Physics of the damage from high-velocity impact

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A physical model is proposed for the damage caused to solids by high-velocity impact. Numerical calculations have been carried out on the dynamics of the damage to the shielding on the Vega space probe as it passes through the dust cloud of Halley's Comet.

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The question of the mechanisms responsible for the damage to solids during high-velocity impact is closely related to several problems of space physics and astrophysics, e.g., research on meteorite craters, the development of certain hypotheses regarding the origin of the planetary atmospheres, and the development of systems for protecting space vehicles from meteoroids. The problem of high-velocity impact has recently attracted particular interest because of three plans for sending vehicles to the vicinity of Halley's Comet.[1] Calculations show that the vehicles should pass through the dust cloud of the comet at velocities between 60 and 80 km/s. These velocities place extremely severe requirements on the system for protecting the vehicles from the dust.

The information available on high-velocity impact deals with velocities no higher than 20 km/s, and for the most part this information is experimental. Velocities on the order of 100 km/s, which are important for applications,[1–3] are not accessible to direct experimental study. Theoretical analysis and numerical simulations of high-velocity impact phenomena thus become very important. In the present letter we describe a physical model and report some corresponding numerical calculations on the damage to metal shielding resulting from the impact of micrometeoroids at velocities on the order of 100 km/s. The ranges of parameters for which the simulations were carried out correspond to the conditions which will prevail when the Vega space vehicle passes through the dust cloud of Halley's Comet in March 1986.

The sequence of events which occur during high-velocity impact can be summarized as follows: At the instant of contact, strong shock waves arise in the striker and the obstacle. The initial energy density behind the wave is two or three orders of magnitude higher than the latent heat of vaporization, so that some fraction of the material evaporates completely in the rarefaction wave. As the shock wave decays, the evaporation becomes only partial, and eventually it gives way to melting and mechanical crushing of the material. When the shock wave reaches the rear of the shielding it may cause material to split off. For a quantitative description of all stages of the damage in the model of a continuous medium we need an equation of state over a broad range of parameters, including the melting curve and the two-phase region; we also need detailed information on the strength and rheological properties of the mate-

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rial of the obstacle. The calculations on high-velocity impact in the literature[4,5] have been based on some extremely simplified models of the medium, and they give only a qualitative description of the various stages of the damage process. The model which we are proposing here gives a quantitative description of the overall process.

We use a semiempirical, wide-range equation of state which meets the requirements stated above. The principles for constructing this equation of state are set forth in Ref. 6. The equation has the correct asymptotic behavior in all limiting cases (low and high densities and high temperatures), and it contains about 20 adjustable parameters, which are to be determined from experiment and from quantum-mechanical calculations. Parameter values for aluminum are given in Ref. 7, and values for other metals are given in Ref. 8. The equation of state is accurate within 1–3% in the part of the phase diagram which has been studied experimentally.

The formation of cracks and the damage to the material caused by tensile stresses are described by a contiuum model. As a measure of the damage we adopt the specific volume of the cracks, V_c. The total volume of the damaged medium is represented as the sum of the volumes of the intact material and of the cracks. The change in V_c is described by the kinetic equation[9]

$$\dot{V}_c = \begin{cases} k_1\left(\sigma - \sigma_0 \dfrac{a}{a+V_c}\right)\left(V_c + k_2\sigma^n\right), & \sigma > \sigma_0 \dfrac{a}{a+V_c} \\ 0, & \sigma < \sigma_0 \dfrac{a}{a+V_c} \end{cases},$$

where σ is that of the three principal stresses which is greatest in modulus; σ_0 is the dynamic tensile strength; and k_1, k_2, a, and n are constants to be determined experimentally. Analysis of experiments on splitting off in aluminum at submicrosecond loading times yields the following values for these constants: $k_1 = 1 \times 10^8$ G/(Pa s^2), $k_2 = 1.5 \times 10^{-3}\rho^{-1}$G/Pa^4, $\sigma_0 = 0.5$ GPa, $a = 10^{-2}\rho^{-1}$, and $n = 4$.

The stress tensor in the elastic region is calculated from Hooke's law for the relationship between the rate of strain and the rate of change of the stress deviator. The transition to plastic deformation is specified by the Mises flow condition. The increase in the yield point due to strain hardening and the decrease in the yield point due to the formation of microscopic cracks are taken into account.

We studied axisymmetric, time-varying flows corresponding to normal incidence of the dust particle on the shield. Because of the high strain levels characteristic of the initial stage of the impact, we did not use the Lagrange formalism. The hydrodynamic equations were integrated by the particle-in-a-box method in this stage,[10] but this method is inconvenient for describing the stage of mechanical damage because of the appearance of a nonphysical "diffusion" of microscopic cracks over the Euler mesh. For this reason, the calculations for the final stage of the damage, in which the strain levels in the solid phase are relatively low, were carried out in the Lagrange representation, with the results calculated by the particle method used as initial conditions.

We turn now to some of the calculated results. Figure 1 shows the state of aluminum shielding 0.5 mm thick at a time 170 ns after the impact of a dust particle with a

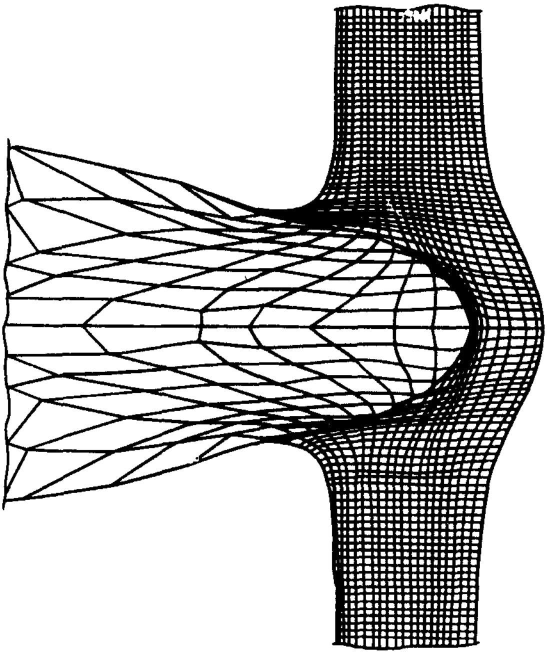

FIG. 1. The flow field caused by the impact of a particle of mass 6×10^{-7} g on an aluminum plate 0.5 mm thick.

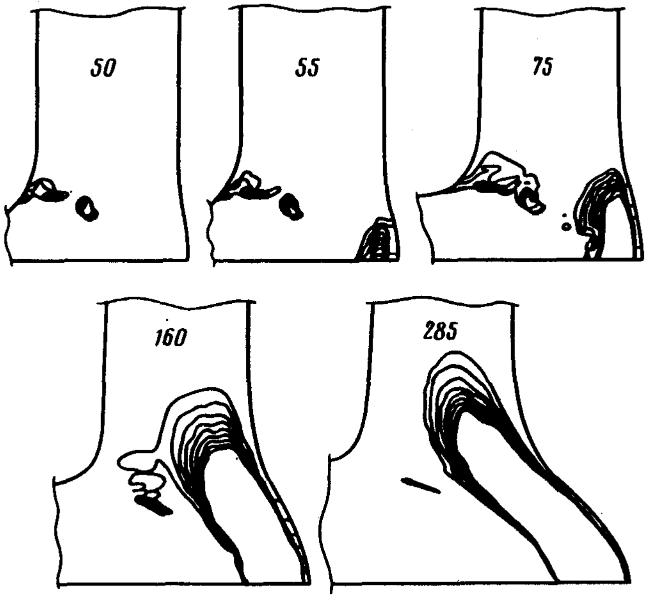

FIG. 2. Dynamics of the damage. The half of the region above the symmetry axis is shown. The mass of the particle is 6×10^{-7} g. The difference between the values of V_c on adjacent contour curves is 10^{-2}. The times shown are the times, in nanoseconds, after the time of contact.

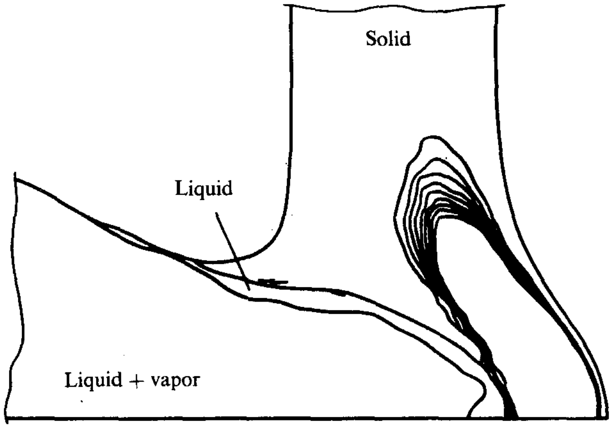

FIG. 3. Phase boundaries and curves of constant damage during the impact of a particle of mass 10^{-7} g on an aluminum plate 0.5 mm thick. The upper half of the region is shown.

density of 1 g/cm^3 and a mass of 6×10^{-7} g at a velocity of 80 km/s. The puncture process has not yet been completed in Fig. 1. A crater forms in the shielding, and a burst of ionized vapor and liquid is ejected.$^{1)}$ The rim of the crater shows a tendency toward rounding, as is observed experimentally (at lower velocities). Figure 2 shows contour curves of the degree of damage V_c = const) at various times. The damage initially occurs at the front surface of the shielding near the rim of the growing crater. After the shock wave has been emitted toward the rear surface and reflected there as a rarefaction wave, a second seat of damage arises near the rear surface on the axis of the striker. This second damaged region grows over time and transforms into a region of splitting off. For a particle of mass 6×10^{-7} g, the velocity of the pieces which split off is 1.5 km/s; their thickness is 2.5×10^{-3} cm; and their diameter is 3×10^{-2} cm. The calculations show that these split-off pieces do not cause any significant damage to aluminum shielding 1 mm thick.

It follows from the calculations that a particle mass of 10^{-7} g (at a density of 1 g/cm^3 and a velocity of 80 km/s) is near the critical level for the puncture of aluminum shielding 0.5 mm thick. Figure 3 shows positions of the phase boundaries and curves of constant damage level for this case at the time 310 ns. The partially ionized two-phase mixture, which occupies most of the volume of the ejected material, is separated from the solid phase by a thin liquid layer. In shielding 1 mm thick, a particle of mass 10^{-7} g leaves a crater 0.3 mm deep and 0.5 mm in diameter. The rear of the shielding remains undeformed. The ratio of the maximum penetration thickness to the crater depth is about two over a broad mass range of the dust particles.

The hydrodynamic calculations carried out by the method described above confirm the scaling of damage proposed in Ref. 2.

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[1)] Nonequilibrium recombination in the expanding burst of emitted material has been studied in connection with the mass spectrometry of dust particles. This process does not affect the damage to the shielding and we did not study it in the present work.

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[1] R. Reinhard, Space Missions to Halley's Comet and Related Activities, ESA Bulletin No. 29, 1982, p. 68.
[2] R. Z. Sagdeev, S. I. Anisimov, A. A. Galeev, V. D. Shapiro, and V. I. Sherchenkop, Adv. Space Res. **2**, 133 (1983).
[3] Proceedings Impact Fusion Workshop, Los Alamos Sci. Lab., Report LA-8000-C, 1979.
[4] K. H. Kreynhagen and S. H. Schuster, in: Impact and Explosion Cratering (ed. D. J. Roddy, R. O. Pepin, and R. B. Merrill), Pergamon, New York, 1977.
[5] R. Kinslow (editor), High-Velocity Impact Phenomenon, Academic, New York, 1970 (Russ. transl., Mir, Moscow, 1973).
[6] A. V. Bushman and V. E. Fortov, Usp. Fiz. Nauk **140**, 177 (1983) [Sov. Phys. Usp. (to be published)].
[7] A. V. Bushman, A. L. Ni, and V. E. Fortov, in: Uravnenie sostoyaniya v ékstremal'nykh usloviyakh (Equations of State Under Extreme Conditions), ITPMN SO Akad. Nauk SSSR, Novosibirsk, 1981, p. 3.
[8] L. V. Al'tshuler, A. V. Bushman, M. V. Zhernokletov, V. N. Zubarev, A. A. Leont'ev, and V. E. Fortov, Zh. Eksp. Teor. Fiz. **78**, 741 (1980) [Sov. Phys. JETP **51** 373 (1980)].
[9] S. G. Sugak, G. I. Kanel', *et al.*, Fiz. Goreniya Vzryva **19**, 121 (1983).
[10] F. Harlow, in: Methods in Computational Physics, Vol. 4. Applications in Hydrodynamics (ed. B. Alder, S. Fernbach, in M. Rotenberg), Academic, New York, 1964 (Russ. transl., Mir, Moscow, 1967).

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