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A method of studying the flow of miniature cumulative jet of copper

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A novel experimental laboratory technique for the flow of miniature cumulative jet of copper and without using explosives, is described. To perform the microcumulative tests, miniature cylindrical specimens with conical pits were used. The dynamic loading of the specimens was performed using a gas gun with a striker accelerated up to speeds of 800 m/s. The optimal specimen geometry and testing regimes, including the focal distance during microcumulation testing, were then determined. The influence of the structural condition of the sample material on the parameters of the cumulative jet has been demonstrated A preliminary analysis of the effects of copper purity and processing regimes on the ultimate dynamic plasticity characteristics was performed

Keywords: High-speed deformation, cumulative jet flow, copper, ultimate dynamic plasticity, light-gas gun.

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Introduction

It is known that the metal behavior during high-speed deformation is determined by both loading conditions and material microstructure parameters [1–3], but methodological difficulties significantly limit the possibility of studying the influence of material microstructure parameters on its behavior during dynamic deformation. A number of techniques are known to study the phenomena occurring during dynamic deformation of metallic materials at speeds above $10^3\,s^{-1}$ [1,4]. These include compressive, tensile, and shear testing of samples using split Hopkinson bars (SHB) [4–6], Taylor's test [7], and cumulative jet testing Graphs of the dependence of the CJ penetration [8–10], but virtually all of these techniques are aimed at evaluating dynamic strength and are limited in their ability to assess dynamic plasticity.

For example, in hat-shaped compression tests using SHB [6], the deformation process does not occur in the entire volume of the material, but only in a narrow band of localization up to $100\,\mu$m wide. In this case, the deformation amount is limited by the tooling, in which the sample is fixed, and a correct assessment of the value of the limit of dynamic plasticity is impossible.

The Taylor test implements complex stress-strain states in the sample material, the deformation and partial failure occur in parallel, which makes it difficult to analyze the deformation behavior [7]. In addition, this method allows us to determine only the average flow stress, which is assumed to be equal to the yield stress. This approach gives good results for materials whose strain diagram is close to ideal-plastic, but for materials with high hardening modulus, this method gives a large error.

The optimal technique for material research during high-speed deformation is to analyze the behavior of the material under cumulative jet (CJ) conditions. In this case, the deformation and fracture processes occur sequentially, the entire volume of the jet material is deformed, but the use of this method has serious methodological difficulties [11]. First, the need to use an explosive substance (ES) significantly reduces the availability of this technique. Second, the high velocity of jet fragments (up to 9 km/s) [11] makes it difficult to obtain a sample after deformation to study the microstructure in order to analyze the flow kinetics of the jet material and identify the mechanisms of plastic deformation.

To level these drawbacks, the authors have developed a method for the formation of the CJ without the use of a ES. For this purpose, a shockwave (SW) of sufficient intensity is formed in the sample with a cumulative notch. The present work demonstrates the possibility of such an approach to study the characteristics of high purity copper CJs.

The purpose of this work is to create a computational-experimental laboratory technique for studying the material under CJ flow conditions without the use of ES. This methodology should allow a comparative analysis of the influence of the material microstructure on the CJ parameters.

1. Materials and methods

The methodology under development is designed to study the flow of the cumulative jet under dynamic loading of miniature samples. The technique is based on the use of a direct impact on a sample, one end of which is flat (the impact is applied) and the opposite end has a conical cumulative notch (Fig. 1).

The technique is implemented on the basis of the PG-20 light-gas gun. When using compressed helium, the gun allows you to throw samples with a mass up to 10 g at speeds up to 800 m/s. The investigated copper samples were made using turning.

In the implemented methodology, cumulative excavation samples (CEMs) were placed in a steel jig. The flat

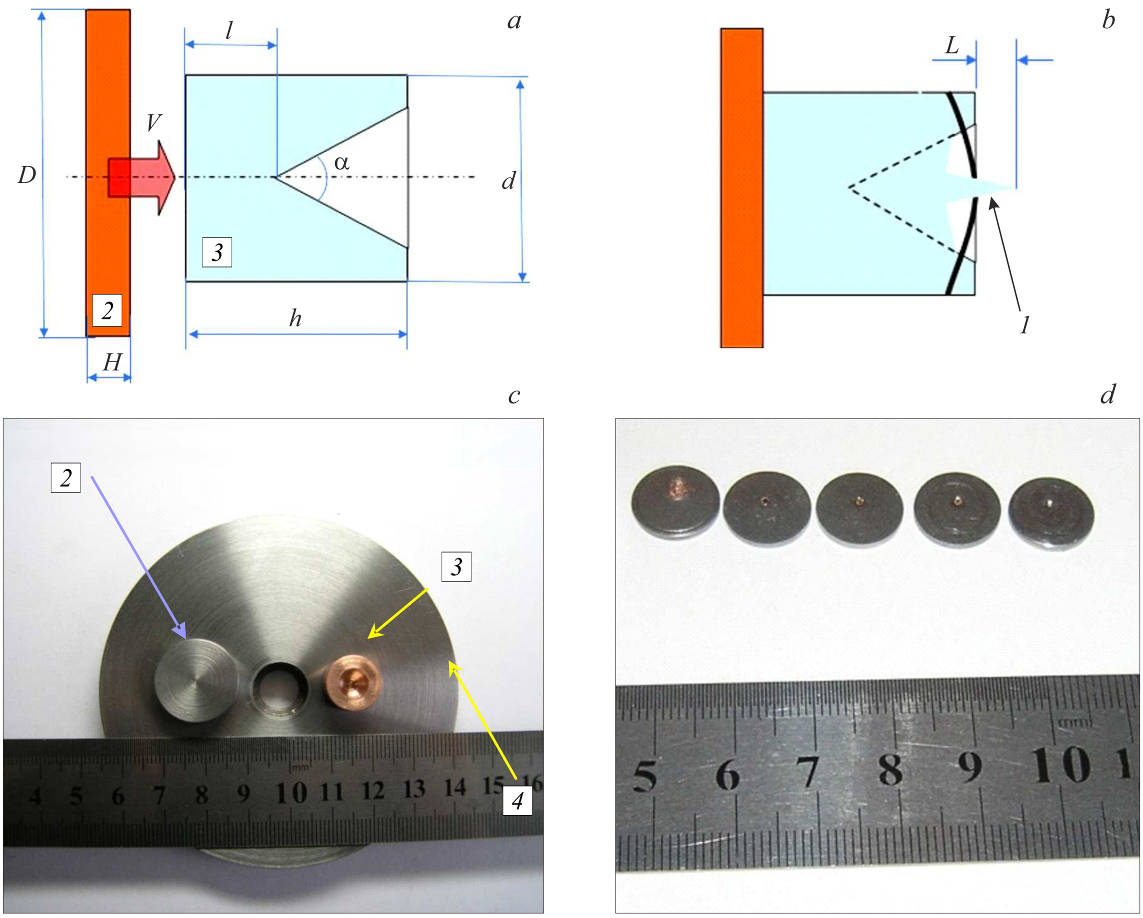

Figure 1. Schematic of the experiment using the cumulative indentation sample: *a* — the sample geometry before impact, *b* — the formation of CJ in the sample after impact, *c* — equipment, projectile and copper sample before test, *d* — 5 punched targets with thickness 1 mm after test. *1* — CJ, *2* — projectile, *3* — sample, *4* — tools.

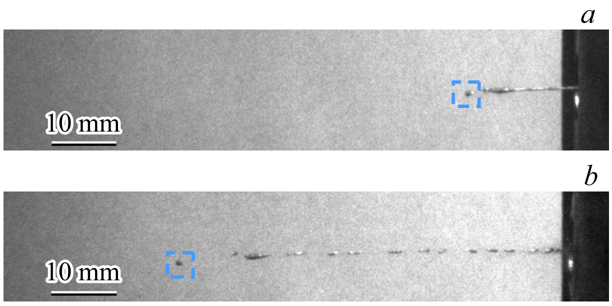

Figure 2. High-speed jet shooting. The scheme of the experiment is shown in Fig. 1. No steel barrier was installed during the shooting, and the jet was free to stretch out to destruction. The CJ head element is marked with a dotted line. The interval between frames it a and it b is 16 μs.

side of the sample was struck directly with a projectile accelerated in the barrel of the gas gun. As a result of the impact, a SW was generated in the sample, leading to the collapse of the cumulative cavity and the formation of the CJ (Figs. 1, 2). The jet length can be measured either directly — by the HSFCpro high-speed camera from PCO (Fig. 2) or indirectly — by the depth of the cavity punched in the steel obstacle (Fig. 1, *c, d*).

High-purity copper of M0b and M00k grades were used to make the samples. The roughness of the inner surface of the conical bore after the final stage of machining did not exceed 50 μm.

To study the effect of strength characteristics of the sample material on the parameters of the CJ, cylindrical copper samples were deformed at room temperature using special equipment and a hydraulic press EU-40 to the degree of deformation $\sim 80\%$ at a speed of 1 mm/s. The deformed samples were subjected to one-hour annealing in an EKPS-10 air furnace at different temperatures. After deformation and annealing, CEMs were milled from the obtained blanks for testing. The hardness of the samples was determined using a Struers hardness tester.

2. Results

2.1. Description of methodology

The main characteristic of the CJ is the depth of penetration into the steel obstacle, which depends on the length of the jet and its velocity. The jet length is determined by the amount of dynamic plasticity of the material and the experiment conditions.

To increase the accuracy of determining the penetration depth using this technique, it is necessary to provide the maximum length of the jet under fixed experimental conditions. In order to maximize the length of the generated CJ, it is necessary to determine the optimal system parameters (Fig. 1, a): sample height (h), sample diameter (d), conical notch depth ($h{-}l$), angle at the top of the conical notch (α), geometric parameters of the projectile (D, H), projectile speed (V). These parameters are determined by numerical experiments.

In order to estimate the velocity of the head part of the miniature CJ, a high-speed survey of the jet in flight was carried out. Dynamic loading of microsamples ($h = 6$ mm, $d = 13$ mm, $h{-}l = 1$ mm, $\alpha = 60^\circ$ (Fig. 1)) of M0b copper was performed with a projectile at ~ 600 m/s. Fig. 2 shows the results of shooting.

Time interval between frames is 16 μs. To estimate the jet length, the distance was tied to the number of pixels. The observed velocity of the jet head element in the experiment is ~ 2700 m/s. This value is substantially lower than the CJ velocity formed when using an ES, but the strain rate in this case is comparable to the strain rate of natural CJ. To estimate the deformation rate, we take the initial jet length formed in the CEM experiment as the length of the forming notch — 5 mm, the final length at the time of jet rupture for copper M0b is ~ 14 mm with a process duration 16 μs. Thus, the deformation rate is $\sim 10^5\,\mathrm{s}^{-1}$, i.e., comparable with the estimate of the strain rate for CJs formed from CO with ES [12,13].

2.2. Numerical optimization of experimental parameters

The finite element system ANSYS WORKBENCH 14.5.7 Academic Research was used as a tool for the virtual experiment. The Johnson−Cook model (Johnson−Cook) [14] was chosen to describe the plastic deformation of the steel projectile material (steel 20):

$$\sigma_T = (A + B\varepsilon_p^n)[1 + C\ln\dot{\varepsilon}_p^{\,*}]1 - T_H^m, \tag{1}$$

where ε_p — effective plastic strain, $\dot{\varepsilon}_p^{\,*}$ — normalized effective plastic strain rate, A, B, C, n, m — consistent models, T_H — homological temperature, given by the relation:

$$T_H = \frac{T - T_{\mathrm{room}}}{T_{\mathrm{melt}} - T_{\mathrm{room}}}, \tag{2}$$

where T — current temperature in the material, $T_{textroom}$ — value of room temperature, $T_{textmelt}$ — the melting temperature of the material.

The Steinberg−Guinan model (Steinberg−Guinan) [15] was used to describe the plastic deformation of copper. This model assumes that the shear modulus of elasticity G increases with increasing pressure and decreases with increasing temperature. This assumption allows modeling the Bauschinger effect. In general, in the model under consideration, the shear modulus and yield strength are functions of effective plastic strain, pressure and temperature.

Table 1. Parameters of the Stenberg−Guinan model for copper (material CEM)

Parameter	$C1$, m/s	$S1$	G, GPa	Y, MPa	Constant of hardeners	Index hardeners
Value	$3.94\cdot10^3$	1.489	47.7	90	36.0	0.45

Table 2. Johnson−Cook model parameters for steel 20 (projectile material)

Parameter	μ	C_1, m/s	S_1	C, J/(kg·K)	G, GPa	A, MPa	B, MPa	n	m	T_m, K
Value	2.17	4569	1.49	452	81.8	400	275	0.36	1	1811

The following equations describe the above relations:

$$G = G_0\left\{1 + \left(\frac{1}{G_0}\frac{\partial G}{\partial p}\right)\frac{p}{\eta^{1/3}} + \left(\frac{1}{G_0}\frac{\partial G}{\partial T}\right)(T - 300)\right\}, \tag{3}$$

$$\sigma_T = \sigma_{T0}\left\{1 + \left(\frac{1}{\sigma_{T0_0}}\frac{\partial \sigma_T}{\partial p}\right)\frac{p}{\eta^{1/3}} + \left(\frac{1}{G_0}\frac{\partial G}{\partial T}\right)(T - 300)\right\} \times (1 + \beta\varepsilon_p)^n,$$

on condition

$$\sigma_{T0}(1 + \beta\varepsilon_p)^n \le \sigma_{T\,\max}, \tag{4}$$

where η — compression, i.e. ratio of initial volume to final volume, G_0 and σ_{T0} the values of shear modulus and yield strength in the reference state ($T = 300$ K, $p = 0$ and $\varepsilon_p = 0$) accordingly, $\frac{\partial G}{\partial p}$ and $\frac{\partial G}{\partial T}$ —products of shear modulus of elasticity by pressure and temperature in the reference state, $\frac{\partial \sigma_T}{\partial p}$ — productive of yield stress in the reference state, $\sigma_{T\,\max}$ — maximum possible yield stress value, β and n - constants characterizing hardening.

The model parameters were determined by the calculation-experimental method and refined in verification experiments using the Taylor test. The model parameters for the materials considered are given in Tables 1, 2.

2.3. Verification of the computational model and experimental optimization of experimental parameters

The experimentally optimized parameters are the depth of the conical notch ($h{-}l$), the value of the angle at the top of the conical notch (α) and the value of the distance from CEM to the barrier (f).

Graphs of the dependence of the CJ penetration depth in the steel barrier on the values α, $l$and focal distance (f) to

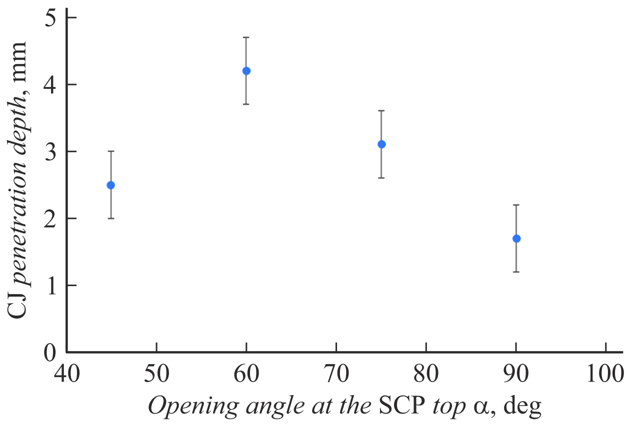

Figure 3. Dependence of the depth of CJ penetration into the steel obstacle on the value of the angle at the apex CEM. Samples of copper grade M0b.

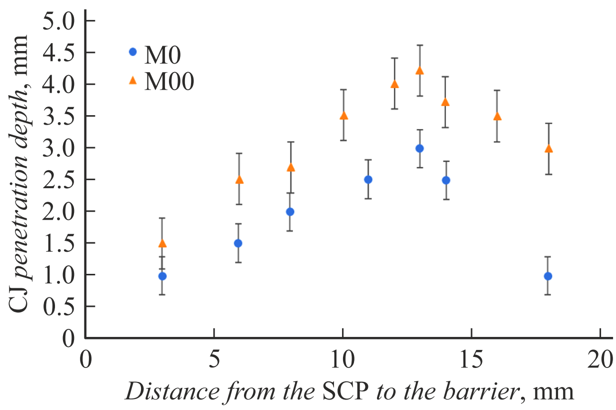

Figure 4. Dependence of the CJ penetration depth in the steel barrier on the distance from the CEM to the barrier for copper samples of M0b and M00k grades.

Table 3. Optimal parameters of the experiment with CEM

Parameter	Value
Sample diameter (d)	13 mm
Sample height (h)	6 mm
Depth of cumulative notch (l)	5 mm
Shape of the cumulative notch	Cone with an angle at the top $\alpha = 60°$
Focal length (f)	13 mm (~ 2 „caliber“)
Projectile diameter	19.8 mm
Projectile height	5 mm
Projectile speed	$\sim$ 600 m/s

the steel barrier 20 are shown in Figs. 3, 4. Each point in these figures is obtained by averaging the results of three experiments. The tests were made at 600 m/s.

Table 4. Results of comparative studies of CJ penetration depth in the steel barrier for different copper grades

Sample №	Depth of CJ penetration into the steel barrier 20, mm										
	1	2	3	4	5	6	7	8	9	10	Average
Copper M0b	3.0	4.0	3.0	3.5	3.5	3.5	3.0	3.0	3.5	2.5	**3.3**±0.5
Copper M00k	4.0	4.5	3.5	4.0	4.0	4.0	3.5	4.0	4.0	3.5	**3.9**±0.5

Figure 5. Photos of CEM after tests. To the left — sample of copper grade M0b, to the right — sample of copper grade M00k.

The optimum parameters of the experiment, which allow to obtain the maximum length of the CJ during the testing of copper CEM, are given in Table 3. The optimal parameters meant the values α, $h-l$ or f, corresponding to the maximum value of the CJ penetration depth into the steel obstacle.

Figure 5 shows a photo of CEMs made of M0b and M00k copper grades after testing. The tapered bulge observed in the lower part of the samples corresponds to the „pestle“ in the case of standard cumulative cladding tests.

2.4. Application of methodology for comparative evaluation of miniature CJ characteristics

2.4.1. Repeatability of results

In order to evaluate the results repeatability at the above test parameters, two series of experiments were conducted, in which 10 samples of M0b copper (series 1) and 10 samples of M00k copper (series 2) were tested. The comparative characteristic was the depth of the cavity formed in the steel barrier. The samples and loading parameters given in Table 3 were used in the experiments. The test results are shown in Table 4. In the course of the experiment, the barrier was a set of plates with a thickness of 1 mm. The rules for determining the insertion depth are as follows: if the plate has an inlet and an outlet hole, then 1 mm is added to the depth, if only the inlet hole, then 0.5 mm.

As can be seen from Table 4, there is a good repeatability of the results for each copper grade.

2.4.2. Influence of mechanical characteristics of the CEM material on the CJ parameters. Copper grade M0b

The analysis of the test results of CEM presented in Table 4 shows that the samples made of M00k copper, which has a higher purity level than M0b copper, have a higher level of penetration depth. The obtained result indicates the high sensitivity of the stability of the cumulative jet flow to the purity of the metal. It can be assumed that impurity atoms segregating along the boundaries of copper grains make it difficult to realize the effect of dynamic recrystallization, which is often considered as one of the mechanisms to ensure stable flow CJ [8,9].

To further verify the sensitivity of the CEM test results to the microstructure parameters, the influence of the copper microstructure on the depth of CJ penetration into the steel barrier was investigated. Hardness was used as a structure-sensitive characteristic. The microstructure parameters were varied by changing the degree of preliminary deformation and the annealing temperature of the copper. The deformation was carried out by Equal channel angular pressing (ECAP) [16] and the deposition of a cylindrical sample in a hydraulic press. In addition, the hardness of CEM material was measured (HRB with a load of 100 kg). The resulting penetration depth was obtained by averaging the tests of the three samples (Table 5).

As can be seen from the data presented in Table 5, with the same hardness value in the initial state, the material can exhibit different depths of CJ penetration into the barrier material, while a significant decrease in hardness does not lead to an increase in the penetration depth. Thus, a decrease in hardness from 64 to 56 HRB leads to an increase in the depth of penetration of the jet into the obstacle from 2.3 to 2.8 mm. A further decrease in hardness from 56.1 to 55.6 HRB leads to a sharp increase in the penetration depth, and a further decrease in hardness from 55.6 to 17.8 HRB, due to the course of recrystallization, leads to a decrease in the penetration depth to 3.5 mm. Consequently, to predict the ultimate dynamic plasticity, it is not enough to certify the strength characteristics of the initial material, but it is necessary to analyze the relationship between the material microstructure and the kinetics of its dynamic deformation and destruction.

Note, that the results obtained indicate the high sensitivity of the developed test methodology to the parameters of the copper microstructure.

Table 5. Results of comparative tests of CEM of M0b

Processing mode	hardness, HRB	depth of penetration of steel barrier, mm
2 ECAP cycles	64.0	2.3
2 cycles ECAP + rolling out	56.1	2.8
2 cycles ECAP + rolling out+230°C	55.6	3.8
2 cycles ECAP + rolling out+280°C	17.8	3.5

3. Discussion and results

1. The results shown in Fig. 4 show that of all the studied values of the angle at the apex of the conical notch, the greatest length of the CJ is observed at the value 60°. This value will be used as the basis for all experiments in the future. In our opinion, reducing the value of the cone angle from 90 to 60° leads to an increase in the velocity of the CJ head part, but at the same time there is a decrease in the jet cross section, which negatively affects the time to rupture [13,16]. With a further decrease in the value of the CEM angle, there is a drop in the penetration depth due to the jet reaching a cross section in which fracture in the drawing process occurs almost immediately after formation CJ.

Note, that the experimental results obtained qualitatively coincide with the results of computer modeling.

2. The results shown in Fig. 4 show that, as in the case of standard cumulation, there is an optimal „focal distance"in the CEM tests. As can be seen from the graph, the penetration depth initially increases as the distance from the CEM to the steel barrier increases. The increase in penetration depth is due to the increased space required by the CJ to be drawn in the high velocity flow mode; the longer the shaped jet, the greater the depth of penetration into the steel obstacle. However, as the length of the cumulative jet increases, more than some critical value, it begins to collapse. As a consequence, the CJ affects the obstacle not as a whole object, but as individual fragments, which leads to a decrease in the value of penetration.

3. The results in Table 5 show that the dependence of the penetration depth on the mechanical characteristics of the material and, consequently, on the microstructure parameters is significantly nonlinear. Additional research is needed to establish the mechanisms of influence of the structure and properties of the CEM material on the depth of embedding.

4. The analysis of the results presented in Tables 4 and 5 shows that the dependence of the depth of CJ penetration into the steel barrier depends, other things being equal, on two factors:

1) metal purity, including the purity of the grain boundaries;

2) degree of preliminary deformation and recrystallization annealing modes.

Increasing the purity of copper leads to an increase in the depth of penetration of the CJ into the steel barrier. Changes in material microstructure and hardness associated with deformation and annealing have a significant effect on the jet penetration depth into the steel barrier.[1] It can be seen that this dependence has the character of a curve with a maximum, and, consequently, a thermomechanical treatment mode can be selected to maximize the penetration depth for a particular material.

Conclusions

1. An experimental technique was developed to study the characteristics of a miniature CJ, allowing us to study the processes occurring during high-speed deformation of the material. The effectiveness of the developed testing methodology of CEM is demonstrated on the example of copper samples of different purity.

2. Numerical model parameters were determined to optimize test conditions for specimens with conical pits. On the basis of numerical calculations and tests, the optimal parameters for the CEM experiment were selected.

3. It is shown that the CJ parameters observed in the tests of copper CEMs are comparable to the parameters of real CJs in terms of strain rate and grain size in the jet material.

4. It is shown that the mode of deformation and heat treatment has a significant influence on the characteristics of miniature CJ. The developed technique makes it possible to conduct a comparative analysis in laboratory conditions of the influence of thermal deformation treatment modes on the depth of CJ penetration into the steel obstacle and to select the modes that provide an increase in the specified characteristic.

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Conflict of interest

The authors declare that they have no conflict of interest.

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[1] The authors did not set out to conduct detailed studies of the effect of copper microstructure on its armor penetration characteristics. Our goal was to develop a test methodology for testing QCD without using ES and to demonstrate its sensitivity to metal microstructure parameters using high-purity copper as an example. Our future works will be devoted to a detailed study of the influence of microstructure parameters on the depth of penetration of a miniature CJ into a steel obstacle.

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