The working conditions analysis of the electrodes of plasma torch EDP-104A in nitrogen plasma

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Abstract. The analysis of the electrode conditions and performance of plasma torches EDP-104A in nitrogen plasma is carried out. It is shown that the life of the plasma torch is determined by the erosion of the tungsten thermal cathode. It is confirmed that the erosion depends on the strength of the current and the oxygen content in the plasma-forming gas. At the current strength of 1 kA with an increase in oxygen content from 0.1 to 0.5%, erosion increases from 10⁻¹² to 10⁻⁹ kg/C. To reduce cathode erosion, it is necessary to limit the oxygen content in technical nitrogen.

1. Introduction

At present, plasma chemical-metallurgical reactors of various designs are used for the implementation of nanotechnology, the most common of which are three-jet ones. In the reactor of this type constructed by SibSIU, Kutateladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences and LLC “Polimet’ three electric arc gas heaters (plasma torch) EDP-104A with capacity of 50 kW each are used. They are installed in the mixing chamber at an angle of 30° to the axis of the reactor and working on a common cylindrical channel. In a 150 kW three-jet plasma metallurgical reactor, the EDP-104A plasmatrons operate at a constant current of up to 200 A and a voltage of up to 250 V on an electric arc. The stabilization of the electric arc is gas-vortex due to the tangential introduction of plasma-forming gas through a special twist ring.

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 with a current strength not exceeding 1 kA. Successes have also been noted in reduction of 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 105 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.

According to the passport data, the service life of the cathodes of plasmatrons EDP-104A in non-oxidizing environments is at least 100 hours. When using nitrogen of technical purity as a plasma-forming gas with an oxygen content of 0.5 – 2.0%, this figure is reduced by almost 2 times. This makes it necessary to develop technical measures to increase the cathode resource.

In this regard, the aim of this work is to analyze the operating conditions of the tungsten thermal cathode of plasma torch EDP-104A in the nitrogen plasma.

2. The device, characteristics and operation of EDP-104A plasma torch

The device, characteristics and operating characteristics of the plasma torch EDP-104A are described in [1–7]. The plasma torch in the assembly, its cathode and anode assemblies, the cathode and anode before and after operation are shown in figure 1.

The plasma torch has sufficient versatility. Its design combines single-chamber plasmatrons with a fixed and self-stabilizing arc length. Depending on the purpose of the plasma torch, power, power source, the output electrode (anode) is selected either with a constant diameter along the length, or stepwise. An arc is excited between the electrodes when the plasma torch is turned on. The gas stream blows the arc out of the interelectrode space and draws it along the axis of the output electrode. The output electrode is made of copper or non-magnetic steel. The internal electrode (cathode) is made of tungsten, zirconium, graphite and other materials, depending on the operating conditions and the type of gas. In environments of hydrogen and nitrogen, tungsten is usually used.

The melting point of tungsten, approximately 3500 °C, is quite sufficient to ensure significant electron emission at a temperature below the melting point. Tungsten is alloyed with lanthanium, yttrium, thorium to reduce the work function. When choosing a plasma-forming medium, the following factors must be considered:

- the ability to achieve high enthalpy values;
- the possibility of use as a reagent;
- inertness in relation to the target products;
cost.

Enthalpy is one of the main parameters of the plasma flow, which largely determines the technological feasibility of the reactor. The comparison of the temperature dependence of the enthalpy of plasma-forming gases at atmospheric pressure shows that the enthalpy of molecular gases (nitrogen, hydrogen) at relatively low temperatures (4.10^3-1.10^4 K) as a result of the dissociation of molecules reaches high values and almost an order of magnitude exceeds the enthalpy of monatomic gases (argon, helium). The use of molecular gases allows high values of the thermal efficiency of plasmatrons to be achieved, which is 60-80% for hydrogen and nitrogen, while for plasmatrons operating on argon and helium, this figure is 40-50%. Along with this, the cost of argon and helium significantly exceeds the cost of hydrogen and nitrogen. For these reasons, the use of plasma-forming molecular gases seems to be more preferable.

Hydrogen and nitrogen in a number of processes can be used simultaneously as a heat carrier and a chemical reagent. The explosion safety of nitrogen, the simplicity of the design and the reliability in operation of the plasmatrons operating on it, for example, EDP-104A should also be noted.

Satisfactory operating life of the thermal cathode is achieved by choosing the material of the cathode insert (zirconium for oxidizing media, tungsten for inert media), applying a protective inert gas to the cathode, using a multi-position electrode assembly.

3. The conditions and performance analysis of the electrodes of plasma torch EDP-104A in nitrogen plasma

Studies of the conditions and performance of the electrodes of plasma torch EDP-104A in nitrogen plasma were carried out in [6, 8-10].

The life of the plasma torch, determined by the erosion of electrode materials, is its most important characteristic. Cathode and anode spots of electric arcs on cold electrodes are characterized by an extremely high level of heat flux density, reaching 104-105 MW/m². Such heat loads in the stationary mode are not able to withstand any of the known materials. To ensure an acceptable level of erosion of the electrode, the electrode sections of the arc are moved along the surface of the electrode by the action of aerodynamic or electrodynamic forces on them. When moving the electrode root, the surface of the electrodes undergoes cyclic thermal shock, as a result of which the crystal lattice “sways” and structural defects (cracks) of the electrode material arise, which leads to its mechanical destruction and decrease in thermal and electrical conductivity.

Therefore, the erosion rate of the electrodes is associated with physical processes in the electrode zones of the arc discharge, on the electrode surface 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 the external magnetic field on the arc column, and the aerodynamics of the gas flow in the plasmatron. Erosion for a cathode also depends on its diameter, design, plasma-forming gas composition, current strength, cyclic operation (number of plasmatron inclusions), quality of thermal contact of the surfaces of a tungsten rod and a copper cathode holder.

The erosion of the copper anode is determined by such factors as cooling conditions of the arc, current strength, magnitude of magnetic induction, and the protection of the surface of the anode with an inert or natural gas. The integral characteristic of the processes of electrode erosion, of course, which does not separately disclose the role of the occurring microprocesses, the presence of oxide films on the surface of the electrodes, thermal stresses in the metal, and the peculiarities of the motion of the electrode roots, is specific erosion, measured in kg/C. The appearance of the erosion of tungsten cathode and copper anode of the plasma torch EDP-104A is shown in figure 2 [6].

The cathode assemblies in the following design options have been investigated, tested in operation (figure 3): the rod cathode (a) in which a tungsten rod with a diameter up to 0.006 m is sealed in the water-cooled copper cage (cathode holder) with a given extension length (most often 0.003–0.005 m); the conical cathode (b), in which the tungsten rod with a diameter up to 0.006 m is pressed into a copper cage (cathode holder) cooled by water flush with its surface.
According to [6], the surface temperature of a working rod tungsten cathode with a diameter of 0.003 m is about 4000 K (the melting point of tungsten is 3650 K), and the surface cooling rate when the current is turned off reaches $10^6$ K/s. In the process, the molten zone is formed at the top of the cathode. With distance from the top, the surface temperature decreases. When working in nitrogen, a cathode spot is formed with a high level of current density and temperature, which leads to the formation, growth, and further decay of a molten tungsten bubble. Its occurrence is due to the expansion of the gas dissolved in tungsten. The specific erosion of the tungsten cathode when operating in nitrogen at a current strength up to 1 kA is about 10-12 kg/C. When the oxygen content in nitrogen is 0.1%, the nature of the destruction of the cathode is preserved.

When the oxygen content in nitrogen increases to 0.5%, particles of molten metal begin to fly out from the cathode surface, which sharply increases the erosion of the cathode. In this case, specific erosion reaches 10-9 kg/C. The conical cathode is characterized by more intensive cooling of the tungsten insert and a smaller working surface that undergoes erosion. According to [6], during the operation of the conical cathode, the end surface of the tungsten rod in the zone where the cathode spot of the arc is located is in the molten state.

Outside the melt, the gas evolution zone develops in the form of separate craters. Craters are formed due to the release of gases dissolved in tungsten through the molten surface. The specific
erosion of the tungsten cathode in nitrogen at atmospheric pressure, oxygen concentration up to 0.5% and current strength of 250–300 A lies in the range \((2 \pm 5) \times 10^{-12}\) kg/C, and with an increase in oxygen concentration to 1.5% reaches \((2 \pm 4) \times 10^{-12}\) kg/C.

The specific erosion of the copper cylindrical anode is also largely determined by the presence of oxygen in the working gas. So, at a current strength of 180 A in high-purity nitrogen containing about 0.001% oxygen, specific erosion is estimated at \(10^{-12}-10^{-11}\) kg/C, and in nitrogen of technical purity (oxygen up to 0.5%) it increases by more than an order of magnitude.

4. Conclusion
The operating conditions analysis of the electrodes of plasma torch EDP-104A in nitrogen plasma was carried out. It is shown that the operating life of the plasma torch is determined by the erosion of the tungsten thermocathode, which at a current strength up to 1 kA and an oxygen content up to 0.1% vol. is approximately \(10^{-12}\) kg/C and reaching \(10^{-9}\) kg/C with an increase in oxygen content to 0.5%. Erosion of the thermal cathode is the result of the action of the electrode root on its working surface (repeated melting, evaporation and crystallization with the occurrence of thermal stresses and the formation of the cracks network in the depth of the cathode material) and oxidation of the cathode material by oxygen with the formation of tungsten oxides.

References
[1] Zhukov M F, Smolyakov V I and Uryukov B A 1973 Electric Arc Gas Heaters (Plasmatrons) (Moscow: Nauka) p 232
[2] Anshakov A S et al 1977 Electric Arc Plasmatrons (Novosibirsk: ITP SB AS USSR) p 87
[3] Zhukov M F 1980 Electric Arc Plasmatrons 1980 (Novosibirsk: ITF SB AN SSSR) p 84
[4] Zhukov M F et al 1992 New Materials and Technologies and Extreme Technological Processes (Novosibirsk: Nauka Sib. Brunch) p 183
[5] Zhukov M F et al 1994 Thermal Plasma in the Technology of New Materials (London: Cambridge Scientific Publishing House) p 580
[6] Zhukov M F et al 1995 Plasmatrons. Research. Problems (Novosibirsk: Publishing House of the SB RAS) p 202
[7] Galevsky G V et al 2008 Basics of the Design of Plasma-metallurgical Reactors and Processes vol 2 (Moscow: Flint: Science) p 228
[8] Galevsky G V and Rudneva V V 2018 Nanomaterial Technology: Lecture Notes (Novokuznetsk: SibSIU) p 106
[9] Galevsky G V, Rudneva V V and Polyakh O A 2018 Fundamentals of Designing Electric Arc Plasmatrons: Learner’s Guide (Novokuznetsk: SibSIU) p 26
[10] Galevsky G V and Rudneva V V 2018 Nanomaterial Technology: Practicum (Novokuznetsk: SibSIU) p 29