Interaction of the metal plasma flows with surfaces of complex geometric shapes

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Abstract. The features of coating formation using vacuum-arc discharge plasma on the inner surface of a cylindrical cavity with transverse ribs in the form of a diaphragm are considered. The mathematical model is developed and expressions for calculation of thickness of coatings are received. The effect of the diaphragm on the thickness distribution and uniformity of the coating is shown. Compression areas directly in front of the barrier affecting the coating deposition rate were found.

During the formation of coatings using vacuum-arc evaporators, metal plasma flows with velocities of the order of $10^4$–$10^5$ m/s and above are formed. Such high speeds determine the peculiarities of interaction of flows with the treated surfaces of complex geometric shapes. This is especially true if the product has hard-to-reach areas in the form of holes and parts that cover the areas for coating deposition [1]. As an example, we can consider a cylindrical cavity with transverse diaphragms inside. This design is typical for anodes of high-power generator lamps (figure 1). In this case, the coating is applied only to the inner surface.

Figure 1. Photographs of the cathode of a cylindrical vacuum-arc evaporator.

Let us consider the penetration of the plasma flow into an open cylindrical conducting cavity (without diaphragms). We assume that the cavity wall is given a negative (relative to the plasma) bias voltage,
for which the saturation current of ions exiting the plasma flow is observed on the cavity wall (the actual displacement ≈100 V and more corresponds to this assumption). We also assume that the axis of symmetry of the cavity (z-axis) is directed parallel to the flow velocity vector.

The dependence of the thickness of coatings applied to such cavities on the z coordinate is described by the following mathematical model based on the balance equation:

\[ I_0 = I(z) + 2\pi r_0 \int_0^z j_{i}(z)dz; \]

\[ I(z) = \pi r_0^2 e \langle n_i(z) \rangle; \quad I_0 = I(z = 0); \]

\[ j_i(z) = 0.5e\overline{z}v_{i0}n_\delta(z); \quad v_{i0} = (kT_i/M_i)^{1/2}; \]

where \( I_0 \) – ion current at the entrance to the cavity; \( j_i \) – ion current density; \( n_i \) – ion concentration; \( \overline{z} \) – average charge number of ions (depends mainly on the cathode material); \( e \) – the elementary charge; \( n_\delta \) – ion concentration in the plasma at the boundary with the cavity walls; \( k \) – Boltzmann constant; \( T_e \) – temperature of the electronic component of the plasma; \( M_i \) – ion mass; \( v_{pl} \) – velocity of the homogeneous plasma flow at the entrance to the cavity; \( r_0 \) – radius of the cylindrical cavity; \( v_{i0} \) – ion sound velocity in the plasma.

The solution of the system of equations allows to obtain:

\[ n_i(z) = n_\theta \exp \left( -\left( \frac{kT_i/M_i}{v_{pl}} \right)^{1/2} \frac{z}{r_0} \right), \]

where \( n_\theta = n_i(z = 0) \) – concentration of ions in the plasma flow at the entrance to the cavity.

From the point of view of the quality of the coating applied to the inner walls of the cavity, its thickness and uniformity is very important. The thickness of the coating \( \delta \) and its unevenness will depend entirely on the growth rate of the coating \( v_\delta \approx j_i/e n_\theta \), where \( n_\theta \) – concentration of atoms in the deposited coating. Thus, on the basis of the above:

\[ \frac{\delta(z)}{\delta_0} = \frac{v_{\delta}(z)}{v_{\delta}(z = 0)} = \frac{j_i(z)}{j_{i\theta}} = \frac{n_i(z)}{n_\theta} = \exp \left( -\left( \frac{kT_i/M_i}{v_{pl}} \right)^{1/2} \frac{z}{r_0} \right), \]

where \( \delta_0 = \delta(z = 0) \) – thickness of the coating at the entrance to the cavity.

Based on the results obtained, it can be stated that \( \delta(z)/\delta_0 \) is virtually independent of the cavity geometry and the magnitude of the negative bias, if the ion current enters the saturation mode. In accordance with the results of calculations and measurements, the relative thickness drop is determined almost entirely by the ratio between the ion sound velocity in the plasma \( v_{i0} \) and the plasma flow velocity. Data on \( T_e \) and \( v_{pl} \) were determined using the probe technique \( (T_e \approx 3.5 \cdot 10^4 \text{ K}, v_{pl} \approx 2 \cdot 10^4 \text{ m/s}) \).

Let us consider a cylindrical cavity with a diaphragm at the entrance (Figure 1, right). The diaphragm is a disc with an outer radius \( r_0 \) with a hole in the center of the disc with a radius of \( r_e \). In this case, a similar mathematical model (1–3) was used to determine the features of deposition of coatings from the metal plasma flow to the inner walls of the cylindrical cavity.

In addition to the relations (1–3), it is necessary to add features of the flow around the barrier by a supersonic plasma flow. The meaning of this feature is that after interaction with the barrier, the flow expands behind it with the ion-sound speed [2]. The angle of expansion (\( \alpha \)) is determined by the ratio

\[ \tan \alpha = v_{i0}/v_{pl}. \]

This expression allows calculating the coordinate \( z_k \) of the touch of the expanded after the diaphragm flow with a wall:

\[ z_k = (r_0 - r_e)v_{pl}/v_{i0}. \]
After the contact of the flow with the wall occurs, the mathematical model (1–3) becomes fair and at \( z > z_k \) we can expect an exponential dependence of the coating thickness on the longitudinal coordinate, similar to the dependence (5):

\[
\frac{\delta(z)}{\delta(z_k)} = \exp \left[ -\frac{v_k(z-z_k)}{v_{pl}^0} \right] \quad \text{for} \quad z \geq z_k.
\]  

(8)

To the equations (7) and (8) it is necessary to add a condition that allows to determine \( \delta(z_k) \) through the parameters of the plasma flow at the inlet of the cavity with the diaphragm. To solve this problem it is necessary to calculate the integral \( \int_0^\infty j_i(z)dz \) for \( z < z_k \). This calculation is complicated, since it is necessary to know the expression for \( j_i(z) \) in the case when the flow does not touch the wall, as for \( z > z_k \), but is separated from it by a vacuum gap and ions enter it with initial velocities in the radial direction. Simplifies the situation the fact that in this case in the first approximation can be neglected ions leaving to the wall at \( z < z_k \). Then

\[
j_i(z_k) = n_i(z=0) \frac{r^2}{r_0^2}; \quad \delta(z_k) = \delta(z=0) \frac{r^2}{r_0^2}.
\]  

(9)

The results of the experimental study of coatings showed that the thickness distribution on the inner wall of the cavity with the diaphragm has the form shown in figure 2. The position of the maximum \( z_k \) and the subsequent decline are satisfactorily described by the relations (7) and (8). Dependence to the right of the maximum in figure 2 corresponds to the exponent (8).

Studies have shown that a coating is also formed after the diaphragm to the boundary of the plasma contact with the surface. The formation of the coating in this case is associated with the extraction of the ion component of the flow from the plasma boundary to the treated surface under the action of an electric field. In this case, only the ion component drifts through a kind of vacuum gap. The dependence of the thickness of the coating on the bias voltage on the substrate on which the coating is formed by ions coming from the plasma boundary through the vacuum gap is obtained on a model specially made for the study of this process. When titanium is applied, the coating thickness increases with increasing bias voltage and decreases only from a voltage of approximately 150 V. That is, only at this voltage the process of spraying the surface with titanium ions begins to prevail over the growth of the coating.

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**Figure 2.** Distribution of the coating thickness on the inner surface of a cylindrical cavity with a diaphragm at the entrance to the cavity.
The case of a cylindrical cavity completely closed at the outlet at a distance $z$ from the inlet was also analyzed. The analysis showed that the thickness $\delta_g(z)$ of the coating averaged over the bottom of the cavity should depend on its arguments as follows:

$$\frac{\delta_g(z)}{\delta_g(z=0)} = \exp\left( -\frac{v_m \cdot z}{v_pl \cdot r_0} \right).$$  (10)

The measured values of $\delta_g(z)$ under the previously noted experimental conditions confirmed that the formula (10) is valid.

In the study of the process of transporting plasma flow through cylindrical cavities with diaphragms or barriers in the flow path (figure 1, left) compression areas directly in front of the barrier were detected. These areas are characterized by an increased concentration of ions and neutral vapor, which leads to a sharp increase in the thickness of the coating on the horizontal portions of the cavity in front of the barrier. Figure 3 shows the relative distribution of the coating thickness along the cavity for different ratios of the aperture diameter $d$ to the cavity diameter $D$ for a cylindrical cavity with a diaphragm on the output. In case of the absence of a diaphragm (curve 5), the distribution obeys the expression (5).

![Figure 3. Distribution of the coating thickness on the wall of the cavity in front of the diaphragm.](image)

The detected compression areas have a relatively short length and are not detected at a distance of 3–4 cm from the surface of the barrier. The coefficient of plasma compression directly at the barrier has a value of about 10. Thus, artificially creating obstacles in the way of the plasma flow, it is possible to significantly increase the speed of coating formation on horizontal or hard-to-reach areas of the surface. The compression layers were considered in the development of technology of deposition coatings on the chamber anodes of generator lamps. Using mobile barriers the uniformity of the coating, including on products of complex shape, can be controlled.

References
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[2] Kuznetsov V G 2007 Vacuum technique and technology 4 297–9