CRATER FORMATION UNDER HYPERVELOCITY IMPACT

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A characteristic section of nonmonotoneity (see sketch) was detected experimentally in investigating the dependence of the ratio between the depth of penetration L and the diameter d of the impactor particle on the impact velocity v_0 in a definite velocity range [1]. This effect was observed in experiments on the impact of a steel ball on a lead obstacle (characteristic velocities $v_0 \simeq 0.7$ km/sec) and foam plastic (velocity $v_0 \simeq 7$–10 km/sec). Analogous nonmonotoneity was observed in [2]. Insofar as is known, there is yet no explanation of the effect noted.

It is shown in [3] that a meteorite intruding to earth at cosmic velocity evaporates, where total evaporation of the metal is achieved for thermal energy densities on the order of 2U, where U is the enthalpy of vapor formation. Noticeable evaporation can occur at energy densities on the order of 0.5U [4] in the presence of a free surface. The velocity of the evaporation wave is here ≈100–200 m/sec. Let us estimate the nature of the dependence of L/d on v_0 by approximately considering that all the impactor kinetic energy goes into evaporation of the impactor and the obstacle. Then a crater in the shape of a hemisphere with radius equal to the depth of penetration L should be formed because of evaporation. The crater volume is $V \simeq 2L^3 = W/U\rho_0$ (ρ_0 is the density of the obstacle material). Since $W = mv_0^2/2 \simeq d^3\rho_i v_0^2/4$, then $L/d = [\rho_i v_0^2/(8\rho_0 U)]^{1/3} = kv_0^{2/3}$ for $v_0^2 > U$ (ρ_i is the density of the impactor material). The computed dependence of L/d on v_0 is shown in Fig. 1 (curve 1) for the collision between the steel ball and the lead obstacle; experimental points are presented here [1]. In the low velocity domain $v_0 \simeq 0$–2 km/sec, there is a considerable divergence between curve 1 and the experimental points. It is caused by the following circumstances. When the kinetic energy is less than the enthalpy $W < Um$ (m is the mass of the impactor), evaporation does not occur and the depth L of the penetration is determined by plastic deformation of the obstacle material. It is related linearly to the velocity v_0 [5]:

$$L = v_0 t - \frac{1}{m}\int_0^t dt \int_0^t F\,dt - \frac{1}{\rho A c_0}\int_0^t F\,dt,$$

where F is the force; ρ, mass density; A, cross-sectional area; c_0, wave velocity; [$c_0 = (E/\rho)^{1/2}$, Young's modulus]. This L/d domain is denoted by the line 2 in Fig. 1. The transition between line 2 and curve 1 is accompanied by a change in the crater shape. If the crater shape is a truncated cone in the domain of low velocities v_0, then in the high velocity domain ($v_0 > 2$ km/sec) the crater shape is a hemisphere [2]. This phenomenon can be the reason for nonmonotoneity of the dependence of L/d on v_0. The ratio between the crater volume and the impactor mass as a function of the velocity squared v_0^2 is hence a linear dependence [2].

An analogous phenomenon (the diminution of the quantity L/d on the velocity v_0) is also detected in the impact of a steel ball on plastic foam, where the range of velocities v_0 in this case is approximately ten times higher than for the impact with the lead obstacle. Since the energy of plastic foam dissociation is of the same order of magnitude as the enthalpy of lead vapor formation (40–50 kcal/mole = 0.8 kJ/g for Pb) and the foam plastic density is two orders of magnitude lower than the density of lead, then L/d for the plastic foam is higher than for lead by approximately $(10^4)^{1/3} \simeq 20$ times, as was also observed in experiment [1].

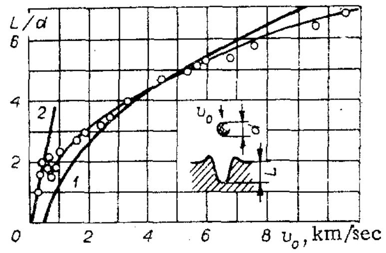

Fig. 1

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ESTIMATE OF FRAGMENT-FORMATION IN THE DESTRUCTION OF A SPHERICAL SHELL

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The study of the unsteady motion of metallic shells up to rupture under the effect of intensive loads is of practical interest. Papers of theoretical and experimental nature are known [1-5] in which the question of expansion of a spherical shell under the effect of explosive loads has been examined.

In this paper the law of the unsteady motion of a hollow sphere subjected to variable internal pressure or an initial velocity field is determined in the scheme of an isotropic incompressible viscoplastic medium. In the case of ideal plasticity the shell rupture time is determined. A formula is derived to estimate the quantity of fragments. The results obtained are compared with known experimental data.

1. Formulation of the Problem

A hollow sphere subjected to a variable internal pressure or an initial velocity field expands nonstationarily for given initial data. On the outer boundary of the sphere there is no motion. The shell material is isotropic, incompressible, and satisfies the relations of a viscoplastic medium.

For central symmetry of the sphere deformation, we have the following equations for the stress tensor components σ_r, σ_θ, σ_φ, the radial component of the velocity vector v in the spherical coordinates r, θ, φ outside the mass force field:

Equation of motion of a continuous medium

$$\frac{\partial\sigma_r}{\partial r}+\frac{1}{r}(2\sigma_r-\sigma_\theta-\sigma_\varphi)=\rho\left(\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial r}\right); \tag{1.1}$$

Continuity equation

$$\frac{\partial}{\partial r}(r^2v)=0; \tag{1.2}$$

The relationships of a viscoelastic medium [6] in spherical coordinates with central symmetry

$$\begin{gathered}\sigma_r=\sigma-\frac{2}{3}\sigma_s+\mu\frac{\partial v}{\partial r},\quad \sigma=\frac{1}{3}(\sigma_r+\sigma_\theta+\sigma_\varphi),\\ \sigma_\theta=\sigma_\varphi=\sigma+\frac{1}{3}\sigma_s+\mu\frac{v}{r}.\end{gathered} \tag{1.3}$$

Here ρ is the density of the sphere material; σ_s, dynamic yield point; μ, dynamic coefficient of viscosity; and $t \geq 0$, time.

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