

Principles of Surface Engineering for Tribological Contact Components Subjected to Complex Dynamic Loading

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Abstract: The relation between the wear resistance of metal and the structural homogeneity of the surface layer is noted. The principles of surface engineering by using the features of forming the nanostructural state of the surface layer are recommended. A concept for improving the wear resistance of tribological systems is proposed based on the principles of structural adaptation of materials during friction. The results demonstrate the potential for controlling the wear resistance of contacting components through purposeful modification of the surface-layer formation processes.

Keywords: Wear, Complex loading, Friction, Surface layer, Tribological contact.

1. INTRODUCTION

At present, both commercial and research interest in the development of wear-resistant materials is increasingly focused on composite materials in which structural effects and phase composition can be tailored to engineer coating materials combining the properties required for specific service conditions. This approach makes it possible to combine the desired physicochemical properties of the surface layer with the essential properties of the substrate, including high strength, impact toughness, and fracture toughness.

In such systems, the mechanical strength of a component or structure is primarily provided by the bulk material, whereas specific functional properties are imparted by another material, namely, a coating or a modified structural state of the component surface layer. These objectives constitute the principal tasks of surface engineering.

Of particular importance is the development of wear-resistant coatings for tribological contact components operating under complex dynamic loading. Wear may result from intensified oxidation processes and high-frequency relative motion, including vibration-induced tangential sliding as well as normal displacements of small amplitude. Combinations of these loading modes may also occur [1, 2].

Under such conditions, the surface layers of the material undergo damage accumulation in the form of microscopic defects. Owing to the discrete nature of real contact, this process develops non-uniformly and depends on the degree of contact discreteness and the prevailing friction conditions. The simultaneous effects of deformation and diffusion of environmental species

result in specific plastic deformation mechanisms associated with surface-layer activation and an increase in the defect density of the metallic structure [3].

2. ASCERTAINMENT OF THE TASK

It should be noted that a substantial proportion of components in the tribological interfaces of machines and mechanisms operate under impact-sliding conditions. In many cases, impact-sliding occurs in two mutually perpendicular directions owing to functional relative movements in different directions, vibration, or combinations of these factors (Figure 1).

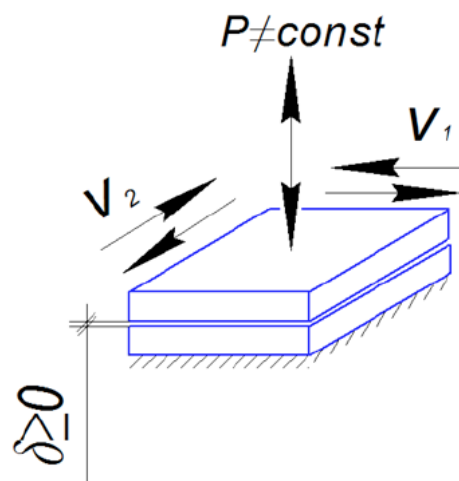


Figure 1: Schematic representation of three-component loading of tribological contacts between flat components under oscillatory sliding with impact loading.

The friction and wear processes, as well as the degradation of surface layers in tribological contacts, are governed by the dynamic nature of load application at the interface and by the amplitudes of relative motion, which determine specific contact-interaction conditions. The combined action of the loading factors initiates deformation processes in the surface layer, resulting in changes in its structural, phase, and stress states and

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in the intensification of diffusion and oxidation processes. These effects have a substantial influence on the wear behavior of the contacting components.

Achieving high wear resistance under complex loading requires an integrated approach to establishing the relationships between the tribological and structural properties of contacting materials under different loading conditions. The loading parameters can be modified, for example, by reducing the clearance in the tribological contact or by damping vibrations. The selection of appropriate design and technological measures should be based on the actual service conditions of the tribological interface and on the physical mechanisms governing material degradation, with particular consideration of the properties of the surface layer.

However, when an increase in wear resistance through changes in component design is associated with substantial difficulties or is practically impossible, technological approaches to ensuring the reliability of the tribological assembly may represent the only viable solution.

3. EXPERIMENTAL TESTS

The results of previous studies [4-7] have demonstrated that the state of the surface layer of tribological contact components changes as a result of structural adaptation of the material during friction. Increased wear has been observed for components characterized by a relatively homogeneous surface layer in terms of crystallite (fragment) size and strength. Such a layer is associated with reduced strength, a more uniform surface microgeometry, and low values and a low spatial variation of the electron work function. Results are presented of the complex evaluation of sample surface states after friction using continuous indentation and indenter scanning and of analysis of the change in the means of electron liberation from the sample surfaces.

As an example of assessing the state of the surface of parts by the tribospectral method, Figure 2 shows tribograms of scanning steel samples by an indenter 60S2A (C60E - AFNOR) after wear under two-component and three-component loading and Figure 3 shows the data on changes in the electron work function (EWF) of these surfaces [4].

Tribograms 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. There is a significant difference between tribograms 1 and 2 from tribogram 3 (Figure 2). The

increased spread of the tangential force when scanning surface 3 is a consequence of the inhomogeneity of the surface layer. This is exactly the surface layer under the considered conditions of friction that is characterized by increased wear resistance. Structural heterogeneity can be promoted by eliminating or reducing impact loading in the tribological contact and by decreasing the amplitudes of transverse and longitudinal sliding [4].

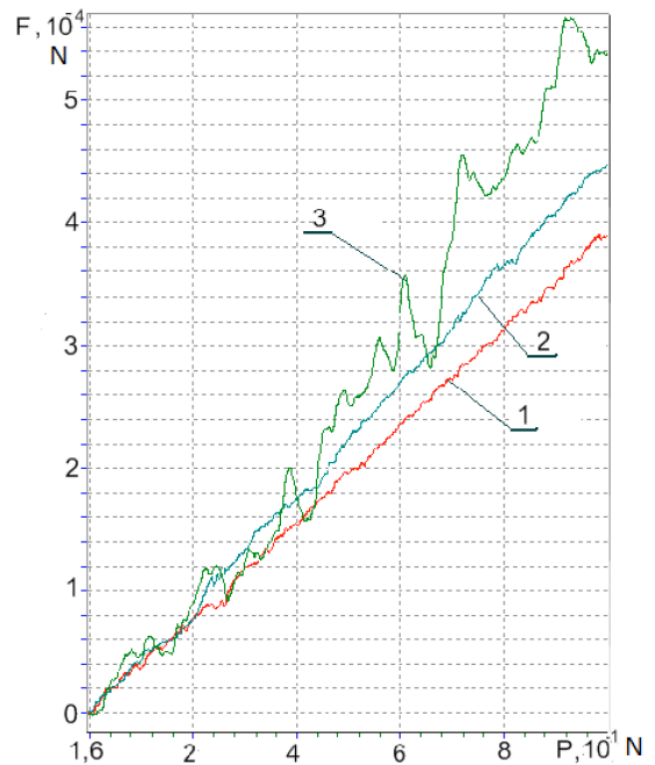


Figure 2: Tribograms obtained in scanning of steel 60S2A samples after testing at different amplitudes of cross slippage (P is loading on an indenter): (1) $A_{trs} = 0.08$ mm; (2) $A_{trs} = 0.06$ mm; (3) $A_{trs} = 0$ mm (two-component loading) [4]. (specific shock loading from 0 to 0,6 H/mm², longitudinal slipping with amplitude a 0,1 mm and by frequency 66 Hertz).

The got results comport with data of change EWF from the surface of standards. In the process of deformation a friction is a structural evolution of surface metals, which is represented in the change distribution of EWF on a surface. State of superficial layer of standards from the alloy of 60S2A to the friction approximately identical and determined EWF about 4 eV (Figure 3). As a result of friction with different amplitude of the transversal slipping the state of superficial layer of standards changed. A friction with a two-component loading ($A_{trs} = 0$) results in the receipt of superficial layer with enhance on a size and large variation of EWF (from 4,0 to 4,1 eV). A presence and increase of amplitude of transversal slipping result in diminishing of size and variation of EWF (about 3,98 eV). Diminishing of variation in the values of WOE specifies on an increase of homogeneity structure superficial layer [4].

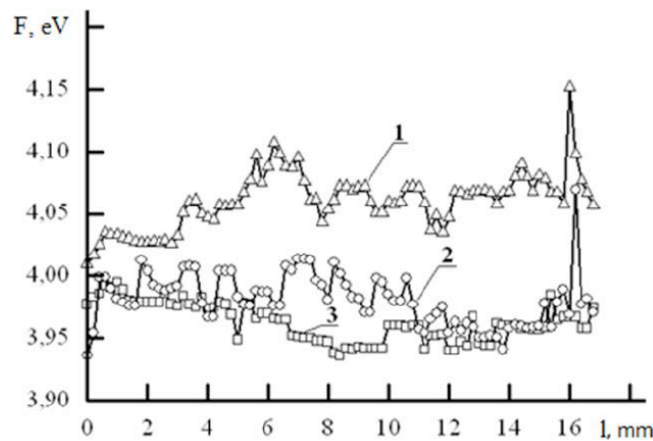


Figure 3: Distribution of electron work function along the surface of standards from the steel 60S2A after a wear with different amplitude of the transversal slipping: (1) $A_{trs} = 0$ mm; (2) $A_{trs} = 0.06$ mm; (3) $A_{trs} = 0.2$ mm [4].

Because of the structural heterogeneity of a material, plastic deformation can occur only through the cooperative deformation of individual structural elements, which are considered here as homogeneous crystallite regions. As deformation proceeds, slip within individual structural elements becomes progressively constrained, resulting in an increase in internal microstresses. These microstresses are a major factor contributing to strain hardening at relatively low plastic strains.

Consequently, one promising approach to the development of wear-resistant components is the formation of surfaces consisting of nanocrystallites (structural fragments) with different sizes and mutually opposite orientations (Figure 4).

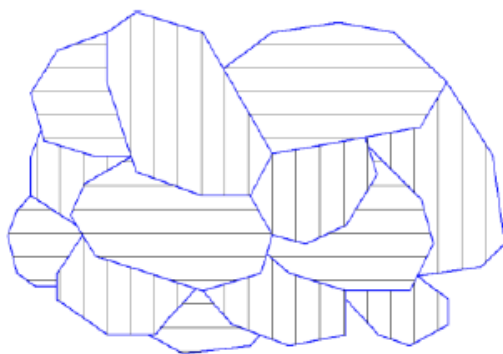


Figure 4: Schematic representation of nanocrystallites with different sizes and mutually opposite orientations.

4. ANALYSIS AND RESULTS

The feasibility of producing such structures has been experimentally demonstrated [8]. Increased hardness can be achieved in coatings consisting of a mixture of nanograins of the same material but with different crystallographic orientations and lattice structures.

As reported in [9], two factors are particularly important for increasing the hardness of such materials. First, the crystallite size should generally be below 10 nm in the direction of deformation in order to hinder dislocation motion. Second, the average intergrain spacing should not exceed approximately 0.5 nm to suppress crack initiation and propagation.

Nevertheless, the dependence of hardness and yield strength on grain size is complex and not monotonic. This behavior is associated with the specific deformation mechanisms of nanostructured materials, including mutual grain sliding along grain boundaries, sometimes referred to as rotational softening.

For relatively large grains, the increase in strength and hardness with decreasing grain size is primarily associated with the increasing number of grain boundaries, which act as barriers to dislocation motion. In very fine nanoscale grains, strengthening is additionally associated with the low density of existing dislocations and the difficulty of nucleating new ones.

Various techniques can be employed to produce surface layers containing crystallites with different orientations [10]. These include template-based methods, nanostructure synthesis in nanoreactors, lithographically induced self-assembly of nanostructures, and severe plastic deformation.

In particular, large plastic strains, such as those produced by high-pressure torsion or equal-channel angular pressing, result in structural fragmentation and crystallographic misorientation. A characteristic feature of nanostructures produced by plastic deformation is the formation of nonequilibrium grain boundaries, which serve as sources of high elastic stresses.

This condition promotes the generation of a high density of dislocations, which are predominantly concentrated near the surfaces of nanoclusters, while also allowing excess energy to be retained within the nanostructure. As a result, nanostructures containing crystallites of different sizes and orientations can be formed [11, 12].

Taking into account the severe thermomechanical loading conditions experienced by the components of the tribological contacts under consideration, the concept of a gradient wear-resistant material with a balanced combination of functional properties has been formulated. The proposed material is intended to withstand impact-sliding loading occurring in two mutually perpendicular directions.

The material has a three-layer nanostructured architecture with different levels of hardness. It

comprises an impact-resistant layer with a columnar or needle-like structure and two textured layers with oppositely oriented crystallites designed to resist wear caused by sliding of the contacting components in two mutually perpendicular directions.

The first and third layers should possess increased hardness, whereas the softer intermediate layer is intended to promote relaxation and redistribution of contact stresses [13].

Under directed external loading, the distribution of stress concentrations evolves toward a state of equilibrium. A continuous competition therefore develops between strain-hardening processes in localized regions of the deformable material and stress-relaxation processes.

The proposed layered coating can reduce the energy required for structural reorganization of the surface layer during operation and thereby contribute to increased wear resistance.

A promising approach to controlling the wear resistance of contacting components is to modify the conditions under which mechanochemical reactions occur in the contact zone of a tribological interface in the presence of free macroradicals and other products of polymer degradation.

This approach expands the technological possibilities for improving the service life of tribological contacts both during the manufacture of machine and mechanism components and during their subsequent operation.

Preliminary studies [14-16] have demonstrated the possibility of controlled introduction of polymer degradation products into the contact zone of a tribological interface or into the tool–workpiece contact

zone during component processing. This makes it possible to modify the structural state of the surface layer in a controlled manner.

A specific structural state associated with a desired level of wear resistance can be achieved by varying the conditions under which free macroradicals interact with the surface. In addition to providing lubricating and cooling effects, polymer-containing media can chemically interact with metals and form chemical bonds whose energies are substantially higher than those associated with the physical adsorption of low-molecular-weight species. Such interactions can therefore modify the strength and deformation characteristics of the surface layer.

Based on the research findings discussed above, a methodology for the surface engineering of tribological contacts subjected to multicomponent loading can be formulated using the approaches summarized in the diagram shown in Figure 5.

5. CONCLUSION

The combined action of multiple loading factors initiates deformation processes in the surface layer that lead to changes in its structural, phase, and stress states and intensify diffusion and oxidation processes, thereby exerting a significant influence on component wear. The tribological principle underlying the minimization of wear and enhancement of material wear resistance consists in establishing contact conditions that promote the formation of a stronger surface layer characterized by increased heterogeneity in both strength and structural-fragment size.

The mechanism proposed for the formation and evolution of the surface layer of tribological contact components under complex dynamic contact loading is sufficiently general to provide a framework for

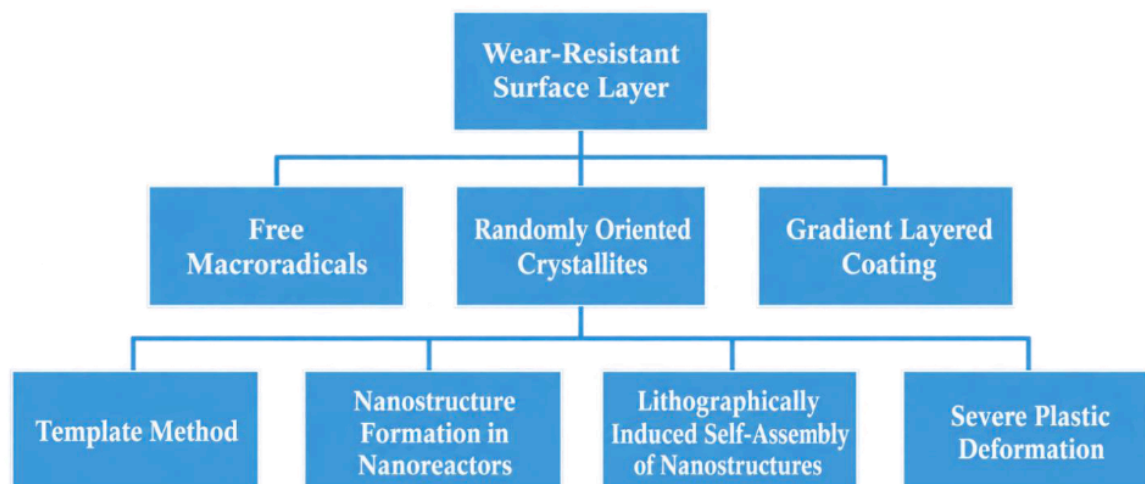


Figure 5: Surface-engineering methods for tribological contacts subjected to complex dynamic loading.

analyzing the physical basis of plastic-deformation and damage-accumulation phenomena in the contact zone. The proposed approach can be used to develop recommendations for producing wear-resistant surface layers on contacting components and may serve as a basis for the purposeful formation of wear-resistant surface structures in components of friction assemblies.

CONFLICTS OF INTEREST STATEMENT

The author declared no conflicts of interest.

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