THE EVALUATION OF THE THICKNESS OF FUNCTIONAL COATINGS OBTAINED BY THE ION-PLASMA METHOD

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Abstract. *In the paper represented a mathematical model of the spray particles distribution on the substrate surface for a magnetron sputtering system, and on this basis calculated thickness of the aluminium and nickel coatings. The calculation took into account the distance from the evaporator to the substrate, the mass and density of the coating material. Furthermore, it was considered several options for calculating the coating thickness, depending on the physical mechanism of the spraying process.*
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The technology of applying thin films for various purposes in a vacuum environment has become widespread in the intensively developing modern industry, in particular, microelectronics, optical industry, mechanical engineering and instrumentation, due to the fact that, in comparison with other known methods of applying functional coatings, it makes it possible to obtain coatings from almost all metals and alloys. The possibility of obtaining a coating on products from polymer bases without changing their original dimensions and properties, and, importantly, coatings obtained by the vacuum-magnetron method are distinguished by a high degree of purity, which is ensured by efficient air evacuation and low pressure in the vacuum chamber, as well as high speed precipitation of evaporating substances, which can significantly improve the consumer properties of products, which is the most relevant and in demand today.

For the development of technological processes for applying functional coatings in vacuum, it is important to determine and predict such fundamental factors as coating thickness. The presence of the coating thickness largely determines the operational properties of products with coatings. In turn, the coating thickness is regulated by such technological parameters as: distance from the evaporator to the substrate; mass and density of the deposited material on a flat (uneven) substrate under various modes (electrical, technological parameters; design features of the installation and sputtering system) of the operation of the magnetron sputtering installation. Ensuring obtaining a high-quality coating on products depends on a pre-planned (predictable) and scientifically substantiated technological process of coating application. Therefore, the prediction of the design parameters of protective coatings and, on this basis, the development of technologies for the formation of coatings is an urgent task.

The purpose of this work is to develop a mathematical model and algorithm for a software product that allows calculating the thickness of vacuum functional coatings for given technological parameters. The objectives of the work are to determine the thickness of vacuum coatings based on Al and Cr obtained by magnetron sputtering.

The calculation of the coating thickness using scanning microscopes and micro interferometers requires complex and expensive equipment, which is not always justified in production or is practically impossible due to the properties of the metals (hard alloys) used. The development of calculation programs for diagnostics and automatic determination of the thickness of vacuum coatings over the entire area of the product will, firstly, reduce the time and costs for determining the thickness of coatings, secondly, preliminarily, upon request, determine the technological modes of the installation, and thirdly, optimize the thickness and properties coatings.

Determining the thickness of coatings in the cycle of the technological process is one of the important parameters that determines the operational properties of a product with a functional coating. This scientific problem is always relevant in the modernizing sphere of production, science and is of interest to many process engineers, research scientists around the world. The question is what should be the optimal thickness of the coating based on the functional purpose, the uniformity of thickness over the entire surface of the workpiece and how the thickness affects the physical and mechanical, chemical properties and adhesive strength of the coating, as well as many other tasks that scientists and researchers periodically face. The thickness of the coatings depends on many factors, is multivariable. It can be designing features, electrical parameters of the vacuum unit, modes of the technological process of coating formation, and the physical properties of the sprayed chemical elements, etc. details. The influence of the location, dimensions and configuration of the workpiece, as well as the loading of the vacuum chamber (the number of parts and their location in the chamber) has been studied.

Given the above, it is noted that the effect of vacuum ion-plasma coating on the part error is determined by the following reasons: part heating, coating thickness error, presence of residual stresses in the coating, coating thickness variation over the entire surface of the part [1-3]. The accuracy of the shape of cylindrical parts, the error of the coating thickness, depending on the size of the area of the hardened parts, were studied. When applying the TiN coating, the cylindrical bushings were arranged parallel and perpendicular to the plasma flow. It is noted that when coatings are applied to cylindrical surfaces that are parallel to the flow axis, there is a deviation of the profile of the longitudinal section - cone shape, and when the cylindrical surface is located perpendicular to the flow, the error will be the deviation of the profile of the longitudinal section - barrel shape. It is shown that the deviation of the part shape (ovality) after coating is equal to the initial ovality of the part, and the error in the thickness of ion-plasma coatings depends on the number of parts installed on the holder and their location [1]. However, it should be noted that the influence of the substrate shape on the uniformity of coatings is not considered in the article. As you know, in modern technology, parts of various shapes of double and triple curvature are often used. Also, in the reviewed work, the fact that a group of parts is located at different distances from the source of evaporation has not been studied, since in practice it is often used just such an arrangement of the arrangement of parts in a vacuum chamber in order to increase production productivity. All of the above aspects define specific tasks for further research of the technological process, taking into account the specifics of the production of spraying functional coatings.

Depending on the functional purpose, the thickness of the coatings can vary from a few to tens of microns. In particular, the performance properties of multicomponent and multilayer ion-plasma coatings based on titanium, chromium, and vanadium nitrides were studied in [4, 5]. It should be noted that a thin sublayer of metallic material up to approximately 1 μm was deposited on the substrate surface before the deposition of the nitride coating. The influence of the thickness, composition, and structure of coatings on microhardness, brittleness, and adhesive strength of coatings with a base was studied.

The method for calculating the distribution of the coating thickness on the surface of a flat substrate during magnetron sputtering was studied in [6]. The work is aimed at the kinematic movement of the planetary mechanism and, accordingly, at determining the thickness of the coating over the entire surface of a flat (linear) substrate making planetary motion. This approach to solving the problem is related to the design of the facility, and the paper considers a dual system of magnetron sputtering as the basic layout. Taking into account a large number of various installations with different layouts for their intended purpose, it is relevant to develop an adequate mathematical model that allows calculating the thickness of coatings.

The principle of developing a mathematical model and algorithm. The development of a program for calculating certain parameters of vacuum coatings is a complex task, for which various programming languages are used, in our case it is the MATLAB language, which is a high-level interpreted programming language that includes data structures based on matrices, a wide range of functions, an integrated development environment, object-oriented capabilities and interfaces to programs written in other programming languages.

To plot the distribution of the thickness of a thin-film coating on the sprayed surface of a part, a computer program for the calculation was developed, the flowchart of the algorithm of which is shown in Fig. 1.

The principle of coating thickness calculation consists of the following steps:

- the material intended for coating is initially selected (based on the physical and mechanical properties of the element, in our case, Al, Ni), then the mass of this material is determined (from 0.1 to 10 g, presumably) the thickness of the future depends on the density of which and the energy of evaporated ions films. The volume of the coating material is calculated by the formula:

$$V_{м} = \frac{M_{mat}}{\rho_{mat}} , (1)$$

where $V_{м}$ - amount of applied material, M_{mat} - mass of material, ρ_{mat}- density of material.

- at the second stage, the location of the evaporators on the target surface is selected: to simplify the visual representation of the material evaporation process, we used a spatial "grid" and divided the distance between the evaporation points with a step of 1 cm. For example, on a grid 5 cm long, (the grid size is selected from 10× 10 to 100×100 cells) there are 5 evaporation points, that is, there is 1 point per centimeter. Fig. 2.

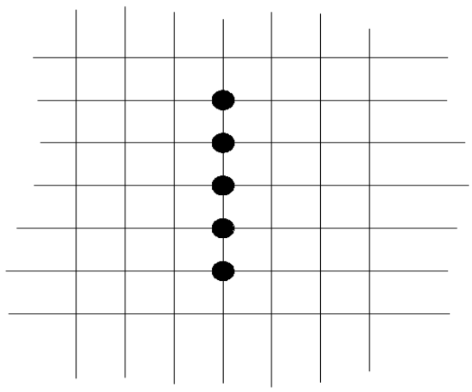

Fig.1. Arrangement of evaporation points on a spatial grid

The volume of the evaporated material is evenly distributed over the points, therefore, at each point of evaporation there is a volume:

$$\frac{V_{mat}}{n_{point}} , (2)$$

- at the third stage, the evaporation of the material is carried out according to the following three options selectively, in our case option a is considered:

a) uniform evaporation at the corners from a point,

b) evaporation into the upper half-plane according to the Cosine law (4),

c) evaporation into a half-plane according to the law $\cos^n \alpha$ (n=1,5), which corresponds to thermal evaporation, magnetron sputtering, and evaporation from the crucible.

Depending on the choice of options a, b, c, the coating thickness d during evaporation from the "point" is calculated by the formula:

$$\text{a) } d = \frac{V \cdot H}{4\pi (x^2 + H^2)^{3/2}}; \ (3)$$

$$\text{б) } d = \frac{V \cdot H^2}{2\pi (x^2 + H^2)^2}; \ (4)$$

$$\text{c) } d = \frac{V \cdot H^{5/2}}{2\pi (x^2 + H^2)^{5/2}}. \ (5)$$

For each point of the "upper" grid, the coating thickness is calculated (in the selected square of n × n points) Fig.2.

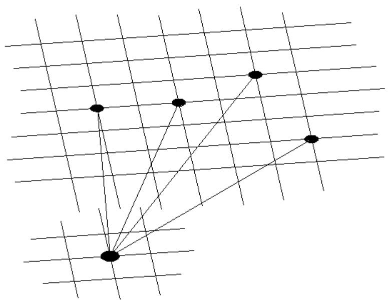

Fig 2. Location of coatings in the "upper" grid

Similar calculations are repeated for all "evaporation points".

The thickness of the coatings at each point of the upper grid dmn is summed up, that is, it is determined by the following expression

$$d_{mn} = d_1 + d_2 + \dots + d_n (6)$$

At the final stage, a "graph" of the distribution of film thickness is built, which determines the maximum thickness of the coating d_{max}.

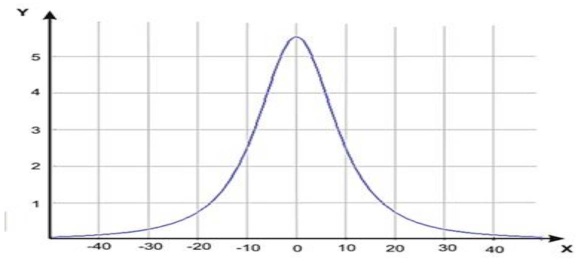

Fig.3. Graph of distribution of coating thickness along the length of the substrate: Material-Al, with part length x=100 mm, height H=50 mm

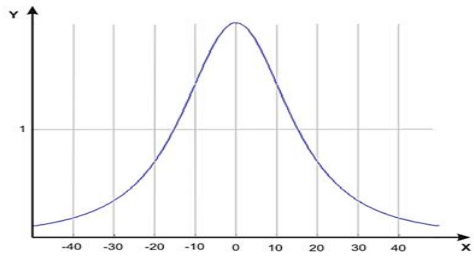

Fig.4. Graph of distribution of coating thickness along the length of the substrate: Material-Ni, with part length x=100 mm, height H=50 mm

Figures 3 and 4 show the graphs of the thickness distribution of Al and Ni thin-film coatings obtained using the developed computer program that implements the described algorithm.

Let us consider a flat substrate located at a distance of H-50 mm from the evaporator cathode. The distribution of the material layer is determined by the formula (3) when x-100 mm is the length of the part, on the graphic image the x-coordinate determines the length of the coated part, the y-coordinate determines the thickness of the coating d.

For aluminum coatings with a material density of 2.6 g/cm³ at a distance of 50-500 mm from the evaporator and a substrate length of 100 × 100 to 500 × 500 mm, the maximum thickness is observed in the center of the substrate, and it is equal to 5.6 microns, respectively. At the periphery, the coating thickness sharply narrows, and the film is thinly distributed over the entire length relative to the center of the substrate.

For nickel coatings with a material density of 8.9 g/cm³ at a distance of 50–500 mm from the evaporator and a substrate length of 100 × 100 to 500 × 500 mm, the maximum thickness is observed in the center of the substrate, and it is equal to 2 μm, respectively. At the periphery, the coating thickness gradually narrows, and the film is distributed in a thick layer along the entire length with respect to the center of the substrate.

Conclusion. Thus, on the basis of the conducted analytical studies and calculations, the following conclusions can be drawn:

A method has been developed for calculating the pre-planned (predicted) distribution of the coating thickness on a deposited surface during magnetron sputtering of targets parallel to the substrate.

Developed a mathematical model and an algorithm for solving the problem using the MATLAB program. Moreover, calculated the thickness distribution of coatings based on aluminum and nickel on the substrate surface on the basis of a computer program.

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