Cathode Spot Motion and Burning Voltage of Low-Current Vacuum Arc with Electrodes of Copper-Chromium Composition in Magnetic Field

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Abstract - The study dealt with the cathode spot (CS) motion and the burning voltage of a low-current vacuum arc with electrodes of composition CuCr30, subjected to a magnetic field. The arcs with current $25 < I < 35$ A burned in longitudinal (normal to the cathode surface) and transversal (tangential) fields as well as in those with the induction vector inclined by angle $5° < \varphi < 65°$ to the cathode surface. Use was made of electrodes with diameter 30 mm and gap 4 mm. The field components, longitudinal B_n and transversal B_t, varied independently in the range from 0 to 0.12 T each. The superposition of the transversal magnetic field on the arc has been found to considerably increase both the constant component and noise level of the voltage. If such arc is superposed also with the longitudinal field, both the constant component and noise level decrease and at $B_n \sim B_t$ the voltage across the arc is weakly dependent of B_t. The velocity of the retrograde (anti-Ampere) CS motion grows approximately in proportion to the growth of the transversal field induction. The proportionality factor is ~200 m/(s·T). The increase in the longitudinal field induction causes a reduction in the magnitude of the velocity vector and its rotation with respect to the anti-Ampere direction through angle θ, its value being proportional to field inclination angle φ. The results obtained were compared with the data in references.

I. INTRODUCTION

Some integral characteristics of a low-current arc in vacuum are yet to be studied in detail notwithstanding the hundred years' history of research into this kind of the arc discharge. Among numerous works, whose results are summarized in a number of monographs and reviews, in particular [1-4], we note those where the study concerned the results of the action of a magnetic field on the burning voltage of an arc on a cold cathode and the motion of its cathode attachment – the so called "cathode spot " (CS).

Vast majority of such research was performed on a rather short (several millimeters) arc superposed with transversal (tangential) magnetic field, i.e. the one with induction vector B_t parallel to the plane of the cathode. A CS was found to move under the action of B_t in the direction opposite to that of the action of the Ampere force upon the current passing through the spot. For this reason, the motion of a CS under the action of the tangential field was termed "anti-Ampere" or "retrograde". Velocity V of the retrograde motion is proportional to the field induction: $V = kB_t$. Proportionality factor k is dependent of the material of the cathode, the state of its surface and arc length h. In short arcs ($<10^{-1}$ cm), the CS motion may slow down markedly and even stop altogether. In [5], there was observed the reversal of the CS motion direction from the retrograde to the forward one (the Ampere direction), yet at rather strong fields ($B_t > 1$ T). This, so far the only, experimental result was obtained under poor vacuum conditions.

The values of k reported by different authors vary greatly. The differences in the order of magnitude are explainable by the diversity of vacuum conditions: CS that burn on contaminated surfaces and in low vacuum and are referred to as the spots of the first type move, other things being equal, much faster than the ones that burn on clean surfaces in high vacuum and are referred to as the spots of the second type [2]. Still, even in the experiments with the spots of the second type there were obtained significantly different values of k [6]. Note also that most of research was performed on cathodes made of pure metals. Investigations on composite materials such as CuCr and others used presently in vacuum switchgear are far-between [7].

Considerably less studied are the phenomena under discussion in the case when a low-current arc is superposed with longitudinal (axial) magnetic field, i.e. the one with induction vector B_n normal to the cathode surface, as well as the field with induction vector inclined at angle $\varphi = \mathrm{arctg}(B_n/B_t)$ with respect to the cathode surface; that is, the field has both components, B_t and B_n. In [8], there was observed that, in presence of B_n component, the direction of CS motion makes some angle θ with the anti-Ampere, retrograde one (defined by B_t component). The value of θ depends on the ratio between B_n and B_t, i.e. on angle φ; namely, $\theta \approx \varphi$. The experiments were performed under poor vacuum conditions. For high vacuum and clean surfaces, the work [9] reports a differing result: $\theta \approx 0.5\varphi$. The measurements in the said work were conducted only on Mo and C cathodes in a limited number of modes. The spread in values is substantial. Therefore, the development of the study is of an indubitable interest.

Quantitative data on voltage U across a low-current arc in dependence on magnetic field are also rather scanty. The voltages across the low current arcs on the cathodes of some pure metals stabilized by longitudinal (axial) magnetic field are given in [10, 11]. Some data on arcs on composite materials one can find in [7]. Voltages across the arc on a Cu cathode subjected to the tangential magnetic field can be found in [12]. Neither are there the data on the burning voltage across an arc subjected to a magnetic field inclined with respect to the cathode surface.

The work we started has as the objective the systematic study of a low-current arc in magnetic fields with wide-ranging induction and alignment of the field at different currents and cathode materials, composite materials included. This kind of data, in addition to the purely physical interest, is necessary for the insight into the processes in high-current arcs stabilized with the axial magnetic field, their active investigation being underway now in view of the development of vacuum switchgear. The present report quotes some results obtained in arcs with cathodes of CuCr30 composition.

II. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUE

Fig. 1 gives the block diagram of the experimental setup.

The measurements were performed in a stainless-steel vacuum chamber of volume ≈5 liters under continuous pumping ($p \approx 10^{-4}$ Pa). The butt cylindrical electrodes of 30 mm in diameter with contact plates of materials under study were used. Electrodes were fixed on bellows-type inlets that allow ensuring the control of the position of their planes with respect to magnetic field and adjusting the interelectrode gap ($0 \leq h \leq 12$ mm).

The axial magnetic field was established with Helmholtz coils situated outside the chamber. The tangential field was established with Helmholtz coils placed into the chamber. The coils were wound onto a rigidly fixed fluoroplastic spool. Both pairs of coils produce a uniform magnetic field at the chamber center in a region of a characteristic size greater than 40 mm. Each pair of coils was powered by separate current sources with controls permitting to adjust the current amplitude, the pulse duration and the time delay of the current turning-on so that the discharge under study burned in a uniform quasistationary field for all the time of its existence (up to 10 ms). The oscillograms of the current of the coil power sources were recorded and stored in a computer.

The discharge was initiated on the surface of the grounded cathode using an initiation needle actuated by an induction-dynamic drive.

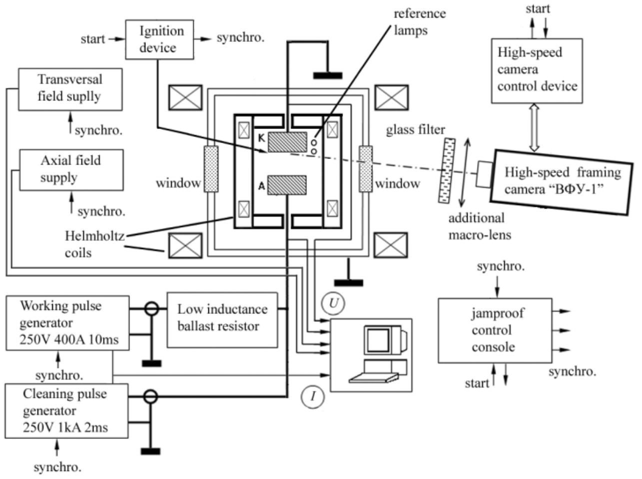


Fig. 1. The block diagram of the experimental setup

The arc was powered by a thyristor-switchable distributed long line charged to 250 V and discharged through an adjustable low-inductions ballast into the arc. The source generated a square pulse of current $I \leq 400$ A with duration up to 10 ms into an ohmic load. The source was connected to the chamber with the help of a current contact jaw of a special design permitting to completely cancel the effect of the magnetic field of the reverse current on the arc.

Prior to starting the measurements, arc cleansing of the surface of electrodes was performed with a train of pulses ($\sim 10^2$) with current ~1 kA and duration 2 ms from a special source. Further on in the course of measurements, each working pulse was preceded by a cleaning pulse, the interval between the two pulses being ~10 s.

The currents of the working and cleaning pulses were recorded with time quantization 2 µs by oscillographs built into power sources. The oscillograms were stored in a computer with the help of special software. Voltage was measured with an oscillograph built directly into a computer and supplied with differential input.

The high-speed filming of an arc was performed using a high-speed photography (HSP) camera that allows capturing 60 sequential images during a filming session. The time of exposure was 25 µs/frame. The filming was done at an angle ~10° with the plane of the cathode. The photography results were input into a computer using a film scanner HP S20 and processed with a special program that allows finding the CS position on the cathode on each of 60 frames. The position of spots was defined relative to reference subminiature lamps (SMN 10-55-2). The lamps were rigidly fixed in the chamber on a special panel and were turned on before the start of filming.

The control of the setup and the synchronization of the power sources and recording equipment were carried out from special jamproof control console.

III. EXPERIMENTAL RESULTS

The present report describes the experiments performed with electrode contact plates of CuCr30 at current $25 < I < 35$ A and arc length $h = 4$ mm.

During the entire pulse, the free arc ($B = 0$ T) burned steadily with relatively low level of noise. Upon superposing the tangential field, the arc became highly noisy and the constant component of voltage increased considerably. At $B_t \sim 0.1$ T, the burning turned extremely unstable, the arc was prone to spontaneous extinction in $\sim 10^{-4}$ s upon initiation, though by the data of [13] an arc with such current at $B_t = 0$ burns on the average for $\sim 10^{-1}$ s.

Fig. 2 gives the results of measuring the voltage across an arc at different values of B_t and B_n. The superposition of B_n is seen to produce a marked effect of lowering the voltage at $B_n < B_t$. At $B_n > B_t$, the arcing voltage dependence on B_t is a weak one.

Let us consider the results of filming of an arc. Fig. 3 gives an example of a CS image. The CS size (the half-width of emission intensity distribution) is seen to be roughly 4-5 pixels (1 pix ≈ 0.067 mm). It is determined by the HSP camera apparatus function, exposure time, scanner sampling, as well as the film grain size. The CS position was found by the maximum blacking of the photographic film to within 1-2 pixels. (Some frames exhibit the division of CS. In such cases, one determined the coordinates of the CS producing a stronger blacking of the negative.) The same can be said of finding the coordinates of reference lamps. Fig. 4 gives examples of processing of the photography results. The results shown on Fig. 4 exhibit small differences in the values of CS displacements from frame to frame in the vertical direction. In the horizontal direction, one can see "leaps" of CS from frame to frame for relatively long distances. These "leaps" are not, in our opinion, due to insufficient cleaning of the cathode surface, but are due to the fact that the cathode image on the film has the shape of an ellipse with semiaxis ratio of about 1:7 and, when the ellipse is transformed into a circumference, small positioning errors increase substantially. Yet, the said inaccuracy in positioning of CS fail to cause sizable errors in determination of the CS motion velocity as the latter is found by the results of processing of several scores of frames, that is for time ≥ 1 ms, during which CS shift for a distance ~10 mm and more.

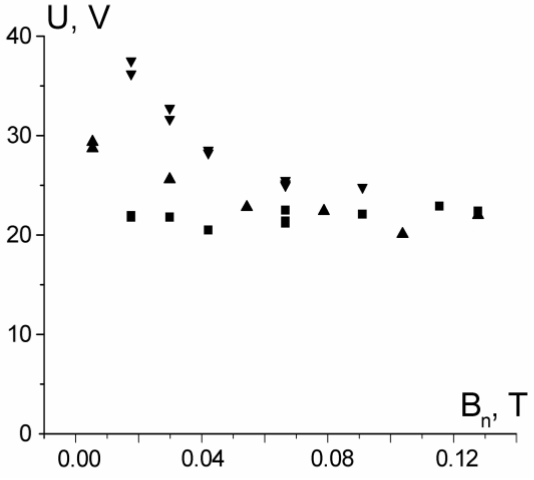


Fig. 2. The voltage across an arc at different values of B_t and B_n
■ - $B_t = 0.04$ T; ▲- $B_t = 0.052$ T; ▼- $B_t = 0.092$ T.

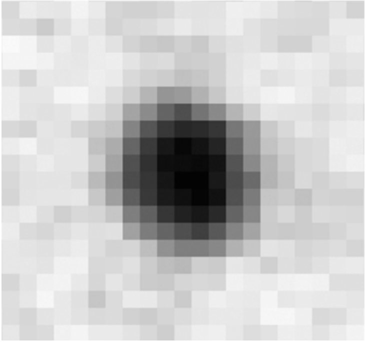
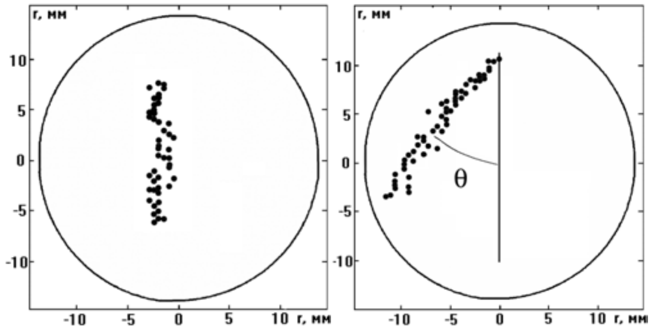


Fig. 3. An example of a CS image.



a) b)

Fig. 4. Examples of processing of the photography results.
I≈30 A, B_t=0.066 T, a) B_n=0 T b) B_n=0.061 T

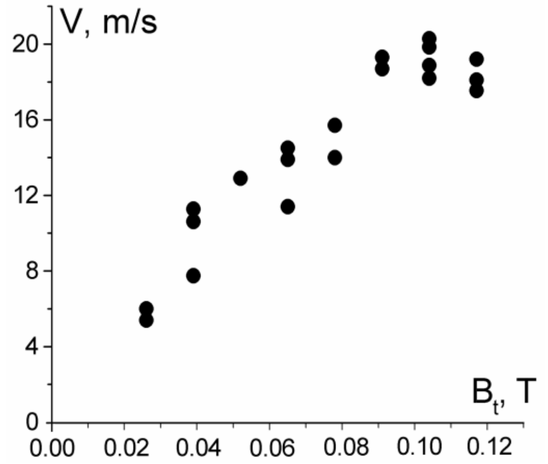


Fig. 5. The velocity of the retrograde motion of CS in the tangential field.
I≈30 A, B_n=0 T.

Fig. 5 shows the results of determination of the velocity of the retrograde motion of CS in the tangential field. The velocity values we obtained (~10 m/s) seem to be reasonable for CS of the second type. The value of k can be estimated by these results as $k \approx 200$ m/(s·T).

Upon superposition of the longitudinal magnetic field, the velocity vector of the CS motion somewhat decreases in magnitude (Fig. 6) and rotates through angle θ, its value being proportional to field inclination angle φ (Fig. 4 and 7).

Note that dependencies of θ on φ for different values of B_t cannot be differentiated within the scatter, while the noise level at the same φ is much higher in arcs burning in strong transversal fields ($B_t > 0.06$ T) than in those burning in weak fields ($B_t \sim 0.01$–0.03 T).

IV. DISCUSSION OF EXPERIMENTAL RESULTS

The values of voltages across arcs under the effect of the transversal magnetic field, which have been obtained in the present work, are in a quantitative agreement with the results obtained under similar conditions for an arc with a copper cathode in [12].

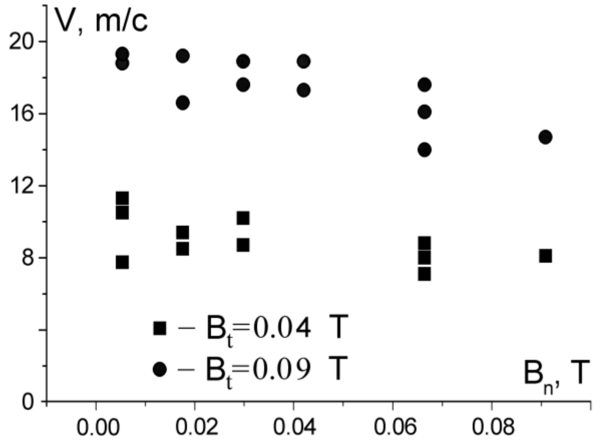


Fig. 6. The velocity of the retrograde motion of CS in the tangential and longitudinal fields. I≈30 A.

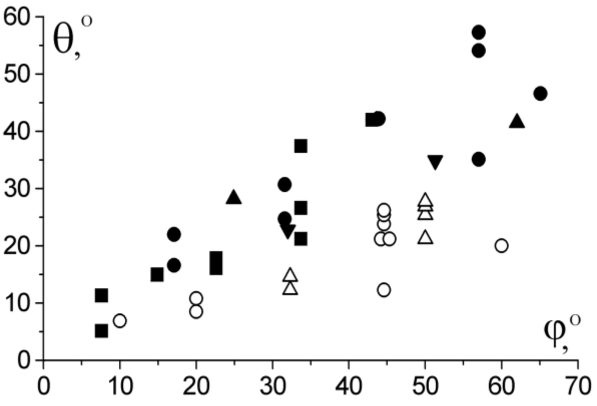


Fig. 7. Dependencies of θ on φ for different values of B_t
● - B_t = 0.04 T; ■- B_t = 0.092 T; ▲- B_t = 0.13 T; ▼- B_t = 0.196 T;
○, △ - Juttner [9], Mo, C.

The character of the CS motion (Fig. 4) and the values of its velocity (Fig. 5) indicate that, under conditions of our experiment, the cathode surface is clean and we study the motion of CS of the second type. For instance, the above-cited work [5] reported the velocity values for the CS motion under poor vacuum conditions at $B_t \approx 0.1$ T, which were higher almost by an order of magnitude: $V \approx 140$ m/s. In fact, the difference is even more striking as the arc was as long as $h = 4$ mm in the present work and but 1.9 mm in [5].

The velocities of the retrograde CS motion in the present work concern the eroded surface of the cathode (after prolonged processing of the cathode with a cleaning pulse). At relatively high values of the field ($B_t = 0.08$ T), the velocity values we obtained agree well with those results in [7], which were obtained in experiments with cathodes with eroded surface. In [7], however, the velocity of the CS motion fell off exponentially with decreasing B_t and became at $B_t \sim 0.03$ T more than fivefold lower. The cause of such marked discrepancy in the data at low values of B_t is presently unclear.

The ratio of angle θ of the CS motion path deviation to inclination angle φ of the magnetic field is seen from the results given on Fig. 7 to be somewhat less than that measured in [8]. The disagreement between our data and those in [9] (see Fig.7) may be attributable just to difference in the cathode materials. Of undoubted interest is the further development of study, including the use of various cathode materials.

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