The object of research is modified epoxy composite materials containing fibrous fillers treated in physical fields. The technological features of the development of tribotechnical epoxy composites, which must withstand the effects of elevated temperatures, have been considered. In this case, it is necessary to modify the structure of the epoxy polymer matrix, which is achieved as a result of the introduction of heat-resistant organosilicon varnish. Organosilicon varnishes and chopped fibers contain technological additives, which complicates the process of structuring epoxy composites and leads to the appearance of structural defects. Removal of technological additives and cleaning the surface of the aramid and glass fibers from lubricants is possible as a result of processing the components of the composition in physical fields. There is a need to study the influence of physical fields on the structuring processes of the epoxy system and the formation of the structure of epoxy composites with specified properties. Modified epoxy composites contain chopped aramid and glass fibers treated with ultrasound. The tribotechnical characteristics of epoxy composites were studied at a sliding speed of V=1.0 m/s with a change in specific load from 0.5 MPa to 1.5 MPa. The temperature in the tribocontact zone during frictional interaction rises to 100 °C with an increase in the specific load. An increase in the density of the surface layer of tribocontact of epoxy composites with fillers treated in physical fields was revealed. The practical recommendations have been compiled for the implementation of the treatment technology of components in physical fields, which ensures structuring of epoxy composites with high tribotechnical characteristics

Keywords: glass fibers, aramid fibers, electromagnetic field, ultrasound treatment, wear intensity

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DESIGNING TRIBOTECHNICAL EPOXY COMPOSITE MATERIALS REINFORCED WITH CHOPPED FIBERS AND MODIFIED WITH SILICON ORGANIC VARNISH

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1. Introduction

At the current stage of scientific development in the field of materials science, significant progress has been achieved in the creation of new polymer composites for friction purposes based on phenol-formaldehyde and phenolic resins with the use of mineral fibers as fillers. Current studies are related to the analysis of the structure of the tribocontact surface, namely investigating the interaction of components in a complex composite system and determining the mechanisms of deformation and structural transformations. However, designed materials do not fully meet the requirements of consumers because of insufficient cohesive strength, thermal and wear resistance of polymer composite systems [1, 2].

Despite significant progress in the development of friction polymer composite materials, there are a number of tasks and problems that still require solutions. Among them, the most relevant are problems related to improving the physical and mechanical characteristics of polymer composites. This applies to the use of fibrous fillers since there is a decrease in adhesive strength at the interface of the phases. As a result, the intensity of wear increases through the formation of microcracks on the tribocontact surface. Treatment of fibrous and finely dispersed fillers in physical fields makes it possible to improve the physical-chemical interaction between components and obtain composites that are resistant to frictional loading [3, 4].

Therefore, research into the identification of features in the structure formation of polymer composite materials to ensure the controllability of processes in the tribocontact zone during the friction loading process is highly relevant. It is also important to determine the optimal composition and modes of the technological process that forms polymer composites for friction purposes, which enables the improvement of the physical-mechanical, thermophysical, and operational characteristics of polymer composite tribo-products.

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2. Literature review and problem statement

The wide use of fiber-reinforced polymer composites in industry requires the development of new materials and the study of their properties, in particular tribotechnical, which includes the influence of various technical parameters on the intensity of wear. It was found that the chemical composition of the fibers, their shape and orientation, as well as the adhesive strength between the components, affect the tribotechnical characteristics of polymer composites. The authors of paper [5] considered the options for improving the tribotechnical properties through the optimization of the morphological composition, conditions of tribointeraction, and the content of components of polymer composites, but the possibility of modifying the structure of polymer composites with the help of physical fields was not considered.

The strength of the fiber, as is known, significantly affects the strength of the developed polymer composite, while the hydrophobicity of the surface of the fibers makes it difficult to impregnate the reinforcing fibrous frame with a polymer binder in the process of forming a polymer composite product [6, 7]. However, to predict and control the properties of composite materials, one needs to know the physicochemical properties and chemical composition of the fibrous filler.

The technology of forming polymer composites on a thermoset basis does not involve special processing methods using physical fields to activate components due to their high reactivity. It was established that the effectiveness of physical fields is manifested at the stage of mixing the components of the polymer composition. At the same time, the adhesive strength of epoxy polymers as a result of ultrasonic treatment of the composition increased by 1.7 times compared to the untreated epoxy system and by 1.5 times compared to epoxy polymers whose compositions were treated with an electromagnetic field [8]. The use of ultrasonic treatment provides for an increase in the homogeneity of the system through the intensification of interaction between the components and a reduction in the defectiveness of the system. However, the application of ultrasound must be carried out in the absence of a hardener since intensive structuring of the polymer matrix takes place.

The main problem of the impregnation of fibrous materials is the replacement of air and moisture with a liquid binder located in the micropores of the fibers. Insufficient impregnation of fibers reduces strength and prematurely destroys polymer composite products. The use of technological techniques [9] enables increased fiber adhesion to the matrix, in particular, preliminary activation of the fiber surface [10] makes it possible to increase the value of the modulus of elasticity of the polymer composite with the same fiber content. This method of surface activation is quite effective, so it needs to be extended to be used for other types of fibers. In studies [11, 12], methods of structure modification using nano-sized structural components, which complicates the process of material formation, are considered.

In work [13] it was established that epoxy composites reinforced with carbon fiber are more resistant to wear than epoxy composites reinforced with glass fiber. However, the use of glass fibers reduces the cost of production, provided high adhesion strength is ensured between the fiber and the polymer matrix. In work [14], it was found that the intensity of weight wear of epoxy composites increased in the range from 16 to 43 % in the case of increasing the content of copper oxide powder to 200 wt. parts. compared to the content of 5.4 wt. parts. A 10 % decrease in the intensity of weight wear occurs in the case of applying a sliding speed of V=3.6 m/s and a specific load of P=3 MPa. This is explained by the occurrence of favorable conditions for the formation of fragments of a protective film on tribosurfaces, which separates the contact surfaces and acts as a solid lubricant. The formation of such a film takes place under a certain regime, which is difficult to ensure under actual operating conditions.

The type of fiber significantly affects the intensity of wear of composite materials. Due to the high bond energy of the main molecular chains of the fibers, the higher hardness of the fiber surfaces, good thermal properties and high tensile strength, the wear resistance can be improved accordingly. In particular, aramid fibers can be used as a reinforcing component to increase the strength of composites and provide for high tribotechnical characteristics [15]. During the manufacturing process, lubricants appear on the surface of such fibers, which reduce adhesiveness and mechanical characteristics.

The use of chopped aramid fibers and glass fibers, which are treated with ultrasound in a solvent environment, provides an increase in the wear resistance of epoxy composites by 30 % compared to the wear resistance of polymer composites containing untreated chopped fibers. Removing the lubricant from the surface of the crushed fibers also enables an increase in the friction coefficient, which positively affects the formation of friction products [16]. In the work, wear resistance was determined at a low sliding speed (0.5 m/s), which requires additional research.

The increase in adhesion of carbon, boron, and ceramic fibers occurs due to the growth of single crystals of silicon carbide perpendicular to the fiber axis [17]. This process helps increase the shear characteristics, modulus of elasticity, and compressive strength without reducing the characteristics in the direction of the fiber axis. This method is relevant for mineral fibers, which limits its use for fibers of organic origin.

The use of organosilicon polymers as modifiers makes it possible to compensate for the shortcomings of epoxy polymers, as it has higher thermal stability, oxidation resistance, and weather resistance [18, 19]. However, in the case of modification of epoxy resin with heat-resistant compounds, the degree of structuring and the glass transition temperature of the polymer decrease.

In global practice, methods for reinforcing the structure of polymers using synthetic fibers are actively applied, which, owing to their high cohesive strength, are able to increase the mechanical characteristics of polymer composites. This happens if the components of the system interact with the formation of strong bonds between the filler and the matrix. Therefore, methods for surface activation of fillers using chemicals or processing in physical fields are widely used. In order to improve the resistance to thermal destruction of polymer composites, it is advisable to use heat-resistant modifying substances, which must have thermodynamic compatibility with the polymer matrix.

3. The aim and objectives of the study

The purpose of our work is to determine the effectiveness of treating chopped fibers and the modifier at the stage of preparation of the components of the multi-filled system in physical fields. This will improve the tribotechnical properties of epoxy composite friction materials modified with organosilicon varnish, filled with discrete glass fibers and aramid fibers.

To achieve this goal, it is necessary to solve the following scientific and practical tasks:

– to establish the intensity of linear and weight wear of epoxy composite materials depending on the specific load;

– to determine the coefficient of friction of epoxy composite materials depending on the specific load;

– to analyze the dynamics of changes in tribotechnical characteristics during triboInteraction;

– to analyze the microstructure of the tribosurface of epoxy composite materials.

4. The study materials and methods

The object of research is modified epoxy composite materials for friction purpose, containing fibrous fillers treated in physical fields. The subject of the study is tribotechnical properties and structural transformations in tribosurface layers of epoxy composite materials.

During the research, a hypothesis was put forward that treating the components in physical fields would enable removal of the solvent from the modifier and cleaning of the surface of the crushed fibers from foreign substances. This could increase the adhesive strength of the fibers to the epoxy polymer matrix and improve the tribotechnical properties of epoxy composites.

The following assumptions and simplifications were accepted within the framework of our study:

– the samples were tested in an air environment without lubricants;

– the linear speed of movement of the counter body was 1 m/s, and the range of specific loads was 0.5 MPa, 1 MPa, and 1.5 MPa;

– the friction distance was 3000 m.

ED-20 epoxy-diene resin was selected as the starting material for the formation of the polymer matrix. Polyethylene polyamine was used to harden epoxy compositions. The following fillers were used to reinforce epoxy composite materials: crushed aramid and glass fibers with a length of 3 to 4 mm, highly dispersed aluminum powder. KO-915B organosilicon varnish (20 wt. parts) was used as a modifier.

Tribotechnical studies were carried out on the M-22M friction machine. The temperature in the tribocontact zone was measured with a chromel-copel thermocouple. St45 steel was used as the counter body material (HRS from 48 to 50, Ra from 0.32 to 0.64 μm, diameter – 40 mm). The samples were made of monolithic epoxy composite material with a rectangular cross-section measuring 10×10 mm and a height of 15 mm. The mass of the samples was determined on the analytical laboratory scales WPS 110/C/1 of the third accuracy class.

The structure of the tribosurface layer of epoxy composite materials was studied by the method of electron microscopy with the help of the raster electron microscope REM-106 I.

5. Results of investigating the tribotechnical properties and structure of epoxy composite materials

5. 1. Studying the intensity of linear and weight wear of epoxy composite materials depending on specific load

The composition of epoxy composite materials and the technology of forming samples (Table 1) for tribotechnical studies were developed according to the results from previous studies [16].

Tribotechnical studies of the developed epoxy composite materials were carried out at a sliding speed of V=1.0 m/s. The specific load was changed from 0.5 MPa to 1.5 MPa.

The intensity of weight wear of epoxy composite material No. 1 (Table 1), depending on the specific load, is from 1.4 to 4.8 mg/km (Fig. 1). The weight wear intensity of epoxy composite material No. 2, which contains ultrasonically treated chopped fibers, is lower in the range of 14.6 to 39.1 % compared to epoxy composite material No. 1, and is between 1.1 and 4.1 mg/km.

The intensity of weight wear of epoxy composite materials No. 3, which contain unprocessed chopped fibers and a modifier treated in an electromagnetic field, is 3 mg/km at a specific load of P=0.5 MPa. With an increase in the specific load to P=1.5 MPa (1.5 mg/km), the intensity of weight wear gradually decreases by a factor of 2. With an increase in the specific load from 0.5 MPa to 1.5 MPa, the intensity of weight wear increases by 2 times for epoxy composite material No. 4 and is from 1.4 to 2.8 mg/km. The weight wear intensity of epoxy composite No. 4 is 7 % lower than that of epoxy composite No. 3, which contains untreated chopped fibers.

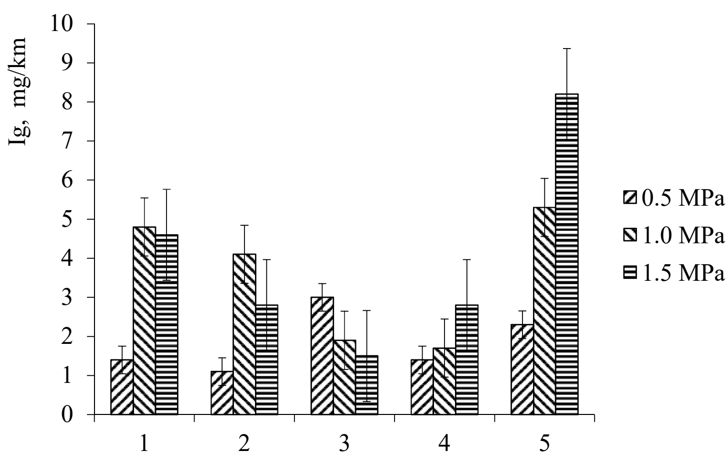


Fig. 1. Intensity of weight wear of epoxy composite materials depending on the specific load at a constant sliding speed (V=1 m/s)

Table 1

Composition of epoxy composite materials for tribotechnical research

Sample No.	Material composition			Fiber treatment	Modifier treatment
	Matrix	Modifier	Filler content		
1	100 wt. parts ED-20+12 wt. parts PEPA	20 wt. parts KO-915B	10 wt. parts glass fibers+1 wt. parts. aramid fibers+7 wt. parts aluminum powder	–	–
2				+	–
3				–	+
4				+	+
5			6 wt. parts glass fibers+2 wt. parts aramid fibers+7 wt. parts aluminum powder	+	+
Chopped fibers were treated with ultrasound in an acetone solution for 5 min. KO-915B organosilicon varnish was treated in an electromagnetic field with a power of 120 W for 10 minutes					

For epoxy composite material No. 5, with an increase in the specific load, a sharp increase in the intensity of weight wear is observed. The highest intensity of weight wear (8.2 mg/km) was found for epoxy composite material No. 5 at a specific load of P=1.5 MPa.

The lowest values of the intensity of linear wear (Fig. 2) are observed for tribo-junctions steel – epoxy composite material No. 1 (10.6 μm/km) and steel – epoxy composite material No. 2 (8.3 μm/km) at a sliding speed of V=1.0 m/s and a specific load of P=0.5 MPa. With an increase in the specific load to 1.0 MPa, the intensity of linear wear of these tribo-junctions increases sharply in the range from 3.9 to 4.2 times and amounts to 44.9 μm/km (No. 1) and 32.2 μm/km (No. 2).

The intensity of linear wear of steel-epoxy-composite material No. 3 and steel-epoxy-composite material No. 4 tribo-junctions is much lower and is 23.1 μm/km and 10.5 μm/km, respectively. With an increase in the specific load to 1.5 MPa, the intensity of linear wear of the tribo-junction steel – epoxy composite No. 3 gradually decreases by a factor of 2 and is 11.6 μm/km. For the tribo-junction steel – epoxy composite material No. 4, the intensity of linear wear increases by 2 times with an increase in the specific load.

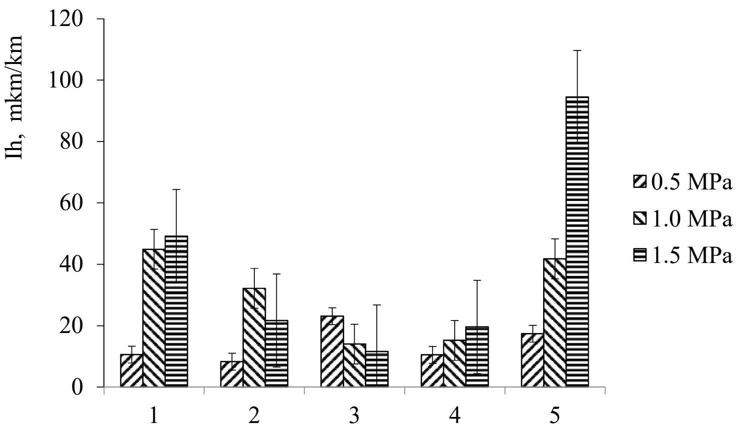


Fig. 2. Intensity of linear wear of tribo-junctions depending on the specific load at a constant sliding speed (V=1 m/s)

For the tribo-junction steel – epoxy composite material No. 5, the intensity of linear wear increases by 5.5 times. A correlation of results related to the intensity of linear and weight wear is observed (Fig. 1), where the lowest wear resistance among the studied materials was found for the epoxy composite material of this composition.

5. 2. Determining the coefficient of friction of epoxy composite materials depending on specific load

It was established that with an increase in the specific load from 0.5 MPa to 1.5 MPa at a sliding speed of V=1.0 m/s, the temperature in the tribocontact zone increases (Fig. 3). With an increase in the specific load from 0.5 MPa to 1.5 MPa at a constant sliding speed of V=1.0 m/s, the temperature in the tribocontact zone increases:

– epoxy composite material No. 1, from 67 °C to 104 °C;
– epoxy composite material No. 2, from 85 °C to 109 °C;
– epoxy composite material No. 3, from 67 °C to 120 °C;
– epoxy composite material No. 4, from 92 °C to 107 °C;
– epoxy composite material No. 5, from 60 °C to 134 °C.

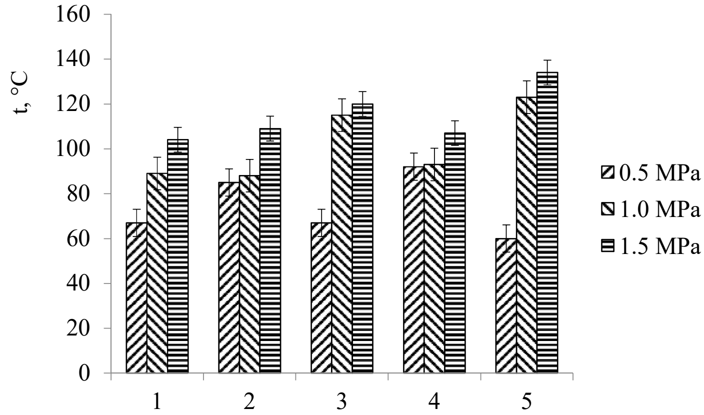


Fig. 3. Temperature in the tribocontact zone "steel 45 – epoxy composite material" depending on specific load at a constant sliding speed (V=1.0 m/s)

The temperature in the tribocontact zone for epoxy composite materials No. 2, No. 3, No. 4 under the friction regime of P=1.5 MPa and V=1.0 m/s is lower compared to the results at a lower sliding speed of V=0.5 m/s [16].

The coefficient of friction of epoxy composite material No. 1 is 0.33 (Fig. 4), epoxy composite material No. 2 – 0.46, epoxy composite material No. 3–0.28, epoxy composite material No. 4–0.45, epoxy composite material No. 5 – 0.37 (V=1.0 m/s, P=0.5 MPa). The highest friction coefficients of 0.46 and 0.45 were recorded for epoxy composite materials No. 2 and No. 4, respectively.

With an increase in the specific load from 0.5 MPa to 1.0 MPa, the friction coefficient decreases in the range from 3 to 33 % (Fig. 4) for epoxy composites No. 1 (f=0.32), No. 2 (f=0.28), and No. 4 (f=0.39) or increases in the range from 16 to 28 % for epoxy composites No. 3 (f=0.30) and No. 4 (f=0.44). The coefficient of friction of all investigated epoxy composite materials decreases by 17–41 % (f=0.19–0.3) in the case of increasing the specific load to 1.5 MPa.

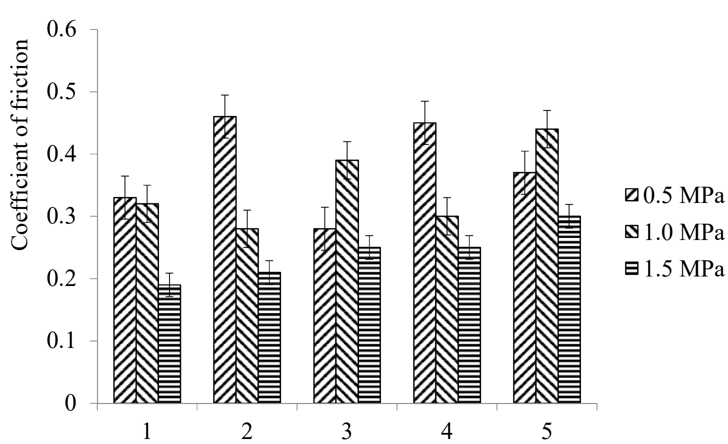


Fig. 4. The coefficient of friction of epoxy composite materials depending on specific load at a constant sliding speed (V=1.0 m/s)

5. 3. Dynamics of changes in tribotechnical characteristics during tribointeraction

Tribotechnical characteristics of epoxy composite materials No. 2, No. 3, No. 4 are given in Table 2. Epoxy composite material No. 2 has the lowest weight wear intensity of 1.1 mg/km and the lowest mass loss of 2.2 mg at a specific load of P=0.5 MPa and a sliding speed of V=1.0 m/s. Epoxy composite material No. 3 has the highest weight wear intensity of 1.9 mg/km and the largest mass loss of 3.8 mg.

The lowest intensity of counter body weight wear of 0.1 mg/km and the smallest change in counter body mass of 0.2 mg was recorded for tribo-junction steel – epoxy composite material No. 3. The highest intensity of counter body weight wear was 0.33 mg/km and the largest change in counter body mass was 0.7 mg found for the tribo-junction steel – epoxy composite material No. 4.

The coefficient of friction of epoxy composite material No. 2 is unstable on the first kilometer of the friction path (Fig. 5, *a*). At the second kilometer, a decrease in the coefficient of friction and its stabilization is observed. The coefficient of friction of epoxy composite materials No. 3 and No. 4 is stable throughout the friction path (Fig. 5, *b*, *c*).

In the process of tribotechnical interaction, the temperature in the tribocontact zone increases for all epoxy composite materials (Fig. 5, *a*–*c*): up to 87 °C – No. 2; up to 69 °C – No. 3; up to 92 °C – No. 4. The intensity of linear wear of the tribo-junction is unstable throughout the friction path for epoxy composite material No. 4 (Fig. 5, *c*), which is due to the high temperature in the tribocontact zone of steel – epoxy composite material No. 4.

Table 2

Tribotechnical characteristics of epoxy composite materials

Characteristics	Epoxy composite materials		
	Sample 2	Sample 3	Sample 4
Intensity of weight wear of the sample, mg/km	1.1	1.9	1.4
Intensity of counter body weight wear, mg/km	0.2	0.1	0.33
Change in mass of samples, mg	2.2	3.8	2.8
Change in the mass of the counter body, mg	0.4	0.2	0.7
Friction mode: P=0.5 MPa, V=1.0 m/s			

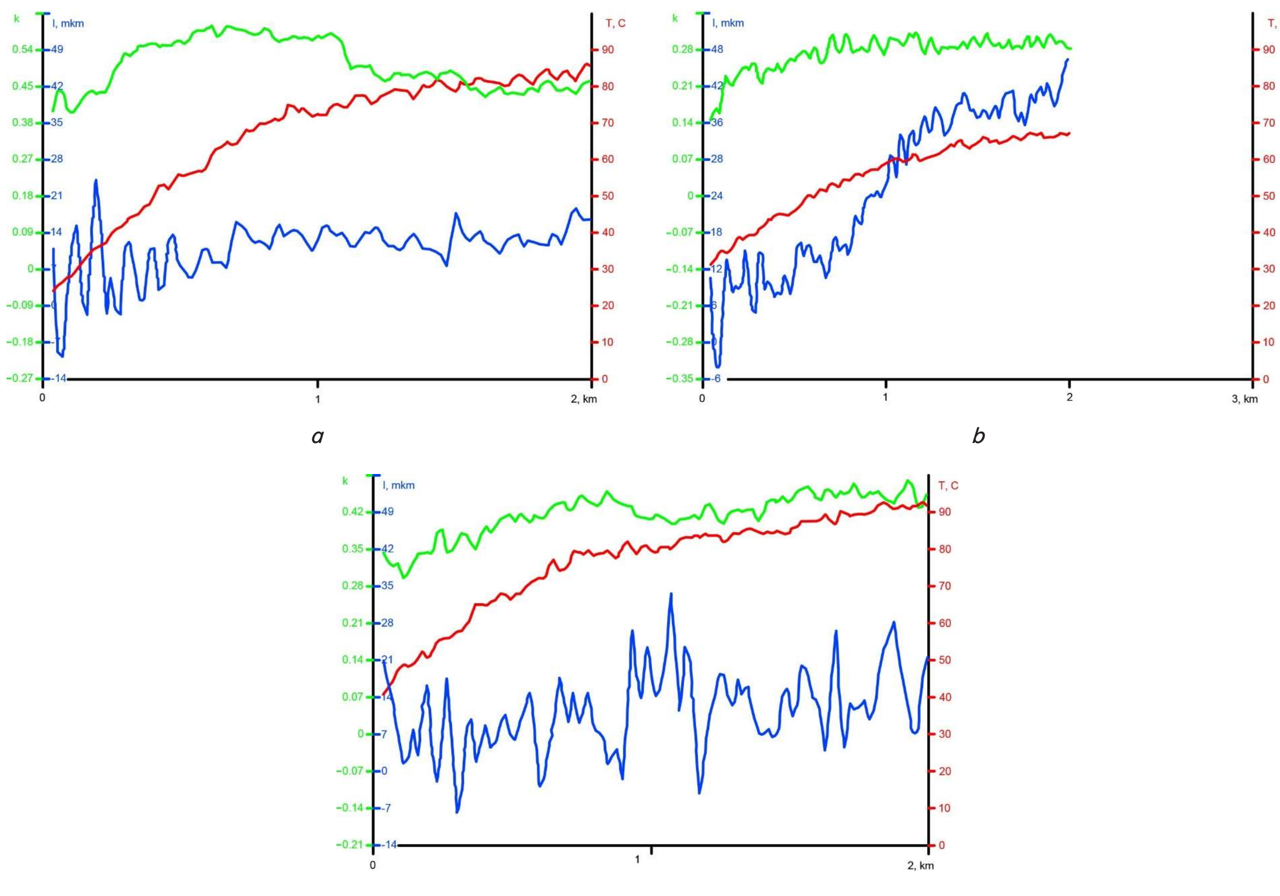


Fig. 5. The dynamics of changes in the intensity of linear wear, the coefficient of friction, and the temperature in the tribocontact zone in the process of triboineraction (sliding speed V=1.0 m/s, specific load P=0.5 MPa, friction path S=2 km) of epoxy composite materials: *a* – No. 2; *b* – No. 3; *c* – No. 4

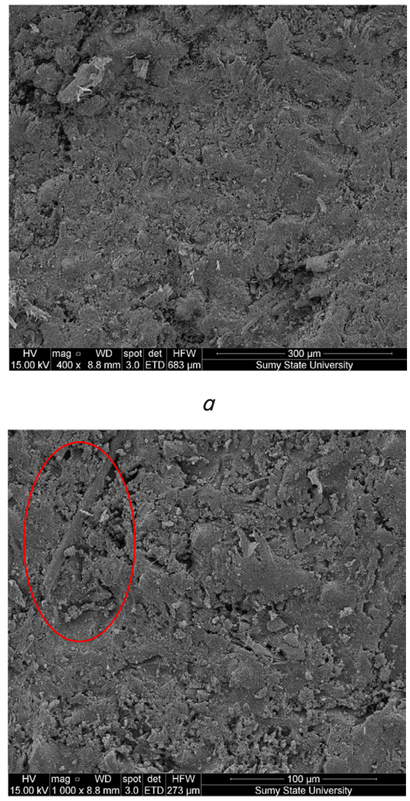
5. 4. Microstructure of the tribosurface of epoxy composite materials

The tribosurface of epoxy composite material No. 1 (Fig. 6, *a*) has a pronounced relief structure. This indicates a highly stressed state of the epoxy composite system. In this epoxy composite material, a cluster of crushed fibers was found (Fig. 6, *b*), which indicates the formation of a heterogeneous structure of the epoxy composite material and explains the obtained high and unstable characteristics of the intensity of weight and linear wear.

The microstructure of the tribosurface of epoxy composite material No. 2 is characterized by a less pronounced surface relief (Fig. 7, *a*) compared to material No. 1, which indicates the formation of an epoxy polymer system with a less stressed state. A significant amount of wear products and evenly distributed micropores were found on the tribosurface of the epoxy composite material (Fig. 7, *b*).

Epoxy composite material No. 3, which contains organosilicon varnish treated in an electromagnetic field, is characterized by a less pronounced tribosurface relief (Fig. 8, *a*). This indicates an improvement in the interaction of the modifier with fillers and the epoxy polymer matrix compared to epoxy composite materials No. 1 and No. 2. On the tribosurface of epoxy composite material No. 3, a significantly smaller number of micropores is observed (Fig. 8, *b*) compared to epoxy composite materials No. 1 and No. 2.

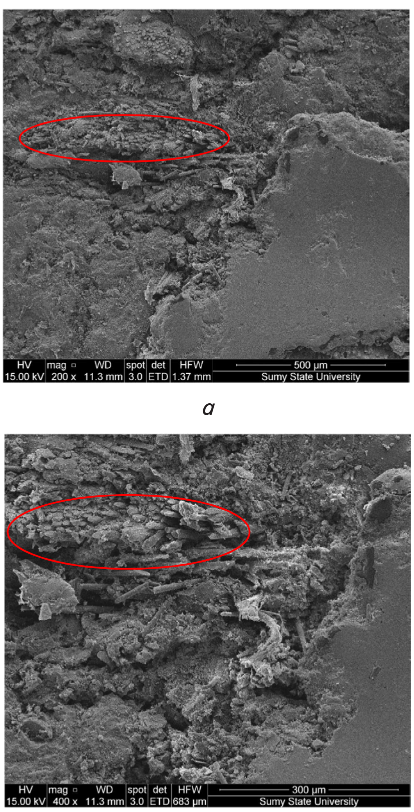
Epoxy composite material No. 4 is characterized by the uniformity and evenness of tribosurfaces (Fig. 9, *a*), especially near fibrous fillers (Fig. 9, *b*). Ultrasound-treated fibers are more evenly distributed in the matrix as they are less prone to clumping.



a

b

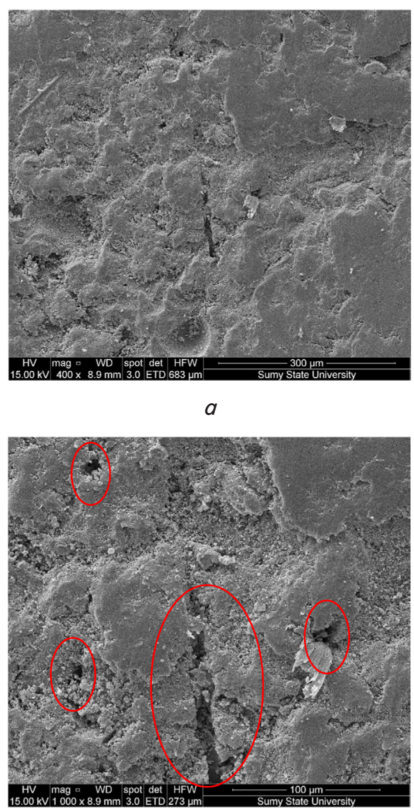
Fig. 7. Microstructure of the tribosurface of epoxy composite material No. 2: *a* – ×400; *b* – × 1000



a

b

Fig. 6. Microstructure of the tribosurface of epoxy composite material No. 1: *a* – ×200; *b* – ×400

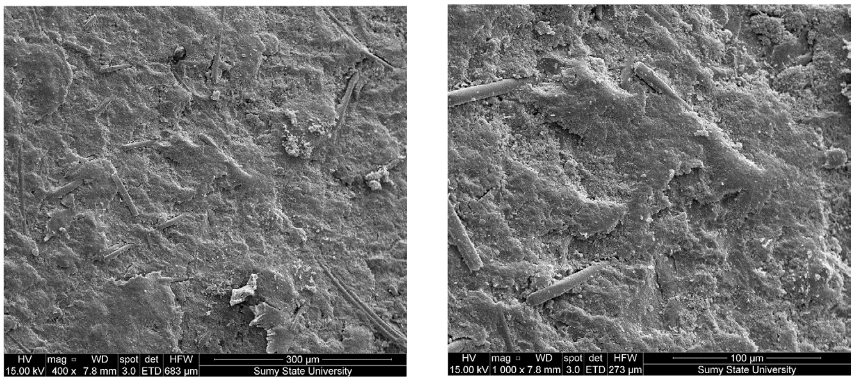


a

b

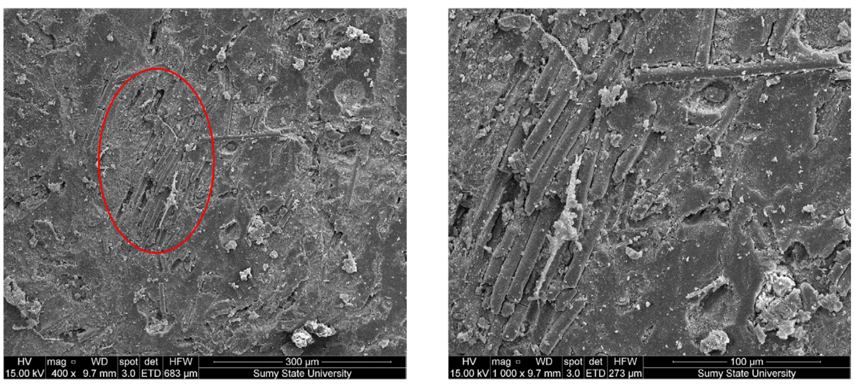
Fig. 8. Microstructure of the tribosurface of epoxy composite material No. 3: *a* – ×400; *b* – ×1000

Epoxy composite material No. 5, which contains less glass fibers (6 wt. parts) and more aramid fibers (2 wt. parts), has a flat tribosurface (Fig. 10, *a*) since intensive wear of the material is not observed during tribointeraction.



a *b*

Fig. 9. Microstructure of the tribosurface of epoxy composite material No. 4: *a* – ×400; *b* – ×1000



a *b*

Fig. 10. Microstructure of the tribosurface of epoxy composite material No. 5: *a* – ×400; *b* – ×1000

Wear products and inclusions in the form of agglomerated particles of highly dispersed aluminum powder of different sizes (Fig. 10, *b*) are unevenly distributed on the tribosurface (Fig. 10, *a*).

6. Discussion of research results related to tribotechnical properties and structure of epoxy composite materials

The decrease in the intensity of weight wear of epoxy composite material No. 3 (Fig. 1) can be explained by the formation of a film on the tribosurfaces of the epoxy composite material and the counter body under the given friction conditions. This film reduces wear of the tribo-junction, which as a result stabilizes the process of tribointeraction. The increase in the intensity of weight wear of epoxy composite material No. 4 occurs in accordance with the increase in the specific load in the range of values from 0.5 to 1.5 MPa since the protrusions on the surface of the tribolayer are deformed and the area of tribocontact increases.

For epoxy composite materials No. 2–4 (V=1.0 m/s, P=1.5 MPa), a lower temperature in the tribocontact zone (Fig. 3) was recorded compared to the results of research at a lower sliding speed V=0.5 m/s [16]. These epoxy composite materials have a lower intensity of weight wear due to the formation of secondary structures on tribosurfaces under this friction mode.

For epoxy composite materials No. 3 and No. 4, the stability of the friction coefficient is observed throughout the entire friction path (Fig. 5, *b, c*), which is ensured by the presence in the composition of these materials of organosilicon varnish treated in an electromagnetic field. Treatment in an electromagnetic field at a high frequency provides an improvement in the adhesion strength of the polymer matrix to the surface of the fillers in the epoxy composite material due to the formation of additional physical bonds [9]. At the same time, all components in one mixture were processed simultaneously. An increase in treatment efficiency is achieved in the case of applying the effect of a physical field on a separate component of the polymer composite material.

On the microstructures of the tribosurface of epoxy composite material No. 1, it was found that the destruction of part of the material followed by its removal in the form of wear products occurs near the surface of the fibers (Fig. 6, *a, b*). This indicates insufficient adhesive strength of the components of the epoxy composite material, which is explained by the presence of a lubricant on the surfaces of glass and aramid fibers. Lubricant prevents the formation of physical and chemical bonds between the epoxy polymer matrix and the fibers. On the tribosurfaces, unevenly distributed pores of different sizes were found on the surface of the material, which reduce the theoretically possible structural strength of the epoxy composite. An increase in adhesive strength is possible due to the treatment of components with chemicals that form a transition layer [10]. This makes it possible to form structures with strong chemical bonds in the "matrix-modifying layer-filler" system. This method is complex and appropriate for a limited class of materials.

Conducting ultrasonic treatment of glass and aramid fibers makes it possible to form epoxy composite materials with a more uniform structure compared to epoxy composite material No. 1, i.e., without clusters of fibers in the volume of the material (Fig. 7, *a, b*). Removing the lubricant from the surface of the fibers made it possible to obtain epoxy composite materials with higher cohesive and adhesive strength (Fig. 7, *b*) compared to epoxy composite material No. 1. This is due to the formation of a greater number of physical and chemical bonds between the epoxy polymer matrix and fibers. Similar results were obtained in [13], in which the authors used untreated carbon and glass fibers as fillers. It was determined that epoxy composites have higher hardness and wear resistance in the case of using carbon fibers, which, owing to their antifriction properties, reduce the destruction of the tribolayer. Cleaning the surface of carbon fibers will provide an additional increase in the mechanical characteristics of polymer composite materials.

The homogeneous structure (Fig. 8, *a, b*) is characterized by a less stressed state and is formed due to the removal of toluene, which contains organosilicon varnish of the KO-915B brand. Toluene is a solvent, so it prevents the formation of chemical bonds in epoxy composite materials. In the epoxy composite material No. 3, discontinuities were detected near the fibers (Fig. 8, *b*), which were caused by the cracking of the epoxy polymer matrix with its subsequent removal in the form of wear products. This indicates the low adhesive strength of this material, which contains untreated fibers.

Epoxy composite material No. 4 is characterized by the formation of a homogeneous composite system with a high degree of structuring and low internal stresses (Fig. 9, *a*). The effectiveness of treatment in the physical fields of crushed glass and aramid fibers, as well as organosilicon modifier at the stage of preparation of the components of the multi-filled system is confirmed by the formation of a homogeneous structure of the epoxy composite material. This is due to the use of ultrasound treatment of fibers and organosilicon varnish in an electromagnetic field, which increase the cohesive and adhesive strength of the epoxy composite material (Fig. 9, *b*). Epoxy composite material No. 4 has a higher impact strength compared to epoxy composite materials No. 1–3, which is evidenced by the less pronounced relief of the surface (Fig. 9, *b*). The use of treated organosilicon varnish provides an increase in impact toughness, plasticity, and structural strength of epoxy composite material No. 4. The amount of micropores and wear products on the tribosurface of this material is small.

On the microstructure of epoxy composite material No. 5, an accumulation of crushed fibers was found (Fig. 10, *a, b*), which is caused by their high content, as a result of which a highly viscous epoxy composite system is formed. In a highly viscous system, the process of fiber distribution and their wetting with an epoxy polymer matrix is complicated, which explains the high wear intensity of this material.

Restrictions on the formation of epoxy composite material for the study of tribotechnical characteristics relate to the use of a fixed content of the organosilicon varnish KO-915B and a certain set of glass and aramid fibers with a length of 3 to 4 mm.

The disadvantage of the study is that the results of tribotechnical characteristics were obtained at one sliding speed (V=1.0 m/s). This does not allow us to evaluate the behavior of the epoxy composite material under more difficult operating conditions.

In the future, it is advisable to conduct a study on the tribotechnical characteristics of epoxy composite materials at a higher sliding speed (V=1.5 m/s) in order to determine the material's resistance to the harsher conditions of the tribointeraction regime.

7. Conclusions

1. The intensity of weight wear of epoxy composite material No. 2 is lower in the range from 14.6 to 39.1 % compared to epoxy composite material No. 1 (P=0.5 MPa, V=1.0 m/s). The intensity of weight wear of epoxy composite material No. 3, containing treated in an electromagnetic field organosilicon varnish and untreated chopped fibers, gradually decreases by 2 times with an increase in the specific load from 0.5 MPa to 1.5 MPa. A low intensity of weight wear of 1.6 mg/km was recorded for epoxy composite materials No. 4 at a specific load of P=1.0 MPa and 2.8 mg/km at a specific load of P=1.5 MPa. Low values of the intensity of linear wear (from 8.3 to 11.6 μm/km) are demonstrated by epoxy composite materials No. 2–4. A high intensity of weight wear of 8.2 mg/km and a sharp increase of 5.5 times the intensity of linear wear of the tribo-junction was found for epoxy composite material No. 5 at a specific load of P=1.5 MPa.

2. A high coefficient of friction of 0.45 and a low intensity of weight wear were recorded for epoxy composite material No. 4. Ultrasonically treated glass and aramid fibers increase the coefficient of friction. With an increase in the specific load to 1.5 MPa, a decrease in the coefficient of friction is observed for all the studied materials, which is ensured by the presence of organosilicon varnish treated in an electromagnetic field in the composition of these materials.

3. It was established that with an increase in the specific load from 0.5 MPa to 1.5 MPa at a sliding speed of V=1.0 m/s, the temperature in the tribocontact zone increases. Epoxy composite material No. 1 has the lowest temperature (104 °C) in the tribocontact zone. The intensity of linear wear of the tribo-junction is unstable throughout the friction path for epoxy composite material No. 4, which is due to the high temperature in the tribocontact zone. The stability of the friction coefficient during tribointeraction under these conditions is observed for epoxy composite materials No. 3 and No. 4.

4. The resulting microstructures of tribosurfaces of epoxy composite materials confirm the results of tribotechnical studies. Epoxy composite materials No. 2–4 have the highest wear resistance (fibers treated with ultrasound, organosilicon varnish treated in an electromagnetic field). The microstructure of the tribosurface of such epoxy composite materials is more homogeneous, characterized by a less pronounced relief, a smaller number of micropores, and the absence of fiber clusters. This indicates a high degree of structuring of epoxy systems and increased adhesive strength of components of epoxy composite materials.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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