Investigation of the current distribution at the anode of a vacuum arc in a longitudinal magnetic field

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Interest in physical processes occurring in the near-anode region of arc discharges has increased appreciably in recent years. A new stage in the investigations in this field was largely stimulated by the results of Refs. 1 and 2, where a relationship was established between the magnitude of the near-anode voltage drop in low and medium pressure arcs and the form of the near-anode region of the discharge. In particular, it is shown in Ref. 2 that for low current densities at the anode the near-anode layer of the discharge has a diffuse character. As the discharge current increases, the current density on the anode increases; at some critical current density an anode spot forms. In the process, as the current density increases, the anode voltage drop, initially negative, decreases in magnitude, and at some current density close to the critical value it changes sign. This leads to unimpeded flow of electrons onto the anode, which gives rise to local heating of the anode to high temperatures, intense vaporization, and as a consequence the formation of an anode spot. In the case of vacuum arcs burning in a longitudial magnetic field, the arc column is compressed as the field intensity increases, and as a consequence the discharge current density increases, which can also lead to a change in the sign of the anode potential and the formation of an anode spot above some critical value of the magnetic field for a fixed (and weak) discharge current. In this work we therefore addressed the problem of studying the effect of a longitudinal magnetic field on the character of current transport in the near-anode region of a vacuum arc.

The experimental setup consisted of a vacuum chamber, placed between the poles of a magnet system. A vacuum arc was ignited between a copper cathode, made in the form of a truncated cone with a working end surface $5 \cdot 10^{-3}$ m in diameter and a coaxial water-cooled copper anode disk. The experiments on the measurement of the distribution of the anode current were performed with a sectioned anode – a collector in the form of coaxial copper rings $3 \cdot 10^{-3}$ m with a gap of $1 \cdot 10^{-3}$ m between them. The current on each ring was measured with a multichannel automatic plotter. The law resistance of the measuring circuit in each section of the anode–collector ensured the required equipotentiality of its surface. The power supply for the arc, based on a current stabilizer scheme, ensured stability of the discharge current to no worse than ±2% upon voltage variations of up to 60%.

The plasma density distribution over the cross sectionof the discharge was measured by two methods: 1) according to the ion saturation current of a flat Langmuir probe (the probe potential equalled −50 V relative to the cathode) 2) and by the spectral method, according to the radial distribution of the radiation intensity of the spectral lines of the copper ions Cu^+ ($\lambda = 248.9$ nm) and Cu^{++} ($\lambda = 248.2$ nm).

The construction of the apparatus ensured that the uniformity of the longitudinal magnetic field in the discharge region was not worse than 5% and enabled varying the length of the discharge gap in the range $0.01 < \ell_g < 0.1$ m. The results of experiments with disk-shaped anodes, where the voltage drop across the arc was measured as a function of the longitudinal magnetic field, are presented in Fig. 1. One can see that for $d_a \geq 4 \cdot 10^{-3}$ m the voltage across the arc increases monotonically as the magnetic field strength increases, in agreement with the data of Ref. 4. For $d_a = 2 \cdot 10^{-2}$ m the voltage on the arc at first decreases as the magnetic field strength increases, and then at H = 300–400 Oe it begins to increase, practically repeating the dependence obtained with anode disks of large diameter. The magnitude of the voltage drop across the arc as $H \to 0$ in the case of an anode with $d_a = 2 \cdot 10^{-2}$ m is much greater than the corresponding value for anodes with large diameters.

Figure 2 shows the radial current density distributions at the anode for different longitudinal magnetic field strengths and different interelectrode gapwidths, obtained with the use of a sectioned anode. A characteristic feature of the distributions shown is the change in the direction of the current at the periphery of the discharge.

Figure 3 shows the dependence of the characteristic radius of the zone of current flow at the anode (obtained at half-height of the radial distributions of the current density) for different interelectrode gapwidths (1- ℓ = 3.2, 2-4.6, 3-11 cm) and the radii of the zones of luminosity of copper ions Cu^+ (4) and Cu^{++} (5), characterizing the conduction zone of the arc column. The figure also shows the radii of the conduction zone measured with a Langmuir probe under conditions of saturation of the ion current (6). These data correspond to a distance of 5 cm from the cathode. Curves 7 and 8 are plots of the radius at which the direction of current flow changes for two interelectrode gapwidths (7- $\ell = 1.3 \cdot 10^{-2}$, 8-$4.6 \cdot 10^{-2}$ m) versus the magnetic field.

To explain the ascending sections of the curves of the voltage drop across the arc versus the longitudinal magnetic field strength, we shall examine the channel model of an arc,[3] i.e., we shall assume that the entire current of the arc flows in some near-axis zone of radius r_σ, where the temperature and therefore the electrical conductivity are constant, outside this zone the conductivity equals zero. In this case, the electric field intensity can be written as

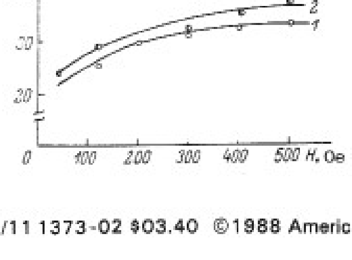

FIG. 1. The voltage drop across the arc versus the magnitude of the longitudinal magnetic field for d_a = 8 (1), 4 (2), and 2 cm (3). I_d = 150 A.

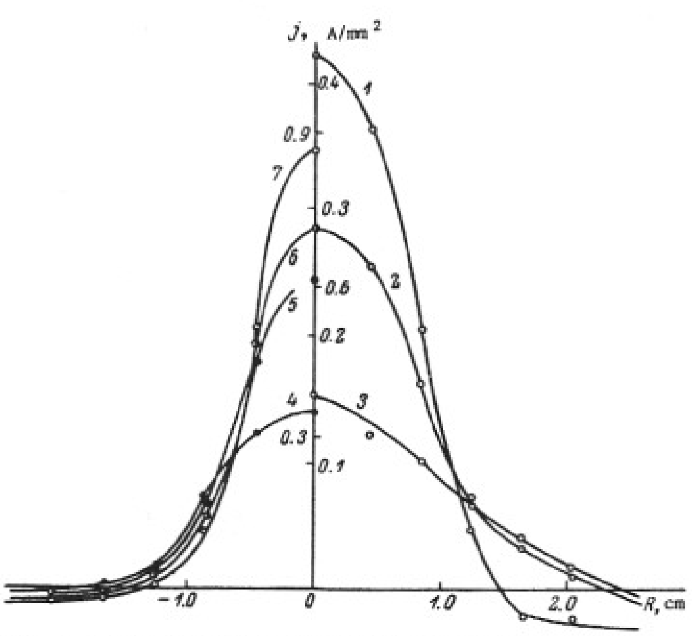

FIG. 2. Radial current density distributions at the anode for interelectrode gaps of ℓ = 1.3 (1), 4.6 (2), 11 cm and H = 35 Oe and longitudinal magnetic field strengths H = 70 (4), 125 (5), 180 (6), 300 Oe (7) and ℓ = 11 cm.

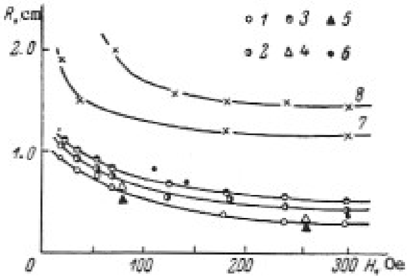

FIG. 3

$$E = I/\pi r_\sigma^2 \sigma(T). \tag{1}$$

Identifying the conduction zone with the zone of luminosity of singly charged ions and employing a power-law approximation for the radius of the ion luminosity zone as a function of the magnetic field according to the data presented in Fig. 3, we obtain for strong magnetic fields

$$\bar{r}_\sigma \sim \bar{H}^{-1/2}, \quad \bar{E} \sim \bar{H}, \tag{2}$$

where $\bar{r}_\sigma = r_\sigma/r_{\sigma 0}$, $\bar{E} = E/E_0$, $\bar{H} = H/H_0$, $H_0 = 20$ Oe. The dependence (2) corresponds approximately to the data presented in Fig. 1, right up to H ≈ 300 Oe. In the case when the diameter of the anode is less than the diameter of the conduction zone, the anode potential must be increased in order to ensure a fixed strength of the current in the arc. As shown in Refs. 1 and 2, the magnitude of the negative anode voltage drop ϕ_a satisfies the Langmuir relation

$$\frac{q\varphi_a}{kT_e} = \ln\frac{j_x}{j_a}, \tag{3}$$

where j_x is the density of the random current in the plasma and q is the electron charge. Setting $j_a = I_g/\pi r_a^2$, $j_x = I_x/\pi r_\sigma^2$, where r_a is the anode radius, r_σ is the characteristic radius of the zone of random current flow, and I_x is the maximum random electron current in the discharge, we obtain from (3)

$$\varphi_a = \frac{kT_e}{q}\ln\frac{r_a^2}{r_\sigma^2}\frac{I_x}{I_g}. \tag{4}$$

Then, assuming that the sum v_0 of the voltage drops in the arc column and in the near-cathode region and also r_σ are independent of the anode diameter, the voltage drop across the arc can be written as

$$v_g = v_0 - \frac{kT_e}{q}\ln\left(\frac{r_a^2}{r_\sigma^2}\frac{I_x}{I_g}\right). \tag{5}$$

Expression (5) holds for $r_a < r_\sigma$. For $r_a > r_\sigma$, ϕ_a is independent of the anode radius. With decreasing $r_a < r_\sigma$, the current density at the anode increases, and for $r_a \geq r_\sigma\sqrt{I_a/I_x}$ it becomes close to the value of the random current density. As a result, as was shown in Refs. 1 and 2, conditions under which an anode spot forms are realized.

To check ths possibility the following experiment was performed. A vacuum arc was ignited on an anode with a diameter $d_a = 1\cdot 10^{-2}$ m with a current I_g = 150 A and a magnetic field H = 300 Oe. These parameters correspond to the ascending branch of the dependence in Fig. 1. In addition, $r_a > r_x$, and the normal regime of a discharge with $\phi_a < 0$ was realized. Then the magnetic field was reduced. The voltage across the arc at first dropped in accordance with the dependence presented in Fig. 1, and then it began to increase. At H = 100 Oe an anode spot formed, characterized by a zone of fusion with a diameter of $0.5\cdot 10^{-2}$ m at the center of the anode.

The change in the sign of the current density at the anode as the distance from the axis of the discharge increases can be explained if it is taken into account that a potential difference arises between the axis and the periphery of a vacuum arc in a longitudinal magnetic field (for H = 100 Oe this potential difference reaches 5-7 V.[4] At the location where $j_a = 0$ the anode potential must correspond to the floating potential on the probe relative to the plasma at the boundary of the anode layer. As the distance from the axis of the discharge increase further, the plasma potential will continue to increase, leading to an increase in the magnitude ϕ_a. In this case, the ion component must predominate in the current balance, and this causes the sign of the anode current density to change.

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