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FORMATION OF HIGH-VELOCITY MICROJETS IN DIFFERENT VARIANTS OF SUPERDEEP PENETRATION

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The process of formation of a composite material in different variants of dynamic loading of an obstacle of 40 steel by a flux of high-velocity microparticles has been considered. The influence of the loading conditions on the realization of superdeep penetration has been analyzed.

Introduction. It has been noted in the process of long flights of spacecraft that the operation of elements of computer equipment is unstable. The reason for this can be an unusual physical phenomenon — superdeep penetration (SDP) of cosmic-dust bunches through the shells of apparatuses, which has been known since 1974. When it is realized, the energy of the microimpact of a bunch is cumulated in narrow channel zones, which provides the penetration of microparticles to depths of 10^2–10^4 of their calibers [1]. It has been revealed in numerous experiments that when bunches of microparticles moving with velocities of 300–3000 m/sec bump against metal obstacles, a structure of a composite material is formed. At a depth of tens or hundreds of millimeters it is reinforced by channel zones. Microstrikers lose their mass in the process of penetration and their dimensions decrease in half. It has been established using new techniques that, as a result of the passage of a bunch of microstrikers through a metal obstacle, there arise microjets consisting of the introduced substance and the matrix material [2]. Additional investigations made it possible to detect the remains of microjets. In the central zone of a channel formation, there is a rod consisting of the introduced and matrix materials.

Discussion on the mechanism of this phenomenon is aimed at explaining the disbalance in the expenditure of energy as a result of penetration and at searching for the mechanisms that would make it possible to decrease the expenditure of energy on the static resistance of the obstacle material and the mechanisms responsible for the redistribution of the kinetic energy of the impact in the channel region.

Setting of the Experiment and Results of Investigations. In the present work, to estimate superdeep penetration we used the notion of realization of superplasticity effects under the conditions of energy cumulation and intense shear deformations. If a striker enters the zone of a material where the phase transition is not completed and its penetration causes intense plastic deformations, the resistance to penetration drops abruptly under superplasticity conditions. In our opinion, consideration of the mechanisms of superdeep penetration with regard for reconstruction of the parameters of the material as a result of the phase transition makes it possible to explain to the largest extent the experimental dependences recorded. This approach became more promising when it was proved that there exists a concentration of pressure fields in the local zones to a level orders of magnitudes higher [1] than the background pressure in the obstacle.

Since superdeep penetration is realized in the process of collision of a bunch of microparticles with an obstacle, the time of dynamic loading can be changed by varying the geometric and velocity parameters of the flux. Based on the model notions of the process of superdeep penetration [3] and the experimental quantitative information (Table 1), the authors consider the order of formation of the composite material at the level of functioning of a single channel for the following variants of dynamic loading:

I) acceleration of the flux of silicon-carbide microparticles by a cumulative explosive accelerator;

II) variant I with the imposition of synchronized explosive compression by an explosive charge (the time of loading is ~400 μsec in the case of superdeep penetration, and the time of compression is ~20 μsec);

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TABLE 1. Results of the Quantitative Metallographic Analysis

Variant of treatment	h, mm	$d_{c.m}$, μm	D, mm^{-2}	C, %	$M_d \cdot 10^{-2}$, kg	$M_t \cdot 10^{-3}$, kg
I	3.5–58	5.4	299	0.6844	0.525	33.9
II	3–45	1.957	534.5	0.1606	0.0906	38.24
III	3.5–58	6.12	590	1.7803	1.368	25.47

III) variant I with the introduction of 10% of the mass of the ballast elements (steel scales of dimension ~400 μm) into the flux;

IV) variant I with the introduction of ballast elements and compression of the obstacle at a time.

The dynamic treatment was carried out by the scheme of [4] for the following parameters: average velocity of particles 700 m/sec, time of action ≈400 μsec, obstacle material 40 steel, microstriker material SiC powder of fraction 63–70 μm. The parameters of the composite material formed are presented in Table 1.

Analysis of the Results. Let us consider the ejection of mass from a single channel and assume that it is the same in the forward and return jets in the standard variant:

$$m = \frac{M_t}{2SD} .$$

Then for variants I and II, the ejection of mass in the forward jet is

$$m_1 = \frac{M_{t1}}{2SD_1} = 2.89 \cdot 10^{-8} \text{ kg} , \quad m_2 = \frac{M_{t2}}{2SD_2} = 1.823 \cdot 10^{-8} \text{ kg} .$$

Hence it is evident that the specific ejection of mass in the forward jet decreased by 58.5%.

For variant II, the total time of the loading process is $\tau_{long} = 4 \cdot 10^{-4}$ sec and the time of compression (additional compression) is $\tau_{c.a} = 2 \cdot 10^{-5}$ sec. It follows that in the time interval $T = \tau_{long} - \tau_{c.a} = 380 \cdot 10^{-6}$ sec the process of superdeep penetration follows variant I:

$$D_1 \approx D_{2T} ; \quad d_{c.m1} \approx d_{c.m2T} ; \quad C_1 \approx C_{2T} .$$

These indices can be refined using the relations

$$D_{2T} = \frac{D_1 T}{\tau_{long}} = 284 \text{ mm}^{-2} ; \quad d_{c.m2T} = \frac{d_{c.m1} T}{\tau_{long}} = 5.13 \cdot 10^{-6} \text{ m} ; \quad C_{2T} = \frac{C_1 T}{\tau_{long}} = 0.65\% .$$

The observed deviations of the parameters in variant II relative to variant I arise within $\tau_{c.a}$:

$$\Delta D = D_2 - D_{2T} = 250.5 \text{ mm}^{-2} ; \quad \Delta d = d_{c.m2} - d_{c.m2T} = -3.173 \cdot 10^{-6} \text{ m} ; \quad \Delta C = -0.489\% .$$

According to variant I, M_{2T} mass is ejected over the period T. We introduce the specific index of ejection of the mass in the channel in a unit time:

$$\gamma_{m1} = \frac{2m_1}{\tau_{long}} = 1.445 \cdot 10^{-4} \text{ kg/sec} ,$$

then over the period T we have

$$M_{2T} = \gamma_{m1} T D_{2T} S = 30.6 \cdot 10^{-3} \text{ kg} ,$$

$$M_{2,\tau_{c.a}} = M_{t2} - M_{2T} = 7.64 \cdot 10^{-3} \text{ kg} .$$

over the period $\tau_{c.a}$ we have

$$M_{2,\tau_{c.a}} = M_{t2} - M_{2T} = 7.64 \cdot 10^{-3} \text{ kg} .$$

Thus, in the period $\tau_{c.a}$ the ejection power was $6.13 \cdot 10^{-4}$ kg/sec, which exceeds this parameter by a factor of 4.24 in the time T . Simultaneously one must take into account the fact that the mean diameter of the channel is equal to $5.13 \cdot 10^{-6}$ m in the time interval T and $1.957 \cdot 10^{-6}$ m in the period $\tau_{c.a}$. With this result, the mass ejection from a unit cross section of the channel in a unit time (kinetic head) accounts for $6.312 \cdot 10^{6}$ kg/(sec·m^2) for variant I and, for variant II, $6.99 \cdot 10^{6}$ kg/(sec·cm^2) during the action of an additional compression and $2.039 \cdot 10^{8}$ kg/(sec·cm^2) in the other periods of dynamic loading.

Let us assume that $E_s = E_t + E_{com}$:

$$E_s = \frac{M_f v_{com}^2}{2} + \frac{(M_f - M_d)\, v_t^2}{2} .$$

Hence

$$v_{com1} = \sqrt{\frac{2E_s}{3M_f - 2M_{d1}}} = 1048 \text{ m/sec} , \quad v_{t1} = 1482 \text{ m/sec} ,$$

$$E_{t1} = \frac{M_{t1} v_{t1}^2}{2} = 3.727 \cdot 10^{4} \text{ J} , \quad E_{com1} = E_s - E_{t1} = 2.153 \cdot 10^{4} \text{ J} .$$

The energy in the single channel is

$$\frac{E_s}{D_1} = \frac{E_{t1}}{D_1} + \frac{E_{com1}}{D_1} , \quad \frac{E_{t1}}{D_1} = 6.35 \cdot 10^{-2} \text{ J} , \quad \frac{E_{com1}}{D_1} = 3.66 \cdot 10^{-2} \text{ J} .$$

Taking into account the features of variant II, we introduce the specific power parameter: $\zeta = E_s / D$. For variant I we have

$$\zeta_{t1} = \frac{E_{t1}}{D_1} = 1.587 \cdot 10^{2} \text{ J/sec} , \quad \zeta_{com1} = \frac{E_{com1}}{D_1} = 0.915 \cdot 10^{2} \text{ J/sec} .$$

For variant II, we consider the process in the following order. The first stage

$$\frac{E_{1com2}}{D_1} = \zeta_{com1} T = 3.47 \cdot 10^{-2} \text{ J} , \quad \frac{E_{1t2}}{D_1} = \zeta_{t1} T = 6.03 \cdot 10^{-2} \text{ J} .$$

At the second stage, to form D_1 channels according to the standard variant it is necessary to form the volume of the high-pressure zone of mass M_f. The increase in the number of channels in the period $\tau_{c.a}$ is due to the additional compression. The mass of the high-pressure region in the interval $\tau_{c.a}$ is

$$M_{2f} = \frac{M_f D_2}{D_1} = 69.96 \cdot 10^{-3} \text{ kg} .$$

The energy necessary to restructurize this region is

$$B = \frac{M_{2f} P_r}{\zeta} = 10.586 \cdot 10^{4} \text{ J} .$$

Due to the energy of the microparticle flux, in the interval $\tau_{c.a}$ there appears the energy

$$E_{s,c.a} = \frac{E_s \tau_{c.a}}{\tau_{long}} = 0.294 \cdot 10^4 \text{ J} .$$

It may be suggested that a part of the defect zones was formed in the period T; then the energy necessary to restructurize the material in this period is equal to $8.868 \cdot 10^4$ J.

The energy of the explosive charge realized in $\tau_{c.a}$ accounts for $49.6 \cdot 10^4$ J, and the energy portion used for compression accounts for 17.87%.

The mass of the high-pressure single channel zone is

$$m_{2f} = \frac{M_{2f}}{\Delta DS} = 14.23 \cdot 10^{-8} \text{ kg} ,$$

and the mass ejected from the channels formed under the action of additional compression over the period $\tau_{c.a}$ is $1.226 \cdot 10^{-8}$ kg; channels with an ejection mass of $2.89 \cdot 10^{-9}$ kg exist at a time according to variant I.

The expenditure of energy of an additional explosive charge for one channel is as follows:

$$b_2 = \frac{B_a}{\Delta DS} = 0.1803 \text{ J} .$$

Thus, in the period $\tau_{c.a}$ the rate of compression of the channel zone is equal to 1470 m/sec and the rate of ejection of mass in the jet is 2087 m/sec.

In the variant with additional compression, as distinguished from the standard variant, the behavior of the obstacle material is more complex. At both stages there are channels acting according to variant I. At the second stage there arise simultaneously a large number of channels ejecting jets more intensely (with higher rates) through smaller cross sections. Thus, the dynamic destabilization of the obstacle material increases abruptly.

The use of ballast elements in variant III allows the assumption that the exit of the return jet will be completely blocked:

$$m_3 = \frac{M_{t3}}{SD_3} = 2.2 \cdot 10^{-8} \text{ kg} .$$

The mass ejection decreased in comparison with the two stages of variant II by a factor of 3.3 and 109.2, respectively. In this case, in variant III the compression rate will be 1142 m/sec and the rate of ejection of mass in the jet will be 1615 m/sec.

If the assumption is made that the return jet is blocked incompletely, the mass carried away by it will have a negative value.

Variant IV is analogous to variant III during the period of time $T = \tau_{long} - \tau_{c.a}$, and for $\tau_{c.a}$ the features of variant II are imposed on it. It makes sense to assume that an increase in the pressure will make it possible to unblock the frontal surface of the channels for ejection of the return jet.

If the energy introduced into the obstacle is the same in variants II and IV (this follows from the setting of the experiment), it is obvious that the difference $M_{d4} - M_{d2} = 0.3024 \cdot 10^{-2}$ kg is the result of the expenditure of energy on unblocking the channels.

According to the results of the investigations, the energy expended on ejecting mass is as follows (for variants): I) $E_1 = 291.2 \cdot 10^2$ J, II) $E_2 = 328.48 \cdot 10^2$ J, III) $E_3 = 218.78 \cdot 10^2$ J, and IV) $E_4 = 302.539 \cdot 10^2$ J.

The energy introduced into the obstacle does not exceed $E_s = E_{s1} = E_{s3} = 588 \cdot 10^2$ J for variants I and III and $E_{s2} = E_{s4} = E_s + B_a = 1474.8 \cdot 10^2$ J for variants II and IV. In this case, the energy utilization efficiency coefficient χ is as follows: $\chi_1 = 0.495$, $\chi_2 = 0.222$, $\chi_3 = 0.372$, and $\chi_4 = 0.205$. It is evident that variant I is the most efficient from the viewpoint of dynamic mass transfer.

TABLE 2. Change in the Parameters of Formation of the Structure of 40 Steel as a Function of the Initial Dimension of the Striker

$d_p \cdot 10^{-6}$, m	$d_{c.m} \cdot 10^{-6}$, m	$\sigma_{SDP} \cdot 10^{11}$, J/m^3	$M_d \cdot 10^{-3}$, kg	M_d, %	$M_t \cdot 10^{-3}$, kg	v_t, m/sec	v_{com}, m/sec	C, %	D, mm^{-2}
12.5	3.47	2.808	4.82	3.77	9.64	1460	1033	0.4915	520.83
66.5	5.44	7.5804	6.81	5.33	13.63	1482	1048	0.6949	299.14
100	4.58	11.3236	8.29	6.49	16.59	1499	1060	0.8455	513.48

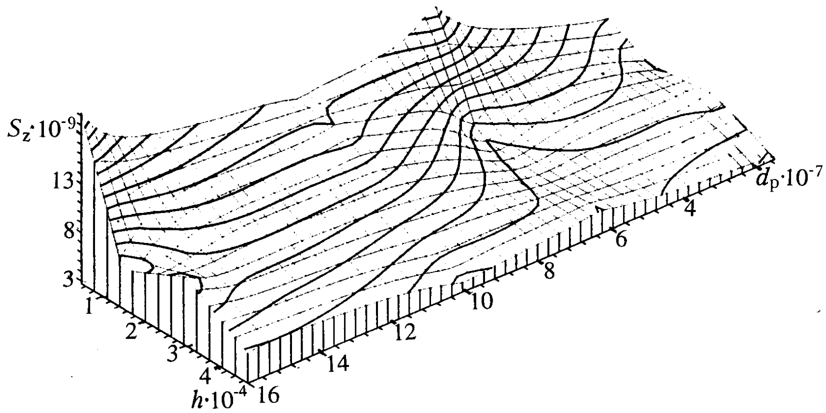

Fig. 1. Change in the parameters of formation of the structure of 40 steel as a function of the initial dimension of the striker. h and d_p, m; S_z, m^2.

In a number of investigations devoted to the study of the phenomenon of superdeep penetration, attention was repeatedly drawn to the exceptional significance of the dimensional parameters of the strikers. The peculiar sensitivity of superdeep penetration to the dimensions of the strikers manifests itself in the formation of boundaries of the region of realization of this unusual phenomenon as well as within the accepted range of conditions. The averaged results of the change in the parameters of formation of the jet and the structure of 40 steel as a function of the initial dimension of a striker are presented in Table 2 and in Fig. 1. They yield a direct relation between the changes in the apparent porosity, the residual imperfection, and the dimensions of the strikers. The totality of experimental data on the residual material in channel zones makes it possible to estimate, based on the generally accepted approach [1], the energy density in the channel region of the obstacle (Table 2). In this case, the diameter of the defect zone was taken for the finite diameter of the collapse. Such an assumption gives an obviously underestimated value of the energy density. Under the conditions considered, its maximum value is attained when strikers of dimension 100 μm are used. The obtained estimate $\sigma_{SDP} = 11.32 \cdot 10^{11}$ J/m^3 is three times larger than the analogous parameter in the case of a macroimpact. Clearly, it is impossible to predict the behavior of materials in the case of superdeep penetration on the basis of the known information on a macroimpact.

There is good reason to believe that superdeep penetration is observed in nature. The conditions necessary for its realization occur in the case of a collision of cosmic-dust bunches with artificial objects. In this case, microstrikers penetrate through metallic shells with thicknesses of tens or hundreds of millimeters. The material is ejected from an obstacle in the form of long-dimensional microjets whose action is apparently a serious hazard to apparatuses and biological objects. Study of the behavior of materials under the action of a high-velocity microparticle flux becomes pressing because of the observed instability of operation of the elements of computer equipment of spacecraft.

Clearly, the process of superdeep penetration cannot be ignored in designing protection for spacecraft. The experiments carried out must initiate a new direction in investigations in astronautics. In connection with the realization of superdeep penetration, a number of fairly complex technical problems that must be solved in designing spacecraft can be set at present. They include the following problems:

(a) calculation of the force, thermal, and physicochemical actions of microparticle fluxes on the structural elements of spacecraft (problems of strength and operational reliability);

(b) prediction of the influence of microstriker jets on the operation of spacecraft optical and computer equipment.

At the present time, study of the action of superdeep penetration on the operation of spacecraft is at the earliest stage of its development. Researchers are solving problems of the model type. The problems of interaction of microparticle fluxes with spacecraft under actual space conditions are being considered on a limited scale. The main reason is the complexity and the high cost of solution of problems of this kind. Experimental investigations involve substantial difficulties. It is not easy to carry out modeling of the distribution of cosmic-dust bunches in space under laboratory conditions. Natural experiments make it possible to simplify the modeling, but they require the solution of no less complex problems on providing measurements.

CONCLUSIONS

The process of mass transfer and forming (shaping) of the obstacle material can be controlled in real time by imposition of additional factors on the process of superdeep penetration and variation of the parameters of microstrikers. The comparison of the results of a set of experiments carried out allows the following conclusions:

1. In variant II, the absolute value of the removal of material increases. All the changes recorded (as compared to the initial variant I) are realized at the instant of additional compression, i.e., over a period no longer than 5% of the entire period of dynamic loading. Because of this, the intensity of mass ejection from the single channel in this period is 4.2 times higher than that in the standard regime.

2. In variant III, as was detected with the use of a ballast element, the channels are completely blocked on the frontal-surface side and the mass ejection is 3.3 and 109.2 times smaller than that at the first and second stages of variant II, respectively.

3. Variant IV represents a three-factor process and is to a large measure a combination of variants II and III. Its qualitative difference from variant III is the unblocking of the channels on the treated surface in the period $\tau_{c.a}$.

4. It has been shown by successive comparison that the difference in energy and mass transfer between variants II and IV is explained by the expenditure of forming energy in a time interval of $1.42 \cdot 10^{-6}$ sec as a result of compression.

5. Comparison of the energy utilization efficiency coefficients has shown that process I is the most efficient. Additional regulating processes lead to a decrease in this coefficient.

6. It is shown that at least three velocity ranges exist in a metallic obstacle: v_{com1} = 1048 m/sec, v_{t1} = 1482 m/sec; $v_{com,c.a}$ = 1470 m/sec, $v_{t,c.a}$ = 2078 m/sec; v_{com3} = 1142 m/sec, v_{t3} = 1615 m/sec, which suggests realization of large gradients of pressure, deformation, and energy at submicro-, micro-, and macrolevels.

7. Consideration of the problems in designing protection for spacecraft in the context of the existence of the superdeep-penetration effect requires taking into account the dynamic characteristics of the materials in the range of energy densities of 10^{10} to 10^{18} J/m^3.

8. It has been established that the maximum efficiency of the superdeep-penetration process is attained with microstrikers of dimension 40–70 μm.

NOTATION

M_t, mass of the material ejected from the obstacle; S, cross section of the obstacle; D and D_{2T}, number of channel formations in the cross section of the obstacle in the direction to the flux and for variant II in the time interval without imposition of additional compression; τ_{long}, total time of the loading process; $\tau_{c.a}$, time of action of additional compression; $d_{c.m}$ and $d_{c.m2T}$, mean diameter of the channel after the action and for variant II in the time interval without imposition of additional compression; Δd, difference between them; C and C_{2T}, recorded porosity and for variant II in the time interval without imposition of additional compression; ΔC, difference between them; T, time of the loading process before the imposition of additional compression; γ_{m1}, specific mass-ejection index in the channel in a unit time, variant I; m, mass ejection in the forward jet; M_{2T} and $M_{2\tau_{c.a}}$, mass of the material ejected from the obstacle in variant II in the time period without imposition and with imposition of additional compression; E_s, energy introduced into the obstacle in the process of loading; E_{com}, energy in the channel zone expended on compressing the walls; v_t, rate of ejection of the mass from the channel; v_{com}, rate of compression of the channel walls; M_f and M_{2f}, mass of the material in the high-pressure region in the periods of loading and imposition of additional compression; M_d, mass of the material of the channel defect zone; E_t, energy in the channel zone expended on ejecting the mass; B, energy of restructuring of the material in the high-pressure region in the time interval of imposition of an additional compression; P_r, pressure of the phase transition; $E_{s,c.a}$, energy of a microparticle bunch in the time interval of imposition of additional compression; B_a, energy realized in the case of additional compression; ζ, specific power parameter; b_2, expenditure of the compression energy of additional explosive charge on one channel; m_{2f}, mass of the high-pressure single channel zone; E, energy expended on ejecting the mass; χ, energy utilization efficiency coefficient; d_p, diameter of the initial striker; σ_{SDP}, energy density in the case of dynamic loading in the regime of superdeep penetration; h, depth of treatment; S_z, area of the recorded defect zone. Subscripts: t, ejection; a, compression; c.a, additional compression; T, time; c.m, medium channel; m, material; s, impact; com, compression; f, formation; d, defect; r, restructuring; long, duration; SDP, superdeep penetration; p, striker; 1, 2, 3, and 4, for variants I, II, III, and IV, respectively; z, zone.

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