MODELLING OF DYNAMIC CHARACTERISTICS OF A PULSED ARC WITH REFRACTORY CATHODE

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Self-consistent model of non-stationary processes of transfer of energy, pulse, mass and charge in the column and anode region of electric arc with refractory cathode was the basis to perform a detailed numerical analysis of dynamic characteristics for atmospheric-pressure argon arc with tungsten cathode and water copper-cooled anode at pulsed variation of electric current. An essential difference in dynamic behaviour of local and integral characteristics of arc plasma is shown, as well as the specifics of dynamics of thermal and electromagnetic processes running in the pulsed arc column and anode region. It is established that the velocities of transient processes in arc plasma at the pulse leading and trailing edges can also differ significantly. 28 Ref., 14 Figures.

Keywords: *pulsed electric arc, refractory cathode, water-cooled anode, arc column, anode region, current pulse, dynamic characteristics, mathematical modelling*

Nonconsumable electrode welding with pulsed modulation of arc current is becoming ever wider applied in modern welding fabrication, owing to additional possibilities of controlling the depth and shape of metal penetration, thermal cycle of welding, and, as a consequence, properties of the produced welded joint. These possibilities can be implemented through appropriate selection of the shape of welding pulses, duration and frequency of their repetition, value of base current and maximum pulse current. An important task, which is to be solved for theoretical substantiation of optimum modes of nonconsumable electrode welding with pulsed modulation of welding current, consists in numerical studies of non-stationary processes in the plasma of the column and near-electrode regions of the arc with the refractory cathode (primarily, anode processes, determining the interaction of arc plasma with the metal being welded) at pulsed variation of electric current.

There are a great number of publications devoted to theoretical study and mathematical modelling of processes of energy, mass and charge transfer in the column, near-electrode regions and in the electrodes of the arc with refractory cathode, in particular, in the metal being welded in nonconsumable-electrode inert-gas welding [1–14]. However, the results presented in the majority of these publications pertain to stationary arcs running at direct current, except for [12–14], which are devoted specifically to the processes of metal penetration in nonconsumable-electrode pulsed-arc welding. As regards the dynamic characteristics of pulsed arc with refractory cathode proper, note, for instance, works [15, 16], the first of which is devoted to experimental study of the above characteristics, whereas [16] gives the results of computational investigations of dynamic behaviour of both electric arc and weld pool in nonconsumable-electrode pulsed-arc spot welding. However, calculation data presented in this work do not allow analyzing the dynamic characteristics of pulsed arc at various rates of welding current variation at the leading and trailing edges of the pulse.

At arc running in pulsed mode it is possible to *a priori* single out two characteristic cases. If the rate of current variation is comparatively low, then non-stationary processes of transfer of energy, pulse, mass and charge in arc plasma run in the mode of a sequence of stationary states, each of which corresponds to the state of the stationary arc for instantaneous current value. Such a quasi-stationary arcing mode is realized, if the velocity of transient processes in the arc is significantly higher than the rate of current variation. In the second case, i.e. at high rates of arc current variation, the dynamic characteristics of arc plasma are the dominating factor. Computational investigation of these characteristics, as well as obtaining quantitative evaluations of current variation rates separating the quasi-stationary and non-stationary modes of running of pulsed argon arc with refractory (tungsten) cathode and copper water-cooled anode (Figure 1), is exactly the purpose of the work.

We will study the influence of pulsed variation of arc current on thermal, gas-dynamic and electromagnetic characteristics of its column, as

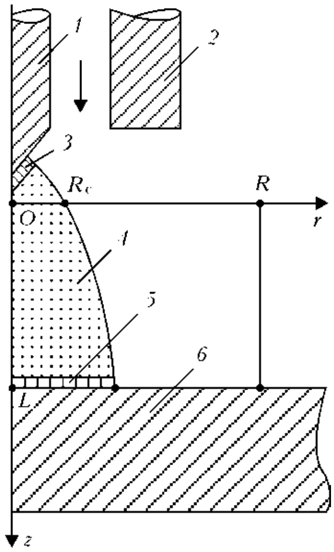

Figure 1. Schematic of design region for numerical modelling of pulsed arc with refractory cathode: *1* — tungsten cathode; *2* — nozzle for shielding gas feed; *3* — cathode region; *4* — arc column; *5* — anode region; *6* — copper water-cooled anode

well as on characteristics of its thermal and electric interaction with the anode surface separately for pulse leading and trailing edges (Figure 2). We will assume that arc current changes linearly both at leading and trailing edges of the pulse at the values of rise and fall times of current pulse b = 5, 20, 100 and 200 μs. We will also assume that having achieved its maximum (minimum) value, current remains constant during the time, sufficient for establishing of the respective stationary state of the arc.

Computational modelling of electric arc at the considered variation of current requires application of non-stationary mathematical model of the processes of energy, mass and charge transfer in arc plasma, which should incorporate the following interrelated models: model of thermal, electromagnetic and gas-dynamic processes in arc column plasma and models of near-electrode processes (see, for instance, [9, 16]). Model of anode processes is required for closing the model of non-stationary arc column by self-consistent boundary conditions on the anode, as well as for determination of the characteristics of thermal and electric interaction of such an arc with the anode surface [17]. As regards the model of cathode processes, then, as the theory of cathode phenomena, as well as processes in the near-cathode plasma of the electric arc with refractory cathode has been developed in sufficient detail [10, 18–21], results of, for instance, [21], can be used as boundary conditions near the cathode.

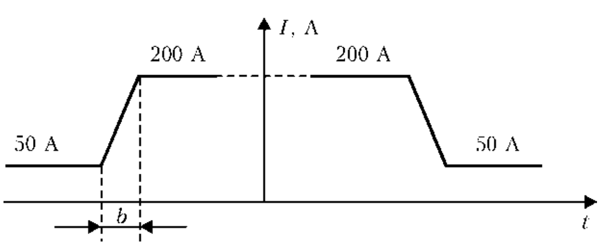

Figure 2. Diagram of arc current variation at pulse leading and trailing edge

At description of the processes in the plasma of the column of pulsed argon arc with tungsten cathode and copper water-cooled electrode we will use the model of isothermal ionization-equilibrium plasma [9, 22], and processes in near-anode plasma and on the anode surface will be described by the model of anode region, proposed in [17], as in the case of non-evaporating electrodes considered here, arc plasma can be regarded as single-component one, i.e. containing only the particles of shielding gas (argon). Let us use the data of [23] to determine the thermodynamic characteristics, transfer coefficients and radiation losses of such plasma, depending on its temperature and pressure. We will also assume that the considered system (see Figure 1) is axially symmetrical.

System of differential equations corresponding to the assumptions made, which describe the non-stationary thermal, gas-dynamic and electromagnetic processes in the arc column plasma, as well as dependencies of heat flow to the anode q_a and anode potential drop $U_a = -\Delta\varphi$ (where $\Delta\varphi$ is the difference of potentials between the outer boundary of the anode region and anode surface) on near-anode plasma temperature and electric current density in the anode, are given in [22]. It should be noted that at the frequencies of variation of arc electromagnetic characteristics $\omega \le 1.26 \cdot 10^6$ s^{-1}, considered in this work, which are determined by the rise and fall times of the current pulse, the skin-layer thickness [24] for arc plasma (atmospheric-pressure argon plasma at the temperature of 15,000 K) appears to be more than 3.3 cm, i.e. it is significantly higher than the characteristic dimensions of the arc. Therefore, application of Ohm's law and equation for scalar potential of electric field at description of non-stationary processes of charge transfer in arc plasma [22], i.e. neglecting bias currents, is quite justified.

We will define the design region, in which we will calculate the distributed characteristics of non-stationary arc plasma, as $\Omega = \{0 < r < R;\ 0 < z < L\}$, where L is the length of design region, actually equal to arc length, and R is the radius of design region, which is knowingly greater than the transverse dimensions of the arc (see Figure 1). As boundary conditions for the above equations, we will use the conditions on design region boundaries, described in detail in [22], considering that we will interpret the boundary conditions for electromagnetic characteristics as those corresponding to the current value of arc current $I(t)$, changing in time. As regards the initial conditions, we will assume that the distributed characteristics of arc plasma at moment of time $t = 0$ correspond to characteristics of the stationary arc at current, equal to the initial current value.

This boundary problem was solved numerically, by the finite difference method. Gas-dynamics and convective heat transfer equations were solved using joint Euler–Lagrange method [25, 26], adapted to the conditions of compressible medium. During calculations model parameters were selected as follows. Dimensions of design region were $L = 3$ mm, $R = 8$ mm; net parameters were time step $\tau = 0.5$ μs; net steps by spatial coordinates were $h_r = 0.125$ mm, $h_z = 0.06$ mm. Ambient temperature was taken to be equal to 500 K, and temperature of the surface of copper water-cooled anode was $T_s = 720$ K [22]. Value of radius in the region of cathode binding R_c (see Figure 1) was determined on the basis of recommendations of [21] so that the maximum value of density of electric current in this region was constant ($j_{c0} = 10^8$ A/m^2) in the entire studied range of arc current variation (50–200 A). Maximum plasma temperature near the cathode was also selected to be constant ($T_{c0} = 20{,}500$ K) [21].

Dynamics of variation of temperature field and pattern of arc plasma flow at fast variation of arc current ($b = 5$ μm) is shown in Figures 3 and 4 (time in these Figures is calculated from the moment of start of current variation). In Figures 3, 4 the isotherms correspond to the respective temperatures 1; 2; 4; 6; 8; 10; 12; 14; 16; 18 kK from the arc periphery to its axis. Calculation results are quite predictable: at pulse leading edge (at current increase from 50 up to 200 A) the bell-shaped isothermal lines in the arc column become wider; contrarily, at the trailing edge (at current decrease from 200 to 50 A) high-temperature current-conducting region of arc plasma is contracted. In both the cases, a certain time (about 100 μs at increase of arc current and about 120 μs at its decrease) is required for the temperature field and pattern of arc plasma flowing to reach the respective stationary states.

Unlike the above-given general pattern of arcing dynamics, variation in time of individual local and integral characteristics of the column and anode region of the arc with refractory cathode at pulsed variation of electric current has a number of specific features. We will select the following arc column characteristics as those, the variation dynamics of which we will analyze further: T_{col} and j_{col} are the plasma temperature and electric current density on the column axis, calculated in its middle section (at $z = 1.5$ mm); R_{col} is the characteristic radius of current-conducting plasma region in the same section, defined as circle radius, within which 95 % of instantaneous value of arc current is concentrated.

Figures 5–7 give the variation in time (time is calculated since the moment of the start of current variation) of the above characteristics for pulse leading and trailing edges at $b = 20$, 100 and 200 μs (solid, dashed and dotted lines, respectively).

As follows from calculated dependencies presented in these Figures, plasma temperature in the center of arc column is its characteristic with the least inertia. This accounts for practically instantaneous, proportional to current variation (at least, at $b \geq 20$ μs), change of the efficiency of Joule heat sources, leading to the respective increase or lowering of T_{col} (see Figure 5). A slight maximum of arc plasma temperature observed at the leading edge of current pulse at $b = 20$ μs is related to its heating by rising current (see solid curve in Figure 6, *a*) to temperatures, exceeding T_{col} value for a stationary 200 A arc, and to subsequent cooling down due to slower convective cooling (characteristic time of relaxation of arc column plasma temperature under the considered conditions is equal to about 30 μs). With increase of pulse rise time up to 100 μs and higher, this maximum practically disappears, as the rate of convective cooling, determined by inertia of gas-dynamic processes in arc plasma, becomes commensurate with the rate of increase of arc current, and, therefore, also of Joule heating of plasma at b increase (see dashed and dotted curves in Figure 5, *a*). It should be noted that such an effect is practically not manifested at current drop at pulse trailing edge (see Figure 5, *b*).

As regards current density in the center of arc column, since j_{col} is the product of plasma electric conductivity determined by its temperature value in the same point, by electric field intensity, determined by distribution of temperature (electric conductivity) across the entire column section, the above characteristic has somewhat greater inertia than T_{col}. Local maximum of j_{col} observed at the leading edge of current pulse at $b = 20$ μs turns out to be more pronounced (current density in the center of pulsed arc column at the moment, when its current reaches 200 A, is by almost 25 %

higher than the respective value for a stationary 200 A arc), and subsequent lowering of j_{col} and establishing of its stationary value occurs during the time of about 50 μs (see solid curve in Figure 6, *a*). At lowering of the rate of current rise in the pulse (b = 100 and 200 μs), this maximum, similar to temperature maximum, becomes ever less pronounced (see hatched and dotted curves in Figure 6, *a*). Unlike T_{col} behaviour at the pulse trailing edge, electric current density in the arc column at total current drop has a local minimum, the absolute value of which decreases at b increase (see Figure 6, *b*). The features of variation of density of electric current in arc plasma noted here are in many respects characteristic also for variation in time of voltage in pulsed arc column. In particular, the difference in the time of transient processes in the arc at the pulse leading and trailing edges at low values of fall and rise times of pulse current is one of the causes for formation of a hysteresis loop on pulsed arc volt-ampere characteristic [15, 27].

Arc column characteristic with the highest inertia is the radius of its current-conducting region that is attributable to restructuring of temperature filed over the entire column cross-section, necessary for R_{col} variation. Characteristic time for establishment of stationary value of this radius, after the arc has reached its stationary (maximum) value in the case b = 20 μs, is equal to approximately 100 μs (see solid curve in Figure 7, *a*). It should be noted that the characteristic time of R_{col} variation at arc current drop is essentially smaller, and is equal to about 60 μs at b = 20 μs (see solid curve in Figure 7, *b*). Finally, the time of establishment of a stationary value of radius of arc column current-conducting region decreases significantly at b increase due to the fact that R_{col} variation partially occurs already during current rise or drop (see dashed and dotted lines in Figure 7).

Non-stationary processes occurring in the arc anode region, are illustrated by graphs (Figures 8–13) of variation in time of both the local characteristics of anode processes: T_{a0} is the axial value of plasma temperature near anode surface (at z = 3 mm), j_{a0} and q_{a0} are the density of electric current on the anode and density of heat flow to the anode determined in the center of the region of anode binding of the arc, and of the integral characteristics of the above processes: P_a is the total thermal flow to the anode; R_a and R_h are the radii of current channel and region of thermal impact of the arc on anode surface (R_a and R_h are understood to be the radii of circumferences on anode surface, within which 95 % of current values of total arc current $I(t)$ and total heat flow to the anode $P_a(t)$ are concentrated, respectively). Solid, dashed and dotted curves in the above Figures correspond to b = 20, 100 and 200 μs.

Regularities of dynamic variation of local and integral characteristics of the anode region of the arc with refractory cathode and copper water-cooled anode at application of electric current pulse, are not trivial and require detailed physical interpretation. So, for instance, at high rate of arc current variation (b = 20 μs), instead of the anticipated increase of axial value of near-anode plasma temperature at the pulse leading edge, and its decrease at the trailing edge, respectively, first a certain lowering of T_{a0} at the leading edge and its more noticeable increase at the pulse trailing edge is observed (see solid curves in Figure 8). This effect is largely related to the features of thermal state dynamics and pattern of plasma flowing in the arc column at pulsed variation of current. To analyze this effect, we will consider the condition of local heat balance in the anode region [22]:

$$q_\chi + q_j = \Delta\varphi j_a + q_a. \tag{1}$$

Here, $q_\chi = -\chi \frac{\partial T}{\partial z}\Big|_{z=L}$ is the thermal flow from the arc column plasma, where χ is the coefficient of heat conductivity of arc plasma; $q_j = j_a \frac{k}{e}\left(\frac{5}{2} - \delta\right) T\Big|_{z=L}$ is the flow of energy brought to the anode region by column plasma electrons, where $j_a = -j_z\big|_{z=L}$ is the density of electric current in near-anode plasma; k is the Boltzmann constant; e is the electron charge; δ is the constant of electron thermal diffusion; $\Delta\varphi j_a$ are the energy losses for maintaining the anode layer, while values $\Delta\varphi$ and q_a are determined on the basis of the model of anode processes [17], depending on near-anode plasma temperature $T_a = T|_{j=L}$, anode surface temperature T_s and current density in the anode region j_a.

As was already noted, gas-dynamic processes have the greatest inertia in the arc column. At the beginning of the current pulse trailing edge the maximum velocity of plasma motion along the arc column axis is equal to almost 330 m/s (see Figure 4). Despite the fast drop of current at b = 20 μs and respective lowering of volume density of electromagnetic force, the plasma, moving by inertia, continues transporting thermal energy from arc column towards the anode by convective flows for a certain time, thus ensuring the highest q_χ values. At the same time,

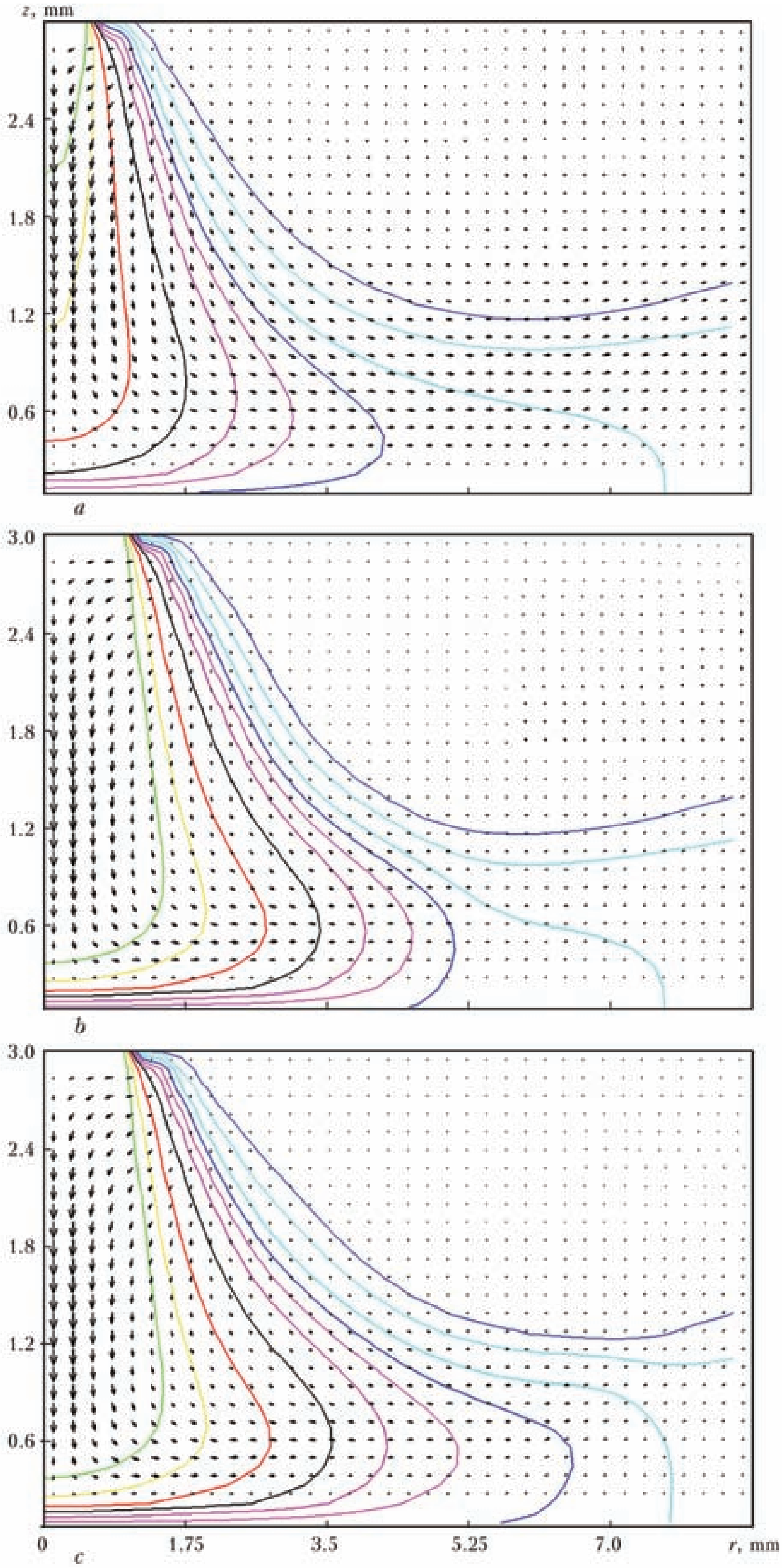

Figure 3. Dynamics of temperature fields and plasma velocity in pulsed arc column at current rise from 50 up to 200 A (b = 5 μs): a — t = 0 (V_{max} = 120.1 m/s); b — t = 50 μs (V_{max} = 328.7 m/s); c — t = 100 μs (V_{max} = 329.2 m/s)

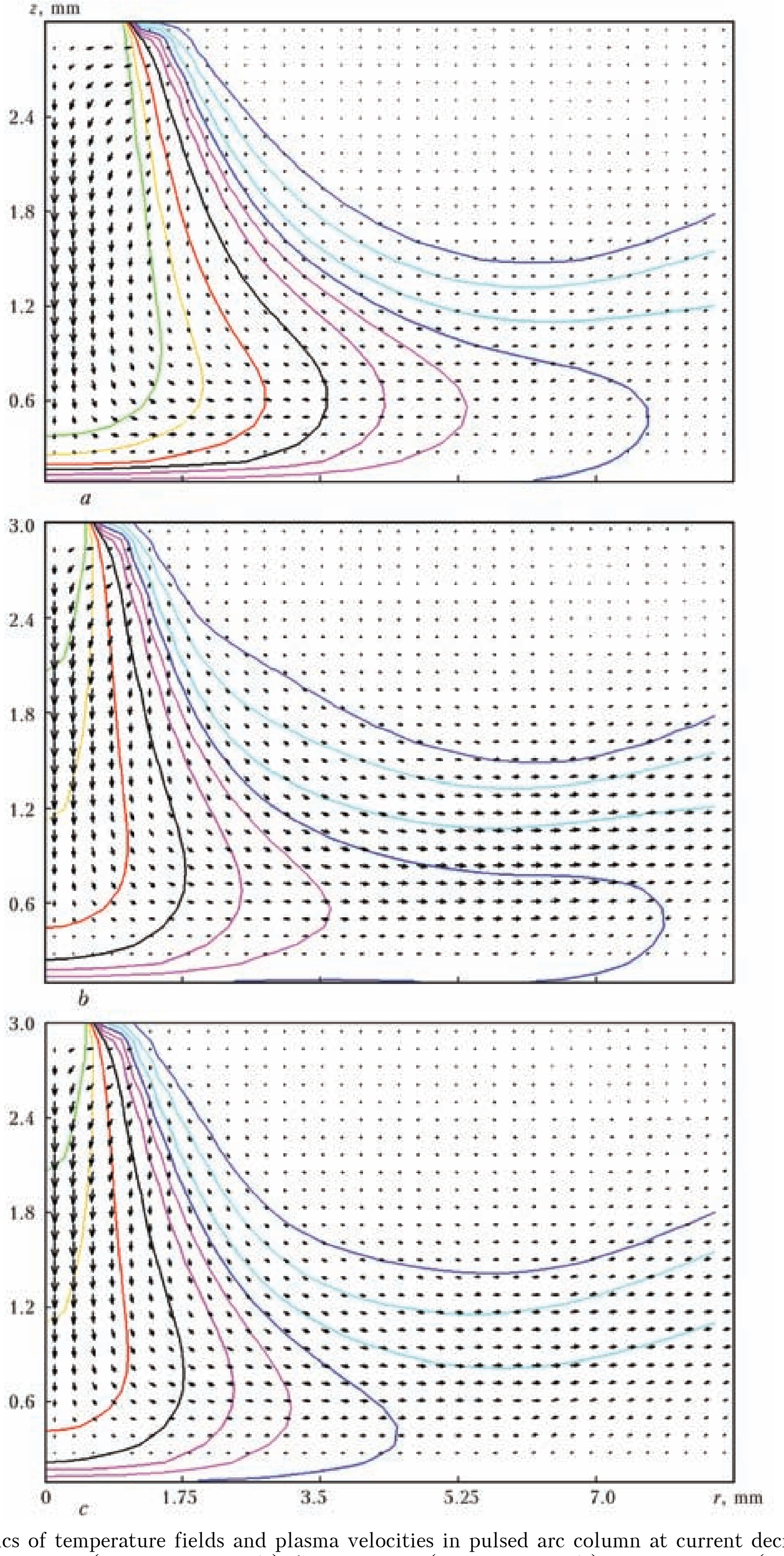

Figure 4. Dynamics of temperature fields and plasma velocities in pulsed arc column at current decrease from 200 to 50 A (b = 5 μm): a — t = 0 (V_{max} = 329.4 m/s); b — t = 60 μs (V_{max} = 120 m/s), c — t = 120 μs (V_{max} = 120.7 m/s)

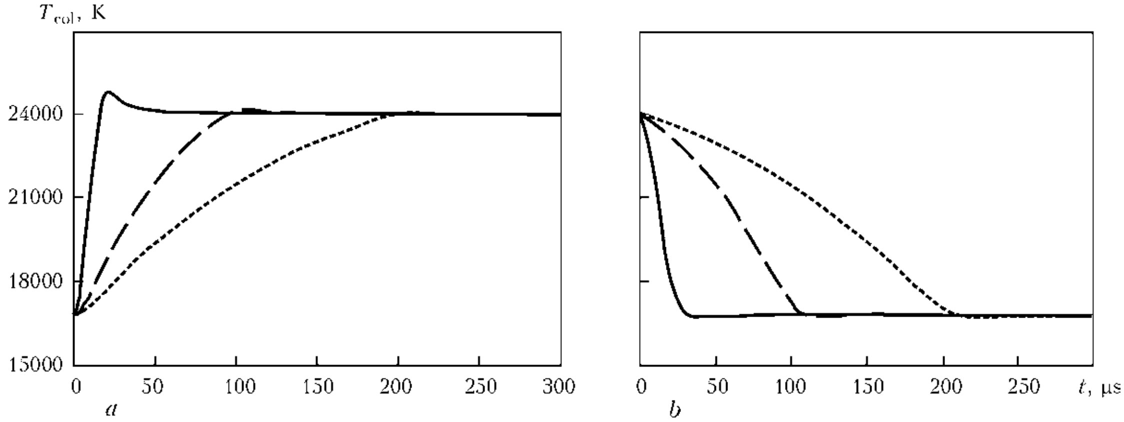

Figure 5. Change of plasma temperature in the center of arc column at leading (a) and trailing (b) edges of current pulse

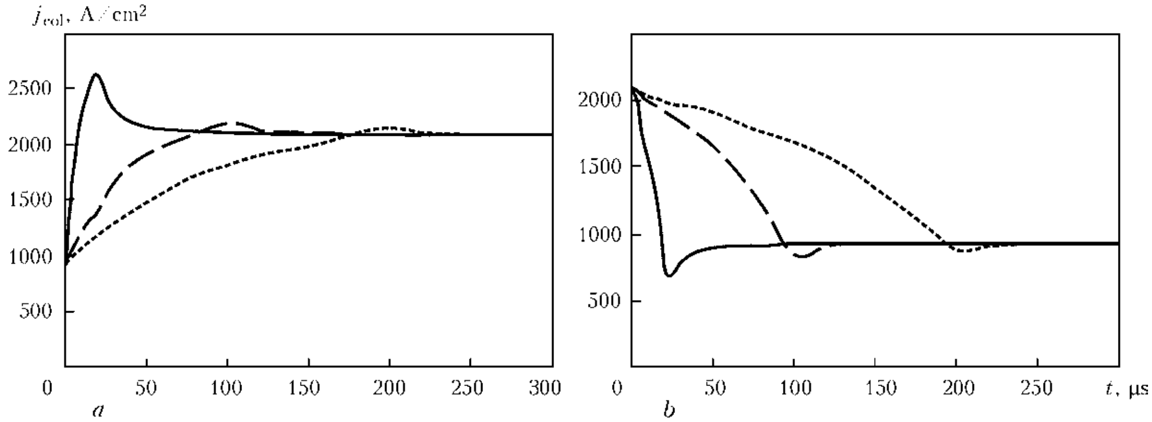

Figure 6. Variation of electric current density in the center of arc column at pulse leading (a) and trailing (b) edges

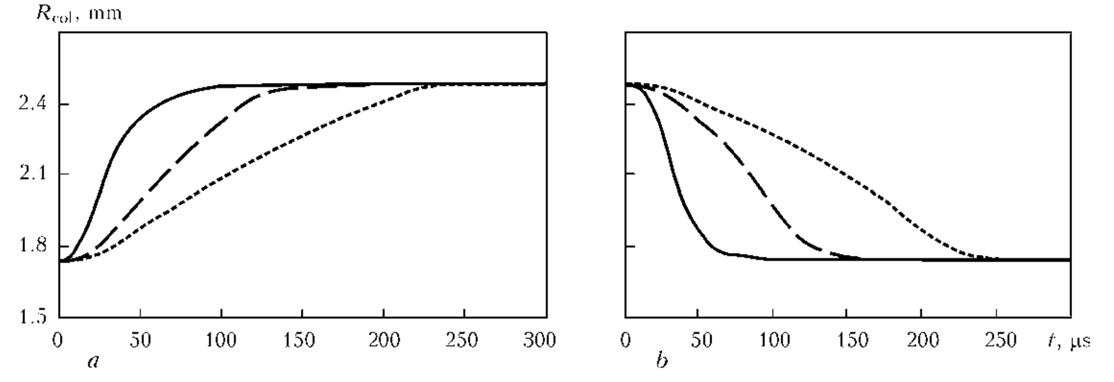

Figure 7. Change of radius of current-conducting region of arc column at pulse leading (a) and trailing (b) edges

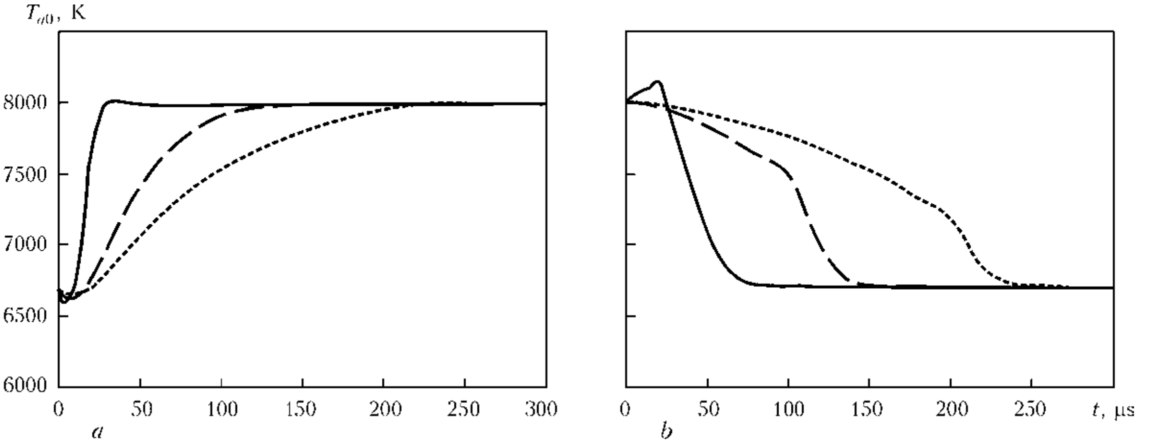

Figure 8. Variation of axial value of near-anode plasma temperature at pulse leading (a) and trailing (b) edges

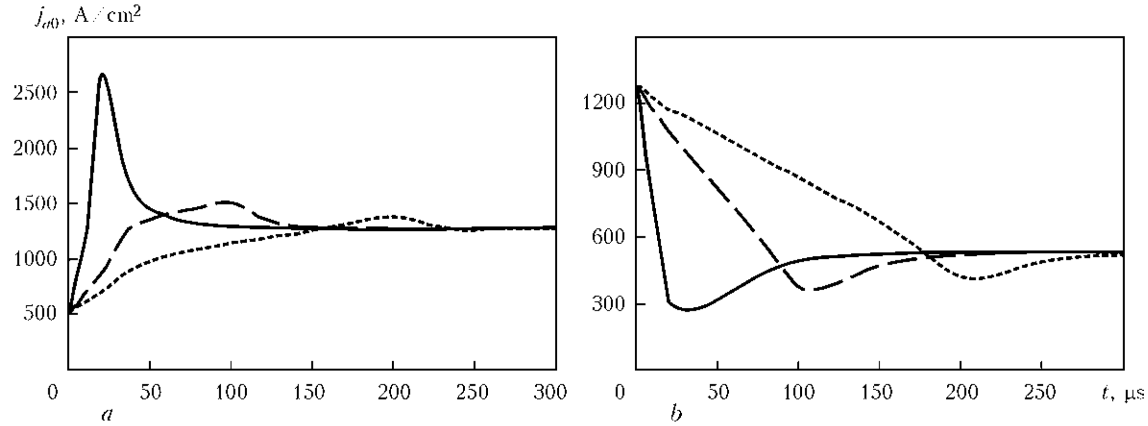

Figure 9. Variation of axial value of electric current density in the anode region at the pulse leading (*a*) and trailing (*b*) edges

at lowering of current density in the anode region (see solid curve in Figure 9, *b*) heat flow density due to energy transfer by charged particles, i.e. q_j value, decreases. The addends in the right-hand part of energy balance (1) also decrease at lowering of total arc current, in view of reduction of current density and density of heat flow on the anode (see solid curves in Figure 9, *b* and 10, *b*). With such a tendency of variation of heat balance components, the heat flow due to heat conductivity, has the dominating role in the initial period of current variation, leading exactly to local increase of T_{a0}. Later on, when the intensity of gas-dynamic flows drops, the temperature of near-anode plasma in the center of the region of anode binding of the arc starts decreasing monotonically to values, corresponding to stationary arc at the current of 50 A (characteristic value of relaxation time at the pulse trailing edge is equal to about 50 μs). A reverse situation is found at the pulse leading edge, the characteristic time of temperature relaxation being essentially lower and equal to a value of the order of 20 μs. The described effect is not observed at $b \geq 100$ μs (see dashed and dotted curves in Figure 8), as with such pulse rise and fall times, the pattern of motion of arc column plasma has enough time for restructuring during current variation.

The non-stationarity effects are manifested to the greatest degree in the dynamics of variation in time of the density of electric current and density of heat flow on the anode in the center of the region of anode binding of the arc (see Figures 9 and 10). The main feature of these dependencies is their non-monotonic nature with formation of local maximums (at the pulse leading edge) and minimums (at the trailing edge), which are reached by the moment of time, corresponding to the end of rise or drop of arc current. In particular, at a high rate of total current increase from 50 up to 200 A ($b = 20$ μs), maximum current density in the axial zone of the anode region is more than 2 times higher than the respective value for the stationary arc at $I =$ = 200 A, and the characteristic relaxation time of j_{a0} is equal to about 80 μs (see solid curve in Figure 9, *a*). At the trailing edge in the minimum point the axial value of current density on the anode turns out to be almost 1.5 times lower than for stationary 50 A arc at somewhat longer relaxation time, equal to about 100 μs (see solid curve in Figure 9, *b*).

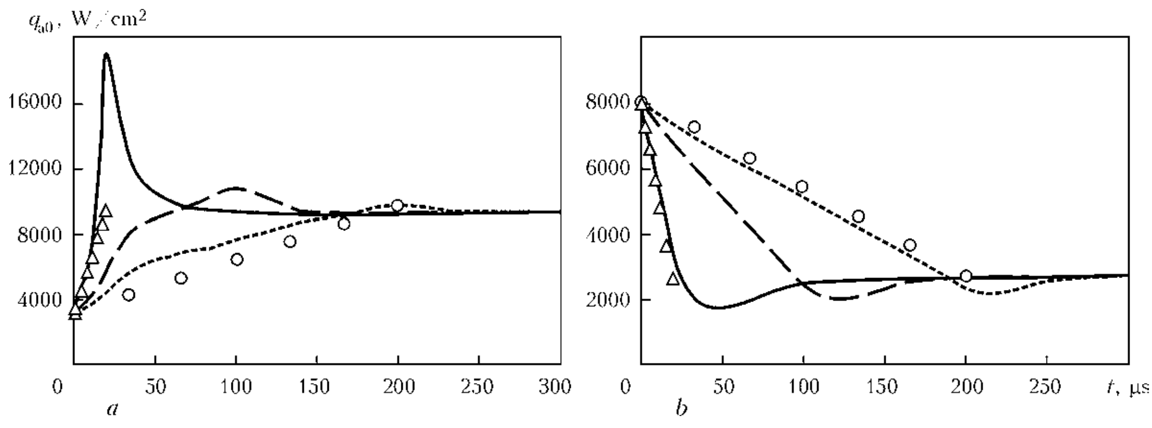

Figure 10. Change of axial value of density of heat flow to the anode at pulse leading (*a*) and trailing (*b*) edges (markers show q_{a0} values for stationary arc at respective current values: Δ — $b = 20$; ○ = 200 μs)

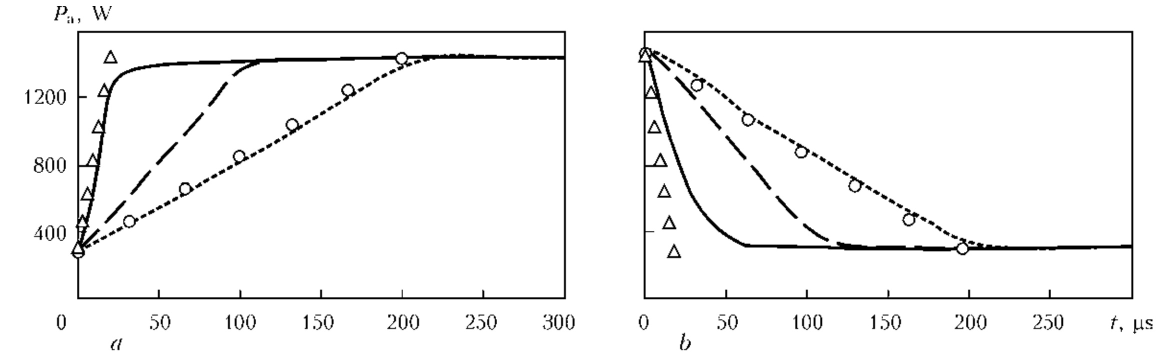

Figure 11. Variation of total heat flow to the anode at pulse leading (*a*) and trailing (*b*) edges (markers show P_a values for stationary arc at respective current values: Δ — b = 20; ○ = 200 μs)

Let us consider the cause for such an extreme change of current density at the pulse leading edge at b = 20 μs, when this effect is manifested to the greatest degree. Let us bear in mind that in this case the rate of arc current variation is essentially higher than the rates of relaxation of gas-dynamic and thermal processes in arc plasma. Moreover, as shown by calculations, the radius of current-conducting region on the anode at total current rise first decreases markedly and only then it starts growing, reaching its steady-state value, corresponding to 200 A arc, during the time of approximately 100 μs (see solid curve in Figure 12, *a*). All that leads to the situation when at the rising arc current its density in the center of the anode binding region first rises abruptly, and then smoothly decreases, as shown in Figure 9, *a*.

At current pulse trailing edge at b = 20 μs the radius of current-conducting region on the anode shows an even more nontrivial behaviour, namely: value R_a during arc current drop decreases somewhat, and then rises and only later it drops again to values, characteristic for the stationary arc at the current of 50 A (see solid curve in Figure 12, *b*). The result of such a behaviour of the radius of current-conducting region on the anode is the fact that j_{a0} minimum turns out to be less pronounced (see solid curve in Figure 9, *b*). Extreme nature of $j_{a0}(t)$ variation is manifested, even though to a smaller degree, also at lower rates of current variation, i.e. at b = 100 and 200 μs (see dashed and dotted curves in Figure 9).

As the density of heat flow to the anode at other conditions being equal, is practically proportional to current density on the anode, dynamics of q_{a0} variation is, on the whole, similar to that of variation of axial value of electric current density in the anode region (see Figures 9 and 10). Axial values of density of heat flow to the anode for a stationary arc at respective values of total current are indicative of the fact that in the case of b = 20 μs, local characteristics of the arc anode region are essentially non-stationary, whereas in the case of b = 200 μs the change of the above characteristics at current variation takes place practically in the quasi-stationary mode, i.e. running of a pulsed arc at b = 200 μs is a sequence of the states of a stationary arc, running at the respective current values. Thus, a value of about 100 μs can be selected as the characteristic time of variation of pulsed arc current (pulse rise and fall times), separating the non-stationary and quasi-stationary modes of arcing in terms of local characteristics of electric and thermal impact on the anode. It should be noted that the extreme nature of variation of local electric and thermal characteristics of anode region of pulsed arc with refractory cathode can

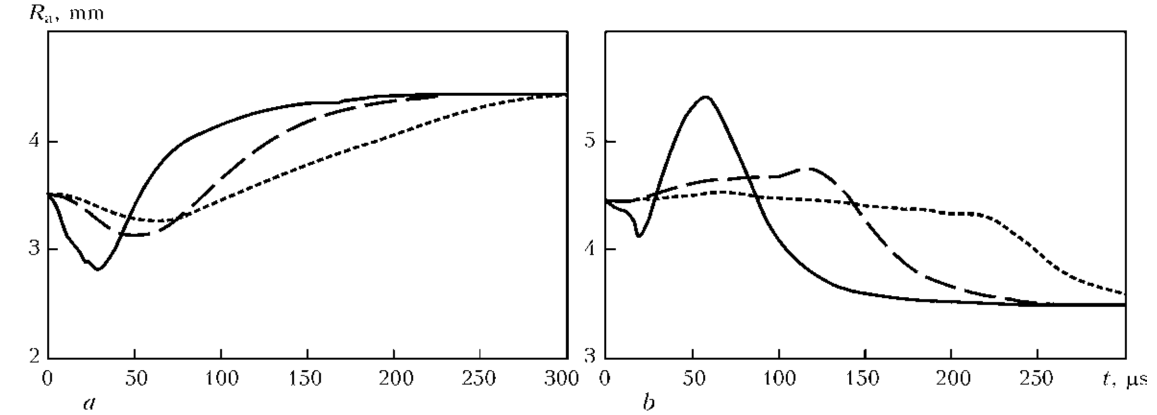

Figure 12. Variation of radius of arc current channel on the anode at pulse leading (*a*) and trailing (*b*) edges

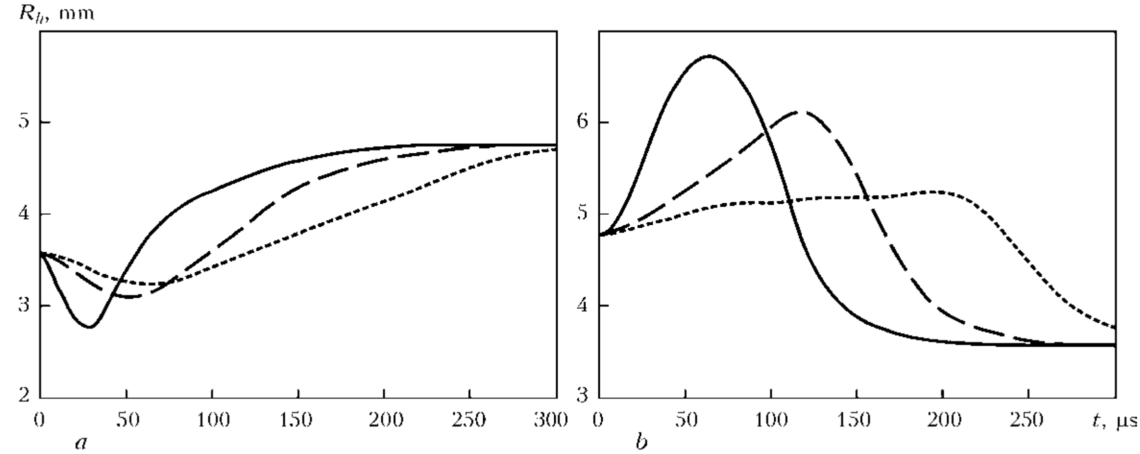

Figure 13. Variation of radius of the region of arc thermal impact on the anode on pulse leading (a) and trailing (b) edges

lead to an important technological result of non-consumable electrode pulsed-arc welding — an essential increase of arc penetrability due to contraction of its electric and thermal impact on weld pool surface and resulting intensification of the processes of heat transfer in its volume.

A characteristic of arc anode region, the most sensitive to the rate of electric current variation, is its such an integral characteristic as total heat power, applied to the anode (see Figure 11). Despite the fact that at low b values the specific heat flow to the anode is essentially non-stationary (compare solid curves and respective markers in Figure 10), P_a value changes in an almost quasi-stationary manner (compare solid curves and respective markers in Figure 11). At larger values of pulse rise and fall times (b = 200 μs) values of power applied to the anode by the stationary arc at respective current values practically coincide with values determined by $P_a(t)$ dependence for the pulsed arc (compare dotted curves and respective markers in Figure 11).

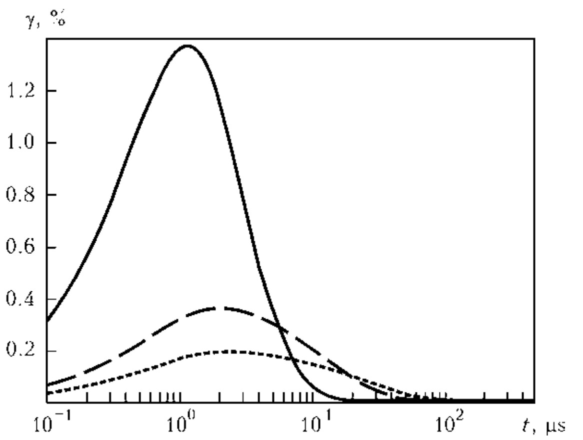

Figure 14. Variations of the degree of ionization non-equilibrium of arc plasma in arc column center at current pulse leading edge at b = 20, 100 and 200 μs (solid, dashed and dotted curves, respectively)

Results of numerical modelling of dynamic characteristics of pulsed arc with refractory cathode and copper water-cooled anode are indicative of the fact that in the studied range of current pulse rise and fall times the characteristic time of variation of arc plasma thermal state can be equal to 10^{-5}–10^{-4} s. As these values are commensurate with the characteristic times of ionization-recombination processes in atmospheric-pressure argon plasma [28], it is necessary to evaluate the appropriateness of application of the model of ionization-equilibrium plasma and calculated on its basis temperature dependencies of thermodynamic characteristics, transfer coefficients and radiation losses of such plasma. With this purpose we will introduce parameter $\gamma = |\alpha - \alpha_e|/\alpha_e$, characterizing ionization non-equilibrium of arc column plasma, where α is the degree of plasma ionization calculated allowing for the final rates of ionization-recombination processes, and α_e is its equilibrium value, calculated using Saha equations. Figure 14 shows the change in time of γ parameter for pulsed arc column plasma at T_{col} variation, according to dependencies given in Figure 5, a. As follows from calculation data given in Figure 14, degree of ionization non-equilibrium of arc column plasma under the considered conditions does not exceed 1.5 % that allows regarding application of the model of ionization-equilibrium plasma as quite justified.

On the whole, regularities of dynamic behaviour of local and integral characteristics of the column and anode region of pulsed arc with tungsten cathode and copper water-cooled anode, described in this paper, lead to the following conclusions.

1. Running of the arc with refractory cathode in the pulsed-periodic mode is accompanied by

an essential variation of electromagnetic, thermal and gas-dynamic characteristics of arc plasma, as well as its electric and thermal impact on the anode surface. Dynamic behaviour of the above characteristics largely depends on the rate of arc current variation at pulse edges and is different for the leading and trailing edges. Gas-dynamic processes are the link with the highest inertia in the process of restructuring of electromagnetic fields, thermal state and pattern of arc plasma flowing at variation of arc current.

2. At great steepness of pulse edges (more than $5 \cdot 10^6$ A/s rate of current variation) change of characteristics of the column and anode region of pulsed arc occurs in two stages: stage of arc current variation and stage of transient processes. At increase (decrease) of current, heat flow density and anode current density can be 2 times greater (1.5 times smaller) than the respective values characteristic for the direct current arc, at current equal to arc current in the pulse (pause). At transient process stage, relaxation of thermal and gas-dynamic state of arc plasma to values characteristic for the stationary arc at the respective current value, takes place. Durations of relaxation processes depend on the value of base current and pulse current, and can differ essentially for the local and integral characteristics of plasma of arc column and anode region.

3. At current variation at pulse edges with at the rate below 10^6 A/s (pulse rise and fall times of more than 100 μs), the processes related to current variation and relaxation processes occur simultaneously, as a result of which the non-stationary process of pulsed arc running is realized as a sequence of states characteristic for the stationary arc at the respective values of current (quasi-stationary mode).

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