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Behaviour of the arc at cathode in combustion products plasma

Petrov S.V. [1], Saakov V.A. [1], Vasenin Yu.L. [2]

[1] *RPE TOPAS, Kyiv, Ukraine,* [2] *E.O.Paton Electric Welding Institute, Kyiv, Ukraine*

Abstract

Processes that involve plasma of the products of combustion of air with a hydrocarbon gas take a special position among plasma technologies used for materials treatment. Owing to unique properties of such a plasma (high values of heat capacity and thermal conductivity, ease of redox potential regulation, availability and low relative cost), the processes on its base attract an increasingly high research and industrial interest. Widening of application of plasmatrons operating with a mixture of air and a fuel hydrocarbon gas (methane, propane-butane) and increase in technological requirements make it necessary to look for new ways of improving performance of heavy-loaded elements, and cathode in the first turn. Studies conducted in this field led to revealing a new, highly promising effect in the cathode processes. As shown by the studies, variation of parameters of the mixture of hydrocarbon gas with air used to blow the cathode leads to variation in the character of behaviour of the arc spot on the surface of electrode with a hafnium or zirconium insert. The arc in the above mixture may operate in two modes. In the first mode the spot is located on the film of the melt according to the air arc type. In the second mode the spot is transformed into a highly contracted one, the current density being 10 and more times as high. A long-time operation is possible in both modes.. Switch of the arc to the mode with a highly contracted spot is always accompanied by formation of a self-recovering cathode. The abrupt contraction of the arc spot is accompanied by a number of peculiarities of the cathode operation and leads to positive results. In addition to increase in service life of the cathode operating with the air-gas mixture, this provides stabilisation of voltage of the arc during its entire service period, as no changes in geometric sizes take place.

Experimental

Experiments were conducted using the plasma unit TOPAS-80 designed for plasma surface hardening [1] and spraying of protective coatings [2]. Here the use is made of an end thermochemical cathode with an active hafnium or zirconium insert, which is blown over with a mixture of air and methane.. In a standard mode, the reference cathode spot of the arc is located on a molten oxynitride or oxycarbonitride (in the case of blowing with the air and methane mixture) film. The working surface of the cathode and near-cathode part of the arc column were examined using a plasmatron with one metallic inter-electrode insert through a quartz glass window at an angle of 45^{o} to the axis (Fig. 1).

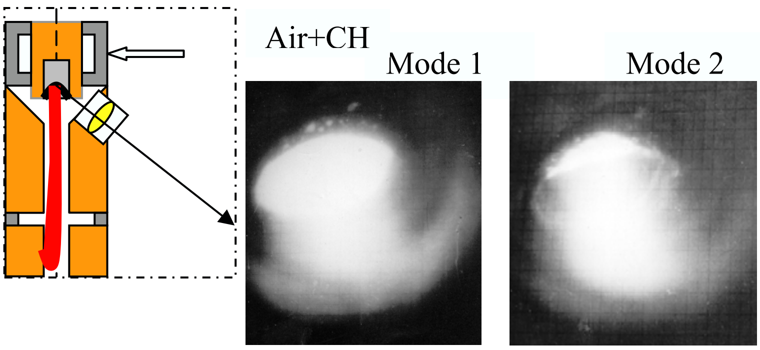

Fig. 1. Appearance of the cathode spot and arc column, I = 200 A

. It has been established that there are two mode in which the arc burning in the mixture can retain its long-time stability. The first mode involves the spot located on the film of the melt, according to the air arc type (mode 1). The second mode involves a dramatically contracted spot (mode 2). Current density in this case, estimated from the heat trace, increases by an order of magnitude. Studies were conducted at the arc current ranging from 100 to 300 A and flow rate of the mixture ranging from 4 to 10 m^3/h. In the first mode, when the a hydrocarbon gas is added to air, diameter of the glowing spot under location of the discharge increases by 5-10 %, and operation with the enriched mixture (where the methane content becomes higher than that stoichiometrically required for complete combustion of fuel) is characterised by an increased mobility of the cathode spot. "Frozen" waves remain on the surface after extinction of the arc (Fig. 2a). In the second mode, at a dramatic contraction of the arc, size of the glowing spot decreases 3-4 times, and a convexity is formed under its location (Fig. 2b). General view of the crater is shown in Fig. 2c.

Fig. 2. Appearance of the cathode surface after extinction of the arc
a – mode1; b – mode 2; c – general view of the crater

With a fuel hydrocarbon gas added to air, the emission film of the cathode becomes saturated with carbon, the content of oxygen in it decreases, and microhardness grows. In operation at an arc current of 300 A for 1 h, saturation of the emission film (under the arc spot) of the zirconium cathode with oxygen and carbon is characterised by the data given in Table 1.

Content of CH_4 in mixture, %	0	10	15
[O], at. %	34	29.5	14
[C], at. %	-	7	30
Hμ, MPa	10^4	$1.28 \cdot 10^4$	$1.56 \cdot 10^4$
Thickness of emission film δ, mm	0.9	1.3	1.1

After the emission films becomes saturated with carbon, transition of the arc from burning mode 1 to mode 2 occurs in an abrupt manner, passing through transient mode 1-2 (Fig. 3)

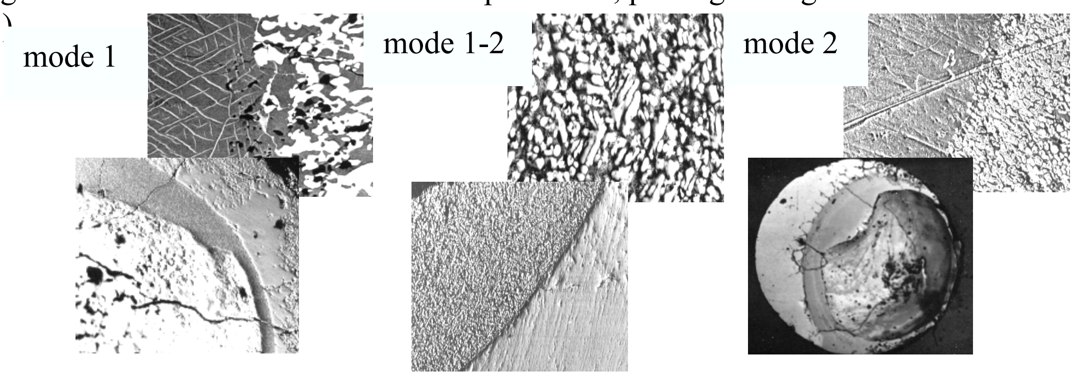

Fig. 3. Microsections of emission film in different modes of cathode operation

Theoretical

Physical model of the cathode region of the electric arc includes description of the mass, current and energy transfer processes. Evaporated atoms of the cathode material and neutral atoms of the plasma gas arriving to the cathode from the arc column in the form of ions move from the cathode surface to the near-electrode layer of plasma. Emitted electrons accelerated by the cathode drop transfer their energy to plasma electrons, which use it to ionise atoms and form the ion flow to the cathode in the space charge sub-layer. Therefore, ions coming from the arc column and ions formed in close vicinity to the space charge layer arrive to the cathode. Ion composition of the near-electrode plasma depends upon the concentrations of neutral atoms, their ionisation potentials and temperature of electrons. This composition was calculated using the Saha equation. Flows of the charged particles form the space charge layer near the surface, the electric field of which affects the process of emission of electrons. The appropriate system of equations was formulated in study [3].

Peculiarities of the cathode processes occur in the case where the electric arc burns in a carbon-containing gas. Formation of a "true" cathode takes place under certain conditions, which is accompanied by extension of service life of the thermochemical insert. As shown by calculations [3], return of an evaporated material may amount to 97 % in the vacuum arc. The similar phenomenon takes place under the "true" cathode conditions. As seen from Fig. 3a, for values of the near-cathode potential drop, $U_c \sim 13$ V and surface temperature $T_c \geq 3500$ K, return of the carbon atoms evaporated from the cathode surface increases in an abrupt manner. Balance of the carbon atoms leaving the surface, lacking to make one, is compensated for by their ingress from the arc column plasma. The fact of occurrence of high temperatures required for evaporation of carbon is proved by the presence of waves seen on the molten surface of the refractory thermionic cathode insert in mode 1, preceding mode 2, i.e. the "true" cathode.

An abrupt change in current density, $J_c = J_i + J_c$, is seen in the vicinity of these values (Fig. 3b). This is associated with the fact that under conditions of an increased return (recycling) of the carbon atoms the current density of ions to the cathode grows, and the intensity of the electric field near the surface increases, which is accompanied by growth of the electron emission current density. As shown by calculations, the flow of energy Q_s to the surface also increases (Fig. 3c), and isolines of this flow crowd together in the vicinity of the above values (U_c, T_c).

Apart from the heat conduction losses the total energy flow Q_s through the metal surface is given mainly by the energy loss Q_v due to the evaporation of atoms, the energy exchange Q_{em} due to electron emission (Nottingham effect), the energy gain Q_{ip} by accomodation of ions and atoms coming back to the surface, and the energy gain Q_{ep} of returning plasma electrons:

$$Q_s = -Q_v - Q_{em} + Q_{ip} + Q_{ep},$$

These components can be described by the following equations:

$$Q_v = \sum_m I_{v0}^m \cdot (1-\beta_m)\cdot(E_v^m + 2kT_c), \qquad Q_{ep} = J_{ep}\cdot\left(U_c - \Delta\varphi_S + \varphi + 2kT_e/e\right)$$

$$Q_{ip} = \sum_m \sum_z \frac{J_{iz}^m}{z}\left((U_c' - \Delta\varphi_S)\cdot z + \sum_{p=1}^{z}(U_{ip}^m - \varphi) + \left(E_v^m + 2kT_c\right)/e + \tfrac{1}{2e}\tilde{Z}kT_e\right)$$

$$Q_{em} = J_{em}^{FT}\cdot(-\varphi_{FT} + \varphi) + \sum_m \sum_z \frac{J_{iz}^m}{z}\gamma_{IFT,m}^z\left(-\varphi_{IFT,m}^z + \varphi\right)$$

Here: I^m_{vo} is the flow of the second-kind atoms leaving (evaporating from) the cathode; β_m is the return coefficient; J^{FT}_{em} is the density of the thermal-field electron emission current; φ, $\varphi^z_{JFT,m}$ and φ_{FT} is the work function and Notingham potentials for thermal-field emission of electrons with and without allowance for the individual ion fields, respectively; J^m_{iz} is the density of the current of z-fold m-kind ions; Δ s is the Schottky correction; E^m_v is the energy taken off by an m-kind atom from the surface during evaporation; T_c is the temperature of electrons in the near-electrode plasma; J_{ep} is the current density of back electrons from plasma; and e is the electron charge. Transition to the "true" cathode mode is also accompanied by an abrupt change of surplus pressure affecting the surface on the side of the near-cathode plasma. As follows from the dependencies shown in Fig. 3d, this difference in pressure may grow almost by an order of magnitude in mode 2, and may cause formation of the observed geometry of the formations on the cathode surface, i.e. peaks and valleys, the relative arrangement of which will be determined by distribution of temperature in the electrode body.

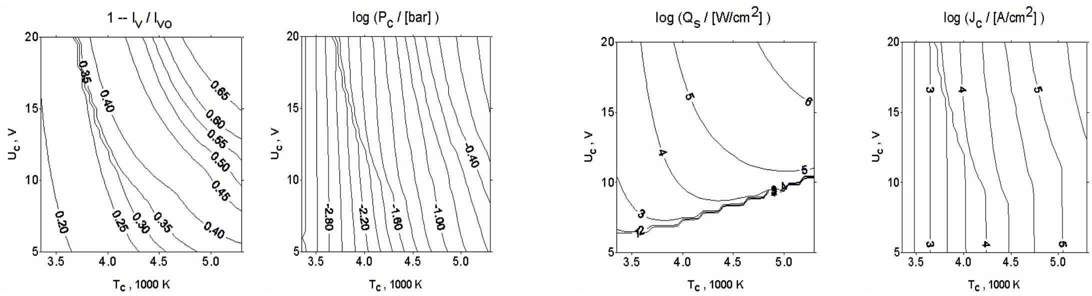

Fig. 3. Boundary conditions on the cathode surface

Results and discussion

The arc switches to the mode of burning with a highly contracted spot in an abrupt manner, after the emission film becomes saturated with carbon, which is followed by increase in the excess-oxidiser-coefficient. This causes transformation of the emission film and formation of convexity under the arc spot location, this convexity acting as a real cathode. No erosion of material occurs, and the fluidised-bed operation mode is reached, where the amount of an evaporated material is balanced by return of ions of both cathode material and carbon. Switch of the arc to the mode with a highly contracted spot is always accompanied by formation of a self-recovering cathode. Therefore, the abrupt contraction of the arc spot is accompanied by a number of peculiarities of the cathode operation and leads to positive results. In addition to increase in service life of the cathode operating with the air-gas mixture, this provides stabilisation of voltage of the arc during its entire service period, as no changes in geometric sizes take place.

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