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DEPENDENCE OF THE SUPERDEEP-PENETRATION EFFICIENCY ON THE ENERGY PARAMETERS OF AN EXPLOSIVE ACCELERATOR OF POWDER PARTICLES

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The dependence of the superdeep-penetration efficiency on the energy parameters of the particle flux loading an obstacle has been established.

The assumption that superdeep penetration depends on the parameters of loading, i.e., on the characteristics of an accelerator of powder particles, was made long ago [1, 2]. However, it has become possible to verify it only at the present time when a reliable method of experimental determination of the superdeep-penetration efficiency has been devised [3, 4] and the program to calculate the parameters of the gas-powder flux in an explosive accelerator has been developed (Fig. 1) [5, 6]. To change the parameters of the particle flux one varied only one characteristic of the acceleration scheme — the height of the regulating support H. The program described in [5, 6] made it possible to determine the manner in which the parameters of the flux (its energy characteristics, first of all) change at the level of the obstacle surface. These data are presented graphically in Fig. 2, from which it is clear that the maximum quantity of energy is transferred by the particle flux to the obstacle at $H \sim 90$–105 mm. At the same time, a series of experiments was carried out by the assembled-specimen method [3, 4] at different values of H equal to 6, 45, 90, 180, and 270 mm. The assembled-specimen method has been modified somewhat in comparison with [3]. A powder of electrolytic bronze with a mean diameter of the particles of $d \sim 55$ μm was used for the experiments. Electrolytic bronze has a pronounced spherical shape; it is sufficiently hard and contrasts well in color with aluminum foil, which is important for the assembled-specimen method. Evaluating the results of the experiments, we determined the diameters of the inclusions found on the foil; their height was measured by resighting the microscope from the plane of the foil to the top of the inclusion treated. From the results of several hundred such measurements carried out in a wide range of variation of the quantities, we have constructed the curve of the relative height of the inclusion h/d as a function of the diameter d (Fig. 3). Because of this, in subsequent experiments it sufficed to measure only the transverse dimensions of the inclusions since their height could be determined from the curve (see Fig. 3), whereupon it was easy to calculate the volume of the inclusions and then the diameter of the sphere used in further calculations. If the block of foil layers positioned in the working chamber of the assembled specimen contains n layers of thickness T each, the velocity of the particle recorded on the kth foil can be estimated based on the general energy considerations. The kinetic energy of the particle (striker) after the punching of the foil

$$\frac{MU^2}{2} = \frac{MU_r^2}{2} + \Delta E\,, \qquad (1)$$

where U and U_r are the velocities before the impact and after the punching, respectively, and ΔE is the minimum energy extended on punching, including the perforation proper, the heat loss, the expenditure on forming of splinters, and so on. The investigation [7] of the punching of aluminum and steel foils of different thickness by solid strikers demonstrates that this value remains practically constant for a very wide range of variation of U and can be expressed in terms of the ballistic limit of punching $U_{\min}$ as

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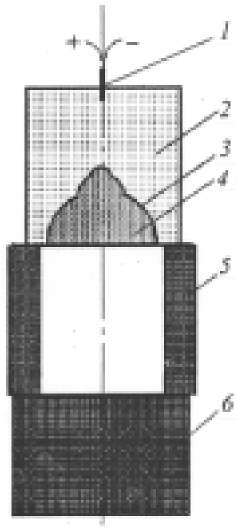
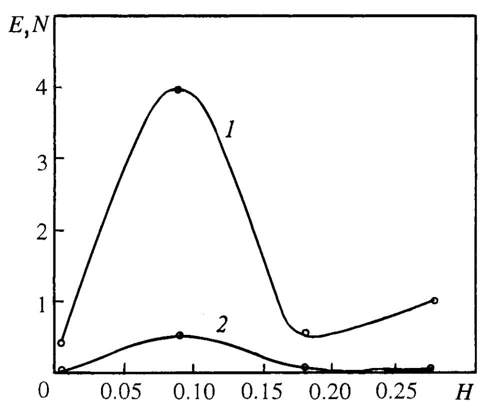


Fig. 1. Schematic diagram of an explosive accelerator: 1) electric detonation; 2) explosive charge; 3) metallic container; 4) powder fill; 5) regulating support; 6) loaded specimen.



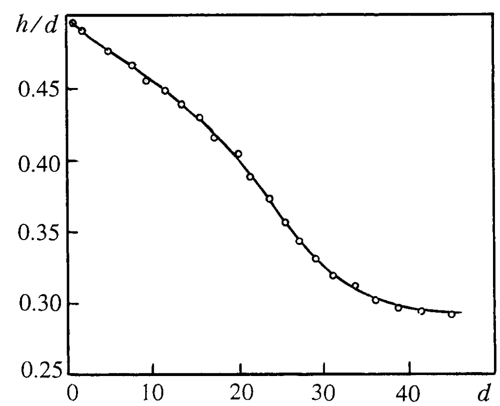


Fig. 2. Power N (10^{-4} J/mm^2·sec) and energy E (10^{-4} J/mm^2) of the flux at the level of the obstacle surface vs. height of the regulating support H (mm): 1) energy transferred to the obstacle by the flux; 2) power of the flux.

Fig. 3. Relative height of the inclusions h/d vs. diameter of the particle d (μm).

$$\Delta E = \frac{MU_{\min}^2}{2}. \tag{2}$$

In this case, the particle punching the $k - 1$ foil layers and jammed in the kth layer must have the initial velocity

$$(k-1)\,U_{\min}^2 \le U_k^2 \le kU_{\min}^2 \tag{3}$$

at a mean velocity of

$$V_k = \frac{\sqrt{k}}{2}\,U_{\min}\left(1 + \sqrt{1 - \frac{1}{k}}\right), \tag{4}$$

where $k = 1, 2, 3, \ldots, n$.

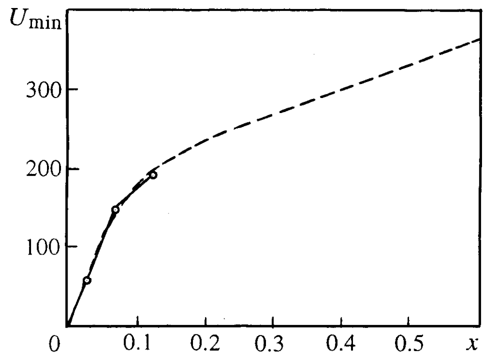


Fig. 4. Minimum rate of punching U_{min} (m/sec) vs. dimensionless parameter x (solid line); the dashed line is the analytical approximation, the points are the experiment.

The problems of determination of U_{min} can be solved both theoretically and experimentally. Data on determination of U_{min} for four cases of punching of foils of different thicknesses T by strikers having the same size, shape, and mass are presented in [6]. Moreover, it is natural that $U_{min} = 0$ for $T = 0$. Taking

$$x = \frac{\rho S T}{M}, \tag{5}$$

where S is the midsection of the striker, as the parameter characterizing the colliding objects, from the data of [6] we can construct the dependence $U_{min}(x)$ shown in Fig. 4 by the solid curve. Interpolating the experimental curve by a dependence of the type (dashed line in Fig. 4)

$$U_{min} = U_{unit}\, x^b \tag{6}$$

and assuming the validity of its extrapolation to the values $x = 2$, which limit the region of variation of x used, we can obtain the following expression for the mean velocity of the particle recorded on the surface of the kth foil:

$$V_k = \frac{\sqrt{k}}{2}\left(1 + \sqrt{1 - \frac{1}{k}}\right) U_{unit}\, x^b, \tag{7}$$

where the values of U_{unit} and b calculated from the data of [6] are equal to 460 m/sec and 0.42, respectively. The value of the velocity obtained in such a way is approximate, and dependence (6) will be refined later as new information becomes available. However, using (7), one can estimate the energy of the particle flux penetrating into the chamber of the assembled specimen:

$$E_f = \frac{\pi}{24}\rho_p U_{unit}^2 \sum_{k=1}^{n} k N_k d_k^3 x_k^{2b}\left(1 + \sqrt{1 - \frac{1}{k}}\right)^2. \tag{8}$$

where n_k and d_k are the number of particles on the kth foil and their mean diameter, respectively. The total mass of the flux is

$$M_f = \sum_{k=1}^{n} N_k M_k = \frac{\pi}{6}\rho_p \sum_{k=1}^{n} N_k d_k^3. \tag{9}$$

Thus, we have determined the main parameters characterizing the flux of particles penetrating into an obstacle to a depth corresponding to the thickness of the front layer of the specimen L_1 (total number of particles N_f equal to

TABLE 1. Mass of the Flux ($\Delta M \cdot 10^{-10}$ kg) Passing in an Assembled Specimen at a Depth of 20 and 50 mm for Different Heights of the Regulating Support H

L, mm	H, mm				
	6	45	90	180	270
20	4.921	4.911	9.17	3.922	3.667
50	1.009	1.016	1.314	0.7323	0.7051

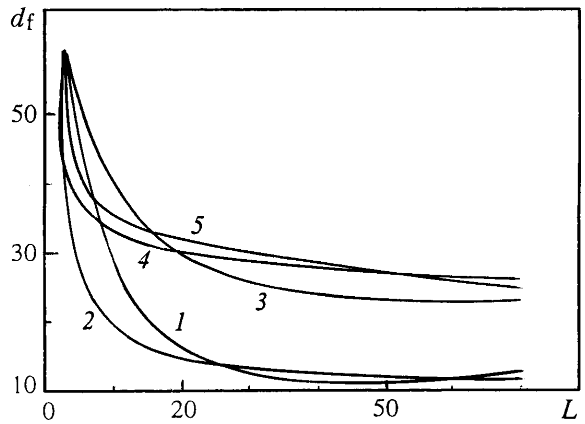


Fig. 5. Mean diameter d_f (μm) of the penetrating particles vs. thickness of the front part of the specimen L (mm) for the height of the regulating support: 1) $H = 6$, 2) 45, 3) 90, 4) 180, and 5) 270 μm.

the sum of all N_k, mass M_f, energy E_f of the flux per unit area of the treated cross section, and velocity distribution of the flux particles). The mean diameter of the flux particles is

$$d_f = \frac{1}{N_f} \sum_{k=1}^{n} N_k d_k = \frac{\sum_{k=1}^{n} N_k d_k}{\sum_{k=1}^{n} N_k} . \quad (10)$$

Having performed a series of experiments for various values of L_1, L_2, L_3, ..., one can construct the experimental dependences $E_f(y)$, $M_f(y)$, $d_f(y)$, and $N_f(y)$. Let us approximate the experimental dependence $M_f(y)$ by the curve

$$M_f(y) = M_f(0) \exp(a y^{\beta}) , \quad (11)$$

where $M_f(0)$ is the mass of the flux through the obstacle surface throughout the process of loading. The last-mentioned quantity is the entire mass of the particle flux, referred to a unit area of the treated cross section. However, the data of the numerical calculations of the parameters of the particle flux [4, 6] point to the fact that no more than 10% of the initial number of particles reach the treated surface of the obstacle because of the action of the shock waves reflected from the obstacle surface and the shielding processes. Thus, if the initial amount of material thrown by the accelerator is M_0 and the area of the treated surface is S_f, the mass of the flux per unit area is

$$M_f(0) = 0.1 \frac{M_0}{S_f} . \quad (12)$$

The meaning of $M_f(y)$ is that throughout the process the flux of the implanted material of corresponding mass passes through a unit area of the cross section at a depth y. It changes in a thin layer of the obstacle dy as

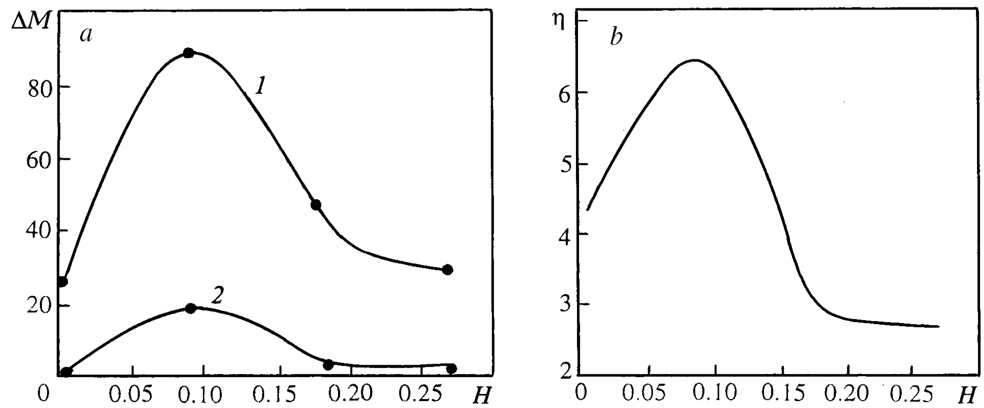


Fig. 6. Mass of the flux ΔM (10^{-11} kg) passed through a cross section of 20 mm (1) and 50 mm (2) (a) and superdeep-penetration efficiency η (10^{-6} %) (b) vs. height of the regulating support H (mm).

$$dM\,(y) = \frac{dM_f}{dy}\,dy = a\beta\, y^{\beta-1} M_f\,(0)\,\exp\,(ay^{\beta})\,dy\,, \tag{13}$$

and the mass concentration of the material (in dimensionless units) is

$$c\,(y) = -\frac{dM\,(y)}{\rho L dy} = -\frac{a\beta M_f\,(0)}{\rho L}\,y^{\beta-1}\exp\,(ay^{\beta}) = -\frac{a\beta M_0 y^{\beta-1}}{10\rho L S_f}\exp\,(ay^{\beta})\,. \tag{14}$$

Here and hereinafter y denotes the running penetration depth referred to the largest thickness of the front part of the specimen. The amount of material implanted between the cross sections L_{min} and L_{max} per unit of the treated surface area is

$$\Delta M = M\,(L_{min}) - M\,(L_{max})\,. \tag{15}$$

Thus, on condition that a series of experiments is carried out with specimens having different thicknesses of the front part and the data obtained are statistically processed in the required way, the assembled-specimen method makes it possible to obtain extensive quantitative and qualitative information on the results of realization of the superdeep-penetration effect. The efficiency of the penetration process is determined as

$$\eta = \frac{\Delta M}{M_0}\cdot 100\%\,. \tag{16}$$

In the course of the verification, we carried out a series of experiments with regulating supports of length 6, 45, 90, 180, and 270 mm in specimens with a front-part thickness of 20 and 50 mm. In each of them, we blocked 15 layers of an aluminum foil of thickness $T = 10$ μm. Particles were counted on an optical microscope with a 600× magnification; the transverse dimensions were determined by the microscope grid accurate to 0.5 μm. Then, we calculated the volume and mass of the penetrating flux by the above-described method. The results of these measurements are presented in Table 1. The data on a change in the mean diameter of particles and the mass of the flux for different H are presented in Figs. 5 and 6a. The superdeep-penetration efficiency as a function of the height of the regulating support is presented in Fig. 6b. When Fig. 2 is compared to Fig. 6, it is seen that to the maximum quantity of energy transferred to the obstacle by the flux corresponds the maximum efficiency of the process and the maximum amount of implanted material, which conforms with the assumptions made in [1, 2].

Thus, in the case of superdeep penetration, the larger the quantity of energy transferred to the obstacle, the larger the amount of material implanted into it.

NOTATION

V, mean velocity of the particles (strikers) after the punching of the foil, m/sec; U_{min}, minimum rate of punching, m/sec; *h*, height of the inclusions, μm; *H*, height of the regulating support, m; *n*, total number of foil layers in the block; *d* and d_k, diameter of the particle and its mean value, μm; *M*, mass of the particle, kg; M_0, initial mass of the powder in the fill of the accelerator, kg; *x*, dimensionless parameter characterizing the colliding objects; *y*, running penetration depth referred to the largest thickness of the front part of the assembled specimen, dimensionless parameter; M_f, mass of the flux through the cross section *f*, kg; N_f, total number of particles penetrating through the obstacle; *T*, thickness of the foil, μm; *c* (*y*), mass concentration of the implanted material in the cross section *y*, dimensionless parameter; *L*, thickness of the front part of the specimen, mm; η, superdeep-penetration efficiency, %; α, β, approximation coefficients; ρ, density of the foil, kg/m^3; ρ_p, density of the inclusion particle, kg/m^3. Subscripts: unit, coefficient in the approximation of the minimum rate of punching; *k*, ordinal number of a foil layer in the chamber of the assembled specimen; f, free surface of the foil; *r*, value of the parameter after the punching of the foil; min, minimum level of change of the parameter; max, maximum; 1, 2, and 3, ordinal numbers of the experimental thickness of the front layer.

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