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HEAT EXCHANGE IN LOW-TEMPERATURE-PLASMA PROCESSES

INVESTIGATION OF THE PARAMETERS OF A NONSTATIONARY ARC SPOT ON A COPPER CATHODE BY THE THERMOSPECTROSCOPIC METHOD. I. CURRENT DENSITY

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A new procedure of determination of the effective density of the current in a nonstationary arc spot with the use of thermophysical and spectroscopic measurements has been proposed and tested. The procedure is based on recording of the critical cathode temperature corresponding to the instant of sharp increase in the intensity of the CuI λ = 5218 Å atomic spectral line, which coincides with the beginning of intense emission of a copper vapor from the spot, according the hypothesis proposed. New results are compared to those obtained earlier by purely thermophysical methods.

Introduction. The density of the current in an arc spot is one of the most important parameters determining the erosion and service life of the electrodes in electric-arc gas heaters (EAHs) and other arc devices. One traditionally calculates it from the data of measurements of the current and the dimensions of the arc spot, taking the symmetry of the latter to be circular, i.e., $j = 4I/\pi d^2$. Two methods are usually used to measure the diameter: those of autographs and high-speed photorecording. In the autograph method, the dimension of the emitting region of the spot is taken to correspond to the size of the craters left by it, whereas in the method of high-speed recording, it is taken to correspond to the dimensions of the luminous region of the cathode plasma [1, 2].

As has been revealed with the modern technique of optoelectronic recording with a high temporal and spatial resolution, the arc spot on a cold cathode has a very dynamic structure and consists of a large number of individual short-lived microspots that have a complex hierarchic structure and are in continuous motion. Moreover, as the recording technique is improved, this hierarchy increasingly expands toward revealing the finest details of the internal microstructure. Such a situation makes determination of the current-conducting zone of the spot very difficult and dependent on how the situation observed corresponds to the dimension of the zone [2]. In [3], an attempt was made to measure the average dimension of this zone by moving the spot slowly through an insulating gap of a special current sensor divided by this gap into two halves in recording a change in the current in each half. However, the presence of such a gap can substantially distort the shape and dimensions of the conducting zone; therefore, this method applies only to specific conditions of slowly moving spots with a size much larger than the gap size, because of which Szente et al. used it for a plasma cutting arc. In [4, 5], traversal of a special linear magnetic sensor by the spot instead of the traversal of an insulated slot was used for such measurements in an electric-arc unit with a magnetic movement of the arc, which introduced no disturbances into the spot itself. However, such a method gives only the linear current density, which is difficult to convert to the real one without knowing the spatial current distribution. Therefore, we proposed that the concept of the effective current density in the arc spot, determined from the thermal effect by recording

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the beginning of the fusion of the electrode surface on a macroscopic scale (of the order of the integral spot size), be used in thermal calculations of the electrodes. This gives a value of the current density in the spot that is immediately averaged by the thermal effect and can directly be used in calculations of the thermal regime and erosion of EAH electrodes [6–8]. In this work, we have presented another diagnostic procedure (called a thermospectroscopic one) that will be used for determination of the effective density of the current on a copper cathode in an air medium as a function of the external magnetic field moving the arc with a high velocity. This procedure enabled us to substantially increase the sensitivity and reliability of recording of the beginning of macrofusion in the spot, which is required for determination of the current density.

Experimental Setup and Procedure. Measurements of the effective current density as a function of the magnetic field with the use of the thermospectroscopic method were performed on a coaxial electric-arc unit with movement of the arc by an external magnetic field. The design of the unit was described earlier in [6, 9] in detail; therefore, we do not give it here. The experiments were carried out for a magnetic induction B = 0.015–0.32 T, an arc current I = 200–400 A, and a velocity of movement of the arc on the electrodes v = 45–717 m/sec. The unit was equipped with uncooled annular electrodes manufactured from commercial copper. The external electrode (cathode) with an inside diameter of 40 mm and a width of 3 mm was equipped with two Chromel-Alumel thermocouples installed on its lateral surface and was insulated from the adjacent parts of the unit with heat- and electric-insulation spacers. Air fed in the axial direction without a twist and at a nearly atmospheric pressure was used as the working gas. The unit was equipped with an optical system enabling us to collect light from the annular interelectrode gap (3 mm) and transfer it via an optical-fiber line to the inlet of a Czerny–Turner "SPEX-1401" spectrometer fitted with a photomultiplier that could be tuned to the recording of the spectral line selected. Acquisition of data from the spectrometer, the thermocycles, and the current and voltage sensors and control of the operation of the unit were carried out by a computer with a specially developed program in the LabView environment.

Thermal and Thermospectroscopic Methods of Determination of the Current Density in the Arc Spot. As has been shown in [8–12], averaged thermal characteristics of the spot can be used for applied engineering calculations of the EAH electrodes. Assuming that the heat-flux density q_0 is distributed uniformly inside the spot, we can write the average current density j in the form of the relation $j = q_0/U$, which immediately follows from determination of the thermal volt-equivalent of the arc spot $U \equiv Q_0/I = q_0F/I$, where Q_0 is measured by an independent calorimetric method [6, 9, 12].

Since the size of the arc spot on the cold cathode is very small as compared to the length of the electrode's circle and the trajectory of the arc spot experiences longitudinal displacements along the electrode axis, the temperature field relaxes very rapidly after the traversal of the spot, as compared to the time of return of the arc spot to the same point, and the temperature of the electrode surface in front of the moving spot differs little from the average one [13]. The latter is determined primarily by the energy parameters of the arc spot and the character of heat exchange between the electrode and the arc plasma. This heat exchange substantially depends on the method of movement of the arc on the electrode — either with a magnetic field or a vortex gas flow [14–16].

For a certain combination of the operating parameters, the time of thermal exposure of a given point of the electrode inside the arc spot can attain the value of $\tau = \tau_0$ required for heating to the fusion temperature T_f [14]:

$$\tau_0 = \frac{\pi}{4a}\left[\frac{(T_f - T_0)\,\lambda}{q_0}\right]^2, \qquad (1)$$

and then macrofusion will begin in the spot. If we simultaneously record the beginning of macrofusion, the surface temperature of the electrode, and the velocity of movement of the arc spot, the effective average current density can be calculated according to the relation [7, 12]

$$j = \frac{\pi}{4}\left[\frac{\lambda^2 v}{an\sqrt{I}}\left(\frac{T_f - T_{cr}}{U}\right)^2\right]^{2/3}. \qquad (2)$$

Formula (2) is written in the general form suitable for continuous and discontinuous (step-by-step) movements of the arc spot which are allowed for by the parameter $n = L/d$, where L is the length of the spot's step, or the dis-

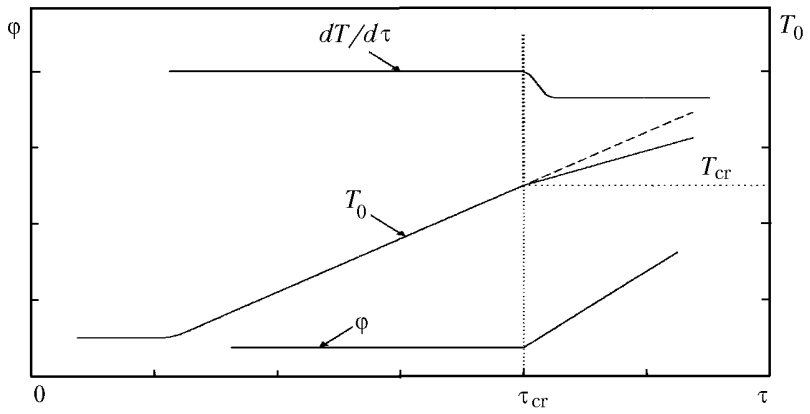

Fig. 1. Diagrammatic representation of the thermospectroscopic procedure of determination of the effective density of the current in an arc spot.

tance between the subsequent stops of the spot. For step-by-step motion, we consider the regimes where the subsequent positions of the spot do not overlap, i.e., $n \geq 1$. For continuous movement, we always take $n = 1$ in (2) [7, 10–12].

Measurement of the step length requires that the spatial-temporal resolution of the equipment used be very high. Since we did not have such equipment, we took $n = 1$ in all the experiments. If the arc motion was step-by-step with $n > 1$ rather than continuous, in such an approach we obtained only the "apparent" density of the current $j_a = jn^{2/3}$ and not the real density j, since the thermal effect of nonuniformity of the motion was included in the results of measurements [7, 10–12]. This density corresponded to the real current density only if the arc motion was uniform.

From solution [17, 18] of the problem of heating of an infinitely long hollow cylinder on the interior surface with boundary conditions of the second kind (i.e., for the prescribed heat-flux density q = const) and with a heat-insulated exterior surface it follows that, when the value of the Fourier number is $\text{Fo} = a\tau/[(R_2^2 - R_1^2)/2R_1]^2 \geq 0.4$, we have a regular regime of heating. It is characterized by a linear increase in the temperature with time, i.e., $dT/d\tau$ = const for any point of the electrode. However, after the beginning of macrofusion, heat supply to the electrode must decrease owing to the processes of fusion and evaporation of the material, and the derivative $dT/d\tau$ must accordingly decrease.

Examples of the curves of heating of a cathode, written in actual experiments and used to obtain the current density in the arc spot by a purely thermophysical method, are presented in [6, 7]. Here Fig. 1 gives an idealized schematic diagram of thermophysical and spectroscopic experiments in combined form for visualization of the thermospectroscopic procedure proposed. The idea of a purely thermophysical experiment implies that if the average temperature of the electrode surface $T_0(\tau)$ is recorded at the instant of deviation of the regime of heating from the linear one (T_{cr} on the diagram), we can take that it is equal to the critical temperature at which local macrofusion begins inside the spot. This temperature is much lower than the fusion temperature of the cathode material (copper); therefore, we do not observe integral fusion of the surface here. The essence of the spectroscopic method is that the critical temperature of the electrode surface must be determined from the beginning of a sharp increase in the intensity of the selected copper spectral line CuI λ = 5218 Å rather than from the deviation of the regime of heating of the electrode from the linear one. In [19], it has been shown that the intensity of this line radiated from the cathode region of the arc is in proportion to the intensity of erosion. Therefore, it is taken in the new method that the onset of macrofusion corresponds to a sharp increase in the radiation intensity of the copper line. The value of T_{cr} (see Fig. 1) was determined from the sharp increase in the intensity of the copper line CuI λ = 5218 Å rather than from the inflection of the curve of representation of the temperature irrespective of the presence and position of the point of inflection (this aspect is pronounced on the curve of the intensity of the spectral line φ). Unlike the ideal case shown on the diagram, these temperatures do not necessarily coincide in the experiments, as will be shown below.

The drawback of a purely thermal method is that it is necessary to meet certain additional requirements even after the condition $\text{Fo} \geq 0.4$ is satisfied for the annular electrode so as to obtain an ideally straight line $T = f(\tau)$ in practice. These requirements are due to the fact that, in addition to the motion on the electrodes' circle, the arc spot

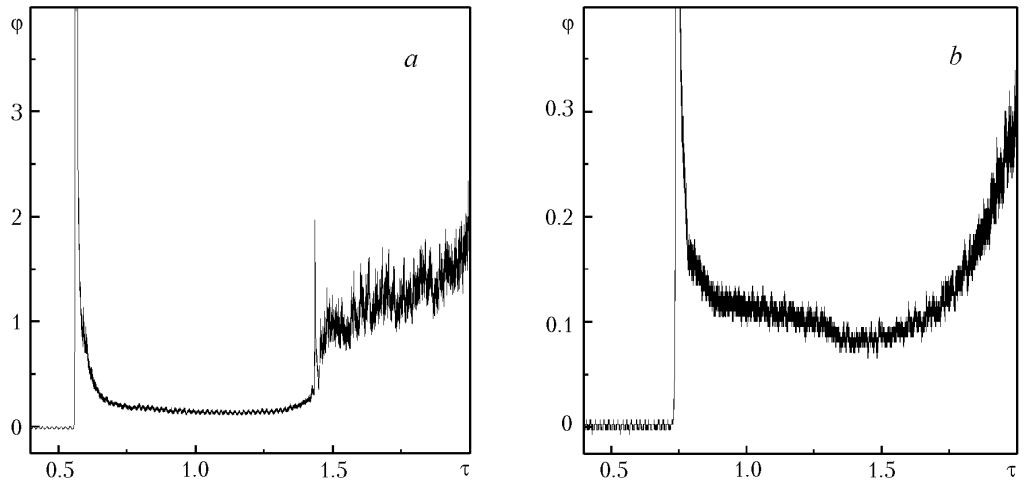

Fig. 2. Comparison of the signals of the intensity φ of the copper spectral line CuI λ = 5218 Å, recorded on a new cathode (a) and on that having 10 running seconds (b).

executes random longitudinal movements on the annulus width. These movements, occurring with a low axial velocity, produce low-frequency temperature fluctuations in the zone where the thermocouple is installed; the temperature fluctuations are recorded by the equipment and make it difficult to determine the instant of deviation of the regime of heating from the linear one. The electrode width constructed should be close to the spot's diameter so as to limit these displacements. Furthermore, the best relation between the axial gas velocity and the magnetic field applied must specially be selected for the spot to move predominantly in the midplane of the annulus. Such measurements are difficult to carry out in practice for currents less than 1 kA, since the diameter of the spot is only 1 mm even for a current of 1 kA [6].

These additional requirements are removed for the thermospectroscopic method, since the instant of the beginning of macrofusion in the spot is determined from the ejection (recorded spectroscopically) of a copper vapor. Therefore, we can disregard the disturbances in the linearity of the heating curve due to the displacements of the trajectory of the spot along the electrode axis.

Also, we compared the results of determination of the current density with nonstationary and stationary experiments. In the latter, we measured the erosion as a function of the current, with the remaining controlled parameters (magnetic field, flow rates of the cooling water and the gas) being constant. The method of determination of the current density with such experiments has been described in [8, 20] in detail; therefore, here we restrict ourselves only to a brief description of it. The method is based on the assumption that the onset of macrofusion in the spot corresponds to a sharp increase in erosion (beginning of macrofusion), which is clearly seen on the plot of the erosion as a function of the current. We took that the regime of microfusion characterized by a low value increasing only slightly with current is observed as long as the time of thermal exposure in the spot remains shorter than the time (τ_0) it takes for the surface to be heated to the fusion temperature. Assuming that a sharp increase in erosion is observed, when the condition $\tau = \tau_0$ is satisfied, and applying (2) to the measured critical values I_{cr}, T_{cr}, and v_{cr} in the regime of the beginning of increase in the erosion, we obtained j by the stationary method.

Discussion of the Results. Figure 2 shows examples of the change in the intensity of the λ = 5218 Å copper spectral line during the experiment for cathodes having different integral operating times and differing, as a result, in the degree of contamination of the surface by erosion products. Ignition of the arc, when it only began to move, was always accompanied by the intense radiation of this line (peaks in the left-hand parts of the figures in the region 0.6–0.8 sec). On the next portion (to 1.4–1.5 sec), the intensity of this line is constant or nearly constant, which was taken as the microerosion regime, in which the electrode temperature was still lower than the critical one, in accordance with a thermal erosion model. According to our hypothesis, the beginning of macroerosion corresponded to a sharp increase in the line of copper (beginning from 1.4–1.5 sec) as a result of its enhanced evaporation. It was revealed that the variation of the intensity of this line with time changed from experiment to experiment and depended on the state of

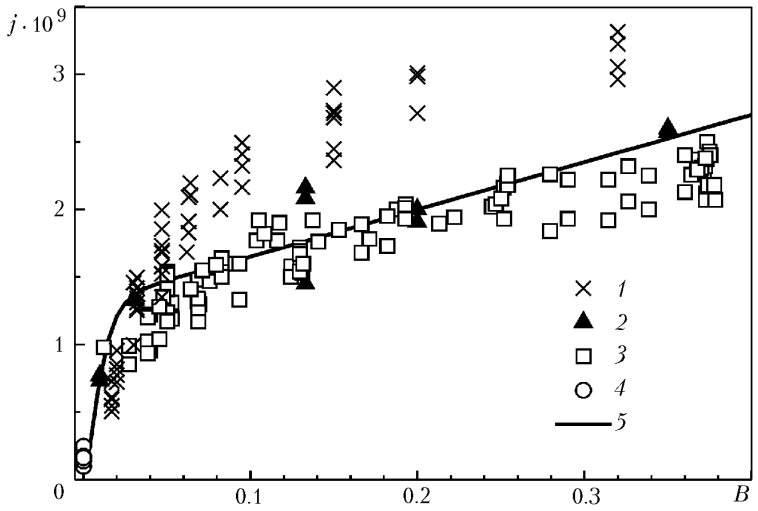

Fig. 3. Effective density of the current in a cathode arc spot j as a function of the magnetic induction B: 1) data of the present work obtained by the thermospectroscopic method; 2) stationary data from [8, 20], obtained by modeling erosion; 3) data of nonstationary thermophysical measurements from [7]; 4) data of electric measurements from [3] for $B = 0$; 5) coapproximation of the stationary data [8, 20] and the data of electric measurements [3], according to [20].

the cathode surface (this state was determined by the accumulated operating time). It is apparent that the oxide layer accumulating gradually on the surface began to affect the supply of copper to the arc and the radiation of the line. Thus, after an accumulated time of 10–15 sec, a fairly intense CuI line began to be radiated from the very beginning of the experiment, in practice, making it difficult to determine the beginning of macrofusion (compare Fig. 2a and b); therefore, it was necessary to replace the cathode by a new one after 5 to 6 experiments of duration 2–2.5 sec each.

The results of measurement of the current density obtained by the thermospectroscopic method are shown in Fig. 3. For the sake of comparison, we give here the results obtained by the stationary and nonstationary thermal methods from [6–8, 20] and the data from [3], obtained by electric measurements for the zero magnetic field. From this figure it is clear that, according to [7], nonstationary thermal methods yield a nearly exponential increase in the current density in the range of magnetic fields 0.01–0.38 T and agree with thermospectroscopic methods only for low magnetic fields — to 0.05 T. Above this range, the data of the thermospectroscopic method exceed those of the stationary and nonstationary thermal methods. The difference in the data of the last two methods is attributable to the difference in the state of the cathode surface. The stationary data were obtained in experiments with a duration of 10 min each, whereas the nonstationary data were obtained in experiments with a duration of only 1–2 sec. Accordingly, in the stationary experiments, the cathode surface was covered with a much thicker oxide layer than that in the nonstationary experiments. As has been shown in [21–24], thick oxide layers on the cathode surface decrease the mobility of a cathode spot and make its motion discontinuous (characterized by $n > 1$), simultaneously increasing erosion, and, conversely, thin oxide layers contribute to a uniform motion of the arc spot ($n = 1$) with a reduced erosion. Since $n = 1$ was taken for all the experiments, we were to obtain overstated (relative to the real ones) values of the current density. Indeed, the current density measured by the stationary method (points 2 in Fig. 3) somewhat exceeds the data of the nonstationary method (points 3). However, this is not the reason why the thermospectroscopic data obtained (points 1) lie above points 2. To understand this we analyzed the possible influence of the oxide layers on spectroscopic recording of the copper line, too. As has been shown in [25], the oxides CuO and Cu_2O are always present on the copper surface in air at atmospheric pressure. The stability of Cu_2O decreases at temperatures higher than 250^{o}C. Above this temperature, we have decomposition of the Cu_2O oxide to form a more stable CuO and to release atomic copper, i.e., $Cu_2O \rightarrow CuO + Cu$.

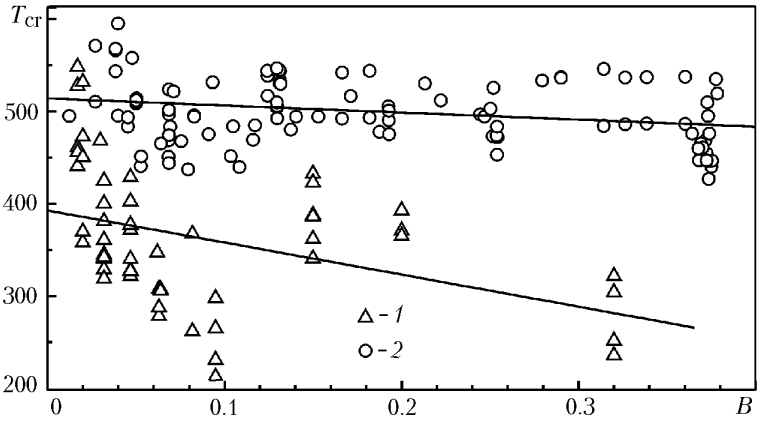

Fig. 4. Critical temperature of the cathode surface T_{cr} vs. magnetic induction B: 1) data of the present work obtained by the thermospectroscopic method; 2) data of thermophysical experiments from [7].

TABLE 1. Activation Energies of Elementary Processes That Can Be Involved in the Process of Erosion [25]

Category	Mechanism	Process	Effective activation energy (eV)
Chemical	Breaking of interatomic bonds	*Decomposition of oxides*	
		$Cu_2O \rightarrow CuO + Cu$	0.87
		$CuO \rightarrow Cu + O$	0.82
		Evaporation	
		Cu	0.57
		CuO	3.87
		Cu_2O	5.69
Physical	Relaxation or weakening of interatomic bonds	*Fusion*	
		Cu	0.13
		CuO	0.19
		Cu_2O	0.29

Figure 4 compares the critical temperatures of the copper cathode T_{cr} as a function of the magnetic field that have been recorded in the experiments according to the two nonstationary methods described above. It is seen that T_{cr} obtained by the thermospectroscopic method (points 1) always lies lower than that obtained by the thermal method (points 2). The difference in these temperatures (150–200^{o}C) increases with magnetic field, which is the reason for the differences in the current densities obtained, in accordance with formula (2). Therefore, we can assume that the CuI atomic line can be radiated even before the beginning of the fusion of the basic cathode material owing to the low-temperature decomposition of the copper oxide Cu_2O; this effect becomes stronger as the magnetic field increases, since the basic material does not necessarily manage to warm up with decrease in the exposure time.

Table 1 (composed according to the data of [25]) gives the activation energies of elementary processes that can be involved in the erosion of the copper cathode. It is seen that the total expenditure of energy in fusing and subsequently evaporating copper (which refers to the basic cathode material) are very close to the expenditure in decomposing the oxide $Cu_2O \rightarrow CuO + Cu$ on the surface. Therefore, in the experiments, we can record both the CuI line radiated owing to the evaporation of copper from the basic material (substrate) and the same line radiated by the atoms that are released owing to the decomposition of the surface oxides. If there are a large number of oxides on the surface, they can predominate in the radiation of the CuI line in the process of decomposition.

As our experiments show, the motion of the arc becomes less stable and more discontinuous for low magnetic fields, which is attributable to the dominance of the specific "surface" resistance to the spot motion [21, 22] over the ponderomotive force $\mathbf{I} \times \mathbf{B}$ moving the arc. Therefore, for low magnetic fields, the real time of the immobile state of

the arc spot can be much longer than that calculated by us from the measurements of the average velocity and quite sufficient for fusion of the basic substrate of the electrode. This can reduce the influence of the surface oxide layers on the results of thermospectroscopic measurements. To check this assumption it is necessary to carry out special experiments with gases not contaminating the cathode surface, for example, with inert gases.

CONCLUSIONS

The thermospectroscopic method of recording of the beginning of the macrofusion of the cathode surface in the arc spot enables one to significantly simplify and improve the reliability of determination of the point of transition from micro- to macroerosion as compared to the purely thermal method. The effective current density obtained with such a method on a copper cathode in an air medium coincides with that obtained earlier by the purely thermal method for low magnetic fields and significantly exceeds it for high magnetic fields. The reason may be the specific properties of copper oxides formed on the cathode surface in the air medium and decomposing to release free copper atoms even before the beginning of fusion of the basic material. To obtain more accurate data on the current density it is desirable to record not only the average velocity of movement of the spot but also the duration of its stops, if it moves discontinuously, and to use gases not forming chemical compounds on the film surface.

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NOTATION

a, thermal diffusivity, $m^2 \cdot sec^{-1}$; B and **B**, scalar and vector magnetic inductions, T; d, diameter of the arc spot, m; F, area of the arc spot, m^2; Fo, Fourier number; I and **I**, scalar and vector currents, A; j and j_a, real and apparent current densities respectively, $A \cdot m^{-2}$; L, absolute length of the step of the arc spot, m; n, dimensionless length of the step of the arc spot; R_1 and R_2, internal and external radii of the cathode, m; Q_0 and q_0, heat flux and density of the heat flux in the arc spot respectively, W and $W \cdot m^{-2}$; T_0, T_f, and T_{cr}, surface, fusion, and critical temperatures, K; U, thermal volt-equivalent, V; v, velocity of movement of the arc spot on the electrode, $m \cdot sec^{-1}$; φ, spectral-line intensity, arbitrary units; λ, spectral-line wavelength, Å; τ and τ_0, time and time of heating of the surface to the fusion temperature, sec. Subscripts: a, apparent value; f, fusion; cr, critical value; 0, value on the surface.

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