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Method for estimating the initial welding current of closed high-current contacts under pulsed heating

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A study of the softening process of contact spots of closed high-current copper contacts caused by recrystallization of the material during short-circuit shock currents has been carried out. An original method has been developed for calculating the magnitude of the pulse current, which initiates the welding of contacts, which does not require preliminary experimental measurements.

Keywords: Electrical contact, pulse heating, numerical calculation, welding.

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Introduction

High-current contacts during operation are exposed to stationary and pulsed currents, which cause their heating. The highest temperature is reached in the vicinity of contact spots (CS), where the current density is maximum, and additional heat is released compared to other parts of the current-carrying systems. There are several levels of heating that have a significant effect on the parameters of the contacts and their performance properties: heating to the softening temperature of the contact material T_s, the temperature of the start of their welding T_w and the melting point T_m.

When the softening temperature is reached, the process of recrystallization of the contact material begins, their mechanical properties noticeably change. This leads to the fact that the size of the contact spots increases, the value of the contact resistance — one of the main characteristics of the contacts — decreases, reducing the additional heat generation. This phenomenon must be taken into account when designing high-current contacts.

Recrystallization causes a change in the size of the spots rather quickly, within a few milliseconds [1], so this effect must be taken into account even with such short-time current effects as short-circuit (SC) shock currents, the flow of which causes maximum heating of the contact spots for about 10 ms.

Another effect that has a noticeable influence on the operation of high-current contacts is the diffusion transfer of material at the points of contact. The diffusion process occurs even in the case of cold contacts. In [2] and subsequent papers the appearance of the so-called sticking of contacts is specified if the contact spots are plastically deformed. Note that plastic deformations are almost always present in high-current contacts. The sticking of contacts does not have any noticeable effect on their work.

Diffusion processes strongly depend on temperature. Starting from a certain value of T_w, a sudden rise of the intensity of contact welding is observed. It can be assumed that this temperature delimits the mode of contacts sticking and the mode of their diffusion welding.

With the temperature increasing of the contact spots up to T_m, welding of the contacts is caused by another mechanism: their melting and melt crystallization during subsequent cooling. Fusion welding is almost always fatal to electrical apparatus that fails.

The loss of performance is due to two reasons. Firstly, the force required to break the weld may, in this case, be greater than the maximum force developed by the apparatus when the contacts are opened. Secondly, even if the welding is broken, the destruction of the contact surface turns out to be so strong that when they are subsequently closed, a sudden increasing of contact resistance will be observed, which will lead to the overheating of contacts and adjacent elements of the current-carrying system (CCS) above permissible values.

In most cases the fatal welding of the contacts of electrical apparatus occurs during the flow of emergency short-circuit shock currents, characterized by the presence of an aperiodic component, leading to current surges in the first half-cycle, the value of which is almost twice the steady-state value of the short-circuit current. Below we will consider the heating of closed high-current contacts with just such currents.

Let us denote by I_w and I_m the magnitudes of the short-circuit shock current, the flow of which causes heating of the contact spots to the temperature of T_w and T_m, respectively. Currents $I < I_w$ are safe for the contacts, currents $I > I_m$ will cause their fatal welding. Thus, the maximum permissible value of the short-circuit shock current lies in the range $I_w < I_{\max} < I_m$. In [3] it is shown how I_m can be determined with a high degree of certainty. Below we will discuss the possibility of calculating another limit of the range — current of the start of contact welding I_w.

It is impossible to experimentally determine how the temperature of the contact spot changes. Therefore, numerical calculations are used to solve this problem. The existing calculation methods are reviewed in [1]. The main difficulty in calculations lies in the correct description of the process of the size change of contact spots during heating to temperatures above the recrystallization temperature, especially when heated by pulsed currents of short duration. Accounting for the effect of the contact spot spreading changes the maximum value of the heating temperature to 100% compared to the case when this effect is not taken into account. The processes of spot softening and its welding occur already in the first half-cycle of the short-circuit current in the presence of an aperiodic component.

Papers [4–6] use models that assume that the softening of the spot occurs instantly when the temperature of the beginning of material recrystallization is reached. The value of the radius jump of the CS is determined from the measured values of the contact resistance before and after the CS softening. This approach gives significantly underestimated values of the contacts overheating.

In [1] a method for calculating the contacts heating by pulsed currents is described, which makes it possible to obtain data on how the dimensions of the contact spot change during its softening, and to calculate the change in the temperature distribution in the contacts over time. This method assumes the presence of experimentally measured oscillograms of current and voltage on the contacts and, in this sense, is not autonomous. However, it provides the possibility of a detailed study of the heating process of the contact area in a wide temperature range up to melting. In this case, the error in determining the temperature does not exceed 10%.

Briefly, the essence of the method is as follows. A non-stationary nonlinear thermoelectric problem of contacts heating by a known current is solved. The solution is carried out iteratively. Sequentially, at each time step the current value is set, and such a value of the contact spot radius is selected that ensures the specified proximity of the calculated value of the voltage on the contacts to the experimentally measured value, i.e. by selecting a function $a(t)$ describing the change in time of the contact spot radius, we approximate the calculated contact stress curve to the experimental oscillogram. As a result of calculations, the temperature distribution in the contact area is determined at each moment of time, and the change in the radius of the contact spot during heating also becomes known.

This method will be used by us to calculate the passage of short-circuit shock currents, which caused heating of the contact spots to temperatures at which softening and diffusion welding of the contacts occur. The analysis of the obtained results will make it possible to propose a method for estimating the value of the welding start current without the need for any preliminary experimental measurements.

Note that technically pure copper M1, the material of which is taken as the basis in this paper, is hardly the only material used as contacts in high-voltage devices. For example, refractory materials and their composites with copper are widely used in switching devices. The study of their properties may be a topic for further research.

1. Analysis of measurement results and numerical calculations

We will perform heating calculations based on the results of the experiments performed for cylindrical copper contacts connected by one round contact spot (Fig. 1, *a*). One of the electrodes had a flat contact surface, the other — a rounded one, which provided a round spot shape (Fig. 1, *b*). Typical oscillograms of current and voltage are shown in Fig. 1, *c, d*.

The experiments were carried out on the equipment and according to the method described in [3]. The electrodes were brought into mechanical contact by applying an external force, and a pulsed current passed through them. The oscillograms of the current and voltage on the contacts were recorded, and when welding occurred, the force of contact separation was measured. The value of the contact resistance was measured before and after the current passage.

In the light of the problem being solved, we were primarily interested in those implementations of current passage that caused the initial welding of contacts. To detect the effect of the welding occurrence, a series of current pulses with an increasing amplitude was successively passed through each pair of contacts. After each pulse the contacts were separated, and the force required for this was measured.

Table 1 shows typical measurement results for three pairs of contacts at contact pressing forces F 300, 1000, and 2500 N. The current value, at which welding starts, lies in the range, the boundaries of which lie in the interval between the maximum current value, at which welding did not yet taken place, and the minimum value when welding was detected. These are the second and third lines in Table 1.

Let us calculate the contact heating according to the method mentioned above [1] for the case of passing the shock current of 30 kA at a contact pressing force of 2500 N. Fig. 2 shows the time dependences of the contact spot radius and the maximum contact temperature (temperature of the contact spot edge).

It follows from the graphs that intense spreading of the contact spot began at a temperature of 460 K. For this pair of contacts the initial diffusion welding with a pull-off force of 0.8 N occurred when the temperature reached 760 K in the contact region.

The contacts heating were calculated for all boundary implementations of passage of short-circuit shock current similar to those given in Table 1. Besides, cases of a single passage of current through previously unused contacts were

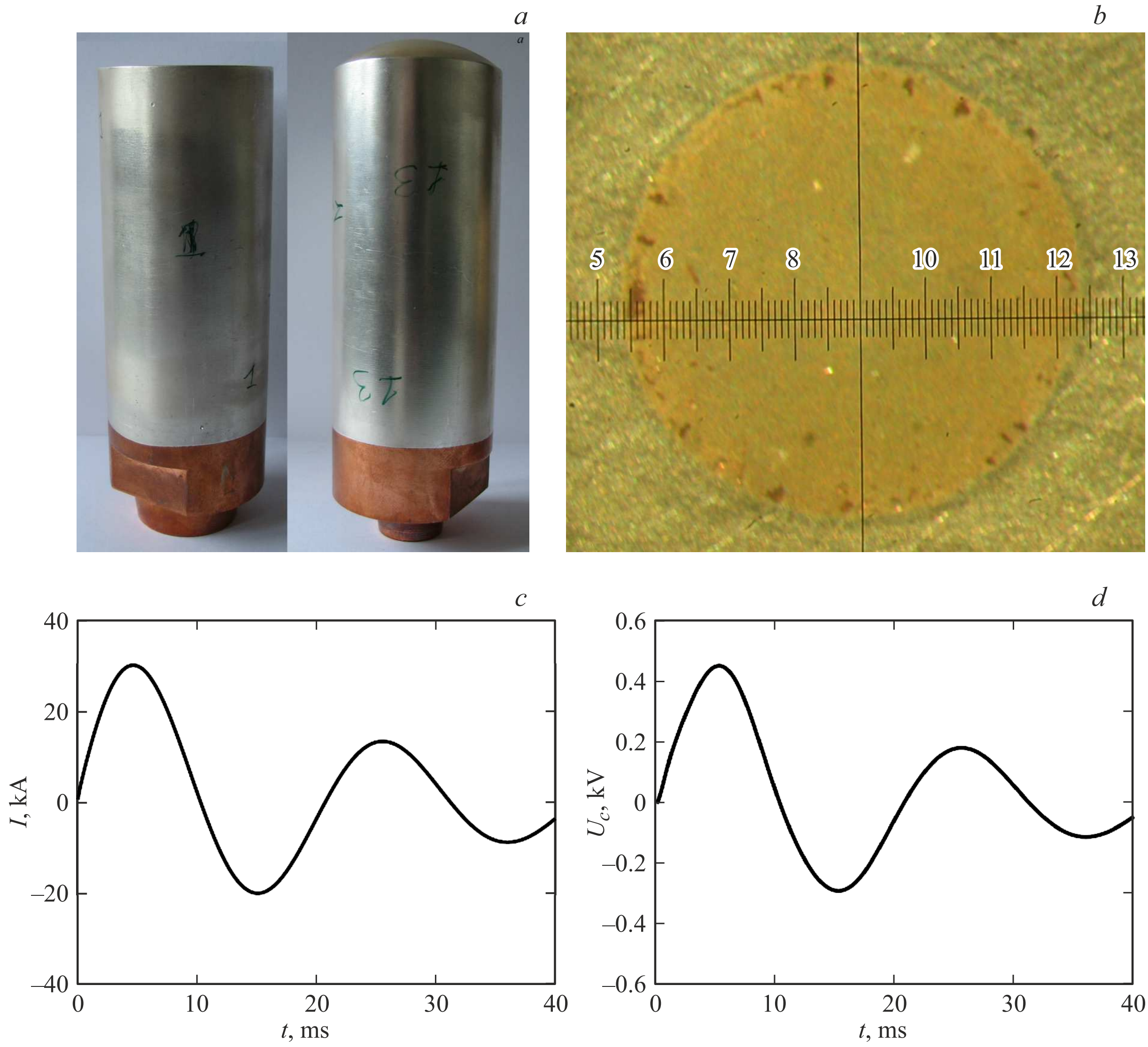

Figure 1. Cylindrical electrodes with a flat and spherical contact surface (a), micrograph of the contact spot (b), oscillograms of current (c) and contact voltage U_c (d).

Table 1. Measurement results for three values of contact pressing force

$F = 300$ N		$F = 1000$ N		$F = 2500$ N	
I, kA	F_b, N	I, kA	I, kA	I, A	F_b, N
7.5	0	9.8	0	20.0	0
8.8	0	12.4	0	25.1	0
10.4	1.1	14.9	1.6	30.0	0.8
12	1.3	17.5	3.2	35.0	1.3

considered, if at that welding was recorded without melting of the contact material. In this case, the welding pull-off force could approach a value of about 1000 N.

The analysis of a significant number of current implementations made it possible to separate the temperature range from the initial to melting, and to indicate the values of the pull-off force of copper contacts welding that are characteristic for these ranges. The results are shown in Table 2.

From these data, it can be concluded that the temperature, at which diffusion welding of contacts begins, is 650 K. Strictly speaking, it is the temperature that should be chosen for copper as T_w. However, the contacts designer can increase this value, for example, by 100–120 K, if minor diffusion welding is acceptable under the contact operating conditions. Selecting the value T_w, it is necessary to find the value of current I_w, which heats the contacts up to this temperature.

To solve this problem, we analyze the spreading of the contact spot during heating, caused by the material

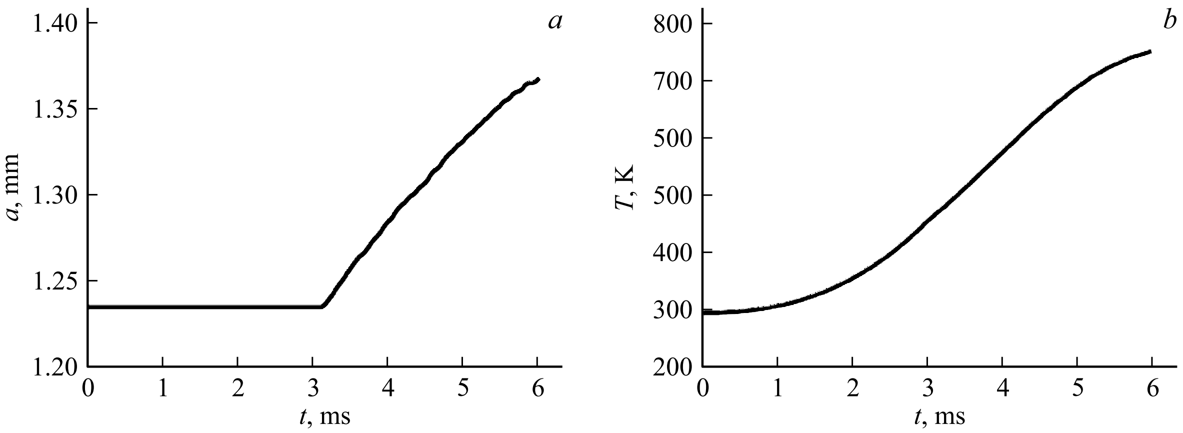

Figure 2. Contact spot radius (a) and maximum contact temperature (b) vs. time.

Nable 2. Welding pull-off force vs. temperature

Temperature range	Welding pull-off force	Notes
Less than 650 K	0 N	No contacts welding occurs in this temperature range
From 650 to 770 K	Not more than 50 N	The first diffusion welds with slight pull-off force appear
From 770 to 910 K	From 50 N to 150 N	Pull-off forces increase significantly
From 910 K up to melt point of 1356 K	Can be more than 500 N	Pull-off forces rise sharply and approach values typical for initial welding caused by melting
1356 K	Over 1000 N	Welding is fatal for contacts

recrystallization. The process of metals and their alloys recrystallization, including its initial phase, has been studied in sufficient details and described in papers [7].

The spot begins to spread intensively when the temperature of the recrystallization beginning of the contact material T_s is reached. This temperature is reached first at the contact spot in the region of its edge, then the area of the softened material spreads in its vicinity. Obviously, the size increasing of the contact spot at a constant force of contact pressure is a consequence of size increasing of the softened material region, i.e. the region where the temperature is higher then T_s. Let us try to establish this relation quantitatively.

Fig. 3 shows the temperature distributions on the surface of one of the electrodes in the immediate vicinity of the contact spot at different times. When plotting two shades of gray were used. Dark gray indicates the region where the temperature does not exceed T_s, light gray — the region where the initial recrystallization occurred. The regions are separated by an isotherm T_s. The black circle corresponds to the boundary of the contact spot at the selected time. The initial size of the contact spot in all Figures is indicated by a dashed line.

Fig. 3, a corresponds to the time $t = t_s = 3.1$ ms, when the temperature T_s of the recrystallization beginning was reached on the spot. The spot and its surroundings are unsoftened. Fig. 3, b, c correspond to times $t = t_s + 1.4$ ms and $t = t_s + 2.9$ ms. These Figures illustrate the movement of the contact spot edge with increasing area following the $T = T_s$ isotherm, which is the boundary of the material region where recrystallization begins.

The speed of the boundary propagation of the softened material area determines the speed of the boundary movement of the contact spot. Let us establish a quantitative relationship between these speeds. To do this, we follow the movement of the T_s isotherm and the movement of the contact spot edge. Let us denote their coordinates x_T and x_{sp}, respectively. Fig. 4, a for the implemented current passage under consideration shows the time dependences $x_T(t-t_s)-x_{sp}(t_s)$ and $x_{sp}(t-t_s)-x_{sp}(t_s)$. These curves leave the origin of coordinates, since the T_s isotherm at the moment of the beginning of the contact spot spreading t_s is located on its edge, i.e., the region of maximum heat release. Further, the spot boundary moves after the boundary of the softened region, which is determined by the T_s isotherm.

Fig. 4, b shows the time dependence of the distance between the T_s isotherm and the spot edge. It is well approximated by a straight line. Thus, the relative speed $V_r = d\big(x_T(t)-x_{sp}(t)\big)/dt$ remains practically constant during the entire time of the spot spreading. This statement turned out to be true for all implementations of the current passage through the contacts, which led to the occurrence of diffusion welding.

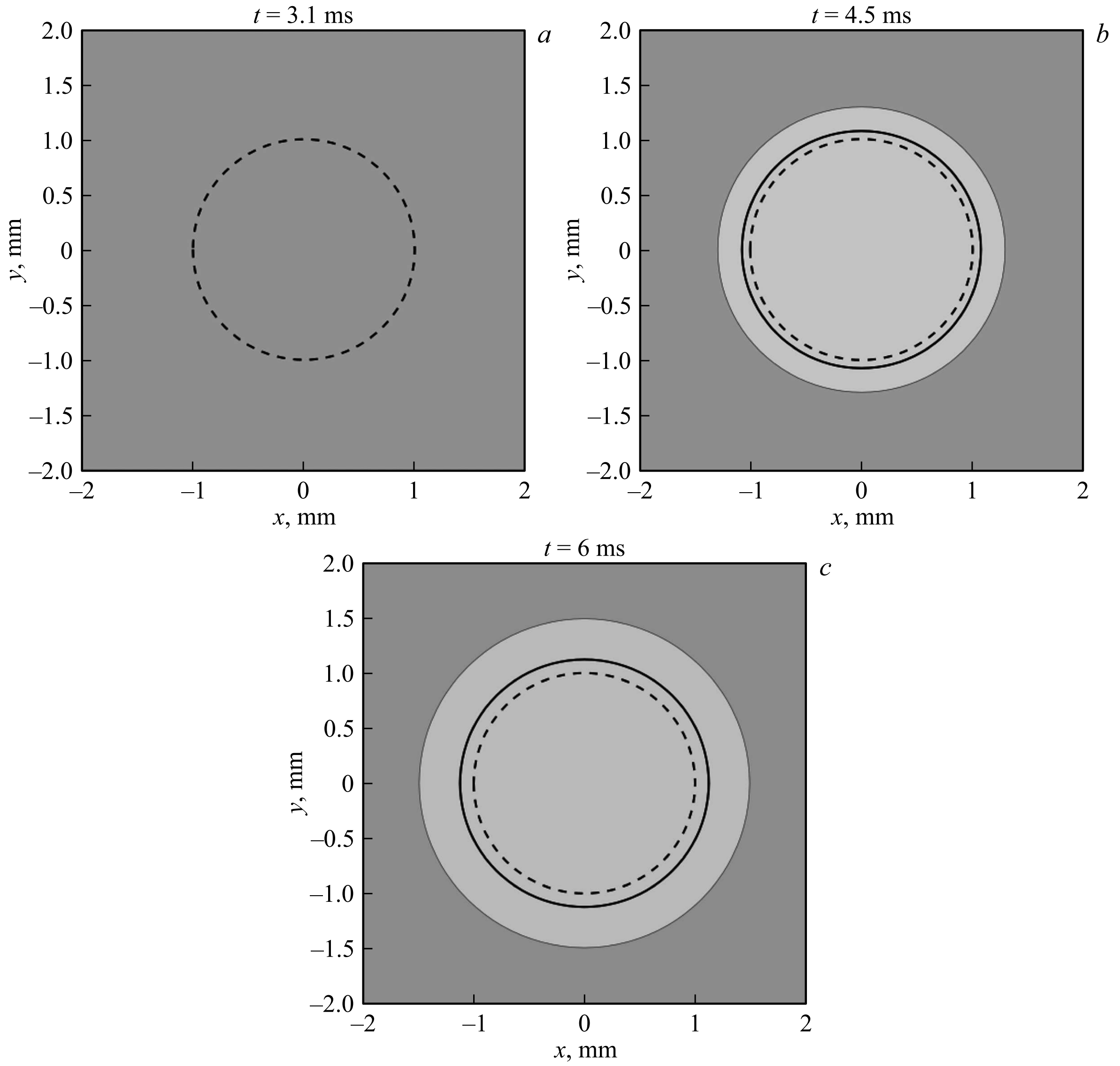

Figure 3. Movement of the contact spot boundary (dashed line) and of the softened material region boundary (solid line) during the contacts heating.

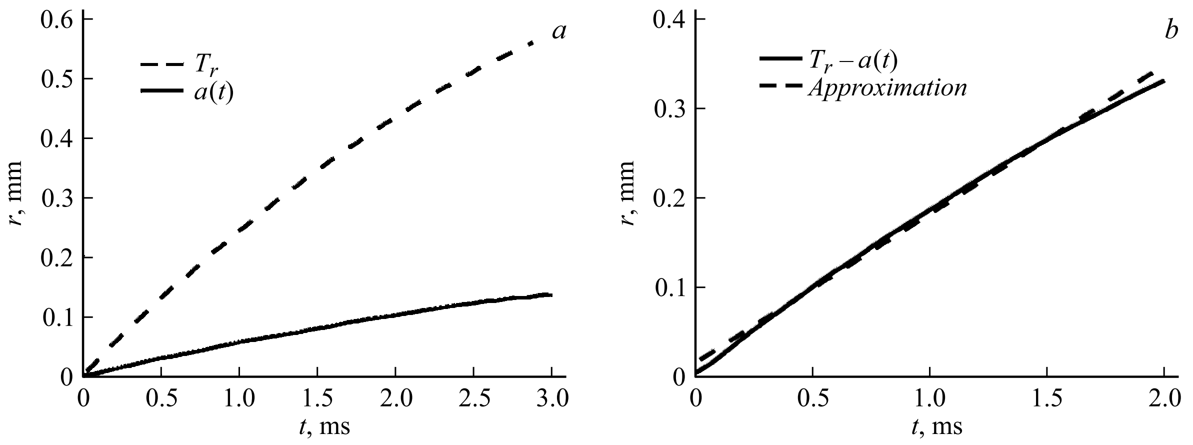

Figure 4. Propagation of the recrystallization front (T_s) and contact spot radius increasing $(a(t))$ after the time $t_s = 3$ ms (a) vs. time; the distance between the isotherm T_s and the edge of the spot $(T_s - a(t))$ and a linear approximation of this dependence (b).

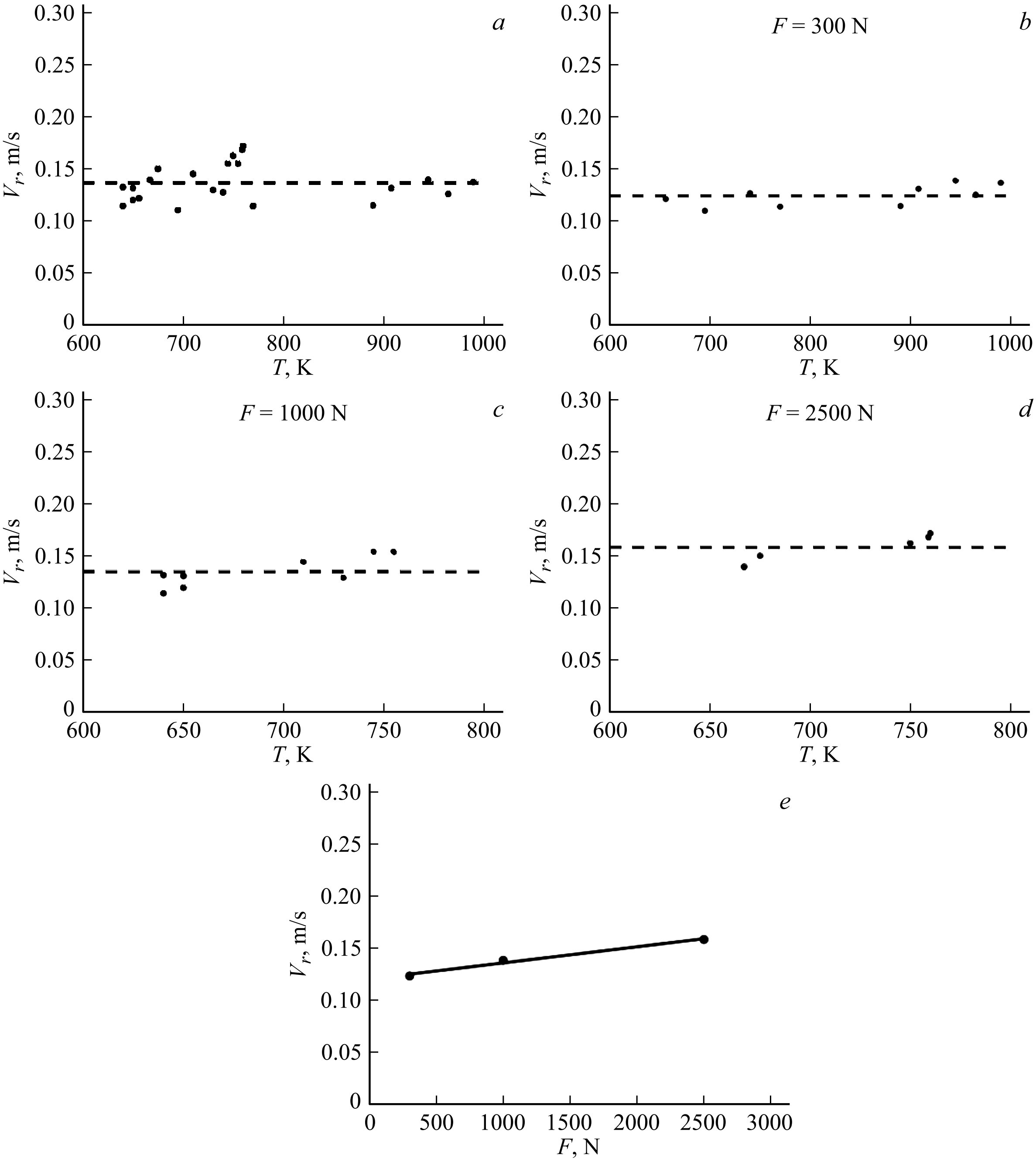

Figure 5. Relative velocity V_r vs. contact spot heating (a–d) and vs. contact pressing force (e).

Let us calculate the value of the relative speed V_r for more than twenty implementations of the flow of short-circuit shock current, which led to diffusion welding of various intensity. We present their values depending on the value of the maximum heating temperature of the contact area by the flowing current (Fig. 5, a).

The maximum V_r deviation from the mean value is 23%. This value can be significantly reduced (by more than 30%) if the implementations are grouped according to the magnitude of the contact pressing force (Fig. 5, b–d). The dependence of the relative velocity on the magnitude of the contact pressing force is shown in Fig. 5, e. It is almost linear. It can be used in calculations for any values of the contact pressing force from the considered range.

2. Procedure for calculating welding start current

If the value of the relative speed V_r is known, then it is possible to describe the process of the CS spreading and the contacts heating to temperatures at which diffusion

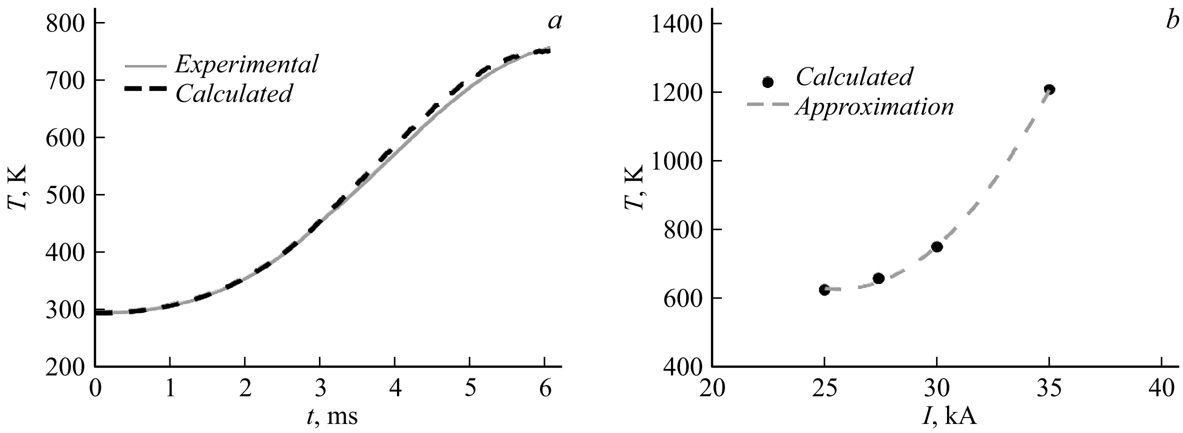

Figure 6. Maximum temperature of the contacts, obtained using the experimental data and (a) method vs. time and maximum temperature vs. short-circuit shock current, calculated using (b) method.

welding begins, without any preliminary measurements. The sequence of actions here is as follows.

1. Knowing the shape of the contacts, the magnitude of the contact pressing force, and $\sigma - \varepsilon$ characteristics of the material at room temperature, determine the location and size of the CS. This is a standard contact problem, the solution of which is not associated with any computational difficulties.

2. Specify the shape and magnitude of the short-circuit shock current and solve the problem of heating the contacts by the flowing current until the temperature T_s is reached.

3. When the indicated temperature is reached on the contact surface, one should proceed to the iterative procedure of making the solution, taking into account CS spreading. At each time interval d_t the current value is set, the position of the isotherm T_s is determined, and the edge of the spot moves after it with a known relative speed V_r.

4. The next current value is taken, and the solution procedure is repeated.

5. Further, when the temperature reaches its maximum value, which occurs approximately in $1-2$ ms after the current passed its first maximum, this value is compared with the temperature of the start of contact welding.

6. By changing the current value, the dependence of the maximum temperature on the current value is plotted, from which the value is determined, leading to the initial welding, i.e. to heating to the selected temperature T_w.

Let us estimate the accuracy of the contacts temperature calculation by this method. To do this, we apply the proposed method for contacts heating calculation in the considered case of current 30 kA passage at a contact pressing force of 2500 N and compare the results with those given above. Fig. 6, a shows curves of maximum temperature change calculated by the method based on the use of experimental data [1] and by the method proposed above. The difference in the temperature value at the time $t = 6$ ms is 10 K.

Similar calculations were also carried out for other implementations of the short-circuit shock current flow in the range of maximum heating temperatures from 600 to 1000 K and in the range of contact pressing forces from 300 to 2500 N. Differences in the heating of the contact area obtained by this method and by the method based on experimental data [1] do not exceed 10%, which is sufficient for practical calculations.

Now find the value of the welding start current. Take the value 650 K as T_w. Plot the dependence of the maximum temperature on the magnitude of the short-circuit shock current (Fig. 6, b). From here obtain the desired value of the welding start current. In this case, it was $I_w = 27$ kA.

Conclusion

Based on the summarizing of experimental data and the results of accompanying numerical calculations of contacts heating by short-circuit shock currents, a relationship was established between the change in time of the size of the contact area heated above the temperature of the beginning of the material recrystallization and the change in the size of the contact spots.

This made it possible to propose a method that makes it possible to calculate the contacts heating to temperatures at which the process of their welding starts with an accuracy sufficient to solve practically significant problems. Since calculations do not require any preliminary measurements, it can be applied at an early stage in the design of high-current electrical contacts, when their prototypes have not yet been created.

When determining the limiting values of short-circuit shock current, the designer of contacts can choose the maximum temperature value T_w, based on the allowable value of the welding pull-off force, and calculate the corresponding value of current I_w, the flow of which will not cause the loss of operability of the switching equipment.

Conflict of interest

The authors declare that they have no conflict of interest.

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