12

# Changing the characteristics of contact spots when short-circuit currents flow through closed high-current electrical contacts

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Numerical simulation of heating of the vicinity of contact spots of closed copper high-current contacts by short-circuit currents of various shapes is carried out. The relationship between the parameters of thermal and mechanical fields when heated to temperatures exceeding the recrystallization temperature of the material is established. The dynamics of changes in the sizes of elastic and plastic deformations and their localization is shown. It is revealed in which cases the results of heating the contact surroundings may differ significantly with the flow of thermally equivalent currents.

**Keywords:** electrical contact, pulse heating, numerical calculation, welding.

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## Introduction

Short-circuit currents flowing through closed high-current contacts, as a rule, result in irreversible changes in mechanical properties of the material in the immediate points of contact due to heating over the recrystallization temperature. A so-called softening of the material takes place that leads to an increase in the size of contact spots (CS), through which the current flows, and to a change in the contact resistance

Contact resistance is the main characteristic that affects the dynamics and level of contacts heating by fault currents flowing through them. Its level at any given time is defined by the following two factors. First, the size and geometry of contacts spot (CS) at a given moment of time, which depends on the distribution of mechanical properties of the material near the spot at a given contact press force; second, the distribution of temperature in the contact neighborhood that affects the distribution of specific electrical resistance. In this context, the studying of change in characteristics of thermal and mechanical fields of contacts under pulse heating is an actual problem.

Solving this problem is associated with a number of difficulties. First of all, it should be noted that experimental measurement of CS temperature is impossible even in the stationary mode, when the sport is heated uniformly. All the more, it is impossible for short pulse current impacts, when we ought to speak not about temperature of the spots, but about thermal fields in their neighborhood.

The same is also referred to mechanical fields, which are extremely difficult for experimental study. Some conclusions regarding the change in mechanical properties of material as a result of their heating can be made by applying the existing methods of metal structure investigation. For example, it is possible to estimate the size of region where material softening has occurred by the change in material structure caused by recrystallization. However, in modern literature there are no publications on contact problems where results of such investigations are reported.

It seems, that numerical simulation is the most effective method to analyze the processes caused by flowing of short-circuit currents localized in the CS neighborhood.

By now, a rather large number of works have been published on the heating of main circuit elements of electrical devices by short-circuit currents. In the majority of them, contacts themselves are considered as parts of current-carrying systems, and heat release in them is taken into account in an approximate way. For example, in [1–3] an assumption is made, that CS radius and, consequently, contact resistance changes instantaneously as the softening temperature of material is achieved. It means, that experiments are needed prior to carry out calculations. At the same time, the change in temperature of CSs themselves over time is estimated by the Holm–Kohlrausch method [4], which is valid, in the strict sense, only for stationary processes. With an approach like this, mechanical characteristics of the CS neighborhood are not subject to calculations and estimates. Note that the approximation of instantaneous change in the CS radius at softening can result in a significant underestimation of calculated temperatures, because in a real situation the radius changes in a few milliseconds.

A more reliable method to calculate the heating of contact neighborhood by fault currents based on the iteration selection of CS size was applied in [5,6]. It allows describing the heating and change in CS size in a wide range of temperatures, even to the point of melting, however it gives no information on the change in mechanical characteristics under the heating. In addition, it also assumes the availability of experimental data, i.e. oscillograms of contact current and voltage, which makes this method nonautonomous.

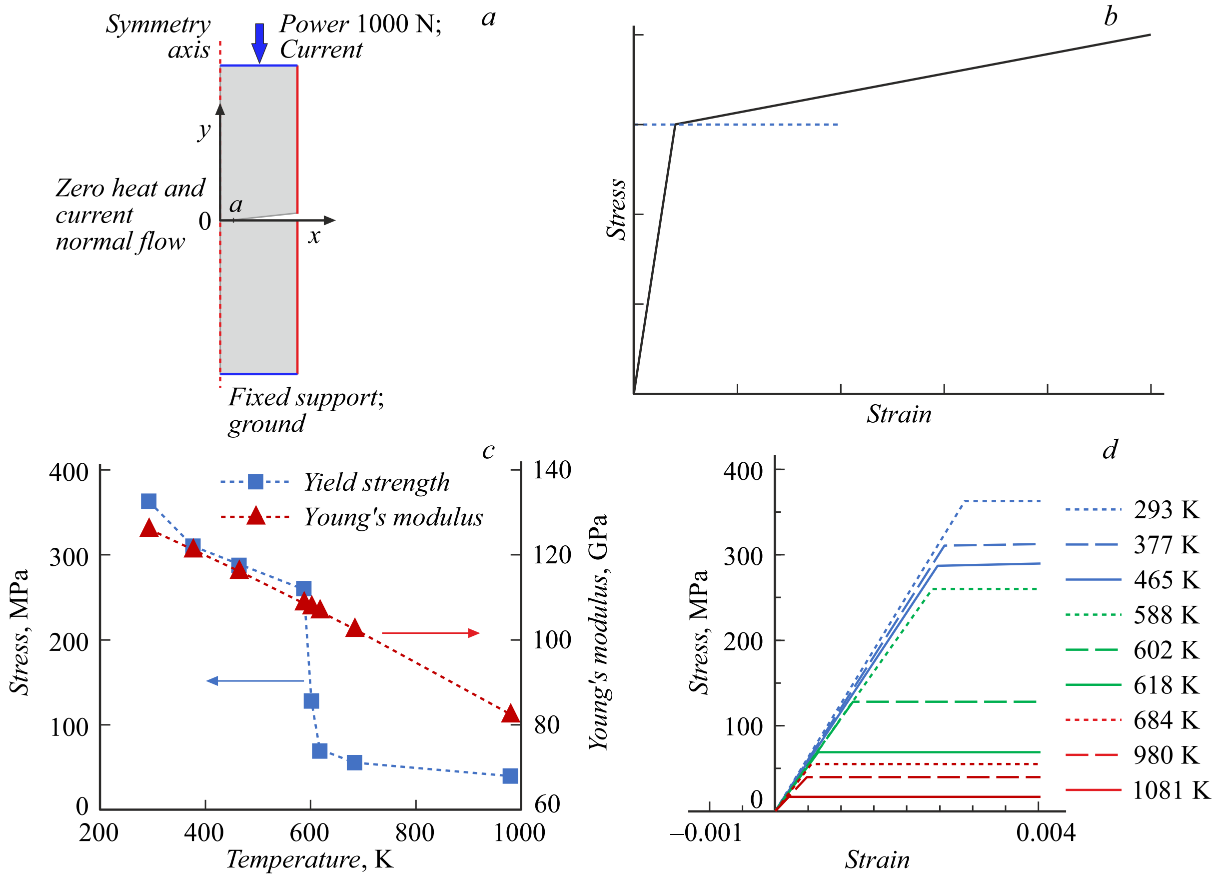


**Figure 1.** Calculation model and boundary conditions ($a$), typical $\sigma\varepsilon$-curve ($b$), Young modulus and yield strength as functions of temperature ($c$), family of $\sigma-\varepsilon$-curves for different temperatures ($d$).

One more method exists to directly calculate short-circuit currents flowing through contacts and adjacent parts of current-carrying systems, which is based on numerical solution of the thermo-electro-mechanical contact problem. It is an autonomous method that does not require any preliminary measurements. To solve the problem, it is necessary to set geometry of contacts, external impacts (current and contact press force) and mechanical, thermal, and electrical properties of material depending on temperature in the range of expected heating.

The main obstacle for the use of this method is the lack of comprehensive information on the mechanical properties of material at high temperatures, especially at temperatures close to the melting point. However, in a narrower range of temperatures, including the temperature of recrystallization, this method can give detailed information on the heating of contact neighborhood. It is this method that will be used in this study.

## 1. Object of the study and method of simulation

We shall consider the current flowing through copper cylinder coaxial contacts connected by one CS of circular shape, to which an external contact press force of 1000 N is applied. This shape of the spot is provided by the „plane–canted cone“type of contact surfaces, the canting angle is 3°. Fig. 1, $a$ shows the calculation model. The center of CS coincides with the coordinate origin $X0Y$, while its edge is at $x = a(t)$. Taking into account the symmetry of contacts, the problem will be solved as a two-dimensional axisymmetric problem.

This figure also shows the conditions set on the surfaces of the calculation model. The bottom end of contacts is earthed and secured mechanically. On the top end the contact press force and the flowing current are set. On the outer contact surfaces an adiabatic approximation can be set, if the duration of current is not more than 1 s [7,8]. Also, on these surfaces the condition of zero normal component of the current is set.

Cold-worked grade M1 copper of commercial purity is selected as the material of contacts. Mechanical and thermophysical properties of copper are described in [9–13].

In the calculations we shall use a bilinear model of $\sigma-\varepsilon$ characteristic of the material, which is qualitatively shown in Fig. 1, $b$. With a fixed temperature the model is set by three parameters: Young modulus $E$, yield strength $\sigma_t$, and hardening modulus $\beta$. Fig. 1, $c$ shows Young modulus and yield strength as functions of temperature.

With increase in temperature in the region of 600 K, the yield strength decreases by almost 4 times, which corresponds to a sharp change in mechanical properties of the material due to recrystallization. This temperature is referred hereinafter as the softening temperature $T_s$.

Fig. 1, $d$ shows a family of bilinear $\sigma - \varepsilon$ curves plotted at different temperatures that are used in the following calculations. We investigate the heating by short-circuit currents. Their shape and duration are defined by standards [7,8].

### 1.1. Numerical solution procedure

To build up the solution of problems of contact heating by pulse currents, an iteration mechanism will be used, which block-diagram is shown in Fig. 2.

In equations (1)–(4) shown in Fig. 2, $\varphi$ is electrical potential (calculated value of module *2*), $j$ is electric current density, $\rho$ is specific electrical resistance of material, $T$ is temperature (calculated value of module *3*), $\kappa$ is thermal conductivity, $\gamma$ is volume density, $C_p$ is heat capacity, $u$ is displacement (calculated value of module *4*), $\sigma$ is mechanical stress, $F$ is external force.

The interval of time from $t = 0$ to $\tau$, for which the solution is to be built, is split into short intervals $\tau$, for which the following three problems are successively solved: current passage problem, problem of heat conductivity, and mechanical problem. Each problem has its module in the procedure. Solution procedures inside each module are carried out independently from other modules, then the module exchanges the resulted data with other modules. It is assumed in the study, that at a sufficiently small $\Delta\tau$ the linked successive solution to these three problems converges to a joint solution of thermo-electro-mechanical

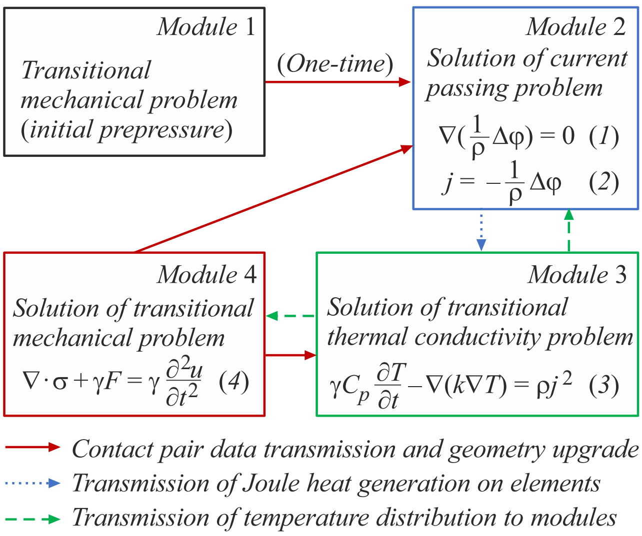


**Figure 2.** Solution procedure and equations solved in the modules.

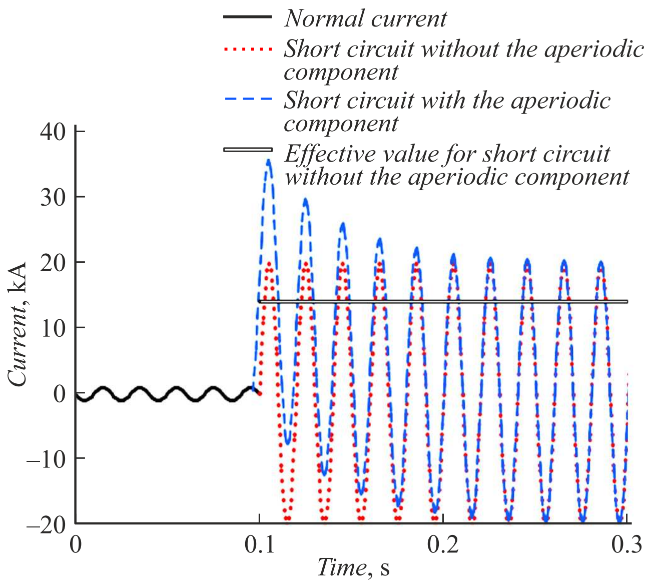


**Figure 3.** Typical oscillograms of thermally equivalent short-circuit currents.

statement. In addition to the convergence in greed division, the convergence in time division ($\Delta\tau$) was achieved.

In the following, the implementation of solution procedure is described in detail. In module *1* the mechanical problem is solved to determine the primary contact pad when an external force is applied. The information on contact pieces and updated geometry is transferred to modules *3* and *2*, where contact pieces are „spliced" in pairs by temperatures and stress, respectively.

In module *2* the problem of current passage is solved, the distribution of electric potential and current density is determined. The resulted distribution of current density is used in module *3*, where the transient thermal conductivity problem is solved. Then the temperature distribution in the contact model is transferred to other modules. Then the mechanical transient problem (4) is solved. The information on updated geometry and contact pieces is transferred to modules *2* and *3*. Thus, the cycle of mechanical→electric→thermal problems is closed. In modules *3* and *4* a transient problem with a duration of $\Delta\tau$ is solved.

Similar iteration procedures have been used in a number of studies [14–19]. In these studies the problems of pulse heating by flowing current have been solved for different current-carrying systems with contacts.

Short-circuit currents $I_{sc}$ acting on closed contacts may be considerably different in terms of their shape. A fault current can achieve its steady-state value $I_{sc}$ at once, without emerging of any transient processes or can contain a significant aperiodic component fading throughout several periods with subsequent achievement of the same value of $I_{sc}$. It depends on the phase of the nominal current where the fault occurred. A spike in the first half-period of the fault current, which can be almost twice higher than $I_{sc}$, is known as the initial short-circuit current.

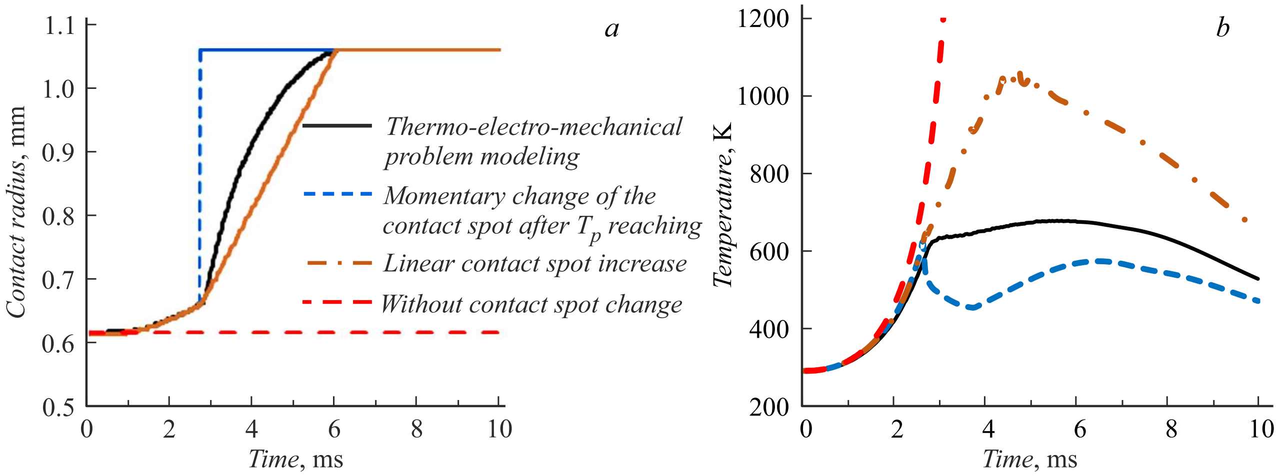


**Figure 4.** Comparison between the full contact problem and approximations for a sinusoidal current of 17.5 kA. Time dependence of CS radius (*a*) and maximum temperature (*b*).

According to GOST [7], the thermal impact of short-circuit currents on current-carrying systems of electrical devices and their elements, in particular, electrical contacts, can be determined for currents regardless of their shape, if they have the same values of the Joule integral:

$$Q = \int_{t_{cir}}^{t_{off}} I(t')^2 dt',$$

where $t_{cir}$ and $t_{off}$ — start and end times of the short-circuit current flowing.

These currents are considered thermally equivalent. Fig. 3 shows three examples of thermally equivalent currents: short-circuit currents with and without the aperiodic component and direct current equal to effective value of $I_{sc}$ without the aperiodic component. In this work we shall consider the results of heating by these currents and compare them.

## 2. Results of numerical calculations

Let us consider the results of the impact of thermally equivalent currents of different shapes on closed contacts and show what the difference in their heating can be. Also, we shall analyze distributions of temperature and mechanical characteristics in the CS neighborhood under heating.

Let us start from the case of contact heating by sinusoidal short-circuit currents without the aperiodic component. Let us show the necessity of correct description of the change in CS radius under heating to a temperature over the material recrystallization temperature, which is close to 600 K in the material model used.

The curve of heating obtained as a result of solving the thermo-electro-mechanical contact problem (maximum contact temperature as a function of time) and the change in CS radius are shown in Fig. 4 as solid lines.

The maximum temperature is achieved by the moment of time 6 ms and exceeds the temperature of crystallization by 80 K. The CS radius by the time of 2.7 ms, when a temperature of $T_s$ on the spot is achieved, increases by 7% in comparison with the initial value. With further heating up to the maximum temperature, i. e. by the moment of time 6 ms, the radius has increased much larger, by another 60%, due to a sharp change in yield strength in this temperature range. Then the radius has remained almost unchanged.

Let us show, what is changed in heating estimates if the process of CS blurring is not taken into account or is taken into account in an approximate way. The above-considered variant of calculation will be referred to as the base variant. If the increase in CS is not taken into consideration, then temperature will achieve the melting point $T_m = 1356$ K as early as by $t = 3.2$ ms, while in the base variant of calculation it is 680 K. With the use of the approximation of instantaneous increase in radius at the moment of temperature $T_s$ achievement, the maximum overheating of the spot (in relation to the initial temperature of 293 K) appears to be underestimated by 34% in comparison with the base case. If the approximation of linearly growing radius in the time interval from the softening start to the moment of maximum temperature achievement is used, then the overheating appears to be overestimated almost twice, by 96%. All this shows, how important is the reliable information on the change in spot sizes under pulse heating.

Note, that blurring of the spot caused by recrystallization of material starts with a certain time delay after the maximum temperature has achieved the level of softening temperature. In the case under consideration is approximately 80 $\mu$s. The delay increases slightly with the presence of the aperiodic component in the short-circuit current, but does not exceed 150 $\mu$s.

Now let us consider mechanical and thermal characteristics of the contact neighborhood for somewhat higher

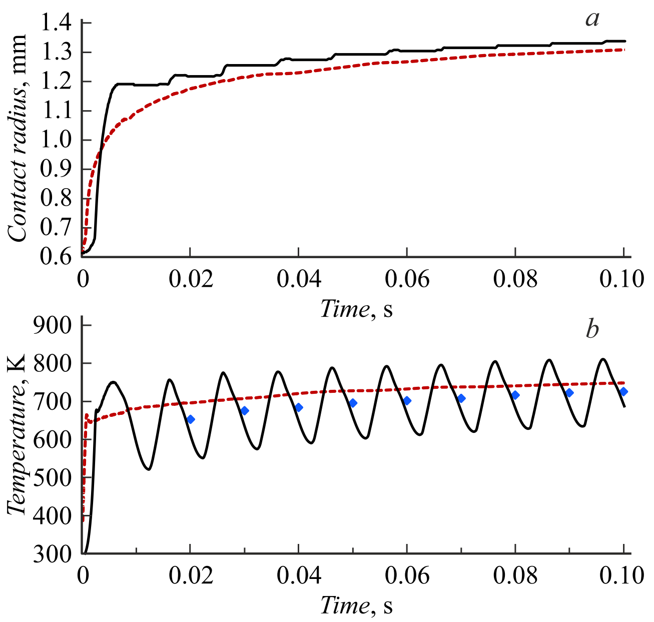


**Figure 5.** Time dependence of CS radius ($a$) and maximum temperature ($b$). Solid lines — sinusoidal current 21.2 kA, dashed lines — effective value, dots — mean value for sinusoidal current at half-period.

temperatures of heating, when the CS is heated over $T_s$ several times during the period of current flowing. Let us set the current impact as a harmonic current with a frequency of 50 Hz, an amplitude of 21.2 kA, which allows achievement of the temperature of 750 K at the first half-period. Fig. 5 shows time dependencies of contact spot radius and maximum temperature for sinusoidal current and its effective value.

The moment of CS blurring start can be seen on the time dependence of CS radius and even more clear on the dependence of maximum temperature. At the same time the temperature is 670 K, which is due to the above-mentioned time delay. Then quasi-periodic changes in temperature take place in relation to the monotonously increasing mean value. The amplitude of temperature fluctuation decreases over time.

The spot blurring occurs at the first half-period of current. This process is caused by irreversible plastic deformations. The irreversibility of the process is confirmed by the fact, that with a decrease in temperature below the recrystallization point, which is observed during first four periods of current, no noticeable decrease in spot radius occurs. The radius decreases insignificantly with a decrease in temperature due to the presence of small regions in the contact neighborhood, where the material deformation is elastic.

With a heating by thermally equivalent direct current with a magnitude equal to the effective value of the harmonic current, the process of CS blurring takes place much earlier, approximately at the moment of time 0.6 ms. In this case the heating rate changes sharply. The maximum temperature for this current impact and its mean value for the corresponding harmonic current converge and become almost indiscriminable at $t = 1$ s (the typical time for testing electrical devices for resistance to short-circuit currents [7,8]). That is in the considered case thermally equivalent currents give close values of the heating by the time of end of short-circuit currents flowing, but the dynamics of heating is somewhat different.

Let us consider in more detail the distribution of temperature for one half-period of sinusoidal current. Let us select the thirtieth half-period. By this time the thermal process are close to periodic. The temperature of CS surface and its nearest neighborhood at any moment of this half-period exceeds $T_S$. Distribution of temperature is shown in Fig. 6 in the range from 620 K, which is somewhat higher than $T_s$, to the maximum temperature at the given half-period.

During the half-period the position of maximum temperature migrates along the spot. This is related to two processes. The first process is the release of Joule heat, predominantly at the edge of the sport, the second process is heat loss to the external region of electrodes. Both processes occur continuously, but the heat generation depends on the instant current value.

From the beginning of half-period, when the instant current is zero, to 0.26 of the half-period length cooling of the contact takes place, because the instant current value is not enough to heat the contact. At the time interval of 0.26−0.60 of half-period the heat release exceeds the heat loss to the external region, therefore the neighborhood of the CS edge is heated intensively. For the rest of the half-period the current decreases and the contact starts to cool. The CS center is surrounded by „hot" copper and, as a consequence, it cools longer than other regions. The closer is the point to the spot center, the slower it cools. Due to these two factors in some moments the temperature is distributed in a nonmonotonic way over the contact surface. This is clearly seen at 0.8 of half-period.

The described-above change in temperature distribution is typical for any half-period, where the contact surface has stopped its accelerated increase (softening).

Fig. 7 shows joint distributions of temperature in relation to elastic and plastic deformations in the CS neighborhood. At the initial moment of time the deformation of this neighborhood is predominantly plastic. But the contact pad itself and a small area near it (10% of the CS radius) are deformed 4 times less. Elastic and plastic deformations are comparable with each other.

At the moment $t_s$ a small toroidal domain of softened copper starts to form, where temperature $T > T_s$ (it can be clearly seen in Fig. 7 for the time $t_s + 0.1$ ms) . Due to the similarity in shape in the shown cross-sections for this visualization it is referred to as „drop". It is reflected on deformation graphs as well. In 0.3 ms the drop already occupies a half of the linear CS size. Plastic deformations inside the drop are two orders of magnitude bigger than elastic deformations. After another 0.1 ms all the CS is already softened and plastic deformations become the main

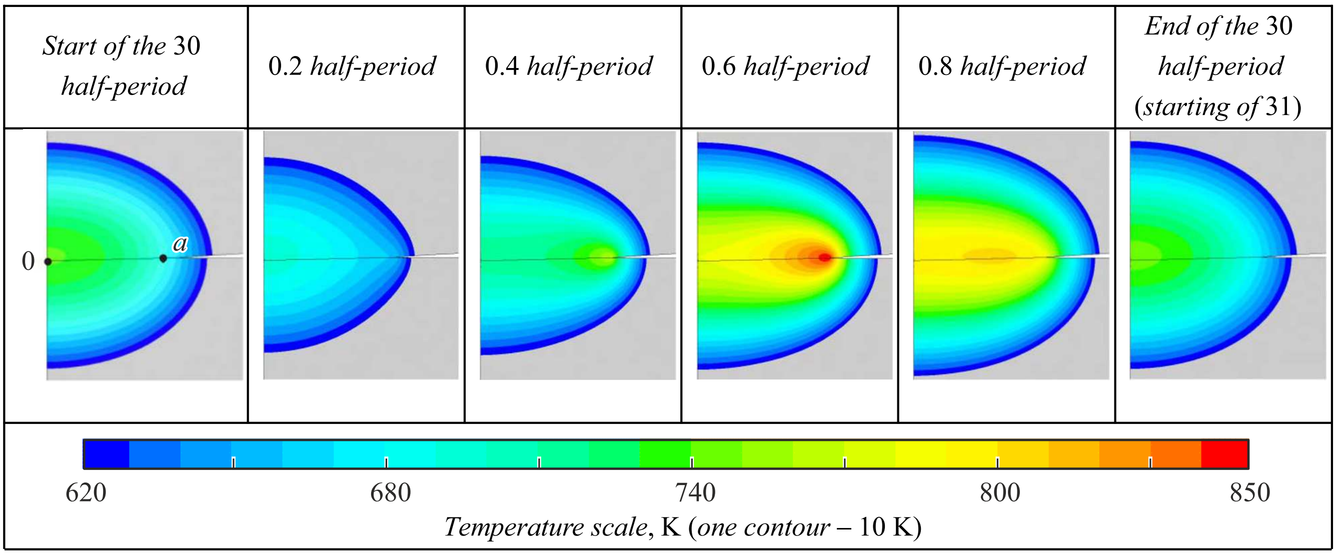


**Figure 6.** Distribution of temperature at different moments of time for one half-period (the 30-th).

type of deformation over all the contact surface. Up to the moment $t_s + 3.2$ ms (6 ms) the drop is only blurring. And even after tens of periods the drop blurring takes place and, as a consequence, the plastic deformation region changes. However, this already has no effect on the increase of CS radius.

## 3. Comparison of thermally equivalent currents impact on contacts

It was noted before, that to calculate contact heating by short-circuit currents, GOST [7,8] allows the use of currents with the same value of the Joule integral. These can be currents with sinusoidal waveform with the aperiodic component that is manifested within first periods and a direct current equal to the effective value of the harmonic current (Fig. 3).

A series of problems were solved for different values of current and, respectively, different levels of heating, that provide a basis for the following conclusion to be made. For a sinusoidal current and a direct current equal to its effective value, CSs are heated up to nearly the same temperatures for both the case of considerable exceedance of the recrystallization temperature at the first half-period and the implementations where this temperature has not been achieved. Such example has been given in Fig. 5.

The situation can change significantly, if value of the sinusoidal short-circuit current is such that within the first half-period a temperature close to $T_s$ is achieved, for example, a temperature in the range of 550–600 K. In this case no softening takes place, as well as for the corresponding direct current. But the current with the aperiodic component, which in the first maximum has much higher value, can cause softening of the material and, as a consequence, a change in CS. It means that later the short-circuit current with the aperiodic component will flow through the contacts at a considerably lower level of contact resistance, than that for thermally equivalent currents of other waveforms.

Such example has been given in Fig. 8. The short-circuit current flows through the contacts with its steady-state value equal to 10.6 kA. Maximum temperature within the first half-period and subsequent half-periods is almost equal to $T_s$, which does not cause recrystallisation, and no spot blurring occurs: the radius increases by 33% in comparison with initial value. The radius changes approximately in the same way under the impact of the effective direct current. Mean for the period value of temperature for the sinusoidal current differs from the case of heating by the effective value of direct current by 30%.

For the current with the aperiodic component the heating occurs in a radically other way. At the moment $t = 6$ ms a sharp growth of the CS radius starts, in 4 ms its value is increased almost twice in comparison with the initial radius and then it remains almost unchanged. This makes approximately twice lower the contact resistance. The heating of CS (the exceedance of mean temperature over its initial value of 293 K) decreases 6 times as compared with its peak value at the first half-period of the current.

After 10 periods of current the mean heating of CS for the sinusoidal current is 260 K, for the direct current it is 310 K, while for the current with the aperiodic component is is almost 4 times less, as low as 80 K. This example clearly demonstrates the possibility of unacceptably large errors in the results of calculation of contact heating by short-circuit currents with the use of the concept of thermally equivalent currents.

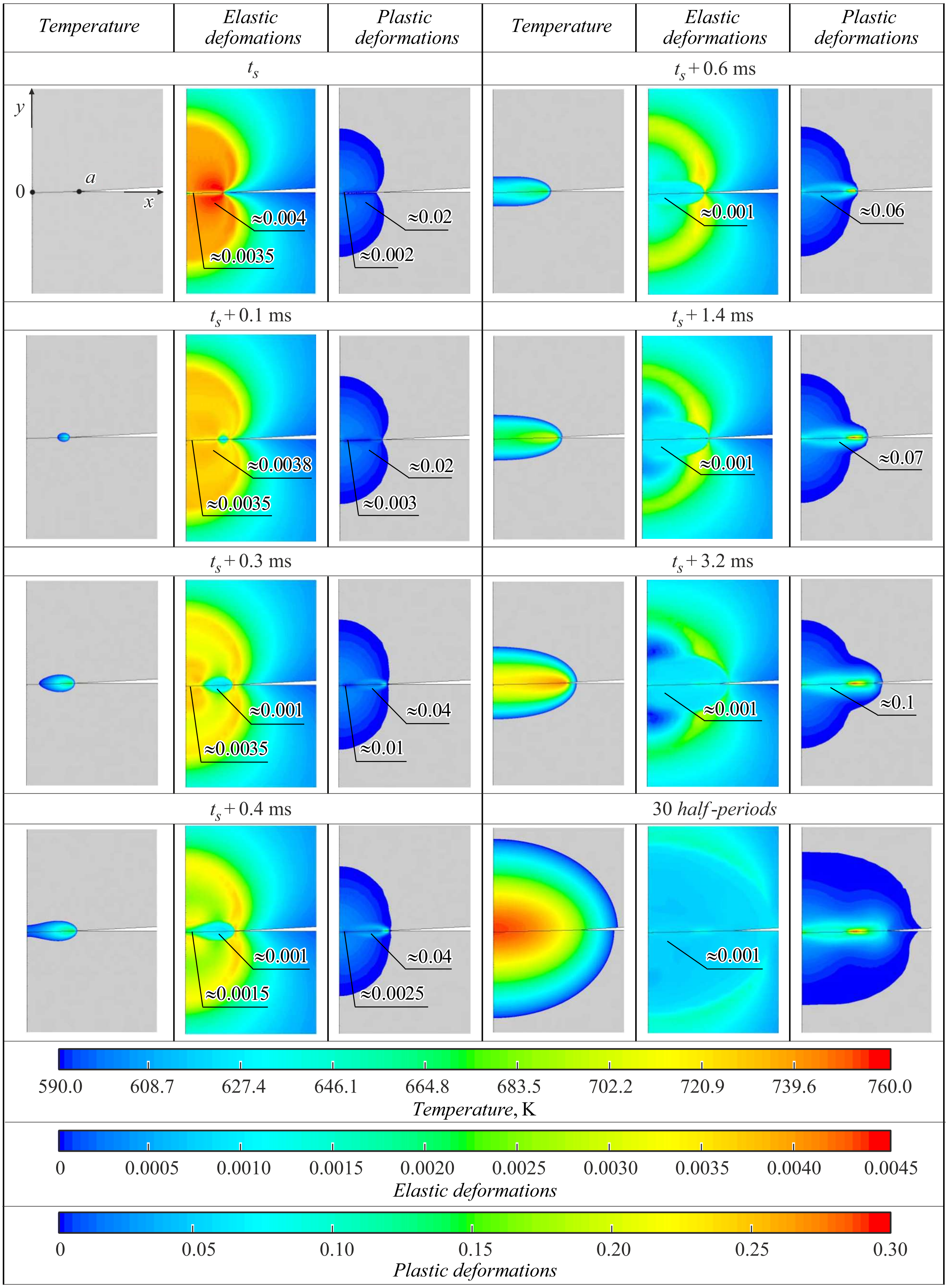


**Figure 7.** Distribution of temperature, relative elastic and plastic deformations.

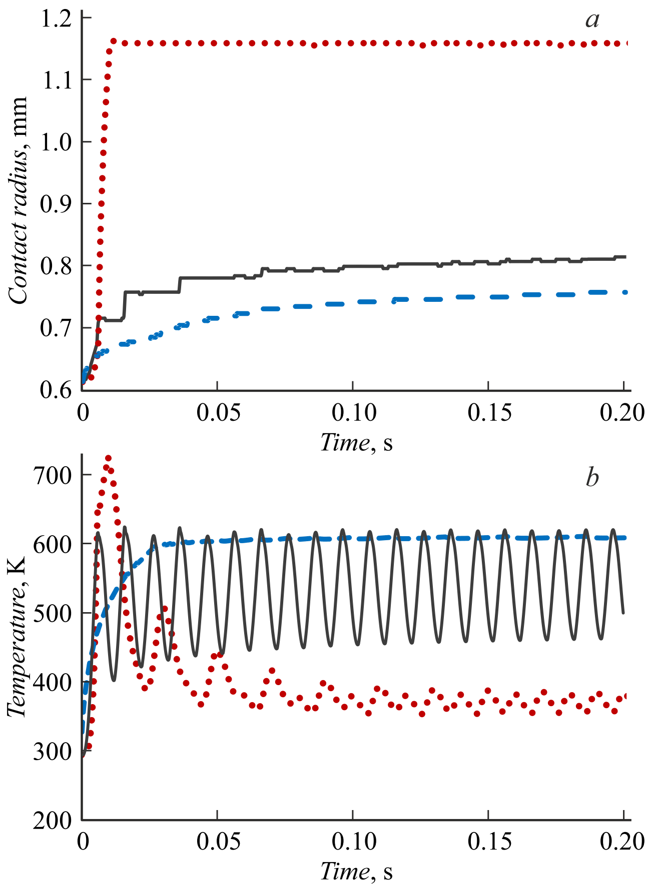


**Figure 8.** Graph of CS radius ($a$), maximum temperature of electrode ($b$) (black — sinusoidal current of 10.6 kA, dashed line — effective value, dotted line — initial short-circuit current).

## Conclusion

In this work the method of direct numerical simulation was used to investigate the dynamics of CS neighborhood heating by short-circuit currents with a duration of tens of periods. Distributions of temperature and mechanical fields are obtained for the entire process of heating. The calculation results made it possible to specifically estimate changes in parameters of contacts caused by short-circuit currents. In particular, it is shown that the widely used concept of thermally equivalent currents may appear to be incorrect for the calculation of heating.

At certain conditions the CS overheating for thermally equivalent currents with different waveforms can be multiple times different. The condition of equal Joule integral for the currents with different waveforms is not sufficient for the heating equivalence. In addition to this condition, it is necessary that thermally equivalent currents flow through contacts with the same values of contact resistance.

Temperature fields responsible for the deformation of the contact neighborhood are built and described for different stages of heating. It is shown, how the change in elastic and plastic domains occurs at the initial stage of the heating.

The rate of response of the CS size change is estimated when the temperature becomes higher than the recrystallization temperature. The time between the moment of achievement of recrystallization temperature and the beginning of accelerated deformations is two orders of magnitude less than the period of power current.

## Conflict of interest

The authors declare that they have no conflict of interest.

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