Journal of Applied Mechanics and Technical Physics, Vol. 41, No. 1, 2000

BOUNDARIES OF THE PLASMA-FREE REGIME OF ELECTROEXPLOSION OF A FOIL

V. A. Demidov and V. I. Skokov

UDC 621.316.5:537.529

Results of the experimental studies of the commutation characteristics of an electroexplosive breaker upon heating of a copper foil by a current pulse of duration $\tau \approx 1$ msec are given. The dependences of the electric-field strength and the specific power of the circuit breaker during an electroexplosion of the foil on the specific power of the source P_s are found and it is shown that the transition of the plasma-free regime of electroexplosion of the foil to a plasma regime occurs for $P_s = 30$–40 GW/g.

Introduction. It is known that upon heating of a foil by current pulses of duration $\tau \approx 1$ msec its electroexplosion (EEF) can occur in two basic regimes. In the first regime [1], after an EEF the foil resistance is $R \to \infty$, and the current is $I \to 0$. This regime of EEF (we call it a plasma-free regime) is used in electroexplosive breakers (EEB) [2].

Proceeding from the temperature of liquid copper at the initial point of the EEF [3] for $\tau \approx 1$ msec, the process of foil heating is characterized by the rate of increase of its temperature $dT/dt \geqslant 10^9$ K/sec. According to calculated estimates [2, 4], a significant degree of overheating (metastability) of the liquid metal is reached in this case, and the EEF (transition to a two-phase liquid–vapor state) occurs by way of homogeneous vaporization (volume boiling), which is accompanied by an abrupt decrease in pressure and density of the metal. For example, Baikov et al. [5] found that the rate of expansion of the electroexplosion products of an aluminum foil is $v \approx 4$ km/sec for$\tau \approx 1$ msec; this predetermines the high rate of foil-resistance growth, because $v \sim d\gamma/dt \sim dR/dt$, where γ is the density of the foil. For the model used in [2], this rate is one order of magnitude smaller. The measurements [6] of the shock wave generated by an electroexplosion of a copper foil of thickness 40 μm during $\tau \approx 1$ μsec in Plexiglas showed that the pressure profile of the EEF products is close to a triangle with an amplitude equal to approximately 10 GPa and its duration is less than 1 μsec. Here the density and the pressure decrease.

The high rate of foil-resistance growth and the abrupt decrease in density and pressure which accompanies the EEF for $\tau \approx 1$ μsec facilitates the development of ionization (plasma) processes in the electroexplosion products. These processes depend on the degree of ionization and are accompanied by a quasipause of the current [1, 2, 7] and by further increase in the current after the EEF [8]; the latter is used for generation and study of the plasma regimes after an electroexplosion.

To use the EEF for $\tau \approx 1$ μsec in the EEB and obtain its maximum commutation characteristics (to attain high voltages and power and short communication time), a plasma-free regime is required. The energy ranges that must ensure these regimes are not yet known. This study deals with the solution of this problem.

Choice of the Parameter that Determines the EEF Regimes. The parameter at which the EEF regimes are analyzed was chosen based on the following considerations. Andrezen et al. [1] used the specific power of thermal-energy supply to the foil, which was determined at the initial point of the EEF,

Institute of Experimental Physics, Sarov 607190. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 41, No. 1, pp. 14–20, January–February, 2000. Original article submitted April 1, 1998; revision submitted September 22, 1998.

 0021-8944/00/4101-0010 $25.00

as a parameter that determines the degree of metastability of the liquid phase and the subsequent growth of foil resistance in the electroexplosion at the stage of heating. This parameter can be found by means of calculations or by using the power of a source.

Indeed, for a power source, the EEB are an actively inductive LR-load. The energy of the source is spent to create the magnetic energy connected with inductance, and the foil is heated to the state of an overheated liquid. Therefore, at the stage of foil heating and magnetic-energy accumulation, the balance of the source power P_s reduced to the foil mass m_f is of the form $P_s = g + p$, $g = LI(dI/dt)/m_f$, $p = I^2R/m_f$, where L is the inductance of the circuit and I is the current strength. When the source begins to operate ($R \approx R_0$), it is necessary that the source power be spent for magnetic-flux storage in the circuit, i.e., $P_s \approx g$, $P_s \gg p$, and $R_0 \ll L(dI/dt)/I$. However, at the initial point of the EEF ($t = 0$), we have $R \approx (25\text{–}30)R_0$) [1], $I = I_{max} = I_0$, and $dI/dt = 0$; therefore, $P_s = p$. Thus, at this point the specific energy-absorption power of the foil is equal to the specific power of the source.

For $t = 0$, we now specify the linear law of increase in the resistance of the breaker and find its commutation characteristics: the maximum values of voltage U_m, power P_m, and commutation time t_E. At the plasma-free stage of the EEF, the change in foil resistance is generally described by an exponential dependence [1]; however, the ability of the breaker to commutate is determined by the integral $\int R(t)\,dt$, which depends little on the form of $R(t)$. Therefore, for $t > 0$, we specify the resistances of the breaker in the form

$$R = kt, \tag{1}$$

where k is the coefficient of high-speed response of the breaker. According to [1], the quantity k increases with the current density j_0^2 at the initial point of the EEF in the plasma-free regime. In the EEF, the resistance of the foil increases by 2 or 3 order of magnitude [2]; therefore, we ignore the value of R for $t = 0$.

In the case of an arbitrary dependence of the breaker resistance R on the time, the current strength changes by the following law:

$$I = I_0 \exp\Big(-\int \frac{R}{L}\,dt\Big). \tag{2}$$

Since the voltage U and power P of the breaker are determined as

$$U(t) = I(t)R(t), \qquad P(t) = I^2(t)R(t), \tag{3}$$

after substitution of (1) into (2) and then into (3) and differentiation of U and P with respect to t, we obtain the maximum voltage at the breaker and the power

$$U_m = 0.6\Phi_0\sqrt{k/L}, \qquad P_m = 0.43\Phi_0 I_0\sqrt{k/L}, \tag{4}$$

where $\Phi_0 = LI_0$. It follows from (4) that U_m is proportional to $\sqrt{k}$ and Φ_0, and P_m to $\sqrt{k}$ and Φ_0^2. The maximum electric-field strength in the foil and the specific power of the EEB in the EEF are determined as follows: $E = U_m/l$, $P_{sp} = P_m/m_f$, where l is the foil length.

The process of energy transfer from the inductive storage circuit to the load is accompanied by selection of a fraction of the accumulated energy in the breaker in the form of heat, and the commutation time t_E is determined by its power. For an infinitely great load, the total energy $Q_0 = LI_0^2/2$ is released in the breaker, and $t_E = Q_0/P_m = 1.17\sqrt{L/k}$.

The effect of the source power on the output voltage and power of the EEB in the plasma-free regime is schematically shown in Fig. 1; one can see the dependence of the relative resistance of the foil R/R_0 on the specific absorbed energy w_R for various source powers. The dependence $R/R_0 = f(w_R)$ consists of two segments with different angles of slope to the w_R axis. The segments of foil heating, OA_1 and OA_2, are approximated by the linear dependence [2] $R/R_0 = 1 + \beta w_R$, where β is a constant, and correspond to heating of a solid-state metal, its melting, and heating of a liquid metal prior to the beginning of vaporization. The change in the density of the metal at this stage is comparatively insignificant, because the metal is in the condensed state. The stage of electroexplosion proper (segment 2) is characterized by an abrupt and

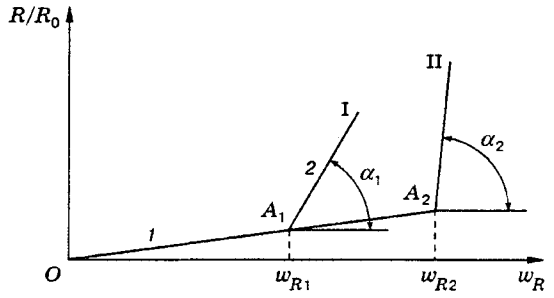

Fig. 1. R/R_0 as a function of the specific energy w_R absorbed at various values of the source power: curves I and II refer to the specific power P_{s1} and P_{s2}, respectively ($P_{s2} > P_{s1}$); segment 1 corresponds to foil heating and segment 2 to the electroexplosion proper.

significant expansion of the foil, which is accompanied by an increase in its resistance by several orders: $R/R_0 \approx 100$ [α_1 and α_2 are the angles of slope of the dependences $R/R_0 = f(w_R)$ to the w_R axes after the electroexplosion]. The points A_1 and A_2 in Fig. 1 correspond to the onset of the EEF.

As is shown in [1], as P_s increases, one can observe two important changes in the dependence $R/R_0 = f(w_R)$:

1) the initial point of the electroexplosion (point A_1) is shifted toward the larger values of w_R and R/R_0 (point A_2), $w_{R2} > w_{R1}$;

2) the foil resistance at the electroexplosion stage grows more rapidly, $\alpha_2 > \alpha_1$.

Since $P_s = p = j_0^2\rho/\gamma$ (ρ is the specific resistance and γ is the density), the current density increases with P_s at the initial point of the EEF. According to [1], for small j_0 this leads to an increase in the coefficient of high-speed response of the breaker k; simultaneously, the broken magnetic flux Φ_0 also increases with the EEB in the circuit, other conditions being equal. It follows from (4) that the quantities U_m and P_m also increase with k and Φ_0. At the same time, for certain values of P_s and j_0, the character of the dependence $R(t)$ in the EEF should change owing to transition of the electroexplosion products to a plasma state [7–9]. However, because the broken magnetic flux continues to grow and the dependence of U_m and P_m of the EEB on Φ_0 is stronger than on k, it is likely that the voltage and power of the EEB also will continue to increase; as a result, a characteristic break should appear in the diagrams of the dependences of the electric-field strength $E(P_s)$ and the specific power of the breaker $P_{sp}(P_s)$, and the angle of slope of these dependences should decrease. These are the considerations on the basis of which we determined the limiting value of P_s in the plasma-free EEF regime from experimental data.

It is noteworthy that the function $P_{sp}(P_s)$ is, in essence, the coefficient of power amplification of the breaker.

Scheme of Experiments. The effect of the specific power of a source on the commutation characteristics of the EEB was studied experimentally on a stand whose electric circuit is shown in Fig. 2. The initial flux in the storage inductance L_0 was formed upon discharging of the capacitor bank C after a breakdown of the discharger D. The charge voltage of the capacitor bank was selected in such a manner that the maximum strength of the current I_0 was 23–25 kA. At the moment of reaching the maximum I_0, an explosive breaker (EB) operated and the circuit with the EEB was simultaneously switched on by an explosive switch (ES). When the storage inductance L_0 was broken, the EB formed a triangular current pulse of duration of order 1 μsec and amplitude of about 10 kA at the EEB.

In all the experiments, a copper foil of thickness 20 μm and section $S_f = 0.02$ mm^2 was used in the EEB; the foil length ranged from 10 to 75 mm. The initial resistance of the foil R_0 was 8.6–65.0 $\mu\Omega$. The power of the source in the experiments was changed from 70 to 220 MW owing to the use of different types of EB. Thus, the specific power of the source varied from 5 to 125 GW/g. The dependence of the electric-field strength E and the specific power P_{sp} in the EEF on the specific power of the source P_s were studied for

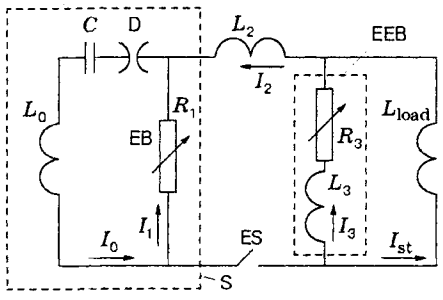

Fig. 2

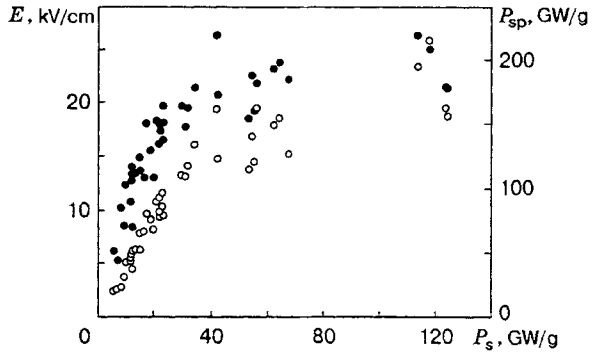

Fig. 3

Fig. 2. Electric circuit of the experimental stand: $L_0 = 4.40$ μH is the inductance of the storage circuit, $L_2 = 0.51$ μH is the buffer inductance, $L_3 = 0.16$ μH is the EEB inductance, $L_{load} = 0.64$ μH is the load inductance; the EB and the EEB are the explosive and electroexplosive breakers, respectively, D is the discharger; the ES is the explosive switch, C is the capacitor bank (240 μF); S is the energy source for EEB charging, R_1 and R_3 are the EB and EEB resistances, respectively, I_0, I_1, I_2, I_3, and I_{st} are the storage-circuit, EB, buffer-inductance, EEB, and load currents.

Fig. 3. Maximum electric-field strengths in the EEB and the specific EEB power in the EEF on the specific power of the power source: filled points refer to the experimental dependence $E(P_s)$, and open points to $P_{sp}(P_s)$, respectively.

current densities of up to $7 \cdot 10^7$ A/cm^2. The electroexplosion of the foil was performed in a medium of quartz sand with grain sizes not larger than 0.5 mm.

In the experiments, integrating Rogowski coils registered the currents in all the circuits, and differentiating Rogowski coils were employed to register the derivatives of the current dI_3/dt and dI_{st}/dt. The total voltage at the EEB U_3 was measured by an ohmic divider assembled from TVO-10 resistors or it was measured with the use of the measured dependence dI_{st}/dt. The measurement accuracy of these quantities in a separate experiment was no less than 10%. The quantities P_s, R_3, E, and P_{sp} (see [1]) were determined with the use of the measured U_3, I_3, dI_3/dt, and dI_{st}/dt at the stage of magnetic-flux storage in the EEB and foil-heating circuits and at the electroexplosion stage proper.

Experimental Results. The experimental dependences $E(P_s)$ and $P_{sp}(P_s)$ are depicted in Fig. 3. In the range $P_s = 5$–125 GW/g, the experimental dependence $E(P_s)$ is satisfactorily approximated by the expression

$$E = 5.68 \ln P_s - 1.55, \tag{5}$$

where E is measured in kilovolts per centimeter, and P_s in gigawatts per gram.

The resulting dependence $E(P_s)$ is a monotonically increasing function having two characteristic intervals with different rates of E increase. For $P_s = 5$–28 GW/g, this dependence is linear, and $k_E = dE/dP_s \approx 0.8$; for $P_s = 28$–35 GW/g, there is a break on the curve; in the interval $P_s = 40$–125 GW/g, the mean value of k_E is approximately 0.1.

The experimental points $P_{sp}(P_s)$ in the studied range of P_s are approximated by a dependence similar to (5). The monotonically increasing function also has two intervals with different coefficients of power amplification $k_p = dP_{sp}/dP_s$. The lengths of the first intervals, on which k_E and k_p are much greater than those on the second ones, are almost the same ($P_s = 5$–35 GW/g). On these intervals, the EEB operates in the mode of a power amplifier with constant amplification coefficient $k_p = dP_{sp}/dP_s \approx 4$. For $P_s = 35$–40 GW/g, the dependence $P_{sp}(P_s)$ has a break, and, for $P_s = 45$–125 GW/g, the EEB operates in the mode of power attenuation ($dP_{sp}/dP_s \approx 0.7$).

It follows from our experiments that to reach the maximum voltage and power of the EEB, it is necessary to increase the power of an energy source. The efficiency of the breaker depends greatly on the value of P_s.

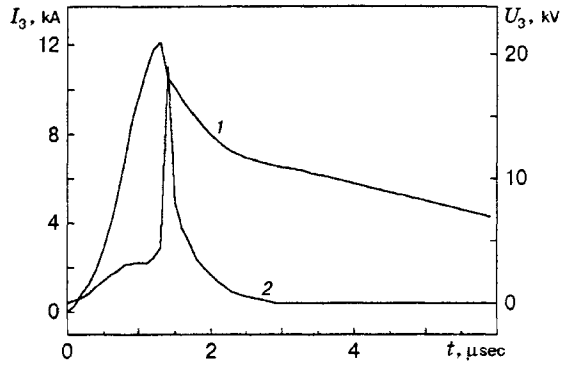

Fig. 4. Oscillograms of the foil electroexplosion for $P_s = 69$ GW/g: curves 1 and 2 refer to $I_3(t)$ and $U_3(t)$, respectively.

For $P_s \leqslant 30$ GW/g, the coefficients of power k_p and voltage k_E amplification are maximum and are the constant parameters of the breaker. As a function of the source power $W = P_s m_f$, the peak values of U_m and P_m are determined as follows: $U_m = k_E W$ and $P_m = k_p W$. For $P_s > 45$ GW/g, the values of k_E and k_p decrease significantly. We now clarify the possible reasons of this phenomenon. Based on the experimental dependences $E(P_s)$ and $P_{sp}(P_s)$ and our considerations concerning the experimental procedure, one can assume that, for $P_s = 30$–40 GW/g, the character of the dependence $R(t)$ changes owing to transition of the electroexplosion products to a plasma state. Figure 4 shows the oscillograms $I_3(t)$ and $U_3(t)$ in one of the experiments for $P_s = 69$ GW/g and $j_0 = 6.04 \cdot 10^7$ A/cm^2.

The character of change of the foil resistance in the experiment is similar to the experimental curves $R_3(t)$ obtained in [7–9]. Upon heating of the foil to the initial point of the EEF, the foil resistance $R_3(t)$ grows slowly and then abruptly and attains its maximum for approximately 0.1 μsec; and then it smoothly decreases almost to zero for about 1 μsec. One can observe the stage of current quasipause in the EEB: after the EEF, the current in the breaker is not interrupted and remains quite high (5–6 kA) for more than 3 μsec at an almost zero voltage.

Detailed studies [2] of the electroexplosion of an aluminum foil located in a dusty quartz have confirmed that the formation of a quasipause of the current is related to the development of light ionization (plasma) phenomena. Burtsev et al. [2] register light ionization phenomena in the regimes in which the quasipause of the current was not observed.

The value of P_s at which the electroexplosion of an aluminum foil passes to a plasma regime can be estimated on the basis of the following considerations: $P_s^{Al} = P_s^{Cu} Z$, where Z is the reduction coefficient. The correction coefficient is equal to

$$Z = \frac{j_{Al}^2}{j_{Cu}^2} \frac{\rho_{Al}}{\rho_{Cu}} \frac{\gamma_{Cu}}{\gamma_{Al}}. \tag{6}$$

At the initial point of electroexplosion, the cofactors in (6) are determined via the physical properties of liquid aluminum and copper [10, 11]. The first cofactor is determined by the specific integral of action of the current in aluminum and copper in a liquid state [10] and is approximately 0.4. The second and third cofactors are approximately 1.6 and 3. Thus, we have $Z \approx 2$, and the values of P_s for aluminum that ensure a plasma regime coincide in order of magnitude with the value of P_s for the copper foil.

When the EEF passes to a plasma regime, the phenomenon of voltage pulsation in the foil was also revealed. In Fig. 5, the oscillograms of $I_3(t)$ and $U_3(t)$ for $P_s = 118$ GW/g are shown. The frequency of damping oscillations is approximately 12 MHz, and their duration is greater than 3 μsec. Since the active voltage component is almost zero ($R_3 \approx 0$) in this regime, the voltage oscillations after the EEF can be connected with variation in the natural inductance of the foil. Upon expansion of the EEF products, the pressure in them decreases abruptly, whereas the pressure in the magnetic field remains almost constant

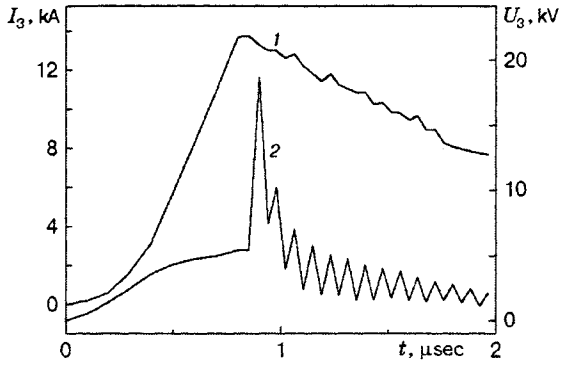

Fig. 5. Oscillograms of electroexplosion of the foil for $P_s = 118$ GW/g: curves 1 and 2 refer to $I_3(t)$ and $U_3(t)$, respectively.

($I_3 \approx$ const); this causes deceleration and reverse plasma motion. The phase of EEF-product expansion is replaced by their compression. The internal pressure again rises during the axisymmetric deceleration of the products, and the electroexplosion products again expand.

To substantiate this assumption, we now estimate numerically the values of $I_3(dL_3/dt)$. According to [12], the expression for the inductance of a single rectangular wire at high frequency can be approximated in the form

$$L_3 \simeq \frac{\mu_0 l}{2\pi}\left(\ln \frac{nl}{\delta + b} - 1\right), \tag{7}$$

where μ_0 is the magnetic permeability; l, b, and δ are the length, width, and thickness of the foil, respectively, and n is a constant. We differentiate (7) with respect to t, assuming that L_3 changes only if the foil thickness changes in the EEF, and multiply the resulting expression by I_3. Then

$$I_3 \frac{dL_3}{dt} \simeq -I_3 \frac{\mu_0 l}{2\pi} v(b + \delta)^{-1}, \tag{8}$$

where $v = d\delta/dt$ is the rate of foil expansion. Substituting $I_3 = 10^4$ A, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m, $l = 25 \cdot 10^{-3}$ m, $b + \delta = 10^{-3}$ m, and $v = 10^6$ m/sec into (8), we find that at the stage of foil electroexplosion, the term in the expression for U_3, which is related to variation in foil inductance, can be approximately 5 kV. This estimate is in satisfactory agreement with the experimental dependence of U_3 (see Fig. 5) whose oscillation frequency after the EEF relative to the mean position is also several kilovolts.

It is necessary to mention that the current $I_3(dL_3/dt)$ can appear only in the plasma EEF regime. In addition, the estimate of $I_3(dL_3/dt)$ and its possible change from experiment to experiment because of the change in the electric-field pattern make it possible to explain the significant scatter of the experimental points $E(P_s)$ and $P_{sp}(P_s)$ in the plasma regime; therefore, registration and analysis of the commutation characteristics of the EEB in this regime are not meaningful.

Conclusions. In the studied range of specific powers of the source $P_s = 5$–125 GW/g, for a heating regime of a copper foil with current density $j \approx 10^7$ A/cm^2 and current-pulse duration $\tau \approx 10^{-6}$ sec, the electric field strength E and the specific power of the EEB P_{sp} in the EEF increase monotonically from 5.4 to 25 kV/cm and from 20 to 214 GW/g, respectively. As P_s increases, the quantities E and P_{sp} grow rapidly in the same manner on the intervals $P_s = 5$–28 GW/g and $P_s = 5$–35 GW/g, respectively. For $P_s < 30$ GW/g, the dependences $E(P_s)$ and $P_{sp}(P_s)$ are linear, and the EEB has a constant factor of power amplification. After the EEF, the angle of slope of the curve of $E(P_s)$ and $P_{sp}(P_s)$ at $P_s > 45$ GW/g and $j > 6 \cdot 10^7$ A/cm^2 in the EEB decreases owing to transition of the copper foil to a plasma state. The plasma-free EEF regime occurs at a specific power of the source equal to $P_s < 30$ GW/g.

REFERENCES

1. A. B. Andrezen, V. A. Burtsev, V. M. Vodovozov, and A. A. Drozdov, "Commutative properties of electrically exploded foils in arc-extinguishing media," *Zh. Tekh. Fiz.*, **50**, No. 11, 2283–2294 (1980).
2. V. A. Burtsev, N. V. Kalinin, and A. V. Kuchinskii, *Electric Explosion of Conductors and Its Application to Electrophysical Devices* [in Russian], Énergoatomizdat, Moscow (1990).
3. M. M. Martynyuk and O. G. Panteleichuk, "Determination of the critical temperature of metals by the method of electric explosion of conductors under pressure," *Teplofiz. Vys. Temp.*, **14**, No. 6, 1201–1205 (1976).
4. M. M. Martynyuk, "Role of evaporation and boiling of a liquid metal during an electric explosion of a conductor," *Zh. Tekh. Fiz.*, **44**, No. 6, 1262–1270 (1974).
5. A. P. Baikov, V. A. Belago, A. M. Iskol'dskii, et al., Study of the electric explosion of foils," *Fiz. Goreniya Vzryva*, No. 2, 286–290 (1973).
6. A. B. Pavlovskii, V. I. Kashintsov, B. L. Glushak, and S. A. Novikov, "Generation of a mechanical pulse by an electroexplosion of a conductor," *Fiz. Goreniya Vzryva*, No. 3, 124–126 (1983).
7. A. P. Baikov, L. S. Gerasimov, and A. M. Iskol'dskii, "Experimental study of the electrical conductivity of an aluminum foil during an electric explosion," *Zh. Tekh. Fiz.*, **45**, No. 1, 49–55 (1975).
8. V. A. Burtsev, A. M. Bezdol'nyi, V. A. Dubyanskii, et al., "Study of the electric explosion of cylindrical foils in air. 3. High-power divergent discharge," *Zh. Tekh. Fiz.*, **50**, No. 6, 1216–1225 (1980).
9. A. P. Baikov, A. M. Iskol'dskii, and Yu. E. Nesterikhin, "Electric explosion of wires at high rates of energy supply," *Zh. Tekh. Fiz.*, **43**, No. 1, 136–141 (1973).
10. H. Knoepfel, *Pulsed High Magnetic Fields*, North Holland, Amsterdam–London (1970).
11. G. R. Gathers, "Thermophysical properties of liquid copper and aluminum," *Int. J. Thermophys.*, **4**, No. 3, 209–226 (1983).
12. P. L. Kalantarov and L. A. Tseitlin, *Calculation of Inductances* [in Russian], *Atomenérgoizdat*, Leningrad (1986).