CURRENT DENSITY IN ELECTRODE SPOTS OF ARC WITH METAL ELECTRODES

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The dependence of the total current density in the spots on its different components and the current is examined by considering the energy balance of the electrode sheaths. The factors affecting electrode erosion are determined. Results of measurements of the current density in spots on iron electrodes in arcs with different currents are given.

In [1-3] the determination of the current density in the electrode spots of an arc between graphitized refractory electrodes was considered from the standpoint of the power balance in the electrode sheaths. It was of interest to find out if the results obtained apply also to metal electrodes.

The current density in any steadily burning arc can be determined by considering the power balance of the electrode (plasma) sheath, as was done in [1-3], or the electrode power balance. The variation of current density in the spots in relation to the electric circuit parameters was discussed in [1].

Since the electrical energy of the electrode sheath is completely converted to heat and is removed from it by radiation and convection to the surroundings, and also by conduction to the electrode, then from a consideration of the power balance per unit area of the spot we can write

$$P_{el} = P_{rad} + P_{conv} + P_{cond}. \tag{1}$$

The components of the electric power P_{el} which enter the electrode sheath and are converted to heat can be expressed in the form

$$P_{el} = \Delta i_{el} U_{el} \tag{2}$$

In Eq. (2) only the potential drop due to release of heat in the electrode sheath, i.e., due to the thermal effect, is taken into account.

Substituting (2) in (1) we obtain after some elementary algebra

$$\Delta i_{el} = \frac{I_{arc}}{S_s} = \frac{P_{el}}{U_{el}} = \Delta i_{rad} + \Delta i_{conv} + \Delta i_{cond}. \tag{3}$$

Expression (3), which connects the conditions of conversion of electrical energy within the electrode sheath (left half of equation) with the conditions of removal of heat energy from it (right half of equation), indicates the close relationship between electrical and thermal effects in an electric arc (law of conservation of energy). According to this expression, in steady-state conditions the mean current density, which is closely connected through the temperature with the potential drops at the electrodes [1-3], depends on the conditions of removal of the heat energy from the electrode sheaths. Since the heat energy is removed by radiation, convection, and conduction, the total current density can be regarded as consisting of three components (Δi_{rad}, Δi_{conv}, Δi_{cond}). It may be determined mainly by one or other component, depending on the conditions.

As was shown earlier [1-3] in the case of an arc between graphitized electrodes in air, Δi_{rad} can be determined from the expression

$$\Delta i_{rad} = \frac{m e T^4_{arc}}{U_{el}} 5.67 \cdot 10^{-12}, \tag{4}$$

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where m and ε are exponential functions of the arc current and predetermine the exponential relationship $\Delta i_{rad} = f(I_{arc})$. They depend on the electrode material and the medium in which the arc burns [2, 3].

In view of the shortness of the region of the arc axis occupied by the electrode sheaths we can assume that approximately half of their radiation power (at temperature T_{arc}) is directed into the surroundings, and the other half ($0.5\ P_{rad}$) is directed towards the electrode, where some of it is absorbed ($0.5\ P_{rad}\varepsilon$) is Some of the energy ($0.5\ P_{rad}\varepsilon$) is reflected, and the rest ($0.5\ P_{rad}\varepsilon$) $(1-\varepsilon)$ is used up on heating the electrode.

The emissivity ε of graphite and carbon electrodes is fairly high (0.8–0.9) and the power spent on heating the electrode is small – $0.5\ P_{rad}\ (1-0.9)\cdot 0.9 = 0.045\ P_{rad}$. In these cases the erosion of the electrode is mainly due to electrochemical reactions (on the anode), in accordance with Faraday's electrochemical laws, and not to melting and evaporation. On the other hand, the emissivity ε of metal (unoxidized) electrodes is low (0.15–0.6), the absorption is high – $0.5\ P_{rad}\ (1-0.5)\cdot 0.5 = 0.125\ P_{rad}$ and, hence, the erosion of the electrodes due to their melting and evaporation is considerable. Electrochemical reactions are practically absent, since the arc burns in the electrode vapor.

Using the Fourier and Newton–Rikhman laws we can write the heat powers and the corresponding current densities for heat removal by conduction and convection in the form

$$P_{cond} = \lambda \frac{\partial T}{\partial n}, \quad \Delta i_{cond} = \frac{\lambda \frac{\partial T}{\partial n}}{U_{el}}; \tag{5}$$

$$P_{conv} = \alpha \Delta T, \quad \Delta i_{conv} = \frac{\alpha \Delta T}{U_{el}}. \tag{6}$$

Since the arc temperature does not change much when the current changes, and the temperature of the electrode material under the spot is close to T_b, it follows from Eqs. (5) and (6) that because of the components $\Delta i_{conv} + \Delta i_{cond}$, which are proportional to the difference in temperatures of the end of the arc and the electrode, or the end of the arc and the medium, the current density in the spots is not greatly affected by variation of the arc current in a wide range. If we take into account the fact that at high currents (much greater than the corresponding Δi_{max}) the emissivity of the electrode sheath ε_{sh} tends to zero [2, 3], we arrive at the conclusion that at high currents the total current density in the electrode (anode) spots is determined almost entirely by the components $\Delta i_{conv} + \Delta i_{cond}$, and it remains constant in a wide range of current. In the electrode sheaths in this case ($\Delta i_{rad} = 0$, $\varepsilon_{sh} = 0$) all the radiation is absorbed internally, which actually corresponds to conditions in which the electrode region is transformed from a bulk radiator to a surface radiator – a black body [2].

The graph of $\Delta i_{el} = f(I_{arc})$ is obtained experimentally and the sum of the components $\Delta i_{conv} + \Delta i_{cond}$ is determined from the part parallel to the I_{arc} axis. It is then easy to find $\Delta i_{rad.max} = \Delta i_e - (\Delta i_{conv} + \Delta i_{cond})$. This provides a simple method of separating the components Δi_{rad} and $\Delta i_{conv} + \Delta i_{cond}$.

In the case of an arc burning in air between graphitized electrodes, the sum $\Delta i_{conv} + \Delta i_{cond}$ in the anode current density is approximately 80-90 A/cm^2 and at the common maximum of current density is 20-25%. These components play a much smaller role in the cathode current density [2, 3]. The great predominance of radiative heat transfer in the cathode spot predetermines the high current density here in comparison with the anode spot and the higher temperatures.

In determination of the current density in the electrode spots it is important to know the magnitude (thermal effect) of the potential drop at the electrode. According to investigations [1], the electrode potential drop at the cathode is given by the formula

$$U_{el.c} = U_{ic} + \varphi_{out} \tag{7}$$

and combined with the thermal effect it will be $\sim U_{ic}$. For an arc with carbon or graphitized electrodes burning in a medium which interacts chemically with carbon the potential drop at the anode, according to [1], is given by the formula in [3]:

$$U_{el.a} = U_{iAgas} + \varphi_{in}. \tag{8}$$

If the arc burns in the vapor of the anode material, as in the case of metal electrodes, then $U_{iAgas} = 0$ – there are no chemical interactions; φ_{in}, however, may not be zero (if the column gas is not the anode vapor).

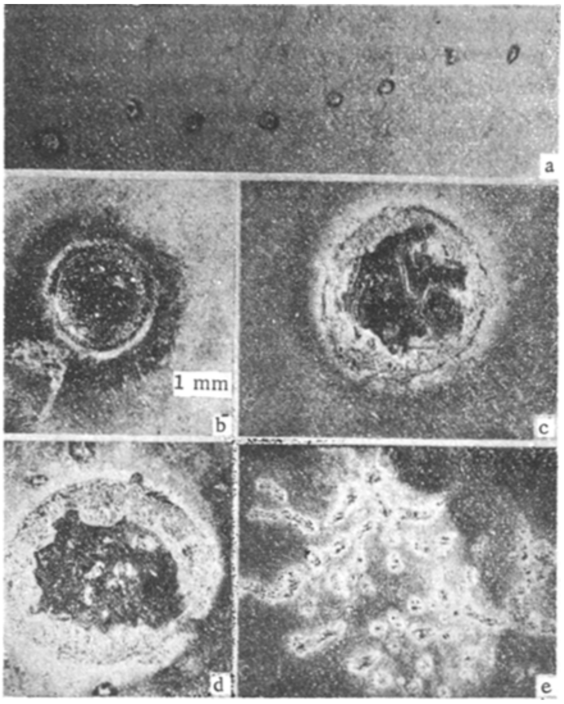

Fig. 1. a) Photograph of iron strip with cathode spot marks (current 400 A). Photomicrographs of anode and cathode spot marks: b) current 300 A, current density 9500 A/cm^2; c) anode, current 210 A, current density 2800 A/cm^2; d) anode, current 300 A, current density 2380 A/cm^2); e) photomicrograph of divided cathode spot marks (current 320 A).

These considerations enable us to determine the power transferred from the electrode sheath to the metal electrode. Together with the Joule power (as the current spreads from the spot over the electrode) it is

$$P_e = 0.5\, P_{rad}(1-\varepsilon)\,\varepsilon + P_{cond} + P_J \tag{9}$$

It is obvious that this power is expended on erosion (melting and evaporation) of the electrodes and is partially removed by heat conduction from the spot into the electrode

$$0.5P_{rad}(1-\varepsilon)\,\varepsilon + P_{cond} + P_J = P_{eros} + P_{cond.\,el}. \tag{10}$$

The transfer of heat by conduction (P_{heat}) from the cathode sheath to the cathode is impeded by the intense electron flux from the cathode into the column. This is obviously the reason why the cathode is usually eroded more slowly than the anode. Our experiments with iron electrodes show that the erosion of the cathodes, despite the much higher current density in them, is certainly not greater than the erosion of the anodes.

After some very simple transformations of Eq. (10) and some feasible assumptions, we obtain

$$P_{eros} = 0.5\, P_{rad.\,max}\, m\varepsilon_{sh}\, \varepsilon\, (1-\varepsilon) + P_J + C, \tag{11}$$

where $C = P_{cond.sh} - P_{cond.el} \approx \text{const}$; $P_J = \Delta i^2 R_{el}$. If we assume $R_{el} \simeq \text{const}$ for the given conditions, then $P_J = C\Delta i^2$. The specific electrode erosion (referred to an area of 1 cm^2) is proportional to P_{eros} and, hence, it follows from formula (11) that it depends in a fairly complex manner on the arc current and has a maximum at currents corresponding to Δi_{max} (m and $\varepsilon = 1$).

Equation (11) indicates measures which can be taken to reduce electrode erosion: the operating current of the apparatus must not be equal to the current corresponding to Δi_{max}; the electrodes can be cooled artificially with water (or in some other way); the electrode spots should be made to move rapidly over the electrode; the solid electrode spot should be broken up into a large number of separate spots, which is equivalent to reduction of the mean current density. In general, all measures which reduce the mean current density in the electrode spots lead to a reduction of the specific electrode erosion. The erosion can be significantly reduced by an increase in the specific resistance of the electrode material immediately under the spot, as this leads to a reduction in current density [1]. It appears that this (the change in the state of of the electrode surface immediately under the spot) is the main reason for the change in current density in the spots when they are cooled with water or additionally heated, or in the case of prolonged burning of the arc on one spot. This could account for the spread of the experimental points for the same arc current.

To illustrate the above ideas in the case of arcs with metal electrodes we made measurements of the current density in electrode spots (cathode and anode) on iron (carbon steel 3) electrodes. Since the electrode spots on metal electrodes are not bright enough and it is difficult to photograph them through the bright arc column (it is difficult to fix the contraction of the arc at the electrodes) we determined the spot current density, for lack of a more accurate method, from the marks left by the arc on moving electrodes.

The electrodes were iron strips 700 mm long, 90 mm broad, and 2 mm thick. The strips moved in horizontal guides at a speed of 2.4 m/sec. The strips were moved during the experiment by an asynchronous motor through a reducer and a flexible rod wound on a pulley. The speed of 2.4 m/sec was chosen to ensure the obtention of distinct marks without significant melting. The arc burned vertically. In measurements of the anode current density the iron strip moved in a horizontal plane in guides and a fixed iron cathode (20 mm in diameter) was mounted vertically over it. The interelectrode gap in all the experiments was 1.5-2 cm. The arc was ignited before the start of the experiment by fine wires. The arc left marks

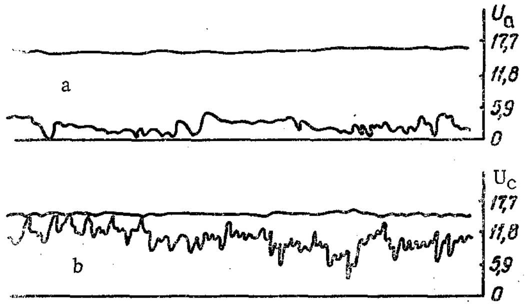

Fig. 2. Oscillograms of anode (a) and cathode (b) potential drops at currents of 90 A (bottom curves); upper curves – current traces; oscillograph speed 50 mm/sec; arc length 1.5 cm.

on the moving strip in the form of a series of spots (due to shunting) 2-2.5 cm apart. The time of burning on one spot was about 0.01 sec, i.e., long enough for the spot to be regarded as stationary, i.e., fully formed.

The current during the experiment was determined with an oscillograph; the start of movement of the strip was synchronized with the start of the current trace on the oscillograph. To determine the current density we used only distinct spots of the largest diameter. Small ones were not used in the calculation; their formation was attributed to splitting of the end of the arc or to its unstable burning. Distinct spots were obtained when the arc burned under the fixed electrode. The size of the spots was determined with a MI-1 measuring microscope from the size of the spot crater (which was assumed to be circular). Knowing the area and the current from the oscillograph trace we determined the current density.

In the experiments we used a 500-V, 150 A dc generator and dc welding generators (for currents of more than 150 A). The current was varied by a ballast resistor and also by a field regulator. Welding generators are less suitable, since their current is less stable, which leads to an additional scatter of the points.

As examples, Fig. 1 shows: a) photograph of iron strip with cathode spot marks (current 400 A); b, c, d) photographs of anode and cathode spots magnified by a microscope, from which the current density was determined; e) photograph of divided spot, illustrating that such spots are possible. Figure 2 shows oscillograms of the anode and cathode potential drops of an arc burning between vertical fixed iron electrodes in air. These drops were measured with iron wires (probes) 1 mm in diameter in an Alundum sheath inserted into the electrode sheaths (the measurements were made on the bottom electrode). Figure 3 shows the anode and cathode spot current densities as functions of the arc current, obtained from the experimental data.

The oscillograms in Fig. 2 indicate that if we allow for the inevitable error of 1-2 V entailed in measurement of the potential drop in an arc column of length equal to the thickness of the tube wall (1.5 mm), and also the potential drop in the electrode, the mean value of the cathode potential drop will be approximately the same as that calculated from formula (7), i.e., 12.6 V (the sharp dips in the curves correspond to contact of the probe with the electrode or to metal droplets), and the anode drop, in accordance with formula (8), is close to zero. In this case the electrode drops due to the thermal effect are 7.9 V for the cathode and 4.77 V for the anode (the cathode drop is reduced by the value of the work function and the anode drop is increased by this value).

Examining the relationship $\Delta i_a = f(I_{arc})$ (Fig. 3B) we see that in the case of iron electrodes, owing to contraction of the arc at the electrodes, the current densities in the electrode spots increase rapidly in comparison with arcs between graphitized electrodes [2, 3]. In addition, at high currents (greater than the corresponding Δi_{max}) the role of the components $\Delta i_{conv} + \Delta i_{cond}$ of the anode current density (horizontal part of curve in Fig. 3B) in the total spot current density is greater than in the case of graphitized electrodes, reaching 50% Δi_{max}, or 2500 A/cm^2 in absolute value (as compared with 80-90 A/cm^2 for a graphitized anode). The increase of $\Delta i_{conv} + \Delta i_{cond}$ in low-melting metal anodes is due to the greater (in comparison with graphitized refractory electrodes) efflux of metal gas (vapor) from the anode region.

From the curves in Fig. 3 $\Delta i_{max,rad}$ for the anode current density is ~2300 A/cm^2, and for the cathode current density is apparently about 11,000 A/cm^2 (the role of $\Delta i_{conv} + \Delta i_{cond}$ is small here). Since the current density maximum due to radiation occurs when m and $\varepsilon = 1$ [2, 3], then from formula (4) the temperature of the anode region (end of arc) is

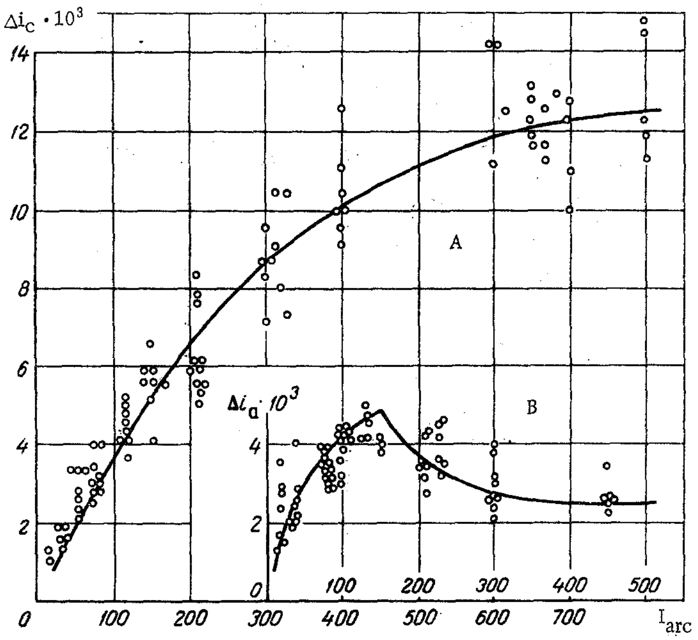

Fig. 3. Relationship $\Delta i = f(I_{arc})$ for cathode (A) and anode (B) in an arc burning in air between iron electrodes; arc length 1.5 cm.

$$T_{arc\,a} = \sqrt[4]{\frac{\Delta i_{a\,max} U_{el,\,a}}{5.67} 10^{12}} = \sqrt[4]{\frac{2300 \cdot 4.77}{5.67} 10^{12}} = 6300\ ^\circ K$$

and that of the cathode region is (10,000-11,000)°K. These temperatures are close to the corresponding temperatures for graphitized electrodes. Formulas (3), (4), and the calculation from the experimental data show that the low potential drops at the electrodes of arcs with metal electrodes predetermine their contraction in the electrode sheaths, which is responsible for the increase in current density and maintenance of the concentration of energy and temperature at the level close to that of graphitized electrodes. The role of the electrode potential drops is brought out very clearly by a comparison of the anode current density on graphitized [3] and iron electrodes. For instance, U_{ea} (graphite) = 24.4 V and the maximum density is 400 A/cm^2; for iron U_{ea} (iron) = 4.77 V and the maximum current density is about 4800 A/cm^2. It is very interesting that in the case of high temperatures the thermal conductivity of graphite and iron is approximately the same.

Since the temperatures of the ends of arcs between metal and graphitized electrodes are similar, and the temperature of the electrode spots are close to the boiling points (graphite 4200°K, iron 3000°K) the temperature drop between the arc and the electrodes in the case of metal electrodes is appreciably greater than in the case of graphitized electrodes, which predetermines the more rapid transfer of heat by conduction from the arc to the electrodes and their rapid erosion. Both $\Delta i_a = f(I_{arc})$ and $\Delta i_c = f(I_{arc})$ are of an exponential nature and can be approximated reasonably accurately by the expressions obtained in [2, 3] for graphitized electrodes:

$$\Delta i_c = 13000 \left[1 - \exp\left(\frac{I_{arc}}{275}\right)\right],$$

$$\Delta i_a = 2500 \left\{\exp\left(-\frac{I_{arc} - 150}{75}\right)\left[1 - \exp\left(-\frac{I_{arc} - 35}{50}\right)\right]\right\} + 2500 \qquad (12)$$

(at currents less than 150 A the first exponential factor is taken as unity).

The descending branch of the function $\Delta i_c = f(I_{arc})$ was not obtained experimentally. The maximum cathode current density apparently occurs at currents around 1000-1200 A, which is higher than the currents attained in our experiments.

NOTATION

P_{el}, Δi_{el}	are the total specific power and current density in electrode sheath;
P_{rad}, Δi_{rad}	are the total power and current density due to radiative heat transfer;
P_{conv}, Δi_{conv}	are the total power and current density due to convection;
P_{cond}, Δi_{cond}	are the total power and current density due to heat conduction from electrode sheath to electrode;
S_{rad}, S_s	are the areas of radiation and current of spots;
ε_{sh}, T_{arc}	are the emissivity and temperature of electrode region (end of arc);
ε	is the emissivity of electrode material ($\varepsilon_{sh} \neq \varepsilon$);
T_b	is the boiling point of electrode material;
φ_{out}	is the electron work function of cathode;
U_{ic}	is the lowest ionization potential of cathode sheath gases with possible excitation taken into consideration;
U_{iAgas}	is the ionization potential of gases rapidly produced at anode due to chemical interaction of carbon with gas phase of arc column;
$\varphi_{in} = U_{icol} - U_{iA}$	is the work function for entry of electrode into anode;
U_{icol}	is the lowest ionization potential of column gases;
U_{iA}	is the ionization potential of anode material;
P_e	is the power transferred from electrode sheath to electrode;
P_J	is the specific power produced by Joule heat when current spreads over electrode from electrode spot;
P_{eros}	is the specific power expended on electrode erosion;
$P_{cond.el}$	is the power drawn off from spot into electrode by heat conduction;
T_{arca}, T_{arcc}	are the temperatures of anode and cathode regions;
Δi_a, Δi_c	are the total anode and cathode current densities;
$m = S_{rad}/S_s$;	
U_{el}	is the potential drop at electrode (anode or cathode) due to release of heat.

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