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ESTIMATION OF THE ENERGY EXPENDED FOR SUPERDEEP PENETRATION

S. M. Usherenko,[a] **O. I. Koval',**[b] **and**
Yu. S. Usherenko[c]

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We attempted to take a complex approach to estimation of the energy introduced by microparticles into a metallic obstacle and the energy expended for their superdeep penetration realized in the case where they penetrate into the obstacle to a depth of tens or hundreds of millimeters. The disbalance (two- to ninefold) arising in this case between the expended and the introduced energy was explained by the appearance of an additional energy source under the conditions of dynamic compression of microcavities in the process of superdeep penetration.

An anomaly arising in the case of the impact of microparticle bunches upon metallic obstacles in the regime of superdeep penetration is the appearance of craters with a ratio between their depth and the diameter of the striker of higher than ten. The existence of this physical barrier (of relative depth) to the penetration in the process of such an impact has been revealed in the course of prolonged investigations [1]. The anomaly of crater formation is caused by the change in the mechanism of the interaction and, consequently, in the total energy of the process.

From the standpoint of an ordinary macroimpact, the relative depth of penetration is limited by the static resistance, for overcoming of which a major portion of the energy of the impact is expended (90–98%); in this case, only 2–10% of the energy is expended for overcoming the dynamic resistance. The dynamic resistance arises as a result of the transfer of the material of the striker and of the obstacle with a certain velocity, including in the case of ejection of the material of the obstacle from a crater and in the case of displacement of the material of the walls and the bottom of a cavity [2].

At present the mechanism of superdeep penetration is not clearly understood. This phenomenon is usually explained by the crack formation [3] and the loss of static strength in the process of dynamic transformation of the channel-zone material [1, 2]. The anomaly of crater formation in the case of superdeep penetration of microparticles into a metallic obstacle is explained by the fact that, even if the channel zone in the obstacle is melted, the limiting depth of penetration cannot exceed 100 sizes of the striker [4]. In this case, the possibility of local melting of zones with a diameter of up to 100 μm and a depth of 100–200 mm should be explained. The assumption that cracks are formed in the process of superdeep penetration leads to the exclusion of the dynamic component of the expenditure of energy in the process of channel formation, which is not correct [3].

The recent level of knowledge of the mechanism of superdeep penetration does not give preference to any of its models. Therefore, it makes sense to represent an impact interaction in general terms with account for the maximum possible number of components of this complex process.

The impact of a high-velocity particle bunch upon a metallic obstacle causes a number of changes in the material of the obstacle. The most typical of them, observed both in the case of macroimpact and in the case of superdeep penetration, are the formation of macrocraters on the surface of an obstacle and deformation of the obstacle and of the grains. Among the effects observed only in the case of superdeep penetration of macroparticles into a metallic obstacle are the formation of channels-craters with a relative depth of 10^2–10^4 striker sizes, the appearance of electromagnetic radiation, etc. [1]. Much of the current interest in the effect of superdeep penetration is centered on its features. A large amount of statistical data on the anisotropic structure formed in various materials as a result of

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[a] Institute of Raising the Level of Professional Skill, Ministry of Education of the Republic of Belarus, 77 Partizanskii Ave., Minsk, 220600, Belarus; [b] Minsk Institute of Management, Minsk, Belarus; [c] Belarusian National Technical University, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 77, No. 3, pp. 147–151, May–June, 2004. Original article submitted June 9, 2003; revision submitted December 15, 2003.

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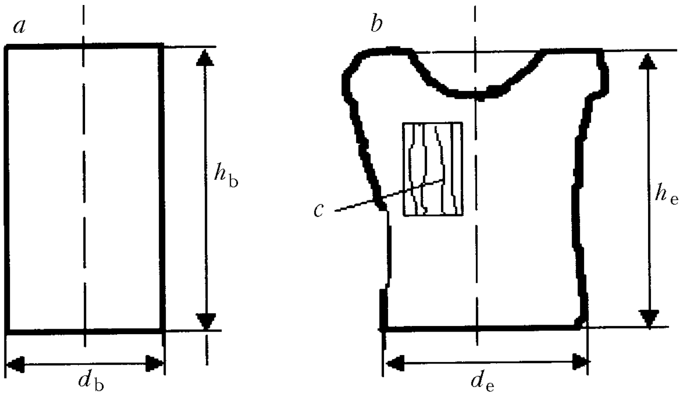

Fig. 1. Changes in the metallic obstacle arising as a result of an impact of a particle bunch upon it: a) initial cylindrical obstacle, b) obstacle after the dynamic loading, c) channel structure.

superdeep penetration of particles into them has been obtained in recent years [4]. Moreover, there are data on the rates of the processes occurring in the channels formed by individual microstrikers in the regime of superdeep penetration [2, 5–7].

The formation of channels in a metal obstacle, subjected to a particle flux, whose material differs in structure and composition from the basic material can be explained in the first approximation by the accumulation of energy and deformations in these regions [1, 8, 9].

At the same time, many qualitative physical and material-science aspects of this process are not clearly understood. With the aim of determining the mechanism of superdeep penetration, the authors have estimated the energy received by a metallic obstacle as a result of an impact of a microparticle flux upon it and the action of a shock wave and also the energy expended for superdeep penetration.

The introduced and the expended energies were compared with the use of the following approach. The kinetic energy introduced by a bunch of high-velocity particles was deliberately overestimated and the energy expended in the process of loading was deliberately underestimated in the calculations. This approach, in our opinion, makes it possible to concentrate attention on only the qualitative aspects of the superdeep-penetration process. The energy balance obtained under the above-indicated assumptions is the first rough approximation to the real pattern and cannot be used for the development of a qualitative model of the superdeep-penetration mechanism.

Changes Arising in a Metallic Obstacle on Dynamic Loading by a High-Velocity Microparticle Flux. Let us consider the geometric and structural changes arising in a metallic obstacle as a result of the impact of a bunch of high-velocity discrete particles upon it. As the obstacles, we used cylindrical samples 50 mm in diameter and 100 mm in height made from steel 40, copper, and aluminum. The properties of these materials under the conditions of macroimpact are well understood [10], which makes it possible to use the available data on them for estimating the macrochanges detected in the obstacles. The dynamic treatment of the model samples was performed by a standard scheme of loading [1, 4]. As the strikers, we used microparticles of SiC powder of fraction 63–70 μm. As the macrochanges in a cylindrical obstacle, we considered the formation of macrocraters in the front part of the obstacle and its deformation. As the microchanges, we considered the formation of a system of channels that could be detected experimentally [1, 8, 9], the twinning, and the change in the structure of the grains.

We did not take into account the energy expended in electromagnetic radiation in the process of superdeep penetration and for acceleration of a metallic sample and ejection of microjets from the free surface of the obstacle [1, 2].

Estimation of the Kinetic Energy of the Shock Wave Formed by a High-Velocity Macroparticle Bunch. The energy received by a metallic obstacle from the shock wave formed as a result of the loading of the obstacle by a high-velocity microparticle flux was calculated with the use of the following parameters: mass of the ejected material (m_1), 0.1 kg; mass of the explosive charge (m_2), 0.2 kg; velocity of the microparticle flux, 1000 m/sec. For these parameters, the kinetic energy of the ejected material is $1.5 \cdot 10^5$ J.

Macrochanges. Formation of a Macrocrater. The changes detected in the geometry of an obstacle are shown in Fig. 1.

TABLE 1. Estimation of the Energy Expended in the Crater Formation

Obstacle material	$K \cdot 10^9$, J/m^3	$V_c \cdot 10^{-6}$, m^3	E_k, J
Steel 40	2.6	0.98	2548
Copper	2.0	7.0	14,000
Aluminum	2.3	20.0	46,000

TABLE 2. Estimation of the Energy Expended in the Deformation of Metallic Obstacles

Obstacle material	$V_b \cdot 10^{-2}$, m^3	$F_b \cdot 10^{-2}$, m^2	$F_e \cdot 10^{-2}$, m^2	φ	ε	$\sigma_{0.2} \cdot 10^7$, J/m^3	$\tau \cdot 10^7$, J/m^3	E_d, J
Aluminum	2.131	1.133	1.36	0.2	0.1667	5.63	4.69	9 997
Copper	2.131	1.133	1.17	0.0328	0.0318	6.85	6.632	14,886
Steel 40	1.962	1.962	2.13	0.0256	0.0249	21	20.475	40,1821

A characteristic defect arising in the case of the impact of a particle bunch upon an obstacle is a cavity-crater. The size of the crater depends on the specific weight of the obstacle material and its plasticity and strength, all other factors of the impact being equal [10]. The data obtained with the above-indicated parameters of the action of a silicon-carbide particle bunch on an obstacle are presented in Table 1. The energy of the crater formation was calculated based on the experimental values of the specific energy of crater formation obtained in [10].

The largest craters and, accordingly, the highest energy expended for crater formation have been detected for the aluminum obstacle, and the smallest craters and the lowest energy of their formation have been detected for the steel obstacle.

Deformation of a Metallic Obstacle. The action of a microparticle bunch on a metallic obstacle leads to a decrease in the height of the obstacle and an increase in its mean diameter. The entire volume of the obstacle experiences a plastic deformation [11]. As a result, in it there arise stresses equal to or exceeding the yield stress of the obstacle material.

To determine the true stress in an obstacle subjected to deformation, we used the formula [10]

$$\tau = \sigma_{0.2}(1 - \varepsilon) , \tag{1}$$

where $\varepsilon = \varphi/(1 + \varphi)$ and $\varphi = (F_e - F_b)/F_b$.

The results of estimation of the energy expended in the deformation of the obstacles of steel 40, aluminum, and copper are presented in Table 2. The energy expended in the deformation of the steel obstacle is 40 times higher than that for the aluminum obstacle and 26 times higher than the energy expended in the deformation of the copper obstacle.

Formation of a Channel Structure in the Process of Superdeep Penetration. The energy expended in the formation of a zone with a channel microstructure was estimated with the use of the following assumptions that are standard for problems of this type: the static resistance of the obstacle material is equal to zero and the velocity of movement of the channel walls is equal to the velocity of movement of an individual microstriker.

As a result of the formation of microzones with a channel structure, energy is expended for opening of channels in the direction perpendicular to the direction of movement of microstrikers and for their closing after the passage of the particles. The rate of closing of the channel spaces exceeds the rate of penetration of a microstriker by more than three times [2, 5–7]. The mass of the obstacle material transported in the process of opening and closing of a channel was taken to be equal to the mass of the cylinder of diameter $66 \cdot 10^{-6}$ m (equal to the cross-sectional dimension of the striker) and length 0.1 m formed in the obstacle. The mass of the obstacle material transported in the dynamic regime will also be underestimated in this case since it is assumed that the deformation proceeds without the participation of nearby layers in the process of closing. The total energy expended in the formation of the channel structure was determined as

$$E_{\Sigma} = E_n N\,. \tag{2}$$

The energy necessary for opening and closing of an individual channel was calculated with the assumptions used in [2]. Under these assumptions, the energy expended for opening of a channel is 0.11 J for steel 40, 0.12 J for copper, and 0.07 J for aluminum.

The total energy expended for opening of the channels is $2.25 \cdot 10^4$ J for steel 40, $1.586 \cdot 10^4$ J for copper, and $6.503 \cdot 10^4$ J for aluminum.

The energy expended for closing of an individual channel is 1.69 J for steel 40, 2.38 J for copper, and 0.26 J for aluminum.

The total energy expended for closing of the channels is $93.7 \cdot 10^4$ J for steel 40, $31.5 \cdot 10^4$ J for copper, and $24.1 \cdot 10^4$ J for aluminum.

Estimation of the Energy Expended for Changing the Structure of the Grains. Since the energy expended for the twinning and for changing the structure and sizes of the grains accounts for approximately 5% of the shock-wave energy, the total energy expended for these microstructural changes is less than $5 \cdot 10^3$ J.

Energy Balance. Let us compare the introduced and the expended energies with the use of the above-calculated quantities:

$$E_{\mathrm{p}} \neq E_{\mathrm{k}} + E_{\mathrm{d}} + E_{\mathrm{op}} + E_{\mathrm{com}} + E_{\mathrm{ex}}\,. \tag{3}$$

The energy expended in the dynamic loading is equal to

$$E_{\mathrm{a}} = E_{\mathrm{k}} + E_{\mathrm{d}} + E_{\mathrm{op}} + E_{\mathrm{com}} + E_{\mathrm{ex}}\,. \tag{4}$$

Thus, $E_{\mathrm{a}} \approx 364$ kJ for copper, $E_{\mathrm{a}} \approx 1368$ kJ for steel 40, and $E_{\mathrm{a}} \approx 367$ kJ for aluminum. Since the kinetic energy of a bunch of disperse particles is $1.5 \cdot 10^5$ J, we obtain a two- to ninefold disbalance between the expended and the introduced energies.

Since the energy expended in the dynamic loading of an obstacle was underestimated and the energy introduced into it by a high-velocity microparticle bunch was overestimated in the calculations, the errors of this estimation cannot be significant. It is probable that the energy balance is provided by an additional energy source arising in the process of superdeep penetration:

$$E_{\mathrm{p}} + E_{\mathrm{unc}} = E_{\mathrm{a}}\,. \tag{5}$$

Determination of the Additional Energy Source. Since the process of transformation of the structure of an obstacle subjected to a macroimpact is well understood, it is beyond reason to assume that an additional energy source can arise as a result of a macroimpact. It is more probable that such a source arises in the process of superdeep penetration.

Our investigations have shown that the superdeep penetration of particles into a material leads to closing of microcavities in it. A microcavity formed after the passage of a microstriker closes due to the high pressure in the zone surrounding it. In [2], the change in the specific energy of the channel zone depending on its finite diameter after the passage of a striker was estimated. Some of the estimates obtained in this work are presented in Table 3.

It follows from these data that a pressure of higher than 10^{15} N/m^2 can exist in a microvolume for $\sim 10^{-8}$ sec.

Since the maximum diameter of the channel zone does not exceed the maximum diameter of a microstriker, it is equal to $(80–100) \cdot 10^6$ μm. The diameter of a metallic, cylindrical obstacle is 30–50 mm. Because of this, closing of channels can take place in a chamber with walls whose thickness is six times larger than the size of the channel zone. It is difficult to remove energy from this microvolume because of the short time of the process of dynamic cumulation (Table 3). In the real-time regime, energy can be released from a site of closing only due to radiation. In investigating the superdeep penetration of powder particles into a metallic sample with the use of film detectors we detected tracks left by elementary particles whose energy measures hundreds of megaelectronvolts [12, 13].

The present knowledge of the superdeep penetration effect is far from complete; therefore, we cannot uniquely determine the physical nature of the additional energy source. The solution of this problem calls for additional experimental investigations and statistically verified data.

TABLE 3. Change in the Time of Compression of a Channel and in the Energy Density in the Channel Zone after the Passage of a Microstriker versus the Finite Diameter of the Channel Zone

d_c, μm	$\tau_s \cdot 10^{-8}$, sec	σ_{sdp}, J/m^3
2	4.92	$0.776 \cdot 10^{14}$
0.42	5.05	$8.246 \cdot 10^{15}$

Thus, considering the process of impact interaction of a bunch of high-velocity discrete microstrikers with metallic obstacles of steel 40, copper, and aluminum, we have estimated the energy expended for the crater formation, the deformation of an obstacle, the changes in the structure of the grains, and the channel formation in the process of superdeep penetration. The main results of our investigation are as follows.

1. It has been established with the approach in which the expended energy is deliberately underestimated and the kinetic energy of the impact is deliberately overestimated that the disbalance between the expended and the introduced energy is two- to nine-fold.

2. The disbalance toward the expended energy can be compensated only by an additional energy source that arises under the conditions of dynamic closing of microcavities formed after the passage of a striker in the superdeep-penetration regime.

3. The detection of the radiation of an elementary carrier whose energy measures hundreds of megaelectron-volts can be considered as indirect experimental evidence of the existence of an additional energy source.

NOTATION

d_b, diameter of the obstacle before the deformation; d_c, mean diameter of a channel; d_e, diameter of the obstacle after the deformation; E_a, energy expended in the dynamic loading; E_{com}, energy expended for closing of channels; E_d, energy expended in the deformation of the obstacle; E_{ex}, energy expended for changing the sizes of the grains and for the twinning; E_n, energy expended for opening (or closing) of an individual channel; E_k, energy expended in the crater formation; E_{op}, energy expending for opening of channels; E_p, kinetic energy of an impact of a microparticle bunch; E_{unc}, energy released by an unknown source; E_Σ, total energy expended in the formation of microzones with a channel structure; F_b, mean area of the cross section of the obstacle before the deformation; F_e, mean area of the cross section of the obstacle after the deformation; h_b, height of the obstacle before the deformation; h_e, height of the obstacle after the deformation; K, specific energy of the crater formation; m_1, mass of the ejected material; m_2, mass of the explosive; N, number of channels in the obstacle; V_b, volume of the obstacle in the initial state; V_c, volume of the crater after the dynamic loading; ε, degree of deformation; φ, coefficient of deformation; $\sigma_{0.2}$, yielding limit; σ_{sdp}, density of energy in the channel zone in the case of dynamic loading in the regime of superdeep penetration; τ, true stress as a result of the deformation; τ_s, time of the impact compression of a channel. Subscripts: a, absorption; b, beginning; c, channel; com, compression; d, deformation; e, end; ex, stress; k, kinetic; *n*, ordinal number of a channel; op, work; p, energy; s, impact; sdp, superdeep penetration; unc, uncertainty; Σ, sum; 0.2, load under which a sample elongates by 0.2%.

REFERENCES

1. S. M. Usherenko, *Superdeep Penetration of Particles into Obstacles and Development of Composite Materials* [in Russian], NIIIP, Minsk (1998).
2. S. M. Usherenko, Modern notions of the superdeep-penetration effect, *Inzh.-Fiz. Zh.*, **75**, No. 3, 183–198 (2002).
3. N. N. Sirota, Mechanism of deep penetration of finely dispersed particles into solid bodies, *Vestsi Nats. Akad. Navuk Belarusi, Ser. Fiz.-Mat. Navuk*, No. 3, 55–59 (2003).
4. O. V. Roman, S. K. Andilevko, S. S. Karpenko, G. S. Romanov, and V. A. Shilkin, Effect of superdeep penetration. State of the art and prospects, *Inzh.-Fiz. Zh.*, **75**, No. 4, 187–199 (2002).

5. S. M. Usherenko, O. I. Koval’, L. G. Korshunov, and V. I. Zel’dovich, Recording of the aftereffect of collision between a flow of powder particles and metals in the regime of superdeep penetration, in: *Dynamic Restructurization of Materials* [in Russian], Ch. 2, NIIPM, Minsk (2000), pp. 22–46.
6. S. M. Usherenko, L. G. Korshunov, and O. I. Koval’, Multifactor experiments under superdeep-penetration conditions, *Inzh.-Fiz. Zh.*, **75**, No. 6, 3–6 (2002).
7. S. M. Usherenko, O. I. Koval’, and Yu. S. Usherenko, Formation of high-speed microjets in different versions of superdeep penetration, *Inzh.-Fiz. Zh.*, **76**, No. 1, 93–97 (2003).
8. V. I. Zel’dovich, N. F. Frolova, I. V. Khomskaya, A. E. Kheifets, S. M. Usherenko, and O. A. Dybov, Structural changes in iron-nickel alloys caused by the action of a high-speed flow of powder particles. I. Effects of shock-wave loading, *Fiz. Metal. Metalloved.*, **91**, No. 6, 72–79 (2001).
9. V. I. Zel’dovich, I. V. Khomskaya, N. F. Frolova, A. E. Kheifets, S. M. Usherenko, and O. A. Dybov, Structural changes in iron-nickel alloys caused by the action of a high-speed flow of powder particles. II. Effects of superdeep penetration, *Fiz. Metal. Metalloved.*, **94**, No. 1, 90–98 (2002).
10. J. Herring, High-speed impact from the engineering standpoint, in: *High-Speed Shock Phenomena* [Russian translation], Ch. 9, Moscow (1973), pp. 468–516.
11. V. S. Zolotorevskii, *Mechanical Tests and Properties of Metals* [in Russian], Metallurgiya, Moscow (1974).
12. S. M. Usherenko, V. I. Gushchin, and O. A. Dybov, Results of collision of a flow of microparticle flow with a metal obstacle in the regime of superdeep penetration, *Khim. Fiz.*, **21**, No. 9, 43–51 (2002).
13. S. M. Usherenko, V. I. Ovchinnikov, and O. I. Koval’, Study of the origination of electromagnetic and x-ray radiation under conditions of superdeep penetration of powder particles on dynamic loading of a solid body, in: *Cooperation of the Joint Institute of Nuclear Research with Institutes, Universities, and Enterprises of Belarus* [in Russian], Dubna (2002), pp. 77–79.