DOI: https://doi.org/10.37434/tpwj2022.10.07

SPECIALIZED PLASMA DEVICES FOR PRODUCING GRADIENT COATINGS BY PLASMA-POWDER SPRAYING

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ABSTRACT

A plasma device for plasma-powder spraying of multilayer, composite and gradient coatings was studied. Experimental studies of energy characteristics of plasma arc generator with curvilinear arc channel were performed during operation in plasma-generating air with the purpose of proving the principal possibility of its long-term service with acceptable energy and life characteristics. It is shown that losses into the plasmatron design elements depend on arc current and plasma gas flow rate, and the nature of this dependence does not differ in principle from regular plasmatrons: the losses increase with a rise in current and somewhat decrease at an increase of gas flow rate. Volt-ampere characteristics of the plasma generator are falling. However, the presence of the arc channel bend as a factor stabilizing the arc length, leads to appearance of a neutral region of VACh with a certain tendency to growth at a current rise. Here, the stable range by arc current operation is limited. A variant of improvement of the studied plasmatron design with widening of its functional capabilities of multicomponent coatings deposition is given.

KEYWORDS: plasma-powder spraying, gradient coatings, multilayer coatings, plasma arc generator with a curvilinear channel, plasma-generating air, volt-ampere characteristics, efficiency, specialized plasma device

INTRODUCTION

A considerable number of parts with coatings of metallurgical, chemical, aircraft and other equipment operate under high loads and sharp fluctuations of ambient temperature. In this case, artificially created functional surface layers of products should retain their properties throughout the entire service life. The chemical composition and structure of coatings and, accordingly, physical and mechanical properties of the material, from which they are created, can differ sharply from the properties of the base material (for example, ceramic coatings on metal bases). Often, there is a problem of violation of the mechanical integrity of the “coating-base” system caused by a sharp difference in the coefficients of thermal expansion (CTE) of materials of the base and the coating. Composite coatings of different functional purpose with metal and ceramic components are also widely used. Moreover, the formation of such coatings occurs from components that are separately fed into the zone of a composite coating formation.

For today, the most widespread methods for creating surface layers of such a type are thermal powder spraying (in particular, plasma) and plasma-powder surfacing [1, 2].

Also, the idea of creating an “adiabate” internal combustion engine has not lost its relevance for today [3]. Creating a ceramic diesel with a heat-insulated combustion chamber (called adiabate) will provide an increase in the efficiency of the engine by 1.5 times and reaching the specific mass (per a unit of power) by almost 30 % less than in the conventional design. Such engines can operate on fuels of broad fractional and deteriorated composition, i.e., they are multifuel, since a high temperature of the combustion chamber’s walls contributes to inflammation of hard-flammable fuels. In the course of creating an adiabate engine, along with the use of monolithic parts of ceramics, the use of metal parts with thermal barrier ceramic coatings is provided.

Most often, as a material of thermal barrier coatings (TBC), zirconium and aluminium oxides are used, which is predetermined, first of all, by their low heat conductivity [4]. The working temperature of zirconium oxide coating, which is stabilized by Y_2O_3, is close to 1090 °C. TBC of the new generation based on lantan phosphate and lantan hexoluminate are considered challenging. These materials can operate at temperatures of 1100–1600 °C.

Thermal barrier coatings usually consist of two layers, that perform different functions. The upper layer (ceramic) perceives thermal and erosion effects of gas flow and, having a low thermal conductivity, reduces the temperature of a part, that is protected. Under the ceramic layer, a heat-resistant layer is located, which protects the base from oxidation and helps to increase the adhesion strength of the ceramic layer with the base metal. An additional decrease in heat conductivity of ceramic coatings can be reached by their multilayered deposition.

The use of an intermediate layer of a metal material partially solves the problem of harmonization of CTE materials of the base and a functional coating, but a complete solution is possible only in case of gradual transition from CTE of the base material to CTE of the upper coating layer material. The transition can be realized in a step way by increasing a number of transition layers with a variable value of CTE [4, 5], or in the form of a coating with a smooth change in physical properties of the coating material in the direction from the base to the surface of a product. Such coatings are positioned as gradient.

Creating a gradient coating is possible by using already prepared mixtures of the base functional coating (ceramic) and the underlayer material [4, 5]. Such ready mixtures have a variable proportion between components. First, a coating layer, consisting of only a metal component is deposited, and then subsequent layers are deposited of ready mixtures, in which the content of a ceramic component gradually increases. The most upper functional coating layer contains only a ceramic component. Such a method guarantees the necessary ratio between components in each layer, but it requires the presence of several feeding dispensers (according to a number of layers), which are switched on in series, or refilling the powder with a new ratio of components of a one dispenser (with mandatory cleaning from the previous powder).

The more challenging way is the use of a complex of the equipment, containing a such number of dispensers, that is equal to a number of components of the composition in the future coating (in the simplest case there are two of them) [6].

The operation of such feeding dispensers is realized at the same time according to a certain algorithm, which determines the efficiency of operation of each one. The control (changing the ratio between components in a gas-powder flow) can be carried out in the function of time, if it is possible to accurately determine the thickness of the layer being deposited by the efficiency of the dispenser and the coefficient of using the material, or in the function of a number of passes, if the thickness of a coating produced in a one pass is known. The control is also possible if hardware devices for in-process determination of the coating layer thickness are used. The implementation of the algorithm requires a microprocessor control unit that has a feedback from the coarse of the coating formation process.

Another problem in the realization of technology of depositing gradient coatings is to organize the process of heating the source material, which contains components with sharply different physical properties. Taken into account a significant spatial heterogeneity of temperature, concentration and high-velocity fields of high-temperature gas flow, it is almost impossible to determine one place of introducing components of the source material that would provide optimal conditions for heating and accelerating of both metal as well as ceramic component (needless to say about protection of the material from the undesired effect of active gases from the environment). The ceramic component of the source material requires high temperature and comparatively long-term stay in the active area of the plasma jet. The metal component provides protection against oxidation and restriction of the intensive evaporation process by minimizing the time of staying in the region of ultra-high temperatures.

Considering that the most common way to introduce the source material into the plasma jet is introducing it outside the plasma generator design, the wide opportunities for optimizing the conditions of heating and accelerating the powder are not provided by the designs of modern sprayers. The introduction of the source material (for the ceramic component) at an angle directly into the arc channel significantly reduces the reliability of the process because of the high probability of sticking the material on the walls of the arc channel and the emergency operating modes of the plasmatron. In addition, the reliability of the design decreases due to the need to pass the water jackets for cooling the heat stressed elements of the plasma generator design [6].

It is impossible to feed the source material coaxially with the plasma jet due to the presence of the central water-cooled electrode in the arc generators of a linear circuit [7].

The aim of the work is to prove a fundamental possibility of creating a new generation of plasma devices for deposition of coatings of a complicated structure — multilayered and gradient from materials with substantially different physical and mechanical properties on the base experimental results of arc burning.

PROCEDURE OF EXPERIMENTS

The studies were conducted in a two-electrode plasmatron with the arc channel, consisting of several sections placed at an angle to each other. The spatial stabilization of the arc is of eddy type.

As a plasma-generating substance, air and a mixture of air with propane-butane was used. The gas mixture was preliminary prepared and supplied into the plasma generator already with a known components ratio.

The electric parameters of the device (arc voltage and arc current) were measured by electron and pointer instruments.

The losses into the plasma generator design elements were determined by measuring the flow rate of cooling liquid and its temperature at the inlet and outlet of cooling circuits of the corresponding units. The temperature was measured by mercury laboratory thermometers with a division value of 0.1 °C.

RESEARCH RESULTS AND DISCUSSION

The known direct methods for deflection of the flow from the axis of the arc channel by applying angular nozzles [7] allow deflecting the jet to a certain angle by changing the direction of leakage of an already formed jet. Such a method has a significant drawback — deflection of the plasma jet at the stage of a developed turbulent flow causes a sharp increase in thermal losses into the nozzle wall at the place of rotation of the plasma jet, which deteriorates the energy parameters of the plasmatron and significantly shortens the life of an initial electrode.

This disadvantage can be eliminated if the plasma jet can be turned at the stage of its formation. For this purpose, the arc channel is produced of two parts joined between each other at some angle. Under these conditions, most of the main region of the arc is placed on the inlet, and the smaller part of the main region of the arc and its near-electrode region is on the outler region of the arc channel, at an angle to the initial and main regions of the arc [8].

Such a burning organization of the arc allows protecting the walls of the arc channel to some extent at the point of changing the direction of movement of the gas flow from the heat of the heated part of the gas by means of the cold layer of gas between the channel wall and the electric arc, stored at the mentioned stage of a plasma jet formation and not fully formed plasma jet.

Figure 1 shows the variant of the device for implementation of the described method.

The output electrode of the device, in which the arc channel is placed, consists of two designing units, fixed together. Each characteristic region of the arc channel is located within its design unit and has an individual independent cooling system. The inlet area of the arc channel is characterized by a relatively low level of thermal losses [7]. Therefore, the unit in which it is located may have air cooling (natural or forced). Within the frames of the same unit, the angular transition of the inlet region of the arc channel to the initial region of the outlet arc channel is located and the powder line passes.

The end region of the outlet arc channel usually has water cooling. In order to rationally use the volume of material and increase the overall life of the output electrode, in the outlet part of the output electrode a number of channels are made, each of which, under certain conditions, can serve as the end region of the outlet arc channel. Under specific conditions, only one of the channels, in which the inlet hole coincides with the outlet hole of the initial region of the outlet arc channel, serves as the end region of the outlet arc channel. All other channels are reserve and sequentially involved in operation when the position of the outlet part of the output electrode relative to its inlet part changes.

The experimental studies of the mock-up of the plasma sprayer, created according to the proposed scheme, showed the technical serviceability of the design in the case of operation at current loads typical for plasma spraying and the use of plasma-generating mixtures of the N–O or N–O–C–H system. The study

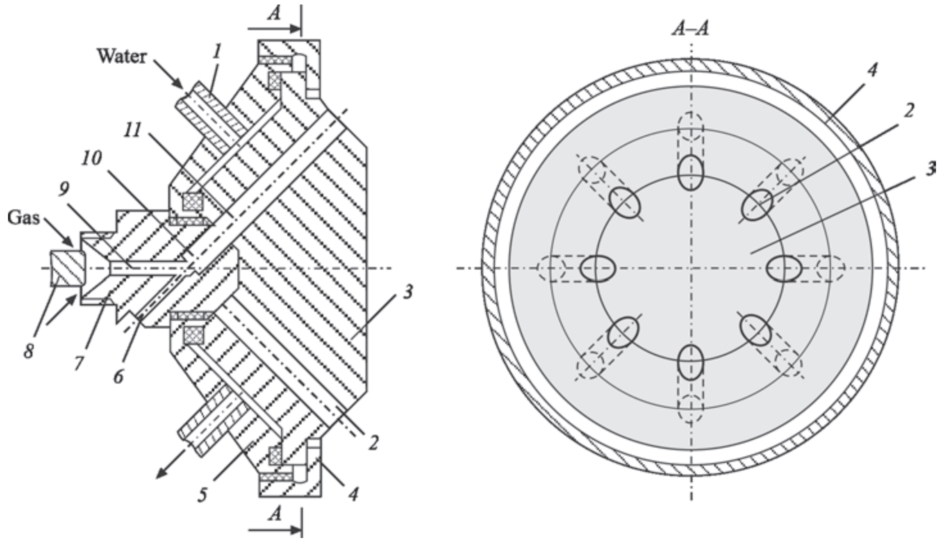

Figure 1. Plasmatron with assembled arc channel: *1* — fitting pipe; *2* — regions of arc channel; *3* — outlet part of the anode; *4* — captive nut; *5* — body part; *6* — powder feed channel; *7* — inlet part of the anode; *8* — cathode; *9* — inlet part of the arc channel; *10* — initial region of the outlet part of the arc channel; *11* — end region of the outlet part of the arc channel

of energy characteristics was carried out in the existing mock-up of the sprayer (Figure 2).

To power the plasmatron, a thyristor current source of APR-402 type was used which stabilizes the arc current in the range of 100–450 A when the operating voltage changes from 100 to 250 V.

The cathode unit and the outlet part of the arc channel within the anode had a direct water cooling, and the inlet part of the arc channel had a natural air cooling.

Variable operating parameters of the plasmatron were the consumption of plasma-generating air (gas pressure in front of the sprayer) and the arc current.

The main results of the experimental studies are shown in Figures 3–5.

The value of the arc voltage is determined by the arc current and the consumption (pressure) of the plasma-generating gas. As the gas flow increases, the arc lengthens and, accordingly, the integral value of the voltage drop on it increases. As the current increases, the arc shortens and the voltage drop becomes lower (Figure 3).

A characteristic feature of the investigated plasmatron is the fact that at a current above 170–180 A, a neutral region of the static volt-ampere characteristics (VACh) with a tendency of transition to a growing arc current above 220–230 A is observed.

Obviously, this is a consequence of fixing the length of the arc at the turn of the arc channel in a certain range of changes in the current and consumption of plasma-generating gas. The beginning of the process of stabilization of the arc length depends on the consumption of plasma-generating gas — the lower the consumption, the lower the threshold value of the current, at which the stabilization of the arc length begins.

Figure 2. Plasmatron with curvilinear arc channel

An increase in the current to the level of 270–300 A leads to the transition to an emergency mode of the plasma generator operation, which is characterized by a jump-like shortening of the arc with its pulling into the narrow part of the arc channel. This mode of the plasmatron operation is characterized by increased energy losses at the initial region of the arc channel. And taking into account that this region in the particular case has a natural air cooling, this will lead to overheating of the electrode material and a sharp acceleration of its erosion process.

Figure 4 shows the dependences of the losses into the anode unit of the plasmatron on the operational parameters of the device.

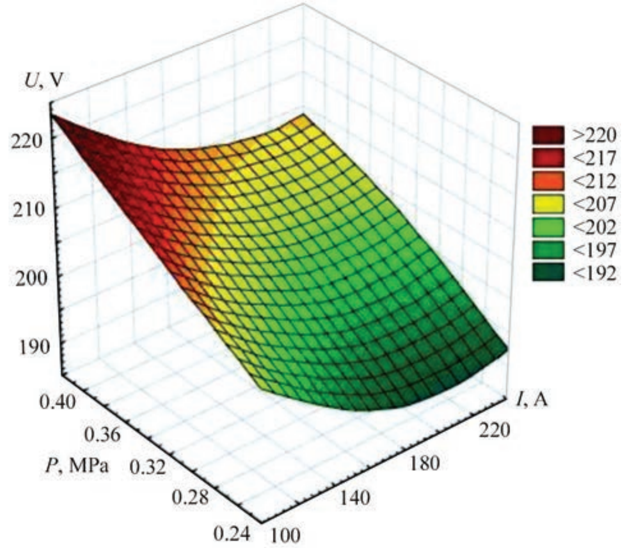

Figure 3. Volt-ampere characteristics of plasma sprayer

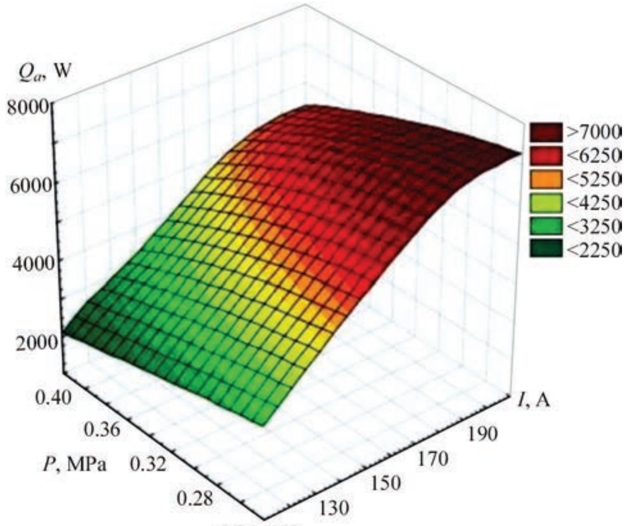

Figure 4. Dependence of energy losses into the anode unit of the plasma generator on arc current and pressure of plasma-generating gas

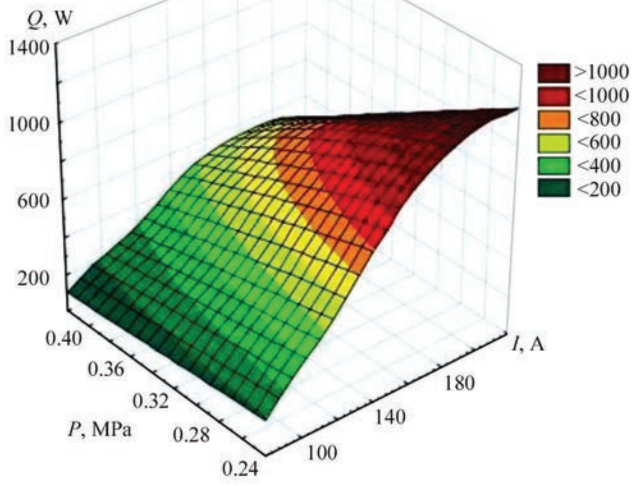

Figure 5. Dependence of energy losses into the cathode unit of the plasma generator on arc current and pressure of plasma-generating gas

Energy losses into the inlet part of the arc channel (region with a smaller diameter) during normal operating modes are practically determined by heat losses through arc radiation, therefore they decrease with a drop in current and an increase in the consumption of plasma-generating gas due to a decrease in the average mass temperature of the plasma.

The losses into the outlet part of the arc channel are mainly determined by the arc current. Simultaneously, with an increase in the consumption of plasma-generating gas, as a result of thickening of the cold gas interlayer between the arc and the wall of the arc channel and the reduction in the region of a developed turbulent flow of a high-temperature gas flow within the ranges of the arc channel, the total level of losses into the output electrode decreases slightly.

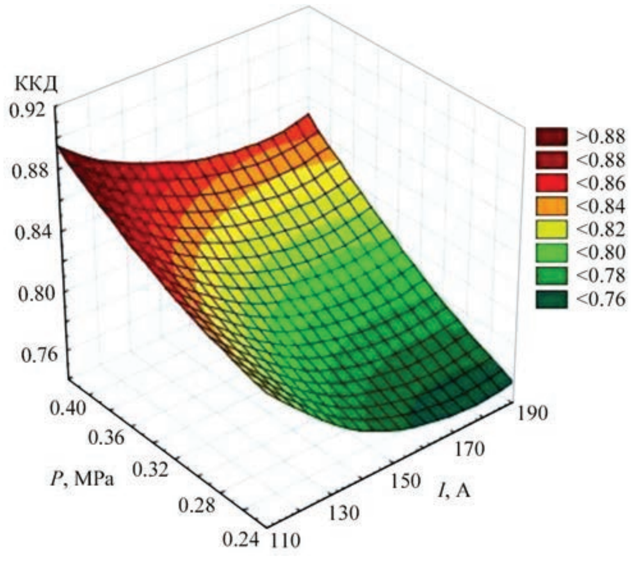

Figure 6. Dependence of the plasmatron efficiency on arc current at different pressure values of plasma-generating gas

The losses into the cathode unit increase as the arc current grows under the condition of a constant consumption of plasma-generating gas, and decrease slightly when its consumption increases (Figure 5). An increase in the consumption of cold plasma-generating gas intensifies the process of heat removal from the design elements of the cathode unit due to intensive blowing of the outer surface of the thermochemical cathode and its attachment unit. Under these conditions, recovery of a part of the energy of the electric arc occurs, which is not lost, but is used for preheating of the plasma-generating gas.

The thermal efficiency of the plasmatron, calculated from the measured energy losses, in this particular case has quite high values in the entire range of arc current changes. Although it should be taken into account that the presence of a region with natural air cooling in the output electrode, the losses into which are not taken into account in the calculations, gives slightly overestimated values of the calculated efficiency (Figure 6).

As the arc current grows, there is a decrease in the efficiency value, but, starting from current values of 160–170 A, a slowdown in the rate of a decrease in the efficiency and its stabilization at the level of 0.76–0.8 is observed. It should be noted that high efficiency values of 0.8–0.86 are typical for the operation of a plasma generator with an increased consumption of plasma-generating gas. Such modes of operation are usually not typical for coating processes due to low values of the specific energy of the high-temperature gas flow.

In the case of using a plasmatron as a sprayer of dispersed material with the introduction of powder together with the transporting gas coaxially with the outlet region of the arc channel, a change in the burning conditions of the electric arc and the nature of the heat exchange with working gases should be expected. The transporting gas takes an active part in the formation of the plasma flow, because it is supplied to the area of the electric arc. The location of the arc binding spot in this case will also partially depend on the consumption and composition of the transporting gas. Whereas the shape and nature of the arc binding spot will depend in a certain way on the composition of the transporting gas with the potential possibility of transition to diffusive arc binding under certain conditions.

The presence of the arc channel region with air cooling in the plasmatron makes it possible to lay the powder line through the anode unit without crossing its cooling jackets (see Figure 1). However, only two variants for feeding components of the composite material remain practically real: at the place of bend-

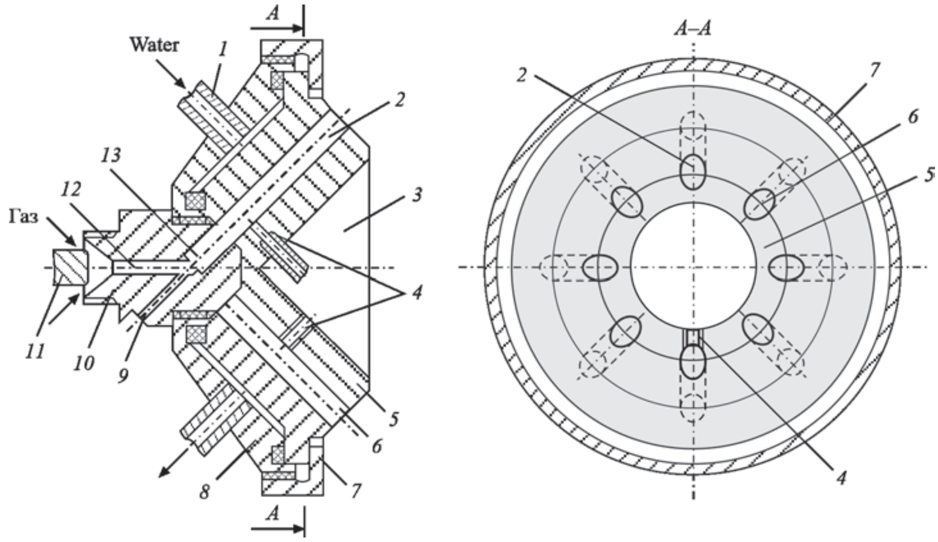

Figure 7. Design of plasma generator for deposition of multicomponent coatings: *1* — fitting pipe; *2* — end region of the outlet part of the arc channel; *3* — cavity; *4*, *9* — powder feed channels; *5*—– outlet part of the anode; *6* — regions of the arc channel; *7* — captive nut; *8* — body part; *10* — inlet part of the anode; *11* — cathode; *12* — inlet part of the arc channel; *13* — initial region of the outlet part of the arc channel

ing the arc channel (under condition that air cooling is used) and outside the arc channel at the section of the sprayer nozzle. All other require crossing of the electrode cooling jackets and the corresponding complication of the design with the loss of the device reliability. This in a certain way limits the possibilities of technology optimization by changing the place of introduction of individual components of the source material into the high-temperature gas flow in order to take into account their physical and geometric characteristics.

The further improvement in the design of the studied plasma generator largely solves the mentioned problem and allows creating a specialized plasma device with wide functional capabilities for applying multilayer and gradient coatings (Figure 7). For this purpose, in the output electrode (anode), a cone-shaped cavity is created, on the surface of which the inlets of the channels for feeding dispersed material are located. The channels are connected with the corresponding end regions of the arc channel. In this case, the location of each channel and the place of its connection with the arc channel are determined by a difficulty in melting of the used material and may be different for the available end regions of the outlet arc channel (in the specific case, there are 8 such sections).

The device shown in Figure for deposition of a multilayer composite coating consists of three structural units fixed to each other. Each characteristic region of the arc channel is located within its designing unit and has an individual independent cooling system. The inlet region of the arc channel is characterized by a low level of heat losses. Therefore, the unit in which it is placed, can have (under certain conditions) air cooling (natural or forced). Within the same unit, the angular transition of the inlet region of the arc channel to the initial region of the outlet arc channel is located and the powder line passes. Usually, the end region of the outlet arc channel has water cooling and is placed at an angle to the longitudinal axis of the outlet part of the output electrode. For the rational use of the material volume and to increase the overall life of the output electrode, a whole number of channels was made in the outlet part of the output electrode, each of which, under certain conditions, can serve as the end region of the outlet arc channel. In a specific case, only one of the channels, in which the inlet hole coincides with the outlet hole of the initial region of the outlet arc channel, serves as the end region of the outlet arc channel. All other channels are reserved and are sequentially involved in operation when the position of the outlet part of the output electrode changes relative to its inlet part of the output electrode. A possible number of channels is determined based on the design, taking into account the mandatory presence of a wall of a certain thickness between adjacent channels, necessary for effective heat removal deep into the output electrode. At the end of the output electrode, a cone-shaped cavity is made, on the surface of which the holes are located. The holes are connected with the outlet regions of the arc channel. The inlet place of the holes into the outlet regions of the arc channel is determined taking into account the melting point of a specific component of the composite material from which the coating is formed. A refractory component of the composite material can be introduced in the transition area from the inlet region of the arc channel to the initial region of the outlet arc channel. The direction of the initial movement of the powder particles and the plasma flow coincide, so a refractory component will not have a radial component of velocity (relative to the longitudinal axis of the arc channel) and will be in the high-temperature zone for the maximum possible time. All other components of the coating material can be introduced through the holes placed at different distances from the section of the nozzle of the plasma device. The choice of the working channel from the entire set of the channels is made based on the melting point and dimensions of the second component of the composite material. These criteria determine the location of joining the powder line with the arc channel of the plasma device and, accordingly, the choice of one or another reserve region.

The arrangement of channels for feeding powder on the surface of the inner central conical cavity does not require crossing the cooling jacket of the output electrode, because the water cooling of the electrode occurs only on the side of its outer surface.

In case of transition to spraying of another composition of materials, it is possible to replace the channel with one of the reserve ones, which is more suitable for feeding new component of the composite material. In the case of a long-term spraying of one composition, the reserve channels are made identical from the point of view of the place of the powder line location. In this case, the presence of reserve channels allows stabilizing the quality of the coating and increasing the overall life of the device. In order to prevent the deterioration of the quality of the coating and the efficiency of the spraying process when the geometric dimensions and configuration of the arc channel change due to the erosion of the electrode material, the outlet regions of the arc channel are periodically replaced.

CONCLUSIONS

1. The use of plasma generators with a curvilinear arc channel is rational in the case of creating multilayer composite coatings with components that differ sharply in their physical and mechanical characteristics.

2. The complex configuration of the arc channel somewhat limits the range of steady operation of the plasma generator in terms of the arc current and consumption of the plasma-generating gas mixture.

3. The general nature of dependences of the energy characteristics of a plasmatron with a curvilinear arc channel on the basic mode parameters is identical to similar dependencies for traditional plasma generators with a rectilinear arc channel.

4. The influence of operating modes of plasma generators with a curvilinear arc channel on their life characteristics requires further studies in order to establish rational operating modes.

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SUGGESTED CITATION

V.M. Pashchenko (2022) Specialized plasma devices for producing gradient coatings by plasma-powder spraying. *The Paton Welding J.*, **10**, 42–48.

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https://pwj.com.ua/en

Received: 31.08.2022
Accepted: 01.12.2022