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MULTIFACTOR EXPERIMENTS UNDER SUPERDEEP-PENETRATION CONDITIONS

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Consideration is given to the possibility of controlling the efficiency of the process of superdeep penetration of a high-velocity microstriker flux into metal obstacles due to the employment of ballast elements in the jet and to additional supply of energy in compression by an explosive charge along the external perimeter.

In outer space and high atmospheric layers, dust bunches collide with artificial metal objects. Such impact interactions were calculated earlier according to the models applied to macroimpact. The inefficiency of such an approach has been proved at present. In experiments with collision velocities of 300–3000 m/sec, one has recorded punching of steel obstacles of thickness 200 mm and of copper obstacles of thickness 60 mm. The existence of a specific region of interaction (the so-called superdeep penetration) has been established within the framework of which the efficiency of punching of metals by microparticles is many orders of magnitude higher than that of the efficiency of punching by macrobodies. Conditions under which the process of superdeep penetration is implemented have been determined in [1]. The particle size must be 10–500 μm, the velocity must be 500–2500 m/sec, and the time of action must be 100–400 μsec. Particles are accelerated by an explosive accelerator. The advanced action of shock waves creates in the target material conditions necessary for penetration of a small fraction (~1%) of accelerated particles, which, penetrating into the obstacle material, form a system of discontinuous partially collapsed channels in it. Thus, the effects observed on microimpact showed the need for special investigations on determination of the actual characteristics of the obstacle material in the range of superdeep-penetration regimes. Practical interest in this field of interaction of bodies is based on the necessity of shielding space modules with equipment and crew in the upper atmosphere and in outer space.

Formulation of the Problem and Results of the Investigation. The present work seeks to study microstructural changes produced by different regimes of shock-wave loading. The dynamic treatment was carried out according to the standard scheme [1] for the following parameters: particle velocity 700 m/sec, time of action ~400 μsec, obstacle material 40 steel, and microstriker material SiC powder with a fraction of 63–70 μm. To reveal the possibility of controlling the superdeep-penetration process due to the dynamic factors we carried out the following versions of treatment:

I. Standard acceleration of the flux of silicon-carbide microparticles by a cumulative explosive accelerator (single-factor process).

II. Standard version I with superposition of the synchronized explosive compression by an explosive charge; the loading time in superdeep penetration is ~400 μsec and the compression time is ~20 μsec (two-factor process).

III. Standard version I with introduction of 10% of the mass of ballast elements (steel scales ~400 μm in size) into the flux (two-factor process).

IV. Standard version I with simultaneous introduction of ballast elements and compression of the obstacle (three-factor process).

After the treatment, the samples of 40 steel were cut along the axis of loading, and the presence of defects in the structure of metallographic sections was determined according to the existing procedure [2].

The results of change in the presence of defects in superdeep penetration without additional factors (I) were taken as the standard values. When versions II, III, and IV were employed, the parameters recorded were compared to the standard values (see Table 1).

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TABLE 1. Results of a Quantitative Metallographic Analysis

Version of treatment	h, mm	d, μm	N, mm^{-2}	C, %
I	3.5–58	5.4	299	0.6844
II	3–45	1.957	534.5	0.1606
III	3.5–58	6.12	590	1.7803
IV	14–51	3.042	704.8	0.512

Discussion of Investigation Results. The analysis of the results obtained is based on the following model ideas of the causality of superdeep penetration proposed by the authors of the present work on the basis of generalization of theoretical and experimental investigations [1–4].

The process of superdeep penetration of microstrikers occurs in narrow deep zones throughout the obstacle volume where conditions sufficient for the phase transition are created because of the superposition of pressure fields. The energy level in these zones is $\sim 10^{10}$ J/m^3. There are no fully adequate explanations at present for dynamically stable energy fluctuations in the system microstriker flux–metal obstacle. We can assume that this is a result of the distribution of shock-wave disturbances, the complex pattern of which arises from the reflections (coincident in time) from the lateral and rear surfaces of the treated sample and from the waves generated in collision of the microstriker flux with the obstacle and in collapse and opening of numerous channel structures in the material volume. Nonetheless, the presence of the experimentally recorded results of phase transformation [3] casts no doubt on the implementation of such an anomalous pattern of energy distribution.

Parameters of dynamic phase transitions can be determined from the structural changes of the obstacle material. Intense deformation processes leading to a stable destructurized state of a substance are implemented against the background of a high local pressure. These conditions exactly correspond to requirements necessary for the "superplasticity" state to occur. Such a possibility was considered earlier just as a theoretically attainable one. Sharply defined zones differing from the remaining mass of the metal in etching color, higher-than-average hardness, and structure arise in the sample from the shock-wave loading.

The microstructure of a composite produced in dynamic loading is formed at a pressure necessary for the beginning of phase transition. We selected iron for which the pressure of dynamic phase transition is 12 GPa as the standard for calculations. For iron, the Hugoniot curve determining the specific volume as a function of the impact pressure shows a bend at 12 GPa and 298 K. This bend results from a sharp change in the compressibility or the specific volume and is attributed to the transition from the body-centered cubic lattice of the α phase to a close-packed, face-centered cubic lattice of the γ phase.

Much of the material subjected to phase transformation is removed due to the ejection of forward and backward jets in collapse of numerous channels. Taking into account that the process of superdeep penetration occurs in the volume of a metal matrix and the time of its manifestation is no longer than the time of loading of the obstacle by the flux, i.e., hundreds of microseconds, restoration of the initial slightly defective state of the material of the channel zone by diffusion is unlikely. Removal of the defect material due to the ejection of forward and backward jets in collapse of numerous channels seems more reliable [2]. When a striker particle traverses the high-energy material zone, experiencing phase transformation, we have the removal of the matrix substance, which is in the plasma state at that moment. Thus, there are many channels in the system that operate asynchronously in the period of loading. During the pulsation of channel formations due to the successive ejection of forward and backward jets, the pressure fields between them are exchanged.

A new superplastic state of the material is formed as a result of dynamic loading only due to the energy of the striker flux. The authors think it appropriate to obviously minimize the expenditure of energy on mass transfer and form change in calculations.

Thus, the metallographic pattern of distribution of defects in the obstacle volume reflects the set of actual processes occurring in superdeep penetration. The errors in employing such an approach can arise due to the inaccurate determination of the experimental pattern of distribution of defects. As the procedures for recording defects and the set of statistical information are improved, the level of possible errors will constantly decrease (due to the allowance for the background defect state, among other things). At the present stage, such an approach enables us to efficiently consider the process of superdeep penetration under actual loading conditions. It turns out to be legitimate in comparing successively experimental results.

Let us consider the relations of structural changes

$$\frac{d_1}{d_2} = 2.76\,,\ \ \frac{N_1}{N_2} = 0.5594\,,\ \ \frac{C_1}{C_2} = 4.26\,;$$

$$\frac{d_1}{d_3} = 0.871\,,\ \ \frac{N_1}{N_3} = 0.506\,,\ \ \frac{C_1}{C_3} = 0.3866\,;$$

$$\frac{d_1}{d_4} = 1.775\,,\ \ \frac{N_1}{N_4} = 0.424\,,\ \ \frac{C_1}{C_4} = 1.3367\,;$$

$$\frac{d_3}{d_4} = 2.038\,,\ \ \frac{N_3}{N_4} = 0.8371\,,\ \ \frac{C_3}{C_4} = 3.477\,;$$

$$\frac{d_2}{d_4} = 0.6433\,,\ \ \frac{N_2}{N_4} = 0.7583\,,\ \ \frac{C_2}{C_4} = 0.3136\,.$$

In comparing the ratios

$$\frac{d_1}{d_2}\ \text{and}\ \frac{d_3}{d_4},\ \frac{N_1}{N_2}\ \text{and}\ \frac{N_3}{N_4},\ \frac{C_1}{C_2}\ \text{and}\ \frac{C_3}{C_4}$$

we observe similarity. Apparently, this is attributed to the employment of the additional technological factor, i.e., compression. Due to the increase in the number of factors, we record a decrease in the relative diameter (2.76–2.038), an increase in the relative density (0.5594–0.8371), and a decrease in the relative apparent porosity (4.26–3.477).

For the versions in which the loading energy remains constant, a comparison of the ratios also shows the presence of similarity:

$$\frac{d_2}{d_4}\ \text{and}\ \frac{d_1}{d_3},\ \frac{N_2}{N_4}\ \text{and}\ \frac{N_1}{N_3},\ \frac{C_2}{C_4}\ \text{and}\ \frac{C_1}{C_3}\,.$$

Due to the influence of the ballast elements the relative diameter decreases (with increase in the number of factors) (0.871–0.6433), relative density increases (0.506–07583), and the relative apparent porosity decreases (0.3866–0.3136).

The preliminary comparative analysis of the structural elements demonstrates that the introduction of additional factors into the process of superdeep penetration produces the characteristic relative changes. In obtaining the ratios of the structural parameters of steel which are formed in the experiment with a smaller number of factors to the structural parameters formed in the experiment with a larger number of factors, we observe a tendency toward a decrease in the relative defect diameter and apparent porosity and toward an increase in the relative density. Clearly, if the energy introduced due to the treatment in the superdeep-penetration regime is constant, the tendencies toward change in the structural elements will be the same. Consequently, only the difference in the variations of the parameters of structural defects can be attributed to the influence of the versions of treatment.

For the comparative analysis we determined the volume of the defect zone recorded in the material for the versions of treatment in question:

$$V_{\text{d1}} = 6.715\cdot10^{-7}\ \text{m}^3\,,\ \ V_{\text{d2}} = 1.1576\cdot10^{-7}\ \text{m}^3\,,\ \ V_{\text{d3}} = 17.469\cdot10^{-7}\ \text{m}^3\,,\ \ V_{\text{d4}} = 5.024\cdot10^{-7}\ \text{m}^3\,.$$

With allowance for the assumption that a quasiliquid superplastic material is formed only due to the energy of the striker flux, the total energy introduced into the obstacle due to the kinetic energy of the particle bunch is

$5.88 \cdot 10^4$ J. Hence, on the basis of the statement that we have phase transition and cumulation of energy, $V_f = A_f / P_r$, $P_r = 1.2 \cdot 10^{10}$ J/m^3, and $V_f = 0.5 \cdot 10^{-5}$ m^3. As a result, the residual mass of the material subjected to phase transformation is $M_d = V_d \rho$ in the sample:

(I) $M_{d1} = 0.525 \cdot 10^{-2}$ kg, 13.43%;
(II) $M_{d2} = 0.0906 \cdot 10^{-2}$ kg, 2.315%;
(III) $M_{d3} = 1.368 \cdot 10^{-2}$ kg, 34.94%;
(IV) $M_{d4} = 0.393 \cdot 10^{-2}$ kg, 10.05%;
$M_f = V_f = 3.915 \cdot 10^{-2}$ kg.

The following amount of mass was removed in the form of forward and backward jets:

(I) $M_{t1} = 33.9 \cdot 10^{-3}$ kg;
(II) $M_{t2} = 38.24 \cdot 10^{-3}$ kg;
(III) $M_{t3} = 25.47 \cdot 10^{-3}$ kg;
(IV) $M_{t4} = 35.22 \cdot 10^{-3}$ kg.

We evaluate the changes by the coefficient of influence of the factors on the removal of the defect mass:

$$\alpha_1 = (M_{t2} - M_{t1}) / M_{t1} = 0.128 \,, \quad \alpha_2 = (M_{t4} - M_{t3}) / M_{t1} = 0.2876 \,, \quad \alpha_3 = (M_{t2} - M_{t4}) / M_{t1} = 0.0891 \,,$$

$$\alpha_4 = (M_{t1} - M_{t3}) / M_{t1} = 0.2487 \,,$$

where α_1 and α_2 are the coefficients of influence of compression on the removal of the defect mass from the obstacle in the case of superdeep penetration in the two-factor (compression) and three-factor (compression, ballast element) processes, respectively, and α_3 and α_4 are the coefficients of influence of the ballast element on the removal of the defect mass from the obstacle in the case of superdeep penetration in the three-factor (compression, ballast element) and two-factor (ballast element) processes.

The quantities α_1 and α_2 and α_3 and α_4 reflect the influence of compression and of the ballast element on the removal of the mass. Here, α_1 and α_4 were obtained in the two-factor process of superdeep penetration and α_2 and α_3 were obtained in the three-factor process:

$$\alpha_1 \neq \alpha_2 \,, \quad \alpha_3 \neq \alpha_4 \,, \quad \alpha_1 + \alpha_4 = \alpha_2 + \alpha_3 \,.$$

The sums of the coefficients of influence on the removal of the defect mass in superdeep penetration due to compression and to the introduction of a ballast element in the two-factor and three-factor processes are equal, with the absolute values of the influence coefficients being unequal.

As a result of the superposition of additional factors on the process of superdeep penetration it becomes possible to control the processes of mass transfer and shape change of the obstacle material in real time. This enables us to state the following:

1. Introduction of additional technological factors makes it possible to influence the process of superdeep penetration in real time and to substantially change the structural parameters recorded.
2. Introduction of a ballast element and of compression by an additional explosive charge produces the characteristic relative changes in the structure, and the most significant changes are attained by additional supply of energy.
3. The sums of the coefficients of influence on the removal of the defect mass in superdeep penetration due to compression and to the introduction of ballast elements in the two-factor and three-factor processes are equal ($\alpha_1 + \alpha_4 = \alpha_2 + \alpha_3$), with the absolute values of the influence coefficients being unequal.

NOTATION

h, treatment depth; d, average diameter of the recorded defect of treatment; N, density of defects; C, recorded porosity; V_d, volume of the recorded defect mass; M_d, mass of the defect-zone material; ρ, density of the obstacle material; V_f, volume of the channel region in which phase transition was realized; P_r, pressure of initiation of phase transition; M_t, mass of the removed material. Subscripts: d, defect; f, formation; r, reorganization; t, exchange (transfer).

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