Solid particle erosion resistance researches of protective coatings formed on titanium alloy samples, made using additive technologies

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Abstract. The paper presents the results of experimental studies of the solid particles erosion resistance of titanium Ti-6Al-4V alloy samples, made using additive technologies with different types of protective coatings based on chromium and carbide chromium (Cr-CrC) and DLC (Diamond-Like-Carbon). By means of complex of laboratory equipment, the characteristics of the formed types of coatings were determined, such as thickness, composition, microhardness. Studies of the resistance to impact of solid particles were carried out on an experimental test stand for the study of solid particles erosion of materials and protective coatings at an air-abrasive flow rate of 170 m/s, a flow angle of attack of 30 ° and a sample temperature of 25 °C. It has been established that an ion-plasma coating based on Cr-CrC, 7–9 µm thick, increases the abrasion resistance of titanium alloy samples made using additive technologies not less than 1.5 times.

1. Introduction
The use of three-dimensional printing technology in industry significantly speeds up the production process, and also allows working with models of parts. In addition, such devices today are able to replace some industrial equipment, while taking up much less space. For example, 3D metal printers are capable of producing parts for various mechanisms that are not inferior to parts made using the traditional method. At the same time, the manufacturing process on the printer takes less time and effort, and the printer itself is much more compact than traditional equipment.

The advantages of additive technologies include [1-4]:
1. Resource efficiency. Products "grow" from scratch, that is, production is completely waste-free. For comparison: when creating blanks using traditional methods, sometimes material losses reach up to 85%.
2. Efficiency. The time from the moment of the development of the model to the receipt of the product can be reduced several times or even ten times without compromising quality.
3. Mobility. The equipment is compact; the transfer of layouts is possible online.
4. Accuracy. Layer-by-layer synthesis provides absolute compliance with specified technical parameters.
5. Weight. This is an important advantage for industry, aircraft and engineering. The weight of individual products is reduced by 40-50%.

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Currently, foreign companies are actively introducing 3D printing technology. The Avio Aero factory manufactured titanium aluminide turbine blades for prototypes of GE9X engines using EBM additive technologies (figure 1). They were made on 3D-printers of the Swedish company Arcam, a member of GE.

![Figure 1. Turbine blades for prototypes of GE9X engines made from TiAl by additive method.](image)

It is known that the new technology of manufacturing or hardening of parts must pass the relevant regulated tests, enshrined in production standards to check the strength characteristics and resistance to various types of wear.

Meanwhile, testing parts created by 3D printing often reveals defects and discontinuities. In this regard, for reliable use of additive manufacturing techniques for parts, not only technological quality control is important, but also testing the product for resistance to various types of wear to which equipment is subject, including the abrasive effect that is characteristic of the compressor first stages of gas turbine engines and energy units.

This paper shows the possibility of applying the method of increasing the resistance of samples made using additive technologies to solid particles erosion due to the formation of protective ion-plasma coatings.

2. Researches

For the formation of several types of protective ion-plasma coatings, the vacuum stand “Gefest+” of National Research University «Moscow Power Engineering Institute» (NRU “MPEI”) was used, which implemented one of the most modern and promising methods for sputtering materials - magnetron sputtering using planar magnetrons.

Titanium (Ti) and chromium (Cr) were used as target cathode materials. High purity argon was used to create and maintain a low-pressure gas discharge, and high purity carbon was used to synthesize titanium carbide (TiC) and chromium (CrC).

To study the properties of the formed coatings in NRU "MPEI", a complex of research equipment was used, which allows to conduct studies of the composition and structure of coatings, measure the thickness, roughness, microhardness of coatings, etc., to determine the resistance of coatings to scratching by scratching testing shock impact, etc.

To conduct research of the abrasive resistance of the formed coatings, an experimental stand of the jet-abrasive type was used, simulating various conditions of the interaction of abrasive particles with the surface of structural materials. The facility allows studies of the solid particles erosion resistance of materials and coatings in a wide range of parameters for the interaction of solid particles with the surface of samples.

Experimental studies were conducted with a certain time step of the test, which was 5 minutes. To build each dependence of the solid particles erosion intensity on the time of testing, at least three experimental samples were used. After each test, the mass loss from the sample was recorded, and the
mass loss from the sample during the test was evaluated relative to its initial mass. According to the results of the tests, the relative resistance to solid particles erosion on the site of the incubation-transition period was evaluated.

3. Results and discussion
For titanium alloy samples made using additive technologies with different coating options, a set of studies of characteristics, such as thickness, composition, microhardness, was carried out, which showed that:

- the total thickness of coatings based on Cr-CrC is from 5.2 to 7.3 microns, DLC coatings is about 3.5 microns;
- microhardness of the surface after the formation of coatings based on Cr-CrC averages 1010 - 1130 HV0.05; DLC coatings - at the level of 750 - 970 HV0.05;
- surface roughness (Ra) of samples from the coatings ranged from 0.85 to 3.9 microns, the initial surface - from 4.2 to 9.8 microns. The surface structure of the coatings is granular, the grain size ranges from 40 to 230 nm for DLC coatings and from 30 to 240 nm for Cr-CrC coatings.

Using NRU "MPEI" stand, comparative solid particles erosion tests of titanium alloy samples made using additive technologies with and without coatings with the following parameters were carried out: the average speed of the air-abrasive flow of 170 m/s, the angle of attack of solid particles of 30 °, the sample surface temperature of 25 °.

The test results of titanium alloy samples, manufactured using additive technologies with different variants of protective coatings based on DLC and CrC to resistance to solid particles erosion are presented in figure 2.

![Figure 2](image_url)

**Figure 2.** Solid particles erosion curves (a) and histograms of relative abrasive resistance (b) of titanium alloy samples made using additive technologies.

Additionally, after completion of the tests, profilograms of sample surfaces were constructed using a mechanical profilometer and the maximum wear depth for each of them was determined. The results are presented in figure 3.
Figure 3. Longitudinal profiles of "abrasive" marks on titanium Ti-6Al-4V alloy samples without coating (a) and with DLC (b) and Cr-CrC coatings (c).

According to the presented data, wear depths show that the Cr-CrC coating also makes it possible to reduce the intensity of wear at a site with a steady erosion rate. This circumstance is explained by the initial increase in the duration of the incubation-transition period, which delays the onset of wear of the base material of the sample.

4. Conclusions
The results of the conducted studies demonstrate the possibility of applying the technology of ion-plasma spraying to increase the solid particles erosion resistance of titanium alloy samples by using additive technologies.

It is revealed that the best of the considered types of coatings is a composition based on Cr-CrC, which showed that its use makes it possible to increase the resistance of a sample of titanium Ti-6Al-4V alloy to the effects of solid abrasive particles in the duration of the incubation-transition period not less than 1.5 times.

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