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Managing the Composition of the Plasma Flow of the Technological Plasma Sources by Changing the Temperature of the Cathode Working Surface

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The problems of managing the amount of drop fraction in the plasma flow of technological plasma vacuum-arc discharge sources by controlling the changing the cathode surface temperature were considered. The possibilities for regulation and stabilization of cathode surface temperature by cooling the front and the lateral cathode surface were investigated. Designs of cathode assemblies in which the control of temperature of the working surface cathode is exercised by changing the coolant flow rate and by changing distance between the cathode working surface and its cooling area were developed.

Keywords: Plasma source, Vacuum arc, Dripping fraction, Cathode working surface temperature.

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1. INTRODUCTION

The plasma flows generated by the cathode spot of a vacuum-arc discharge are widely used. They are used for production of the nanostructured coatings [1], diamond-like carbon films [2], getter and anti-emission coatings [3] and other.

In papers [2, 4] it was show that the plasma flow of vacuum arc contains a significant amount of the micro-dripping fraction. These micro-drops determine the quality characteristics of coatings. In many cases the presence of micro-drops in the precipitating flow is undesirable. This fraction eliminates by passing plasma flow through separation devices. In other cases, on the contrary, the large amount of micro-dripping fraction is required. Such cases are the production of getter coatings and cathode material powders [2, 5].

The amount of micro-dropping fraction in the plasma flow is determined by the temperature of the cathode working surface (in other equal conditions). So managing the amount of micro-drops is possible by changing the temperature.

The aim of this paper is to investigate the possibilities of changing the temperature of the cathode surface during plasma source operation and the development of plasma sources construction with controlling plasma flow composition.

2. STATE OF THE ISSUE TO THE PRESENT

The investigation of the influence of the integral cathode temperature on the characteristics of the plasma generated by a stationary vacuum-arc discharge (performed in [6]) showed that changing the cathode temperature leads to:

- redistribution of the average energy of the different charge multiplicity ions;
- changing the relative content of ions with lower charge multiplicity;
- changing the amount of dripping fraction in the plasma flow.

It is obvious that such a change of the plasma flow parameters will inevitably influence on the composition and characteristics of the coatings.

The investigation of vacuum arc cathode erosion depending on cathode temperature due to its cooling mode is performed in [2]. The changing of the electrical transfer coefficient μ of the cathode material when cooling conditions deteriorate was ascertained. According to [7] $\mu = \mu_i + \mu_n$, μ_i characterizes the mass loss due to the ions, μ_n – the mass loss due to the expense of the neutral components (micro-drops and vapor). Since μ_i is independent of the discharge current either from the time of its burning, so the change of the μ_i is determined only by μ_n.

In the most constructions of ion-plasma systems (Bulat, NNV, etc.) the cooling of the cathode is performed by using the principle of a constant flow of cooling liquid (usually water). But the application of a constant flow of cooling liquid is ineffective for the following reasons. First of all, in this method cooling liquid consumption calculates from the point of the maximum value of the energy released at the cathode of vacuum arc discharge. This fact leads to increasing the cooling liquid consumption. Secondly, during the operation the length of the cathode rod is constantly decreasing, so its heat resistance also reduces and it leads to appropriate changing of the cathode surface temperature. So the composition of the plasma flow of the plasma source will vary at the beginning and in the end of operation.

For obtaining the reproducible coating composition in the paper [8] was proposed the performing a periodic reducing of the cut diameter in the cathode body near its cooling surface. In this way the temperature of the cathode working surface keeps in a definite range during the cathode operating time. The main disadvantage of this method is the need to disassemble the plasma source cathode assembly after each treatment cycle. This leads to a wasteful expenditure.

For increasing the cathode material reserves in work [9] is proposed to cool the cathode lateral surface and to displace the cathode with its evaporation speed. In this case it is possible to ensure a stable operating temperature of the cathode surface and, as a consequence, a plasma flow with a constant content of the dripping fraction. The possibility of changing the temperature of the cathode working surface in such a plasma source construction is not provided.

3. RESULTS AND DISCUSSION

3.1 The Plasma Source With the Cooling by Butt-end Surface

The heat flux Q enters on the cathode working surface during the operation of the plasma source. This flux might be considered as uniformly distributed due to bypass of the cathode spot across the working surface is in ~ 10^{-2}-10^{-1} s. [6] (Fig. 1). If provide that the lateral cathode surface is adiabatic, the flow Q leads by coolant with the rate q through the non-working end of the cathode.

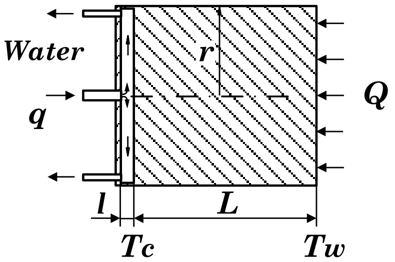

Fig. 1 – The heat flow at the butt-end surfaces of the cathode of vacuum arc discharge during the plasma source operation

The value of Q is determined by the rate of the discharge energy evolved at the cathode. The energy ratio P_a / P_k released at the anode P_a and the cathode P_k in the arc and spark discharges might be bigger or smaller than unity. This ratio is determined by many factors such as type and pressure of the gas, discharge current, its duration, length and others [10, 11]. In the first approximation we can assume that $P_a = P_k$ and energy losses by emission are equal to about 20 % of the general discharge capacity.

During the plasma source operation in a certain mode $Q = const$ so the density of the heat flux $q_c = Q / S_c$, where S_c – area of the cathode working surface (also constant). From the theory of thermal conductivity

$$q_c = (T_w - T_c) / R\,, \qquad (1)$$

where T_w – cathode working surface temperature; T_c – the temperature of its cooling surface; R – the cathode thermal resistance which equal to, where L – the length of the cathode; λ – thermal $R = L / \lambda$ conduction coefficient of the cathode material.

In existing constructions of plasma sources with a rod cathode the reduction of the cathode length L results in a reduction of its thermal resistance R and, according to (1), leads to reducing the temperature difference $T_w - T_c$ (while $q_c = const$). As the temperature of cooling surface T_c is practically constant the temperature of cathode working surface T_w will be changing. T_w might be fixed by one of the following methods:

- by increasing the temperature of the cathode cooling surface T_c while the q_c is constant;
- by increasing the heat flux Q on the cathode working surface while the temperature of cooling end-butt surface T_c is constant.

The first method is limited by the range of possible changes of coolant temperature which determines the temperature of cathode cooled surface T_c and usually leads in the range ~ 293-353 K. The lower limit of this range is specified by the temperature of the cooling water and the upper – by the operating temperature of gasket material (for example, vacuum rubber 9024 (black) has a maximum operating temperature for about 80 ºC [12]) and the water boiling temperature. In any case this range is much smaller than the temperature range of the cathode working surface T_w the due to the change of thermal resistance R.

The second method has greater capabilities and is associated with the increasing of vacuum arc discharge capacity P. This parameter is defined as $P = U{\cdot}I$, where U – discharge voltage; I – arc current. The arc voltage practically doesn't vary during the increasing arc current, so the increasing the energy released in the discharge could be achieved by increasing the current in the arc discharge. The range of current I is limited by the minimum current of existence of a vacuum arc cathode spot and by the abilities of discharge supply and of the plasma source cooling system. The restrictions of the current discharge range might be imposed by the process requirements.

The construction of a plasma source with an upgraded cathode assembly and butt-end cathode cooling system is shown in Fig. 2. The main difference of this assembly is the control of the coolant temperature by a sensor 12 and 13 (thermocouples). The signal from the sensor 13 about the water temperature at the outlet of the cooling system is able to stabilize this temperature at a predetermined level (by controlling the flow rate through the valve 6 managed by PID regulators of the control unit 9).

The construction of the cathode cooling systems has limited opportunities for managing the temperature of its working surface. It is related to a small variation range of temperature of the cathode cooling surface T_c. The increased heat flow to the cathode (occurred by increasing the cathode working surface temperature while the current of arc discharge growths) is outputted to the cooling system by increasing the coolant flow.

It should be noted the operating costs reducing and high efficiency of application of the temperature control of cooling liquid with at the same time the flow managing through the cooling zone. The usage of this system allows does not consume the cooling liquid at the initial moment of the plasma source operation. In this way the coolant consumption reduces and the time for providing the cathode operation mode also reduce. Graphs illustrating the change of the coolant temperature T and its distribution q are shown in Fig. 3. Small increases of coolant flow q during operation associated with an increasing the heat flow which comes to the cooling zone during the cathode operation.

The time t_1 (Fig. 3) for the cathode plasma source of system "Bulat-6" for it warms up to 353 K is about 21 seconds. The delay of coolant supply allows economize about 16,200 liters of coolant in a year for one plasma source (the process duration is about 1800 seconds with two shifts working). The similar solution for the other cooling assembles of ion-plasma sources (for example, a diffusion pump) allows to significantly reducing of the cooling liquid consumption and, consequently, to increase the efficiency.

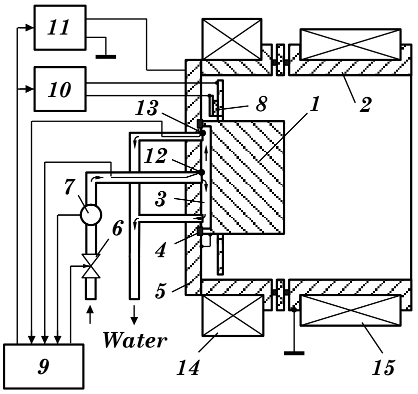

Fig. 2 – The plasma source with temperature control in the cooling zone of the cathode: 1 – cathode; 2 – anode; 3 - cooling zone; 4 – seal; 5 – flange; 6 – operated valve; 7 - water meter; 8 – ignition; 9 – control system; 10 – power supply unit; 11 – ignition unit; 12, 13 – thermocouples; 14, 15 – solenoids

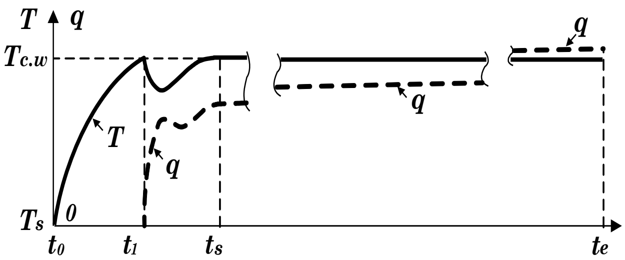

Fig. 3 – The changing coolant temperature T and its flow rate q during operation of the plasma source without the initial flow

3.2 The Plasma Source with the Cooling by Lateral Surface

Systems with the cathode cooling by lateral surface have more opportunities for the temperature control of the cathode working surface. In this case the reducing of the cathode thermal resistance R is easy to recover by moving the cathode. This permanent movement provides an unchanged working length between the cathode working surface and its cooling zone.

The plasma source with the cathode cooling by lateral surface is shown in Fig. 4.

The temperature of the cathode working surface T_w in the source plasma of such construction could be varied in the range $T_{min} \div T_{max}$. Tw is set by the distance L between the cathode working surface and the zone cooling. This distance could vary in the range of $L_{min} \leq L < L_{max}$. The minimum distance between the cathode working surface and the beginning of the cooling zone L_{min} is determined by the construction of the cathode assembly. Generally, the maximum distance between the cathode working surface and the beginning of the cooling zone L_{max} (for cathodes that are made from low-melting materials) is restricted by the condition $T_w < T_m$, where T_m – melting temperature of the cathode material. In the case when the cathode is made from refractory metals L_{max} is limited by the condition $T_w < T_t$, where T_t – cathode surface temperature at which the arc mode transits to the thermoemission mode.

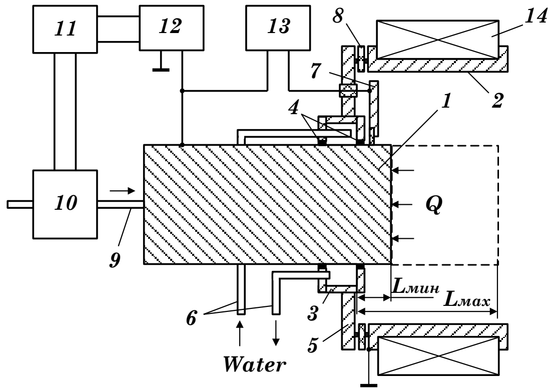

Fig. 4 – The plasma source with the cathode cooling by its lateral surface: 1 – cathode; 2 – anode; 3 – cooling zone; 4 – seal; 5 – flange; 6 – tubes; 7 – ignition; 8 – insulator; 9 – shaft; 10 – drive; 11 – control system; 12 – power supply unit; 13 – ignition block; 14 – solenoid

At the cathode working temperature T_{min} there are the minimum contains of microdroplets in the plasma flow. The increasing distance L between the cathode working surface and the beginning of cooling zone leads to increasing the cathode working surface temperature with a corresponding increasing the amount of microdripping fractions in a plasma flow. The maximum amount of droplets contains in the flow when the distance between the cathode working surface and the beginning of the cooling zone L_{max} and when the maximum value of T_w is achieved. So, changing the distance between the cathode working surface and the cooling area it is possible to adjust the temperature of the cathode working surface and the content of microdroplets in the plasma flow.

It is necessary to maintain a distance between the cathode working surface and the beginning of its cooling zone to keep the cathode surface temperature at a constant level during the operation of plasma source with cathode lateral cooling surface. This is possible by moving the cathode at a rate equal to the rate of its erosion.

It is known that the amount of cathode material m that evaporated by cathode vacuum arc spot is defined as

$$m = \mu \cdot I \cdot t , \qquad (2)$$

where t – time of the discharge existence. The mass loss occurs on the cathode working surface area S, the cathode is made from a material with density ρ, and for the time t the cathode layer evaporation ΔL will occur. Then (2) ΔL is

$$\Delta L = \frac{\mu \cdot I \cdot t}{S \cdot \rho} . \qquad (3)$$

According to (3) the evaporation speed of cathode material is defined as

$$V = \frac{\mu \cdot I}{S \cdot \rho} . \qquad (4)$$

The evaporation speed of the cathode material V might be determined from the relation (4). It will be different at different temperatures of the cathode working surface as the electron transport coefficient μ will change. According to the experimental data given in [2] the value of μ is a function of cathode cooling and changes more than in four times (from 39 to 210 mg/C). So keeping $L = const$ the speed of the cathode displacement must be different- lesser and greater at L_{min} at L_{max} (at different distances L between the cathode working surface and the beginning of its cooling).

If the cathode movement speed will not correspond to it during predetermined distance L, there will be variation in the distance L to the point at which the rate of erosion and speed are equal. This fact could be a criterion for the correctness of setting the μ value in determining the velocity of the cathode displacement by the relation (4).

We also should note the following. With increasing the temperature of the cathode surface the radiation losses non-linearly increases and become significant at temperature T_w. Therefore (and due to increasing the lateral surface area with increasing distance L) the dependence $T_w = f(L)$ is non-linear.

With a plasma source constructed as in Fig. 4 two series of experiments were carried out to obtain the coatings: with a minimum of dropping fraction at $L_{min} = 10^{-2}$ m and with a maximum of dropping fraction at $L_{max} = 7 \cdot 10^{-2}$ m. Such values of the distances L during operating the plasma source correspond to titanium cathode electron transport coefficients $\mu = 37$ mg/C at $L = 10^{-2}$ m and $\mu = 148$ mg/C at $L = 7 \cdot 10^{-2}$ m.

Moving the cathode in the cycles of coating deposition was carried out using stem 9 (Fig. 4), actuated by stepper motor 10 based on the engine ShD-5D1M. Velocity of the cathode 1 (number of pulses on the stepper drive 10 per time) was determined from the equation (4) in the drive control system 11 where the data were carried preliminary: the working area of the cathode surface S, electron transport coefficient μ of the cathode material and the density ρ of the cathode material. The signal magnitude of vacuum arc current I was outputted from the arc power supply 12. Time for coating deposition on the steel plate made from steel $Cr_{18}Ni_9Ti$ (20 × 20 × 2 mm) was 30 min.

The speed of movement of the cathode 1 was about 2.5 microns for 10 seconds when $L = 10^{-2}$ m and 10 microns for 10 seconds when $L = 7 \cdot 10^{-2}$ m. After a total duration of cathode usage for 2.5 hours in each series of measurements it was showed that the pre-set distance between the working surface of the cathode 1 and its cooling area L_{min} did not changed.

Specimens (10 items) processed in different modes were studied using electron microscope SEM-106. Coating on the samples (5 items) obtained when the distance between the cathode working surface and the beginning of its cooling zone was $L = 10^{-2}$ m are characterized by low surface roughness. This is caused by small amount of microdrops. Coating on the samples (5 items) obtained when the distance between the cathode working surface and the beginning of its cooling zone was $L = 7 \cdot 10^{-2}$ m have a high roughness due to big amount of microdroplets present on the surface. Transverse sections for both samples showed uniformity of coating composition.

In plasma source with cathode lateral cooling surface it is possible to change the temperature of the cathode surface directly during the deposition process. This change might be done by changing the distance between the cathode working surface and the cooling zone (by a stepping drive according to a predetermined program).

4. CONCLUSIONS

The results obtained in this paper could be summarized as follows:

- the changes of the dripping fraction amount in plasma flow of vacuum arc plasma source could be performed by changing the temperature of the cathode surface;
- the parameters determining the temperature of the cathode working surface are: the density of heat flow from a discharge to the working surface of the cathode; the thermal resistance of the cathode that is determined by the distance between the cathode working surface and its cooling area; the temperature of the cathode cooling surface;
- in the construction of the plasma source with the cooling of the butt-end cathode surface the restricted cathode surface temperature control is able by changing the temperature of cooling cathode butt-end. The application of the temperature control of cooling liquid and at the same time control of its flow through the cooling zone could significantly reduce the operating costs;
- the plasma source with the cathode cooling by lateral surface allows to change the temperature of the cathode working surface over a wide range by varying the distance between the cathode working surface and the cooling area. The stabilization of the set temperature of the cathode surface is maintained by setting the distance between the cathode working surface and the cooling area (by moving the cathode with a speed equal to the speed of cathode material evaporation;
- the plasma source with the cathode cooling by lateral surface the changing of the changing of the cathode working surface temperature is able during the deposition process by changing the distance between the cathode working surface and the cooling area (according to a predetermined program).

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