The application of strengthening vacuum ion-plasma treating for the surface layer of constructional metal materials in mechanical engineering and the features of its formation

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Abstract. The paper lays bare the constructive scheme of technological effects of gas and metal plasma flows while exploiting VIP treating to process structural materials and structural changes the surface layer undergo at the technological stages of VIP treating. Moreover, it considers the complex system to ensure the operational properties of structural materials during VIP treating. The application of VIP treating turns out to be exceptionally efficient to reduce damages of the friction unit surfaces under fretting conditions.

1. Introduction
At present, vacuum ion-plasma (VIP) coatings used to protect various functional parts are widely employed in diverse branches of engineering. The coatings formed by surface VIP treating methods possess a number of significant advantages over traditional surface treating methods, including electroplating ones. First, it is the pro-environmental character of the process, which is extremely vital nowadays. Second, VIP coating provide large-scale technological capabilities: the surface modification with gas and metal plasma, possible condensation of multicomponent multilayer coatings using nanostructures, combined treating, including surface modification and application of various functional coatings in a single technological cycle.

The VIP processing method allows creating complex compositions of various types of coatings, as well as to carry out compound processing with preliminary diffusion modification. In its turn, the latest is able to form gradient structures of surface layers with special properties without deterioration of mechanical properties in the product bulk.

2. The processes of formation of multilayer coating
The processes of formation of multilayer coatings based on nitride, carbide, and oxide compounds and the set of properties they implement are considered to be complicated processes, since the formation of the given coatings, especially multilayer ones, is a multi-step procedure, as all component parts of VIP treating technologies are involved into this process implementation:

- obtaining the primary flux of metallic plasma and its uniform distribution in the working space of the vacuum chamber and density;
- the defectiveness of the nanostructured surface layer formed by condensation of a metallic plasma flux onto the treated surface;
- the formation of single-layer coatings in the intermediate layers and their combination while creating multilayer compositions, as well as the defectiveness occurring in this case;
- the emergence of barrier layers with diverse types of structures, including nanostructured compositions, which reduce base ions diffusion in the coatings.

Each of the abovementioned stages affects the quality and rank of the formed properties of the final product, i.e. multilayer coating compositions. Therefore, the creation of coatings with high-performance properties calls for the evaluation of all processes involved in the formation of the required coating compositions.

The need to consider each stage of multi-layer coatings formation can be explained by the fact that only a multi-layer coating composition is able solve the problem of creating fretting wear resistant compositions.

The most rational solution to the problem of improving the surface layer efficiency is the creation of functional coatings on the surface, which will implement the required set of performance properties. The four-step process of producing such coatings is rather complicated [1].

Step 1: The formation of active atoms of saturating elements in the reaction space at saturation temperatures.
Step 2: The interaction between active atoms of saturating elements with the base metal surface (adsorption of the formed active atoms of saturated surface).
Step 3: The diffusion of saturating elements in the surface layer of the processed product.
Step 4: The formation of primary clusters, the increase in their number, and the formation of the coating surface, the growth of the formed coating.

One of the essential conditions for obtaining high-quality coatings is to control the properties of both the coatings and the various technological steps of their formation.

Ion-plasma coatings are promising for improving the performance of structural metal materials. However, further expansion of applicability of these coatings is connected with the regularity of the formation of various coating structures, the internal stresses formation and distribution both at the metal-coating boundary and within the coating itself, with the electrochemical interaction between the diverse components of the coating, with the coating defect formation, with establishing the reasons of their occurrence and elimination.

That is extremely crucial both for predicting the coating performance and making the right decision when choosing further directions in design of new coatings.

One of the vital issues of coatings is the residual internal stresses appearing at the metal-coating boundary [2]. These stresses can cause cracking, loss of adhesion and complete condensate destruction. Thus, a chief aspect of ensuring the coating performance is its phase composition, texture, microhardness, thickness, property stability and reproducibility, as well as quality assessment and control over the technological stages of the coating formation process.

The technological processes of VIP surface layers formation by coating deposition are carried out by exposing the ions of gas and metal plasma of diverse compositions and energies to the treated surface. The order of impact of ionic fluxes of various energies on the surface determines the technological process stages.

The technological process of coating deposition includes the following steps:
- surface decontamination and activation;
- heating the treated surface to a predetermined temperature;
- coatings deposition.

The first stage implies surface decontamination and activation, since the effectiveness of the initial surface decontamination affects such properties, as the coating defectiveness, its porosity, adhesion, the rate of diffusion processes and the uniformity of their occurrence over the surface. The presence of impurities and oxides in local areas of the surface contributes to the formation of structural defects, both in diffusion and coating formation processes. Only the complete removal of oxide layers and contamination allows obtaining defect-free coatings and diffusion boundary (buffer) layers. The change in the surface potential magnitude demonstrates the efficiency of surface decontamination and
activation processes. All structural metal materials applied in mechanical engineering have a negative value of the initial surface potential $V_s$. A negative potential value indicates the presence of contamination, adsorption layers, and oxides. As the contaminants are removed, the value of the surface potential increases and reaches the value of the oxide potential. Metals have different oxide potential values. For instance, titanium alloys, depending on the presence of a simple or complex alloyed oxide on the surface, have a value of the surface potential $V_s$ equal to $-60$ mV to $-200$ mV. The surface potential of aluminum alloys ranges from $-1000$ mV to $-1500$ mV. Alloy additions to the steel provide a surface potential from $-50$ mV to $-400$ mV.

The oxides removal by ion bombardment (etching) from the metal surface contributes to the formation of surface potential values with a positive sign. The greater the surface potential value, the more complete the oxides removal from the surface, whose activity increases with decreasing oxide layer thickness. However, the complete removal of the oxide layer leads to ion etching of the base metal, which is accompanied by the defective layer formation that is not desirable for the process of applying fretting wear resistant coatings. Therefore, the optimization of the surface decontamination and activation stage is a key factor for the formation of high-quality fretting wear resistant coatings.

The value of the reduced surface potential $V_s$ can be an assessment of the quality and effectiveness of the given stage. Having the information on $V_s$ value of a clean juvenile surface and $V_s$ value after carrying out the decontamination and activation stage, it is possible to calculate the difference of these potentials and judge the effectiveness of ionic surface treatment.

The second stage of the coating deposition process consists in heating the surface to a predetermined temperature range. The surface heating is accompanied by an increase in surface energy. While exploiting VIP treating, the most effective heating can be achieved by bombarding the surface with an electron-ion flux of gas or metal plasma.

The third stage includes diffusion saturation and deposition. It is carried out when gas and metal plasma of lower energies is exposed to the ion flux surface. $V_s$ value allows defining the formation of diffusion layers and condensate, since each chemical compound formed on the surface corresponds to a certain value of $V_s$ potential. This potential value may vary within the limits of changes in defects in its structural formation. The correlation dependence of the potential value on the structure defectiveness makes it possible to conclude about the quality of the formed coating and the diffusion layer. Thus, the value of the surface potential can serve as an evaluation characteristic to assess the effectiveness of technological stages of coating deposition at VIP treating.

3. Conclusions
The application of VIP processing technologies leads to a radical change in the properties of the surface layers of constructional metal materials, thereby ensuring their efficiency increase. VIP treating processes result in the appearance of a new set of physical, chemical and operational properties, which makes it possible to ensure the operational performance of the part surface layers in modern operating conditions.

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