

A shock-wave model of the effect of superdeep penetration of powder particles into metallic materials*

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A shock-wave model of the effect of superdeep penetration of explosion accelerated powder particles into metallic materials has been created. A criterion for the phenomenon proceeding by explosive loading of a target by a flow of particles is obtained. It is established that a flow action results in an homogeneous radial stretching of the target material. The stretching occurs by mobile cavities which carry particles into the target material.

Key words: *superdeep penetration; shock waves; explosive loading; powder particles*

1. Introduction

Under special conditions of loading, a small part of the torrent of explosion accelerated dispersed powder particles can penetrate into metal barriers. The depth of their penetration exceeds the size of the particles by 100–1000 times. The phenomenon is known as superdeep penetration (SDP). For “traditional” penetration, the relation of the depth to the diameter of the particles does not exceed 10. The conditions necessary for SDP are: particle speed greater than 300 m/s, particle size less than 500 μm , loading time over 100 ms, and an average torrent density of more than 10^3 kg/m^3 [1].

The equipment used in experiments with superdeep penetration is shown in Fig. 1. The charge of explosive substance 1 is detonated by means of the detonator 2. The powder 3 is located in a focusing lens 4. The discoverers of the phenomenon [1] empirically estimated an optimum form of the lens for achieving the superdeep penetration. The lens forms a homogenous flow of powder particles, flying at a speed of 500–1000 m/s. The diameter of the flow is approximately 50 mm. An aluminum plate 5 holds the powder

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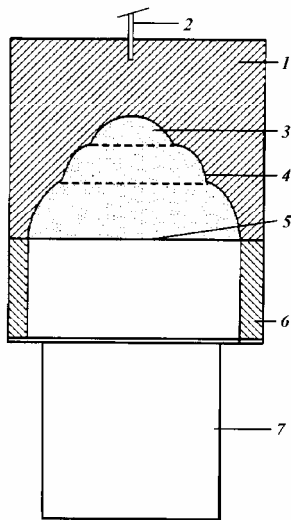


Fig. 1. Scheme of the experimental equipment

in the lens until the explosive charge detonates. The distance from plate 5 to the target 7 is adjusted by the height of the support 6. An all-metal sample or cartridge containing several samples usually forms the target. The majority of the particles do not penetrate the target – about 99% of the powder will stay on the surface and only 1% of particles will achieve the superdeep penetration. These particles can move in the target material. The length of the motion is tens of millimetres [1].

At present there is no theory of the physical nature of SDP. The purpose of this work was to construct a physical model of the phenomenon, to prove empirically the estimated conditions of superdeep penetration, and to answer the following questions:

1. Why does SDP occur only with a dense flow of particles? SDP never occurs for a lonely particle.
2. Why does not the superdeep penetration occur with large (more than 500 μm) particles?
3. How do low-strength particles penetrate into high-strength targets?

The existing models contain the assumption that the toughness of a particle exceeds the toughness of the target. According to these models, the particle can “resist” external influence, such as a cumulative jet [2].

2. Results

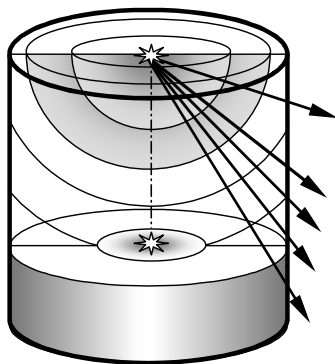


Fig. 2. “Spreading” of a cylindrical target

The model of the phenomenon put forward in this note is based on the shock-wave description of the interaction between a particle and a target material. When a particle strikes the surface of a cylindrical target (Fig. 2), an un-convergent shock wave appears in the target material. The wave carries the substance of the target. In the place where the particle hits the surface of the target, a crater is formed, its diameter being approximately equal to the diameter of the particle. The deformation of the target occurs, but the volume of the substance is constant. The target “spreads” as is shown in Fig. 2.

It is shown that the field of distortion of a substance in the target is a Coulombian field. The generalization from a single particle to a flow using the appropriate integrated equation allows the curve of the radial dependence of the deformation $\varepsilon^{(r)}$ of a cylindrical target (Fig. 3) to be drawn. Inside the area covered by the flow of particles

$$\varepsilon^{(r)} = \text{const}$$

outside this area

$$\varepsilon^{(r)} = -2\pi \frac{\sigma R_p^2}{r^2}$$

where R_p is the radius of the area covered by the flow, σ is the constant of the density distribution of particles.

In Figure 3, it is shown that the integrated field of a stress created in the target by a flow of particles results in a radial deformation of the material. In the area covered by the flow ($r < R_p$), this deformation is caused by homogeneous radial stretching. Outside the flow there is a radial compression. The compression is inversely proportional to the distance squared (Fig. 2). The extent of deformation is determined only by the physical characteristics of the flow and target, and does not depend on the size of particles. The field of stress created by a flow of particles is inhomogeneous, because each strike of a separate particle on the surface of the target has a discrete influence resulting in fluctuations of the stress field. The characteristic time τ of this process (the time during which stress at any point in the target is nearly constant) is approximately 10^{-7} s for particles with the diameter $d_0 = 100 \mu\text{m}$. In such dynamically varied conditions, the deformation of the target is basically elastic. The relaxation of the stretching stresses occurs by means of fractures in the target material. Thus, the homogeneous radial stretching of the target in the field of a flow means that cavity formation decreases the average density of the material. The lifetime of a cavity $\tilde{\tau}$ is the interval between the moment of its opening and closing. This time is about 10^{-6} s. During loading, the stress situation in the depth of the target is the same as on the surface, but there is a time delay corresponding to the limitations of shock-wave velocity c (approximately equal the velocity of sound, because the shock wave is not powerful). Thus the point of closing follows the point of opening into the target.

The movement of a cavity is shown in Fig. 4. The plane (X, Y) in a Cartesian system of coordinates is connected with the surface of the target ($Z = 0$). Assuming that at the point ($X_1, Y_1, 0$) and at the moment $t = t_0$ the conditions were most favourable for the formation of a cavity, the situation will be repeated at the point (X_1, Y_1, Z) and time $t_0 + Z/c$. Thus, the disclosing point of the channel will move along the Z axis with the

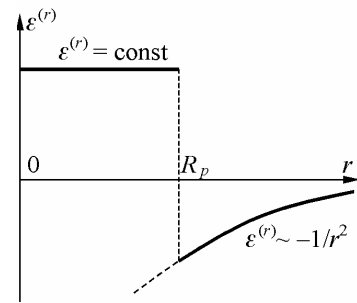


Fig. 3. Radial dependence of deformation.
 R_p is the boundary of the flow

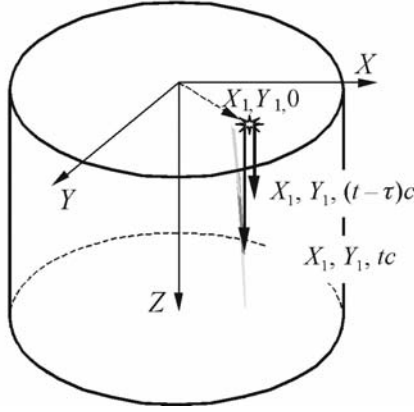


Fig. 4. Motion of a cavity ("transport capsule")

velocity of sound c . If at time $t = t_0 + \tilde{\tau}$ the conditions at the point $(X_1, Y_1, 0)$ become unfavourable, the channel will close. The same situation will be observed at the point (X_1, Y_1, Z) and moment $t_0 + \tilde{\tau} + Z/c$. Hence, the point of closing follows the point of disclosing at a distance of $c\tilde{\tau}$ (the length of the cavity). The mobile cavities (transport capsules) carry particles inside the barrier. For $\tilde{\tau}$ of the order of 10^{-6} s, the length of a capsule is approximately 5 mm. If a particle is located in the capsule, it will be transported inside the target. Thus, the movement of a transport capsule can be accompanied by cumulative jets [2, 3] or high-speed fracturing of the material [4, 5]. The particle located in the capsule can be crushed [6]. Within the framework of the shock-wave performance, these effects are secondary, because the particle does not participate in the creation of its own capsule. The transported particle passively enters a capsule and does not spend energy on punching the material.

The diameter of capsules depends on the depth:

$$\delta(L)/\delta|_{L=0} = \sqrt{\frac{\Delta R(L)}{\Delta R|_{L=0}}} = \left(\frac{R^2}{R^2 + L^2} \right)^{3/4} = \left(\frac{1}{1 + \xi^2} \right)^{3/4}$$

where L is the depth, R is the radius of the target, $\xi = L/R$ is the relative depth.

The following criterion for SDP is obtained:

$$\frac{4\pi}{3} \sqrt[3]{\frac{1}{c} \frac{h}{\Delta t}} > 1$$

where h is the thickness of a layer of particles in the explosive accelerator (lens 4 in Fig. 1), Δt is the duration of loading, c is the velocity of sound. In the real experiment, h and Δt are not independent. An increase in h results in an increase in the flow length of particles, therefore Δt will also increase. Actually, the value of $h/\Delta t$ characterizes the density of the flow of particles.

3. Conclusions

- According to the established criterion for SDP, the penetration of particles into metallic materials can occur under the condition that $h/\Delta t > 5 \times 10^{-2}$, which corre-

sponds to the particle flow density of $\rho \geq 1 \text{ g/(s}\cdot\text{m}^3)$. The penetration of particles at a flow density less than $1 \text{ g/(s}\cdot\text{m}^3)$ is impossible.

- The characteristic time of fluctuations τ is proportional to the size of particles d_0 . If the diameter of a particle is larger than $500 \text{ }\mu\text{m}$, the value of τ will be of the order of 10^{-6} . This value exceeds the time of plastic relaxation for the majority of metals. In this case, the target is deformed plastically and transport capsules do not arise.

- Within the framework of the model offered, the toughness of particles does not play a significant role, because transport capsules can even carry liquids inside the target.

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