Selection the optimal value of the smoothed variable during the PVD coating thickness calculation

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Abstract. The operating experience of axial single-wheels indicates the need to protect the blades from erosion damage. This can be achieved by applying a protective coating. We have proposed a method for processing bladed disk by biaxial rotation in a vacuum volume. The selection of the trajectory is supposed to be carried out using numerical simulation methods. An important parameter in this case is the smoothed variable to eliminate noise from the coating thickness. The article presents the selection of this parameter based on an experiment with samples of various forms with a protective coating of the (Ti-V)N system.

1. Introduction
In recent decades, the design of the gas turbine engine compressor has undergone significant changes. First of all, this is due to increased temperature and power loads. This led to the introduction of an integrated disk design with blades, known as bladed disk (blisk), which increased the resource, as well as reduced the weight of the part [1].

The operating experience of this design indicates the need to protect the axial unicycle blades from erosion damage [2]. One of the successful approaches to solving this problem is applying a protective vacuum ion-plasma coating. The results of the research [3] demonstrate an increase in erosion resistance by 3-4 times for single blades, which indicates the prospects of the method for bladed disks. It should be noted that the surface treatment of a single blade is already a problem due to its complex form. However, for axial single-wheels, the problems are even more acute, since there are areas of optical shadow in the path of the particles of the deposited coating material. In the overlapped areas of the blades of the bladed disk, the plasma density is noticeably lower, and therefore their processing can be uneven. The classic way to solve this problem is to create such a trajectory of the body relative to the plasma vaporizers, which ensures the maximum uniformity of processing [4].

Selecting the above-described law of motion of a part in a vacuum chamber experimentally would require significant time and material costs. In this regard, the use of computer simulation methods and numerical calculations based on existing theories can significantly reduce the time to obtain the optimal trajectory of movement of the single-wheel.

In the literature, numerical models are considered for calculating various parameters accompanying vacuum-plasma processes, including cathodic ones (vacuum spot movements and temperature distribution),
volumetric, and others. Of greatest practical interest are the models describing the parameters of parts coating after vacuum ion-plasma treatment. Initially, these models were presented in a very simplified form, for example [5], where the practically important option of creating multi-layer coatings by condensing streams generated by several simultaneously operating sources on a rotating surface is not considered. These problems are solved in the article [6], which is based on the Lambert-Knudsen law for vaporized particles of matter, as well as the assumption that under vacuum conditions of $10^{-2} - 10^{-3}$ Pa and weak magnetic fields, the ion trajectories can be considered as straight lines. However, the article [6] does not consider the possibility of researching the coating parameters for parts of complex forms with the optical shadow areas.

We have developed a numerical model for qualitative analysis of the distribution of the coating thickness over the surface of the part under conditions of biaxial rotation in a vacuum chamber. It is assumed that the material particles sprayed from the cathode move along straight trajectories without interacting with the environment and condense directly at the points of impact with the substrate surface. This approach was tested on flat samples [7], showing satisfactory results.

When calculating the distribution of the coating thickness on the surface of complex geometry products, there is a problem of noise. To get rid of it, the "smoothed variable" $\mathbf{R}$ was introduced. Its significant influence on the calculation results is shown in figure 1, where $l$ is the length of the target surface. It can be seen that the base curve ($\mathbf{R}=0$) has sharp jumps, which does not correspond to the physics of the process. Adding $\mathbf{R}$ in the range of 0.1-0.3 of the target surface length results in a curve close to the theoretical form of a Gaussian curve.

![Figure 1. Dependence of the results of calculating the particle concentration on the substrate surface on the parameter R.](image)

2. Experiment description

The samples shown in figure 2 are made of stainless-steel sheet and consist of C-shaped plates of various radii of curvature (diameters are 35, 50, 75, 100, 115 mm) with $\mathbf{Ra} = 0.06-0.08$ microns, each of which is located between the flat bases. They were coated with a vacuum-plasma coating of the (Ti-V)N system. The samples were placed in the center of the vacuum chamber and processed from two sides with uniaxial rotation relative to the vertical axis of the chamber. The processed samples were examined using a scanning electron microscope JSM-6490 LV, where the thickness of the applied coating in the longitudinal section was measured. The measurement results are shown in figures 3 and 4 together with the calculation data.
The constructed CAD model of samples was imported into the COMSOL MULTIPHYSICS program, where calculations were performed using the Deformed mesh and Mathematical particle tracing modules. The angular distribution of the Lambert-Knudsen particle density relative to the source is obtained using a function of the form

\[ \text{rnd} = \text{random}(\text{pt.pidx}) \]  

(1).

This function assigns each particle an angle with a given probability in the specified range. In the calculation a direct solver was used. The characteristic shape of the curves is shown in figures 3 and 4 on examples of a sample with a radius of curvature of 37.5 mm.

**Figure 2.** Appearance of coated samples.

**Figure 3.** Experimental and calculated distribution of the coating thickness over the surface of the sample trough with a radius of curvature of 37.5 mm.
3. Results discussion
In figures 3 and 4, we can distinguish a straight line corresponding to R=0.12l (blue color, dotted line). It does not have sharp jumps corresponding to smaller values of R, but it does not lose the form of the original function.

It is worth noting that not all calculated curves have a high degree of coincidence with the actual results, which, for example, can be seen in figure 3. However, despite this, the model is suitable for qualitative analysis of the dependence of the coating thickness distribution on the part surface on the trajectory of its movement. It was found that with a decrease in the radius of curvature of the sample from 62.5 to 17.5 mm, the spread between the maximum and minimum values of the coating thickness increases. For the first sample, the values were 0.72-0.98 on the back and 0.92-1.06 on the trough, for the latter, with the lowest value of the curvature radius of 1.23-1.39 and 1.69-2.8, respectively.

4. Conclusion
It was found that for an adequate interpretation of the data on the thickness distribution of the vacuum-plasma coating on C-shaped experimental samples with concave and convex sides, the most optimal is R=0.12l, which ensures no noise and preserves the function monotony. This provides a qualitative analysis of the coating thickness depending on the geometric parameters of products of complex form, such as the blades of the gas turbine engine compressor, including axial single-wheel.

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