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Fig. 1 and Fig. 2

Figure 1: Fig. 1 and Fig. 2

Abstract

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IMPACT OF A BODY AT HIGH VELOCITY ON ROCKS

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The paper presents the results of a study of crater formation when balls a few millimeters in size strike specimens of strong rocks, tuff, and pumice at a velocity $v_0 = 3$—11.5 km/sec (^{1}); separate experiments were carried out with sand.

At the initial stage of the process of a meteoritic impact, conditions may arise that are sufficient for evaporation of the material of the body and the target. The maximum increase in internal energy behind the shock-wave front

Fig. 1

Fig. 2

Fig. 1. 1 –hornfels, 2 –andesite, 3 –dunite, 4 –gabbro-norite, 5 –obsidian, 6 –pumice

Fig. 2. a –section of a crater in dunite; steel ball, $a_0 = 1.75$ mm, $v_0 = 7.3$ km/sec; dashed line –crater in duralumin at the same parameters.
b –sections of craters in pumice; $\rho = 0.6$ g/cm^3; steel ball; solid line $-a_0 = 1.95$ mm, $v_0 = 3$ km/sec; dashed line $-a_0 = 1.75$ mm, $v_0 = 7.3$ km/sec

at $v_0 \simeq 30$—100 km/sec is much greater than the heat of evaporation of any materials. During expansion in the rarefaction wave, the material evaporates and scatters in the gaseous state. Interaction with rarefaction waves rapidly reduces the intensity of the shock wave traveling into the target. According to (^{2}), at $v_0 \simeq 12$—15 km/sec a mass $m \simeq m_0$ evaporates (m_0 is the mass of the body); at $v_0 \simeq 100$ km/sec, $m \simeq 100\, m_0$, which corresponds to a zone of size $l \simeq 5a_0$ (a_0 is the size of the body). At $v_0 < 6$—8 km/sec, conditions for evaporation are not realized at all.

Fig. 3

Figure 2: Fig. 3

Subsequently, the motion behind the shock-wave front still substantially exceeds the strength of the target material: the flow of material leads to the beginning of crater formation (the so-called hydrodynamic stage of the process); in plastic materials (metals), a significant part of the final crater volume is formed already at comparable values of the pressure level and the target strength. Methods for estimating crater dimensions developed for plastic materials ([3—6]) do not provide information on possible crack formation and brittle fracture during the passage of waves through rock. Existing schemes simplify the phenomenon. In ([7]), the mass M of fragmented and ejected material is assumed proportional to the kinetic energy of the body E:

$$M \sim E/\varepsilon, \tag{1}$$

where ε is a quantity characterizing the strength of the crystal lattice of the target material.

In experiments with dunite, basalt, gabbro-norite, porous andesite, biotite-pyroxene hornfels, and pumice, the assumption (1) was tested. The results are given in Fig. 1: $v_1 = 3.0$ km/sec (the body is a steel ball); M_1 is the mass of rock ejected from the crater at velocity v_1, referred to unit mass of the body; M is the same at velocity v_0. The crater volume was measured by filling it with mastic. The linear dependence (1) is not observed under the conditions studied; one can speak of closeness to (1) in individual cases only to order of magnitude. For each of the rocks the form of the dependence $M/M_1 = f(v_0^2/v_1^2)$ is different.

Figures 2 and 3 show schematic sections and photographs of craters in monolithic rock. The ratio of crater depth to diameter remains constant for each of the rocks in the interval 3-11.5 km/sec. The main part of the crater volume is formed as a result of destruction of the material at the surface of the target. In the experiments, large fragments from this zone, sometimes having the form of flat spalls, remain near the crater, i.e., their ejection velocity is small. Even at $v_0 = 3$ km/sec the crater dimensions exceed the dimensions of the body by an order of magnitude. Taking into account estimates of the size of the evaporation zone (2), one may conclude that the final shape and size of the crater are determined by brittle fracture during wave processes in the target.

Fig. 3. Porous andesite. Large crater $a_0 = 1.75$ mm, $v_0 = 7.3$ km/sec; alongside it $a_0 = 1.95$ mm, $v_0 = 3.0$ km/sec. The ball is steel; on the label is a ball $\varphi 2$ mm

Analytical investigation of the dynamic stress field in the vicinity of the point of application of an impulsive load on the surface showed that the boundary of the rock-fracture zone in depth is close to the surface of a cone with inclination angle

Fig. 4. Angular distribution of fragments ejected from the crater

Figure 3: Fig. 4. Angular distribution of fragments ejected from the crater

$\varphi_0 = \arcsin(v_s/v_p)$, where v_s, v_p are, respectively, the propagation velocities of transverse and longitudinal sound waves (8, 9). For the rocks studied, $\varphi_0 \simeq$ 31-39°. Qualitatively, this corresponds to the values of 20-30° obtained in the experiments. We note that the schemes of the processes here are nevertheless quite different.

In contrast to monolithic rocks, for light, weak materials an increase in velocity is accompanied by a change in the penetration mechanism. At a comparatively low velocity the level of the pressures that develop is not high, and the material of the body can retain a compact form. A well-like cavity is formed in the target (Fig. 2b), the depth of which can be estimated from the usual assumption for hypersonic motion that the decelerating forces $F \sim v^2$ (v is the instantaneous velocity). Already at 5-6 km/sec destruction of the body and a decrease in crater depth occur. An increase in target density and a decrease in the strength of the body material (glass) reduce the value of the velocity corresponding to the change in mechanism.

In experiments with loose materials (sand), the final shape is strongly affected by slumping of the material, and the crater has the form of a shallow depression. If cohesive forces are present between the particles (for example, wet sand), a relatively deep crater is formed (depth-to-diameter ratios of order 1 are possible).

The angular distribution of fragments ejected during impact was investigated on specimens of biotite-pyroxene hornfels for $v_0 =$ 3-10 km/sec. The fragments were caught by the soft coating of a trap covering the specimen.

Three main zones of scattering have been determined (Fig. 4). The lateral ejection α_3 is formed at the final stage of crater formation, during destruction of the material at the surface, and contains about 4/5 of the entire ejected mass. The value $\alpha_3 \simeq 80^\circ$ and does not depend on v_0. It has already been indicated that the velocity of fragments in this zone is small.

The zone of cumulative splash-out α_2 is formed at the hydrodynamic stage of penetration during the flow of the materials of the body and the target. The angular width $\Delta\alpha_2 \simeq 7^\circ$. In the experiments carried out, $\alpha_2 \simeq$ 25—28° and depends only weakly on v_0, which is evidently connected with the identical inclination of the crater wall at this moment for different v_0. The fragments of this zone may be crater-forming, i.e., they move with a sufficiently high velocity. The energy of the fragments is $E_e < E$. Taking into account the mass ejected in zones α_1, α_2, from the experimental results one may obtain that no more than 5% of the entire ejected mass moves with velocity $v_e \geqslant 1$ km/sec. Measurements have shown that, at the scale of the experiment, velocities of 1-2 km/sec correspond to fragment sizes of tens of microns. In (10) it is assumed that for $v_e \geqslant 1$ km/sec, $E_e \simeq 0.3E$.

Fig. 4. Angular distribution of fragments ejected from the crater

The last of the fragment zones corresponds to the ejection of material along the normal during elastic recovery after compression. The width $2\alpha_1 \simeq 10°$. The results agree with the study of the dependence $v_e = f(\alpha)$, performed in (10) by means of high-speed motion-picture photography; the discreteness and ejection in zones α_1, α_3 were not considered in (10).

Laboratory experiments do not permit a direct comparison with data on the shape of large craters, measuring units or more kilometers (for example, on the surface of the Moon), since the scales differ by 5-6 orders of magnitude. In the final form of the crater in this case, the peculiarities of the ejection in the presence of gravitational forces will have a substantial effect. Processes of this kind were considered in (11, 12). Deviations are also possible as a result of differences in the deformation of large rock masses.

At scales close to laboratory ones, such data can be used to estimate the impact parameters and the final shape of the crater. For an impact direction close to the normal, a flat crater shape indicates monolithic rocks or possible slumping of the material (experiment shows that the picture of impact into a monolith does not change when the deviation is 40-50° from the normal). For weak rocks with cohesion between particles, relatively deep craters will be characteristic.

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Note: Figure translations are in progress. See original paper for figures.