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Material processing using arc plasmatrons with thermochemical cathodes

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Abstract. To heat oxygen-containing media in various technological processes, a special class of electric arc plasma generators is used, which use a thermochemical cathode based on hafnium or zirconium. Information about such electrodes is given and their performance in plasmatrons for cutting metals, spraying powder materials, heating gases with a power of 10–50 kW is shown.
Keywords: arc plasmatrons, thermochemical cathodes.

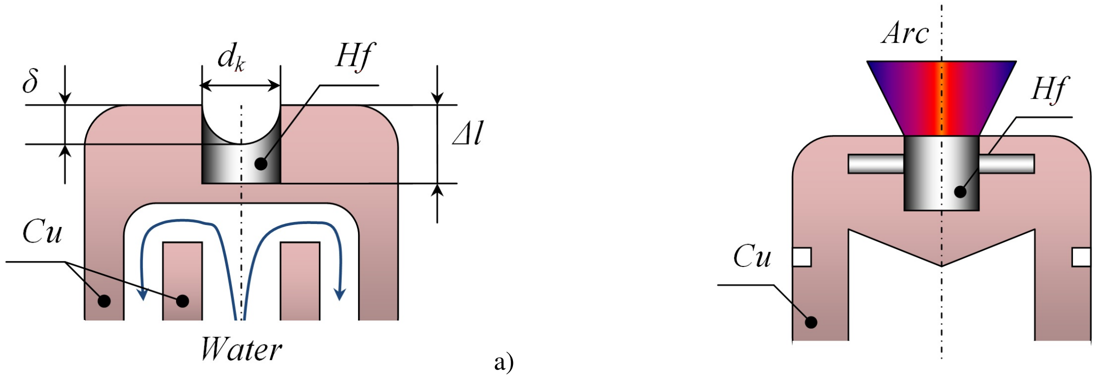
1. Introduction

The designs of electric arc gas heaters (plasmatrons) can be classified according to many criteria. For example, according to the number of vortex chambers, the type of plasma-forming gas, the type of cathode (hot and cold), methods of fixing the average arc length in the discharge chamber, and technological purpose of direct (one reference arc spot is on the metal being processed) and indirect (plasma jet generation) action. The choice of one or another plasmatron construction is determined by the required gas heating temperature, the arc discharge power, the available power source, the necessary service life, etc. The choice of design is influenced by the type of gas, pressure in the discharge chamber, technological and overall requirements associated with the purpose of the plasmatron.

2. Thermochemical cathodes

Despite the variety of design schemes of electric arc plasmatrons, there is always a need for low-power plasma devices (10–50 kW) for heating air and other oxygen-containing media, for example, in the technologies of plasma cutting of metals, plasma spraying, for modifying surfaces and synthesizing various materials. In this case, thermochemical composite cathodes are widely used (Fig.1). The electron emitter in such cathodes is zirconium Zr or hafnium Hf insert soldered or pressed into a water-cooled copper body.

In essence, the thermochemical cathode is a thermionic cathode, and got its name due to the fact that in air the near-electrode high-temperature surface of zirconium (hafnium) insert chemically interacts with nitrogen and oxygen, forming an oxynitride film with good emission properties, electrical conductivity and thermal stability. The resulting film protects the zirconium (hafnium) insert reliably from further oxidation, which ensures operability of the cathode in air.



a) b)

Fig.1 Schemes of thermochemical cathodes.

The location of a single Hf or Zr insert (Fig.1a) with diameter d_k and depth Δl = 3 mm, insert recess δ, and cathode with four Hf inserts modified to increase the electrode life (Fig.1b) are shown in Fig.1. The latter differs from the cathode with a single thermal insert by the fact that, in addition to the central insert, three more radial rods are pressed into the copper body with a step of 120°. The diameter of the central insert is d_k = 2.45 mm, and diameters of the side inserts are 1.6 mm.

Our studies and the results of other authors allowed the establishment of general regularities of parameters of thermochemical cathodes in terms of current density, heat fluxes, specific erosion, optimization of insert diameter d_k with respect to current, including dependence on the method of Hf insert embedding into the copper holder. Despite the significant scatter of experimental data, the specific erosion of thermochemical cathodes has an almost linear dependence on the arc current and amounts to 10^{-11}–10^{-10} kg/C. At low discharge currents ($I \le$ 200–300 A), the resource of their continuous operation reaches several tens of hours.

When it concerns the cathode service life, one should rely on the values of δ (the depth of Hf insert burnout) and G^{-} (specific erosion of the cathode material). The δ value was measured using a MIR-12 microscope with an accuracy of ±0.05 mm. The loss of the electrode material was determined on a laboratory balance with an accuracy of 10^{-3} g.

Particular attention was paid to the method of embedding the hafnium rod into a copper clip. The paper presents investigation results of an Hf cathode soldered with silver solder in vacuum. It has been experimentally shown that in the range of discharge currents I = 50–500 A, the heat flux into the cathode is a linear function of the current strength.

Fig.2 shows how the depth of a Hf rod with 1% yttrium additive changes depending on time of plasmatron operation at a constant current value.

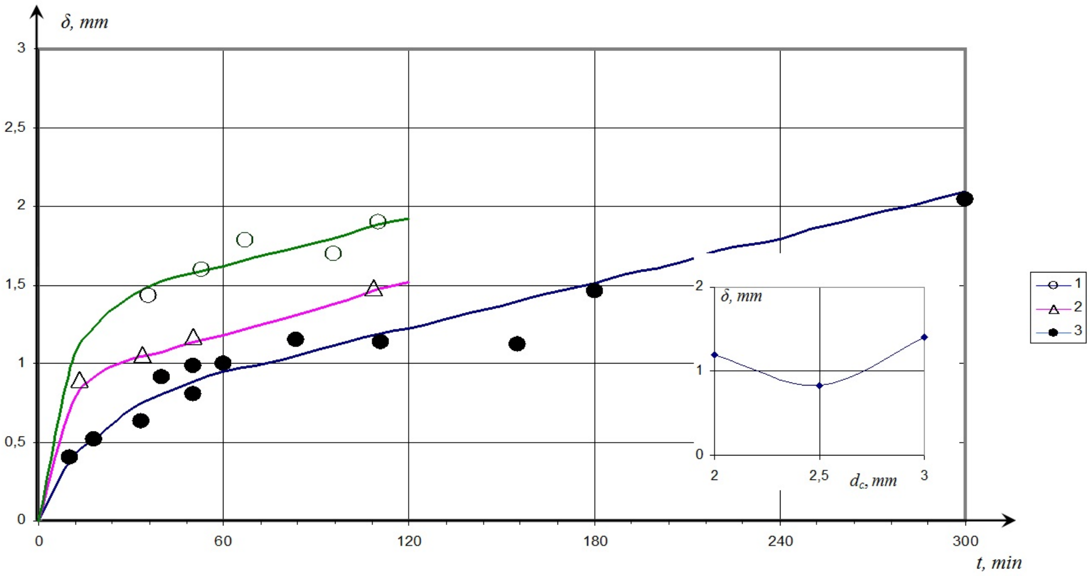


Fig.2. The depth of hafnium cathode destruction depending on the arc burning time and cathode diameter. I = 300A, *1* – d_c = 0.3 cm, *2* – d_c = 0.2 cm, *3* – d_c = 0.25 cm.

According to the diagram, the rate of cathode destruction over time is uneven. The depth of thermochemical cathode wear δ depends on the insert diameter d_k and has an optimum in d_k as well as for a tungsten thermal cathode [1].

One of the main results of thermocathode investigation is optimization of the diameter of the Hf insert d_k to a certain value of the arc current [2]. It has been established, for example, that the optimal diameter of the Hf or Zr insert at a current of 300 A is 2.5 mm. For different currents, it is recommended to use thermal inserts of different diameters d_k: at $I \le 80$ A d_k = 2.5 mm; at $80 \le I \le 200$ A d_k = 2 mm; at $200 \le I \le 300$ A d_k = 2.5 mm; at $300 \le I \le 400$ A d_k = 3 mm. This is due to the fact that the heat from the arc spot is removed to the copper clip through a narrow belt of the wall (insert). If the cathode spot of the arc on the insert is smaller than its diameter, then the working surface of hafnium is heated to a temperature higher than necessary to ensure the density of emission current according to the Richardson-Deshman formula. If d_k is less than optimal, then the cathode erosion is strongly affected by copper burnout.

3. Air-plasma cutting of metals

Plasma cutting and welding of metals are among the most common industrial electrical technologies, which use an electric arc discharge. The essence of plasma cutting of metals is that under the action of a powerful energy release in a constricted arc, the metal melts in a narrow (local) area, and an intense flow of plasma gas blows it out of the cutting area. The arc is compressed by a gas flow and a forming nozzle.

A diagram of the nozzle chamber of a plasmatron for air-plasma cutting of metals of the PVR type (development of the Russian Welding Institute (VNIIESO)) is presented in Fig.3.

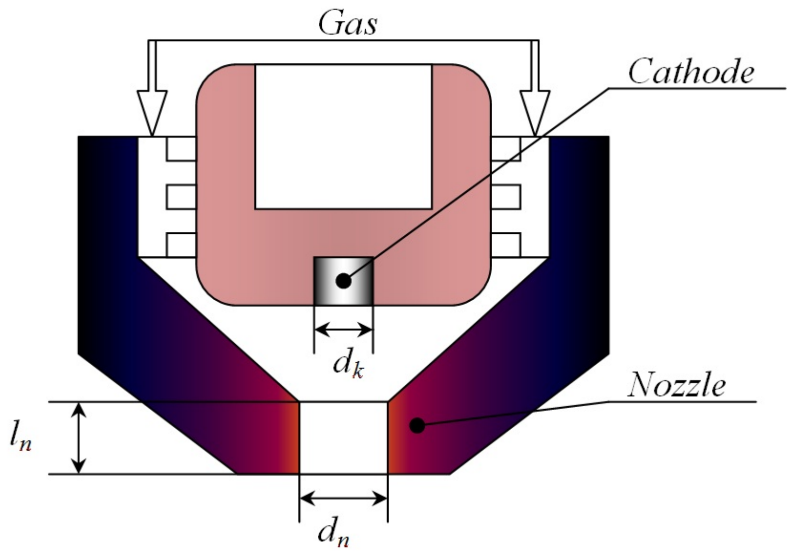


Fig.3. Nozzle chamber of plasmatron PVR-402.

The plasma gas flow rate is determined by the thickness of the metal being cut and the need to create a cold gas layer near the nozzle surface. The latter, as a rule, is carried out by vortex gas supply in the cathode-nozzle assembly of the plasmatron. The main purpose of the flow swirling sleeve (swirling apparatus) is strict localization of the arc cathode region near the vertical axis of the plasmatron. When the cathode spot is displaced relative to the active insert center, the rate of cathode destruction increases sharply.

The resource (number of one-minute turnings on) of hafnium cathodes with diameter d_k = 2.45 mm at I = 200 A (d_c = 3 mm, air flow rate G = 1.4–2.2 g/s) is 350 and at I = 300 A (d_c = 3 mm, G = 1.8 g/s), it is 220 turnings on. Studies of hafnium doped with yttrium, boron, and lanthanum have shown that its resistance can be significantly increased.

Using air as a plasma gas provides not only economic benefits, but also significant technical advantages. Plasma cutting of carbon steels ensures high productivity in addition to very high cutting quality. For example, at I = 200 A and a sheet thickness of up to 50 mm, the cutting speed increases by 2–3 times as compared to oxy-fuel cutting. An increase in the current to 300 A leads to an increase in cutting speed by another 1.5–2 times (3–6 m/min for a thickness of 10–20 mm).

As it was already mentioned, a modified cathode with four hafnium inserts has been developed and tested (Fig.1b) [2]. In the initial period of operation, erosion of the central Hf rod is the same as with a single insert. When its consumption reaches 2.2–2.5 mm, the cathode spot is distributed to all four inserts. In this case, the binding area of the arc reference spot is approximately 1.5 times larger than that with a single insert. Accordingly, the current density and heat flux are reduced. It has been experimentally established that the specific erosion of a cathode with four inserts is 10^{-12}–10^{-11} kg/C in the current range of 125–300 A (for a single insert $G = 2\cdot10^{-11}$–$8\cdot10^{-10}$ kg/C). For a plasma cutter with nozzle diameter d_c = 3.0–3.2 mm and a current of 300–320 A, the resource of a cathode with four hafnium inserts is 2–4 times higher than that for a cathode with a single insert.

The tested electrode for increasing the current load of up to 1000 A, the so-called multi-arc thermochemical cathode, is noteworthy [3]. It is a glass-shaped copper electrode with 3–6 hafnium inserts 2.5 mm in diameter, pressed around the circumference in one cross-section (Fig.4).

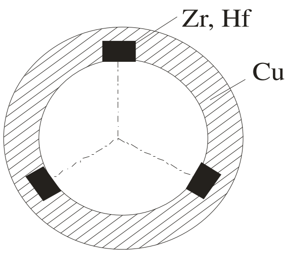


Fig.4. Layout of active inserts in the body of a copper cathode.

Fig.5. Stationary division of the arc radial section in a copper cathode with active hafnium inserts.

The inner diameter of the copper body is from 8 to 12 mm, the air flow rate is 0.8–2.0 g/s. The photograph (Fig.5) illustrates the formation of stationary burning radial sections of the arc. Six hafnium inserts are embedded in the electrode, designed for the current of up to 1000 A.

Erosion of the multi-arc cathode (Fig.6) was determined by the mass loss [4]. Each launch lasted from 30 to 50 minutes. The maximum current per each insert did not exceed 170 A. As compared to thermochemical cathodes with a single insert, G^{-} is almost independent of the total arc current and even tends to decrease with increasing current.

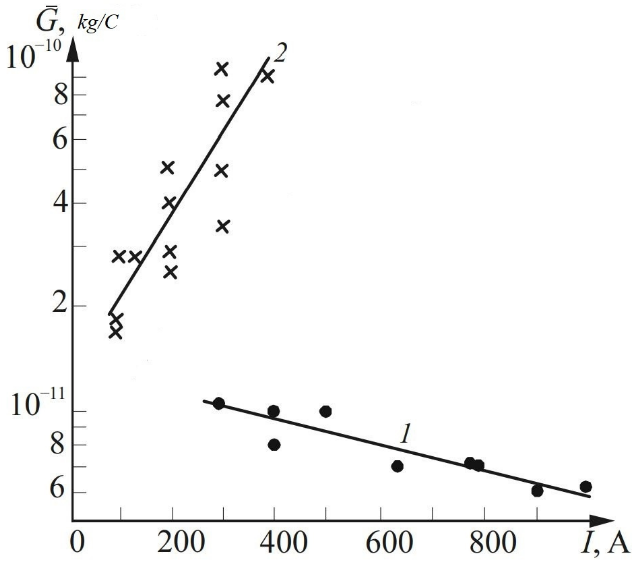


Fig.6. Erosion of the thermochemical cathode during long-term operation: *1* – multi-arc cathode with hafnium inserts; *2* – single end hafnium cathode (air) [4].

4. Plasma spraying

This technological process is a widespread method of applying powder materials for protective coatings of various functional purposes. In addition, this method can create all kinds of composite materials.

A wide temperature and dynamic range of plasma jet parameters, the possibility of using various working gases (neutral, oxidizing, and reducing) allow a combination of both phase and chemical transformations and deposition of materials with a given structure in one technological process.

To increase the strength of coating adhesion to the base and reduce porosity, the deposited layer is treated with a laminar plasma jet or an electron beam.

At present, plasmatrons with a sectioned interelectrode insert (IEI) are most widely used in plasma spraying technology. They allow significant reduction (by many times) in the velocity and temperature fluctuations of the plasma jet as compared to existing designs.

The above said is illustrated by the results in Fig.7 [5].

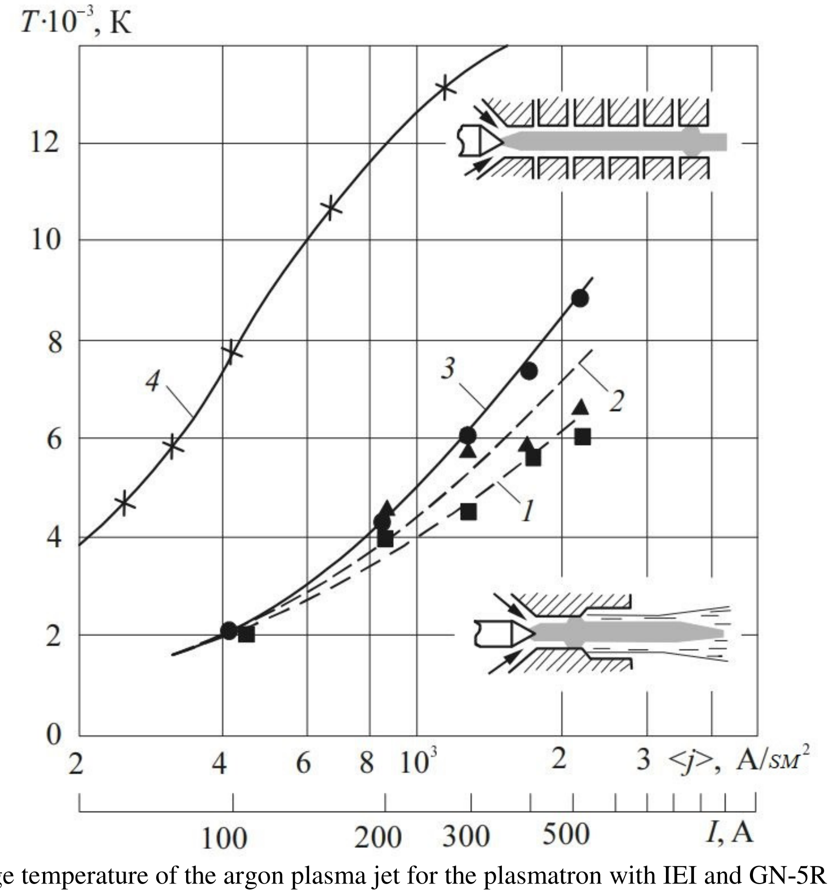


Fig.7. Mass-average temperature of the argon plasma jet for the plasmatron with IEI and GN-5R at gas flow rates, g/s: *1* – 0.39; *2* – 0.67; *3* – 1.23; *4* – 0.67.

Comparative data on the temperature of plasma jets of the GN-5R plasmatron (curves *1–3*) of the UPU-3D installation and the plasmatron with an IEI (curve *4*) are presented in this figure. It can be seen that a serial plasmatron ensures a mass-average jet temperature of 6000 K at a current of 300–500 A, and a plasmatron with a sectioned IEI ensures such temperatures at a current of 80 A.

When spraying metal oxides, air is used as the plasma gas. For these purposes, a small-sized plasmatron with an IEI of a 30–50 kW power with a thermochemical hafnium cathode of the EDP-167 type is used (Fig.8).

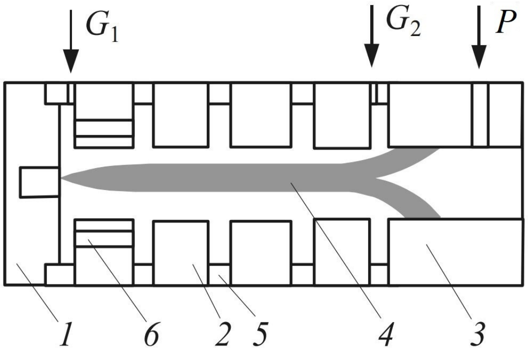


Fig.8. Scheme of an air plasmatron with IEI for spraying: working gas: air; *1* – cathode; *2* – IEI section; *3* – anode; *4* – electric arc; *5* – intersection insulators; *6* – longitudinal holes; *P* – powder supply.

In this design the supply of the main (working) gas G_1 (air) and additional (shielding) gas G_2 (propane) is provided. Total flow rate is $G_1 + G_2 = 1.0–1.1$ g/s. The shielding gas increases the dielectric strength of the section-anode gap, and also affects the near-anode region of the arc. In the body of the IEI launch section there are longitudinal holes with a diameter of 1.5 mm. Part of gas, flowing through them, loses swirling, and in the anode region the gas is not swirled, which is required for the plasma spraying technology.

Fig.9 shows the dimensionless profiles of the dynamic head at the nozzle outlet of the EDP-167 plasmatron with an IEI (curve *1*) and the serial plasmatron of the UMP-68 installation (curve *2*).

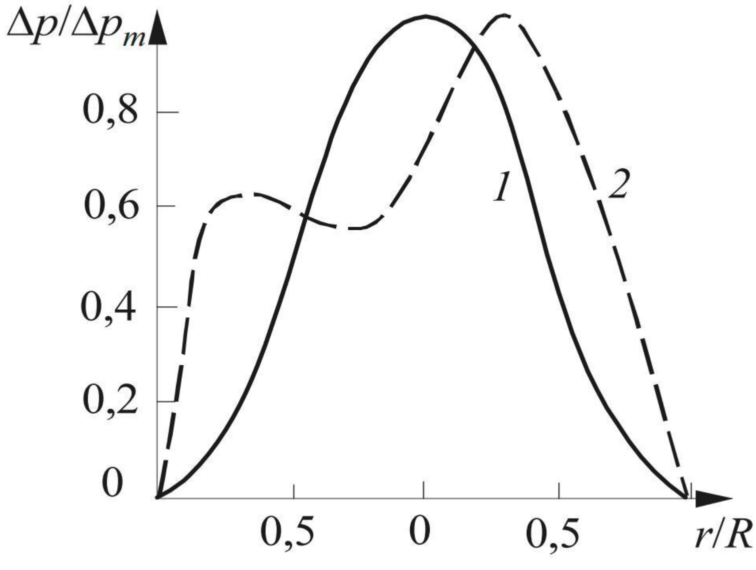


Fig.9. Dimensionless profiles of the plasma jet dynamic head at the nozzle outlet: at I = 150 A, G = 1 g/s; gas – argon.

It can be seen that the plasma jet of the EDP-167 plasmatron with a confuser anode is symmetrical and more compact as compared to a serial plasmatron, when the jet characteristics depend on location of the arc reference spot in the output electrode and have an asymmetric shape. In the latter case, it is impossible to achieve the repeatability of the technological process, which affects the quality of deposition.

The productivity of plasmatron EDP-167 in terms of sprayed ceramic powder is 6 kg/h. The stock utilization ratio is not less than 0.85.

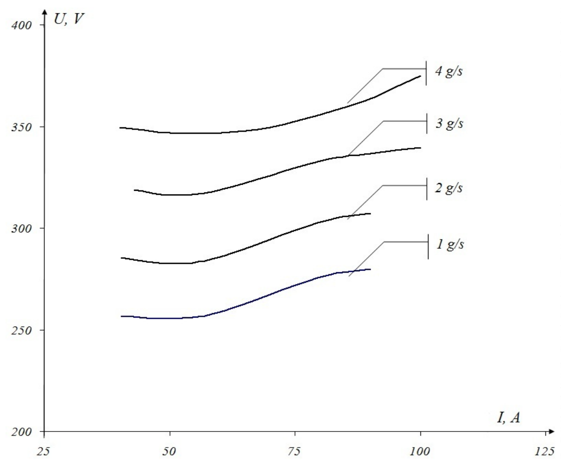
5. Surface treatment of products with a plasma jet

To implement the technology, a single-chamber jet plasma generator with gas-vortex arc stabilization of the EDP-104 type, developed at the Institute of Thermophysics of the Siberian Branch of the USSR Academy of Sciences, is useful. It is distinguished by good stability of arc discharge combustion and the ability to vary its power easily in the range from 20 to 50 kW [2, 3].

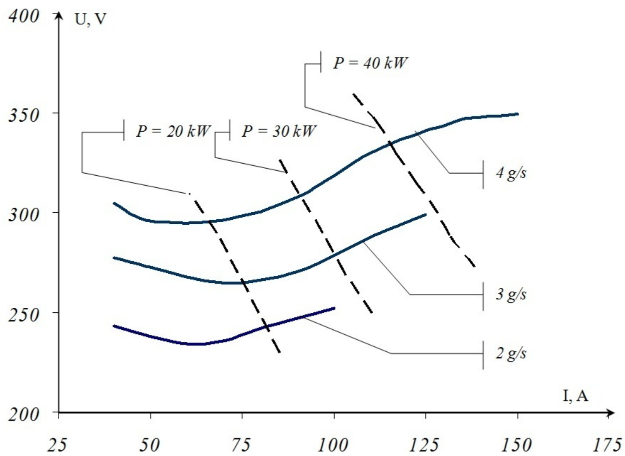
The plasmatron has a compact plasma jet for carrying out technological processes of hardening the surface of materials (cementation, melting, etc.). The stable regime of arc discharge combustion ensures high repeatability of the technology.

The output electrode can be made as a tubular electrode of a constant diameter, or in the form of an electrode with a variable cross-section by a sharp transition from diameter d to a larger diameter D (ratio D/d = 1.5) to fix the average length of the arc with a “ledge” in order to obtain ascending current-voltage arc characteristics. Hafnium is the material of a cylindrical thermionic insert embedded in a copper water-cooled holder for heating air and carbon dioxide. The voltage-current characteristics of the arc for a plasmatron with a stepped output electrode (d = 8 mm, D = 12 mm) are shown in Fig.10.

Due to the simplified plasmatron design, availability of inspection of all its components, simplicity of their replacement, and stability of the arc, it has become an indispensable tool in research institutes and educational institutions when developing various technological solutions; it is an effective device for surface treatment of products with a plasma jet.



(*a*)



(b)

Fig.10. Voltage-current characteristics of the arc in the EDP-104 plasmatron with stepped output electrode.

Main technical characteristics: plasma gas flow rate – 1–5 g/s; thermal efficiency – 0.8; maximum current – 200 A; anode outlet diameter– 5–10 mm; anode resource – 100 h; resource of thermochemical cathode – 30 h; mass – 1.45 kg.

6. Conclusion

Based on the research performed, their results on the creation of efficient electric arc plasmatrons for air-plasma cutting of metals, plasma deposition of powder materials for protective coatings and surface treatment of products with a plasma jet are presented in detail.

1. Materials for thermochemical cathodes (hafnium, zirconium) are comprehensively presented, taking into account their embedding in a water-cooled copper casing. Favorable conditions for continuous and discrete operation of thermal cathodes have been considered for various technological processes. The optimal parameters of Hf and Zr inserts for a wide range of arc

discharge currents have been determined. The constructive schemes of thermochemical cathodes for operation at high currents have been analyzed.

2. A structural layout of an air plasmatron torch with an IEI for deposition has been developed. The efficiency of the plasma jet is shown in comparison with known designs. The conditions for repeatability of the technological process have been established.

3. A thermochemical cathode is used in an EDP-104 arc plasmatron with a power of 20-50 kW to heat air and carbon dioxide. The plasmatron is designed for surface treatment of materials with a plasma jet.

Acknowledgments

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5. References

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