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Estimation of the melting current of closed high-current electrical contacts during pulsed heating

© M.A. Pavleino, O.M. Pavleino, M.S. Safonov

St Petersburg University, The Faculty of Physics,
198504 Peterhof, St. Petersburg, Russia
e-mail: s.pavleino@yandex.ru

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Based on the generalization of a large number of experimental data, an estimated formula is proposed that makes it possible to determine the value of the minimum melting current of closed contacts by short-circuit shock currents. The accuracy of the obtained results was estimated, which makes it possible to conclude that this formula can be used to carry out practically significant calculations.

Keywords: short-circuit currents, contact spots, melting current, cold contacts.

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Introduction

In case of accidents in the power grid, short-circuit currents flow through closed contacts for several dozen periods until the protection system identifies the resulting current as an emergency current and the contacts are disconnected [1,2]. At the same time, in the first half-cycle, there may be a surge of current (impact short-circuit current, ISC), the value of which may be almost twice the steady-state value of the emergency current $I_{\mathrm{SC}} : I_{\mathrm{IC}} :\approx 1.8 I_{\mathrm{SC}}$ [3,4]. The presence of such a surge in current leads to a short-term increased power release. The heat released in this case leads to local heating of the vicinity of the contact spots (CS) — the heat front does not have time to move to a distance of more than 3–4 radii of CS during the current rise from the beginning of the short circuit to the first maximum [5]. This causes a sharp jump in the temperature of the CS, which can reach a melting point of T_m.

CS melting almost always leads to fatal welding of contacts and loss of operability of electrical devices. This makes the question of how to estimate the current value at which their melting begins relevant when designing contacts. This current value is denoted by I_m.

We will look for a way to estimate the melting current based on a generalization of experimental data on the heating of contacts when pulsed currents are passed through them, representing a sinusoidal oscillation that decays over several periods. Block diagram of the experimental setup [5] is shown in Fig. 1, *a*.

It is a battery of high-voltage capacitors with high capacity, which is connected to the contacts under study via a transformer Tr. The current that is passed through the contacts is formed by an oscillating circuit formed by a battery of capacitors and the primary winding of the transformer (Fig. 1, *b*). The amplitude of the current in the first half-cycle can vary in the range of 0–100 kA. Its value depends on the charge level of the capacitor bank. The current flows through a pair of investigated contact-the melting current of the parts. The lower one was fixed motionlessly, and a contact pressure force was applied to the upper one using a mechanical drive, the value of which could vary within $F_{\mathrm{CP}} = 0 - 2500\,\mathrm{N}$. There are three channels for measuring the current flowing through the contacts $I(t)$, the voltage across them $U_c(t)$ and the force of contact pressure $F_{\mathrm{CP}}(t)$.

Massive cylinders with diameters of 20 and 40 mm with a flat end or conductive buses with a thickness of 2 to 10 mm were used as fixed contact parts (Fig. 2). The upper movable contact parts were cylinders with diameters of 5, 20, and 40 mm with a spherical or conical contacting surface, as well as a surface resembling the tip of a powerful soldering iron. Thus, the contacting surfaces were of the type „plane–sphere", „plane–cone" or „plane–tip". As a result of mechanical interaction, a circular or filamentous CS is formed. In the case of using flat buses as lower electrodes, it was possible to move the upper electrodes along the axis of symmetry of the bus from its center to the edge.

A method for calculating contact heating by pulsed currents is described in Ref. [5–11], based on experimentally measured oscillograms of the current flowing through the contacts $I(t)$ and the contact potential difference $U_c(t)$. It allows calculating the temperature distribution in the contact vicinity during the flow of current over a wide temperature range up to the melting point. To perform calculations, there is no need to repeatedly solve a mechanical contact problem to determine the change in the size of the contact spots over time. This information is obtained from the knowledge of the dependency $U_c(t)$.

Numerous calculations of the heating of axisymmetric cylindrical contacts have been carried out. Their results

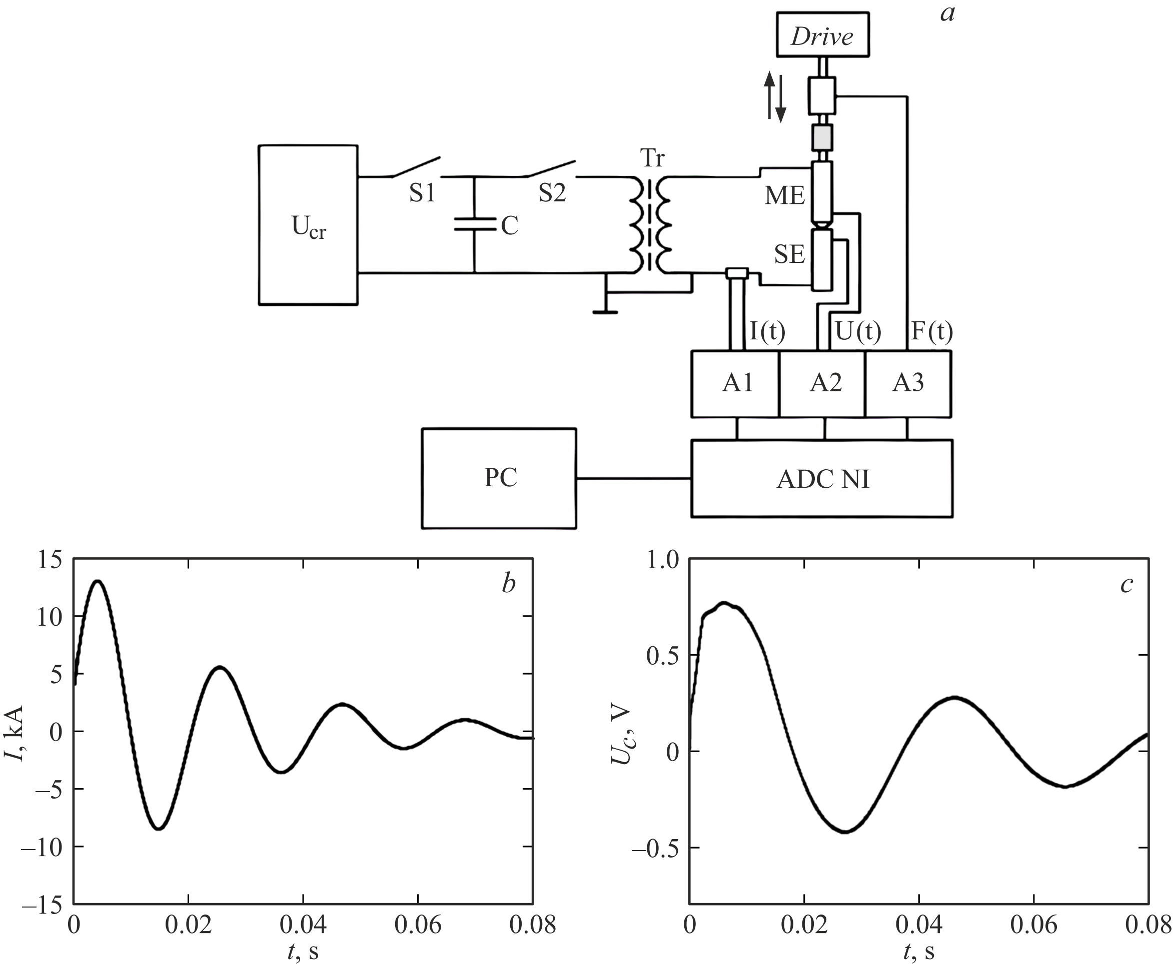

Figure 1. Block diagram of the experimental setup (*a*), a typical oscilloscope of the generated current (*b*), an oscilloscope of the voltage drop across the contacts (*c*).

show that the heating of the contacts to T_m and the beginning of the melting process correspond to the appearance of a feature on the contact voltage waveform when the increase in the value of $U_c(t)$ stops with increasing current. Such an oscilloscope is shown in Fig. 1, *c*. The presence of this feature is analogous to the behavior of the $R{-}U$-characteristics of contacts when approaching the melting point [12,13] for direct current heating in the case of pulsed currents. Thus, the analysis of voltage waveforms on the contacts allows you to record the fact that the melting point has been reached and determine the time when this happened.

1. Obtaining an estimation formula for finding the melting current

The following main parameters have a significant effect on the value of the melting current:

— contact pressure force,

— contact spot shape,

— the proximity of the contact spot to the contact part boundary.

All these parameters could vary widely during experiments to determine the melting current.

As noted, the force of the contact pressure could vary from 0 to 2500 N, the shape of the CS ranges from round to filamentous. The distance from the CS to the border varied as follows. In the case of two cylindrical electrodes, their surface approached the spot by reducing the radius of the cylinders. In case of usage of flat buses, the distance from the control panel to the border (the lower surface of the bus) was changed by changing the thickness of the bus, or by moving the movable electrode along the axis of the bus to its end at a distance comparable to the size of the control panel.

As a result of the measurements, a large database has been accumulated on measuring the melting current in a wide range of contact pressing forces for contacts that differ in their geometry, shape of the CS and the proximity of the spot to the boundaries of the contact parts. The material

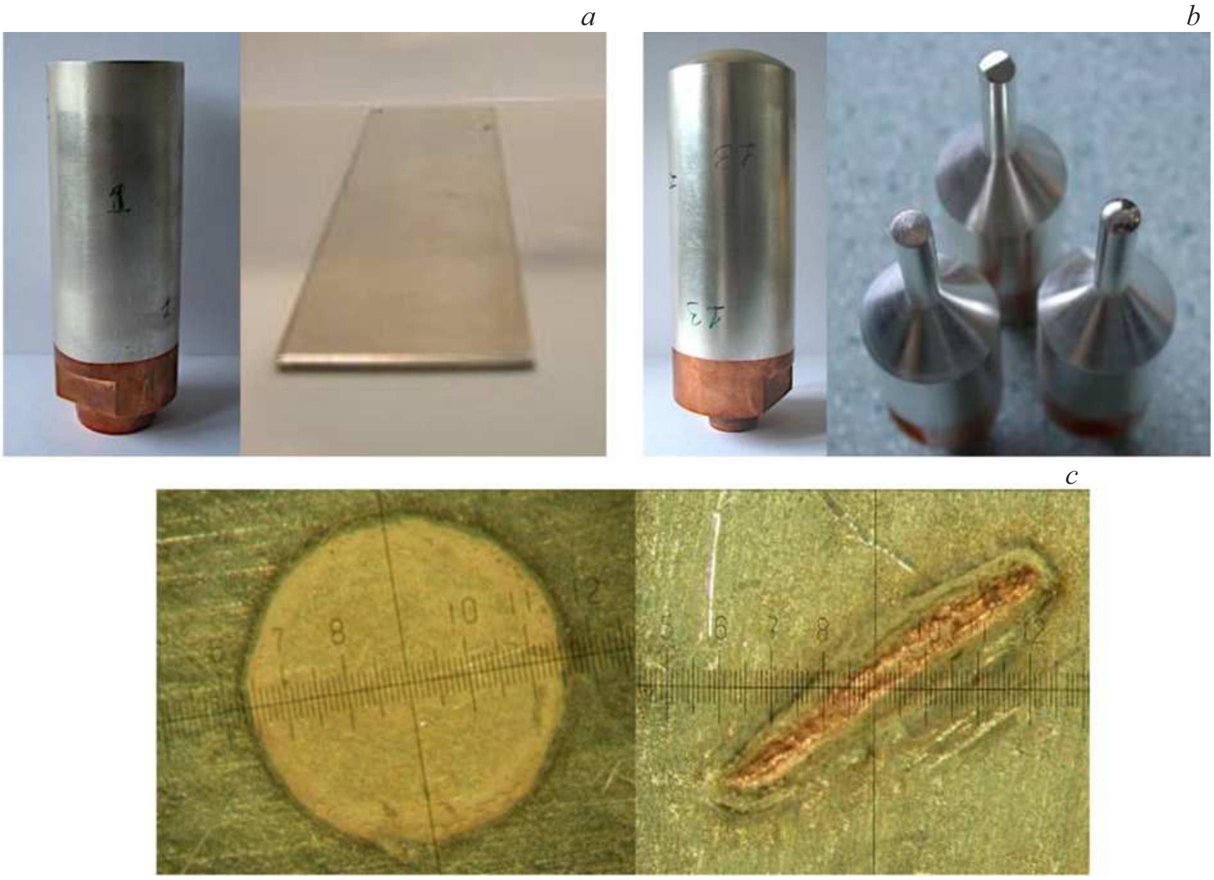

Figure 2. Lower fixed electrodes (a), upper movable electrodes (b), contact spot micrographs (c).

from which the contacts were made is a technically pure copper grade M1E.

To obtain an estimated formula for I_m, we write down the ratio that relates the values of current, contact voltage, and contact resistance at the moment of melting $t = t_m$:

$$I(t_m) = \frac{U_c(t_m)}{R_c(t_m)}. \tag{1}$$

This expression is not a standard notation of Ohm's linear law, which relates voltage and current at any given time, but refers only to the moment $t = t_m$. The contact resistance is not constant, it depends in a complex way on the temperature distribution in the contact area and the size of the CS, which change over time.

The expression (1) implicitly includes a large number of parameters characterizing a specific type of contacts. To identify the most significant of them, let us turn to Fig. 3 that shows the dependences of R_c on the above factors for cylindrical electrodes are shown.

Fig. 3, a shows the change of R_c/R_{c0} in case of change of the shape of the CS from a circle to an ellipse, λ — the ratio of the semi-axes of the ellipses, R_{c0} — contact resistance for the case of a round CS. Fig. 3, b shows the dependence of R_c on the proximity of the spot to the lateral surface of cylindrical electrodes; parameter s is equal to the distance from the edge of the CS to the surface of the electrode. Fig. 3, c shows the dependence of R_c on the magnitude of the contact force for cylindrical contacts with a diameter of 40 mm with the shape of the contacting surfaces „cone-plane“.

In the first two cases, the contact resistance changed by tens of percent, while in the third case, it changed by a multiple. Such very rough estimates allow us to assume that the contact pressure has the greatest effect on the value of the contact resistance and, consequently, on the melting current. Therefore, we will systematize the experimental data according to this parameter.

Let's write (1) in a slightly modified form:

$$I_m = \frac{K_U U_m^{Cu}}{K_R R_c^{cold}}. \tag{2}$$

The value $K_U = \frac{U_c(t_m)}{U_m^{Cu}}$ represents the dimensionless melting stress. Here, the value $U_m^{Cu} = 0.43\,\mathrm{V}$ is the melting voltage of copper under stationary heating [12], which is a characteristic of the material. The value $K_R = \frac{R_cC(t_m)}{R_c^{cold}}$ is the dimensionless contact resistance at the moment of melting; it characterizes the change in contact resistance when heated to melting compared to the initial value of the resistance of cold contacts R_c^{cold}.

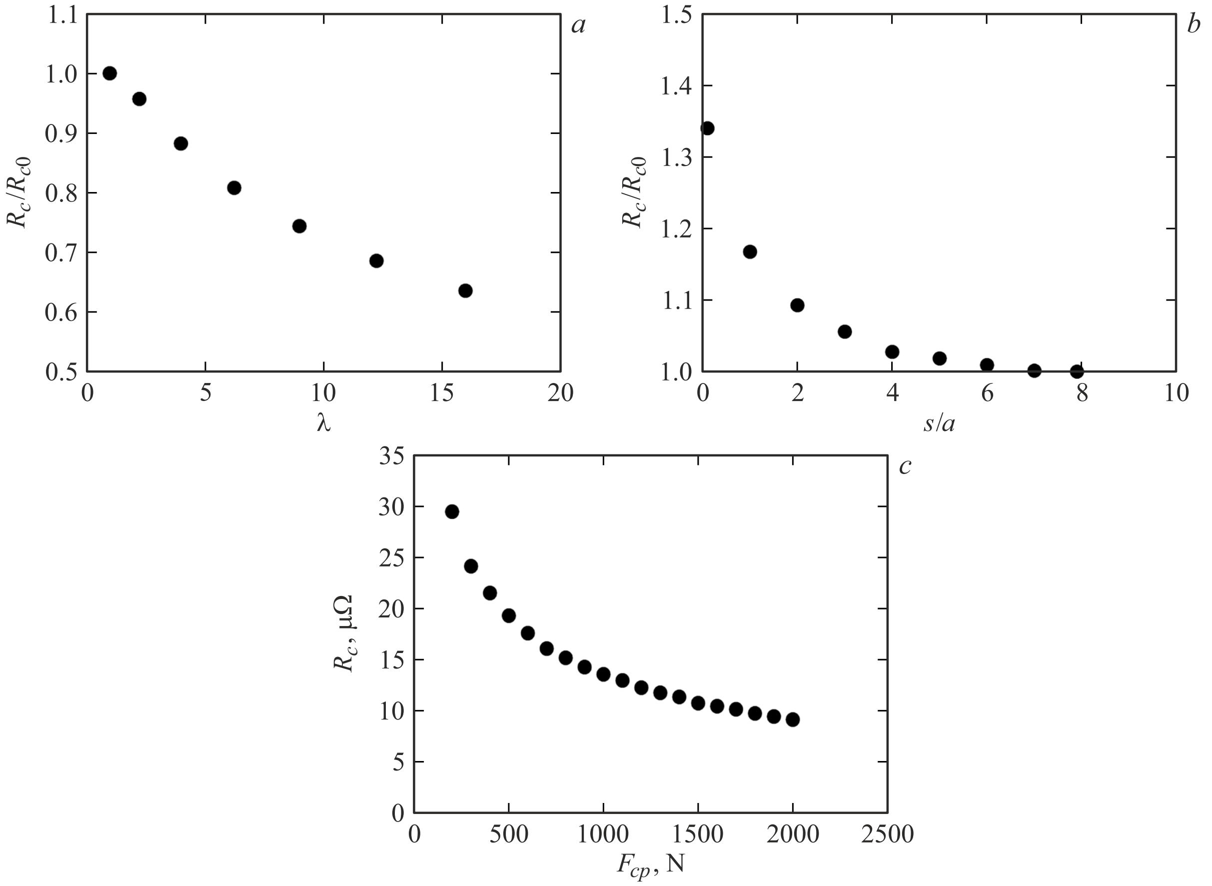

Figure 3. The dependence of the contact resistance on the shape of the contact spot (a), the proximity of the contact spot to the side surface of the cylindrical electrodes (b), the force of the contact pressure (c).

Comparison of melting current for contacts of different types

Type of contacts	Type of contact surfaces	Contact spot shape	F_{cp}, N	R_c^{cold}, $\mu\Omega$	I_m, kA
Cylinder–cylinder	Cone - plane	Round	500	18.7	15.4
Cylinder–Bus	„Tip“–plane	Filamentous	300	18.8	15.0

We present experimental data on the melting voltage and contact resistance for electrodes of various shapes with different CS shapes, grouping them only by the value of the contact pressing force (100, 300, 1000 and 2500 N) — Fig. 4. The abscissa axis shows the implementation number of the current transmission that led to the melting of the contacts at a given contact pressure. The moment of the beginning of melting was determined by the appearance of a feature on the voltage waveform. A solid line marks the average values of the values given in each figure.

The following conclusion can be drawn based on the analysis of these dependencies, . For each value of the contact pressing force, the value of the contact voltage and contact resistance measured at the moment of the beginning of melting is practically independent of the geometric factors characterizing the tested contacts, for all their diversity. The values shown have deviations from their average within 10 %.

The average values themselves increase monotonously with a change in the force of the contact pressure from $F_{cp}^{\min} = 100$ N to $F_{cp}^{\max} = 2500$ N (Fig. 5).

The same figure shows the dependence of the quotient of two entered values on the force of the contact pressure $K = \frac{K_U}{K_R}$. This coefficient is practically independent of the applied force when it varies over a wide range by 25 times. Its average value is 0.65.

Considering this, the expression for the minimum melting current has the following form:

$$I_m = 0.65\,\frac{U_m^{Cu}}{R_C^{cold}}. \quad (3)$$

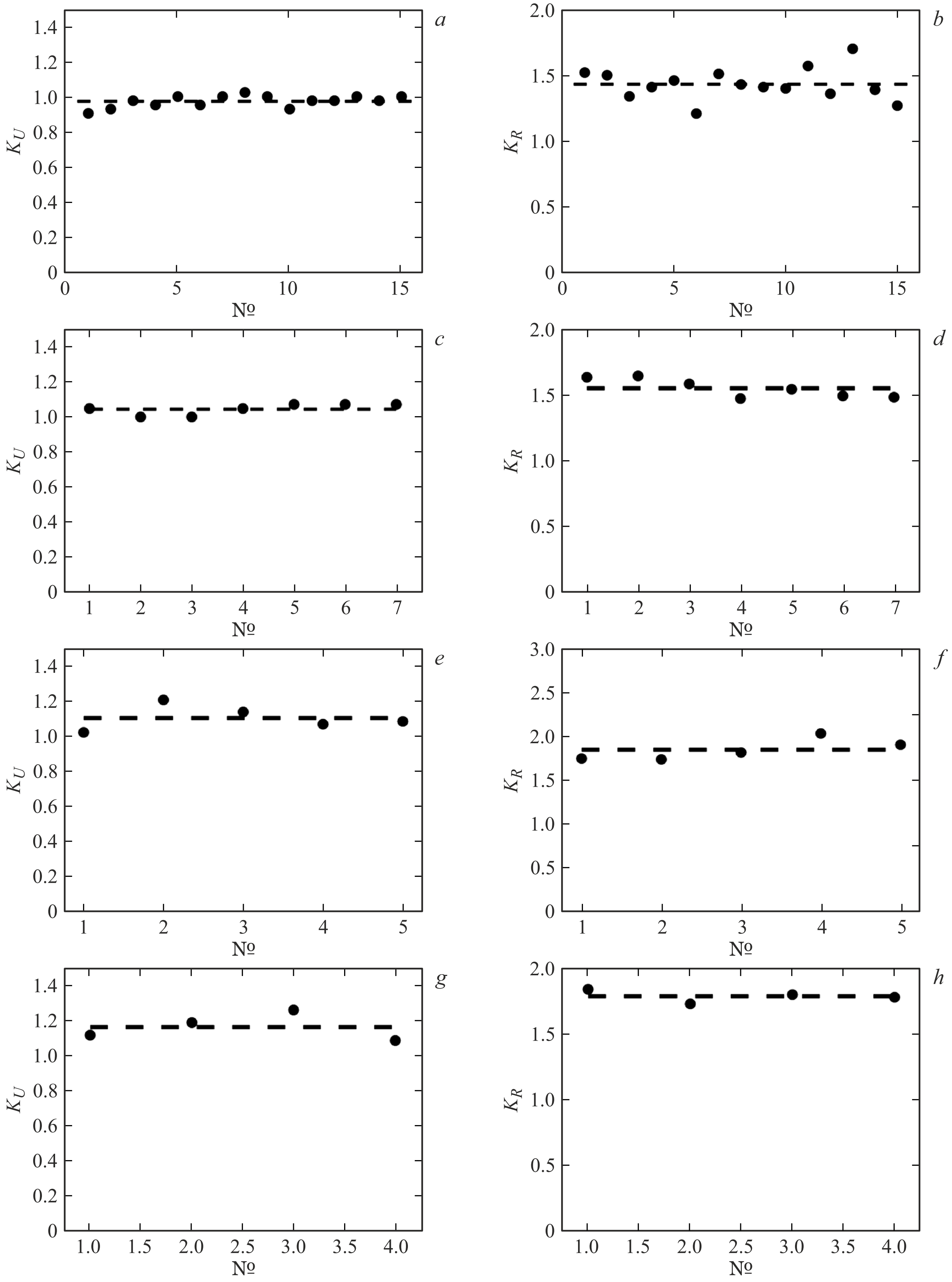

Figure 4. Values of coefficients K_U and K_R for different values of contact pressure: *a*, *b* — 100; *c*, *d* — 300; *e*, *f* — 1000; *g*, *h* — 2500 N. № — the number of the current transmission implementation.

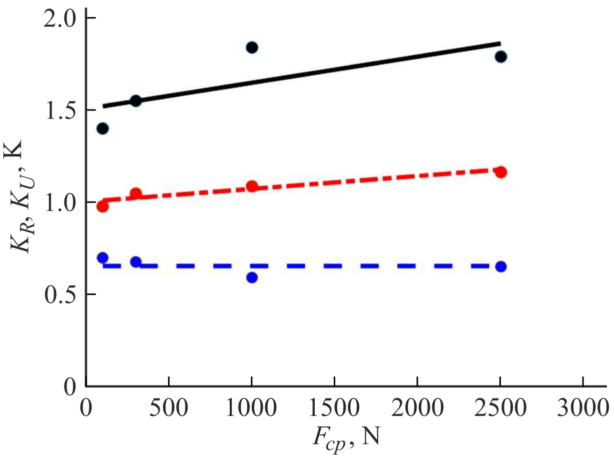

Figure 5. Dependences of coefficients K_R (upper graph), K_U (middle graph) and K (lower graph) on the force of the contact pressure.

Let's show how close the estimate of the minimum melting current obtained using this expression is to the experimentally measured values. Such a comparison is shown in Fig. 6. Here are data on all experimentally recorded cases of melting during the passage of shock current through electrical contacts of all listed types.

Since (3) explicitly does not include the force of contact pressure and the geometric characteristics of the electrodes, the information shown in the histogram is ordered by melting current, and not grouped by any other criteria.

Analyzing the data presented in Fig. 6, we can conclude that the proposed formula (3) allows estimating the minimum melting current with an accuracy acceptable for solving practical problems. The average deviation of the calculated value I_m from the experimentally measured value is 10 %.

Thus, the minimum melting current can be estimated by the only characteristic of the contacts, which is their contact resistance R_c^{cold}. Even if the electrodes differ significantly in their geometry, the shape of the contact spot, and the force applied to them, but have similar contact resistances, they will be characterized by similar melting current values. Let's illustrate this with a typical example.

Let's consider two pairs of different types of electrodes. The first of them (Fig. 7, *a*) comprises cylindrical electrodes with a diameter of 20 mm with the type of contact surface „plane–cone". The contact spot has the shape of a circle, the force of the contact pressure is 300 N.

The second pair (Fig. 7, *b*) is formed by a cylindrical electrode with a diameter of 5 mm with a surface of the type „tip" and a bus with a rectangular cross-section with a width of 40 mm and a thickness of 10 mm. The contact spot has a filamentary shape, the force of the contact pressure is significantly greater than in the previous case and equals to 500 N.

The values of the contact pressing force are chosen so as to ensure in both cases close values of the contact resistances R_C^{cold} (see table). As a result, the measured values of the minimum melting currents practically coincided.

The above example clearly illustrates that contacts that differ markedly in shape and force of contact pressure, but have similar contact resistances, are characterized by a similar level of melting current.

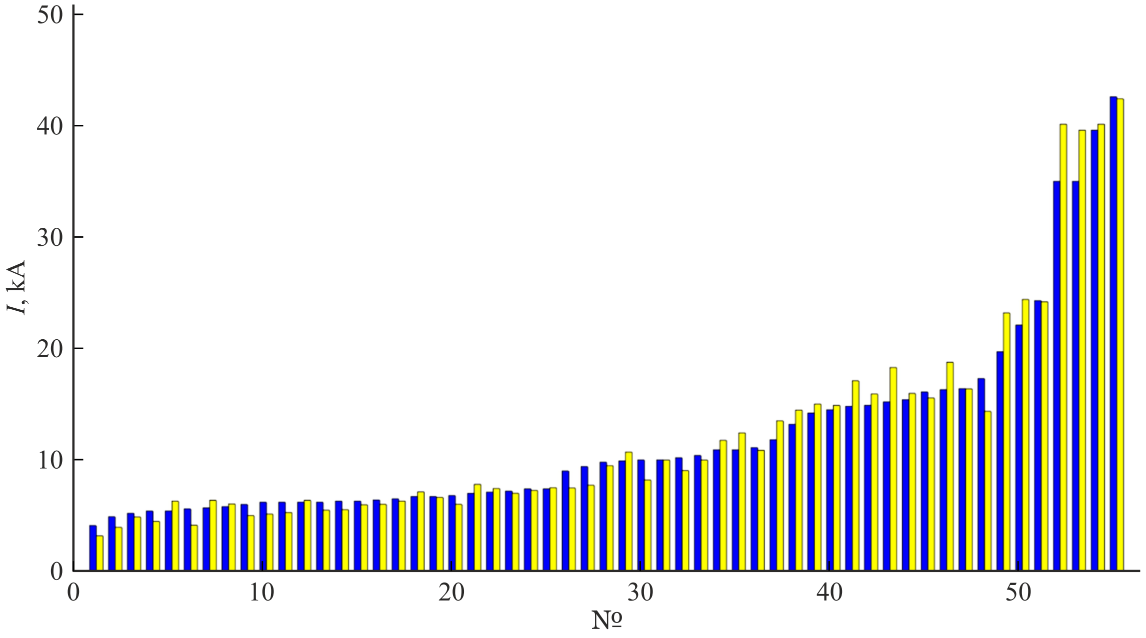

Figure 6. Values of the minimum melting current: dark columns — experimental values, light ones — calculated using the formula (3), № — the number of the current transmission realization.

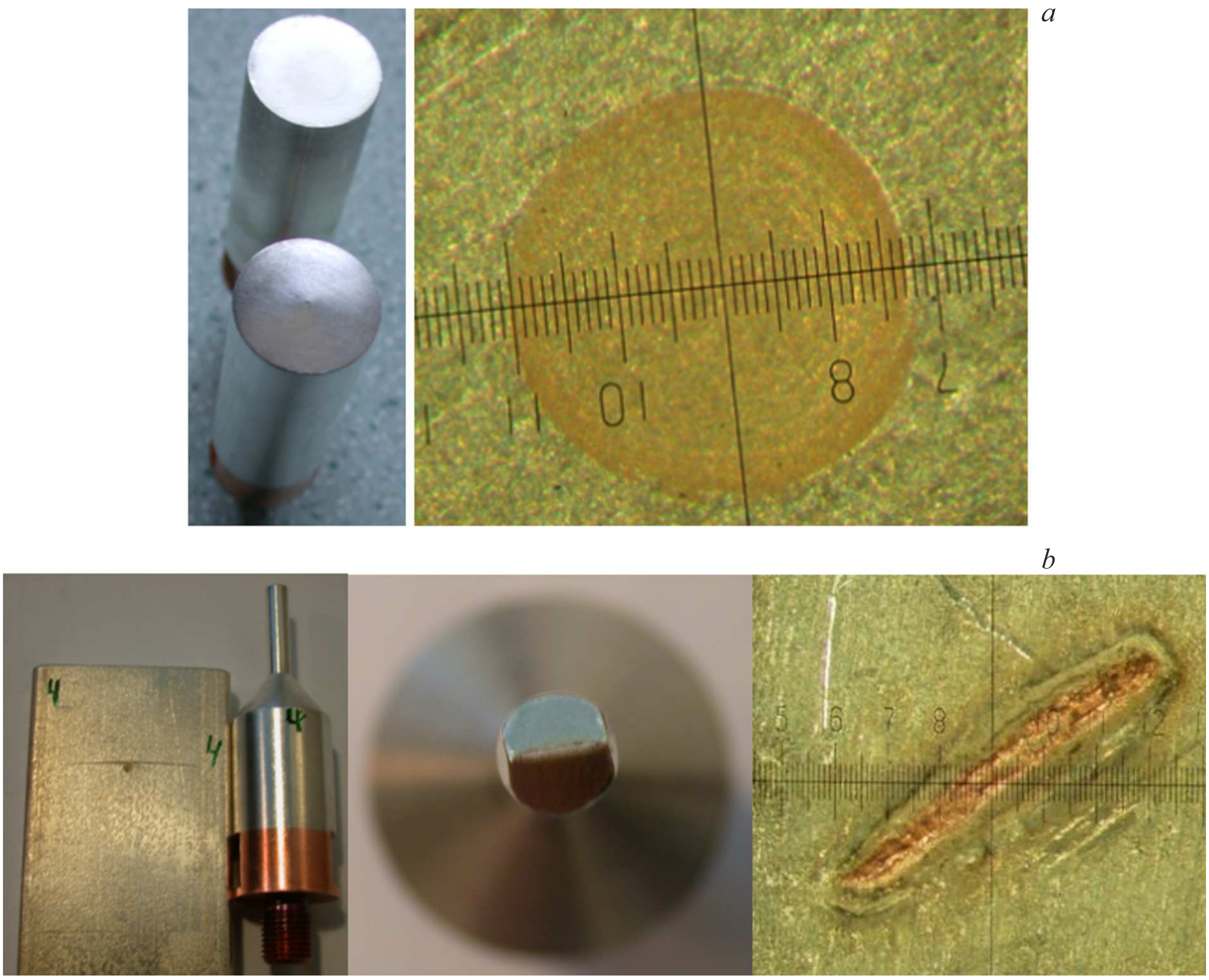

Figure 7. Photographs of electrodes and micrographs of their contact surfaces.

Let's make a number of explanatory remarks about the use of the expression (3) to evaluate the melting current. This expression establishes a direct relationship between the desired value I_m and the resistance of the cold contacts. All other parameters characterizing the contacts, such as the area and shape of the contact spot, the distance from the spot to the electrode boundary, and the force of contact pressure, are clearly not included in this formula, although a change in each of them entails a corresponding change in the melting current. The impact of these parameters on the melting current is present here indirectly through the value of the contact resistance.

In this sense, when developing contacts, in an effort to reach a certain maximum permissible level of shock currents that do not lead to their melting, it is possible to focus only on ensuring the required value of contact resistance R_c^{cold}. To a certain extent, the developer has the freedom to choose constructive measures to achieve this goal.

The relation (3) does not provide any specific recommendations on the choice of the shape and size of the contacts and the force of the contact pressure. This increases the importance of research aimed at determining the influence of various factors on contact resistance, including by performing numerical calculations on model problems.

Conclusion

By generalizing experimental data on shock melting of high-current copper contacts of various configurations over a wide range of contact forces, it was found that the melting current can be determined by the magnitude of the contact resistance of cold contacts. An estimated formula for determining the melting current is proposed. It is shown that the calculations carried out with its help correspond to experimental data with sufficient accuracy for practical use.

Conflict of interest

The authors declare that they have no conflict of interest.

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