Modeling Spots on Composite Copper–Chromium Contacts of Vacuum Arcs and their Stability

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***Abstract*— Cathode spots on copper–chromium contacts of vacuum interrupters are simulated by means of a self-consistent space-resolved numerical model of cathode spots in vacuum arcs developed on the basis of the COMSOL Multiphysics software. Attention is focused on spots attached to Cr grains in the Cu matrix in a wide range of values of the ratio of the grain radius to the radius of the spot. In the case where this ratio is close to unity, parameters of spot are strongly different from those operating on both pure-copper and pure-chromium cathodes; in particular, the spot is maintained by Joule heat generation in the cathode body and the net energy flux is directed from the cathode to the plasma and not the other way round. An investigation of stability has shown that stationary spots are stable if current controlled. However, under conditions of high-power circuit breakers, where the near-cathode voltage is not affected by ignition or extinction of separate spots, the spots are unstable and end up either in explosive-like behavior or in destruction by thermal conduction. On the other hand, spots live significantly longer-up to one order of magnitude-if the spot and grain sizes are close; else, typical spot lifetimes are of the order of 10 μs. This result is very interesting theoretically and may explain the changes in grain size occurring in the beginning of the lifetime of contacts of high-power current breakers. A sensitivity study has shown that variations in different aspects of the simulation model produce quantitative changes but do not affect the results qualitatively.**

***Index Terms*— Cathode spot, grain size, spot extinction, spot lifetime, stability, vacuum circuit breaker, vacuum interrupter.**

I. Introduction

UNDERSTANDING plasma-cathode interaction in switching arcs in vacuum circuit breakers is a question of significant interest for the optimal interrupter design. An important issue that has not been clarified yet is the effect on cathode spots produced by the granular structure of contacts.

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A variety of approaches have been developed so far toward modeling cathode spots in vacuum arcs. As far as a study of the effect of grains is concerned, one should choose a space-resolved description of spots with at least two spatial variables; 0-D (integral) or 1-D descriptions (e.g., [1]–[4] and references therein) can hardly give meaningful information on an effect that is multidimensional by nature. 2-D numerical modeling of vacuum arc spots is reported in [5]–[14]. In particular, in [12] and [13] cathode spots on composite CuCr contacts have been studied in the case where chromium grains are large, which occurs at initial stages of life of contacts of high-power circuit breakers. It was found that in this case spots with currents of the order of tens of amperes operating on the copper matrix coexist with spots with currents of the order of one or few amperes on chromium grains.

This paper represents a continuation of [12] and [13] and is concerned with simulation of spots attached to Cr grains in the Cu matrix in a wide range of values of the ratio of the grain radius to the radius of the spot. Also studied is the stability of stationary spots as well as the sensitivity of the obtained results with respect to variations in different aspects of the simulation model.

The outline of this paper is as follows. The numerical model is briefly introduced in Section II. The results of numerical investigation of stationary spots attached to chromium grains in the copper matrix and of their stability are reported in Sections III and IV, respectively. Section V is dedicated to the sensitivity analysis. The conclusions are summarized in Section VI.

II. Model

Simulations of this paper have been performed by means of the space-resolved numerical model of plasma-cathode interaction of arc discharges which exploits the fact that a significant electrical power is deposited into the near-cathode space-charge sheath. The model allows one to simulate the cathode and the near-cathode plasma layer independently of the arc column and sometimes is called the model of nonlinear surface heating. The model is used in the theory and modeling of arcs in ambient gas (see [15]–[22] as examples of more recent references) and has been extended to vacuum arcs [13]. In this paper, the model of nonlinear surface heating has been used in the same form as in [13] and its description is skipped for brevity; we only note that the specific heats of copper and chromium have been evaluated with the use

Fig. 1. Micrograph of copper–chromium contact material: copper matrix (reddish/dark gray) and chromium particles (silver/light gray areas).

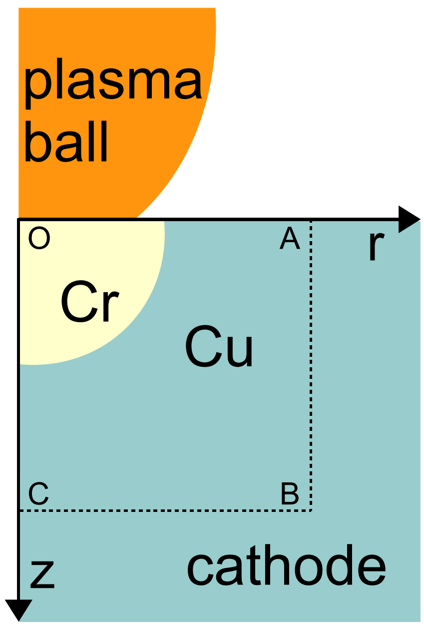

Fig. 2. Schematic of the model of a cathode spot.

of data from [23] and [24], respectively, with account of the latent heat of melting introduced along the same lines as is done in the simulation of metal casting [25].

Chromium grains in contacts of vacuum interrupters have a complex shape as shown in Fig. 1. However, attempts to consider this complex shape in numerical modeling would be unwarranted at this stage. Equally unwarranted would be attempts to take into account protrusions on the cathode surface. Results reported in this paper refer to the case where the grain has a hemispherical shape as shown in Fig. 2 and the cathode surface is flat. This is a convenient test case for elucidating the underlying physics. On the other hand, one should keep in mind that results obtained for this case may turn out to be only qualitatively correct as far as real devices are concerned. For example, values of the spot lifetime obtained for cathodes with a flat surface and hemispherical grains represent an upper estimate of lifetime of spots in real devices.

Distributions of temperature T and electrostatic potential φ in the cathode body are computed by means of solving in the cathode body the time-dependent heat conduction equation, written taking into account the Joule heat generation in the cathode body, and the current continuity equation supplemented with Ohm's law. The simulations are axially symmetric and are performed in a cylindrical domain designated $OABC$ in Fig. 2.

III. Stationary Spots Attached to Cr Grains in Cu Matrix

This section is concerned with stationary spots attached to chromium grains of various sizes. An example of distributions of temperature along the cathode surface and along the axis of symmetry for a near-cathode voltage of 20 V and three values of the grain radius, $R_{\mathrm{Cr}} = 2.5$, 5, and 10 μm, are shown in Fig. 3. For comparison, also shown are distributions of temperature on cathodes made of pure copper ($R_{\mathrm{Cr}} = 0$) and pure chromium ($R_{\mathrm{Cr}} = \infty$). Similar to what happens for cathodes made of pure copper and pure chromium [13], there is a well-pronounced spot with a virtually constant temperature of the cathode surface. Distributions of other parameters are skipped for brevity and we note only that similar to what happens for cathodes made of pure metals, the spot edge may be identified with the maximum in the distribution of the density of energy flux from the plasma; the current outside the spot is negligible; the maximum of distribution of potential in the cathode body occurs on the surface at the center of the spot.

For $R_{\mathrm{Cr}} = 2.5$ μm, the grain radius is substantially smaller than the spot radius. Unsurprisingly, the surface distribution of temperature for $R_{\mathrm{Cr}} = 2.5$ μm in Fig. 3(a) coincides to the graphical accuracy with that for $R_{\mathrm{Cr}} = 0$, i.e., for a pure-Cu cathode. The same is true of the distribution of temperature in the cathode body in Fig. 3(b) except for a region $z \lesssim 2.5$ μm, where the temperature distribution for $R_{\mathrm{Cr}} = 2.5$ μm has a maximum. The latter is an indication of a significant Joule heat production in the cathode.

For $R_{\mathrm{Cr}} = 10$ μm, the grain radius substantially exceeds the spot radius. Unsurprisingly, the distributions of temperature over the cathode surface and in the cathode body for $R_{\mathrm{Cr}} = 10$ μm are rather close to those for $R_{\mathrm{Cr}} = \infty$, i.e., for a pure-Cr cathode.

For $R_{\mathrm{Cr}} = 6$ μm, the temperature distribution is strongly different from those in the cases of pure-Cu and pure-Cr cathodes: there is a maximum inside the cathode positioned beneath the spot center and this maximum is significantly higher than that for $R_{\mathrm{Cr}} = 2.5$ μm and its separation from the cathode surface is bigger.

Integral parameters of the spots, namely, the spot current and its components, the maximum temperature of the cathode body, and the radius of spots (defined as the radial position of a point at the cathode surface where the distribution of the energy flux density attains the maximum value) are plotted in Fig. 4 as functions of the radius of the grain. Here I_{Cr} and I_{Cu} designate currents coming from the plasma to chromium and copper parts of the cathode surface,

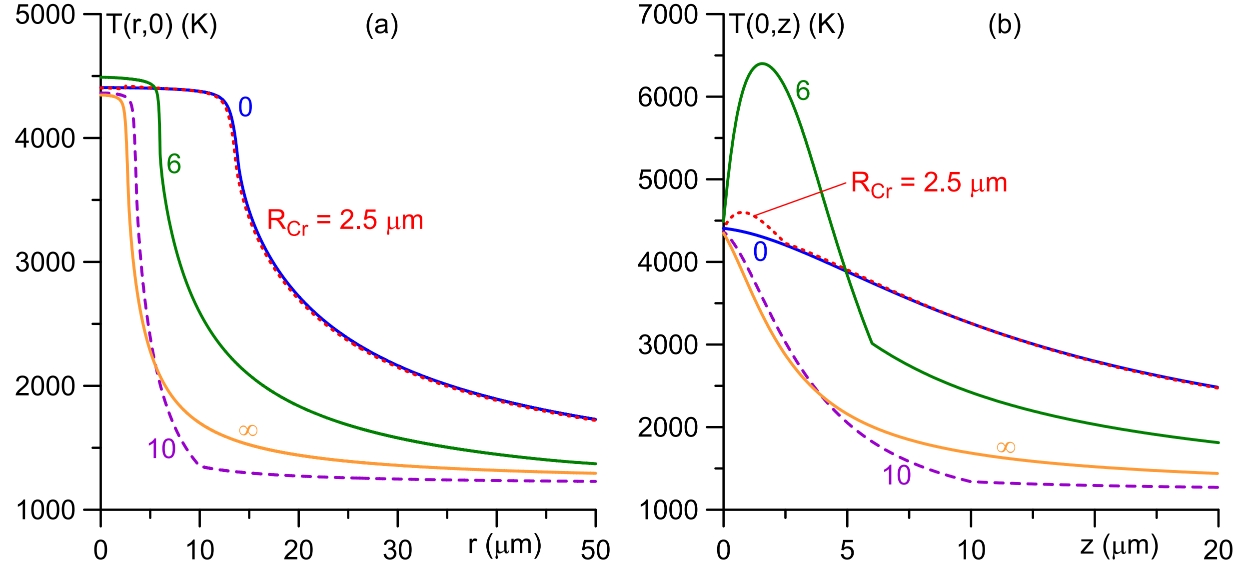

Fig. 3. Distributions of the temperature along (a) surface of composite cathode and (b) axis of symmetry. $U = 20$ V.

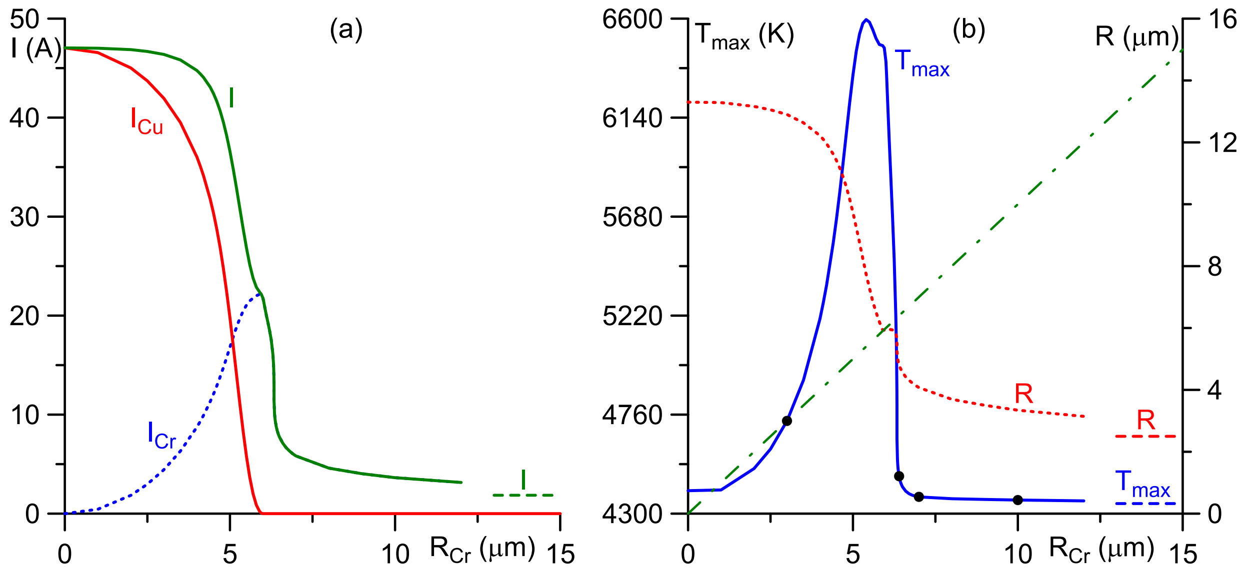

Fig. 4. (a) Spot current and its components. (b) Spot radius and maximum temperature in the cathode body. $U = 20$ V.

$I = I_{Cr} + I_{Cu}$ is the total current per spot, and R is the spot radius. The horizontal dashed lines in Figs. 4 and 5 refer to a cathode made of pure chromium. The dashed-dotted straight line in Fig. 4(b) represents the function $R = R_{Cr}$; note that the spot radius coincides with the grain radius for $R_{Cr} \approx 5.9$ μm, $R < R_{Cr}$ for $R_{Cr} \gtrsim 5.9$ μm, and $R > R_{Cr}$ for $R_{Cr} \lesssim 5.9$ μm.

The power balance of a spot is illustrated by Fig. 5. Here $(Q_p)_{Cr}$ is the power delivered to the grain by the plasma, Q_p is the total power per spot delivered to the cathode by the plasma, $(Q_J)_{Cr}$ is the power dissipated in the grain due to Joule effect, and Q_J is the total power per spot dissipated in the cathode.

One can observe from Figs. 4 and 5 that spot parameters for $R_{Cr} \lesssim 3$ μm, where the grain size is substantially smaller than the spot radius, are close to those of spots on pure-Cu cathodes. Spot parameters for $R_{Cr} \gtrsim 7$ μm are close to those of spots on pure-Cr cathodes. Parameters of spots in the range 4 μm $\lesssim R_{Cr} \lesssim 6$ μm are quite different from the parameters of spots on both pure-Cu and pure-Cr cathodes. It is to mention that the spot radius in this interval is about the same as the grain radius, so this result is not very surprising. Note that in the interval 4.8 μm $\lesssim R_{Cr} \lesssim 6.3$ μm the power that the grain loses to the plasma exceeds the power coming to the copper surface and the net power Q_p is slightly negative, which means that it is the cathode that heats the plasma and not the other way round. What maintains the spot in this case is a very substantial Joule heat generation inside the chromium grain. For example, one can mention that 84% of the Joule heat is generated in the grain and 16% in the surrounding copper for $R_{Cr} = 6$ μm. Note that the maximum value of the voltage drop in the cathode body (i.e., the potential difference between

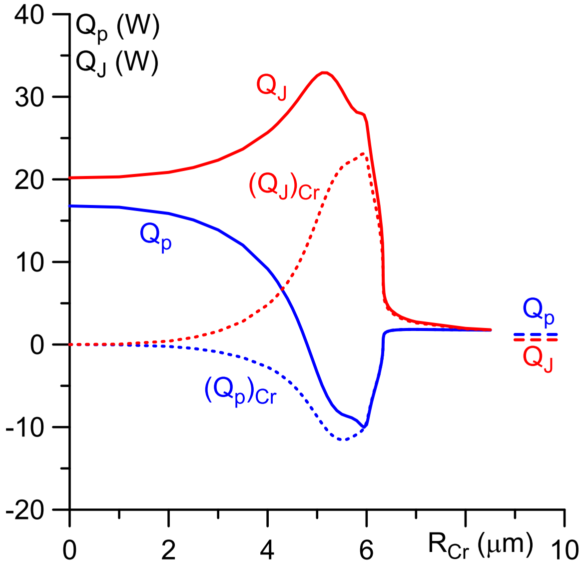

Fig. 5. Power balance of a spot. $U = 20$ V.

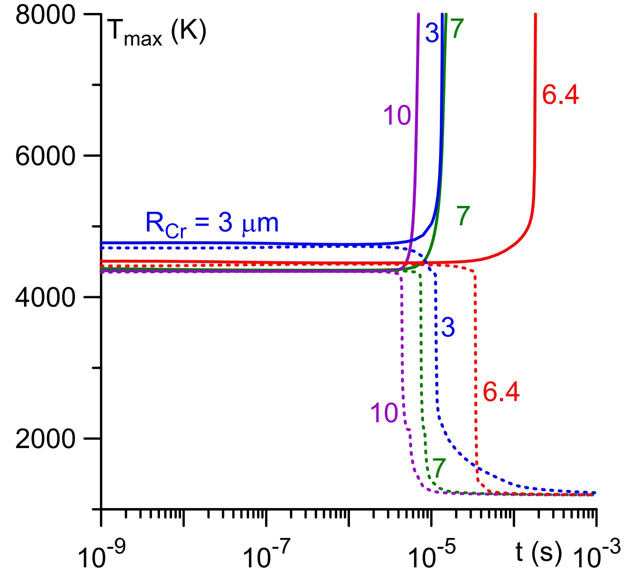

Fig. 6. Development of perturbations of the stationary spot on chromium grains. Solid line: perturbation with an initial level of $+1\%$. Dotted line: perturbation with an initial level of -1%. $U = 20$ V.

the center of the spot and points far away from the spot) is attained at $R_{Cr} = 5.3$ μm and equals 2.0 V. While sufficient for producing a strong Joule effect, the voltage drop in the cathode is still much smaller than the near-cathode voltage U.

IV. Stability of Stationary Spots

Stationary solutions describing steady-state spots attached to Cr grains in the Cu matrix, reported in the preceding section, have been computed by means of the steady-state solver of COMSOL Multiphysics. An important question is whether these solutions are stable. In this connection, their stability was investigated through following the development in time of perturbations imposed over the stationary solution. The nonstationary solver of COMSOL Multiphysics was used to this end.

The perturbations of the distribution of the cathode temperature at the initial moment $t = 0$ were assumed in the form $\beta[T(r,z) - T_\infty]$, where $T(r,z)$ is the stationary distribution of the cathode temperature, T_∞ is the average temperature of the cathode (which was assumed to be equal to 1200 K in all the simulations reported in this paper), and β is a given parameter. There was no perturbation of the distribution of electrostatic potential at $t = 0$. Two limiting cases of loading conditions were considered, namely, spots operating at a fixed current and spots operating at a fixed voltage. The model of a spot operating at a fixed current is of interest in connection with low-current arc devices and small-scale experiments, where there is only one arc attachment to the cathode and the arc power supply is current controlled. The model of a spot operating at a fixed voltage is appropriate for conditions where a very large number of spots operate simultaneously and ignition or extinction of a spot does not affect appreciably the arc voltage, which is the case for, e.g., high-power circuit breakers.

It was found that in the course of temporal evolution of spots operating at a fixed current, the perturbations decay and the system returns to the stationary solution. In other words, spots operating at a fixed current are stable.

On the contrary, spots operating at fixed voltage are unstable. Scenarios of the development of the instability are illustrated in Fig. 6, where temporal evolution of the maximum temperature of the cathode body is shown for two levels of initial perturbations, $\beta = \pm 1\%$, and four values of the grain radius marked by circles on the curve $T_{max}(R_{Cr})$ in Fig. 4(b). At first, the perturbations decrease, although this is not seen on the graph since the initial level of perturbations is too low. Then there is a period during which the perturbations are more or less constant. After this, the perturbations start rapidly growing and enter the nonlinear phase. In the case of positive perturbations, $\beta > 0$, the temperature maximum is shifted from the surface into the cathode volume and T_{max} rapidly increases up to extremely high values. In the case of negative perturbations, $\beta < 0$, the spot rapidly cools down to temperatures below 2000 K. These two outcomes of the development of instability have been found also in the investigation of the stability of stationary spots on pure-Cu cathodes [14] and have been termed, respectively, thermal explosion and destruction of the spot by thermal conduction.

Time scales characterizing development of perturbations of spots in chromium grains of different sizes are given in Table I. Here t_1 represents the time during which the amplitude of the perturbation is reduced to one-half of its initial value and may be interpreted as the time scale of the initial decay of the perturbation; t_2 designates the time in which the amplitude of the perturbation attains 500 K and may be interpreted as the time of beginning of the nonlinear phase of the instability; and t_3 designates the time in which the amplitude of the perturbation attains 2000 K, so $t_3 - t_2$ may be interpreted as the time scale of the nonlinear phase. Note that the amplitude of the perturbation here is defined as $|T_{max} - T_{max}^{(st)}|$, where $T_{max} = T_{max}(t)$ and $T_{max}^{(st)}$ are the maximum values of the temperature of the cathode body described by, respectively, the perturbed (time-dependent) and stationary solutions.

TABLE I
CHARACTERISTIC TIME SCALES OF DEVELOPMENT OF INSTABILITY OF VOLTAGE-CONTROLLED SPOTS ATTACHED TO CHROMIUM GRAINS OF DIFFERENT SIZES. $U = 20$ V

	$\beta = 1\%$			$\beta = -1\%$		
R_{Cr} (μm)	t_1 (ns)	t_2 (μs)	$t_3 - t_2$ (μs)	t_1 (ns)	t_2 (μs)	$t_3 - t_2$ (μs)
10	0.8	5.8	0.8	0.8	4.4	0.3
7	4.3	10.8	2.9	0.8	7.5	0.2
6.4	83.0	147	32.0	82.0	34.0	0.6
3	325	11.3	2.0	290	11.3	0.4

One can see that the time of beginning of the nonlinear phase of the instability is of the order of 10 μs in the cases R_{Cr} = 3, 7, and 10 μm, where the spot radius R is significantly different from the grain radius R_{Cr}, and by up to an order of magnitude higher in the case $R_{Cr} = 6.4$ μm. In other words, spots live significantly longer if the spot and grain sizes are close.

V. Sensitivity Analysis

The sensitivity of calculation results with respect to different aspects of the model used can be illustrated by the following example. It was found that the simulation results are affected by the way in which the Murphy–Good formalism in the calculation of electron emission is implemented. The approach employed in this paper, as well as in [13], is based on the method in [26]. The latter relies on Padé approximants and is accurate in the whole range of validity of the Murphy–Good theory from field to thermo-field to thermionic emission, while being as simple and computationally efficient as possible. It is of interest to compare the present results with those obtained with the use of a straightforward evaluation of the Murphy–Good formalism. The latter implies, among other things, a fixed step of integration over the electron energy (which was equal to 10^{-20} J in the simulations reported here) and is significantly less accurate from the mathematical point of view for certain combinations of surface temperature and electric field.

As far as the energy flux from the plasma to the cathode surface is concerned, such a comparison can be found in [26, Fig. 4]: the results are qualitatively similar, although quantitative difference is rather significant. Simulations of spots on a pure-Cu cathode with the use of a straightforward evaluation of the Murphy–Good formalism, performed in this paper, gave results that are qualitatively similar to those reported in Section III for $R_{Cr} = 0$: in both cases, there is a well-pronounced spot with a virtually constant temperature of the cathode surface, negligible current outside the spot, and a maximum of the density of energy flux from the plasma being positioned at the spot edge. And again, there is a visible quantitative difference: the maximum values of the temperature inside the spot are lower by about 600 K, the voltage drop inside the spot is lower by about 200 mV, and the spot radius is somewhat higher.

The effect on simulations of spots attached to chromium grains in the copper matrix is illustrated by Fig. 7,

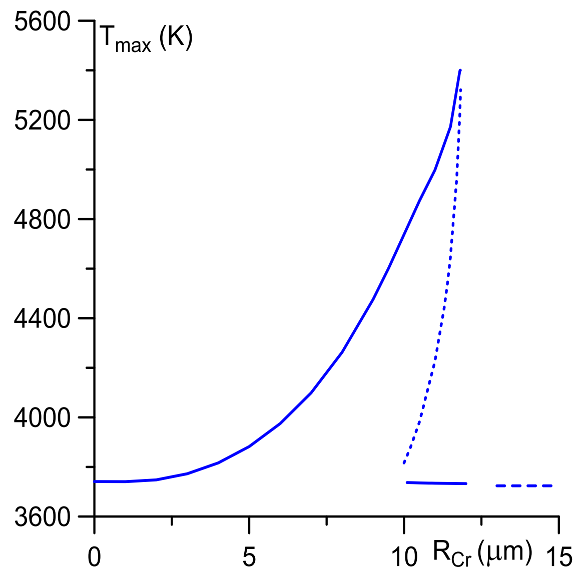

Fig. 7. Maximum temperature of the cathode body as a function of the radius of the chromium grain. Straightforward evaluation of the Murphy–Good formalism. $U = 20$ V.

where the maximum temperature of the cathode body calculated with the use of the straightforward evaluation of the Murphy–Good formalism is shown. The horizontal dashed line in this figure refers to a cathode made of pure chromium. Fig. 7 is to be compared with Fig. 4(b). The main differences between the two figures are as follows.

1) The range of values of R_{Cr} at which spot parameters are quite different from the parameters of spots on both pure-Cu and pure-Cr cathodes is shifted in the direction of higher R_{Cr} (to values around 10 μm).
2) The transition from a pure-Cu cathode to a pure-Cr cathode is accompanied with hysteresis.

Let us proceed to the effect on stability of stationary spots attached to chromium grains. Current-controlled spots have been found to be stable, similar to what was reported in Section IV. Voltage-controlled spots are stable if attached to grains whose radius belongs to the section shown by the dotted line in Fig. 7; outside this section, voltage-controlled stationary spots attached to chromium grains are unstable.

Thus, switching from a straightforward method of evaluation of the Murphy–Good formalism to a more accurate method affects numerical results on spots attached to chromium grains in the copper matrix in three ways: the dependence of parameters of spots on the grain radius remains qualitatively the same, although the range of values of R_{Cr} where the spot radius is close to the grain radius and spot parameters are quite different from the parameters of spots on both pure-Cu and pure-Cr cathodes has shifted in the direction of lower values; the hysteresis in this range has disappeared; however, the variation of spot parameters in this range remains abrupt; although voltage-controlled spots are no longer stable at these values of R_{Cr}, they are long-lived, which in practical terms is essentially the same.

The above results describe the effect of changes in the way of evaluation of electron emission from the cathode surface, which affects characteristics of the near-cathode plasma layer. The sensitivity of spot characteristics with respect to properties of the cathode material can be illustrated by simulations performed for a pure-Cu cathode with the electrical conductivity of the cathode material being constant, reported in [14]. It was found that there are again visible quantitative variations in the steady-state solutions and their stability; however, there are no qualitative variations.

In summary, changes in different aspects of the simulation model produce quantitative changes in the simulation results but do not affect the results qualitatively.

VI. Summary and Concluding Remarks

Simulations of spots attached to chromium grains of different radii in copper matrix have shown that a transition from a pure-Cu cathode to a pure-Cr cathode is nonmonotonic: when the grain radius is about the same as the spot radius, parameters of spots operating in these regimes are strongly different from those of spots operating on both pure-Cu and pure-Cr cathodes. The spot is maintained by Joule heat generation in the cathode body and the net energy flux is directed from the cathode to the plasma and not the other way round. These regimes, which are of significant interest, are investigated in detail.

The overall pattern of stability of stationary spots on composite CuCr cathode is similar to that of spots on pure-Cu cathodes [14]: the spots are stable if they operate at a fixed current, which is the case typical of low-current arc devices and small-scale experiments; the spots are unstable if the near-cathode voltage is not appreciably affected by ignition or extinction of an individual spot, which is the case typical of high-power circuit breakers; two scenarios of development of the nonlinear phase of instability are possible, namely, thermal explosion and destruction of the spot by thermal conduction. A feature specific to spots on composite cathodes is that the time of beginning of the nonlinear phase is rather long if the grain and spot sizes are close.

Significant variations in different aspects of the simulation model produce quantitative changes in the simulation results but do not affect the results qualitatively.

Modeling of this paper shows that an appropriate multidimensional numerical model is capable, at least in principle, of describing different phases of life of cathode spots on composite contacts of vacuum arcs. On the other hand, results reported in this paper refer to cathodes with a flat surface and hemispherical grains; therefore, values of the spot lifetime reported in this paper represent an upper estimate. One could think of a more advanced numerical model that would account for geometrical nonuniformities on the cathode surface, nonhemispherical grain shape, and physics of thermal explosion. One can expect, however, that qualitative conclusions drawn in this paper will not be changed by the results of such sophisticated modeling.

The conclusion that spots on composite cathodes live significantly longer if the grain and spot sizes are close, drawn in this paper, in addition to being very interesting theoretically, may also be important for applications due to the following reason. Cr grains in fresh composite CuCr contacts of high-power circuit breakers are of the order of a few tens to hundred μm in size, depending on the production process. After several switching events, the grain size is reduced down to values of the order of 10 μm. In the general case, the final grain size can be determined by metallurgical effects or/and arc-cathode interaction. Metallurgical effects are relevant if a large section of the cathode surface has been melted. If the cathode is cold, the final grain size is presumably determined by arcing effects and one should suspect that there may be a relation between this size and the conclusion that spots live longer if the grain and spot sizes are close.

It is well known that the chopping current is of the order of 10 A on pure-copper contacts and of the order of few amps on CuCr contacts [27]–[31]. This difference is consistent with the reduction of computed current to a spot attached to a Cr grain with respect to current to a spot burning on a pure copper cathode, which is seen in Fig. 4(a). Furthermore, the computed current to a spot attached to a Cr grain is not significantly affected by the Cr grain size if the latter is not too small [$R_{Cr} \gtrsim 6$ μm under conditions of Fig. 4(a)]. This is consistent with the experimental fact that the mean values of the chopping currents are unaffected by the grain size if the latter is on the scale of several micrometers [27] (although such dependence appears on the nanometer scale [30]).

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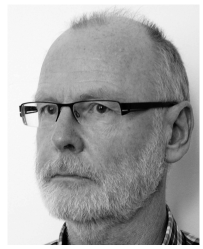

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