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ON THE ISSUE OF THE THERMAL EMISSION CATHODE RESOURCE ON THE OXIDE FILMS OF HAFNIUM AND ZIRCONIUM

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Abstract. The article shows the results of research on the destruction of the thermionic cathode of an arc plasma torch when inserting hafnium and zirconium along the trace of the spot of a gas-discharge arc by means of electronic metallography with spectral analysis in the control region. The depth of penetration of the spot into the metal of the cathode insert was determined due to the discrete mechanism of action on the metal at the time of attachment. The erosion rate of zirconium oxide films was experimentally established, the extension of the operating life substantiated while mechanisms for its increase were revealed, and two types of arc contact with a hafnium or zirconium insert - the "contracted" and "diffused" ones - were offered. The theoretical operating life of the cathode is calculated.

Keywords: plasma, surface scanning, erosion, erosion mass, attachment spot.

1. Introduction

The development of modern plasma technology entails a classical contradiction between the efficiency of the thermionic cathode, its temperature and the duration of its operation - the resource, which is explained by the difference in energy between the work function and the ionization potential [1]. The ionization potential of plasma-forming gas is four times higher than the work function of copper or iron from which the electrodes are made. For example, the ionization potential of CO_2 is 14.3 eV [2], and the work function of copper is 4.4 eV [3]. The energy input to the spot is 4.5 eV per atom of the substance [4]. And the most effective cooling water provides heat dissipation $q_B = 1\,\mathrm{kW\,cm^{-2}}$ due to the low thermal conductivity of the metal. The life time of a spot is a long period of time, taking up approximately 10^{-3} s, during which the metal in the spot passes into gas (sublimation) or melts, evaporates and ionizes. The pulsed thermal effect of the spot arc leads to variable loads, and when their value exceeds the yield strength with repeated exposure, the material cracks deep. In this case, the erosion rate is much higher than the erosion rate during melting or evaporation (sublimation).

The service life of any DC electric arc plasma torch designed for the implementation of continuous technological processes is an important indicator of the reliability and technology implementation. It is determined by the service life of a plasma torch cathode - the sublimation flow rate referred to the density of the emitted current, which determines the degradation of its thermionic elements. Given the impossibility of using contact methods for studying the fastening of the attachment spot and its surface, despite publications on this topic, there is no picture of the effect of the spot on the inserted material. Therefore, in this work, we studied additional features of the destruction of the cathode of the PUN-1 plasma torch and ways of extending its service life.

2. Experiments and methods

The object of the study was the trace of the cathode spot of the arc on a standard insert of the PUN-1 plasma torch (Paton Electric Welding Institute for the deposition of metal films) whose capacity ranged between 20 and 10 kW. Variable values were: cathodes of various diameters with a standard zirconium or hafnium insert, as well as the discharge current from 70 to 100 A and the flow rate of plasma-forming gas of 25–46 $\mathrm{l\,min^{-1}}$ air with the addition of 9 % of propane-butane, as a gas envelope, pressure ranging from 0.15 to 0.4 MPa. We used water cooling at a pressure of 0.4 MPa and temperature of 20 °C.

The study of changes in the surface microstructures of the cathode insert was conducted along the trace of the arc discharge spot, using the metallography method. The enlargement of its image from 10 to 300 times under the Metal Microscope MIG-4 and the MBE-10 digital camera, as well as the high resolving power CCDDX-4, showed two different spot mounts - the "contracted" contact with a discrete mechanism for penetrating into the metal of the hafnium and zirconium inserts to a depth of 10 to 300 microns and intense ablation. Also, it showed the "diffused" contact related to the evaporation of metal and a significant increase in the area of emission. We succeeded in detailing the nature of the destruction of the electrode surface at the attachment point with the help of the Zeiss EVO 50 XVP scanning electron microscope, which detects the minute chemical composition of the surface of the spot trace and its impurities by means of scanning spectroscopy [5].

3. Results and discussion

During the experiment the standard cathodes of the PUN-1 plasma torch with a hafnium and zirconium insert were used, the photos of which are shown in figure 1 (a, b, c).

During continuous operation of the PUN-1 plasma torch for 20 min and vortex gas flow in the gap of 0.5 mm between the cathode and the anode, a trace of 1 mm in diameter and 1.5 mm in depth was formed at the attachment point of the hafnium insert (see figure 1a). Regarding the zirconium cathode, which operated for 32 hours, the trace was 1.2 mm in diameter and 3.1 mm in depth. The geometry of the destruction of the cathodes is the same. When a gap between the cathode and the anode widened, which was due to a decrease in the diameter of the cathode by a factor of 1.5, the trace diameter increased to 4 mm and a depth of 2.8 mm. The nature of the destruction of the hafnium cathode insert was different. The life of PUN-1 to its complete stop, with the repeat of operating parameters, increased to 72 hours. This motivated the study of the cathode shown in figure 2 - a) the cathode 3.5 mm in diameter with a zirconium insert of 1.5 mm operated for 482 hours before a control weight measurement. The diameter of the track averaged 2.8–3.1 mm. To compare, a control measurement of the evaporation of the mass of the insert of the PUN-1 plasma torch shown in figure 3 b) and c) was taken.

As we used the Zeiss EVO 50 XVP scanning electron microscope, the results of the metallography of the trace of the arc spot on the hafnium and zirconium inserts of the PUN-1 cathode (see figure 1a and figure 1b) showed the same nature of the cathode spot fastening regardless of the operating time. As can be seen from the photographs of figure 3 a) and b), deep cracks are visible over the entire area, as well as annular, stepped and tapering in nature with a distance of 10 to 300 microns of the trace of the reference spot of the material penetrating deeply into the cathode insert, which indicates a discrete mechanism of its operation. This type of spot attachment is called "contracted". An analysis of the chemical composition of the sample with the help of X-ray radiation generated by the electron beam established that carbon, oxygen, and copper accumulate with spot work in time (see table 1) - poisoning by combustion products.

At the cathode of reduced diameter, which worked for 72 hours with a hafnium insert, along the trail of the cathode spot, by metallography, another mechanism of the spot attachment was revealed, which we called "diffused" (figure 1c). The trace over its entire area does not have large and deep cracks, the size is increased several times, and chemical analysis of the samples taken from the insert material shows the absence of "poisoning" of hafnium by combustion products. Obviously, the material of the insert into the arc is supplied by evaporation.

A decrease in the diameter of the cathode and the identification of "diffusion" attachment, with an increase in its resource, suggested an increase in the gap between the cathode and the anode, which could lead to an increase in the dynamic pressure at the point of attachment of the arc spot. For this purpose, a cathode with a diameter of 3.5 mm was manufactured with a zirconium insert of 1.5 mm (figure 1c). The metallography of the trace of the attachment of the arc spot is shown in electronic photograph on figure 4b. The analysis of the samples gives reason to believe that zirconium oxide with a melting point of 3063 K was formed at point No. 1 [6].

The weight loss of the cathode mass was $\Delta g = 0.18\,\mathrm{g}$ at the rate of mass loss $\Delta G = 1.5 \cdot 10^{-13}\,\mathrm{kg\,s^{-1}}$ [7, 8].

To check the revealed effect of reducing erosion of a zirconium insert with a diameter of 1.5 mm while reducing the speed of the eddy flow of the working medium, we measured the critical weight loss of the zirconium insert of the PUN-1 plasma torch (the gap between the cathode and anode is 0.5 mm) At a discharge current of 100 A and duration of operation 3600 s amounted to $\Delta g = 0.05\,\mathrm{g}$, which corresponds to the ablation rate $\Delta G = 0.139 \cdot 10^{-9}\,\mathrm{kg\,s^{-1}}$ and fully corresponds to the values presented in the literature [8, 9] for zirconium insert operating in an air atmosphere.

4. Conclusions

1. The mechanism of the action of the cathode spot of the arc gas discharge with "contracted" and "diffused" attachment to the metal surface on hafnium and zirconium inserts is presented.

2. The depth of the crater in the metal under the cathode spot reached 1.5 – 2.8 mm. The walls of the crater in the case of a "contracted" attachment are a tapering stepped terrace with a step in width of 10 – 300 microns.

3. It is shown that a decrease in the vortex flow velocity in the gap between the cathode and the anode can reduce the rate of metal entrainment from the insert crater by two orders of magnitude.

4. The theoretical life-time of the cathode assembly with a zirconium insert with a diameter of 1.5 mm with a "diffused" attachment at 70 A discharge current amounted to more than 7000 hours.

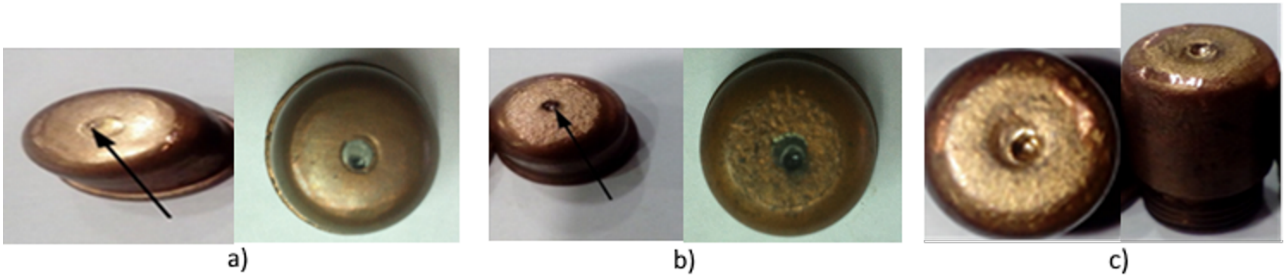

Figure 1. Top view of the cathode PUN-1 with hafnium insert a) the cathode operated for 20 minutes, with zirconium b) it operated for 32 hours before the complete cessation of arc burning, and with hafnium c) it operated for 72 hours. The attachment location of the reference spot is indicated by the arrow.

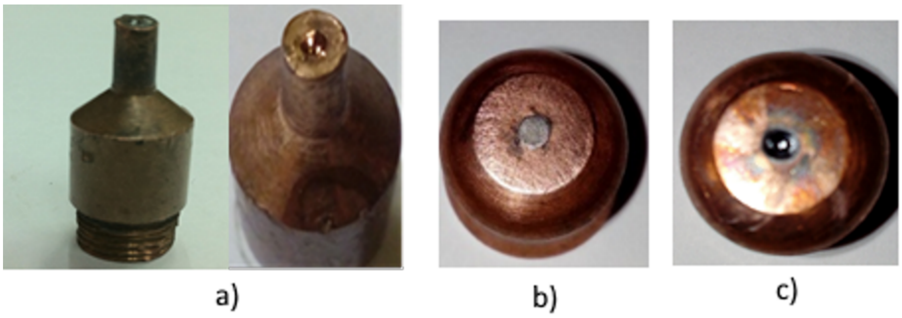

Figure 2. a) Side view and top view of the cathode 3.5 mm in diameter with a 1.5 mm zirconium insert, which operated for 482 hours before a control measurement in a standard medium with modified parameters of the discharge, discharge current - I_P = 70 A, discharge voltage - U_P = 180 V, pressure = 0.15–0.25 MPa, flow rate = 25–32 l min^{-1}; b) Copper cathode with zirconium insert of the PUN-1 plasma torch before the control test; c) Photo of the same cathode after the test.

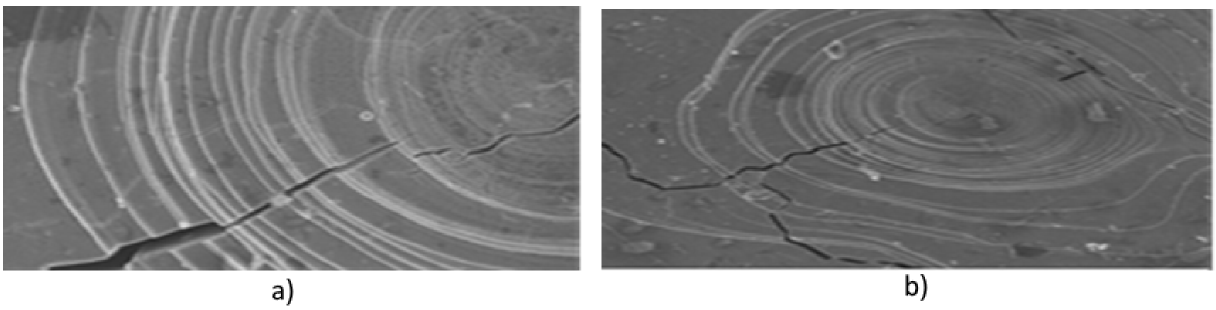

Figure 3. a) a photograph of the trace of the cathode spot on the surface of the hafnium insert (20 minutes of work) and b) a photograph of the trace of the cathode spot on the surface of zirconium insert (32 hours of operation).

Spectrum	**In statics**	**Carbon**	**Oxygen**	**Copper**	**Zirconium**	**Hafnium**	**Total**
1	Yes	18.17	32.73	0.46	48.31	0.33	100

Table 1. The composition of the material in the trace of the cathode spot on the zirconium insert.

Spectrum	**In statics**	**Carbon**	**Oxygen**	**Copper**	**Zirconium**	**Hafnium**	**Total**
1	Yes	7.33	29.40	0.46	62.63	0.16	100

Table 2. The composition of the sampling samples from the cathode spot on the zirconium insert at the attachment point No. 1 (figure 4b).

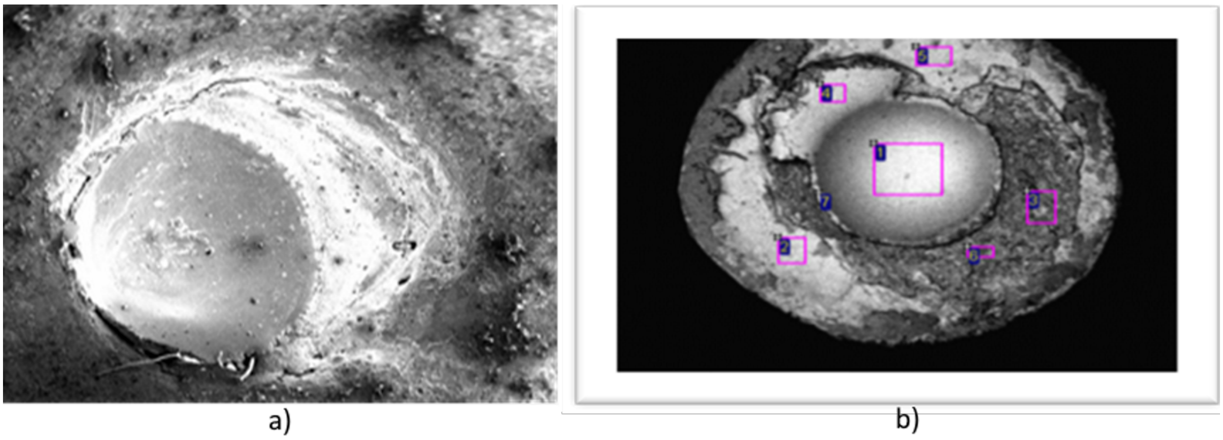

Figure 4. a) an electronic photograph of the trace of the cathode spot on the hafnium insert, which worked for 72 hours, with a reduced cathode diameter (see figure 1c); b) an electronic photograph of the attachment of the spot indicating the sampling location of the zirconium insert, which worked for 482 hours before weight control.

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