Effect of Body Porosity on Hypervelocity Impact[1]

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An analytical and computer solution is presented of the hypervelocity impact of solid and porous bodies. Very low density micrometeoroids are found in space and some are believed to originate in comet tails. If well outgassed micro-micrometeoroids collide in the vacuum of outer space, their rough tips can usually weld from the intermolecular forces. An aggregate of these particles would form a porous micrometeoroid of the observed density. These considerations require an analytical investigation of the effect of porosity on hypervelocity impact.

A considerable amount of analytical and computer work has been performed on the hypervelocity impact of normal density materials (Bjork, 1958; Walsh, 1964). Papers describing shock propagation in solid-body, hypervelocity impacts were presented to the Academy by former members of this group (Lake, 1962; Sodek, 1963). There has been little investigation of the hypervelocity impact of porous bodies. This paper compares impacts by flat plates of solid iron and of iron with a pore volume of 50% at 118,000 ft/sec on a thick aluminum slab. This velocity is much greater than the velocity of sound in aluminum, which is 16,740 ft/sec; hence, the impact is called "hypervelocity." The problem was written in FORTRAN IV for an IBM 7040-7094 computer assembly.

Hydrodynamic Flow and Other Equations

Pressures of many megabars are generated in the hypervelocity impact; and consequently, the elastic limit and other mechanical properties of the solid may be neglected. On this basis, the assumption was made by Bjork (1958), and others after him, that the shock propagation may be calculated as a hydrodynamic shock in a nonviscous fluid. The solution in this paper was obtained from the Eulerean equations of hydrodynamic flow, additional equations and the proper boundary conditions. The three equations for hydrodynamic flow are listed as a, b and c in Fig. 1. They express the conservation of mass, the conservation of momentum and the conservation of energy, respectively. In these equations, *rho* is the specific density, u is the material flow velocity, p is the pressure, E is the total specific energy, t is the time and x is the space coordinate. Since the problem considers a thin plate impacting on a thick slab, the problem requires only one space coordinate.

There are four variables, *rho*, u, p and E, in the three equations so a fourth equation is required to obtain a solution. The propagation of the shock can be calculated, provided the equation of state is known for the medium (Bethe, 1942). Walsh, et al. (1957) have shown that the Mie-Gruneisen equation of state may be employed for the fourth equation since this relation includes the increase in entropy across the propagating shock front. Hugoniot showed that the entropy must increase across the shock front. A substitute equation of state for solid and porous materials was recently suggested by Tillotson (1962) and is given as Equation d in Fig. 1. This equation with his recommended constants was employed for the different materials in this problem.

The shock front is a discontinuity for the usual solution for propagation with a digital computer. In order to remove this discontinuity and to permit a computer solution, one technique is to introduce a pseudo-viscosity term which is added to the pressure. It replaces the jump discontinuity by a large, but continuous gradient. This technique was suggested

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a. $$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial x}(\rho u)$$

b. $$\frac{\partial(\rho u)}{\partial t} = -\frac{\partial p}{\partial x} - \frac{\partial(\rho u^2)}{\partial x}$$

c. $$\frac{\partial(\rho E)}{\partial t} = -\frac{\partial}{\partial x}(pu) - \frac{\partial}{\partial x}(\rho u E)$$

d. $$p = \left[0.5 + \frac{1.5}{\frac{E}{E_0 n^2} + 1}\right]\rho E + A\mu + B\mu^2$$

Fig. 1. Hydrodynamic flow equations and equations of state

by von Neumann and Richtmyer (1950). A relation for the dissipative term was suggested by Landshoff (1955), and it is

$$q = A_1 \operatorname{div} \vec{V}(\mid \operatorname{div} \vec{V} \mid + A_2)$$

where $\vec{V}$ is the material velocity vector, and A_1 and A_2 are constants that are found by trial. At the shock front, where there is a large gradient in the flow velocity, q has a value comparable to the peak pressure of the shock wave. Behind the front, where the flow velocity is fairly uniform with no large gradients, q has a negligible value. The pseudo-viscosity term is introduced into the flow equations of Fig. 1 by replacing p with the sum of the two terms, $p + q$. To facilitate the numerical solution with the computer, the equations are converted to the dimensionless form.

Presentation of Results

The solution for the hypervelocity impact of the porous and the solid thin plates onto a thick aluminum slab are obtained from the computer as numerical values of the variables at different instants of time during the impact. Graphical presentations are presented of the pressure, the

flow velocity, the density and the internal energy at several instants during the impact. For this linear solution of impacting solid plates, the solution in dimensionless variables may be scaled to problems with different velocities and different thicknesses of the impacting plate. The scaled solutions will be correct until the shock reaches the back face of the thin plate. The rupture of the back face of the thin, solid plate cannot be scaled. The solution with different porosities of the thin plate cannot be scaled.

The distribution of the pressure throughout the impact-affected zone is presented for specified instants of time during the impact. For the results in Fig. 2 and in subsequent figures, the heavy, dashed, vertical

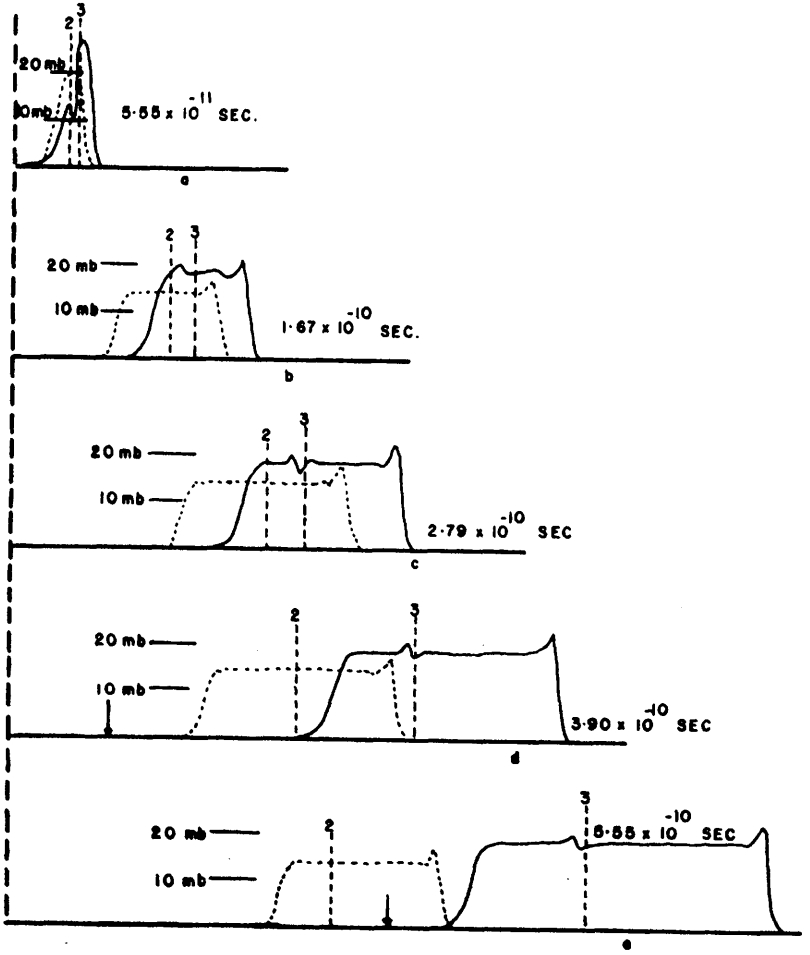

Fig. 2. Pressure profiles

line on the extreme left is the position of the interface at $t = 0$ when the plate and slab first touch. The thin iron plate is on the left and is moving to the right into the rest position of the uncompressed, stationary aluminum slab. The interface position at the indicated time on each curve is designated by 3 for the solid iron-aluminum interface and is designated by 2 for the porous iron-aluminum interface. The pressure distribution is shown solid for the solid plate and dotted for the porous plate. In next to the lowest curve, the rear faces of the porous and of the solid plate are shown by the vertical arrow. In the last curve, the arrow is for the solid plate. The porous plate has been compacted into a solid and the shock has ruptured off sections of the rear of the porous plate. The curves as a group show the more rapid penetration of the solid plate which results from its greater mass. The pressure for the solid plate impact averages about 18 megabars, while the pressure of the porous plate impact is only about 14 megabars.

After consideration of the pressure profiles, the velocity profiles do not have any unusual features. The velocity profiles are shown in Fig. 3 where dimensionless units are given for the velocity. As was stated, the velocity of approach is 118,000 ft/sec. After impact, the shock fronts to the left and right of the interface must propagate at equal speeds into the solid iron and into the solid aluminum. This material flow velocity is less for the porous plate, as a consequence of compacting the pores in the plate. The position of the shock front to the left is indicated by a rise in velocity to that of the approaching plate, and to the right by a decrease of the velocity to zero.

The density profiles are very similar to the pressure curves except for the compaction of the porous plate. The results are presented in Fig. 4. In dimensionless units, the density of aluminum is 1.0 as appears to the right of the interface and ahead of the shock front. The solid horizontal line to the left of the interface represents the normal density of iron which is 2.82 (corresponds to 7.86 g/cm^3). The profiles show the expected steep, but continuous variation of the density across the interface. The true interface is not continuous to the scale in the figure. The appearance of the continuous variation results from the insertion of the term q into the calculations.

The most significant difference between the impact of the solid and porous plates is the difference in the internal energy that is generated in the two materials. The internal energy does not include the kinetic energy, only the energy that appears as heat. The average energy content of the shock-compressed porous plate is indicated by the height of the dotted curve to the left of 2. This is to be compared with the energy content of the solid plate which is the height of the solid curve to the left of 3. As for the preceding variables, some porous material has been ruptured from the rear face of the porous plate in the lower curve (Fig. 5).

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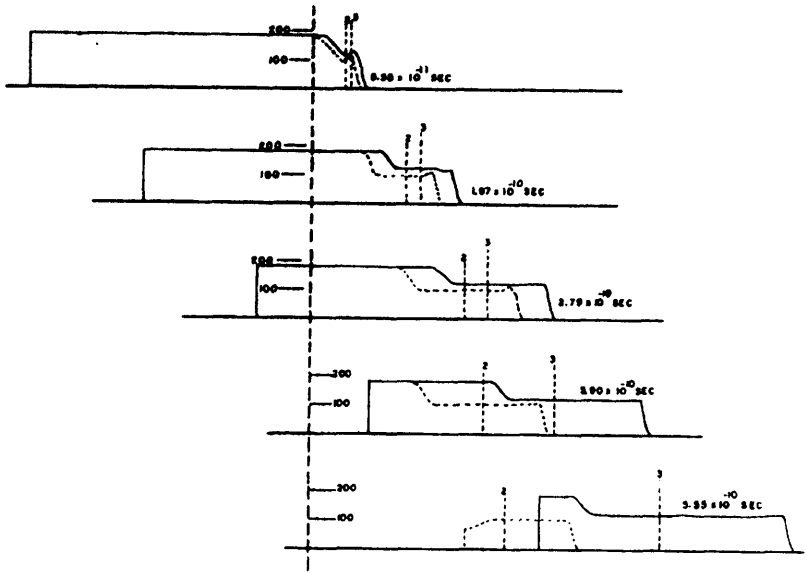

Fig. 3. Velocity profiles

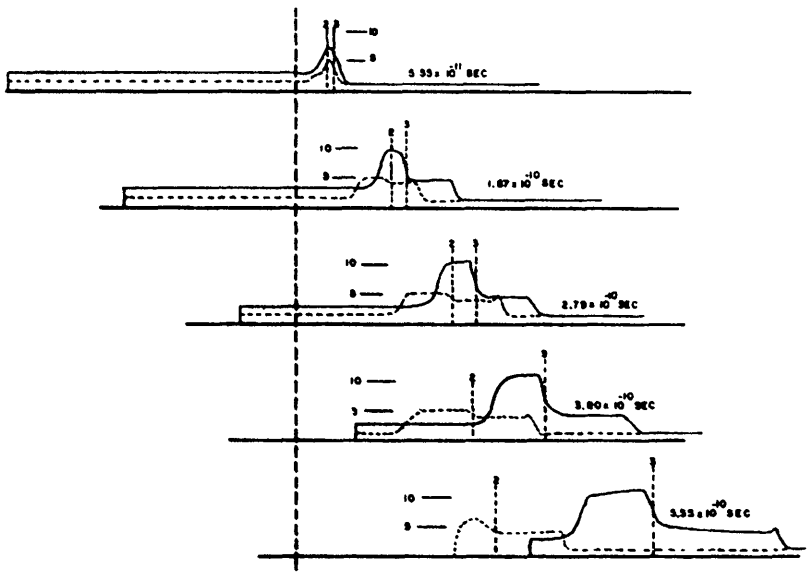

Fig. 4. Density profiles

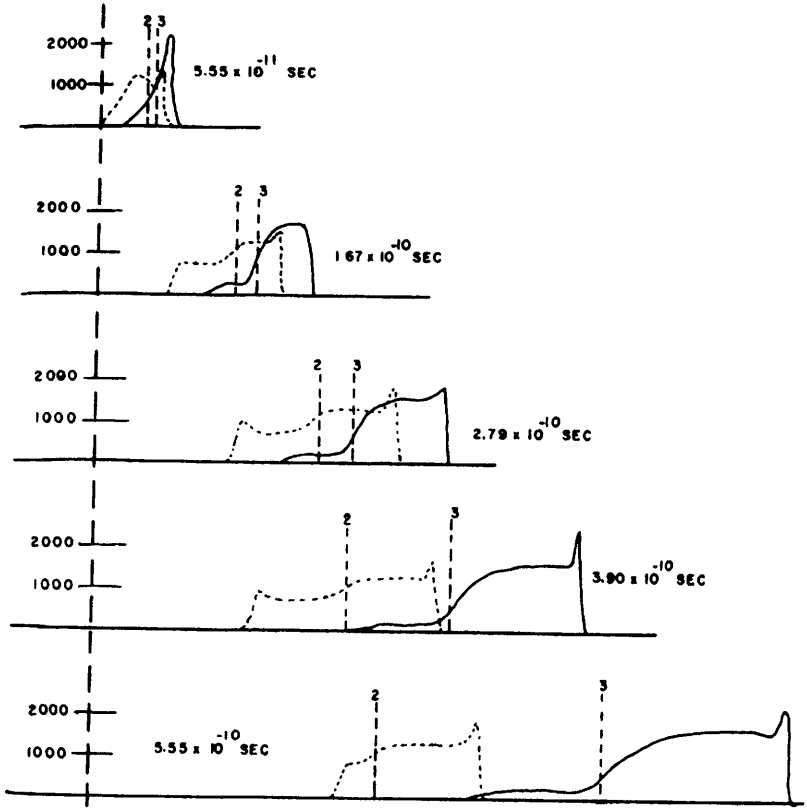

Fig. 5. Specific internal energy profiles per gram

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