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WEAR RESISTANCE OF NANOCOMPOSITE COATINGS IN VACUUM

One of the developing areas of tribotechnical materials science is the development and study of nanocomposite materials for movable joints operating under extreme conditions, which are not only increased thermomechanical loads and high sliding speeds, but also, mainly, the effect of a gaseous medium, in particular, vacuum. Detonation-gas spraying was carried out with the developed nanocomposite powders of the Fe-Ti-SiC-MoS_2-MgC_2 system. Particles of solid lubricant corresponding to fractions of 30-40 μm were mixed with the initial nanopowders by the wet method. To eliminate powder adhesion to the chamber walls and optimize the process of spheroidization of a mixture of its components, we used a developed and tested technology with the use of ultrasound. Tests in vacuum were carried out on a friction machine M-22PV, designed for laboratory and experimental evaluation of tribological characteristics and quality control of coatings. Investigation of the wear resistance of coatings during friction, their tendency to set were evaluated by the intensity of wear in a vacuum (at a vacuum of 1.33×10^{-5} Pa). The study of the quality of surface layers, in which the processes of activation during friction proceed, were carried out using modern methods of physicochemical studies, including metallography, scanning electron microscopy, and X-ray structural phase analysis. As a result of external influences and the relative movement of the contact surfaces, the first and main manifestation of external friction arises - elastoplastic deformation, which causes the emergence of a set of surface phenomena that determine the essential properties and qualitative regularities of friction processes. The results of metallographic analysis and surface studies confirm the presence of a surface passivating film of molybdenum disulfide. The use of the optimal combination of the properties of MoS_2 and graphite films significantly improves the tribotechnical characteristics. The recommended graphite content, as established, is 10-12% (wt.%), which corresponds to the maximum lubricating effect of the formed complex film, which prevents the adhesion interaction of juvenile surfaces, while individual foci of destruction are localized in the near-surface layers and annihilate in the process of grain boundary sliding, excluding any kind of damage.

***Keywords**: friction, wear, structure and properties.*

Introduction. One of the developing areas of tribotechnical materials science is the development and study of nanocomposite materials for movable joints operating under extreme conditions, which are not only increased thermomechanical loads and high sliding speeds, but also, mainly, the effect of a gaseous medium, in particular, vacuum.

Experimental studies of the structure of nanocrystalline materials [1,5] have shown that a significant portion of their volume is occupied by grain boundaries and triple joints, which determine the action of specific deformation mechanisms that determine the dynamic factors of its evolution under friction conditions.

Based on the analysis of the work carried out in this area, it has been established that, despite the results achieved, it remains relevant to ensure the wear resistance of nanocomposite materials during operation in a vacuum.

In aviation and space technology, these are practically all the main tribotechnical parts from precision joints to threaded contacts. Their serviceability and reliability form the basis of the technical condition of aerospace technology [3] ease of use.

Materials and research methods. Detonation-gas spraying was carried out with the developed nanocomposite powders of the Fe-Ti-SiC-MoS_2-MgC_2 system. Particles of solid lubricant corresponding to fractions of 30-40 μm were mixed with the initial nanopowders by the wet method. To eliminate powder adhesion to the chamber walls and optimize the process of spheroidization of a mixture of its components, we used a developed and tested technology with the use of ultrasound. The spraying of the investigated coatings was carried out according to the established technique, which provides for the presence of two dispensers. The first is filled with a nanostructured powder composition Fe-Ti-SiC, the second was loaded with MoS_2-MgC_2 powder. First, the first dispenser was turned on and the nanocomposite layer was sprayed, then the powders were simultaneously fed from two autonomously operating dispensers. The thickness of the coatings after finishing was 0.30-0.35 mm at Ra = 0.63-0.32.

Tests. Tests in vacuum were carried out on a friction machine M-22PV, designed for laboratory and experimental evaluation of tribological characteristics and quality control of coatings [1,2]. Investigation of the wear resistance of coatings during friction, their tendency to set were evaluated by the intensity of wear in a vacuum (at a vacuum of 1.33×10^{-5} Pa). The wear characteristics of nanocomposite coatings were compared with the values of wear resistance of coatings of the VK15 type and surface layers obtained as a result of thermal diffusion saturation with boron, vanadium, and chromium compounds, which were tested under the same conditions and conditions as nanocomposite materials.

The study of the quality of surface layers, in which the processes of activation during friction proceed, were carried out using modern methods of physicochemical studies, including metallography, scanning electron microscopy, and X-ray structural phase analysis.

Research results. As a result of external influences and the relative movement of the contact surfaces, the first and main manifestation of external friction arises - elastoplastic deformation, which causes the emergence of a set of surface phenomena that determine the essential properties and qualitative regularities of friction processes. The graphical functional dependence of the parameters of the coatings under study is shown in Fig. 1.

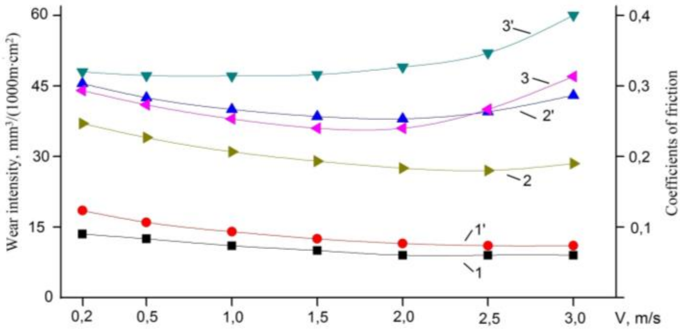

Fig. 1. Dependence of the wear rate (*1*, *2*, *3*) and friction coefficients (*1'*, *2'*, *3'*) at P = 3.0 MPa on the sliding speed of the Fe-Ti-SiC-MoS_2-MgC_2 coatings (*1*, *1'*), vanadated samples (*2*, *2'*), and chrome samples (*3*, *3'*)

The wear of surfaces under these conditions is a complex sequence of active influence of both external influences and intrastructural transformations, which reflect the commonality of their quantitative laws and are determined by an ordered causal relationship. The high wear resistance under the given friction conditions of the Fe-Ti-SiC-MoS_2-MgC_2 coatings (Fig. 1, dependences *1*, *1'*) is due to the structural adaptability, which, as a universal phenomenon, is realized due to the structurally free molybdenum disulfide.

The results of metallographic analysis and surface studies confirm the presence of a surface passivating film of molybdenum disulfide.

The energy stored by the friction surface is concentrated, as is known, in the thinnest surface layer, the effective volume of which extends to a depth of the order of tens and hundreds of nanometers. The change in its density in a local microvolume under friction loading tends to a critical value that can be absorbed by the activated surface layer before destruction. The quantitative energy value of the specific work of wear, obtained during running-in, was about 104 kJ/mm^3 and was necessary and sufficient to achieve the level of thermal solid-phase decomposition of magnesium carbide contained in the coating composition with the formation of structurally free α-graphite. The shape of the particles, the graphite structure is close to flaky, consisting of randomly located polydisperse crystallites, including up to four planar lattices of atoms. The distance between the planes is likely to be about 0.6 nm.

The obtained research results, supplemented by X-ray structural analysis data, make it possible to establish that the initial nanostructured coatings represent an ultrafine conglomerate of intermetallic compounds Fe_2Ti, FeTi, silicide colonies TiSi2, Ti_5Si_3, $FeSi_2$, Fe_3Si_3, Mg_3Si carbides TiC, Ti and Si in α-Fe. On electron diffraction patterns from the contact layer directly adjacent to the friction surface and separating the coating material from the antifriction film formed by solid lubricant, the presence of diffusion halos with textured maxima was determined, which corresponds to modern concepts of the nature of an ultradispersed structure with a directed orientation in the friction field. Moreover, their organization under conditions of oxygen deficiency, in our opinion, is due to phase transformations, when, as a result of mechanothermal alloying and frictional hardening, oxygen-free structures are formed by the mechanism of formation and properties close to the structure of martensitic phases. However, the surface structures formed under extreme temperature-time and load conditions by the martensitic mechanism differ in mechanical properties from the properties of quenched martensite obtained by traditional heat treatment. Thus, the hardness of martensite after heat treatment is 7.5-9.5 GPa, and the corresponding values for martensite structures formed on friction surfaces reach 10.5-13.5 GPa.

Of the samples subjected to diffusion alloying, the least wear corresponds to vanadium friction surfaces (Fig. 1, curve *2*), which is associated with the formation of a working layer saturated with vanadium carbides, characterized by high mechanical properties, in particular hardness and refractoriness [3, 4]. In this case, along with VC carbides, V_2C carbides are formed, which have a hexagonal close-packed crystal lattice; in addition, compressive stresses arise in the surface layer.

Thus, the studied detonation coatings Fe-Ti-SiC-MoS_2-MgC_2, developed for the needs of practice, showed high tribotechnical characteristics in the entire range of tests simulating the operation of the friction unit in a rarefied atmosphere. At the same time, a means of regulating wear and ensuring high antifriction of coatings in a vacuum is the use of solid lubricants in their composition, through their structure influencing the level of adaptation during friction due to modified surface layers capable of blocking destruction and screening unacceptable setting processes.

It should be noted that the developed nanostructured powder can be used in the restoration and strengthening of parts by any technological methods using powder materials.

The nature of wear of steel samples hardened by thermal diffusion chromium plating (Fig. 1, curve *3*, *3′*) is similar to the general laws of wear of vanadium coatings. The increased values of the wear of chromium-plated specimens are due to the tendency to seizure caused by the relatively low surface strength under the given conditions of friction in vacuum.

Conclusions. The use of the optimal combination of the properties of MoS_2 and graphite films significantly improves the tribotechnical characteristics. The recommended graphite content, as established, is 10-12% (wt.%), Which corresponds to the maximum lubricating effect of the formed complex film, which prevents the adhesion interaction of juvenile surfaces, while individual foci of destruction are localized in the near-surface layers and annihilate in the process of grain boundary sliding, excluding any kind of damage.

Modification of the friction surface by regeneration of solid-phase lubricating films determines the value of the friction coefficient in the entire test range up to 0.1. According to the authors, under these conditions, the value of the friction coefficient is not so much a function of the normal load as the dependence of the tribophysical processes arising as a result of the additive action of the load, sliding speed, temperature and the generalized vector of friction parameters (materials, environment, conditions, etc.) ... Thus, a solid lubricating surface film or an active over the surface layer, in addition to an antifriction effect, also has antiwear properties, which in these conditions ensures a high resistance of coatings against wear.

The study of electron micrographs of the topography of the surface layers made it possible to establish that the nature of the distribution of their fragments is row-oriented, oriented in the direction of force effects under friction loading, which, in our opinion, is an expression of the formation of solid-phase surface structures by self-adaptation mechanisms [6]. From an energy point of view, this structural transformation can be considered as adequate elementary adaptation mechanisms in the process of structural adaptability of the friction system in a vacuum. On the other hand, due to the statistical regularities of phase formation, the fragmentation of surface structures in different contact areas does not coincide, and on the other hand, the formation of the structure of the solid lubricant layer is not indeterminate, but is controlled by the minimal principles of dissipation.

1. By means of theoretical prerequisites and experimental studies, the optimal structural-phase composition of nanocomposite coatings that do not contain scarce and expensive components has been realized. At the same time, by controlling the technological process of spraying nanopowders, it was possible to provide not only the desired chemical composition, but also to obtain a predicted structure that modernizes the friction surface due to a solid lubricant medium that prevents molecular-adhesive interaction.

2. Established high tribotechnical properties by creating a passivating solid-phase lubricating film. At the same time, it was noted that individual centers of destruction are localized in the near-surface layers and annihilate in the process of grain-boundary sliding.

3. The physical mechanism is considered and the main factors determining the level of thermodynamic passivation are indicated. When studying the nature and patterns that determine antifriction, it was noted that its implementation was carried out due to solid-

phase tribochemical and diffusion processes of the formation of quasi-layered solid lubricant structures and finely dispersed near-surface phases of the components that make up the composition.

4. It has been determined that the protective solid lubricating surface structure contributes to a decrease in the adhesive component of the friction force, and its plastic deformation is not associated with significant heat costs and contributes to the minimum degree of energy losses.

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ЗНОСОСТІЙКІСТЬ НАНОКОМПОЗИТНИХ ПОКРИТТІВ У ВАКУУМІ

Дослідження в рамках феноменологічного підходу детонаційних нанокомпозиційних покриттів у вакуумі, з використанням у якості твердих мастил, дисульфіду молібдену та карбіду магнію, який утворює карбід графіту в умовах термічної дисоціації.

Ключові слова: тертя, знос, структура та властивості.

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