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INFLUENCE OF THE STRUCTURE AND THERMOMECHANICAL PROPERTIES OF ORIENTED CARBON PLASTICS ON THEIR TRIBOTECHNICAL CHARACTERISTICS

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It has been established that carbon plastics are increasingly used in various industries as structural materials. By the set of their properties, carbon plastics outperform steel, cast iron, alloys of non-ferrous metals. However, the application of these materials for parts of machine friction units is still limited due to the difficult operating conditions of modern tribosystems. This work aims to conduct a comprehensive experimental study of the tribological properties of materials in the tribosystem "carbon plastic-metal" taking into consideration their structure, as well as the mechanical-thermal characteristics. Comparative tests of the dependence of the friction coefficient on load for metal and polymeric anti-friction materials have shown a decrease in the friction coefficient for plastics by 3...4 times (textolite, carbotextolite, and carbon-fiber plastics). The influence of the filler orientation relative to the slip plane on the anti-friction properties of carbon-fiber plastics was investigated; it was found that the direction of fiber reinforcement in parallel to the friction area ensures less carbon-fiber plastic wear. A linear dependence of the wear intensity of carbon-fiber plastics, reinforced with graphite fibers, on the heat capacity and energy intensity of the mated steel surface has been established. Based on the microstructural analysis, a layered mechanism of the surface destruction of carbon-fiber plastics was established caused by the rupture of bonds between the fiber parts, taking into consideration the direction of the fibers' location to the friction surface. The results reported here could provide practical recommendations in order to select the composition and structure of materials for the tribosystem "carbon-fiber plastic-metal" to be used in machine friction units based on the criterion of improved wear resistance

Keywords: polymeric composites, oriented carbon plastics, thermal conductivity, wear intensity, friction coefficient

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1. Introduction

Metal materials are mainly used as structural ones for parts of machine friction units: steel, cast iron, non-ferrous metals and alloys. However, various working conditions of friction units, environments, and conjugate surfaces require the use of new materials with specialized properties [1]. In terms of their properties, carbon plastics are often significantly superior to conventional metals, so their use in mechanical engineering is promising. Carbon plastics demonstrate a low density, high elasticity module, strength, heat resistance, high wear resistance, the low temperature coefficient of linear expansion.

Carbon plastics have proven efficient and were extensively scientifically tested as structural elements' materials in the automotive industry, aviation, and other industries. At the same time, special features in the use of carbon plastics for parts of friction and lubrication units in machines require additional research. This is due to the complicated operating conditions of the tribosystems: large contact loads, increased speeds of relative slip, exposure to local and volumetric temperatures, etc. Comprehensive experimental studies into the influence of the structure and physical-mechanical characteristics of carbon plastics on the performance of parts of friction units are required. The tribological behavior of parts made from carbon plastics also significantly depends on the properties of conjugate surfaces in a tribosystem.

Substantiated recommendations for the choice of the structure and properties of carbon plastics for tribosystems, taking into consideration operational factors, could improve durability, reduce the cost of repair and maintenance of machines.

2. Literature review and problem statement

Composite non-metallic materials for machine friction units require high mechanical, thermal, and anti-friction properties, as well as the stability of dimensions during operation. Modern materials do not fully meet these requirements; at high mechanical properties, they have low thermal properties or insufficient rigidity. For example, antifriction calcined graphite (AO, 2P-1000, K-0), while demonstrating a low density and rather high thermal conductivity, can work reliably only at pressures of 3.0...4.0 MPa. Impregnating these materials with resins or metals can increase their strength by 2 times but, at the same time, their thermal conductivity significantly reduces [2]. The materials that are based on a mixture of artificial graphite with phenol-formaldehyde or polysiloxane resins withstand specific loads of up to 8 MPa but have insufficient wear resistance [3]. The composite materials that are based on polytetrafluoroethylene have a low friction coefficient but are used only under low pressure since the main disadvantage of materials of this type is low deformation resistance and low thermal conductivity [4]. The properties of textolites also do not fully meet operational needs. Textolite at friction without lubrication works satisfactorily under specific loads of up to 1 MPa. Increasing the load by 1.5 times leads to an increase in the wear intensity by more than 10 times. With lubricants, textolites can work at specific loads of up to 10 MPa but the low thermal conductivity of these materials causes their delamination and a strong warming-up of a friction unit [5].

Given this, recent years have seen the search for the composition and studies into the properties of composites based on thermoreactive resins reinforced with carbon fibers and carbon fabrics. Paper [6] investigated the impact of carbon fiber use on the tribological behavior of various polymeric materials. The results demonstrated that the friction coefficient of carbon fiber-reinforced polyetheretherketone (CFRPEEK) is the lowest and fluctuates at 0.11. The authors of work [7], in order to strengthen the interconnection within the polyamide–carbon system, modified the composites by introducing a transition layer of polydopamine (PDA) whose active groups ensure adhesion strength. The CF–MoS2 composite tensile strength increases by 43 %; the friction coefficient and wear rate decrease by 57 % and 77 %, respectively, compared to pure polymer. Epoxy composites reinforced by carbon fiber with different percentages were developed in works [8–10] to study tribological properties. The studies were carried out when rubbing the cylindrical pin and ball only on a circular trajectory [8]. The authors established a decrease in the coefficient of friction and wear, and an increase in the mechanical strength in samples with carbon fibers [9] without taking into consideration their structure. It was found in [10] that epoxy composites are less susceptible to fatigue compared to pure epoxy resins; however, the wear processes were not considered. Multiwall carbon nanotubes were used as a filler for epoxy resins, which led to a decrease in the porosity and an increase in the wear resistance of the composite coating. Paper [11] studied interrelations between the physical-mechanical properties of metal materials mated with carbon-fiber plastic and the wear intensity and a friction coefficient. At the same time, the physicochemical mechanisms of these relations were not considered. Article [12] investigated the effect of fiber orientation on wear when treating carbon fiber-reinforced plastics at certain angles of inclination. A 45° angle layer resulted in significant wear while layers under 90° gave the worst edge rounding radius and a worn area regardless of rotational speed. This did not take into consideration the effect of temperature on the wear of the polymer. The influence of the structural orientation of the fragments of the microstructure of metal materials on the processes of friction and wear was modeled in work [13]; however, the features of the structure of polymers were not taken into consideration in the model. Modeling an active experiment established correlation influences of the strengthened steel surface on the wear of the polymer in [14] without taking into consideration the frictional heating of surfaces. The influence of composition modification on the sliding friction and wear of supporting steel was investigated for the developed binary epoxy composites in [15, 16]. The materials studied included microcapsules [15] filled with hexamethylene diisocyanate, microcapsules filled with wax, and short carbon fibers [16] in different ratios. The sliding friction and wear resistance of the binary epoxy composites tested on a steel ball demonstrated better self-lubricating properties. It was found that the addition of carbon fibers reduced the friction and wear of epoxy composites; however, the mechanisms of this action were not described. The authors of [17–19] built the mathematical models that make it possible to predict sample wear when rubbing on a steel surface according to the friction track width [17] and the amount of applied frictional force and pathway [18]. At the same time, those models do not take into consideration the chemical composition of steel and structural transformations in it in the process of friction. The wear resistance criteria, which are determined from a model reported in [19], can be used for limited working conditions and individual groups of materials.

An important role in determining the operational characteristics of carbon plastics belongs to the thermal-physical properties. Filling polymers with fiber or powders increases their thermal conductivity along with the wear resistance of the material [20]. Carbon fibers significantly affect the thermal conductivity of composites when they are reinforced with thermoplastics. However, most studies do not find direct interrelations between the thermophysical and wear-resistant characteristics. The author of paper [21] emphasizes that thermal conductivity in the direction that is perpendicular to the plane of laying the fibers is sensitive to the presence of pores and causes delamination at the interface. Other possible areas of reinforcement a polymer with fibers were not considered in the cited paper.

Our review of the scientific literature has shown that carbon plastics are promising materials for use in tribosystems with improved anti-friction and anti-wear properties. When studying the properties of reinforced composites, the focus is on the mechanical characteristics of the material compared to tribological properties. In addition, when conducting friction and wear tests, the impact of the structure of carbon plastics on wear resistance is not taken into consideration. Most studies did not establish interrelations between the thermomechanical and tribological properties. There are practically no studies relating the mutual impact and compatibility of materials in the tribosystem "polymer-metal" and friction processes in the contact zone.

Thus, to reliably assess the wear resistance of the tribosystem "carbon-fiber plastic-metal", an experimental study into the influence of the structure and thermomechanical properties of mated materials on their tribotechnical characteristics is required.

3. The aim and objectives of the study

The aim of this work is to determine the effect of the structure and thermomechanical properties of oriented carbon plastics on their tribotechnical characteristics. This would make it possible to improve wear resistance and reduce friction losses in the polymer-metal tribosystems.

To accomplish the aim, the following tasks have been set:

– to conduct comparative tests for the friction of common anti-friction materials (carbon-fiber plastic, gray cast iron, bronze) in the absence of lubrication;

– to investigate the dependences of the anti-friction, anti-wear, and thermomechanical properties of carbon-fiber plastics on the contact temperature and reinforcement direction with carbon fiber tapes;

– to establish the dependences of the tribological characteristics of carbon-fiber plastics on the composition, mechanical, and thermal-physical characteristics of the mated surfaces materials;

– to investigate the microstructure and surface structure of oriented carbon plastics and determine the mechanisms of carbon-fiber plastics wear in the absence of lubrication at different loads and temperatures.

4. The study materials and methods

To determine the mechanisms of influence of the structure of carbon-fiber plastics on their tribological properties, a set of experimental studies was carried out. The experiments were aimed at establishing the anti-friction, anti-wear, and other mechanical characteristics of materials in the tribosystem "carbon-fiber plastic-metal" for different operating conditions.

For the current study, we used carbon-fiber plastic, a composite material for tribotechnical purposes, reinforced with the carbon tape LU-2 (GOST 28006-88) made from graphitized fibers (graphitization temperature, 2,400 °C, fill factor, 60 %). The matrix is epoxy phenol, we used the resins ED-20 (EPOXY-520) (GOST 10587-84) and RFN-60 (Russia, TOV "Doncarb Graphite" (GOST 20907-2016). We heated the resin ED-20 to 80 °C and added the resin RFN-60. The mixture was stirred; we lubricated the layers of the reinforcing tape with it. After receiving the package, the load P=0.2 MPa was applied; it was left for hardening at a temperature of 120 °C for 2 hours; at a temperature of 140 °C, for 2 hours; and at a temperature of 160...180 °C, for another 2 hours. The resulting packages were cooled and used for the manufacture of samples.

The material was studied for the following directions of reinforcement; the designations are generally accepted in the foreign literature [11, 22]:

– LLLL – the layers of the tape and fiber in the tape are parallel to the friction surface and a slip velocity vector;

– RRRR – the layers of the tape and fiber in the tape are perpendicular to the friction surface and a velocity vector;

– LLLT – the layers of the tape are parallel to the friction surface and a velocity vector; the fibers are parallel to the friction surface and perpendicular to a velocity vector;

– RLRR – the layers of the tape are perpendicular to the friction surface and parallel to a velocity vector, the fibers are perpendicular to the friction surface and a velocity vector.

The samples were shaped like a cut cone with an angle at the top of 90° and a height of h=45...50 mm. The adjustment involved a counter-body with roughness within Ra=0.2...0.4 µm.

The friction coefficient for the group of anti-friction materials was determined under conditions of stepped load in the mode of self-heating (the specific pressure changed from 40 to 500 N). The moment of friction was recorded by a two-dimensional potentiometer.

The friction coefficient was calculated from the following formula:

$$f=\frac{LF}{R_f N}, \tag{1}$$

where L is the distance from the center to the dynamometer thrust; R_f is mean friction radius, mm; N is the normal load, N; F is the bending force of the load cell, N.

The characteristics of wear resistance were investigated using a friction machine (Fig. 1) according to the "cone-plane" scheme. The rotational motion to sample 3 was provided from the spindle of friction machine 1 through four-ball loading pyramid 2. The spindle is connected to a digital speedometer to measure the frequency and number of revolutions during the test. The specimen holder is made with three nests with a diameter of 10 mm. A counter-body was mounted on support bearing 4 and cooled with water. The self-installation of samples was carried out with the help of two-row spherical bearing 5. The dependence of the moment of friction on temperature was determined using two-coordinate potentiometer 7. The counter-body temperature was measured by chromel-copel thermocouple 6 at a distance of 0.5...1 mm from the surface.

The reproducibility of the results acquired from the friction machine is within f=±0.011...0.070. The coefficient of variation in the friction coefficient is υ=2.6...18.6 %.

The amount of wear products was determined from the following formula:

$$V=\frac{\pi}{24}\left(D_1-D_0\right)\left(D_0^2+D_0D_1+D_1^2\right), \tag{2}$$

where D_0 is the diameter of the sample after adjustment, mm; D_1 is the diameter of the sample after testing, mm.

We determined the heat capacity of the studied samples at temperatures of 50, 75, 100, 125 °C, for two directions of the filler reinforcement RRRR and LLLL.

Structural changes that occurred during the friction of the carbon-fiber plastic were investigated using the metallographic microscope MIM-10 (Ukraine, TOV VTP “ASMA-PRYLAD”) (GOS 8.003-2010) and the electron microscope SEM JSM 6490 LV, Jeol (Japan). We analyzed the carbon-fiber plastic wear products on steel 45 using the X-ray diffractor DRON-30 (Russia, NVP “Burevestnik”) (TU 4276-077-00227703-2008).

According to standard procedures, the following thermophysical characteristics of the mated pairs materials and their mechanical characteristics were determined: the hardness was measured at the device PMT-3 (Russia) (TU 3-3.1377-83); the thermal-physical properties were measured at the device IT-s-400 (Kazakhstan) (TU PU2.899.002) in the temperature range 25...125 °C.

The effect of the mated surface on the wear of carbon plastics was investigated according to the “plane–plane” scheme under the mode of self-heating at friction without lubrication for two directions of th filler reinforcement – RRRR and LLLL. The slip speed was 0.54 m/s; the specific load, P=2 MPa; the friction path, 3 km. The following mated surfaces were chosen: carbon – steel 45, and alloy steels – 38XMYuA, 10Ch18N9T, 10Ch17N13M3T.

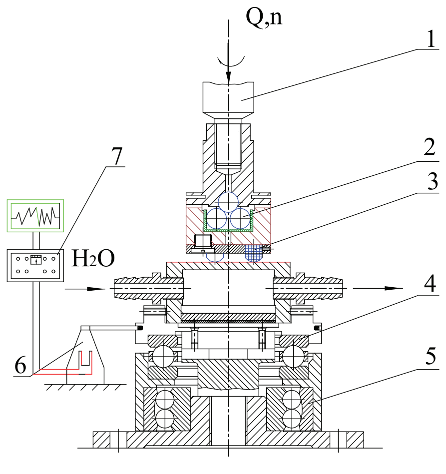


Fig. 1. Friction machine: 1 — spindle; 2 — four-ball pyramid; 3 — examined samples; 4 — support bearing; 5 — spherical self-inserting bearing; 6 — thermocouple; 7 — potentiometer

The energy intensity of the plastic deformation E_d of the mated surface material was calculated from the following formula:

$$E_d = \sigma \cdot \delta_{\max}, \qquad (3)$$

where σ is the limit of steel strength, MPa; $\delta_{\max}$ is the resource of steel plasticity.

5. Results of the experimental study into the tribological properties of oriented carbon plastics

5. 1. Results of studying the loading capacity of anti-friction materials in the absence of lubrication

Comparative tests of anti-friction properties of the materials studied were carried out: gray cast iron, bronze, textolite, and carbon plastics at stepped loading under a self-heating mode (Fig. 2).

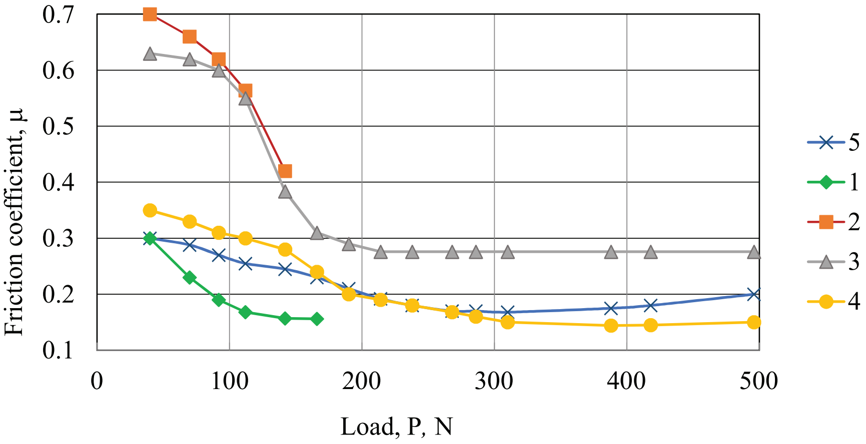


Fig. 2. The dependence of friction coefficient on normal load: 1 — BrOF10-4 bronze; 2 — cast iron SCh 20; 3 — textolite PTC; 4 — carbotextolite; 5 — carbon-fiber plastic

Test results showed that under small loads, the highest friction coefficient was demonstrated by the cast iron SCh20 and the textolite PTC, within 0.65...0.7. Under these test conditions, a low friction coefficient was demonstrated by the samples of carbon-fiber plastic and carbotextolite. The maximum friction coefficient values for carbon plastics, 0.30...0.32, correspond to normal loads from 40 to 120 N. When the load increases to 500 N, the coefficient of friction decreases to 0.16...0.18.

5. 2. Results of studying the anti-friction, anti-wear, and thermomechanical properties of carbon-fiber plastics

The effect of reinforcement direction on the anti-friction properties of carbon plastics is shown in Fig. 3.

Our thermal-friction study (Fig. 3) has shown that the carbon-fiber plastics reinforced with fibers demonstrate a decrease in the friction coefficient with an increase in temperature. The maximum values of this indicator are typical of the temperatures of 70...75 °C, and with further increased temperatures, the friction coefficient decreases and practically remains within 0.1...0.09.

Table 1 gives data on the wear intensity of the “composite–steel 45” tribosystem for the corresponding reinforcement directions of the tested samples. The wear resistance of mated surfaces for different reinforcement directions varies by 5...8 times.

Fig. 4 shows the dependences of the wear of samples on the sample surface temperature and the reinforcement direction. The charts show a general increase in wear depending on temperature.

Contact between a metal surface and carbon plastic leads to a change in the physical and mechanical characteristics of the contacting surfaces. A change in the hardness of the mated surface when rubbing carbon-fiber plastic against it is shown in Fig. 5.

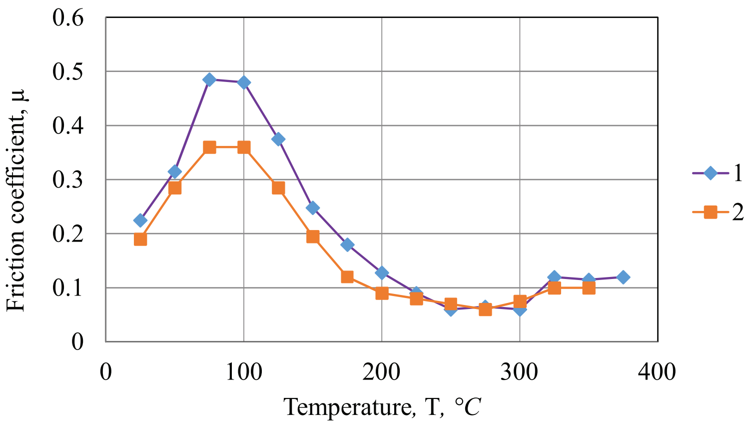


Fig. 3. Dependence of the carbon-fiber plastic friction coefficient on the mated surface temperature and reinforcement direction: 1 – RRRR reinforcement direction, 2 – LLLL reinforcement direction

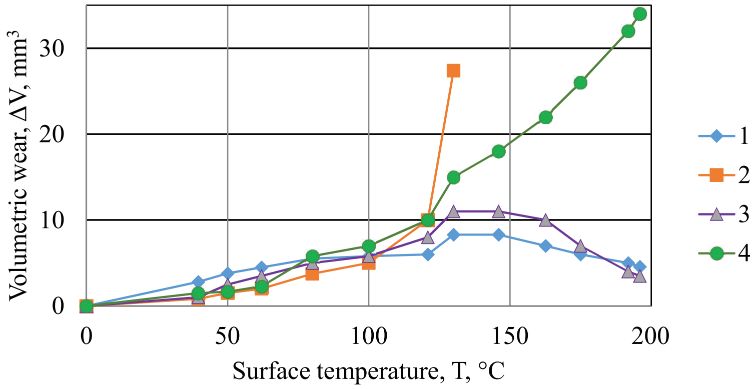
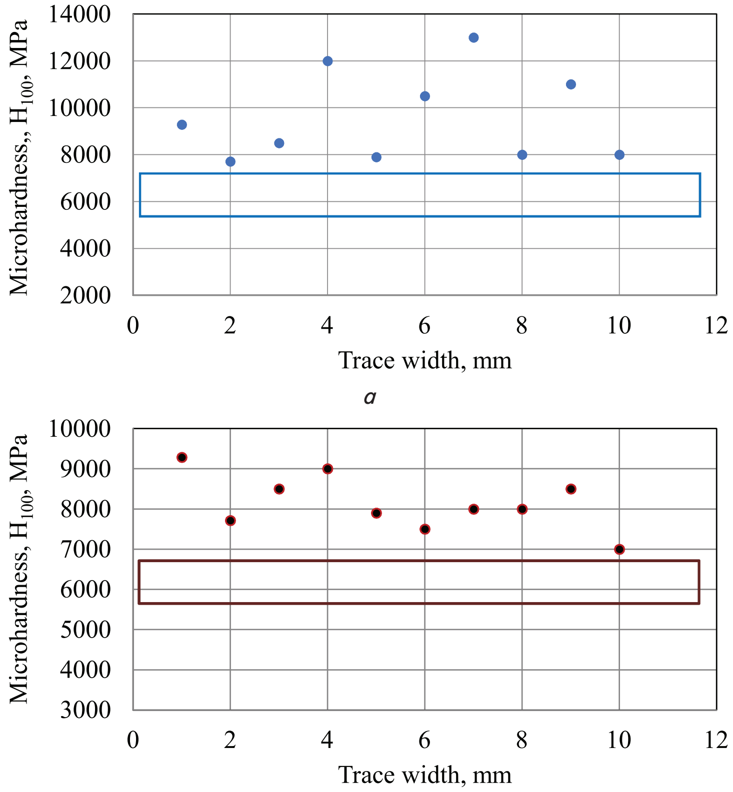


Fig. 4. Dependence of carbon-fiber plastic wear on the mated counter-body temperature (steel 45) and the reinforcement direction: 1 – LLLT, 2 – RRRR, 3 – LLLL, 4 – RLRR



a

b

Fig. 5. Change in the microhardness of the mated surface (steel 45) when carbon-fiber plastic is rubbed against it (the boundaries of the initial values of microhardness are indicated by a rectangle): *a* – LLLL reinforcement direction; *b* – RRRR reinforcement direction

Table 1

Wear intensity of the friction pair
“composite–steel 45”

Rein-forcement direction	Wear intensity, I, mm^3/Nm	
	Metallic surface, $I\cdot10^{-11}$	Carbon-fiber plastic, $I\cdot10^{-7}$
RLRR	3.6	5.4
RRRR	5.1	6.5
LLLT	0.5	7.6
LLLL	1.1	8.1

The results of the hardness measurement showed that during the operation of the friction pair, the hardness of the mated surface increases from 5.5...6.8 to 7.5...13.0 GPa. The increase in hardness occurs in the case of rubbing the carbon-fiber plastic, reinforced both in the direction LLLL (Fig. 5, *a*), and in the direction RRRR (Fig. 5, *b*).

We analyzed changes in the thermal-physical characteristics of carbon-fiber plastic when changing operating conditions for the alternating friction and wear processes. The results of measuring the thermal-physical properties of carbon-fiber plastic depending on the reinforcement direction are shown in Fig. 6.

The chart in Fig. 6 clearly demonstrates that the introduction of carbon fibers into a polymeric matrix leads to an increase in the thermal conductivity of the composite.

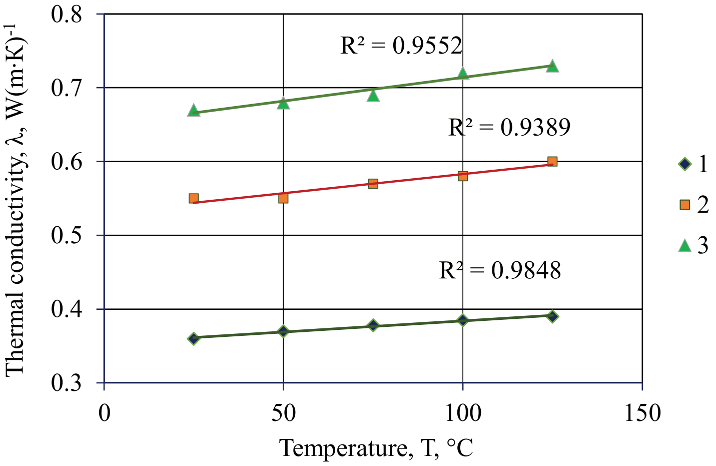
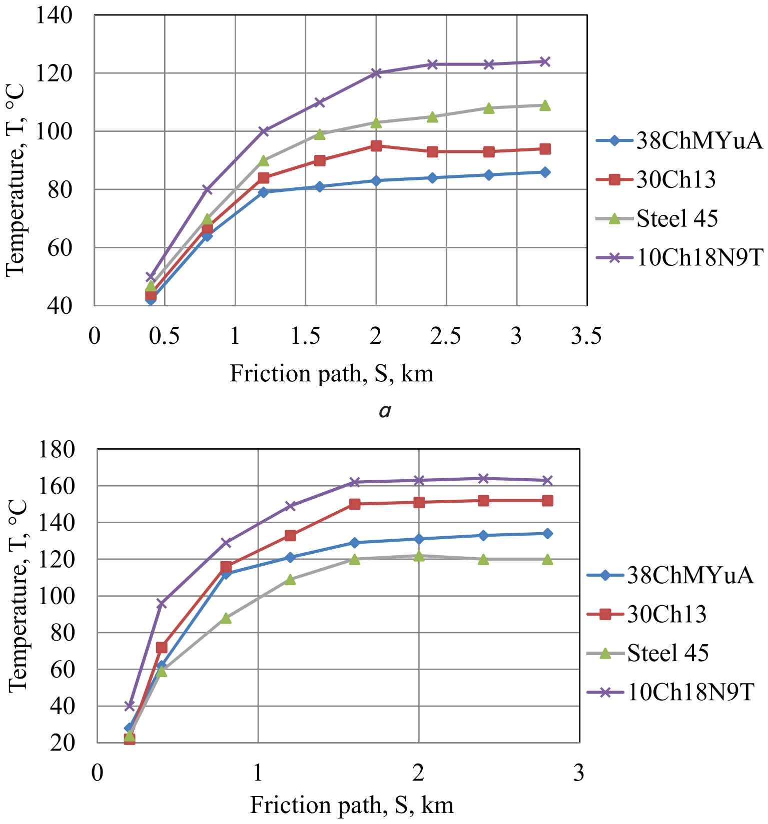


Fig. 6. Linear approximation of the dependence of carbon-fiber plastic thermal conductivity on temperature:
1 – plastic based on the epoxy resin ED-20 without a filler;
2 – a composite with parallel arrangement of filler layers;
3 – a composite with a perpendicular arrangement of filler layers

5. 3. Results of studying the influence of the composition and properties of the mated surface material on the tribological characteristics of carbon-fiber plastics

The effect of the properties of the mated surface on the anti-wear and anti-friction properties of carbon-fiber plastic are given in Tables 2, 3.

The kinetics of temperature changes in the tribosystem “carbon-fiber plastic-steel” is shown in Fig. 7.



a

b

Fig. 7. Temperature dependence in the friction zone on friction path for the pair carbon-fiber plastic-steel: a – reinforcement direction LLLL; *b* – reinforcement direction RRRR

Table 4 gives the indicators of thermal conductivity and energy intensity of various steel materials and the corresponding values of the wear intensity of carbon-fiber plastic.

The results of our study showed a linear relationship between the thermal conductivity and energy intensity of mated materials and the wear of carbon-fiber plastic.

Table 2

Results of testing carbon-fiber plastic at rubbing against mated surfaces of various compositions

Steel grade	HB, MPa	Reinforcement direction			
		LLLL		RRRR	
		Wear intensity, I, mm^3/Nm	T, °C	Wear intensity, I, mm^3/Nm	T, °C
45	1,850	4.36	110	4.57	100
38ChMYuA	1,900	5.25	90	6.2	110
30Ch13	1,750	5.45	100	7.8	135
10Ch18N9T	1,200	6.14	130	10.6	155

Table 3

Effect of the mated surface on the indicators of the carbon-fiber plastic friction process

Steel grade	HB, MPa	Friction coefficient			
		Reinforcement direction			
		LLLL		RRRR	
		min	max	min	max
45	1,850	0.3	0.38	0.24	0.46
38ChMYuA	1,900	0.27	0.49	0.23	0.53
30Ch13	1,750	0.24	0.38	0.21	0.66
10Ch18N9T	1,200	0.24	0.46	0.38	0.82

Table 4

Physical characteristics of the mated surface and the wear of carbon-fiber plastic

Steel	Thermal conductivity coefficient, λ, W/m K	Deformation energy intensity, E_d, MPa	Wear intensity, $I \cdot 10^{-6}$ mm^3/N m
10Ch18N9T	26.1	549	9.9
30Ch13	31.6	510	7.8
38CnMYuA	39.0	424	5.2
45	47.8	343	4.6

5. 4. Studying the microstructural and surface structure of oriented carbon plastics

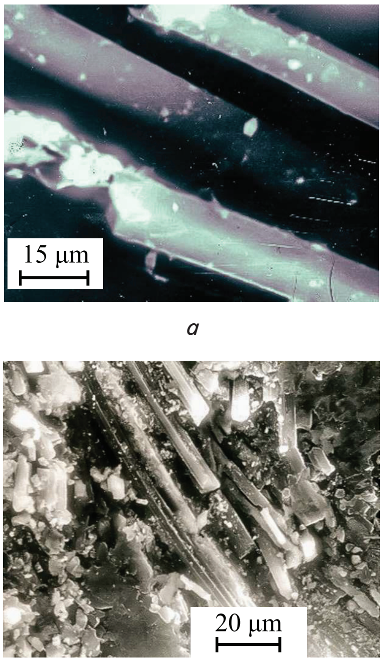
To analyze the mechanisms of destruction and wear of surface layers of carbon-fiber plastics, microstructural analysis of the structure of contact surface layers was carried out. Fig. 8 shows the surface of carbon-fiber plastic after rubbing against steel 45 under the load conditions of up to 5 MPa and at temperatures not exceeding 20...3 °C.

Fig. 9, 10 show defects in the surface layer of carbon-fiber plastic in the form of cracks and destruction of fibers under the action of increased loads.

The mutual influence exerted on the structure of the mated surfaces of the tribosystem "carbon-fiber plastic-steel" is shown in Fig. 11.

The effect of destructive processes on the structure of carbon-fiber plastics, caused by elevated operating temperatures (300 °C and above), is shown in Fig. 12.

The image of the carbon-fiber plastic surface indicates the intensification of the processes of destruction of carbon fibers during operation at elevated temperatures.



a

b

Fig. 8. The surface of carbon-fiber plastic after rubbing against steel 45: *a* – reinforcement direction LLLL (×1,670); *b* – reinforcement direction RRRR (×680)

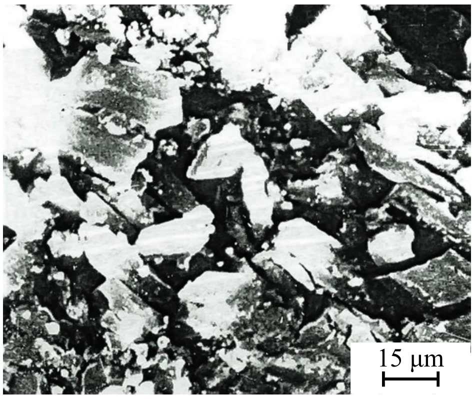


Fig. 9. Cracks in the matrix of carbon-fiber plastic after rubbing against steel, the specific load is P=10...15 MPa (×1,830)

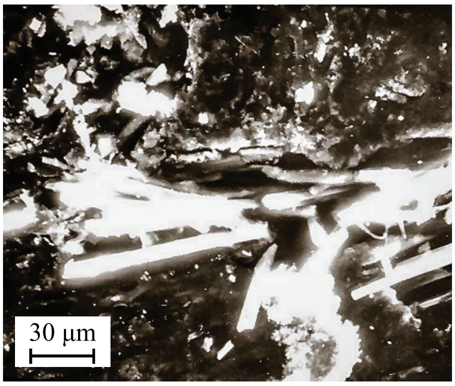
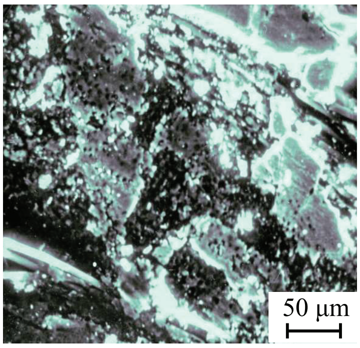


Fig. 10. Destroyed carbon fibers after rubbing against steel 45 (×850): the specific load is P=10...15 MPa; reinforcement direction LLLL

a



b

Fig. 11. The surface structure of the friction pair "carbon-fiber plastic-steel": *a* – the macrostructure (×8) of the steel surface (steel 45, HRC 45-50) after rubbing the carbon-fiber plastic against it; *b* – the surface of carbon-fiber plastic after rubbing it against steel 45 without lubrication (×270)

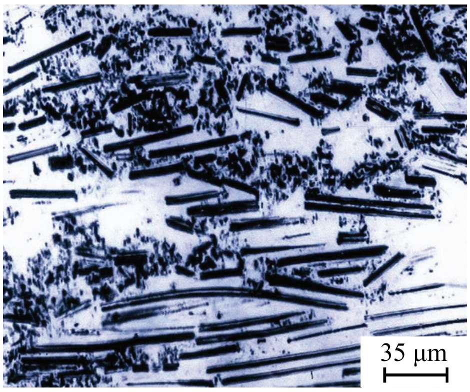


Fig. 12. The surface of carbon-fiber plastic (×420) with destroyed fibers after rubbing it against steel 45 (P=2 MPa, a temperature in the friction zone is 300 °C); the reinforcement direction LLLL

6. Discussion of results of the experimental study into the properties of oriented carbon plastics

In the performance of slip tribosystems, the anti-friction characteristics of materials that are responsible for energy losses in the tribounit and have an indirect effect on the durability of operation play an important role. Our comparative tests of dependence of the friction coefficient on loading (Fig. 2) for metallic and polymeric antifriction materials have shown a tangible advantage of the latter. The results of tests without lubrication demonstrate a steady decrease in the friction coefficient for plastics (textolite, carbotextolite, and carbon-fiber plastic). At the same time, metallic materials at high initial friction coefficients have compromised their performance with an increase in load by more than 120 N. The cone part of the sample was completely worn out. Under these test conditions, the low friction coefficient and high wear resistance were demonstrated by samples of carbon-fiber plastic and carbotextolite. However, under the same initial loads, the high friction coefficient values (0.7...0.9) during the sliding of samples of the textolite PTC cause the warming of the mated surface and an increase in the temperature of the counter-body to 220...250 °C. When rubbing carbon plastics, the friction coefficient is much lower (0.3...0.35) while the temperature in the friction zone does not exceed 120 °C.

Thermomechanical influence contributes to the improvement of the structure of carbon fibers: there is a transition from a two-dimensional layered structure to the turbo-stratum one, approaching the graphite three-dimensional ordered structure. In carbon-fiber plastics, the fibrils that form threads are not intertwined, which does not limit the mobility of fibers as in textolite. The layered structure of the composite graphite fibers ensures a decrease in the friction coefficient (Fig. 3) due to the thin layer of the portable film, which is formed at the steel surface. In the temperature region of 50...90 °C, there is a jump-like increase in friction when the friction coefficient reaches μ=0.4...0.5. At the beginning of tribopair operation, this is due to the effect of the roughness of the mated steel surface. Graphitized fibers have a smooth surface, so separating the wear particles from them at low temperatures is difficult due to the increased thermal conductivity of fibers. With a further increase in temperature to 150...200 °C (Fig. 3), the friction zone of carbon fibers experiences thermomechanical destructive processes. Fiber wear particles fill the micro-depressions of the metal counter-body, a protective film is formed at its surface. The carry film significantly affects the anti-friction properties and wear resistance. At temperatures of 200...300 °C, the friction coefficient decreases and almost stabilizes since the film formation is accelerated by the oxidative processes of the fiber and matrix and the transformation of the elementary fiber lattice. After 350 °C, the composite loses its performance due to the appearance of cracks in the polymeric matrix; the delamination of the filler and its behavior are difficult to explain without special studies.

At temperatures of the mated surface of up to 100 °C, the orientation ratio for the wear amount is as follows: RRRR<RLRR<LLLL<LLLT; for the friction coefficient: LLLL<LLLT<RLRR <RRRR. An increase in the temperature of the metal surface from 150 to 250 °C, which leads to destructive processes in the polymeric matrix, the destruction of the carrying film, and the oxidation of the mated metal surface, changes the nature of friction. In this case, the reinforcement directions that provide for the best wear indicators are LLLL and LLLT; for the friction coefficient, they coincide with the previous ones. When the temperature rises to 200...250 °C, the adhesion between the fiber and matrix deteriorates, the composite monolithicity is disrupted, which causes the stratification of the sample reinforced in the RRRR direction. For samples reinforced in the direction of LLLL and LLLT, stratification of the sample does not occur, which reduces the wear of the composite by almost an order of magnitude (Fig. 4, Table 1). During friction, the

metal surface is exposed to intensive oxidation processes that contribute to the formation of FeO, Fe_2O_3, Fe_3O_4 oxides. The wear process of the steel surface occurs through layer-by-layer destruction of the surface and the intensive oxidation of wear products.

Significant changes in the properties of the mated surface, which occur as a result of carbon plastics friction, have predetermined this research into the influence of the composition and structure, the mechanical and thermal-physical properties of these surfaces on the anti-friction properties of the friction pair.

Carbon plastics significantly change the properties of the mated surface. Graphitized high-module fibers under the action of friction forces form a portable film on the steel surface from the polymer's destructive products and fiber particles. A significant increase in the hardness of the metal surface in the LLLL direction (Fig. 5, *a*) is explained by the slight destruction of longitudinal graphitized fibers and the accumulation of wear products in the friction zone. The peeled particles of fiber during friction carbonate the steel surface, as a result of which its microhardness increases. When sliding carbon-fiber plastic, reinforced in the RRRR direction, plastic deformation processes of the steel surface under the end action of fibers occur, as a result of which the surface is expanded and its microhardness increases (Fig. 5, *b*).

Thermal-physical properties play an important role in predicting the operational characteristics of anti-frictional carbon plastics. Our study into the thermal-physical properties of the examined materials showed that these characteristics depend on the reinforcement direction of the filler (Fig. 6). The introduction of carbon fiber fillers into epoxy resin significantly increases its thermal conductivity. Thermal conductivity almost doubles. A value of the thermal conductivity coefficient is also affected by the nature of the placement of layers of the filler in the composite relative to the direction of the heat flow. It was established that the composite with the location of carbon fibers perpendicular to the surface of the heat meter accepts greater values of the thermal conductivity coefficient compared to materials in which carbon fibers are placed in parallel to the plane of the heat meter. The thermal conductivity of carbon plastics during the passage of the heat flow along the fibers of the reinforcing filler is almost 2 times higher than across the fibers.

Our tests for wear have shown that the effect of the mated surface on the wear process is manifested in the same way for both reinforcement directions. For the reinforcement direction of RRRR and LLLL, it was found that the wear intensity is the lowest when rubbing against carbon steel, and, when rubbing against alloy steels, the wear increases with an increase in the content of alloying elements (Table 2). When heating the steel surface up to 100...200 °C, the secondary structures of the first type are predominantly formed. These are the solid oxygen solutions in iron, which are quite plastic, easily deformable during friction, change little the roughness of the surface and the friction coefficient. When rubbing against the alloyed steels 30Ch13, 10Ch18N9T, the temperature in the friction zone rises to 140...155 °C. That contributes to the formation of secondary structures of the second type of oxides, nitrides, which are stronger and less plastic, which changes the roughness of the surface, increases the friction coefficient and the wear of the composite (Tables 2, 3). The coefficient of friction and the wear of the composite are significantly influenced by a portable film, which is formed at the steel surface due to the smearing of carbon fiber particles and a polymeric matrix. When reinforcing carbon-fiber plastic in the direction of LLLL, the film is more uniform in the thickness and width of the friction path but, over time, the film peels off and its particles pass into wear products. For the direction of RRRR, the film formation process on the mated surface is slowed down as the end of the fiber contacts the steel surface. In the transverse direction, fibers do not have such lubricating ability (taking into consideration the layered structure of graphite) as under the conditions of parallel arrangement relative to the contacting surface. The film is applied under a discrete mode, has a fragmented character. Table 5 demonstrates that the friction coefficient has higher values for the RRRR reinforcement direction than those for the LLLL direction. Measuring the microhardness of the steel surface friction trace has shown that a significant increase in microhardness after working in pair with carbon-fiber plastic is characteristic of steels 30Ch13, 1Ch18NT. The surface layer of the mated surface is carbonated during friction. The maximum values of the friction coefficient increase with an increase in the number of carbide-forming alloying elements in steel. It does not depend on the direction of composite reinforcement.

The kinetics of temperature change in the contact of materials of the studied tribosystems is an important factor in assessing the performance of carbon-fiber materials. Entering a stable thermal regime and the achieved temperatures determine the ability of a tribosystem to adjust and ensure normal operating conditions. Our analysis of temperature change in the friction zone has revealed that a significant increase in temperature occurs at the beginning of the friction path (up to 800 m). The temperature rises to almost 110 °C. When the friction path increases to 1.6 km, the temperature rises to 130...160 °C, after which it almost does not change (Fig. 7). For alloyed steels, temperature stabilization in the friction zone is slower depending on their thermal conductivity. Fig. 7 demonstrates that when reinforced in the direction of RRRR, carbon plastics operate under worse thermal conditions than for the LLLL reinforcement direction, especially for high-alloy steels. In this case, the maximum temperature values rise to 155...135 °C but temperature fluctuations within 10...20 °C do not radically change the wear of carbon plastics. The main factor influencing the wear of carbon-fiber plastic is the composition of the mated surface. The more alloying elements, the greater the wear of carbon plastics. This dependence persists for both reinforcement directions.

The analysis of our results did not make it possible to reveal a clear dependence of the wear resistance of carbon plastics on the mechanical characteristics of the metal surface. At the same time, a relation between the intensity of wear of the composite and the coefficient of thermal conductivity, and the energy-intensity of plastic deformation of the materials of the mated surface has been established. The higher the coefficient of thermal conductivity in the mated surface, the less carbon plastics wear out, and the higher the energy intensity of plastic deformation, the greater the wear of the composite (Table 4). The correlation relationship between the intensity of carbon plastic wear and energy intensity makes it possible to use an energy approach to explain the effect of the nature of the mated surface on the wear resistance of the composite. This approach is based on the principle of accumulation of damage in the material until the separation of metal particles, which significantly affects the wear of carbon plastics on such a surface.

Our microstructural study has made it possible to reveal the mechanism of carbon plastics wear under different temperature and force conditions of friction. Carbon fibers of the composite perceive the bulk of the load, practically without collapse under normal loads and temperatures. Reinforcing fibers after friction have no cracks and tears (Fig. 8). At increased loads (P=10...15 MPa), cracks appear in the polymeric matrix (Fig. 9), and there is fragile destruction of carbon fibers (Fig. 10), which activates the wear of carbon-fiber plastic. Breaking the solidity of the composite and weakening the bonding forces between the matrix and the filler, the cracks intensify the wear of carbon plastic, especially when reinforcing fibers in the direction of RRRR.

When reinforced with carbon-fiber plastic in the LLLL direction, the surface of the fibers remains smoother after friction. The destruction of graphitized fibers occurs layer by layer due to the rupture of the bonds between the graphitized and less graphitized parts of the fiber. Due to the high strength and elasticity indicators, the graphitized high-modular fibers of the LU-2 tape smooth out the micro-intrusions of the metal counter-body. Wear products, which consist of fiber-exfoliated parts during friction and a polymeric matrix, form a portable film on a metal surface. At the same time, the structure of the surface layer of the composite changes: the binder particles stick to the surface of the carbon-fiber plastic, covering the carbon fibers, while changing the friction mode (Fig. 11, *a*, *b*). The appearance of microcracks between the fiber and binder (matrix) affects less significantly the wear of carbon plastics than the destruction of the fibers themselves. Carbon fibers retain the bearing capacity and thereby provide increased wear resistance to the composite reinforced in the direction of LLLL. The destruction of graphitized fibers reinforced in the RRRR direction also occurs as a result of the appearance of cracks in places where inter-atom connections are weakest. Cracks appear at the edge of zones with varying degrees of graphitization. The orientation of the fibers perpendicular to the friction surface provides increased wear resistance of the composite, which is due to the greater energy intensity of the fiber destruction process. In this case, the fibers are bent prior to the destruction, and only after that their rupture occurs, as well as the separation from the matrix. The size of the cracks is limited by the diameter of the carbon fiber, which is hundreds of times smaller than its length.

At elevated temperatures, when thermodestructive processes begin in the matrix, the number of cracks increases. That disrupts the monolithicity of the composite and causes the destruction of carbon fibers and the increase in the intensity of composite wear (Fig. 12).

Thus, we have investigated the influence of the filler orientation relative to the slip plane on the anti-friction properties of carbon-fiber plastic and identified the priority reinforcement direction, which ensures less carbon-fiber plastic wear. The dependence of the wear intensity of carbon-fiber plastic, reinforced with graphitized fibers, on the heat capacity and energy intensity of the mated steel surface has been established.

At the same time, this study has shown that the anisotropy of anti-friction properties for carbon-fiber plastics does occur and almost does not depend on the composition of the material with which carbon-fiber plastic works in pair. In the future, we plan to hybridize the polymeric matrix by adding modifiers or nanopowders to improve the anti-friction properties of carbon-fiber plastics.

7. Conclusions

1. Carbon plastics have high anti-friction properties at friction without lubrication. The maximum friction coefficient values do not exceed 0.30...0.32 when operating under normal loads of up to 120 N and reduce to 0.16...0.18 with increased loads of up to 500 N.

2. Carbon plastics can manifest the effect of reducing the friction coefficient at an elevated temperature of the mated surface. The thermal-physical properties of carbon plastics significantly affect their wear resistance. The thermal conductivity of carbon-fiber plastic during the passage of heat flow along the fibers of the reinforcing filler is almost 2 times higher than when passing across the fibers. It was established that to ensure the increased wear resistance of carbon-fiber plastics, the following reinforcement directions are in priority: LLLL and LLLT.

3. It was established that oriented carbon plastics significantly change the properties of the mated surface; the carbonation and expansion processes occur. A correlation relation between the wear resistance of the pair "composite metal" and the thermal-physical and mechanical characteristics of metal was found, which makes it possible to apply the coefficient of thermal conductivity and the energy intensity of plastic deformation to predict the wear of carbon plastics at friction against steel surfaces.

4. Based on the microstructural analysis, we have established the mechanisms of the surface destruction of carbon-fiber plastics at different temperature and load factors. It is shown that the occurrence of cracks in the surface layer and the destruction of fibers occurs at loads exceeding 10 MPa and at temperatures above 300 °C.

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