one frame was 1 μs, the time between the frames was also 1 μs. The total registration time was 240 μs, which allowed us to record all phases of the process from the beginning of the target plate puncture to a complete degradation of the debris cloud. A typical frame sequence demonstrating the debris cloud evolution for the case of a tilted projectile impact on the target is presented in Fig. 3.

It is important to note that in contrast to conventional experiments where metal projectiles [13,14] are used, the speed of sound in a plastic projectile is lower. In the case of impact speeds of 5–6 km/s a collision gives rise to a shock wave in a plastic projectile, while only a compression wave propagates in a metal projectile. This leads to different pictures of projectile destruction during hypervelocity impacts on plates.

3. Experimental results

The experiments were conducted for θ=0°, 30°, 45°, and 60° (Table 1).

The specific features of the debris cloud formation observed in the experiments were as follows:

1) An increase in the incidence angle of the cubic projectile on the target θ leads to an increase in the portion of the fragments flying in the direction close to the normal to the target plate surface. At one and the same angle, the direction of burst of the major part of the fragments for the impact velocities differing by 15–20% was approximately the same.
2) The velocity of the fastest fragments (or the cloud head) depended on the impact velocity. In the case of the same targets and angles of impact, an increase in the cubic projectile velocity by about 10% led to a noticeable change in the time during which the fast fragments reached the witness plate.
3) The cloud of flying fragments at the titled impact was substantially inhomogeneous. Note that the region with the highest fragment density did not necessarily correspond to the highest fragment velocity region. The flight direction of the major part of the fragments was close to the normal to the plate surface.
4) The hypervelocity impact led to an inhomogeneous distribution of the craters on the witness plate formed by the debris cloud. This distribution manifested itself mainly for thin targets. A longer time of interaction of the projectile with the target till unloading, i.e., a thicker plate or a lower impact velocity, resulted in a more uniform distribution of the fragments.
5) The orientation of the cubic projectile before the impact did not exert a strong influence on the spatial and temporal distribution of the debris cloud.

Analysis of the witness plate region affected by the debris cloud also revealed the specific features which, to our knowledge, have not been observed in the experiments on hypervelocity impact on composite targets. In addition to typical craters which resulted from hypervelocity collision and were caused by small fragments of the target plate