Simulation of damage to the protective shields of the Vega space vehicles by means of intense relativistic electron beams

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Experiments have been carried out to simulate the damage to the protective shields of the Vega space vehicles by means of intense relativistic electron beams. The role played by split-off particles in the damage to the second shield is determined.

The space vehicles Vega-1 and Vega-2, launched in December 1984, are to pass through the dust cloud of Halley's Comet in March 1986. These vehicles will be subject to a stream of dust particles moving at a relative velocity of about[1] 80 km/s. The interaction of dust particles with the protective shields of space vehicles cannot be studied directly at present because we lack laboratory methods for accelerating solid objects to such high energies without heating them. It thus becomes particularly important to simulate high-velocity impact phenomena by means of pulsed systems capable of producing the required energy densities in the condensed matter. A simulation of this sort is possible because at a sufficiently high collision velocity (in practice, beginning at 10 km/s) the mass and momentum of the expanding material of the obstacle are much greater than the mass and momentum of the striker. Important characteristics of the collision in this case are the total energy of the striker and the time over which this energy is transferred to the obstacle. The necessary values of these parameters and the corresponding conditions for spatial focusing can be achieved in experiments with laser beams and intense relativistic electron beams. Demidov and Martynov[2] have pointed out the similarity between the events caused by high-velocity impact and the effect of a relativistic electron beam on a metal.

The greatest danger to the Vega vehicles may be posed by a collision with a micrometeoroid with a density ~ 1 g/cm^3 and a dimension ~ 1 mm. In the collision of such a particle with a shield, an energy ~ 3 kJ is released in ~ 10 ns. Strong shock waves with an initial pressure of tens of megabars are formed in the micrometeoroid and the shield. The condensed matter of the shield and of the meteoroid evaporates in rarefaction waves; the plasma jet that forms is restrained by a second protective shield. Calculations[3,4] show that a quantitative simulation of the damage caused by the impact of such a micrometeoroid would require a relativistic electron beam(1) with a pulse length ~ 10 ns, a diameter ~ 1 mm, an electron stopping depth < 0.5 mm, and a total energy $\gtrsim 3$ kJ. Electron beams with such characteristics cannot be produced at the present state of the technology of intense relativistic electron beams. Accordingly, experiments on the interaction of intense relativistic beams with the protective shields of the Vega probes have been carried out in beams with the following characteristics: a pulse length of 50–100 ns, a focus diameter of 1–2 mm, an electron stopping depth of

0.4–1.5 mm in the shield, and a total energy of 1–5 kJ. The maximum energy flux density in such a beam is 10^{13} W/cm^2, and the corresponding ablation pressure is about 10 Mbar. This pressure is considerably higher than that which would be exerted by a laser beam with the same energy flux density, since the energy of the electrons is released in denser matter. Thus circumstance and the large total energy are advantages of electron beams over laser beams for simulating impact.

A pressure of about 10 Mbar arises at the time at which an ice (H_2O) particle makes contact with an aluminum shield at a velocity ~ 40 km/s. In the model experiment, however, the energy of the electron beam is from the outset transferred to a slightly greater mass of material than in the collision of a particle. For this reason, estimating the velocity of the "equivalent particle" by equating the ablation pressure to the initial pressure in the shock wave is not absolutely correct and should result in a slight underestimate of the velocity. It can therefore be expected that in experiments with relativistic electron beams having the characteristics listed above the overall picture of the interaction of dust particles with the protective shields of the Vega probes should be reproduced quite well. To determine the quantitative relations between the characteristics of the micrometeoroid and those of the pulsed relativistic electron beam, it will be necessary to carry out detailed numerical calculations.

Experiments on the damage to protective shields have been carried out at two intense-beam accelerators, the Kal'mar[5] (electron energy of 0.35 MeV) and the Mirazh[6] (electron energy of 0.8 MeV). Single-layer and multilayer shields and systems of shields of various thicknesses of metals and various alloys were exposed to the relativistic electron beams. The results of these experiments show that the best material for the first shield is a plastic metal, in particular, aluminum or certain of its alloys. Such materials generate a less intense flux of split-off particles than does, say, steel. According to the calculations of Refs. 3 and 4, the second shield should be at least 5 cm from the first. The diameter of the apertures in the first shield (Fig. 1) turns out to be slightly greater than predicted by calculations based on the model of Ref. 3. A possible reason

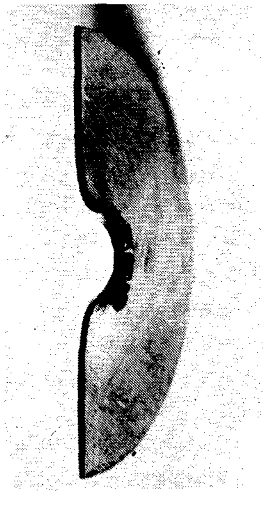

FIG. 1. Photograph of a section of a first shield of the alloy AMg6M, 0.8 mm thick, punctured by a relativistic electron beam with an energy of 1 kJ at its focus.

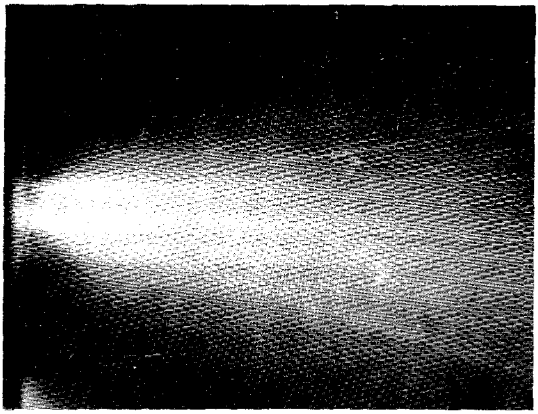

FIG. 2. Photograph of the split-off particles, moving at 7 km/s, which are formed when a 1-kJ relativistic electron beam strikes a first shield of the alloy AMg6M, 0.8 mm thick.

for this difference is the motion of the focus along the surface of the target during the pulse.

In the course of the experiments, it was found that the split-off fragments of the first shield are extremely important. At the second shield, these fragments form an annular zone of damage to and, in some cases, punctures of a second shield of aluminum, 0.6 mm thick and 10 cm away. Analysis of the craters and holes in the second shield yields estimates of the mass and velocity of the split-off particles. The largest particles have a mass $\sim(2\text{–}5)\times10^{-4}$ g and a velocity of about 2 km/s, in agreement with the calculations of Refs. 3 and 4. The split-off particles of very small masses are accelerated to $\sim$7–9 km/s in the plasma jet (Fig. 2). When a composite material 0.5 mm thick is deposited on the second shield, there is usually no complete puncture.

Experiments on the effect of relativistic electron beams on protective shields, carried out in parallel with a numerical simulation of this effect, have resulted in a refinement of the physical model proposed in Ref. 3 for high-velocity puncture. These results also lead to recommendations for improving the overall reliability of the shielding system. An optimization of the characteristics of the protective shields by means of the experiments with relativistic electron beams shows that good results can be achieved by placing a first shield of the alloy AMg6M, with a thickness of 0.4–0.6 mm, 10 cm from a second shield consisting of a 1-mm thickness of the same material, coated with a millimeter-thick layer of a composite. Three protective shields of the AMg6M alloy should be used in the most critical regions.

[1)] It should be kept in mind that there is an important distinction between the mechanisms by which an electron beam and a condensed particle interact with the material of a shield. The energy of a beam is transferred to electrons, and only part of this energy goes into producing the reactive momentum.

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