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# Texture of materials of elements of tribological systems of machines and mechanisms in non-equilibrium processing and functioning conditions

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**Abstract**

The article is devoted to microtexturing of metal and polymer materials of tribological system elements, its influence on the characteristics and properties of working surfaces of samples and parts. Various types of microtexture of steel and composite materials based on zirconium oxide are considered. The mechanism of their formation is clarified. Mainly, the mechanisms of microtexturing are associated with the field of tension created during friction and laser processing. It is determined that laser processing of steel samples leads to combined microtexturing and a texture gradient along the depth of the surface layer of the sample. Texture in composites is revealed both during laser processing and during friction testing. It is shown that the revealed texture positively affects the operational characteristics of parts, increasing the level of reliability and wear resistance, as well as the tribological efficiency of tribocouplings of parts of assemblies, systems, units of machines and mechanisms.

**Key words:** steel, composite, tribological system, microtexturing, X-ray radiation, laser processing, texture perfection, friction testing, reliability, wear resistance.

## Introduction

Increasing the durability of mating parts, assemblies, systems and units of machines and mechanisms in general is one of the important and priority tasks of modern mechanical engineering. This problem can be solved only on the basis of an integrated approach, which includes the creation of new materials from which parts are made, the development of effective innovative technologies, manufacturing, strengthening and manufacturing and modification of working surfaces of parts. At the same time, during strengthening, restoration and modification, it is necessary to take into account the influence of technological parameters on the initial, intermediate and final state of the material of the part as a whole. This means that first of all it is necessary to determine the microstructure, to find out its texture, to identify the distribution of alloying elements and phase composition, stress-strain state, that is, to find out the evolutionary development of the material of the part during processing by various technologies and during operation [1].

The main task of texturing is to reproduce the roughness and surface finish of materials of tribological system (TrS) elements, which, thanks to microtexture, are constantly used to reduce friction and wear and increase the tribological efficiency of the system.

The microtexture of the working surfaces of mating parts of machines and equipment has a synergistic triple effect: reserve for liquid and solid lubricants; collection of wear particles; limitation of abrasion and formation of a hydrodynamic film.

The microstructuring of the friction surface can be optimized using mathematical methods, finite element methods, and computational hydrodynamics based on the Navier-Stokes and Reynolds equations for the hydrodynamic mode of operation of the TrS.

The latter method simulates the flow of the lubricating medium and makes it possible to predict the bearing capacity, velocity and pressure field in the TrS, and also takes into account inertial effects. Artificial intelligence

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(AI) methods are used to model the evolutionary behavior of the TrS with optimized microtexture, primarily the genetic algorithm method.

The shear effect, which is characteristic of hydrodynamic lubrication in the TrS, the film thickness, the friction coefficient and energy consumption are associated with the artificially formed texture of the working surfaces of triboelements (parts). The texture has a positive effect both in conditions of dry friction of mating parts, and for friction with solid and liquid lubrication in the presence of a layer of oil, grease, ceramic composite or solid lubricant.

Texturing the friction surface and controlling its properties, such as roughness, is one of the methods for increasing the efficiency of the friction surface. Texturing methods are definitely relevant methods for improving the characteristics and properties of the working surfaces of tribo-coupling parts made of metal and composite materials, since they effectively reduce friction and wear processes. Changing the roughness and surface relief guarantees an improvement in the tribological properties of the mating surfaces by the components and measures involved, which significantly increase the TrS.

**Literature review**

It is known that the surface of the material of parts is considered textured if there is a preferential orientation of crystallites in polycrystalline materials and high-molecular compounds in composites relative to the external coordinate system [2].

Texture is formed under the influence of various types of anisotropies, forces, during material production, part formation, and external influences of various physical and chemical nature.

The practical interest in the textures of materials is due to the fact that they determine the anisotropy of the characteristics and properties of the working surfaces of tribocoupled parts. If all the crystallites of the polycrystal of metals and high-molecular compounds in composites have one predominant orientation, then such a texture is single-component [3]. If there are several groups of crystallites and high-molecular compounds, each of which is characterized by its own orientation, then such a structure is multicomponent.

In real conditions, there is a certain deviation of the orientation of some crystallites or high-molecular compounds in the textured material from the "ideal" location relative to the direction of the influence that causes texture formation by a certain angle $\delta$. This phenomenon is due to the scattering of the texture. The degree of scattering of the texture is generally greater, the stronger the external influences acting on the material of the parts. This may be the degree of plastic deformation.

The formation of the surface texture of a triboelement (TrE) changes the contact area between them, reduces friction and increases the tribological efficiency and service life of the TrS. Non-equilibrium strengthening, restoration and modification technologies are widely used to create the texture of the working surfaces of parts, including laser processing [4] . They allow you to create a microtexture that can perform different functions depending on the operating conditions: accumulate and direct the lubricant, and then release it at the stage of use. Depending on the geometry of the texture, friction decreases, hydrodynamic pressure increases.

The effects of surface texturing strongly depend on the operating conditions of the TrS, which can enhance or weaken them.

To improve the tribotechnical characteristics, it is possible to apply a coating to the textured surface, i.e. to treat the textured surface. In this case, the shear resistance is reduced, the substrate is protected by a soft coating, the contact area between mechanical parts and friction is reduced, and solid lubrication is implemented. The key parameters when using solid lubricants are the contact area between moving TrE, the load, its effect on microstructural changes in the contact areas and the formation of a film between the mating surfaces [5].

The texture of the working surfaces of parts can change heat transfer, implement better heat removal from the contact zone, which increases the wear resistance of parts. The distribution of the stress field in the surface layers of the material of the mating parts and the wettability of their surfaces can also change.

There are various texturing methods: micromilling, microcasting, electrochemical processing, etc., but laser texturing of the working surfaces of parts has the most advanced texture, since it is created under non-equilibrium conditions [2,3,21].

By adjusting the parameters of the texturing process, it is possible to control the shape and optimize the geometric factors of the surface structure of the part itself. However, the method is difficult to apply on a large scale due to high energy consumption.

It is known that the stress-induced martensitic transformation in zirconium oxide ceramic $ZrO_2$ from the metastable tetragonal (T) to the stable monoclinic (M) phase, on the one hand, and twinning, on the other hand, are two competing mechanisms of deformation of composite materials [4,6,22]. This occurs at a temperature at which the stress-induced TM transformation is more likely to be observed in the material. With increasing temperature, when the thermodynamic stimulation of the transformation decreases, another strengthening mechanism begins to operate, based on the reorientation of coherent mechanical twins in the field of applied stresses. In the literature, this is defined as ferroelasticity [6,23]. The action of the ferroelasticity mechanism in ceramic materials during laser processing and under friction conditions is practically indistinguishable. Ferroelasticity is observed under conditions of high temperatures and high sliding speeds or under high-temperature friction [15-17].

Usually, the reorientation of crystal lattices by the mechanism of ferroelasticity is accompanied by the appearance of a texture, which is detected by the X-ray method [8,9,22,23]. This is manifested in a change in the relative intensity of X-ray lines in the doublets (002)-(200), (202)-(220), (113)-(311), (004)-(400) and others of the T-phase [8,9,22,23]. Unfortunately, ferroelasticity for the T -phase of zirconium dioxide cannot be considered the only reason for the appearance of such a texture. In work [9] it was determined that the effect of the appearance of a texture during grinding of samples of ceramic materials is explained by the reorientation of the crystal lattice due to the reversible martensitic transformation, which occurred as a result of surface heating. According to [10,11], it is possible to separate these two named deformation mechanisms by simultaneously observing the behavior of the monoclinic phase content on the friction surface and in wear particles. It should be noted that the structural state of the friction surface at the time of its destruction (wear) is observed in the wear particles [12-14].

Thus, the analysis of literary sources and operational data shows that the cause of failure of about 80% of machine and mechanism parts is the wear of their working surfaces. This indicates that it is the working surfaces with a whole complex of tribological properties created during the hardening process that limit the service life of the mating parts [18-20].

At present, a sufficiently substantiated scientific approach has not been developed that would allow adequately describing and explaining the influence of a complex of technological measures, including laser processing and alloying and evolutionary factors on tribological properties. Thus, the scientific literature indicates that a positive effect on the tribological properties of working surfaces is their texture [24,25]. At the same time, there is practically no data on the influence of the microtexture of the working surface and the surface layer on the operating conditions of mating parts and their durability and tribological efficiency.

**Purpose**

The purpose of the work is to clarify the possibilities of implementing microtexturing of materials (metals and polymers) of elements of tribological systems using laser processing, the type of formed textures and improving the characteristics and properties of surface layers of materials, as well as the tribological efficiency of conjugated parts of machines and mechanisms.

To achieve the set goal, the following tasks were solved:

– refinement of the methodology for X-ray microtexture studies of steel and composite materials;

– identification of types of microtextures of metallic materials after laser processing and study of their influence on the characteristics and properties of surface layers and increasing the efficiency of tribological systems;

– identification of microtexture types of ceramic materials after laser processing and friction testing and study of their influence on the characteristics and properties of surface layers and increasing the efficiency of tribological systems.

**Results**

In practice, two types of texture are most commonly encountered: axial and bounded.

Axial (axisymmetric) texture is a texture in which all crystallites or macromolecular compounds are established in a predominant crystallographic direction $\langle uvw \rangle$ along a certain direction on the surface and surface layer of the material of the sample (part). The direction $\langle uvw \rangle$ is the texture axis, and *uvw* are the direction indices. The latter determine the orientation of crystallites or macromolecular compounds along the direction of influence of any nature, which caused the formation of the texture. The greater the angle of deviation from the direction of the ideal texture axis, the greater the degree of texture scattering. In the case of a multicomponent axial texture, a composition of textures is formed in metal or polymer materials:

$$\langle u_1 v_1 w_1 \rangle + \langle u_2 v_2 w_2 \rangle + \langle u_3 v_3 w_3 \rangle + \ldots + \langle u_n v_n w_n \rangle . \quad (1)$$

Axial texture is formed under the influence of forces acting predominantly in one direction: drawing; extrusion; compression; deposition from a gaseous medium; crystallization, etc.

There is also a limited texture, in which crystallites or high-molecular compounds are fixed in a certain position: there is a certain plane $\{hkl\}$and direction $\langle uvw \rangle$, lying in this plane. A limited texture is formed when the sample (part) is subjected to forces in several directions. A typical example of such a texture is the texture that occurs during rolling. It is formed as a result of the action of compressive forces *Q* in the direction perpendicular to the rolling plane and tensile forces along the rolling direction. After deformation, certain planes $\{hkl\}$in the grains of a polycrystal or high-molecular compounds become parallel to *Q*, in the direction $\langle uvw \rangle$ parallel to rolling. If a strong single-component rolling texture is observed, the crystallites practically lose their degree of freedom and the polycrystalline material becomes similar to an oriented block single crystal.

The rolling texture in general form is denoted by: $\{hkl\}$, $\langle uvw \rangle$. The indices *hkl* and *uvw* are related by the zoning condition, which for the cubic system is written as follows:

$$hu + kv + lw = 0 \,. \tag{2}$$

The observed scattering of the texture during rolling means that the planes $\{hkl\}$ in some of the crystallites are slightly deviated from the plane of the working surface Q, and the directions $\langle uvw \rangle$ are not strictly parallel to the rolling direction. The multicomponent rolling texture is denoted as follows:

$$\{h_1k_1l_1\}\langle u_1v_1w_1\rangle + \{h_2k_2l_2\}\langle u_2v_2w_2\rangle + \{h_3k_3l_3\}\langle u_3v_3w_3\rangle + ... + \{h_nk_nl_n\}\langle u_nv_nw_n\rangle \,. \tag{3}$$

Determination of the nature of the texture in polycrystalline materials and high-molecular compounds in polymers and assessment of their scattering can be carried out by analyzing direct and reverse pole figures constructed according to X-ray structural analysis data on diffractometers of various models using computer equipment and information technologies.

Direct pole figure (DPF) is a homostereographic projection (HSP) defined by the set of crystallographic planes $\{hkl\}$(stereographic projections of normals $N_{hkl}$ to these planes $\{hkl\}$) for all crystallites (grains) of a given polycrystal. The position of the points of the pole figure is defined by two angles $\alpha$ and $\beta$ , where $\alpha$ is the radial coordinate, varying from 0 to 90 °; $\beta$ is the azimuthal coordinate, varying from 0 to 360 °.

In the case of an axial texture, the projection plane is usually chosen parallel or perpendicular to the texture axis. In the case of a limited texture, the projection plane is chosen parallel to the rolling plane, and on the pole figure, the directions of force or field effects and the directions of normal (DN) projections perpendicular to them are fixed.

The inverse pole figure (IPF) is the distribution of pole densities $P_{hkl}$ for a given direction in a sample (part) on a standard triangle of the stereographic projection of the directions of a single crystal of a given system. The pole density on the IPF shows the fraction of crystallites $\{hkl\}$whose plane poles coincide with the specified direction in the sample (part). Therefore, $P_{hkl}$ it represents the probability of the coincidence of a given direction in the sample with the specified crystallographic directions. As a rule, the IPF is used to analyze the orientation of the normal to the studied plane of the sample (part).

The IPF is constructed in the region of a standard triangle, which is understood as a triangle highlighted in the standard projection of a single crystal, the vertices of which connect the three main directions. At the same time, near the different poles of the region of the standard triangle, the corresponding values of the pole densities are marked, which are determined using experimental data on the dependence of the intensity of diffracted X-ray radiation on the position of the sample relative to the incident beam of rays.

The advantages of texture analysis using IPF compared to DPF are as follows:

1. Larger distances of regions from each other, corresponding to different poles on the IPF than on the DPF. This is especially important in the case of scattered and multicomponent structures, when there is an overlap of different orientations on the pole figure.

2. More accurate quantitative determination of orientations describing the texture. In the case of DPF, there is a need to analyze several DPF for different normals, which is associated with an increased duration of the experiment and processing of the obtained data.

3. Ability to quantify texture components and their dispersion.

4. The method of constructing the IPF using the integral intensities of X-ray interference does not require the use of a special prefix, which is necessary for constructing the DPF using the tilt method.

The main disadvantages of studying texture from IPF are as follows:

1. When working with flat samples with a small working surface, it is necessary to analyze a whole set of wires or sections of a set of strips placed next to each other, which can lead to large errors;

2. With a multicomponent texture, the correctness of the choice of the combination of plane and direction indices for the rolling texture should be confirmed by DPF analysis, if necessary.

Let us consider the method of diffractometric analysis of the texture of sample materials.

Using DPF, the analysis is based on measuring the intensity of certain X-ray interferences (HKL) for different positions of the sample. Different positions of the sample are created by its rotation. For an untextured sample, crystallites and high-molecular compounds are arranged statistically randomly and changing the position of the sample in space should not affect the magnitude of the X-ray intensity and $I_{HKL}$.

For a textured sample in which the crystallites have a predominant orientation, changing the position of the sample changes the intensity of the X-ray radiation $I_{HKL}$, which, under certain conditions, reaches maximum values. In this case, texture maxima appear on the diffraction curve. Their angular position and magnitude are determined by the nature of the texture.

Two main methods of taking textures on a diffractometer are used: "reflection" taking, which is used for massive samples, and "transmission" taking on "thin" samples.

The type and method of constructing the DPF, and therefore the method of recording diffractometric curves, depend on the mutual location of the texture axis B and the sample plane q.

When they are parallel, the projection plane is parallel to the direction B and the projections of the normals $N_{hkl}$ on the DPF are located on the parallels that are from the exit of the axis B on the projection circle at an angle α. In this case, it makes sense to analyze only the dependences I(α). When the plane and the texture axis are perpendicular, the center of the DPF coincides with the projection of the axis B and the projections of the normals on the DPF are located on a circle of radius ρ with the center at point O.

If the sample plane is parallel to the texture axis, then the measurement is performed without rotation at an angle β (β = 0). If the sample plane is perpendicular to the B axis, then the measurement is performed with rapid rotation of the sample at an angle β (60 rpm). Typically, the tilt method is used. The angle α is changed by rotating the sample around the horizontal axis of the goniometer discretely through 5˚ in the range from 0 to 75˚.

The axial texture axis (*uvw*) is found from the analysis of the I(α) curves. To find it, the angles $\langle uvw \rangle$ corresponding to the peaks of the diffraction curve βare determined, which are related to the angle $\alpha_{\max}$ between the normal and the texture axis by the relations:

$$\alpha_{\max} = 90^0 - \beta \text{, at } q \parallel \text{B; } \alpha_{\max} = \beta, \quad \text{at } q \perp \text{B.} \tag{4}$$

Analysis of axial texture using diffractometric curves of X-ray structural analysis is a fairly fast method. In the presence of several components of the axial texture and their scattering, it is convenient to use DPF. On the curves I(α), 5...7 levels of identical intensity values are selected, which are plotted on the vertical diameter (β = 0) on the PC monitor at points corresponding to certain angles α. Parallels are drawn through the points using a Wolf grid or circles using a Boldyrev grid. Using a table of angles, based on the I(α) dependencies, the axis of the axial texture is determined. After that, the texture scattering is found and the DPF is constructed.

To record diffraction curves, the sample surface area is set perpendicular to the goniometer plane (α=0). The diffraction curves $I_{HKL}(\theta)$ are recorded in the same way as in phase analysis on a diffractometer. In this case, the sample and the counter are rotated around the goniometer axis, changing their position by angles θ and 2θ, respectively.

During the measurement, all diffraction maxima (HKL) that can be obtained on a given X-ray radiation are recorded. As a rule, when studying the texture of metals with a cubic lattice, hard radiation from a molybdenum anode is used. In this case, secondary characteristic radiation is possible. It is attenuated by a thin aluminum foil, which is installed in front of the counter. For metals with non-cubic grids, softer radiation is used. In a structureless reference sample, the crystallites are arranged randomly with respect to the q plane, so the integral intensity of X-ray radiation is determined only by the radiation intensity multipliers and the measurement geometry.

For a textured sample, the intensity of the X-ray lines also depends on the type of texture. The value of the pole density is determined by the formula:

$$P_{hkl} = \frac{\left(\dfrac{I_{РЛД}}{I_{HKLeK}}\right)\sum_N p_{hkl}}{\sum_N p_{hkl}\left(\dfrac{I_{РЛД}}{I_{HKLeK}}\right)}, \tag{5}$$

where $I_{HKL}$ – the integrated intensity of X-ray interference of the analyzed planes (*hkl*) of the studied textured sample; $I_{HKLeK}$ – the same for the reference sample; $I_{РЛД}$ – the intensity of X-ray lines of the diffraction spectrum; $p_{hkl}$ – the repeatability factor for the planes (*hkl*); *N* – the number of analyzed poles.

The accuracy of determining the pole density corresponds to 10...20%. The untextured sample is made of the same material as the textured one in order to perform the normalization operation. The normalization condition is introduced into the formula in order to take into account the possible unevenness in the spatial distribution of normals due to the texture. The normalization value is performed in such a way that the average value of the pole density in any direction for the untextured sample would be the same:

$$P_{hklek} = \overline{P} = \frac{\sum_N \left(P_{hkl} p_{hkl}\right)}{\sum_N p_{hkl}} = 1. \tag{6}$$

For a textured sample $P_{hklek} \neq \overline{P}$ .

IPF makes it possible to quantitatively determine the proportion of components that determine texture:

$$f_{hkl} = \frac{\left(\dfrac{I_{HKL}}{I_{HKLeK}}\right) p_{hkl}}{\sum_N p_{hkl}\left(\dfrac{I_{РЛД}}{I_{HKLeK}}\right)}. \tag{7}$$

If the operating conditions of the part, the shape and location of the surfaces of maximum tangential stresses are known, then it is possible to theoretically calculate or experimentally determine which orientation of the crystals in the part provides the greatest strength and durability. The predominant orientation of crystallites in polycrystalline materials and high-molecular compounds occurs under directed external influence or the orienting action of the external environment.

In real conditions, there is often not one, but several preferred orientations of crystallites or high-molecular compounds, that is, a multicomponent texture of triboconjugates of machines and mechanisms arises.

When manufacturing and operating parts and their tribo-coupling parts, it is necessary to take into account both the texture of the source material and the methods that allow creating and controlling a certain texture.

The authors of the work believe that one of the effective ways to create and control texture can be laser processing of the working surfaces of parts and their mating surfaces.

The research was carried out on cylindrical samples (d=22 mm; h=12 mm) with the initial texture <110> and grain size 30...40 μm. Laser processing was carried out on laser installations "Kvant-16" (λ=1.06 μm; $\tau=5\cdot10^{-3}$ s), LGN-702 (λ=10.6 μm; P=780±20 W). The surface after laser irradiation is a set of tracks both without overlap and with overlap of 15...30%.

The conditions for the formation of the texture of the surfaces of parts made of metal materials during their hardening by laser technologies, as well as the influence of technological parameters on the quality of the texture, were revealed. The research was carried out on samples that were subjected to the following laser hardening technologies: thermocyclic, thermomechanical laser technology of thermal treatment and complex laser alloying. Laser treatment was carried out in continuous and pulsed radiation modes with and without surface melting. The materials under study were: samples of steel 3, 45, ШХ-15, 40Х, 65Г; aluminum alloys АЛ-5, АЛ-9, АК–7. The model materials were carbonyl iron and pure aluminum and copper.

The texture analysis was carried out using direct and reverse pole figures, which are built on the basis of the diffractometric method. The texture was determined using the dependences of intensity on the angle of inclination using a PC. The samples were examined on X-ray installations УРС-60, ДРОН-3М using K αCO - X-ray radiation. When a texture gradient was detected, the samples were subjected to sequential etching from the surface in a helium atmosphere or by an electrolytic method.

The metal samples were studied after laser heat treatment, chemical-thermal boriding, and laser boron doping.

The tilt method was used to remove the lines <001>, <110>, <112>, <123>, <200>, <002>, <211>, <202> both from the surface and from different depths of the laser exposure zone, etching the layers in steps 0,1 mm.

The initial texture on the samples of steel 3 was <110>, and on steel 45 – <001>.

As a result of laser processing, it was found that laser irradiation, depending on the power density, can form different types of textures, the degree of perfection of which is not uniform in the depth of the laser impact zone. This was found both in the case of laser heat treatment and in the case of laser alloying. It is characteristic that during laser processing a whole series of textures appears, which is not observed during mechanical impact, when there is one type of texture. For example, during laser heat treatment of steel 3, textures <210>+<211>+<321> were recorded, with the initial axial texture <110>. Note that the power density of laser radiation did not exceed the critical one, at which melting was observed.

It has been determined that during the crystallization of the material after laser melting, a texture appears: the dendrites have a directional direction in the laser exposure zone.

It was found that the degree of perfection of the axial crystallographic texture along the depth of the boride layer varies exponentially. For steel 45 with the initial texture of the $Fe_2B$ <001> phase:

$$P = 6{,}60 + 8{,}82\big(1 - \exp(-0{,}0026h)\big),$$

where $h$ is the depth of the boride layer.

After laser irradiation, the strengthened layer was also textured in depth, and the degree of perfection of the texture of the $Fe_2B$ phase varies according to a linear law:

$$P = 5{,}87 + 0{,}26h\,.$$

Correlation analysis was performed using the usual method: $r = 0{,}861$ .

Studies have shown that there is a relationship between the texture of the working surface of metal parts strengthened by a laser beam and their wear resistance: the higher the degree of perfection of the texture, the greater the wear resistance.

The work also established a correlation between the degree of texture perfection and wear resistance of samples boronized by laser doping: the greater the thickness of the doped layer and its texture, the higher the wear resistance.

The authors explain the detected effects both by the redistribution of carbon and boron in the studied steels, and by the orienting action of the laser beam, its various effects on the structure of the material.

We also note that the study of textured structural materials has not only practical but also great theoretical importance, because textured polycrystalline materials are closer to single crystals the more perfect their texture is, even though they have crystallite (grain) boundaries.

Studies have shown that in the field of laser radiation, a whole spectrum of textures can be obtained on the surface of a structural material. In addition, during sequential etching of samples, texture was detected even at a certain depth to 0,5 mm. It is characteristic that at different levels of the surface layer a different texture is observed, that is, we have a gradient of textures during laser processing of the surface of samples of metallic materials.

The latter indicates the specifics of the effect of laser radiation on structural metal materials.

Gradient texture allows for targeted production of functional, reinforced surface layers on parts, which will ensure their high performance. This is especially true for parts of tribological systems.

Comparative analysis of textures obtained during thermocyclic, thermomechanical and laser treatments showed that the degree of perfection of textures on the same materials is different. Laser treatment has a higher degree of perfection. These results can be explained by the different intensity of laser radiation energy directed at the material and the different duration of its absorption by the material surface.

As ceramic materials for the study, ceramics with a composition of 98 wt.% $ZrO_2$ (zirconium oxide) + 2 wt.% $Y_2O_3$ (yttrium oxide) were selected. Ceramic material of this composition was prepared by sintering in vacuum at a temperature of 1879 K with different holding times. The technology for preparing this ceramic provided different grain sizes, and accordingly, different contributions of the transformation strengthening mechanism. In the initial state, all ceramic samples consisted of tetragonal and cubic phases. Friction and wear tests of ceramics based on zirconium oxide were carried out on a УМТ-1 friction machine using the "disk-finger" scheme. The speed increase was provided stepwise, under conditions of friction without lubricant. The main sample made of ceramics was a finger. The conjugate specimen was a disk rotating in a vertical plane, made of cast high-speed steel, the hardness of which was HRC 60.

X-ray examination of wear particles and friction surfaces of ceramics in the initial state and after friction was carried out on a ДРОН-УМ1 X-ray diffractometer with Cu-$K_\alpha$ radiation. The shooting was carried out at points in the angle interval $2\theta$: 20...48°. The accelerating voltage was 40 kV, the tube current was 22 $\mu A$. Using special computer software, the relative intensities $I$ of the X-ray lines (002) and (200) of the tetragonal modification of zirconium oxide were analyzed. For each friction mode, the ratio $I_{(002)}/I_{(200)}$ was determined. The content of the monoclinic phase on the friction surface was determined by the ratio of the integral intensities of the lines of the {111} type of tetragonal and monoclinic modifications.

An X-ray study of the surface of samples of ceramic materials based on zirconium oxide $ZrO_2$ after laser processing without melting and dry sliding of the samples in a wide range of speeds was carried out. The surface structure was analyzed and it was shown that the textural state of the friction surface is similar to the textural state observed previously on the surface of samples of similar materials after rough grinding. The main trends in the change in the ratio of the intensities of the X-ray lines I(002)/I(200) of the tetragonal phase $ZrO_2$ depending on the sliding velocity and grain size of the ceramic were identified. The mechanisms of lattice reorientation operating at different sliding speeds are substantiated. It is determined that high-strength ceramics are a promising material for tribotechnical use. The implementation of the wear mechanism of ceramic materials can be associated with the processes of deformation of surface layers in the material both under laser processing and friction conditions. This is especially important for ceramic materials that are prone to structural changes under the influence of created or applied stresses.

Studies conducted on samples that were not subjected to laser processing without surface melting showed that in all friction modes, a microtexture is formed on the working surface of the ceramic. The samples that were subjected to laser processing also had a microtexture (table 1).

Table 1

**Dependence of the ratio of X-ray intensities $I_{(002)}/I_{(200)}$ on the speed of movement of the sample during friction. Ceramic grain size 1.6 µm**

| Surface type | Sample movement speed during friction | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 |
| Textured under friction conditions | 0.5 | 0.8 | 0.9 | 1.0 | 1.2 | 1.4 | 1.5 |
| Polished | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Laser processing | 2.2 | 2.2 | 2.0 | 2.0 | 2.0 | 2.1 | 2.1 |

After friction, the ratio $I_{(002)}/I_{(200)}$ increases in such a way that it always exceeds the value characteristic of a random orientation of crystal lattices, which is approximately 0.5. Note that in the initial state, a pre-polished surface was considered.

It is determined that after a speed of movement of 0.2 m/s the ratio $I_{(002)}/I_{(200)}$ reaches a value of the order of 0.2, and after laser treatment 2.2. Further increase in the friction velocity causes a smooth increase in the ratio of the intensity of X-ray lines $I_{(002)}/I_{(200)}$ on the untreated laser radiation to a value of about 1.5. After laser processing of ceramic samples, a more perfect texture $I_{(002)}/I_{(200)} = 2.2$ was found. This behavior was observed on all studied samples of composite materials regardless of grain size. In addition, it was found that the ratio of the intensity of the lines $I_{(002)}/I_{(200)}$ increases with increasing ceramic grain size (table 2).

Table 2

**Dependence of the ratio of the intensities of the X-ray lines $I_{(002)}/I_{(200)}$ on the size of the ceramic grain and the speed of movement of the sample subjected to laser processing**

| $v$, m/s | Ceramic grain size $\overline{d}$, μm | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.80 | 1.00 | 1.20 | 1.40 | 1.60 | 1.80 | 2.00 | 2.20 | 2.40 | 2.60 | 2.80 | 3.00 |
| 1.1 | 1.30 | 1.32 | 1.36 | 1.38 | 1.40 | 1.43 | 1.48 | 1.50 | 1.54 | 1.59 | 1.60 | 1.62 |
| 0.4 | 0.80 | 0.85 | 0.90 | 0.95 | 1.00 | 1.10 | 1.20 | 1.40 | 1.16 | 1.18 | 1.20 | 1.23 |
| 0.1 | 0.80 | 0.83 | 0.85 | 0.88 | 0.90 | 0.91 | 0.93 | 0.96 | 0.98 | 0.99 | 1.00 | 1.15 |

The ratio of the intensity of the X-ray lines $I_{(002)}/I_{(200)}$ under the specified conditions varied in the range (0.8...2.2).

Analysis of the obtained data on the ratio of line intensities in the (002)-(200) doublets of the tetragonal phase shows that most of the grains of the composite material are oriented relative to the friction direction so that the applicate axis $c$ perpendicular to the friction surface. Taking X-ray diffraction patterns without rotating the sample under conditions of beam diffraction along and across the sliding direction did not reveal differences in the intensity of the lines in the doublets. This indicates that the abscissa $a$ and ordinate $b$ *axes* tetragonal cells are oriented arbitrarily in the plane of the friction surface.

The amount of monoclinic phase in wear particles, as well as on the friction surface, decreases with increasing sliding speed. Already at speeds above 1.1 m/s, there are no traces of martensitic transformation (monoclinic phase) either on the friction surface or in wear particles. In those cases where the monoclinic phase is present after friction, it was found that its content in wear particles is always higher than on the friction surface.

At the lowest speed in the tribocontact zone, the temperatures are low, and therefore reorientation of the composite lattice through the martensitic phase is possible. Obviously, this process takes place at speeds of 0.2 m/s, which is indirectly confirmed by the data of the X-ray structural analysis of the surface of samples of composites based on zirconium oxide, where lines of the monoclinic phase and the strongest inversion of the peaks (002)-(200) of the tetragonal phase are observed. In this, the irreversible oriented tetragonal-monoclinic transformation under the influence of contact stresses prevails. The obtained data indicate that at a speed of 0.9 m/s, a significant proportion of the reversibility of the martensitic transformation appears. This led to a decrease in the content of the monoclinic phase in the wear particles and its almost absence on the friction surface. Reorientation in this case can be carried out according to the scheme: tetragonal-monoclinic transformation under the influence of contact stress and monoclinic-tetragonal transformation under the influence of heating.

The flash temperature estimates [13] showed that with increasing velocity, the contact temperatures initially reach the temperature range ($>1273$ K) of the stability of the tetragonal phase , and then increase within (1773...2273 K) of the two-phase tetragonal-cubic region of the phase diagram of the oxide system ( $ZrO_2 - Y_2O_3$). In this case , the reorientation of the lattice of the composite material through the martensitic phase in this speed range becomes impossible. The texture observed in the composite material of both irradiated and non-irradiated samples during friction can be formed by the ferroelasticity mechanism. In addition, the resistance force for ferroelastic domain switching in ferroelastic materials, similarly to the coercive force for ferromagnetic materials, decreases with increasing temperature. If the test temperature is below the critical (analogous to the Curie temperature) and is about 2373 K, then this corresponds to the transition temperature to the single-phase cubic region. An increase in the ratio of the intensities of the X-ray lines $I_{(002)}/I_{(200)}$ is observed with increasing friction test speed. With increasing temperatures in the tribocontact zone, the increase in the ratio of X-ray line intensities can be due to by increasing the number of reoriented domains in the ferroelastic materials of the composite due to a decrease in the resistance force during domain switching. Similar dependences of the ratio of the intensities of the X-ray lines $I_{(002)}/I_{(200)}$ on the test temperature were obtained after grinding the sample surface.

Increasing the ratio of X-ray line intensities $I_{(002)}/_{(200)}$ with increasing grain size of the ceramic material, which is observed at different test speeds, it is possible to understand on the basis of the mechanisms of texture formation. This is a direct analogy to the well-known Hall-Petch effect for the deformation of polycrystalline materials, when the grain size of the material determines the mobility of dislocations. At the same time, the larger the grain size, the higher the mobility of dislocations in the material. In the case of a ceramic material based on zirconium oxide, the grain size determines the mobility of martensitic and twin boundaries. Plastic deformation both by the martensitic mechanism, due to the movement of martensitic plates, and by the mechanism of reorientation of twins, is easier to carry out in coarse-grained ceramics. At the same time, in the case of martensitic transformation, the strengthening of the surface texture with increasing grain size is also influenced by an increase in the thermodynamic factor of the tetragonal-monoclinic transformation.

The issue of ensuring the required level of tribological properties and characteristics by texturing the working surfaces of part materials requires the creation of physical and technological foundations and a comprehensive approach to solving the problem.

In our opinion, the problem of forming a perfect texture of the working surfaces of tribocoupling parts and methods for obtaining them requires solving a number of tasks:

– search for optimal technologies for creating textured work surfaces;

– evaluation of surface texture characteristics;

– the influence of the degree of texture perfection on the tribotechnical characteristics of the working surfaces of parts;

– obtaining surface layers with texture gradients in the case of laser processing;

– dynamics of changes in texture during the hardening process and under operating conditions;

– physical foundations of the creation and evolution of the surface texture of structural materials of a part under the influence of concentrated energy flows (laser radiation);

– the influence of hardening technologies on the quality of the surface texture of parts;

– further development of the methodology for research and optimization of texture parameters;

– use of computer technologies to assess the texture of the surfaces of parts and their mating surfaces;

– the influence of the degree of texture of the working surfaces of parts on their wear resistance and operational reliability.

**Conclusions**

1. The essence and types of structuring of materials of samples and parts are clarified using the example of steel and ceramic materials. It is shown that the texture of the working surfaces of samples and parts can be formed in the process of various methods and processing methods during strengthening, restoration and modification. Attention is focused on the formation of microtexture in non-equilibrium conditions of laser processing and during friction testing.

2. X-ray methods for detecting the texture of working surfaces of samples and parts made of steel and ceramic materials on diffractometers of various types are considered. The methodology for X-ray studies of texture and the degree of its improvement are specified. The technological parameters of laser processing of samples made of steel and composite materials are determined, both in conditions without melting and with melting of the surface.

3. On steel samples, X-ray lines <001>, <110>, <112>, <123>, <200>, <002>, <202> were recorded by tilting, both from the surface and from different depths in the friction zone and the laser exposure zone. Combined textures were detected, for example, for steel 3: <210> + <211> + <321> , with the initial axial crystallographic structure < 110 > . A gradient of textures with depth was observed. A linear law of change in the degree of texture perfection during laser heat treatment and an exponential law – during laser doping with boron were determined.

4. The study of texture on samples of ceramic materials was carried out using the example of ceramics with the composition: 98 wt.% zirconium oxide + 2 wt.% yttrium oxide. The composite was obtained by sintering in vacuum at a temperature of 1873 K with different holding times. The samples were also subjected to laser processing in the mode of non-fusing the surface. The degree of texture was studied by the ratio of X-ray lines $I_{(002)}/I_{(200)}$. The fact of the formation of texture of samples of the studied composite was established both during laser processing and during friction testing.

5. It is shown that the texture of the surfaces of the mating parts makes it possible to provide the tribosystem with the necessary level of tribological properties and characteristics. At the same time, there is a need to create physical and technological foundations and a comprehensive approach to solving the problems of increasing the tribological efficiency of assemblies, systems, units, machines and mechanisms by texturing the mating surfaces of parts. For this purpose, a number of tasks have been formulated that need to be solved.

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**Аулін В.В., Манько Є.В., Чумак В.М., Лисенко С.В., Деркач О.Д., Макаренко Д.О.** Текстурованість матеріалів елементів трибологічних систем машин і механізмів в нерівноважних умовах обробки та функціонування.

Стаття присвячена мікротекстуруванню металевих і полімерних матеріалів елементів трибологічних систем, впливу його на характеристики і властивості робочих поверхонь зразків і деталей. Розглянуто різні типи мікротекстуру сталевих та композитних матеріалів на основі оксиду цирконію. З'ясовано механізм їх утворення. Переважно механізми мікротектурування зв'язують з полем напруженості, створених в процесі тертя та лазерної обробки. Визначено, що лазерна обробка сталевих зразків призводить до комбінованого мікротекстурування і градієнту текстури за глибиною поверхневого шару зразка. Виявлена текстурованість у композитах як при лазерній обробці, так і при випробуванні тертям. Показано, що виявлена текстурованість позитивно впливає на експлуатаційні характеристики деталей, підвищуючи рівень надійності і зносостійкості, а також трибологічну ефективність триботряжень деталей вузлів, систем, агрегатів машин і механізмів.

**Keywords:** сталь, композит, трибологічна система, мікротекстурування, рентгенівське випромінювання, лазерна обробка, досконалість текстури, випробування тертям, надійність, зносостійкість.