ANODIC CURRENT DENSITY OF AN ELECTRIC ARC WITH CARBON ELECTRODES

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We present the results obtained in measuring the current density of anode spots in a carbon arc in air and we show its relationship to the magnitude of the arc current, analogous to the cathode spot.

Many researchers [1–4] have noted the inadequate attention devoted to the anode region of an electric arc.

Below we present the description of anode-spot current-density measurements, as well as the relationship between this current density and the magnitude of the current strength and length of column.

An arc was burned vertically in an air atmosphere in our experiments; the cathode was formed by the upper electrode (graphitized carbon) 30 mm in diameter; the anode was formed by the lower electrode, made in the form of a plate 200 × 200 × 20 mm in size (cut from a graphitized electrode 400 mm in diameter), on which the anode spot was studied. The upper electrode (cathode) was used to regulate the length of the interelectrode gap. Copper wires were used to ignite the arc. Power was supplied by a dc motor-generator through an adjustable wire-wound resistor and an inductive reactance (2 chokes from welding transformers). The generator voltage was kept within 40–500 V by a by-pass rheostat. The maximum possible direct current of the generator was ~150 A.

The anode-spot current densities were measured by employing red- and yellow-filter photography (simultaneously). A "Start" camera with a TAIR-300 telescopic lens was used; the exposure times were 10^{-3} sec. The measurements were carried out at arc lengths of 1, 1.5, 2, and 3 cm and at currents of 20–150 A. The area of the photographed spots was determined according to the scale by means of a planimeter. At the same time, an oscillograph and a graphite probe (a pencil lead housed in a porcelain tube) recorded changes in the magnitude of the anode voltage drop. There was no more than 1 mm of clearance between the probe and anode surface, thus the error could not be greater than 1.0–1.5 V.

Figure 1a,b shows the curves for the current density Δi_a of the anode spot as a function of the current I_{arc} for a given length l_{arc} of the interelectrode gap; Fig. 2a,b shows oscillograms of the anode voltage drop for currents of 60–70 and 110–115 A; Fig. 3a, b, as an illustration, shows some of the anode-spot photographs used to construct the curves for $\Delta i_a = f(I_{arc})$.

Photography of the anode spot in the current range of 40–90 A (hissing, whistling, etc.) involves considerable difficulties, since the spot moves vigorously over the anode surface, breaks up, and takes on the most varied of configurations. Moreover, the length of the arc during the burning process in a constant interelectrode gap varies quite substantially, and this shows up in the magnitude of the current densities at the spots and in the magnitude of the electrode drop.

Selective photography was employed in the light of the above, i. e., only at those instants at which the spot was more or less clearly defined on the electrode surface. At currents in excess of 100 A the arc burns more quietly, the spot is organized, and the conditions for photography are improved.

Having analyzed the oscillograms of the anode voltage drop (Fig. 2a, b), we note that it exhibits a pronounced change in magnitude in the range from 5–6 V (Fig. 2b) to 22 V (Fig. 2a) and with a quiet anode spot, i. e., for currents in excess of 100 A, after having become stabilized, approaches 20–22 V (Fig. 2b).

Earlier [5], on the basis of the voltage-balance of the electrode layers, we demonstrated that the magnitude of the anodic voltage jump for a carbon arc in air can be determined from the formula

$$U_a = U_{iA\,gas} + (U_{i\,col} - U_{iA}). \tag{1}$$

In our case we assume that vigorous carbon-monoxide formation (possibly also cyanic [C_2N_2] oxide) is taking place in the near-anode layer, so that ionization may subsequently take place according to the following reactions:

$$\text{a) } CO \to C^+ + O + e, \quad U_i \simeq 22\ V$$

or (the cyanogen ionization potentials are approximately equal to those of carbon monoxide)

$$\text{b) } CO \to CO^+ + e, \quad U_i \simeq 14.1\ V.$$

Nitrogen oxide (NO) with an ionization potential $U_i = 9.5$ V is present in adequate quantity in the arc column; the ionization potential U_{iA} of the anode graphite is ~11.3 V. On the basis of the cited data according to formula (1) the anode voltage jump will be equal to (reaction a):

$$U_a = 22 + (9.5 - 11.3) \simeq 20.2\ V$$

or (reaction b):

$$U_a = 14.1 + (9.5 - 11.3) \simeq 12.3\ V.$$

The oscillograms of Fig. 2a, b show that the calculated values are extremely probable; however, in the period of a nonquiescent anode spot lower values are also found.

Generally speaking, in the near-anode layer, in addition to the cited ionization reactions, with vigorous vaporization of the anode material and with the vapors of the latter filling the arc gap, the ionization

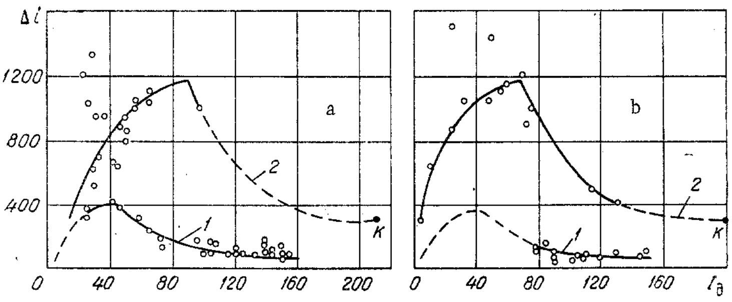

Fig. 1. Current density (A/cm^2) of the anode spot as function of arc current (A): a) For arc 1.5 cm in length; b) for arc 3 cm in length (arc burns in the open air between carbon electrodes; point K is taken from the measurements of K. K. Khrenov).

of graphite vapors become possible, which would correspond to a voltage jump (reaction c)

$$U_a = 11.3 + (11.3 - 11.3) \simeq 11.3\ \mathrm{V}.$$

The latter ionization reaction is most probable for unstable arc burning. Considering the possibility of preliminary excitation of the graphite vapors entering the arc column near the anode, we may find that the anode voltage jump is considerably lower than 11.3 V.

Thus, with respect to the anode voltage drop for a carbon arc burning in air, we can say that within a range of current variations from 20 to 150 A these drops are exceedingly variable and change magnitude at values of about 20 or 12 V, briefly assuming arbitrary values between 5–6 and 20–22 V. With an increase in the current above 100 A, i. e., for stable burning arcs, the jumps at 20 V become increasingly predominant. The nature of the jumps at 12 and 20 V is explained by formula (1) and the cited CO ionization reactions. The values of the anode voltage drops between 12–22 V are explained by the combined progress of the two simultaneous CO ionization reactions, and correspondingly, by the fractions of their participation in the reactions. A drop in the voltage jump below 12 V occurs in unstable regimes.

Earlier [5, 6] we derived a formula to determine the current densities of electrode spots

$$\Delta i_{\mathrm{el.sp}} = \frac{T^4_{\mathrm{arc}}}{U_{\mathrm{el.}}} \exp(-\chi I_{\mathrm{arc}}) \times$$

$$\times \left[1 - \exp(-\chi' I_{\mathrm{arc}})\right] 5.67 \cdot 10^{-12}\ \mathrm{A/cm^2}. \qquad (2)$$

This formula shows that the current density of the electrode spot is a function of a number of factors, including the magnitude of the electrode voltage drop.

Thus, with a reduction in the magnitude of the anode drop, all other conditions being equal, there is an increase in the current density of the anode spot, and consequently, arc constriction-compression. Since the value of the anode voltage drop fluctuates quite regularly about 20 or 12 V, there must correspondingly be two rather clearly defined functions $\Delta i_a = f(I_{arc})$. This is confirmed by experiment: the experimentally derived curves of Fig. 1a,b show as two curves the change in the anode-spot current density with a change in the arc current. There are points indicating a high current density in the anode spot, corresponding to voltage drops less than 12 V (for brief unstable regimes).

The regulation in the anode layer of the electrochemical reactions, as well as of the current density is accomplished in accordance with the principle of minimum resistance or voltage (Shteenbek) or, in other words, according to the second law of thermodynamics; the arc seeks to occupy a more probable state, i. e., a more stable state. During the resulting instabilities, it regulates itself not only by variation of the voltage and current magnitudes, but also by varying the magnitudes of the anode voltage jump. From this standpoint, the upper curves in Fig. 1a,b, i. e., corresponding to the higher current densities, refer to the unstable burning regimes, while the lower curves pertain to the stable regimes.

The experimental data shown in Fig. 1a,b are described with adequate accuracy (approximately) by exponents of the following form.

For an arc of length l_{arc} = 1.5 cm (Fig. 1a): curve 1

$$\Delta i_{a1} = 350 \left\{ \exp\left(- \frac{I_{\mathrm{arc}} - 40}{40} \right) \times \right.$$

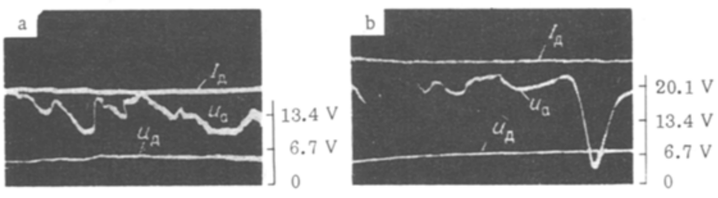

Fig. 2. Oscillograms of arc voltage U_{arc} in V; arc current intensity I_{arc} in A; near-anode potential drop U_a in V: a) at current of 75 A; b) at current of 110 A.

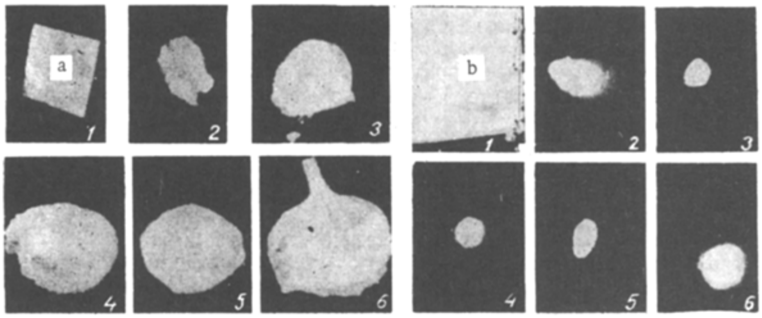

Fig. 3. Photographs of anode spots: a) l_{arc} = 1.5 cm (curve 1, Fig. 1a): 1) scale, 1 cm^2; 2) I_{arc} = 96.5 A; Δi = 187 A/cm^2; 3) 102 and 111; 4) 115 and 36.5; 5) 120 and 107; 6) 155 and 94; b) l_{arc} = 3 cm (curve 2, Fig. 1b); 1) scale, 1 cm^2; 2) I_{arc} = 11 A; Δi = 645 A/cm^2; 3) 25 and 875; 4) 33 and 1050; 5) 54 and 1040; 6) 75 and 1000.

$$\times\left[1-\exp\left(-\frac{I_{arc}-5}{10}\right)\right]\Bigg\}+50, \qquad (3)$$

curve 2

$$\Delta i_{a2}=900\left\{\exp\left(-\frac{I_{arc}-90}{30}\right)\times\right.$$

$$\times\left[1-\exp\left(-\frac{I_{arc}-15}{25}\right)\right]\Bigg\}+300. \qquad (3')$$

For an arc of length l_{arc} = 3 cm (Fig. 1b):
curve 1

$$\Delta i_{a1}=310\left\{\exp\left(-\frac{I_{arc}-40}{35}\right)\times\right.$$

$$\times\left[1-\exp\left(-\frac{I_{arc}-5}{10}\right)\right]\Bigg\}+40, \qquad (4)$$

curve 2

$$\Delta i_{a2}=900\left\{\exp\left(-\frac{I_{arc}-70}{30}\right)\times\right.$$

$$\times\left[1-\exp\left(-\frac{I_{arc}-5}{20}\right)\right]\Bigg\}+300. \qquad (4')$$

These expressions reduce to a single common expression:

$$\Delta i_a=\Delta i_{a\,max}\,\varepsilon\, m+\Delta i_{conv}$$

or, expanding ε and m,

$$\Delta i_a=\Delta i_{a\,max}\left\{\exp\left(-\frac{I_{arc}-n}{I_{arc\,0}}\right)\times\right.$$

$$\times\left[1-\exp\left(-\frac{I_{arc}-n'}{I'_{arc\,0}}\right)\right]\Bigg\}+\Delta i_{conv}, \qquad (5)$$

where n is a constant coefficient for the function $\Delta i = f(I_{arc})$, defining the location of $\Delta i_{a\,max}$ on the axes of the currents, since for n = I_{arc}, ε = 1; for current less than n we assume ε = 1; I_{arc0} is the current constant of the exponential function; Δi_{conv} is the current-density correction factor for convection and heat conduction.

Having analyzed the derived general expression (5) for the current density of the anode spot and having compared it with expression (2) to determine the current density of the cathode spot [6], we note fundamental identities between these: the exponential relationship between the current density and the arc current, the presence of a current-density maximum, etc. To be sure, expression (5) exhibits certain unique features in comparison with expression (2). These features reduce to the following.

1. The current density in the stream function for the anode spot, unlike the cathode spot, is not expressed with a single equation. A minimum of two equations is required, which take into consideration the two most probable ionization reactions occurring in the near-anode layer of neutral gases (CO).

2. Equation (2) for the cathode spot assumes that with an infinite increase in current, the current density in the spot drops to zero. For an anode spot this is not a valid assumption; with an increase in current, the current density tends to some small constant magnitude. This result—derived experimentally—demonstrates that in determining the current density on the basis of an energy balance it is necessary, in considering the heat transferred by the spot, to account not only for radiation, but also for heat conduction and convection, which were not considered in the cathode spot. This feature serves actually as a refinement of formula (2), since in principle the heat conduction and convection (although, admittedly, their role is small here) would have to be taken into consideration in addition to the heat radiation, in determining the current density in a cathode spot.

3. The reduction in the current density of the anode spot, beginning from the maximum, with an increase in the arc current, i. e., with a drop in the emissivity of the spot, proceeds more vigorously than in the case of the cathode spot.

This is explained by the fact that the coefficient of radiation absorption in the region of the anode spot is considerably larger than in the region of the cathode spot.

It is extremely interesting to note that the descending branches of the current-density exponential functions for the anode spots in Fig. 1a,b are independent of arc length (1.5 and 3.0 cm) in all four cases and that the ionization reactions exhibit approximately identical constant currents, equal on the average to 35 A.

The reciprocal of the current constant, representing the absorption coefficient, is equal to $2.81 \cdot 10^{-2}$ A^{-1}. The absorption coefficient in the study of the cathode current density was equal to $5 \cdot 10^{-5}$ A^{-1}, i. e., smaller by several orders than in the near-anode layer. The difference in the absorption coefficients indicates only that the gas phases in the anode and cathode layers are different. This is a generally accepted fact.

Let us also note than in the research conducted on arcs 1.0, 1.5, 2.0, and 3.0 cm in length, a reduction in the length to 2 cm and lower led to an increase in the current density of the anode spot. In arcs longer than 2–3 cm a change in length had little effect on the current-density magnitude.

In $\Delta i_a = f(I_{arc})$ the numerical coefficients before the exponential terms are the maxima of the anode-spot current densities (with addition of a constant component). These maxima, according to formula (2), are expressed as

$$\Delta i_{a\,max} = \frac{T_{a.a}^4}{U_{el}}\, 5.67 \cdot 10^{-12} + \Delta i_{conv},\ \text{A/cm}^2. \qquad (6)$$

Since the current-density maxima are determined experimentally, and in view of the fact that the electrode voltage drops are also known from experiment, by taking the value of $\Delta i_{a\,max}$, from expression (6) we can find the value for the temperature of the anodic zone. For expression (3) and for an anode voltage drop of 20.2 V (this must be increased by the work function of the cathode) we obtain

$$T_{a.a1} = \sqrt[4]{\frac{350 \cdot 24.4 \cdot 10^{12}}{5.67}} \simeq 6250\,^\circ\text{K}.$$

Correspondingly, for an anode voltage drop of 12.3 V, according to the data of expression (3'), we will have ~7100° K.

In the second case, the temperature of the anodic zone is greater by almost 1000° K. There is no doubt that for the points exhibiting a current density in excess of that determined from Eqs. (3)–(5) (there are such points in Fig. 1), the temperature zone of the anodic zone will be correspondingly higher and the anode voltage drop will be correspondingly lower. Thus, the arc current, the current density of the anode spot, the voltage drop, and the temperature in the region of the anode spot exhibit rather close interrelationships with each other. The cited functions may also be used to evaluate the temperature in the region of the anode spot.

In conclusion, we note that the function $\Delta i = f(I_{arc})$ for the anode spot exhibits a maximum, in the same manner as for the cathode spot; the magnitude of the maximum is also determined by the magnitudes of the electrode voltage drop and by the temperature. To reduce electrode consumption it is best to work with spot current densities far removed from the maximum.

NOTATION

I_{arc} is the arc current; l_{arc} is the length of the interelectrode gap; $T_{a.a}$ is the arc temperature in the vicinity of the anode spot; U_a is the anode potential drop; U_{iA} is the ionization potential of the anode material; U_{iAgas} is the gas ionization potential formed intensively because of chemical reactions in the near-anode layer; U_{icol} is the smallest gas ionization potential of an arc column; U_{el} is the near-electrode voltage drop; Δi_a is the current density of the anode spot; $\Delta i_{el.sp}$ is the current density of the electrode spot; ε is the emissivity of an arc in the vicinity of the near-electrode voltage drop; χ and χ' are the optical absorption coefficients in the vicinity of the near-electrode voltage drop.

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