Journal of Engineering Physics and Thermophysics, Vol. 75, No. 2, 2002

CONSIDERATION OF RESULTS ON SUPERDEEP PENETRATION OF PARTICLES INTO METALLIC OBSTACLES

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UDC 534.2

With the use of the procedure of a combined specimen, the limiting depths of penetration of powder strikers of silicon carbide and copper into 45 steel have been found. The efficiency of retardation of the strikers by a block of layered obstacles depending on the foil material has been determined. Based on the complex analysis of the information obtained, it has been proposed that high-speed jets whose forepart consists of the microstriker material and whose main rear part consists of the obstacle metal are formed in the process of superdeep penetration.

The phenomenon of superdeep penetration (SDP) is based on the complex interaction of a particle flux with obstacles. A comparison of experimental results obtained by different researchers makes it possible to determine the field of application of experimental procedures and reveal the distinctive features of this variant of dynamic mass transfer. A distinctive feature of dynamic interaction and its difference from static loading is that the cumulation of energy in local volumes is a rule rather than an exception. However, the fact that this field of interaction conditions has specific features cannot serve as a basis for the abandonment of general physical notions. Because of this, a number of published results and their interpretation are insufficient in our opinion, since they are based on incorrect assumptions and errors in the methodological approach. Numerous investigations on crater formation and penetration of strikers into obstacles made it possible to reveal the existence of a barrier with a relative depth. For a macrostrike, craters with a ratio of the depth to the determining size of the striker of up to 6 are typical, and craters with a relative depth of 6–10 are anomalous [1]. Over a long period of time, the results of the crater formation with relative depths of larger than 10 gauges were not considered at all. This was explained by the fact that the energy of a strike is insufficient for breakdown to depths larger than 6 gauges according to the existing models. The anomalous crater formation was also not studied because of the fact that these results were not reproducible. Only in 1974 were the conditions for superdeep penetration with relative depths of 10^2–10^4, providing a stable repetition of the superdeep-penetration process, realized [1].

As a result of the cycle of investigations carried out at the Scientific-Research Institute of Pulsed Processes with Pilot Production, it has been generally recognized that there is an unusual region of conditions of interaction of a microparticle bunch with obstacles, within the limits of which a jump-like decrease in the resistance to the motion of a microstriker occurs in narrow channel zones. The recognition of this unusual result had both positive and negative consequences. A positive consequence is that when the superdeep-penetration phenomenon (Usherenko effect) was revealed, scientists were forced to focus their attention on the features of dynamic interaction, for example, on the cumulation of energy in local zones, and investigations in this field were intensified. A negative consequence of this recognition is that a number of researchers thought that the established general physical notions could be ruled out.

The complexity of investigation of superdeep penetration lies in the fact that this process is realized in the bulk of a material, in its local zones; the time of duration of the process is shorter than 10^{-3} sec. Therefore, it became necessary to develop new experimental procedures that would allow one to record superdeep penetration or its side effects more efficiently. As such a basic procedure, the method of a combined specimen has been proposed [2]. This method is based on the assumption that a microparticle flux passing through a metallic obstacle is retarded efficiently when it collides with obstacles in the form of detector foils. When strikers break down layered obstacles, their energy

Scientific-Research Institute of Pulsed Processes with Pilot Production, Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 75, No. 2, pp. 191–195, March–April, 2002. Original article submitted June 20, 2001.

 1062-0125/02/7502-0508$27.00

TABLE 1. Variants of Arrangement of Foils in the Target Chamber and the Parameters of the Experiment

Number of experiment	Material of foils, thickness, μm	Variant of arrangement	Depth of targets, mm	Number of foils	Powder, fraction, μm
1	FCD, 80	Without a gap	50, 100, 150, 200, 230	30	SiC, 63–70
2	Al, 10	»	50, 100, 150, 200	31	Cu, 10–30
3	Cu, 10	»	50, 100, 150, 200	26	SiC, 63–70
4	Al, 50	With a gap	50, 100, 200	9	Cu, 10–30
5	FCD, 80	»	15, 50, 100, 150, 230, 290	6	Cu, 10–30

is canceled rapidly and it becomes possible to determine the mass and the velocity of the striker with the use of the existing estimates on breakdown [3]. It is precisely these premises on which the works [4, 5] were based. The analysis of the results presented in them and, consequently, the evaluations of applicability of the method of a combined specimen are made easier by the fact that the work in this direction was carried out by two groups of researchers simultaneously.

Setting of the Experiment. We consider additional results of the investigation of superdeep penetration by the method of a combined specimen. In accordance with [2], we determined the parameters of superdeep penetration of a silicon-carbide powder into a 10-μm-thick copper foil and 80-μm-thick films of flexible computer disks (FCDs) as well as the parameters of superdeep penetration of a copper powder into aluminum foils of thickness 10 and 50 μm (see Table 1). The foils were numbered in ascending order beginning from the obstacle.

The foils were arranged in the chamber in two variants:

(1) without rings providing an air gap between the lower and upper surfaces of the chamber and the foils (without a "gap");

(2) with rings providing an air gap of ≈1.5 mm (with a "gap").

Based on the evaluated data for the collision velocity and the time of interaction of particles with the target, we determined the depths of disposition of the foils: 50, 100, 150, 200, 230, and 290 mm.

The targets were treated according to a standard scheme providing a stable process of superdeep penetration [1]. Inclusions before and after an explosion were identified by the metallographic, electron-microscopic, and x-ray microspectroscopic methods.

In contrast to [4, 5], the detectors (foils) were analyzed for all the types of defects arising after the treatment of the foils without considering their chromaticity range. For comparison with the results presented in [4, 5], we consider one variant (No. 2 in the table), taking into account the chromaticity range. Red and yellow inclusions in the material of an aluminum foil were investigated by x-ray microspectroscopic analysis. In these inclusions, we detected copper, i.e., the striker material: the concentration of the copper changed from 1 to 80%. No copper was recorded in black inclusions. We took into account the inclusions with a size larger than 0.2 μm, which was determined by the resolution of the microscope. With such an approach, the fraction of the red inclusions used as the basis for calculation estimates in [4, 5] did not exceed 25%, the fraction of the yellow inclusions did not exceed 25%, and the fraction of the black inclusions did not exceed 50% of the total number of recorded inclusions.

Results of Investigations and Discussion. Let us analyze the results of the experiments in which the foils were positioned without gaps (Fig. 1, the figures are the target lengths). It has been established that in all the specimens, 30 or more foils were broken down.

The common tendency for all the experiments is that the ratio of the density of defects on the first ten foils to the total number of defects increases with the depth of the target. This is especially clearly seen for a depth of 230 mm.

A comparison of the number of defects recorded on the FCDs and on the foils of Cu and Al after the treatment with the SiC powder of fraction 63–70 shows that the FCDs with a thickness eightfold larger than the thickness of the Al foils possess the greatest retarding effect.

If it is assumed that we have a free breakdown of foils, which means that the foil material is in an unloaded state, and the interaction of an individual particle with the foil is considered, a striker should move with a very high velocity in order that the results presented in Fig. 1 can be obtained.

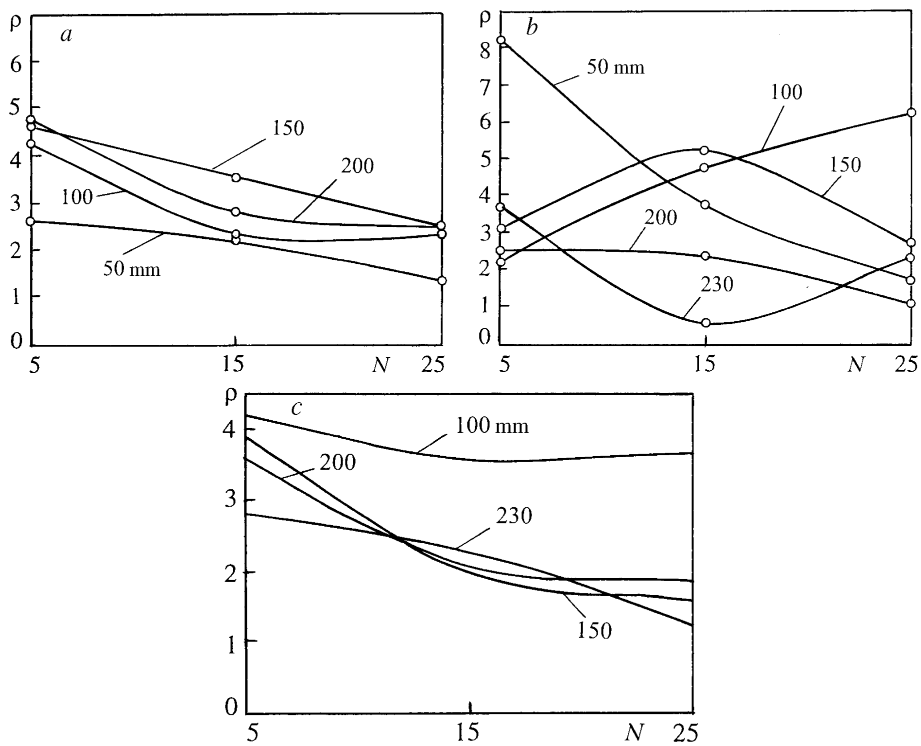

Fig. 1. Dependence of the density of the defects of treatment of an aluminum foil (a), an FCD foil (b), and a copper foil (c) by the striker of SiC of fraction 63–70.

To explain the observed effect (breakdown of 30 or more foils), we make two assumptions:

(1) realization (even though partial) of the mechanism of superdeep penetration in the case of penetration of particles into a block of foils, into a composite material;

(2) formation or retention of a particle leaving the target material in the form of a jet (striker) with a diameter much smaller than its length.

In the second case, the area of collision is smaller than in the case of the strike by a spherical striker of the same mass. Thus, the breakdown energy turns out to be much higher than in the case of collision of a spherical striker with an obstacle considered in [4, 5], and the breakdown of the foils is analogous to the breakdown of an obstacle by a cumulative jet.

When a block of foils is broken down, we have a discrete loss in the kinetic energy of the jet by the value of the energy spent on breaking down one foil. At the moment when

$$E_{\text{breakdown of foil}} > E_{\text{striker}} ,$$

the forepart of the striker is retarded and the entire mass is held in the obstacle (foil).

The material of the striker is in the plastic state and the energy of its deformation is lower than the energy necessary for the breakdown of one foil, i.e.,

$$E_{\text{deformation of striker}} < E_{\text{striker}} < E_{\text{breakdown of foil}} ,$$

the striker must be retarded in the material of the target with a different degree of its deformation.

Photographs of defects in the foils of Al and FCD, made on a scanning electron microscope, are shown in Fig. 2. It is seen on the photographs that the entry of the striker into the target is not perpendicular to its surface.

To justify the assumption of the formation of a striker with a length larger than its diameter, we have carried out the experiments on realization of conditions of "free" breakdown of 50-μm-thick foils. The foils were positioned in a chamber with a gap.

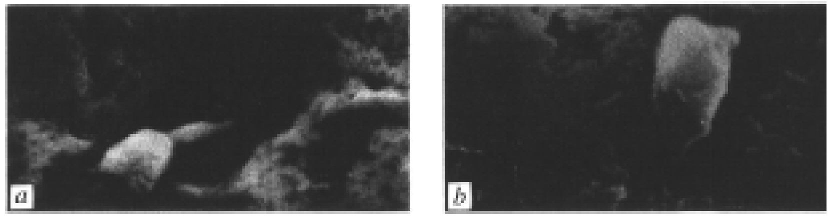

Fig. 2. Residues of the SiC striker in an aluminum foil (a) and in an FCD foil (b). ×1250.

In the course of the experiment, we observed the breakdown of five foils with a thickness of 50 μm each. Assuming that the breakdown of the obstacle is initiated by a particle with a nearly spherical shape and the strike is perpendicular to the foil plane, we calculate the velocities of these particles according to the procedure of [3]. The mean diameter of the defects is 4–8 μm. In this case, the minimum velocity of the particles with a track diameter of 5 μm which are recorded on the sixth foil of thickness 50 μm is v = 7907 m/sec and that of those recorded on the thirtieth foil of thickness 10 μm is v = 59,876 m/sec.

On the assumption that the foils are broken down by an elongated striker (the length exceeds the diameter), the value of the limiting ballistic velocity and the partial increase in the velocity necessary for breaking down each subsequent foil is much smaller.

The calculation of the velocity of a long striker (jet) according to the procedure of [3] gives the result 101 m/sec for analogous experimental conditions.

These velocities are apparently more real than those obtained on the assumption that the breakdown of a block of foils is made by a striker in the shape of a sphere. This scientific proposition is logical and does not seem contrary to the modern notions of the processes investigated in such fields of science as materials science, solid-state physics, and thermodynamics.

The use of the density of the defects with allowance for the thickness of the detector in the variant without a gap as the criterion for the efficiency of retardation in foils allowed us to establish that

(a) strikers are retarded most efficiently by an aluminum detector with a density of 2.7 g/cm^3 (2.987 mm^{-2});

(b) strikers are retarded least efficiently by a plastic detector with a density of 1.4 g/cm^3 (0.370 mm^{-2});

(c) the efficiency of retardation with the use of copper foils with a density of 8.93 g/cm^3 gives intermediate values (2.631 mm^{-2}).

From the viewpoint of an ordinary breakdown, the retardation efficiency must have a different order (Cu–Al–FCD). The difference in the order of the efficiency of retardation of detector materials in the variant without a gap, apparently, indicates the realization of the breakdown conditions with background pressure in the detector material. If we consider the variant with a gap between detectors from this viewpoint and compare the retardation efficiencies of aluminum and plastic foils, we will see the common tendency:

(a) the density of the defects in aluminum detectors increases with the obstacle depth from 8.27 mm^{-2} to 14.86 mm^{-2};

(b) the density of the defects in plastic detectors decreases with the obstacle depth from 15.85 to 1.54;

(c) aluminum detectors retard breakdown more efficiently than plastic detectors (11.3 and 6.0, respectively).

A comparison of the two variants of retardation of penetration with a gap and without it allows the conclusion that

(a) the efficiency of retardation of the breakdown of plastic detectors with a gap exceeds the efficiency of retardation in the same material without a gap by a factor of 16.2;

(b) the efficiency of retardation of the breakdown of aluminum detectors with a gap exceeds the efficiency of retardation in the same material without a gap by a factor of 3.78.

A comparison of the retardation efficiency in the variant with a gap with allowance for the difference in the density gives approximately the same values of the correspondence coefficient determined as the density of the defects on the detector divided by the specific weight of the detector material. Thus, the correspondence coefficient was 4.185 for the aluminum detector and 4.2 for the plastic one.

A comparison of the retardation efficiency in the variant without a gap gives the following values of the correspondence coefficient: 1.106 for aluminum, 0.294 for copper, and 0.308 for FCD.

The coefficients obtained for the given variant of retardation correspond to the real qualitative picture of retardation efficiency.

Evaluation of the presence of defects in 45 steel treated once with an SiC powder of fraction 63–70 μm to a depth of 50 mm gives a more complete picture of the process of superdeep penetration. Metallographic investigation of the specimen included: preparation of a horizontal microsection, chemical etching for better decoration of defects, and counting the recorded defects of treatment using an optical metallurgical microscope with a magnifying power of 500. As a result of this experiment, the density of the detected defects of the treatment was determined at a level of 135 defects/mm^2. The experiment carried out under analogous conditions gives a density of the defects of the order of 6 defects/mm^2. Thus, the coefficient of attenuation of penetration was of the order of 20 times. The results obtained suggest that at the rear cut of the target we have the retardation of particles caused by the influence of the unloading wave and by the decrease in the pressure background in this region of the obstacle. This conclusion has also been drawn in [2], but this was not taken into account in [4, 5].

In analyzing the experimental results obtained, it is necessary to take into account a number of restrictions imposed by the selected procedure of recording. Defects on detectors with a size smaller than 0.2 μm cannot be revealed using an optical microscope with a magnitude power of up to 1000. Defects recorded by chromaticity may not correspond to the introduced material. The data obtained cannot be used for strict quantitative evaluations and the analysis made is aimed at determining the most general tendencies.

In [4], the theoretical evaluations presented are supported by the results of the chemical analysis of foils for cobalt. The investigations carried out in 1998–1999 at the Scientific-Research Institute of Pulsed Processes with Pilot Production have shown that it is difficult to use this approach because of the following factors:

(1) the accuracy and reproducibility of the chemical analysis made on different devices and by different researchers are not the same;

(2) materials used in [4] have a high background content of cobalt.

In the case of a relatively prolonged loading of metallic obstacles, a dynamic removal of the basic cobalt of up to 50% is recorded. Because of this, when a multilayer structure is considered, it is necessary to know the background amount of cobalt in each layer of each metal or alloy, the coefficient of dynamic removal under the analogous conditions of loading, and the coefficient of removal of cobalt from the foil. Thus, when two-layer obstacles and a foil are used, it is necessary to have three values of the background content of cobalt and coefficients of dynamic removal. Analysis of the amount of cobalt introduced into a foil can be made according to the system

$$Y = X_1 + X_2 + X_3 + X_4 - X_5 ,$$

where X_1 is the concentration of the cobalt introduced by the flux into the foil, X_2 is the concentration of the initial cobalt in the foil, X_3 is the cobalt mass removed from the lead to the foil, X_4 is the cobalt mass removed from the iron to the foil, X_5 is the cobalt mass removed from the foil, and Y is the total concentration of cobalt recorded in the chemical analysis.

Since in [4] there is no description of the experimental procedure and the components of the process are not taken into account, we cannot judge the reliability of the results presented there. Moreover, evaluation of the mean size of the recorded inclusions gives values lying beyond the resolution of optical metallurgical microscopes, which makes an exact identification of inclusions practically impossible. Information on results of the chemical analysis, procedures of treatment, and investigations carried out at the Scientific-Research Institute of Pulsed Processes with Pilot Production according to [4] is absent.

The reliability of the results and conclusions presented in this work is provided by the reproducibility of the theoretical and experimental investigations and by the use of the approved experimental procedures.

CONCLUSIONS

1. The procedure of a "combined specimen" at today's level can be used only to record the limiting penetration depths.

2. The procedure of a "combined specimen" made it possible to establish that when the customary design of a launching accelerator, a steel obstacle, and powder strikers of silicon carbide and copper are used, penetration depths of up to 200–320 mm are recorded.

3. The efficiency of retardation of strikers by a block of layered obstacles depends on the foil material. In the set of materials (Cu, Al, FCD), the highest retardation efficiency is displayed by detectors of aluminum.

4. In a block of detector foils positioned without a gap, background pressure is realized. Because of this, the process of interaction of the flux of strikers with this block cannot be considered from the viewpoint of an ordinary breakdown. A calculation of the velocity parameters of the strikers on the basis of the generally accepted notions gives values exceeding the velocity of a shock wave in an obstacle, i.e., it is not reliable.

5. A complex analysis of information on the breakdown of a block of detectors by strikers formed on the rear (free) surface of the obstacle allows the suggestion that high-speed jets are formed under these conditions. The forepart of the jet consists mainly of the microstriker material, while the main rear part consists of the obstacle material.

6. The density of defects in the structure of a metallic obstacle is higher than that in the structure of the materials of detector foils by a factor of several tens. This allows one to evaluate the influence of the unloading wave on the rear surface of the obstacle as a retarding factor.

7. In our opinion, the results on the chemical analysis of the process of penetration presented in [4] do not take into account the fact that the process is multifactor.

The difference between the data presented in this work and the results of [4, 5] can be explained by the methodological errors made in [4, 5].

This work was carried out with support from the Belarusian Republic Foundation for Basic Research, contract Nos. T98–199 and F99R-195.

NOTATION

E, energy; v, velocity of the microstriker particles; X, concentration of the material; Y, total concentration of the material; ρ, density of the defects, defects/mm^2; N, number of foils.

REFERENCES

1. S. M. Usherenko, in: *Superdeep Penetration of Particles into Obstacles. Creation of Composite Materials* [in Russian], Minsk (1998), pp. 7–48.
2. O. V. Roman, S. K. Andilevko, O. A. Dybov, S. S. Karpenko, and O. I. Koval', *Dokl. Nats. Akad. Nauk Belarusi*, **44**, No. 5, 113–115 (2000).
3. J. Zukas, in: *Impact Dynamics* [Russian translation], Moscow (1986), pp. 110–168.
4. S.. K. Andilevko, O. V. Roman, and S. S. Karpenko, *Inzh.-Fiz. Zh.*, **73**, No. 5, 1050–1055 (2000).
5. O. V. Roman, S. K. Andilevko, S. S. Karpenko, and G. P. Okatova, *Inzh.-Fiz. Zh.*, **73**, No. 5, 1056–1063 (2000).