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DISRUPTION OF SHAPED-CHARGE JETS BY A PULSED CURRENT

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This paper gives results from experimental studies of the effect of electric-pulse parameters on the development of current instability and disruption of shaped-charge jets. A simple physical model for the development of current instability and the decrease in the cavern depth in the target is proposed. Notations are introduced and analytical expressions are obtained for the critical current (critical linear current density) and the ideal shape of the current pulse required for the disruption of shaped-charge jets. It is shown that the estimate of the final cavern depths in steel target for the proposed model is in fairly good agreement with both experimental values of cavern depths in targets and with the results of numerical calculations using quasi-two-dimensional unsteady models of MHD *instability and volume disruption.*

Key words: *shaped-charge jet,* MHD *instability, electromagnetic energy.*

Introduction. It has been shown experimentally and theoretically [1–7] that the effect of a pulsed electric current on metal shaped-charge jets (SCJs) significantly changes the jet structure and decreases the time of its disruption. The analysis of this process is of interest both from a practical point of view (reduction in SCJ penetration into targets) and from a methodical point of view — in studies of material behavior and the structure and physical characteristics of shaped-charge jets. The mechanisms of SCJ disruption by a current pulse and the effect of the current on the SCJ penetration into targets practically is not understood. When a current is passed through a jet, the effect of the current on the SCJ is variously manifested (heating of the jet by the current, heating of the jet in contact arcs, thermal softening of the jet material, compression of the jet by the magnetic field, accelerated development of initial necking hydrodynamic instability, volume disruption of the SCJ material when the jet elements leave the electrode system, etc.). Therefore, in [1–3], a generalized concept of the current instability of shaped-charge jets was introduced. Experimental and numerical studies [7] have shown that the passage of a current through a SCJ gives rise to both development of necking MHD instability and volume disruption of the SCJ when the jet elements leave the electrode system. As follows from calculations, the development of a particular mechanism of SCJ disruption due to passage of an electric current through a jet depends on the experimental conditions, electric-pulse parameters, and the time of current passage through the SCJ. Experimentally, these problems have been studied inadequately. In the literature [1–7], one can find primarily illustrations of the possibilities of SCJ disruption by a pulsed current whereas a comprehensive analysis has not been performed.

The present paper reports for the first time results from systematic experimental studies of the effect of electric-pulse parameters on the development of current instability and SCJ disruption. The experimental results suggest a simple physical model for SCJ disruption by a pulsed current, which is convenient for obtaining express estimates of the effect of electric-pulse parameters on the jet disruption and its penetration into targets.

Setup of Experiments. A diagram of the experiments is given in Fig. 1. The experiments were performed using shaped charges of 50 mm diameter with conical copper liners. A current began to flow through the SCJ at the moment the electrodes were closed by the jet. In the experiments, we varied the current and the time derivative of the current ($I = 100$–500 kA and $dI/dt = 3 \cdot 10^9$–10^{11} A/sec), the electric-pulse shape, the time of current action on various jet elements, and other parameters. X-ray photography of the SCJ in the interelectrode gap and in free flight was performed. The difference in the times of photography between experiments with and without a current

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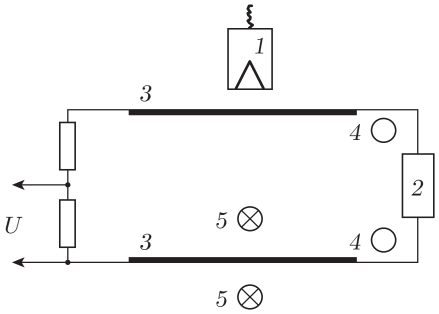

Fig. 1. Diagram of experiments: 1) shaped charge; 2) source of electromagnetic energy; 3) electrodes; 4) inductive probes for measuring the current and the derivative of the discharge current; 5) sites of X-ray photography.

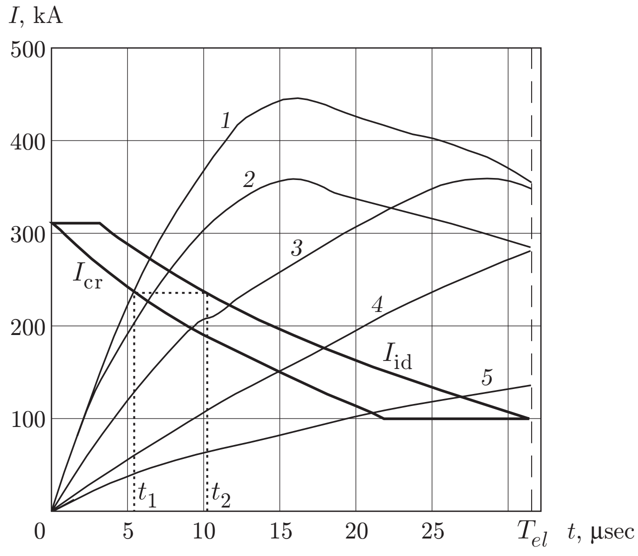

Fig. 2

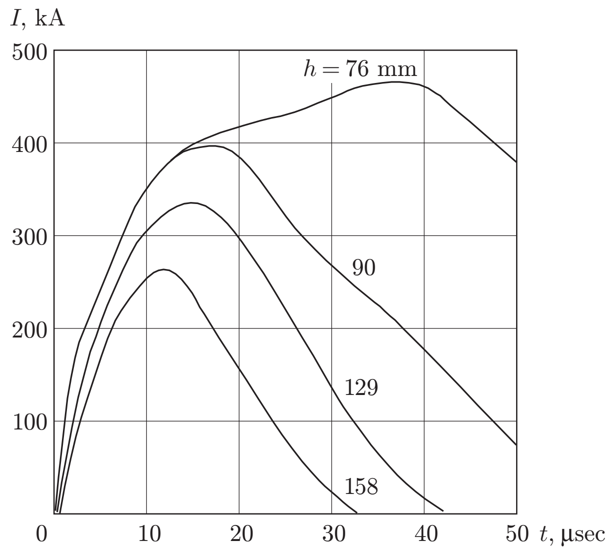

Fig. 3

Fig. 2. Experimental time dependences of a discharge current flowing through a shaped-charge jet: $I_{\rm cr}$ is the critical current; $I_{\rm id}$ is the ideal current shape; T_{el} is the total time of motion of the jet between the electrodes a 50 mm diameter shaped charge; the curve numbers correspond to the experiment numbers in Table 1.

Fig. 3. Experimental time dependences of a discharge current flowing through a shaped-charge jet for $dI/dt \approx$ const.

was not larger than 0.5 μsec. In addition, the effect of the electric current on the SCJ was judged from the depth of jet penetration into the target.

Results of Experiments. Figures 2 and 3 show the characteristic curves of variation of a discharge current flowing through a shaped-charge jet penetrating into a steel target. For each curve in Fig. 3, the penetration depth in the target corresponding to the given condition of electrodynamic effect is indicated. In control experiments without passage of an electric current through the SCJ, the penetration into a steel target was (205 ± 10) mm.

The results of experiments presented in Fig. 2 illustrate the effect of the current rise rate on the final depth of jet penetration into the target. Figure 3 shows the effect of the amplitude and shape of the current pulse on the final penetration depth for a nearly constant initial current rise rate. For $dI/dt \leqslant 3 \cdot 10^9$ A/sec and a current amplitude of less than 100 kA, the current flowing through the jet hardly affects jet disruption and its penetration into the target.

The experiments do not allow one to draw a conclusion on the optimal shape of the current pulse and amplitude required for the controlled action of the current on the final depth of SCJ penetration.

The SCJ penetration depth in a steel target versus capacitor bank energy is shown in Fig. 4. It is evident that for rather moderate values of the source energy (20–40 kJ), the SCJ penetration can be decreased by severalfold.

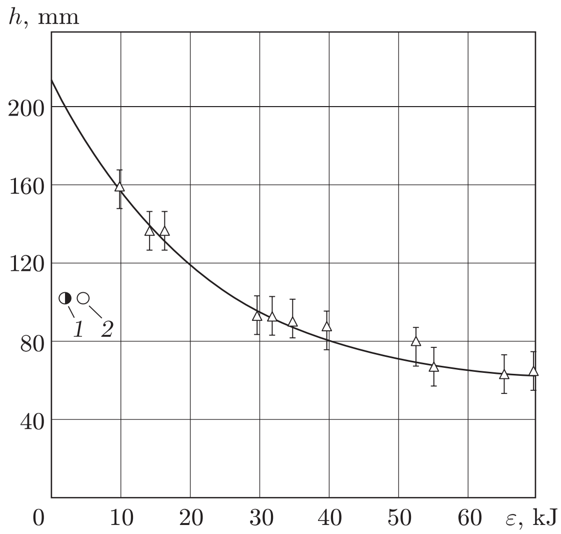

Fig. 4. Experimental curve of the penetration of a shaped-charge jet into a steel target versus the energy accumulated in the capacitor bank: points 1 and 2 are the calculated energies required to decrease the cavern depth by a factor of two for the optimal electric-pulse profile taking into account $I_{\rm cr}(t)$ and $I_{\rm id}(t)$ for a total circuit resistance equal to $5 \cdot 10^{-3}$ and 10^{-2} Ω, respectively.

Figure 5a–c shows pairs of X-ray photographs of SCJ without a current (on the left) and with a current (on the right) taken at various times. The curve of $I(t)$ for these experiments with indicated times of recording is given in Fig. 5d. From Fig. 5a it follows that at the time of exposure, the shapes of the jets without a current and with a current ($I \approx 250$ kA) and are virtually identical. In Fig. 5b and Fig. 5c, the structures of the jets with a current and without a current differ from each other. It can be seen in the X-ray photographs that in the experiments with a current, the SCJs have discontinuities in front of the lower electrode and a noticeable increase in the jet diameter above the discontinuities. Figure 5d clearly shows the development of necks and the formation of a broken segment of the jet. After passage through the lower electrode, the jets with a current break up into separate fragments with axial dimensions equal to about one to three jet diameters. Volume disruption of the elements is observed. The fragments expand in the radial direction and reach five to ten jet diameters in the same cross sections as in the experiments without a current.

An analysis of the X-ray photographs taken at the same time shows that the number of necks on the jet without a current agrees well with the number of fragments in the experiments with a current. From this it follows that magnetic pressure favors the accelerated development of initially small perturbations of the initial hydrodynamic necking instability of shaped-charge jets. The pulsed electric current affects the SCJ elements primarily in the interelectrode gap. This ensures the necessary time of electrodynamic action on the SCJ elements for the development of necking MHD instability.

The experiments did not reveal the occurrence of bending instabilities. The intense expansion of the jet elements in the radial direction after passage through the lower electrode is due to the removal of the magnetic-field pressure and unloading of the jet material. This leads to a subsequent decrease in the average density of the jet material and the effective jet length, and as a consequence, a reduction in the jet penetration capability.

An analysis of the experiments leads to the important conclusions: for an effective action on a shaped-charge jet, the current rise rate and the current amplitude should exceed certain threshold values. The experiments show that it is possible to produce conditions under which the SCJ elements subjected to the action of a current exceeding the threshold value do not contribute to the SCJ penetration into the target after leaving the electrode system. This can serve as a basis for the development of a simple physical model for SCJ disruption by a pulsed current and the decrease in SCJ penetration into the target.

Physical Model for the Effect of an Electric Current on a Shaped-Charge Jet. We consider the effect of an electric current on a SCJ, which is shown schematically in Fig. 6. The current begins to flow through the jet when the electrodes are closed by the jet (Fig. 6a). If the current amplitude and duration do not exceed certain critical values, current instability of the jet does not develop. This corresponds to the case shown in Fig. 5a. In this case, the finite cavern depth does not differ from the control one.

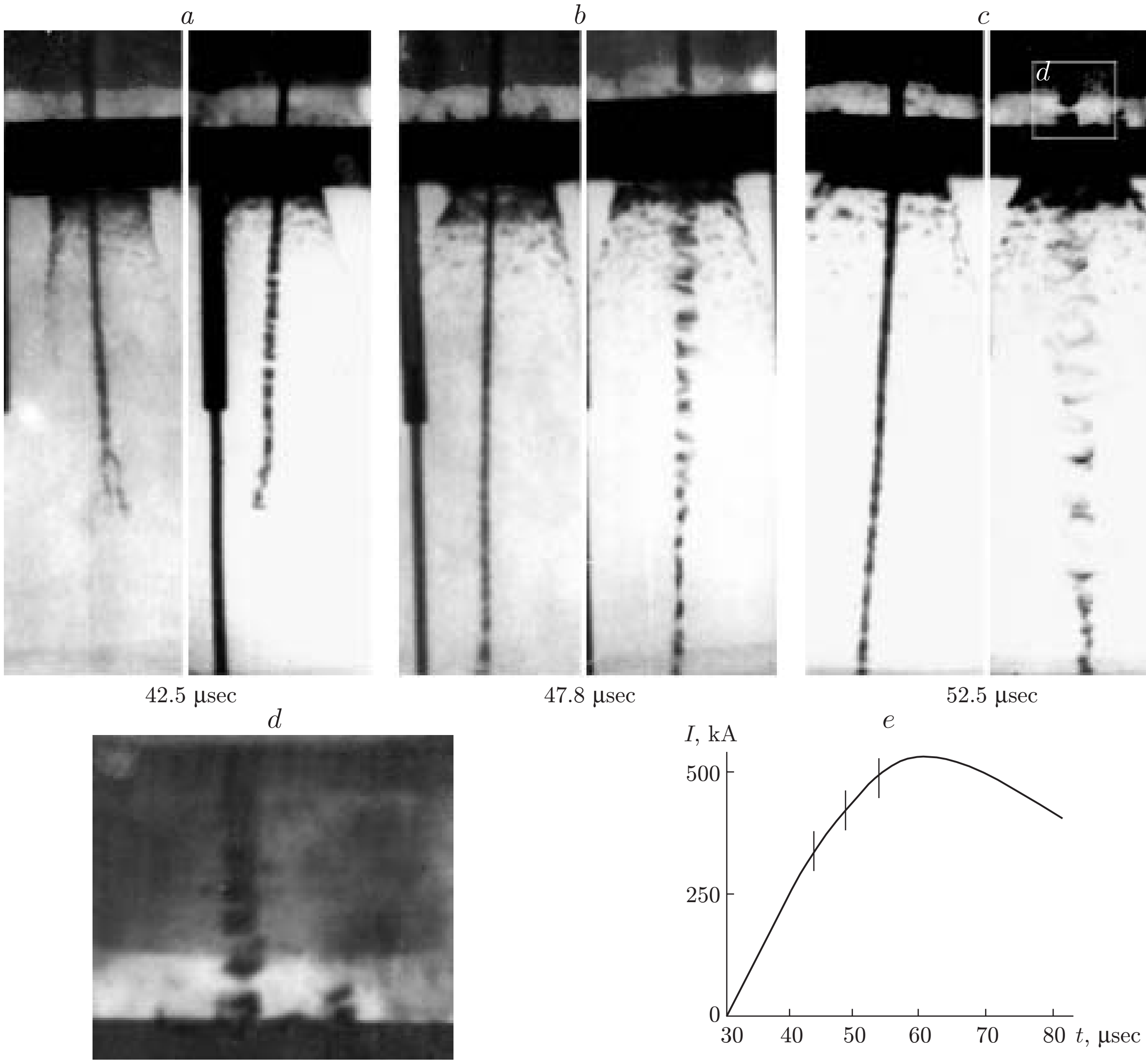

Fig. 5. X-ray photographs of shaped-charge jets without a current (on the left) and with a current (on the right) recorded at various times and the current curve for these experiments with indicated times of recording.

We assume that at the moment t_1 (Fig. 6b), the current flowing through the SCJ reaches the critical value I^* and the SCJ elements leaving the electrode system begin to fail. In Fig. 6b, the first of such elements is shown by a cross. If, in the period of time from this moment to the cessation of SCJ motion in the interelectrode gap, the circuit current exceeds the value I^*, the final SCJ penetration into the target is determined by the length of the SCJ segment from the section indicated by the cross to the bottom of the cavern. Obviously, the faster the current reaches the critical value (the higher the derivative of the current), the smaller the length of the jet segment that has passed through the electrodes without disturbances and the smaller the final depth of the cavern. If, beginning with a certain moment $t_1 + \tau^*$, the current flowing through the jet becomes smaller than I^*, the current instability develops only in the average segments of the jet. The jet tail makes an additional contribution to the penetration depth (see Fig. 6c). From the aforesaid it follows that there may be an optimal energy contribution to the jet to obtain a maximum reduction in SCJ penetration into the target.

The problem of the stability of a liquid conducting cylinder (jets and exploding wires) in the intrinsic magnetic field of an axial electric current was investigated extensively (see, for example, [8–11]). Without discussing the basic propositions and conclusions made in the cited papers, we note only the main result. It has been shown that a liquid metal cylinder of finite conductivity through which an axial electric current is passed is unstable to axisymmetric perturbations of all wavelengths. The natural time of development of necking MHD instability is

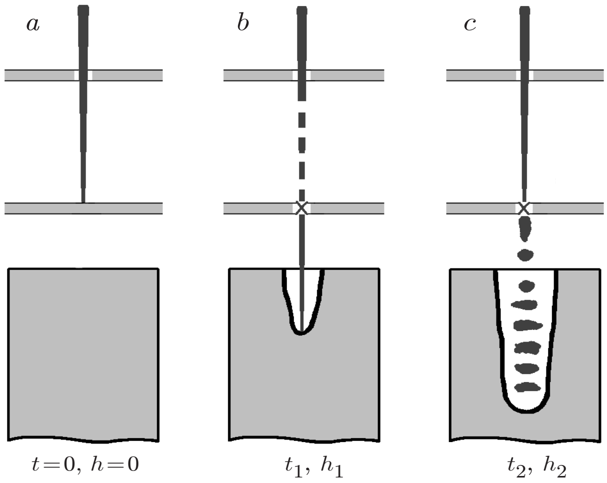

Fig. 6. Diagram of the effect of an electric current on a shaped-charge jet.

given by $\tau \approx \alpha r_0/C_H$, where $C_H = B/(\mu_0\rho)^{0.5}$ is the Alfvén velocity, B is the magnetic-field induction, ρ is the density, r_0 is the jet radius, and α is a coefficient of about unity. Under the conditions of the present experiments, the magnetic-field pressure in the jet far exceeded the strength characteristics of the SCJ material (taking into account the strain rate and temperature). Therefore, the above result can be used in this case, too.

The experimental studies have shown that in order that a shaped-charge jet be substantially affected by an axial current, the following two conditions must be satisfied:

1) the current in the jet should exceed a certain threshold value I^*;

2) the time of residence of the jet element between the electrodes should be sufficient for development of necking MHD instability. The last condition can be written as

$$\tau = \alpha r_0/C_H \leqslant \Delta/u_i, \tag{1}$$

where Δ is the interelectrode distance and u_i is the velocity of the ith jet element.

Substituting the value of the Alfvén velocity C_H [taking into account that $B = \mu_0 I/(2\pi r_0)$] into expression (1) and solving it for the current I, we obtain

$$I \geqslant 2\pi\alpha r_0\sqrt{\rho/\mu_0}\,u_i/\Delta. \tag{2}$$

The average value of the SCJ radius for a conical shaped-charge jet liner is defined by the formula (see [12])

$$\bar{r}_0 = \sqrt{R_c\delta_0/\psi}\,\sin(\varphi/2). \tag{3}$$

Here R_c is the radius of the cone base, φ is the cone angle, δ_0 is the initial thickness of the cone, and ψ is the coefficient of jet elongation under the penetrating conditions. Bearing in mind that $\psi = l_{\rm eff}/l_0$ (l_0 is the length of the generatrix of the cone and $l_{\rm eff}$ is the effective SCJ length), we write Eq. (3) as $\bar{r}_0 = R_c\sqrt{(\delta_0/l_{\rm eff})}\sin(\varphi/2)$. Substituting this relation into expression (2), we obtain

$$I_{\rm cr} = 2\pi\alpha R_c\delta_0\sin(\varphi/2)\sqrt{\rho/\mu_0}\,u_i/(\Delta l_{\rm eff}). \tag{4}$$

Expression (4) is obtained from the condition that the time of development of MHD instability is equal to the time required for the jet element to traverse the interelectrode gap.

If the current amplitude does not exceed $I_{\rm cr}$, MHD instability does not develop. At the time t_1, let the current reach the critical value $I_{\rm cr}$. However, in order that necking MHD instability could develop in the jet element above the upper electrode, this current should be maintained constant in the time interval during which this element traverses the interelectrode gap Δ, from the time t_1 to the time $t_2 = t_1 + \Delta/u_i$.

If in the following, the condition $I > I_{\rm cr}$ is satisfied during the time of passage of all SCJ elements, the final depth of the cavern in the target is determined only by the part of the jet equal to the interelectrode distance. The thus defined shape of the electric current is called the ideal shape of the current pulse.

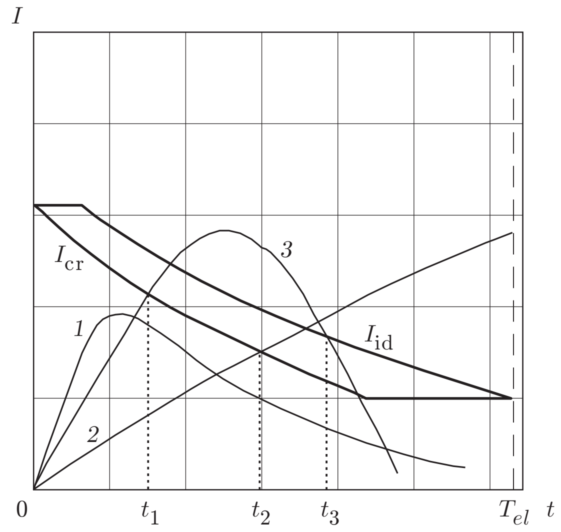

Fig. 7. Effect of electric-pulse parameters (amplitude, shape, and duration) on the cavern depth in the case of electrodynamic action on the shaped-charge jet.

It is known that the velocities of the shaped-charge jet elements along l_{eff} are different; therefore, the values of I_{cr} and I_{id} are determined by the radius and velocity of the jet element at a given time. Assuming that the velocity distribution along the jet has the form

$$u(x) = u_0[1 - \gamma(x/l_{\mathrm{eff}})^n], \tag{5}$$

where u_0 is the velocity of the head element of the jet, $\gamma = 1 - u_{\mathrm{cr}}/u_0$, u_{cr} is the velocity of the tail element of the jet, and n is a factor determined from experiment, then the ideal shape of the current pulse is defined by

$$\frac{I_{\mathrm{id}}(t)}{I^*} = \begin{cases} \varphi(n), & 0 \leqslant t \leqslant t_1, \\ \varphi(n)\psi(n,t), & t_1 \leqslant t \leqslant T_{el}, \end{cases} \tag{6}$$

where $I^* = 2\pi\alpha\bar{r}_0\sqrt{\rho/\mu_0}\,u_0/\Delta$ is the limiting current required for the action on the head element of the jet, $\varphi(n) = 1 - \gamma(\Delta/l_{\mathrm{eff}})^n$, $\psi(n,t) = 1 - \gamma_n(t^*/T^*_{el})^n$, $\gamma_n = 1 - u_{\mathrm{cr}}/u_\Delta$, $t^* = t - t_1$, $T^*_{el} = T_{el} - t_1$, $T_{el} = \gamma\Delta(1 + l_{\mathrm{eff}}u_{\mathrm{cr}}/(\gamma\Delta u_0))/u_{\mathrm{cr}}$, u_Δ is the velocity of the jet element located on the upper electrode at the moment of closure of the electrodes by the jet.

Figure 7 shows the qualitative effect of electric pulses of different amplitudes, shapes, and duration in the case of electrodynamic action of a pulsed current on a SCJ. If the current amplitude is smaller than I_{cr} (curve 1), the effect of the current on the jet is not manifested. For the version shown by curve 2, the effect of the current is manifested at $I > I_{\mathrm{cr}}$ and continues from t_2 to the moment T_{el} when the element leaves the electrode system at a velocity u_{cr}. If the dependence $I(t)$ is described by curve 3, SCJ disruption occurs only in the interval from t_1 to t_3.

Obviously, the experimental current profiles (see Fig. 2) are not optimal from the point of view of minimum expenditures of electric energy for the required reduction in SCJ penetration into the target. In Fig. 4, points 1 and 2 indicate the values of the source energy required for a twofold decrease in SCJ penetration into a steel target if the source ensures the optimal electric-pulse profile taking into account $I_{\mathrm{cr}}(t)$ and $I_{\mathrm{id}}(t)$ for a 50-millimeter charge with a total circuit resistance equal to $5 \cdot 10^{-3}$ (points 1) and 10^{-2} Ω (points 2), respectively.

Table 1 lists experimental final depths of SCJ penetration into a steel target for the current profiles shown in Fig. 2 and the final penetration depths computed with the use of the proposed model for $\alpha = 2$ and using Lavrent'ev's formula [12] taking into account the elongation of the jet elements. For comparison, Table 1 gives values of h for the models of development of necking MHD instability, volume disruption, and their joint manifestation, obtained by numerical solution of the quasi-two-dimensional unsteady problems of the dynamic deformation of a thermally softening conducting high-gradient rod under a known law of time variation of the total current flowing through the rod [7]. The depths of SCJ penetration into a steel target computed using the physical model proposed in the present study agree well with experimental data and results of calculations using quasi-two-dimensional unsteady models. Therefore, the proposed model can be used to obtain express estimates of the electric-current effect on SCJ disruption and to calculate the final depths of SCJ penetration into targets for specified electric-pulse profiles.

TABLE 1

Experimental and Calculated Final Depths of Penetration of a Shaped-Charge Jet into a Target

Experiment number	h_{exp}, mm	Qualitative model		Volume disruption model		MHD instability model		Unified model of MHD instability and volume disruption	
		h, mm	$\frac{\Delta h}{h}$, %	h, mm	$\frac{\Delta h}{h}$, %	h, mm	$\frac{\Delta h}{h}$, %	h, mm	$\frac{\Delta h}{h}$, %
1	79	74	−6	82	4	160	103	82	4
2	91	81	−11	132	45	200	120	98	8
3	147	108	−27	184	25	200	36	200	36
4	160	158	1	200	25	200	25	200	25
5	195	208	7	200	3	200	3	200	3

$\Delta h = h - h_{\rm exp}$.

Thus, the experiments performed show that by controlling the shape and amplitude of the current pulse, it is possible to achieve effective SCJ disruption and a severalfold decrease in SCJ penetration into a target for moderate values of the current and source energy. Jet disruption is accompanied by development of necking MHD instability of the jet moving in the interelectrode gap and by volume disruption of the jet elements leaving the electrode system.

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