Structure of the mathematical model of applying wear-resistant coatings by a high-frequency induction plasma of low pressure

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Annotation. In this scientific work, we proposed a scheme for the transformation of a physical model of applying the HFI plasma coating to a mathematical one in a mathematical way by stepwise solving the problems of the structural model stages. The equations of conservation of energy of the electron gas, Maxwell, continuity and momentum will be used. It is planned to develop a mathematical model for sputtering dielectric and metallic materials. In this case, boundary conditions will be introduced for the discharge power, flow rate and gas types, pressure and design parameters of the plasma torch.

1. Introduction.

At the present stage of scientific and technological development, traditional manufacturing techniques for demanded and competitive products have exhausted their capabilities in terms of reliability and resource. Many find a way out here in the use of coating technologies on surfaces of parts with special properties based on the use of concentrated energy flows. Concentrated energy fluxes can be in the form of electron beam, laser radiation, plasma, electric-spark, vibro-arc and ion effects. But for all of them in general is the presence of a plasma environment. Plasma dusting is one of the promising technological solutions for hardening, wear-resistant, restorative, protective and decorative coatings.

As is known, the main factors influencing the obtaining of the physicomechanical properties of coatings are the thermal, gas-dynamic, and energy characteristics of a plasma. Therefore, depending on the need to obtain the physicomechanical properties of the coatings, the choice of the discharge and its source is made.

Today there are many publications on the use of plasma to obtain various coatings with special properties in theoretical and practical terms [1 - 5]. In this direction there are a number of publications one of the authors of this material [6 - 10]. The plasma coating process consists of two parts: the first part is associated with plasma-chemical processes occurring in the plasma itself, and the second part is the transportation of sputtered particles of the applied material to the surface of the substrate. Therefore, the development of a mathematical model of plasma spraying is a difficult task. As a consequence, this paper proposes the development of a structural mathematical model for the application of wear-resistant coatings of high-frequency induction (HFI) low-pressure plasma.
Unlike the arc discharge, the HFI discharge does not have any contamination. In the arc discharge there are products of erosion of the electrodes of the arc plasma torch, which will be in the applied coating. The high-frequency induction plasmatron is electrodeless. At the same time, these discharges have the same maximum total temperature of the order of 10,000 °C. When a gas is blown through the discharge, we obtain a plasma jet for transporting the evaporated particles of material. At low pressures of the order of 1–10 Pa, the plasma jet is significantly longer than the jet at atmospheric pressure. This allows you to have zones in the plasma with a total temperature of the order of 100 – 200 °C, which do not affect the state of the substrate. But at the same time, the temperature of the electrons in the plasma jet is 2 orders of magnitude higher than the average plasma temperature. This allows you to prepare the surface of the substrate prior to the coating process: cleaning it of all kinds of contaminants and heating it to a certain temperature. In the process of coating formation due to electron bombardment, it is possible to additionally strengthen the coating and rid it of various impurities.

2. Materials and research methods.

For research, the HFI plasma torch with an inductor of a copper tube with a diameter of 12 mm was used. The number of turns of the inductor - 3, internal diameter - 60 mm, height - 46 mm. A quartz tube with an inner diameter of 24 mm and a length of 300 mm served as the discharge chamber of the plasma torch. The outer diameter of the cooling jacket is 40 mm. The sprayed material was a quartz rod with a diameter of 2 mm. The experiments were carried out in a vacuum chamber at pressures of 10 - 100 Pa. Research equipment: diffractograph URS-50M, installation of electron-paramagnetic resonance RE-1301, infrared spectrometer UR-20, interferometer MII-4, device SM-55, device PMT-3, laser stand GOS-300.

3. Results and discussion.

The technological process of coating was carried out as follows: a quartz rod was chosen for spraying, it was injected into a plasma clot, sprayed to an atomic state and transported to the surface of the substrate. One of the sputtering modes: the discharge power is 2.5 kW, the plasma gas (argon) consumption is 0.1 g/s, the chamber pressure is 80 Pa, the distance from the end of the plasma torch to the inductor is 125 mm, the length of the plasma jet, starting from the end of the plasma torch (in the absence of the substrate) - 150 mm. The zone in the plasma jet, in which colorless transparent coatings could be obtained, was in the interval of 60–70 mm along the jet axis.

In the course of the study, a physical model of deposition of the plasma under consideration was developed. It is presented in figure 1. At various distances from the plasma torch nozzle the substrate was placed and its type was determined by the color of the coat.

![Figure 1](image-url)
follows from the figure that sputtering of quartz leads to dissociation of $SiO_2$ molecules. In the discharge and the plasma jet, near the discharge, silicon and oxygen atoms are present. The presence of $Si$ is indicated by brown coat on the rod. With distance from the discharge in the direction of plasma motion, the formation of $SiO$ (black coating) first takes place, and then $SiO_2$ (colorless transparent coatings). The main results of studies of applied coatings of silicon dioxide HFI - low-pressure plasma are presented in tabular form (Table. 1).

Table 1. The results of studies of deposited silicon dioxide coatings HFI low-pressure plasma

| Substrate material | Copper, steel, platinum-iridium, aluminum, glass of various grades, sitall ST 50-1 |
|--------------------|----------------------------------------------------------------------------------|
| The diameter of the substrate | Up to 70 mm |
| Coating structure | Uniform, the presence of $SiO_2$ molecules only. Molecules $SiO$, $HO$ and $H_2O$ - absent |
| Coating type | Dielectric |
| Coat growth rate | Up to 1 micron/min |
| Coating thickness | Up to 20 microns |
| The uneven thickness of the coating on the substrate | Not more than 0.5% |
| The coating strength is normal HO 3611-81 | Especially strong, allowing use in field conditions |
| Microhardness | More than 20 GPa |
| Coating strength | 3 or more times higher than the destruction threshold of other vacuum coatings |

The structure and composition of thin coats depends not only on the state of the transported particles to the surface, but also on the temperature of the substrate. In this case, it is determined by the temperature field of the plasma jet. The maximum plasma temperature in the study area is located in the center of the jet and decreases sharply to the periphery. With the introduction of the substrate into the plasma jet, it begins to bathe the surface and the redistribution of the radial component of the plasma temperature occurs. Studies have shown that with the introduction of the substrate into the plasma jet, the temperature of the jet over the cross section is aligned and practically the coating on the surface occurs under the same temperature conditions. Therefore, the structure of the sprayed coat over the entire surface of the substrate does not change. This is of great importance from the point of view of obtaining a coat that is homogeneous in physicochemical properties.

The authors' task was to transform the physical model of applying HFI coatings with low-pressure plasma into a mathematical one. As a result of the research, we will obtain output factors (parameters): stoichiometry ST, type of coating TC, porosity Pr, and utilization rate of the material URM. The input
factors (parameters) are: the input power into the discharge \( W \), the type, composition and consumption of the plasma-forming gas \( G \), the pressure \( P \), the type and grade of the sprayed material \( M \), the design parameters of the plasma torch \( DP \). To build a mathematical model of the plasma spraying process, its main stages were singled out:

1). According to the design parameters of the plasma torch, the values of discharge power, plasma gas flow and pressure, we calculate the specific enthalpy of gas per unit time \( H_{u0} \) at the nozzle exit

\[
H_{u0} = \frac{W - Q}{\rho},
\]

where \( W \) is the input power in the discharge, \( J/s \); \( Q \) is the heat loss of the plasma torch to cool the walls and radiation per unit time, \( J/s \); \( G \) - consumption of plasma gas or mixture gas, \( kg \).

2). Calculate the temperature \( T_0 \) and the jet velocity \( v_0 \).

In this case, we use the equations for the conservation of energy of the electron gas

\[
en_e b_e E^2 = \frac{3}{2} k (T_e - T_a) \frac{2m_e n_e}{m_a T_e} + \alpha_e n_e n_i U_i
\]

and Maxwell's equations

\[
\text{rot} \; \vec{H} = j
\]

\[
\text{rot} \; \vec{E} = -\mu_0 \frac{d\vec{H}}{dt}
\]

where \( e \) is the electron charge, \( n_e \) is the electron concentration, \( b_e \) is the electron mobility, \( E \) is the electric field strength, \( k \) is the Boltzmann constant, \( T_e \) is the temperature of the electron gas, \( T_a \) is the temperature of heavy gas particles, \( m_e \) is the mass of argon atom , \( \tau_e \) is the time interval between two collisions of an electron with gas atoms, \( \alpha_e \) is the electron ionization rate constant of gas, \( n_e \) is the concentration of atoms, \( U_i \) is the ionization potential, \( H \) is the magnetic field strength, \( j \) is the current density, \( \mu \) is the relative magnetic permeability, \( \mu_0 \) is the magnetic constant, \( \mu_0 = 4 \times 10^{-7} \; Gn \cdot m^{-1} \), \( \frac{d\vec{H}}{dt} \) is the time derivative of the magnetic field strength.

Here:

\[
\tau_e = \frac{\lambda_e}{v_e}, \quad v_e = \left( \frac{8kT_e}{\pi m_e} \right)^{0.5}, \quad \lambda_e = \frac{1}{n_a Q_{ae}},
\]

where \( \lambda_e \) is the mean free path of an electron, \( v_e \) is the speed of thermal motion of an electron, \( Q_{ae} \) is the effective cross section for elastic scattering of electrons by gas atoms.

In addition, we take into account the continuity and momentum equations:

\[
\frac{1}{r} \frac{\partial}{\partial r} (r \rho v \frac{\partial v}{\partial r}) + \frac{\partial}{\partial z} (\rho u \frac{\partial u}{\partial z}) = \frac{\partial p}{\partial z} + 2 \frac{\partial}{\partial z} \left( \mu u \frac{\partial u}{\partial z} + \frac{1}{\tau_e} \frac{\partial (\mu u + \mu v)}{\partial z} \right) + \rho g
\]

\[
\rho \left( \frac{\partial v}{\partial r} + u \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial r} + \frac{2}{r} \frac{\partial}{\partial r} \left[ \mu v \frac{\partial v}{\partial r} + \frac{\partial}{\partial z} \left( \mu u \frac{\partial u}{\partial z} + \frac{\partial v}{\partial z} \right) \right] - \frac{2 \mu v}{r^2} + \xi \sigma E_{th} H_z \cos \chi
\]

where \( v, u \) are axial and radial velocities, \( p, \rho \) are plasma pressure and density, \( \mu \) is viscosity, \( \xi \) is free space permeability, \( E_{th} \) is induced electric field strength, \( H_z \) is the projection of magnetic field strength, \( \chi \) is the phase angle between them.

3). Calculate the temperature \( T_e(x) \) and the jet velocity \( v_e(x) \) at different distances from the plasma torch nozzle section using the equations [1]:
\[ T_S(x) = \frac{0.745T_0}{\left[\frac{(0.55C_0(x - 1.5x_n))T_0}{R_cT_\infty} + 1\right]^{2/3}} \]

\[ v_S(x) = \frac{v}{\left[\frac{(0.55C_0(x - 1.5x_n))T_0}{R_cT_\infty} + 1\right]^{2/3}} \]

where \( T_\infty \) is the ambient temperature; \( x_n \) - the length of the initial section of the jet; \( T_0 \) is the jet temperature on the axis on the length \( x_n \); \( C_0 \) is an experimental constant equal to 0.01 for argon and 0.001 for nitrogen (for an argon-nitrogen jet it varies linearly from 0.01 to 0.001, depending on the mass content of nitrogen in the mixture). The length of the initial part of the jet \( x_n \), in the core of which the jet temperature and jet velocity are equal to the values at the plasma torch cut, are found by jointly solving integral relations of the laws of conservation of momentum and energy and the equation of state of the gas.

4). Choose the composition of the plasma gas.

5). Calculate the speed of sprayed particles \( v_p(x) \).

\[ \rho_p \frac{dv_p}{dt} = 0.75C_d\rho_n \frac{(v_n - v_p)^2}{d_p} \]

where \( \rho_n, v_n, d_n \) - density, speed and diameter of particles, respectively; \( \rho_n, v_n \) are the density and velocity of the plasma jet, respectively; \( C_d \) - coefficient of hydrodynamic resistance.

6). Calculate the temperature of the particles \( T_p(x) \).

\[ T_p(x) = T - e^{\frac{6Nu\lambda v_p}{\rho_p\delta^2 cp} + const} \]

where \( \lambda \) is the coefficient of thermal conductivity, W/mK; \( C_p \) is the heat capacity; \( \tau \) is the time of motion of particles. \( Nu \) is the Nusselt number.

7). We determine the type of coating TC and find the dependencies of the porosity \( Pr \) and the composition (stoichiometry) of the ST coating, as well as the utilization rate of the material \( URM \) on the temperature and velocity of particles for different distances from the plasma torch nozzle section.

The sequence of calculations as follows (Fig. 2).

4. Conclusions

1. It is shown that the transformation of a physical model of a high-pressure HFI coating processes to a mathematical one is possible by stepwise solution of the tasks of the structural model stages.

2. A mathematical model is planned to be developed for spraying both dielectric and metallic materials. In this case, boundary conditions will be introduced for the discharge power, flow rate and gas types, pressure and design parameters of the plasma torch.
Figure 2. The structure of the mathematical model of the application of wear-resistant coatings high-frequency induction plasma of low pressure

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