Effect of Surface Phenomena on Target Destruction by a Multiple Impact of Solids

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An explanation is offered for elevated effectiveness of penetration of a group of solids into solid targets with a moderate velocity of a multiple impact.

Key words: multiple impact, solid, liquid phase, interface, adsorption-induced decrease in strength, tensile stress.

The effectiveness and mechanisms of explosion-induced fragmentation are still of interest for academic research and practice [1]. The collective action of macroscopic solids on targets was considered in many papers [2–8]. Various authors [5–8] performed experiments and established the facts of deeper penetration of a group of steel spheres with a diameter \( d = 5 \text{ mm} \) into Duralumin targets, as compared with penetration of an individual sphere with a “moderate” impact velocity \( u = 1.2–1.4 \text{ km/sec} \), in which case the effects of compression and heating are comparatively weak, and the main role belongs to deformation (strength) processes.

In the present paper, we try to explain the effect found from the viewpoint of the commonly known concepts [9] of surface phenomena in solids in the course of their deformation and disintegration caused by an adsorption-induced decrease in strength at the interface between the solid and liquid phases under tensile stresses.

A metallographic analysis of recovered samples reveals the presence of melted layers of thickness \( x = 5–20 \mu\text{m} \) on the walls of holes and craters in cases with individual and multiple impacts, as well as spalls and cracks up to \( l = 10–20 \mu\text{m} \). Similar traces of melting and fragmentation are observed on the projectile “surface.” Penetration of small fragments of projectiles into the targets and the presence of melted particles of the targets on the projectile surface are also noted. At the same time, the specific feature of a multiple impact is the presence of developed side cracks up to 1 mm long and gaps (≈ 1 mm) between the active surface of the projectile and the crater bottom, which are 3 to 5 times greater than the corresponding gaps after individual impacts. The measurements showed that the microhardness on the hole and crater walls is noticeably higher than far from the regions of penetration of the spheres.

The experimental data obtained show that there are simultaneous competing deformation processes [10] of shear hardening (changes in microhardness) and separated embrittlement (spalls and cracks) of the target material. The estimates [8] of characteristic times of thermal wave propagation, based on the thickness of the melted layers (upper estimates of the melting time) \( \tau = x^2/4\chi = 0.1–1.6 \mu\text{sec} \) (\( \chi = \alpha/\rho c_p \) is the thermal diffusivity of the medium, \( \alpha \) is the thermal conductivity, \( \rho \) is the density, and \( c_p \) is the specific heat) and the characteristic scale of time needed for the spheres to penetrate at the initial stage of the impact \( d/u = 3.6–3.8 \mu\text{sec} \) show that the processes of melting in thin layers caused by shear flows of the medium in small spatial scales and proceeding identically under an individual impact and under a multiple impact act as “seeds” for macroscopic destruction of the medium and penetration of the projectile to a significant depth. Under a multiple impact, interaction of stress waves generated by the solids reduces the material resistance owing to the development of original defects; hence, the projectiles penetrate to a greater depth than in the case of an individual solid.

In view of the idea [9] on adsorption-induced reduction of strength (Rebinder effect), the experimental facts [5–8] of melting of the target material, formation of spalls and cracks on hole and crater surfaces, and elevated effectiveness of penetration of a group of “interacting” projectiles testify that the examined process...
of a multiple impact of solids on targets may be affected by the contact of the solid phase with its own melt and a corresponding substantial decrease in free surface energy $\sigma$ at the interface (and, correspondingly, the work of formation of a new surface). The accompanying decrease in strength (embrittlement) of the solid phase leads to initial acts of disintegration on material defects (dislocations, admixtures, grain boundaries, etc.). Tensile stresses lead to irreversible development of these “starting points” of disintegration. The sources of tensile stresses are both the “neighboring” projectiles and the free surfaces of craters generated by these projectiles (stress concentrators). The presence of a competing process of shear (plastic) hardening of the penetrated medium restricts the depth of penetration into “thick” targets, e.g., owing to re-crystallization leading to a noticeable increase in microhardness of the target ahead of the projectile (see [7]).

The estimates made on the basis of relations and data of [9, 11] show that the specific free surface energy $\sigma_{sl}$ for aluminum on the chemically uniform interface between the solid phase and the melt is much smaller than the specific free surface energy $\sigma_1$ of the liquid phase: $\sigma_{sl} \leq \sigma_1 (Q_m/Q_e)$. Here $Q_m$ and $Q_e$ are the changes in energy during melting and evaporation, respectively. Hence, we obtain $\sigma_{sl} \leq 26 \text{ mJ/m}^2$, which is approximately 44 times smaller than the specific free surface energy of solid Al equal to $\sigma_0 = 1140 \text{ mJ/m}^2$. The critical value of tensile stresses in the target, which is determined from the critical condition of equality of the released volume elastic energy stored in the solid and the energy absorbed for the free surface to be formed and is estimated [9] as $p_{ct} \approx (G\sigma_{sl}/l)^{1/2} \approx 10^7 \text{ Pa}$ ($G$ is the shear modulus and $l \approx 10^{-5} \text{ m}$ is the characteristic size of spalls and cracks observed), is approximately two orders of magnitude smaller than the amplitude of waves of elastic stresses generated on the crater surface by the neighboring projectiles, which was estimated in [4] as $p_{max} \approx 10^9 \text{ Pa}$. The above-mentioned interaction of elastic stress waves generated by a multiple impact can lead to an even greater excess of the amplitude of tensile stresses over the critical value $p_{ct}$. Under conditions of brittle fracture of the solid phase, this can lead to a noticeable decrease in the Griffith strength (resistance) $P$, as compared with the initial strength $P_0$: $P/P_0 = (\sigma_{sl}/\sigma_0)^{1/2} \approx 0.15$, i.e., approximately by a factor of 6.6. In accordance with the generalized hydrodynamic model of penetration [12], which takes into account the effect of strength at impact velocities of $\approx 1 \text{ km/sec}$, the depth of the crater in a thick target $z \propto (P)^{-1/6}$ increases by a factor of $\approx 1.4$. In the experiments of [5–8], the relative penetration depth under a multiple impact averaged over 12 measurements $(z)/d = 3.6$ (with a root-mean-square deviation of $\pm 0.1$) is $\approx 1.6$ times the relative penetration depth $z/d = 2.2$ owing to an individual impact under the test conditions described. If we substitute the microhardness of the target material ahead of the decelerated sphere $H \approx 2 \text{ GPa}$ as the medium resistance $P$ in the generalized formula [12] $z/d = (\rho_p a^2/P)^{1/6} \sqrt{\rho_p/\rho_0}$ ($\rho_p$ and $\rho_0$ are the projectile and target densities, respectively), we obtain $z/d = 2.4$ for an individual impact. If we take into account the above-estimated decrease in $P$ by a factor of 6.6, we obtain $z/d = 3.3$. The resultant values coincide within 10% with the measured relative depths of penetration under an individual and a multiple impact.

We may assume that the multiple impact process considered is an example of manifestation of the Re-binder effect under favorable conditions [9]. In this case, polycrystalline metal is subjected to dynamic loading, which generates a complicated stress state with high concentrations of intense shear and tensile stresses under multiple impacts with velocities that ensure formation of thin layers of a surface-active medium: melt on the crater walls and on the projectile surface.

**REFERENCES**