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IMPROVING THE WEAR RESISTANCE OF TITANIUM ALLOYS BY THERMAL SPRAYING METHODS

The study aims to enhance the wear resistance of titanium alloys by applying thermal spray coatings using plasma and detonation spraying techniques. The structural features and phase composition of thermal spray coatings were investigated through chemical analysis and X-ray diffraction. The microstructure, particle size, and hardness were evaluated by microhardness testing and micro X-ray spectral analysis. It was established that the coatings formed by plasma and detonation spraying of titanium carbide powders clad with nickel and copper exhibit a heterogeneous microstructure. Carbide particles are dispersed in a metallic matrix containing oxide inclusions. The microhardness of the particles depends on the cladding material and initial powder size. Detonation coatings showed a more uniform distribution and finer particle sizes (10–15 μm) compared to plasma coatings (20–60 μm). The presence of nickel phosphides and various intermetallic compounds was confirmed in both types of coatings. The detonation method led to a higher phosphorus content in the matrix due to reduced losses during spraying. Despite similarities in phase composition, structural uniformity and lower porosity were more prominent in detonation-sprayed coatings. Titanium alloys possess poor antifriction characteristics, which can be significantly improved by applying thermal spray coatings. Plasma and detonation spraying methods effectively enhance wear resistance, with detonation spraying offering better microstructural uniformity and phase distribution.

***Keywords**: titanium alloys, thermal spraying, wear resistance, detonation spraying, plasma coatings, microstructure, phase analysis, carbide particles.*

Introduction. Titanium alloys are known for their high specific strength, corrosion resistance, and biocompatibility, which makes them indispensable in aviation, medicine, chemical industry, and other fields. However, their main disadvantage is low wear resistance and a high tendency to galling and adhesion under friction, which may lead to rapid degradation of parts, especially those operating under friction and high load conditions. Improving the wear resistance of titanium alloys via thermal spraying is a key direction in modern materials engineering, significantly expanding the application of these unique metals in high-tech industries. Forming wear-resistant thermal spray coatings on titanium alloys is a complex, multifactorial task aimed at enhancing their operational performance.

During the formation of thermal spray coatings, diffusion interaction between the coating material and the titanium substrate can occur, leading to the formation of new intermetallic or oxide phases at the interface, which affects adhesion strength and performance. Residual stresses, especially thermal ones, arise in the "wear-resistant coating – metal substrate" system and can influence the coating's resistance to cracking. Minimizing these stresses is critical. Tribo-oxidative layers and mechanically mixed layers may form on the coating surface during friction. While these layers may provide initial protection, they can deteriorate at high sliding speeds or elevated temperatures, resulting in delamination and adhesive wear. Titanium alloys are susceptible to both mild and severe wear. The formation of tribo-oxide layers often helps shift the wear regime to the mild type.

Ensuring the durability of aviation equipment and improving the performance of parts, assemblies, and mechanisms operating under friction in corrosive environments is essential. Therefore, improving the antifriction properties of titanium alloys is crucial, given their properties (high specific strength, non-magnetic nature), making them promising structural materials. However, their sensitivity to overheating, stress concentrators, and tendency to galling limit the available surface hardening methods.

An effective way to improve the durability and reliability of aviation parts is to use coatings applied by thermal spraying methods (plasma, detonation, flame spraying), which are characterized by high productivity, versatility in applicable materials, low substrate heating temperatures (no more than 200°C), significant coating thickness (up to several millimeters), and the ability to restore worn parts [1; 2].

Thermal spraying, with its broad technological capabilities, allows for the efficient use of powders in various industries. The application of thermal spray coatings to worn parts is determined by their high antifriction properties, which affect the performance of coated materials in friction units depending on technological factors, coating properties, external environmental conditions, and the counter-body material.

Research Results. The article presents the results of a study on wear resistance, structure, and phase composition of plasma coatings on titanium alloys for specific parts of aerospace equipment. A plasma coating is a particular type of material formed as a result of impact, deformation, and extremely rapid crystallization of small (10–150 μm) particles of material sprayed onto a substrate. Sequentially layering on top of each other, the particles form a laminated coating with anisotropic physical and mechanical properties, heterogeneous in structure and chemical composition. It is characterized by a developed surface of particle interfaces and an increased content of oxide inclusions, especially along the boundaries of particles and individual layers. The contact processes occurring during particle impact, deformation, solidification, and cooling, as well as their physicochemical interaction with plasma-forming gases and the environment during movement to the substrate, determine the structure and properties of the coating. In the case of detonation spraying, which is a pulsed process, a single cycle forms a coating about 5 μm thick, i.e., coatings thicker than 40 μm are almost always multilayered. A necessary condition for spraying is partial melting of the material, although to a lesser extent than in plasma spraying. Due to the high concentration of particles, the contact temperature between them during single-layer formation is close to the melting point, which leads to the blurring of boundaries between individual particles. A single layer appears monolithic under microscopic observation, while the boundaries between layers are distinctly visible. A peculiarity of such coatings lies in the formation of layers with varying degrees of melting of the sprayed material, which negatively affects their properties. The coating layer closest to the outer surface is the most weakly bonded with the underlying layers, as it is not additionally strengthened (via impact hot pressing) during the spraying of subsequent layers. A significant factor in detonation spraying is the mutual influence of particles and their high velocity, which forms a structure different from that of plasma coatings. Special attention should be given to gas-thermal coatings based on titanium carbide powder with various claddings, as this material was studied most thoroughly. The structure of the coatings after spraying consists of carbide particles distributed in a metallic matrix, as well as oxides of the cladding elements[3-5]. The microstructure is heterogeneous in the size of the constituents, their microhardness, and distribution. The microhardness of the particles varies depending on the type of cladding metal and the size of the carbides. For initial particle sizes of 80–100 μm, carbide inclusions had a microhardness of 14–29 GPa. As the particle size decreases, a more complete interaction with the cladding material during spraying is observed, resulting in reduced carbide microhardness. Chemical and phase X-ray structural analyses were carried out on the powder and coatings after plasma and detonation spraying. The distribution of C, Ti, Ni, Cu, P, and O_2 elements in phases was studied using micro X-ray spectral analysis with a "Superprobe-733" device. The size of carbide particles in coatings based on titanium carbide clad with nickel and copper was 20–60 μm. The structure showed individual particle conglomerates that were apparently formed during the powder cladding stage. The structure of detonation coatings is characterized by a more uniform distribution of particles in the matrix; their microhardness did not exceed 12 GPa and the particle size was no more than 10–15 μm. Phase analysis revealed a large number of structural components with different crystallographic natures. In addition to the main phase of titanium carbide and the cladding element in the original powder, iron oxides were detected. After gas-thermal spraying, interaction of the powder with the working gas and the environment, as well as the specifics of contact processes with the substrate during spraying, lead to a change in phase composition, as evidenced by the obtained data. The main phases in the structure are: titanium carbide, complex carbide NiC, nickel, copper, their intermetallics, and titanium and copper oxides. A significant amount of iron oxides was found, apparently due to the intensity of diffraction lines, as well as small amounts of chromium and silicon compounds. The presence of these phases was confirmed by micro X-ray spectral analysis. Topograms of the plasma coating surface (TiC, Ni, Cu) were obtained in characteristic X-rays, showing qualitative distribution of elements within the phases. The images showed that nickel is the most uniformly distributed between the carbide particles, followed by copper. Phosphorus tends to accumulate around relatively small carbide particles. In the process of detonation spraying, the phosphorus content in the matrix increases compared to plasma spraying, due to the particle size (not more than 40 μm) of the original powder (and thus a thicker cladding layer), as well as reduced phosphorus loss. X-ray phase analysis showed a small amount of nickel phosphides (Ni_2P), which are present in both detonation and plasma coatings. No significant differences in phase composition between detonation and plasma coatings were found. However, an increase in the phase composition of coatings based on titanium carbide clad with nickel and copper was noted. The complexity of the phase composition and the presence of phases not intentionally introduced into the coating are likely due to technological impurities during powder production, cladding, and spraying. Chemical analysis of the powder and coatings showed the presence of chromium, silicon, and phosphorus in quantities not exceeding 1 wt.%. Spectral analysis revealed small amounts of elements such as Mn, Al, Si, Co, and Mo. The chemical composition complexity, due to the diversity of phases formed during spraying, contributes to structure heterogeneity. No significant interaction between carbide particles and the cladding shell was detected. The cladding metal adheres tightly to the particles; slight dissolution of carbon and titanium in nickel was observed, as indicated by element intensity distribution curves at the carbide-matrix interface. Alongside titanium and carbon, some carbide particles showed iron accumulation, unevenly distributed within the particle. Iron is also present as oxides. Carbon is evenly distributed throughout the carbide particles, but in cases of structural defects such as pores or pits, a reduction in carbon content in those areas was observed. The obtained results indicate the complexity and diversity of phase transformations occurring during spraying, driven by the chemical composition of the feedstock powder and its interaction with the working gas and environment. To obtain a stable phase composition—and hence ensure consistent coating properties—it is necessary to strictly control the chemical composition during powder production, cladding, and employ a controlled atmosphere during spraying.

Conclusions. From the studies conducted, it was established that titanium alloys possess low anti-friction properties: a high and unstable coefficient of friction and a tendency toward galling[6-7]. The main direction for improving the performance of titanium alloys in friction units is the use of coatings on components made from these alloys. The most promising coatings are those applied using various spraying methods, which, in terms of technological capabilities and technical-economic indicators, offer significant advantages over traditional coating methods.

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ПІДВИЩЕННЯ ЗНОСОСТІЙКОСТІ ТИТАНОВИХ СПЛАВІВ МЕТОДАМИ ГАЗОТЕРМІЧНОГО НАПИЛЮВАННЯ

Метою дослідження є підвищення зносостійкості титанових сплавів шляхом нанесення покриттів за допомогою газотермічних методів, зокрема плазмового та детонаційного напилення. Структурні характеристики та фазовий склад покриттів досліджено методом рентгеноструктурного аналізу та хімічного аналізу. Мікроструктуру, розмір частинок і мікротвердість визначали за допомогою мікротвердометрії та мікрозондового рентгеноспектрального аналізу. Встановлено, що покриття, утворені шляхом плазмового та детонаційного напилення порошків карбіду титану, плакованих нікелем і міддю, мають неоднорідну мікроструктуру. Частинки карбіду рівномірно розподілені в металевій матриці з включеннями оксидів. Мікротвердість частинок залежить від матеріалу плакування та початкового розміру порошку. Детонаційні покриття характеризуються більш рівномірним розподілом та меншими розмірами частинок (10–15 мкм) порівняно з плазмовими (20–60 мкм). У складі покриттів підтверджено наявність фосфідів нікелю (Ni_2P) та різних інтерметалідних сполук. Для детонаційного методу характерний вищий вміст фосфору в матриці через менші втрати під час напилення. Незважаючи на схожість фазового складу, детонаційні покриття мають кращу структурну однорідність і меншу пористість. Титанові сплави мають низькі антифрикційні властивості, які можна істотно покращити шляхом нанесення газотермічних покриттів. Методи плазмового та детонаційного напилення ефективно підвищують зносостійкість, причому детонаційне напилення забезпечує вищу однорідність структури та розподілу фаз.

Ключові слова: титанові сплави, газотермічне напилення, зносостійкість, детонаційне напилення, плазмові покриття, мікроструктура, фазовий аналіз, карбідні частинки.

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