Modeling and experimental study of the electrodes erosion of plasma torch EDP-104A in nitrogen plasma

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Abstract. Modeling and experimental studies of the electrodes erosion of plasma torch EDP-104A in nitrogen plasma were carried out. The resource of cathode and anode operation is determined by calculation. The conditions and performance of 178 cathodes were studied. The possibility of using natural gas to protect a tungsten cathode was investigated. The increase in the cathode life to the rated value was confirmed.

1. Introduction
Plasmatrons attract attention due to their effective implementation of chemical, metallurgical and other processes, create practically waste-free technologies, organize complex processing of raw materials, obtain materials with fundamentally new physical, mechanical and chemical properties, miniaturize industrial plants and automate them.

The created technological installations have high productivity. Advantages of electric arc plasmatrons allow their efficient use in industry:
1. The cost-effectiveness of converting electrical energy into heat by existing plasmatron designs, characterized by high values of electrical and heat efficiency.
2. Reliability and stability of the electric arc installation.
3. A large resource of electrodes, calculated in tens and hundreds of hours of operation, depending on the type of plasma torch, its power and the type of working gas.
4. A wide range of power – from hundreds of watts to several megawatts.
5. The ability to heat almost any gas, including reducing, oxidizing, inert, widely used in industrial technologies.
6. The simplicity of automation of the control mode of the electric arc.
7. Small size and rather small metal consumption.

The increasing scale of technical applications of electric arc devices require solution of a number of problems, associated, first of all, with the increase in the service life of the most heat-stressed elements – electrodes. Among them, the problems of increasing the enthalpy of the working gas and the inclusion of gases with complex composition in the technological processes, the need to increase the power consumption of the gas discharge should also be noted. The latter requirement is especially evident in the chemical and metallurgical industries, where the unit power of the plasma torch during long-term stationary operation should reach many megawatts. The implementation of these working conditions inevitably requires an increase in the current strength of the arc and, therefore, the use of
materials with improved physical and mechanical characteristics, since an increase in the current strength leads to an increased erosion of the electrodes material (reducing the resource of their work).

The erosion rate of the electrodes is associated with physical processes in the electrode zones of the arc discharge, on the surface of the electrode and inside the crystal lattice of the metal from which it is made. It is determined by such non-stationary processes as large-scale and small-scale arc bridging, the action of an external magnetic field on the arc pillar, the aerodynamics of the gas flow in the plasmatron, and other factors. For example, bridging leads to the accumulation of damage in the surface layer of the electrodes.

In the last decade, as a result of theoretical and experimental studies, it was possible to improve significantly the quantitative indicators of specific erosion of tungsten thermal cathodes, reducing it to a record low value of $10^{-13}$ kg/C today with a current strength not exceeding 1 kA. Successes have also been noted in reducing the erosion rate of copper cooled cylindrical anodes with a movable supporting arc spot. Typically, the average values of specific erosion of such anodes are at the level of $10^{-9}$ kg/C at a current strength in the range 0.1$^{-4}$ kA, pressure $10^5$ Pa, and for a wide range of gases (air, nitrogen, oxygen, hydrogen).

The physical nature of the near-electrode processes is extremely complex, and their characteristics significantly depend on the material, shape and method of cooling the electrodes, pressure, temperature, nature of the flow and type of gas, as well as the method of organizing the arc discharge in a gas-discharge device. In addition, at high gas pressures (of the order of atmospheric and higher), the thickness of the electrode layers turns out to be very small, which at high current densities significantly complicates the experimental study of the electrode processes. Therefore, in recent years, theoretical methods for studying near-electrode processes have been increasingly used, along with experimental ones, which significantly expands the possibilities of elucidating their nature and determining the features of the process itself.

The aim of this work is the mathematical modeling of the electrodes erosion processes of plasma torch EDP-104A when they are in nitrogen plasma and the technological testing of natural gas to protect the tungsten cathode and increase its service life.

2. Modeling of the electrodes erosion processes of plasma torch EDP-104A when they operate in nitrogen plasma

Usually, the service life of the plasma torch is taken to be equal to the lower value of the service life of one of the electrodes. The experimental determination of the life of the electrodes is very time-consuming and expensive. In this regard, the life of the anode and cathode was estimated by calculation. For this, the complex profile of the anode worn part at the point of attachment of the electric arc behind the ledge was assumed to be similar to a triangle (figure 1 a), and the diameter of the crater formed in the cathode under the influence of the crater arc was equal to the diameter of the arc attachment (figure 1 b).

![Figure 1](image-url)
The volume of the anode material removed as a result of erosion will be, m³:
\[
V_e = 0.5 \cdot h \cdot \pi \cdot I \cdot (d_2 + h). \tag{1}
\]
Taking that \(l=3.6 \cdot 10^{-2} \text{ m} \); \(d_2=12 \cdot 10^{-3} \text{ m} \); \(h=0.2 \cdot 10^{-2} \text{ m} \), then:
\[
V_e = 0.5 \cdot 0.2 \cdot 10^{-2} \cdot 3.14 \cdot 3.6 \cdot 10^{-2} \cdot (12 \cdot 10^{-3} + 0.2 \cdot 10^{-2}) = 1.58 \cdot 10^{-6} \text{ m}^3.
\]
The duration of continuous operation of the copper anode is:
\[
t_a = \frac{\rho_e \cdot V_e}{G_e \cdot I}, \tag{2}
\]
where \(\rho_e\) is the density of copper, \(\rho_e = 8.9 \cdot 10^3 \text{ kg/m}^3\); \(G_e\) - specific erosion of the electrode, \(G_e = 4 \cdot 10^{-12} \text{ kg/C}\); \(I\) – arc current, A.
\[
t_a = \frac{8.9 \cdot 10^3 \cdot 1.58 \cdot 10^{-6}}{4 \cdot 10^{-12} \cdot 200} = 4883 \text{ h}
\]
Define the cathode resource. We select tungsten as the cathode material. The diameter of the cathode tungsten insert [6], m:
\[
d_c = \frac{1.3 \cdot 10^{-4} \cdot I^{0.5}}{1 - 2.15 \cdot 10^{-2} \cdot I^{0.5}}, \tag{3}
\]
\[
d_c = \frac{1.3 \cdot 10^{-4} \cdot 200^{0.5}}{1 - 2.15 \cdot 10^{-2} \cdot 200^{0.5}} = 3 \cdot 10^{-3} \text{ m}.
\]
The length of the insert should be less than or equal to the diameter, \(l_c = 0.003 \text{ m}\) is assumed. The permissible cathode erosion depth, m:
\[
l_c = 0.3 \cdot l_c = 0.3 \cdot 0.003 = 0.1 \cdot 10^{-2} \text{ m}. \tag{4}
\]
The diameter of the crater formed in the cathode under the influence of the arc is equal to the diameter of the arc attachment, m:
\[
d_n = B \cdot I^{0.5}, \tag{5}
\]
where \(B\) is a coefficient equal to \(1.6 \cdot 10^{-4}\) for nitrogen [1].
\[
d_n = 1.6 \cdot 10^{-4} \cdot 200^{0.5} = 2.3 \cdot 10^{-3} \text{ m}.
\]
The volume of material removed as a result of erosion will be, m³:
\[
V_e = \frac{\pi \cdot d_n^2 \cdot l_c}{4}, \tag{6}
\]
\[
V_e = \frac{3.14 \cdot (2.3 \cdot 10^{-3})^2 \cdot 0.1 \cdot 10^{-2}}{4} = 0.42 \cdot 10^{-8}.
\]
By the formula (2), we calculate the time of cathode continuous operation, given that for tungsten \(\rho_e = 19.34 \cdot 10^3 \text{ kg/m}^3\), \(G_e = 2 \cdot 10^{-12} \text{ kg/C}\):
\[
t_c = \frac{19.34 \cdot 10^3 \cdot 0.42 \cdot 10^{-8}}{2 \cdot 10^{-12} \cdot 200} = 56 \text{ h}.
\]
Using the geometric model described above and methods for calculating the cathode life for specific erosion values $(0.4 - 3.0) \cdot 10^{-12}$ kg/Cl, corresponding to an approximate oxygen content in technical nitrogen up to 1% vol., The obtained calculated dependence of the resource of the cathode operation on the specific erosion value is shown in figure 2. The nature of the dependence is confirmed by the erosion mechanism of a tungsten thermal cathode described in [1] in an oxygen-containing nitrogen plasma. Erosion of the cathode as a result of the action of the arc spot on its working surface (repeated melting, evaporation and crystallization with the occurrence of thermal stresses with the formation of a network of cracks in the depth of the cathode material) and its erosion as a result of oxidation with the formation of tungsten oxides. Apparently, the reduction in the erosion of the thermal cathode seems to be real due to the limitation of the oxygen content in technical nitrogen.

![Figure 2. The calculated dependence of the cathode life on specific erosion.](image)

3. Technological testing of natural gas to protect the tungsten thermal cathode of plasma torch EDP-104A

In the conditions of LLC Polimet, which implements plasma synthesis and plasma processing technologies in a three-jet plasma metallurgical reactor with a capacity of 150 kW using technical purity nitrogen as a heat carrier, the analysis of technological documentation that records the operation of the cathodes (installation and replacement dates) was carried out and the average resource for 2015, 2016, 2017, 2018 was determined. The statistical sample of cathodes was, pcs.: 2015 – 42; 2016 – 48; 2017 – 39; 2018 – 45. The oxygen content in the main nitrogen during this period varied within 0.7 – 1.6% vol. In this case, the same cathode could operate in a plasma-forming gas with different oxygen contents, which did not allow the dependence of the resource on the oxygen content to be revealed. The distribution of the average cathode resource by years is shown in figure 3. The average cathode resource was, hours: 2015 – 63, 2016 – 51, 2017 – 58, 2018 – 64.

As it can be seen that the average cathode resource is significantly lower than the declared passport value (100 h) and corresponds to approximate values of specific erosion $(1.8 - 2.2) \cdot 10^{-12}$ kg/l.

The analysis of specialized scientific and technical literature has revealed two possible technological options for increasing the cathode life:

1) preparation of main nitrogen for use as a plasma-forming gas, including the removal of moisture and oxygen in electric column heaters with a chrome-nickel nozzle at a temperature of 500-600 °C, providing a residual oxygen content of not more than 0.01% vol. at a load $(6 - 8) \cdot 10^{-4}$ m$^3$/m$^2$·s [2-4];
2) the use of a mixture of technical nitrogen and gaseous hydrocarbon as a plasma-forming gas, for example, natural gas introduced in an amount necessary for the binding of oxygen to carbon monoxide [5]. However, the first option was not widely used and mastered only at the laboratory level, and the second was not technologically confirmed in real production conditions.

![Figure 3. Distribution of the average cathode resource by years.](image)

In this regard, in the conditions of Polimet LLC, a technological study of the cathode operation of plasma torches EDP-104A of a three-jet reactor with a capacity 150 kW in a heat carrier gas containing nitrogen of technical purity with natural gas additives containing 94.0-96.0% vol. methane at an arc current of 200 A. During the research, the oxygen content in technical nitrogen was (0.6 - 1.2)% vol. The cathode life was determined for three plasma-forming gas compositions: \(N_2 + 1.0\%\) vol. \(CH_4\), \(N_2 + 2.0\%\) vol. \(CH_4\), \(N_2 + 3.0\%\) vol. \(CH_4\). The average value corresponds to the stoichiometric for the reaction of the formation of carbon monoxide with an oxygen content of nitrogen of \(~1.0\)% vol. The results of the study are presented in figure 4 and generally confirm the technological feasibility of this approach: the average value of the resource increased to 105 hours and is achieved with a methane content of 2 to 3 % vol.

![Figure 4. Dependence of the cathode life on methane content in nitrogen (○, Δ – practical and average values).](image)

## 4. Conclusion

1) The modeling of electrodes erosion process of plasma torch EDP-104A during their operation in nitrogen plasma was carried out. Geometric models of a complex profile of cathode and anode worn parts are constructed. For a current strength of 200 A, an oxygen content in nitrogen approximately 1 % vol., specific anode erosion values of \(4 \cdot 10^{-12}\) kg/C, cathode \(2 \cdot 10^{-12}\) kg/C, the anode operating life is
4883 hours, i.e. virtually unlimited, the cathode resource is 56 hours, which is lower than the passport data (100 hours). The analysis of the calculated dependence of the cathode life on specific erosion shows that a satisfactory resource is 100 to 200 hours can be achieved with a specific erosion of (0.4 - 1) kg/C, which corresponds to an oxygen content of significantly less than 0.5% vol.

2) In the conditions of Polymet LLC, the survey of the conditions and indicators of 174 cathodes of plasmatrons EDP-104A for the period 2015 – 2018, achieved during operation in main nitrogen with an oxygen content of (0.7 - 1.6) % vol., was conducted. The average cathode life was 59 hours, which is significantly lower than the declared passport value (100 hours) and corresponds to approximate values of specific erosion (1.8 - 2.2)·10^{-12} kg/C.

3) In the conditions of Polimet LLC, the study of the operation of the plasma torch cathodes EDP-104A of a reactor with a capacity of 150 kW was conducted in a heat carrier gas containing nitrogen, oxygen (0.6 - 1.2) % vol. and natural gas (methane up to 94.0-96.0 % vol.) (1-3)% vol. The increase in the average value of the cathode life up to 105 hours was confirmed when the methane content in the coolant gas is 2–3 % vol., which indicates the technological feasibility of introducing gaseous hydrocarbons into the composition of the plasma-forming nitrogen-oxygen mixture to bind oxygen to carbon monoxide.

References
[1] Zhukov M F et al 1995 Plasmatrons. Research. Problems (Novosibirsk: SB RAS) p 202
[2] Nozdrin I V, Rudneva V V and Galevsky G V 2014 Chromide Boride – Nanotechnology, Properties, Application (Saarbrücken (Germany): LAP LAMBERT Academic Publishing) p 233
[3] Nozdrin I V et al 2012 Bulletin of Mechanical Engineering 12 78–83
[4] Nozdrin I V et al 2011 Proc. of Int. Conf in Metallurgy: Technology, Management, Innovation, Quality (Novokuznetsk: SibSIU) pp 119–123
[5] Nozdrin I V et al 2017 Pat. of the Russian Federation at PM No 107740, IPC H05B 7/18, H05H 1/24. No of appl. 2011121115 03/30/2017 publ. 08/10/2017