FEATURES OF THE FORMATION OF THE NANOSTRUCTURAL STATE OF THE SURFACE LAYER OF STEEL PARTS DURING PROCESSING AND OPERATION

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ABSTRACT

Considered patterns of formation of the nanostructural state of the surface layer of machine parts during friction under conditions of complex dynamic loading. The results of the complex assessment of the state of the surface layer of samples after friction continuous indentation and scanning methods indenter, an analysis of changes in the work function of the electron from the surface of the samples. Shown that during the friction of steel surfaces, an increase in transverse slippage contributes to the formation of a more uniform surface layer. This decreases its strength, wear resistance, and a more uniform surface microgeometry. This is accompanied by a decrease in the magnitude and spread of the electron work function over the surface. The relationship between the nanostructural state of a polished surface and roughness and reflectivity is presented.

Keywords: nanostructural state, complex loading, wear, friction, surface layer.

INTRODUCTION

Improving the reliability and durability of machine parts and mechanisms of motor vehicles, and other products depends on the use of new technologies that improve the quality of the surface, taking into account operating conditions [1]. The corresponding state of the secondary structures of the surface layer is achieved in the process of finishing operations for the manufacture of parts or operation with the application of a certain specific dynamic and thermal load in the triboassembly. Under the influence of operating conditions, changes occur in the surface layers of the metal, which lead to the loss of performance of parts. In this case, the main role in the formation of the nanostructural state of the surface layer of parts is played by the complex nature of the distribution of loading in space and time.

It should be taken into account that most of the tribocouples of machine and mechanism units are under complex loading conditions under the combined effect of the mutual movement of parts and vibrations in different directions. In particular, during operation, the conditions of impact with slippage (two-component loading) and impact with slip in two mutually perpendicular directions (three-component loading) are possible. Including elements of three-component loading are observed in the process of metal cutting and are caused by three factors: cutting speed, longitudinal movement of the tool or workpiece, and vibrations. Due to vibrations during processing in real cutting conditions, the load value is variable, which indicates the complex nature of the loading during the interaction of the tool and the workpiece and, in particular, is decisive if it is necessary to form a surface with minimal roughness.

The pattern of distribution of various materials in terms of wear resistance varies significantly depending on the loading conditions. A change in one or another factor or the appearance of a new factor leads to a change in the wear mechanism, i.e. his physical condition [2]. This explains the limited possibilities of using the general provisions of friction theories, as well as most of the results of experimental studies carried out under the separate action of each of the possible loading factors.

Some authors have studied the regularities of friction and wear with the combination of individual loading factors, considering varieties of two-component loading, but practically without assessing and analyzing the structural state of the surface layer [3 - 5]. The authors of these studies generally come to the same conclusion: it is impossible to evaluate processes under complex loading within the framework of a unified theory, which determines the leading role of experiment in such studies.

In this regard, it is urgent to expand the understanding of physical and mechanical phenomena in the contact zone, to conduct comprehensive studies of the processes of contact interaction under multicomponent loading with an assessment of the features of the formation of the nanostructural state of the surface layer and the kinetics of surface damage.

EXPERIMENTAL

Considering that tests of a full-scale friction unit are not always possible due to the duration of testing and the high cost of conducting a full-cycle experiment, methods of accelerated testing of friction pairs are of great importance, in which the necessary amount of information about wear resistance is obtained in a shorter time. Obviously, the test method based on simulation of full-scale conditions on a dynamic stand may turn out to be the most acceptable.

Techniques and a number of special installations have been developed, investigated and evaluated, which allow implementing complex contact loading at various ambient temperatures and testing flat samples under conditions close to natural ones in order to obtain and study the functional dependences of the friction-wear characteristics of tribopair materials, their comparative evaluation, and physical modeling [6 - 9]. An approach was used to determine the basic principles for modeling the equivalent states of tribological pairs that are operated under multicomponent loading.

The assessment of the effect of finishing by cutting on the state of the surface layer of manufactured parts was carried out on samples after grinding with abrasive belts on a surface grinder converted for belt grinding.

The physical and mechanical properties of the surface layer of the samples were determined based on the change in the electron work function on a specially designed setup, as well as by continuous indentation and scanning with an indenter on a device for sclerometric studies of materials.

The value of the electron work function (EW) is one of the fundamental characteristics of a substance, the physicochemical and mechanical properties of metals. The measurements were carried out by the contact potential difference between the measured surface and the surface of the reference sample. Due to the inhomogeneous state of the measured metal surface, a corresponding relief of the electrostatic barrier arises, due to the divergence of the electron work function for different parts of the surface. Thus, a given metal surface is characterized by an energy relief due to the distribution of the electron work function over the surface. Comparing the initial energy relief (before wear resistance testing) with the relief after testing, it is possible to determine surface areas that have undergone different degrees of plastic deformation. Of great importance in this case is the increase in the number of dislocations and dislocation steps with increasing plastic deformation. As is known, dislocation steps carry an electric charge; form electric dipoles [10 - 12].

The method of continuous indentation of the indenter during sclerometric tests is based on automatic recording of the depth of penetration depending on the applied load on the indenter of the sclerometric device. The scanning method is based on continuous recording of the resistance to movement of the indenter over the surface (scanning force) depending on the applied load. Determining the statistical relationships between the resistances of local micro-volumes of a material to contact deformation makes it possible to make a comprehensive assessment of the state of the surface layer along the scanning path and, in particular, allows one to estimate the average strength along the scanning path, evaluate the spread and inhomogeneity of strength properties, and simulate elementary acts of friction and wear processes [13].

RESULTS AND DISCUSSION

As shown by preliminary studies [6 - 8], during friction under conditions of complex dynamic contact loading, the amount and nature of wear on the working surface to a large extent depends on the distribution of the normal dynamic load, and the complication of the loading scheme leads to increased wear. Thus, the transmission of transverse slips with an amplitude of up to 0.08 mm (specific impact load from 0 to 0.6 N mm^{-2}, longitudinal slips with an amplitude of 0.1 mm and a frequency of 66 Hz) leads to an increase in the volumetric wear rate of various steels and alloys from 1.38 to 2.6 times compared to the volumetric wear rate without transverse slip under two-component loading (under conditions of impact with longitudinal slip).

In this case, increased wear occurs in parts characterized by the alignment of the strength and deformation properties of the surface layer.

As an example of assessing the state of the surface of tribo-coupling parts by changing the work function of the electron (WFE), Fig. 1 shows the distribution of WFE from the surface of 60S2A (Standard of Ukraine) (C60E - AFNOR) alloy samples after wear with different amplitudes of transverse slips. In the process of deformation by friction, the structural evolution of the surface of metals occurs, which is reflected in the change in the distribution of WFE over the surface. The state of the surface layer of the samples before friction is approximately the same and is determined by the WFE of about 4 eV. As a result of friction with different amplitudes of transverse slips, the state of the surface layer of the samples changed. Friction with two-component loading (A = 0) leads to the formation of a surface layer with an increased value and a large spread of WFE (from 4.0 to 4.1 eV). The presence and increase in the amplitude of transverse slips leads to a decrease in the magnitude and spread of the WFE (about 3.98 eV). The decrease in the scatter in the WFE values indicates an increase in the homogeneity of the structure of the surface layer.

The results obtained are consistent with the data on the assessment of the state of the surface of the parts of tribocouplings by the tribospectral method. Fig. 2 shows tribograms of indenter scanning of 60S2A steel samples after wear under two-component and three-component loading. Tribogramsare characterized by a general increase due to an increase in the penetration depth of the indenter and have different values due to different hardness of the surface layer. However, a change in the spread of this force indicates a difference in the strength and deformation properties of the surface layer - its uniformity. There is a significant difference between tribograms 1 and 2 and tribogram 3. The increased spread of the tangential force during scanning of surface 3 is a consequence of the inhomogeneity of the surface layer.

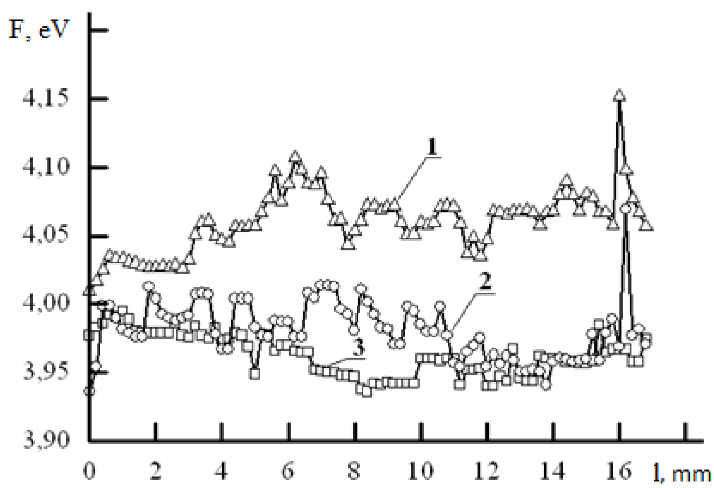

Fig. 1. Distribution of the work function of the electron along the surface of the samples from the 60S2A alloy after wear with different amplitudes of transverse slips: 1 - A_{pop} = 0 mm; 2 - A_{pop} = 0.06 mm; 3 - A_{pop}= 0.2 mm.

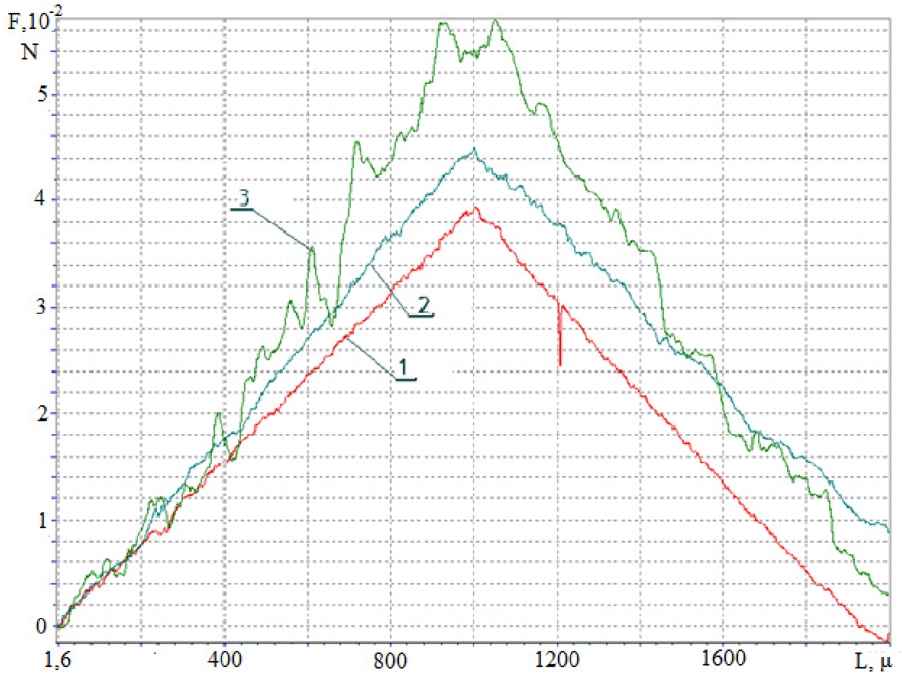

Fig. 2. Scanning tribograms of specimens made of steel 60S2A after tests with different amplitudes of transverse slips: 1 - A_{pop} = 0 mm; 2 - A_{pop} = 0.06 mm; 3 - A_{pop} = 0.2 mm.

Just such a surface layer under the considered friction conditions, as noted above, is characterized by increased wear resistance.

In addition, changes in the strength and structural uniformity of the surface layer, achieved under different friction conditions, lead to a change in the roughness of the contacted surface. With an increase in the amplitude of transverse slips from 0 to 0.2 mm, the surface roughness decreases in the transverse direction from 1.3 to 10 times; in the longitudinal direction from 1.3 to 2 times. An increase in the amplitude of transverse slips is accompanied by an increase in the uniformity of the surface topography; it has a lower roughness and does not contain longitudinal scratches [6, 14].

The results obtained are consistent with the experiments on evaluating the ratio of mechanical properties and structure parameters given in [15], where it was shown that the resistance to brittle fracture depends not only on the grain size, but also on the size of the mosaic block. The flow stress linearly depends on the size of subgrains, which is an element of the substructure. Coarse-grained metal with a highly developed substructure (angle of misorientation of substructure elements, measured in degrees) has a higher hardness and yield strength. Based on the data on changes in the strength and misorientation of blocks, a conclusion was made about the determining influence of the degree of misorientation on the fracture resistance of the metal. Moreover, the nature of the dependence of the flow stress on the grain size, as well as the size of the structural element for a given grain size, indicates an additive effect of two structural parameters. With an increase in plastic deformation, the ratio between the sizes of grains and mosaic blocks decreases [16].

However, considering that the formation of a wear-resistant surface layer of tribo-coupling parts by applying optimal external loading parameters during operation is not always possible, it is advisable to provide it in the process of finishing contacting parts. Modern trends in the production of machine-building parts involve the use of ground and polished workpieces, which eliminates the need for additional surface treatment and significantly improves their quality. Of particular importance is the task of meeting the increased requirements for the quality of the treated surface according to certain criteria by varying the conditions for finishing processing in connection with the formation of a nanostructural state of the surface layer. In particular, this can be achieved by grinding and polishing with endless abrasive belts.

It is impossible to control the technology for

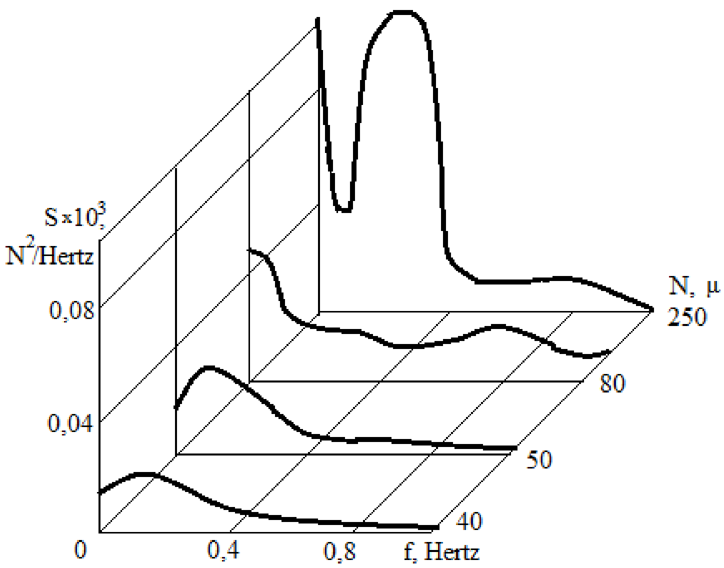

Fig. 3. Curves in the spectral density S of the forces of contact deformation during scanning of samples treated with abrasive belts with different grain sizes, N.

obtaining polished surfaces using only the criteria for the roughness of the machined surface. Certain roughness and grinding and polishing performance can be obtained by using different abrasive belts and processing conditions. At the same time, the energy indicators of abrasive processing differ significantly, which inevitably leads to structural changes in the surface layer of the workpiece. The so-called structural (limiting) roughness arises, associated with the features of the structural state of the boundary layer, which cannot be reduced by simply reducing the grain size of the abrasive belts.

To solve the problem, a set of studies was carried out using the method of identifying the structural state of the surface layer by statistical characteristics on a sclerometric device after strip processing of stainless steel.

The most informative of them is the frequency distribution of the probability density of the deviation of the input (output) signal from the mean value, i.e. spectral density of the input (output) signal, which is used to analyze the main properties of stationary random processes. The spectral density function is introduced into consideration through the Fourier transform. This characteristic gives an idea of the harmonic composition of the signal, the distribution of dispersion over frequencies, and makes it possible to estimate the proportion of large and hard crystallites on the surface by shifting the frequency distribution to the low-frequency region.

Fig. 3 shows the curves of changes in the spectral density of contact deformation forces during scanning of samples treated with abrasive belts of various grain sizes. The spectral density values indicate that the low roughness of the treated surface after reaching a certain limit is determined by the uniformity of the surface layer structure: a more uniform surface layer also corresponds to a lower roughness.

With a decrease in the grain size of abrasive belts, the strength structure of the surface layer changes. So, after grinding for 30 min with belts with silicon carbide abrasive with grains of 250 μm, large-fragment (at a frequency of 0.1 Hz) and small-fragment (at a frequency of 0.27 Hz) components appear in the surface layer of the samples. Reducing the grain size of abrasive belts leads to a decrease in the number and strength of small fragments, and after processing with 40 μm grains, a uniform surface layer with a coarse-grained structure (at a frequency of 0.15 Hz) is obtained. At the same time, the roughness of the treated surface decreased from Ra = 0.2 μm to Ra = 0.1 μm.

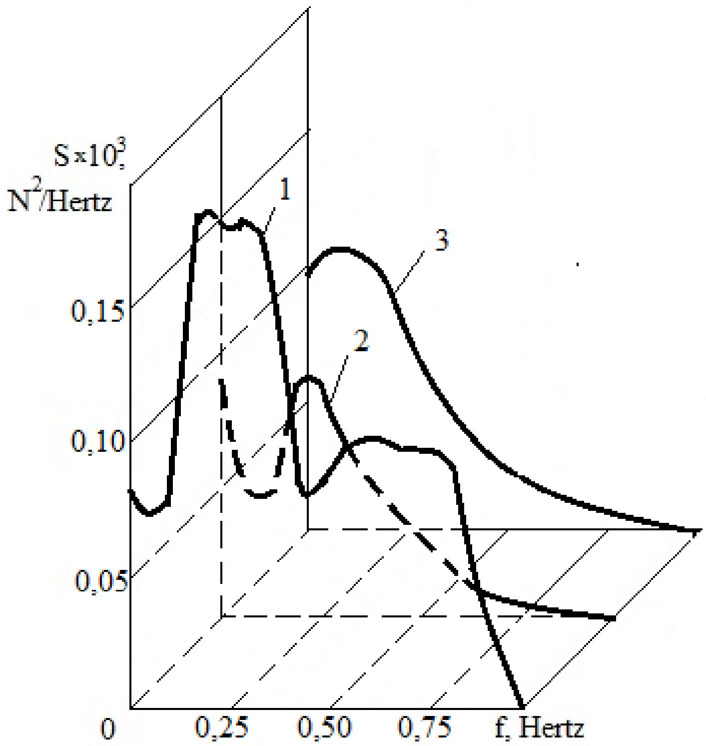

Fig. 4. Curves in the spectral density S of the forces of contact deformation when scanning samples with different reflectivity: 1 - K = 14 %; 2 - K = 18 %; 3 - K = 35 %.

In addition, the control of the nanostructural state of the surface layer makes it possible to evaluate the optical characteristics of the material and ensure the production of a high-quality polished surface with high reflectivity.

Additional studies were carried out to determine the specular reflection value of polished stainless steel samples with a photoelectric glossometer compared to the specular reflection coefficient of a household mirror, the value of which was taken as 100 %. To exclude the influence of surface microgeometry on the magnitude of specular reflection, the surfaces of samples of the same roughness Ra = 0.22 μm were compared in the studies. A different state of the surface layer was obtained by varying the conditions of belt grinding (abrasive material, pressing force, machine processing time).

The obtained changes in the specular reflection coefficient of the samples from 14 % to 35 % are characterized by a significant change in the nanostructural state of the surface layer, which is reflected in the plots of the spectral density of the contact deformation forces, (Fig. 4).

The lowest specular reflectivity of 14% corresponds to the surface layer of an inhomogeneous structure with the presence of large and small fragments at frequencies of 0.20; 0.30; 0.60 and 0.75 Hz (curve 1). A more uniform surface layer with predominant fragmentation at a frequency of 0.25 Hz also has a higher specular reflectivity of 18 % (curve 2). The highest specular reflectivity of 35 % was obtained on a surface with a uniformly stressed large-fragment structure of the surface layer - fragmentation at frequencies from 0 to 0.75 Hz (curve 3).

The presented method for determining the optical characteristics of materials by the nanostructural state of the surface layer makes it possible to determine the reflectivity of the surface of metal parts of complex shape without access to optical instruments with an error of about 30 %.

CONCLUSIONS

Thus, the conducted studies allow us to conclude that a certain nanostructural state of the surface layer of vehicle machine parts and other products is formed depending on the complex nature of loading during manufacture and operation. A change in loading conditions leads to a change in the state of the surface layer and, as a result, a change in the quality of the surface, the wear resistance of the tribocoupling.

An increase in transverse slip during friction with three-dimensional loading contributes to the formation of a more uniform surface layer, a decrease in its strength and wear resistance, and a more uniform surface microgeometry, which is accompanied by a decrease in the magnitude and spread of the electron work function over the surface. In particular, obtaining a uniform state of the surface layer after belt abrasive processing makes it possible to ensure the required quality of the polished surface of parts with minimal roughness and high reflectivity.

The complex interaction of solids in the contact zone should be taken into account when building contact models to predict the surface strength of materials under dynamic loads, and, accordingly, the test conditions should be as close as possible to real operating conditions. Determination of regularities and development of conditions for the formation of a wear-resistant surface layer of tribocoupling parts is possible on the basis of an analysis of the amount of wear and the state of the surface, taking into account the actual type of loading (unidirectional sliding, impact with slip, impact with slip in two mutually perpendicular directions). This will make it possible to consider the physical foundations of plastic-destructive phenomena in the contact zone of tribocouplings, taking into account the action of surface wear products and allows us to formulate the tribological principle of minimizing wear and the wear-resistant ability of materials.

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