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Modeling Cathode Spots in Vacuum Arcs Burning on Multi-Component Contacts

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Abstract- **A self-consistent space-resolved numerical model of cathode spots in vacuum arcs is developed on the basis of the COMSOL Multiphysics software. The model is applied to cathode spots on copper-chromium (CuCr) contacts of vacuum interrupters. In the limiting case of large grains, the main effect of change in cathode material from Cu to Cr is the reduction of thermal conductivity of the cathode material, which causes a reduction of spot radius and spot current. Hence, the model indicates that spots with currents of the order of tens of amperes on Cu coexist with spots on Cr with currents between one and two amperes. The parameters of spots on small Cr grains of the order of 10 µm size are rather close to those of spots on pure Cu, whereas the parameters for spots on medium-size Cr grains of around 20 µm are quite different from those of spots on both pure Cu and pure Cr. The power flux is directed from the cathode into the plasma, i.e., it is the cathode that heats the plasma – and not the other way round. What maintains the spot is a substantial Joule heating inside the cathode bulk. About 70 percent of the heat is generated in the grain and 30 percent in the surrounding copper. One may hypothesize that such grains are highly unstable, leading to explosive-like behavior with a consequent additional loss of cathode material, and a severe limitation in spot lifetime.**

I. INTRODUCTION

For many years, theoretical investigations of plasma-cathode interaction in vacuum arcs have developed along two different lines: on the basis of quasi-stationary evaporation models (e.g., [1]), on one hand, and on the basis of Mesyats' concept of exploding sites (e.g., [2]), on the other. As far as numerical modeling is concerned, however, the difference between the two approaches is not that dramatic, and this has been realized quite some time ago; e.g., [3]. Hence, one can think of developing a unified simulation model which will combine all relevant features of the quasi-stationary evaporation model and of the concept of exploding sites and will provide a complete description of all phases of life of an individual spot.

Estimates [4,5] indicate that ionization of atoms emitted by the cathode surface occurs on (sub)micron distances. This suggests that the energy flux heating the cathode surface inside the spot is generated in a thin near-cathode plasma layer which is appreciably affected by processes in the bulk of the arc. Note also that this assumption is usual in the theory and modeling of plasma-cathode interaction in high-pressure arc discharges and is at the origin of important advances achieved in this field; e.g., [6].

A computation of an individual spot in the framework of such approach is decoupled from the computation of the bulk of the arc and amounts to solving relevant equations in the cathode body, with the boundary conditions at the cathode surface being obtained from analysis of the near-cathode plasma layer where the energy flux to the cathode is generated. The ultimate goal is to develop a complete model which takes into account heat and current transfer in the cathode, motion of molten metal and ejection of macroparticles (similarly to how these effects are taken into account in the modeling of gas metal arc welding), and microexplosions.

On the other hand, one can expect that useful results will be obtained already on earlier stages of development of the model, with account of only heat and current transfer in the cathode body. In this work, this approach is developed and used in order to investigate the effect of granular structure of Cu-Cr contacts.

II. THE MODEL OF INDIVIDUAL CATHODE SPOTS

The model includes solving in the cathode body the heat conduction and current continuity equations, boundary conditions at the cathode surface being $\kappa\, \partial T/\partial n = q(T,U)$, $\sigma\, \partial\varphi/\partial n = j(T,U)$. Here T and φ are distributions of temperature and electrostatic potential in the cathode body; κ and σ are thermal and electrical conductivities of the cathode material, which are treated as known functions of the local temperature of the cathode body: $\kappa = \kappa(T)$, $\sigma = \sigma(T)$; q and j are densities of energy flux and electric current from the plasma to the cathode surface, which are treated as known functions of the local temperature of the cathode surface, T, and of the near-cathode voltage drop U.

The nonlinear boundary-value problem was solved with the use of commercial software COMSOL Multiphysics. Functions $q = q(T, U)$, $j = j(T,U)$ are evaluated with the use of the model of near-cathode plasma layer in vacuum arcs which is based on [7].

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Results reported in this work refer to steady states of individual spots. The near-cathode voltage drop U is considered as an input parameter and the electric current per spot, I, is calculated. Calculations have been performed in the axially symmetric geometry on a strongly non-uniform finite-volume mesh. The temperature of the cathode body far away from the spot was set equal to the melting temperature of copper, 1358 K.

III. SPOTS ON LARGE COPPER AND CHROMIUM GRAINS

The aim of this work is to simulate spots on composite copper-chromium contacts with account of granular structure of the contacts. In this section, the case is considered where the grains are large, which is typical of initial stages of life of contacts. It is assumed that the grain size exceeds significantly the spot size. In this case, independent spots operate on grains of copper and chromium at the same value of the near-cathode voltage. In addition to being of interest by itself, results to be obtained for this case will be helpful for understanding main features of the case of grain size comparable to or smaller than the spot radius, which will be treated in the next section.

As an example, distributions of the temperature and potential in the cathode body for copper cathode and the near-cathode voltage of 20 V ($I = 40$ A) are shown in Fig. 1. Distributions of different parameters over the surface of a copper cathode inside the spot and in its vicinity are shown in Fig. 2 for $U = 20$ V, 18 V ($I = 53$ A), and 16 V (72 A).

In each case, 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; features familiar from the theory and modeling of spots on homogeneous cathodes of high-pressure arcs. Maximum values of the temperature and potential occur at the cathode surface at the centre of the spot. The electric current density, the erosion rate, and the ion backflow coefficient are virtually constant inside the spot, which is unsurprising since these quantities are evaluated in terms of the local surface temperature, which is also virtually constant. The electrostatic potential, which is not directly related to the surface temperature, varies appreciably inside the spot. The energy flux density, in spite of being evaluated in terms of the local surface temperature, also varies appreciably inside the spot, decreasing from the edge to the center. This feature is well-known from the theory and modeling of spots on homogeneous cathodes of high-pressure arcs and originates in the rapid decrease of the dependence $q(T)$ on the right-hand branch of the maximum. The energy flux density outside the spot is small and negative: the cathode surface is cooled by the evaporation and electron emission while the plasma-related heating is absent since there is no plasma near the cathode surface outside the spot.

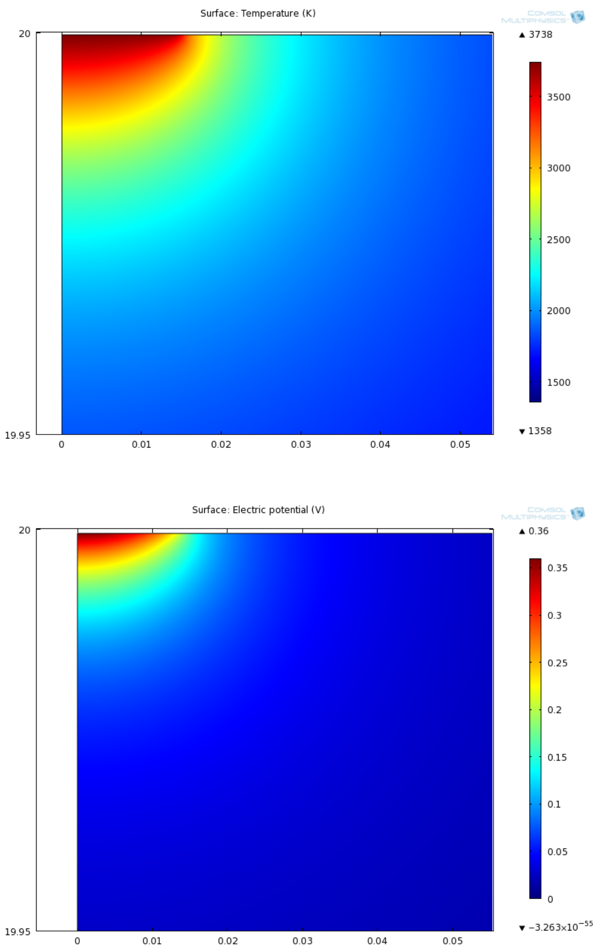

Fig. 1. Distributions of the temperature (above, in K) and potential (below, in V) in the cathode body. Coordinates in mm. Cu cathode, $U = 20$V.

The erosion rate, while being nearly constant inside the spot, possesses a narrow maximum at the spot edge and tends to zero outside the spot. Variations of potential in the cathode body are below 0.5 V in the current range considered, i.e., much smaller than the near-cathode voltage. This is an important result which justifies the model being employed.

As the spot current increases from 40 A to 72 A, the near-cathode voltage decreases from 20 V to 16 V. The temperature at the center of the spot remains virtually constant. Variation of potential in the cathode body slightly increases but remains under 0.5 V. The spot radius increases from 15 μm to 21 μm and the erosion rate increases from 9 μg/C to 13 μg/C. The power coming from the plasma varies very little and is around 18 W. The power dissipated in the cathode body due to Joule effect increases from approximately 11 to 27 W.

The near-cathode voltage drop is usually believed to be approximately equal to the arc voltage. Typical measured values of the arc voltage for copper cathodes are around 20V, so the above-mentioned values of U do not look unreasonable. The erosion rate g estimated in the present work refers to the so-called ion erosion; the erosion due to formation of macroparticles is not considered. Taking into account that experimental values of ion erosion rate for copper are in the range 33-39 μg/C [8], one can presume that the vaporization mechanism can be responsible for about 1/3 of the ion erosion and the rest is due to explosive emission [4].

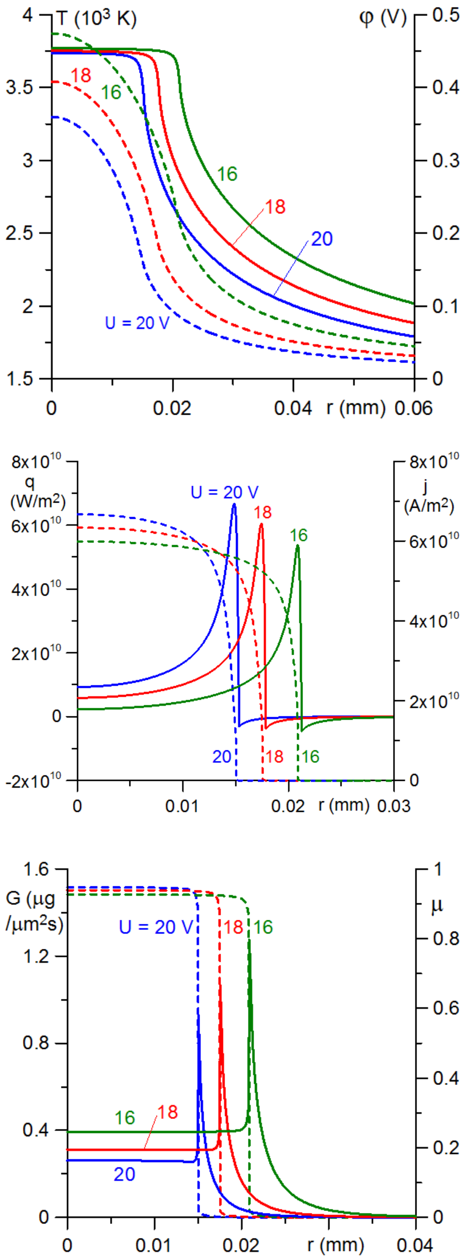

Fig. 2. Distributions of parameters over the surface of a Cu cathode inside the spot and in its vicinity. Above: temperature (solid) and potential (dashed). Middle: densities of energy flux (solid) and electric current (dashed) to the cathode surface. Below: erosion rate (solid) and ion backflow coefficient (dashed).

The power coming from the plasma, which is around 18W, represents only a small fraction of the total power IU deposited by the external circuit into the near-cathode plasma layer, which is around 1 kW. It follows that the most part of the deposited power is transported from the near-cathode layer into the bulk plasma by the electric current and flux of erosion products. The power coming from the plasma exceeds the power dissipated in the cathode body due to the Joule effect at $I \lesssim 55$ A and is below the dissipated power at higher currents.

For near-cathode voltages from 16 to 20 V, which correspond to spots with current of the order of tens of amperes on copper, spots on chromium operate at currents between 1.6 and 2.8 A. The temperatures at the center of the spot on copper and chromium cathodes are close, spot radius and the erosion rate are smaller on chromium. Variations of potential in the cathode body are smaller for chromium. Power coming to a chromium cathode from the plasma is significantly smaller than the power coming to a copper cathode. On the other hand, power coming to a chromium cathode from the plasma exceeds the power dissipated inside the cathode by a factor of about 3. The g-factor on copper exceeds that on chromium by a factor of about 2. Taking into account strongly differing currents, one concludes that the rate of erosion of copper exceeds the rate of erosion of chromium by one or two orders of magnitude.

In order to understand the reason for such a large difference between spots on copper and chromium, modeling has been performed for spots on cathodes with "mixed" material functions. It was found that the switching in each of the material functions (electrical and thermal conductivities of the cathode material and the pair of functions $q = q(T,U)$, $j = j(T,U)$) from Cr to Cu causes an increase of current, the increase caused by the switching in thermal conductivity being the strongest.

IV. Spots on Small-to-Medium Chromium Grains

Results reported in this work refer to the grains having a hemispherical shape; a convenient test case for elucidating the underlying physics. Of course, the shape of real grains is much more complex shape as shown in Fig. 3 and the question of its effect remains open.

As an example, integral parameters of a spot attached to a hemispherical Cr grain which has the radius R_{Cr} and is surrounded by Cu are shown in Fig. 4 and Table 1 for $U = 20$V. Here I_{Cr} and I_{Cu} are currents coming from the plasma to chromium and copper parts, Q_p is power coming to the spot from the plasma, and Q_J is power dissipated in the cathode body. Note that the temperature at the grain center varies within the range 3720-3770 K under these conditions. For comparison, also shown are integral parameters of spots on cathodes made of pure copper ($R_{Cr} = 0$) and pure chromium ($R_{Cr} = \infty$). One can see that spot parameters for the case of grain radius $R_{Cr} = 5\mu$m are rather close to those of a spot on pure-copper cathodes; an unsurprising result given that the grain size in this case is substantially smaller than the spot radius. In particular, Q_p is bigger than Q_J. One of the differences is that the power coming to the grain, i.e., to the central part of the spot, is slightly negative, i.e., the grain loses power to the plasma through electron emission and evaporation cooling. Another difference is a significantly higher voltage drop in the cathode: potential at the center of the spot, φ_c, is nearly double of that for the case of pure copper.

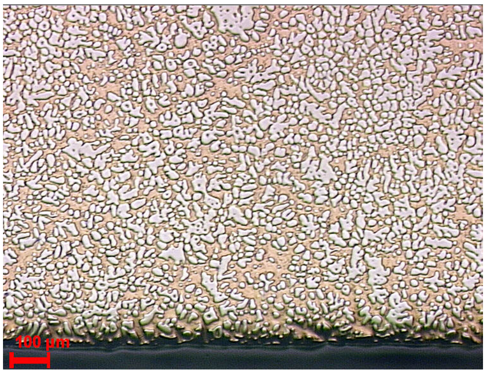

Fig. 3. Micrograph of copper-chromium contact material: copper matrix (reddish/dark grey) and chromium particles (silver/light grey areas).

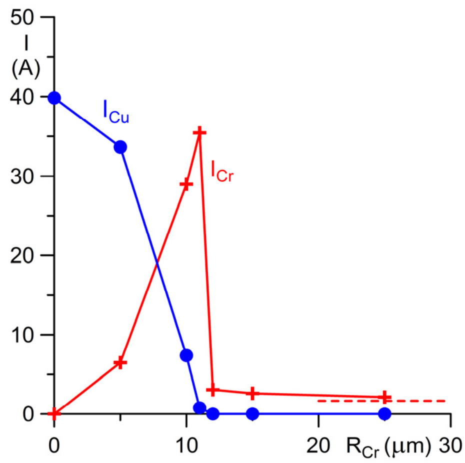

Fig. 4. Current to the chromium grain and the surrounding copper. Dashed: current to a spot on a pure-chromium cathode.

TABLE I. INTEGRAL PARAMETERS OF SPOTS ON COMPOSITE CATHODES.

R_{Cr} (µm)	R_{spot} (µm)	φ_c (V)	Q_p (W)	Q_J (W)
0	15	0.36	17	11
5	14	0.68	15	13
10	12	1.2	–0.64	25
11	11.4	1.3	–7.5	30.8
12	4.1	0.32	1.4	0.77
15	3.8	0.30	1.2	0.71
25	3.5	0.28	1.1	0.51
∞	3.1	0.26	1.2	0.34

Parameters of a spot for the case $R_{Cr} = 10$µm are quite different from parameters of spots on both pure-copper and pure-chromium cathodes. Note that the spot radius in this case (12 µm) is about the same as the grain radius, so this result is not very surprising. In particular, the power that the grain loses to the plasma exceeds the power coming to the copper surface and the net power flux Q_p is slightly negative, i.e., it is the cathode that heats the plasma and not the other way round. Of course, what maintains the spot in this case is a very substantial Joule heating in the cathode body. About 70% of the heat is generated in the grain and 30% in the surrounding copper. One may hypothesize that such grains are highly unstable.

It was found in section III that the main effect of change of the cathode material from copper to chromium is a reduction of thermal conductivity of the cathode material, which causes a reduction of the radius of the spot and a corresponding reduction of the spot current. Therefore, one should expect that an increase of the grain radius from zero (pure-copper cathode) to infinity (pure-chromium cathode) will be accompanied by a reduction of the spot radius and the spot current. One can see from Table 1 that this is indeed the case. However, it follows from the above that a transition from a pure-copper cathode to a pure-chromium cathode is "non-monotonic": when the grain radius is about the same as the spot radius, 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.

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This paper is dedicated to the memory of Dr. Roman Renz, who gave an outstanding contribution to understanding and design of vacuum interrupters.

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