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Tribological Properties of a Carbon Fabric Composite with Different Orientations of Fabric Layers to the Movement Direction during Friction

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Abstract—The tribological properties of carbon–carbon antifriction composite materials reinforced with carbon fabric based on polyacrylonitrile and viscose raw materials have been studied. Tribological tests were carried out according to the ring–disc scheme paired with silicon carbide ceramics under dry friction conditions with different orientations of the composite fabric layers relative to the friction surface in the temperature range of 80–100°C. Dependences of the friction coefficient and wear rate on the fabric orientation relative to friction surface, structure of the composite, and properties of its structural components were obtained at a fixed load and sliding speed. The surface of composites was analyzed after tribological tests using scanning electron microscopy and optical profilometry. The composites friction and wear mechanisms for different contact configurations and different material properties have been revealed. The characteristic features of composite individual structural (fibers, fiber bundles, layers of reinforcing fabric) frictional destruction have been determined. It has been established that the film of wear products formed on the friction surface has a decisive influence on the tribological characteristics of the studied materials. Combinations of the fabric base of the composite, its orientation relative to the friction surface, and the heat treatment mode of the material were determined, which simultaneously provide increased wear resistance and reduced friction in tandem with a ceramic counterbody.

Keywords: C/C fabric composite, polyacrylonitrile fiber, viscose fiber, carbonized fiber, graphite fiber, silicon carbide ceramic, friction coefficient, wear resistance, friction surface structure, third body

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INTRODUCTION

Carbon fiber composite materials are widely used in many industries. Interest in these materials is due to the variety of their performance properties. They are characterized by chemical inertness, low density, good electrical properties, the ability to regulate thermal conductivity and electrical resistance over a wide range, and high values of elastic modulus and strength. The complex of useful characteristics of carbon fibers is determined by the nature of the source material and the structure of carbon fibers, which, in turn, depends on the conditions of their production (heat treatment temperature, precursor material, the presence of alloying modifiers, as well as the presence of defects). Depending on the heat treatment mode, carbon fibers are divided into carbonized and graphitized, and depending on the composition of the precursor, carbon fibers are divided into PAN and viscose ones [1, 2]. Carbon fibers are produced into various textile forms: staple fibers, continuous filaments, woven, or non-woven textile. The structure and properties of carbon composites depend not only on the properties of the reinforcing elements (fibers), but also on the oriented structure of the source materials (prepregs) from which they are obtained (fabric, felt, tape, fiber bundle) [3, 4].

Composites based on carbon fibers and a carbon matrix have been used for several decades as friction materials in tribological interfaces that require high strength and heat resistance of the components [5]. The high thermal stability of carbon fibers in combination with chemical inertness makes their use promising for antifriction materials working in tandem with high-hardness counterbodies [6]. In particular, they are used in the production of carbon fiber reinforced plastics, which are successfully used in sliding bearings [7].

Most of the existing mass-produced carbon–carbon composites for tribological purposes are made

Table 1. Types of investigated composites and specifics of their manufacturing

Sample number	Composite name	Annealing temperature	Precursor material
1	Hardcarb—TP	Carbonization	PAN
2	Hardcarb-TV	T < 1000°C	Viscose
3	Hardcarb—TPG	Graphitization	PAN
4	Hardkarb—TVG	T > 2000°C	Viscose

from fiber bundles and non-woven carbon materials. This limits the choice of fiber orientation relative to the friction surface. Research carried out in [8] shows a significant dependence of the tribological characteristics of carbon–carbon fibrous materials on their structure and orientation of the fibers relative to the friction surface.

Much interest is currently being paid to the study of the tribological characteristics of fabric composites based on carbon fibers. In [3], it was experimentally established that carbon fabric composites based on a polymer matrix have high wear resistance and a stable coefficient of friction, which ensures their use in friction and anti-friction friction units in the automotive industry.

In [9], the authors conducted a series of tests using a finger–disk contact pattern of two carbon composites, the first based on carbon fabric with a parallel arrangement of layers, and the second based on random reinforcement with carbon fibers. The counterbody was made of high-strength steel. The authors conducted a comparative analysis of the dependences of the friction coefficient and wear rate on the load F = 117–313 N and temperature T = 20–240°C at constant sliding speed V = 0.25 m/s, which showed the advantages of fabric composites according to the studied characteristics: their high wear resistance (which was 2 times higher than the wear resistance of randomly reinforced composites) and low values of the friction coefficient (lower by 20–30% compared to randomly reinforced fiber composites).

The use of a fabric base makes it possible to vary the orientation of the reinforcing fibers relative to the friction surface over a wide range, which makes it possible to improve both the strength of the elements of friction pairs and the tribological properties of the coupling. In [10], the authors measured the coefficient of friction of fabric composites based on carbon fibers and an epoxy resin matrix paired with a steel counterbody in an aqueous environment at different orientations of the fabric layers to the friction surface. They found that when the layers of fabric are arranged parallel to the friction surface, the wear resistance of the tribocoupling under consideration doubles.

Objective—An experimental study of the tribological characteristics (friction coefficient and wear rate) of carbon–carbon fabric composites under conditions of frictional interaction with a rigid counterbody (silicon carbide ceramics) at different orientations of the fabric layers to the friction surface. The objective of the study was also to study the dependence of the friction coefficient and wear rate on the composition (PAN/viscose) and structure (carbonized/graphitized) of carbon fibers, as well as the properties of the third body forming on the contact surface.

MATERIALS AND METHODS

Materials under Study

The objects of study were four carbon–carbon composites of the Hardcarb series on a fabric basis, produced by GMK LLC, Taganrog, Russia. These composites differed in the type of reinforcing carbon fabric based on PAN (400 g/m^2, twill weave) and viscose (325–350 g/m^2, plain weave). The materials were produced by pressing fabric preprepreg impregnated with polymer, followed by heat treatment. Next, the workpieces were densified (to a density of 1.3–1.5 g/cm^3, depending on the manufacturing technology) during the deposition of pyrolytic carbon from the gas phase. After densification, the materials were subjected to final heat treatment at different annealing temperatures: carbonization at T < 1000°C or graphitization at T > 2000°C (Table 1).

Silicon carbide-based ceramics was used as a counterbody. The counterbody material was obtained by liquid-phase siliconization of porous carbon blanks according to a technique developed at the Osipyan Institute of Solid State Physics, Russian Academy of Sciences [11]. The material is characterized by high hardness (HRC ≈ 92.5 ± 1.5) and practically does not wear out during testing.

Methods of Tribological Tests

An experimental study of the tribological properties (coefficient of friction and wear rate) of the resulting composites was carried out on a UMT-2 laboratory tribometer (Cetr, United States) using a ring–disc contact scheme (Fig. 1a). The tests were carried out in two variations of the arrangement of layers of carbon fabric relative to the friction surface (Figs. 1b, 1c). First scheme: layers of carbon fabric were located perpendicular to the friction surface (Fig. 1b) in the sliding direction; the composite sample was made in the form of a ring, and the counterbody was in the form of a disk. Second scheme: layers of carbon fabric were located parallel to the friction surface (Fig. 1c); the

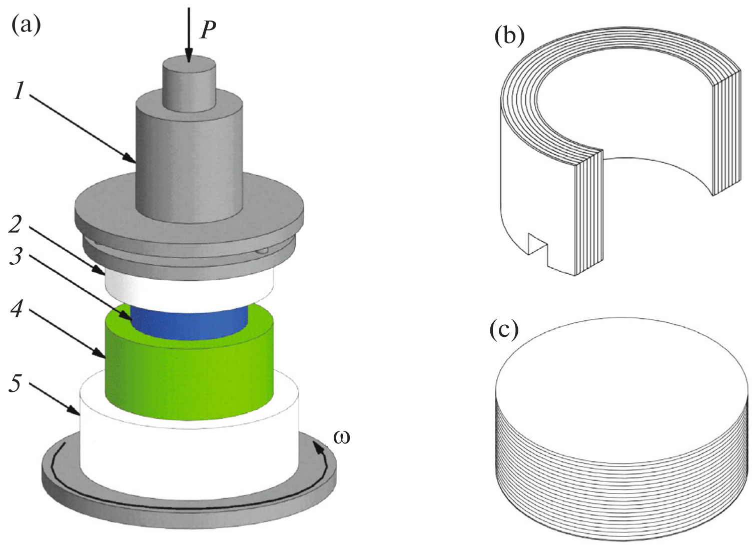

Fig. 1. (a) Installation for tribological tests, where (*1*) self-aligning holder; (*2*) ring holder; (*3*) ring; (*4*) disk; (*5*) disk holder; Location of carbon fabric layers in composite specimens: (b) perpendicular to the friction surface—for the first friction scheme, (c) parallel to the friction surface—for the second friction scheme.

carbon composite was made in the form of a disk, and the counterbody in the form of a ring.

Tests were carried out at fixed load $F = 150$ N (which corresponded to the average pressure in the contact area $P = 0.5$ MPa) and sliding speed $V = 1.25$ m/s in the first scheme and $V = 0.5$ m/s in the second test scheme. The difference in speeds was due to different thermal conductivity of the materials along and across the layers of fabric. This combination of speeds made it possible to keep the temperature in contact, growing due to frictional heating, in the same range of values (80–100°C). During the friction process, non-contact temperature control near the contact zone was carried out using a pyrometer with an error of ±10%. At the same time, the friction regime was maintained, in which the film of wear products on the contact surface does not dry out (since the carbon composite is a hygroscopic material capable of absorbing moisture from the air). The humid film of wear products on the friction surface of the composite provides fairly low values of the friction coefficient and wear rate [12]. To accumulate visible wear, which can be recorded by the equipment used, all experiments lasted about 5 h. Before starting the experiments, in order to ensure the same micro-roughness and geometric shape of the surface of the samples, they were ground in using silicon carbide sandpaper with a grain size of 14–20 μm.

Figure 2 shows typical graphs of the dependence of the friction coefficient and the indicator of the linear proximity sensor of samples on test time. Linear wear of the samples was measured in the area with a steady-state friction regime (Fig. 2b) using a linear proximity sensor built into the tribometer.

Methodology for Studying the Structure of the Surface and Near-Surface Layers of Materials during Testing

In order to analyze changes in the surface of composites during friction at the scale level of individual fibers, an electron microscopic study of the friction surface of the materials under study was carried out. A Quanta-650 scanning electron microscope (SEM) (FEI, United States) with detectors of secondary and back-reflected electrons and analytical equipment EDAX (AMETEK, United States), including an energy-dispersive X-ray microanalyzer, was used. The

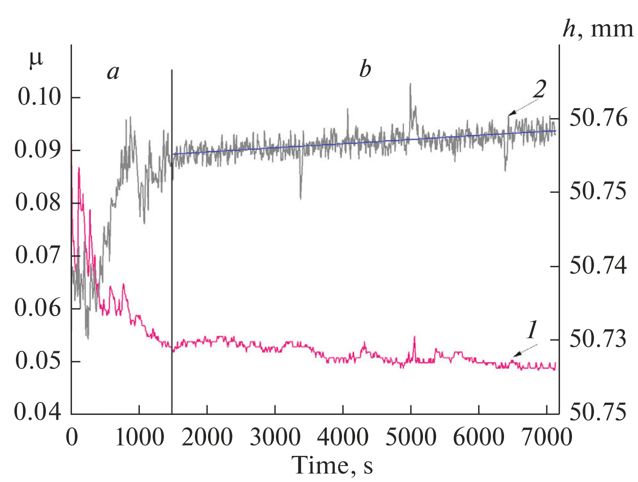

Fig. 2. A typical record of the friction coefficient (curve *1*) and linear proximity sensor samples (curve *2*) on the UMT-2 tribometer, where (a) running-in stage; (b) steady-state friction mode.

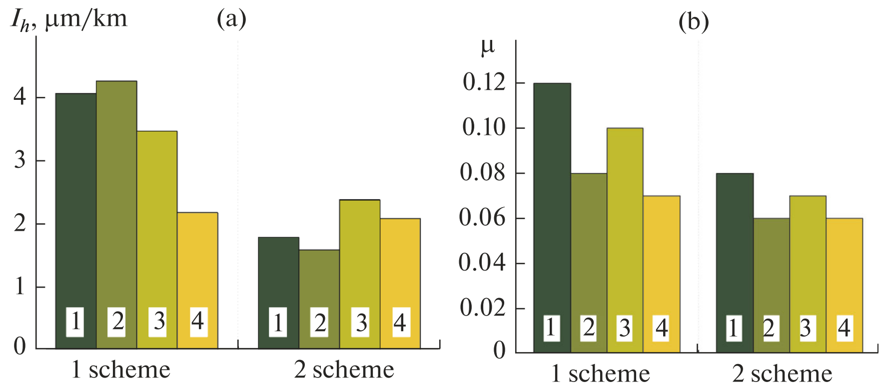

Fig. 3. Dependence of wear rate I_h [μm/km] (a) and friction coefficient μ (b) of investigated composites 1, 2, 3, 4 (Table 1) under two test schemes.

use of two detectors made it possible to collect more complete information about the state of the surface. Thus, working with secondary electrons makes it possible to obtain information about the topography, and back-reflected electrons, to visualize areas with different phase components of the surface.

Changes in the morphology of the friction surface of composites after the above series of tribological tests at the large-scale level of individual layers of fabric were studied by confocal profilometry using an S Neox noncontact optical profilometer (SensoFar, Spain). Measurements of the surface topography of the samples were performed on typically repeating surface areas. In this study, a ×20 confocal objective was used to collect data.

RESULTS AND DISCUSSION

Tribological Test Results

Figure 3 shows the results of tribological tests of fabric composite samples presented in Table 1, which demonstrate the effect on wear rates I_h (Fig. 3a) and friction coefficient μ (Fig. 3b) on the following factors:

— Type of reinforcing carbon fabric.

— Annealing temperatures of the composite (see Table 1).

— The location of the fabric layers relative to the friction surface (see Figs. 1b and 1c).

Analysis of the results shows that when testing samples according to the second scheme (Fig. 1c) (a disk-shaped composite in which layers of fabric are located parallel to the friction surface) the wear rate decreases compared to the first scheme, and for some composites (1—TP and 2—TV, see Table 1) a twofold decrease is observed with $I_h \approx 4$ μm/km up to $I_h \approx 2$ μm/km. The sample of a composite based on viscose fibers with a high annealing temperature (4 – TVG, see Table 1) turned out to be the least sensitive to the test scheme.

The friction coefficients of composites were determined based on continuous measurement and averaging along the friction path under steady-state friction conditions (see curve *1* in Fig. 2b). A comparative analysis shows that composites tested according to the second scheme have lower friction coefficient values (μ = 0.06–0.08) compared to the first test scheme (μ = 0.08–0.12). The highest coefficient of friction for both test schemes was observed for the Hardcarb-TP composite, made on the basis of PAN fiber with a carbonization temperature of less than 1000°C (see Table 1).

In general, based on the results of the tests, we can conclude that carbon composites based on viscose fibers demonstrate lower wear rates and friction coefficients compared to composites based on PAN fibers. This observation is typical for both friction schemes and both modes of heat treatment of the composite.

The Nature of the Destruction of Fabric Composites When the Layers of Fabric are Perpendicular to the Friction Surface (First Test Scheme)

To study the topography of the friction surface of the composite at the micro level, electron microscopic studies were carried out on samples with a third body (TB) formed on the surface. Figure 4 shows SEM images of friction surfaces of composites after tribological tests according to the first scheme.

With this test scheme, the fibers are located both parallel and perpendicular to the friction surface. Analysis of Figs. 4a–4d showed that on the friction surface of the samples a carbon film (TB) is formed from wear products of the composite. The main mechanism of surface destruction is abrasive wear of the fibers. In addition, the ends of the fibers perpendicular to the friction surface can also break off [13], which causes additional wear of the surface. It was also established that the presence of two different mechanisms of surface destruction of the composite and the heterogeneity of its structure (the arrangement of fibers both parallel and perpendicular to the friction surface) prevents the formation of a uniform film of wear products on the entire contact surface of the composite.

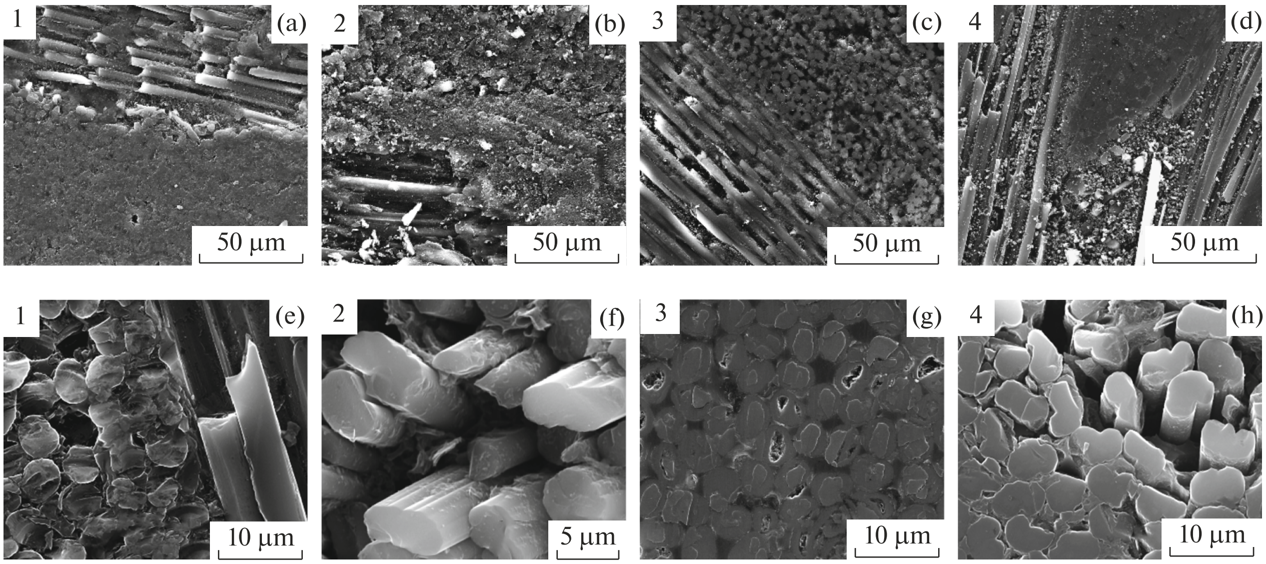

Fig. 4. SEM-images of the surface of carbon composites after tribological tests according to the first scheme: (a–d) with TB film; (e–h) after removal of TB film, for samples 1—TP (a, e); 2—TV (b, f); 3—TPG (c, g); 4—TVG (d, h).

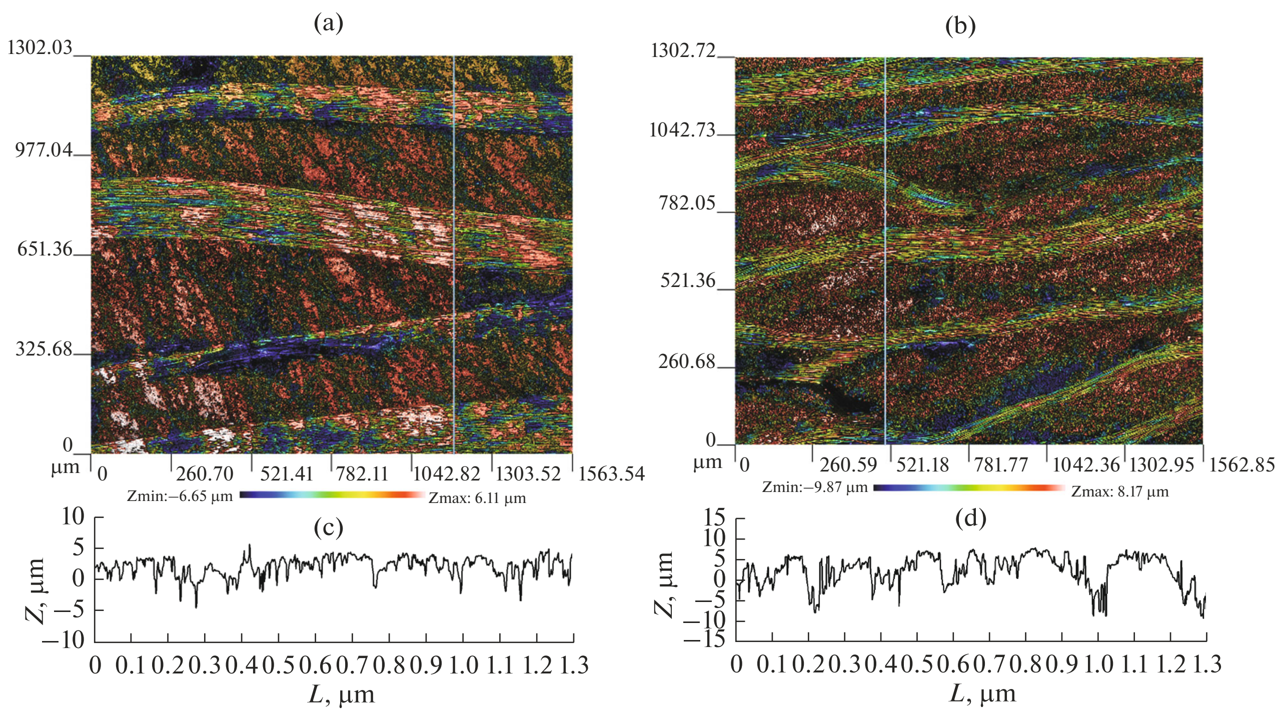

Fig. 5. Profilograms of surfaces (a, b) and their profiles along the conducted secants (c, d) of test specimens tested according to the first scheme: (a, c) material 3 (TPG); (b, d) material 4 (TVG).

In order to study the structure of the worn surface of the composites, the samples under study were cleaned of the film formed during friction. Analysis of SEM images of their worn surfaces (Figs. 4e–4h), obtained at high magnification for the purpose of a detailed study of the structure of the fiber end, allows us to conclude that the end surfaces of fibers of different types differ from each other: a microrelief is observed at the end of the PAN fiber, and the end of the viscose fiber is more uniform and smooth. This difference in surface structure can explain the experimentally established result that viscose-based samples have a lower friction coefficient compared to PAN fiber (see Fig. 3).

The surface of composites (Fig. 5) tested according to the first scheme (layers of fabric are perpendicular to the friction surface) consists of alternating strips (which are sections of individual threads of fabric), in

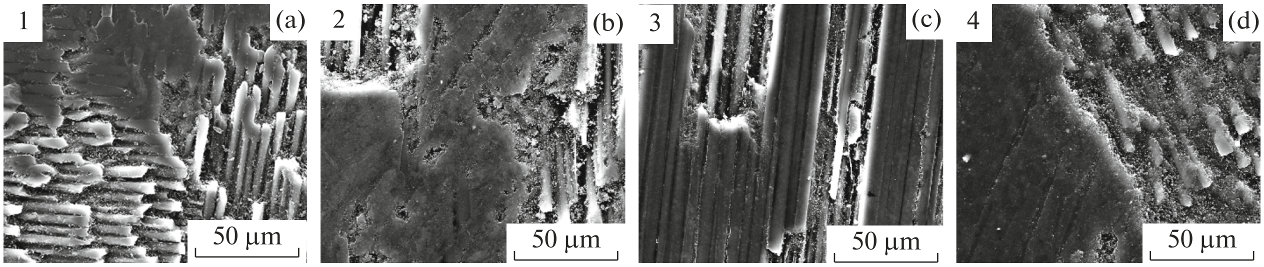

Fig. 6. SEM-images of the surface of carbon composites with TB film after tribological tests according to the second scheme: 1—TP (a); 2—TV (b); 3—TPG (c); 4—TVG (d).

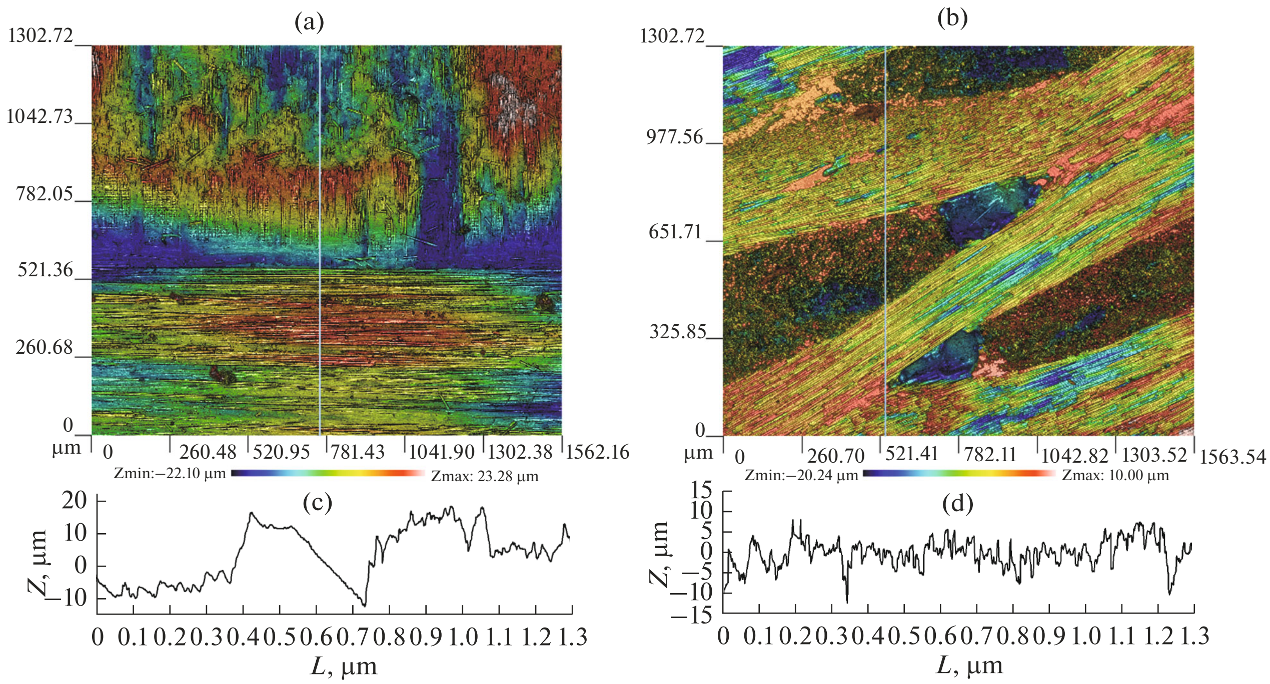

Fig. 7. Surface topography (a, b) and their profiles along the conducted secants (c, d) of test specimens tested according to the second scheme; (a, c) material 3 (TPG); (b, d) material 4 (TVG).

which the fibers are located perpendicular and parallel to the friction surface. In this case, the average height of the stripes varies little depending on the angle of the fibers, and there are deep depressions in the interlayer region. This fact indicates that during friction according to this scheme, significant destruction of the material occurs near the boundary of the fabric layers.

The Nature of the Destruction of Fabric Composites with a Parallel Arrangement of Fabric Layers to the Friction Surface (Second Test Scheme)

Figure 6 shows SEM images of friction surfaces of composite samples at large-scale damage of individual fibers after tribological tests according to the second scheme.

Analysis of SEM images shows that in the friction zone, as in the tests according to the first scheme, a film of a TB is formed, which locally covers the surface, however, the nature of its location on the surface of the composite is different from that observed in the first test scheme (see Fig. 4). In particular, after testing according to the second scheme, the film covers most of the surface (Fig. 6). In this case, the TB film is more dense and covers the protrusions or depressions in the interlayer region, which helps to reduce the coefficient of friction and wear [14]. The observed result can be explained by the fact that in the second test scheme, the fibers in the samples are located predominantly parallel to the surface, so friction occurs mainly along the fibers, which wear mainly by an abrasive mechanism, so the formation of the TB film occurs more uniformly. It is important to note that, as in the first test scheme, the best tribological characteristics are demonstrated by viscose-based samples, in which a denser and more uniform TB film is formed on the surface.

In Figs. 7a and 7b, profilograms of the surface of the materials Hardcarb-TPG and Hardcarb-TVG washed from the TB film after tribological tests according to the second scheme at the scale level of individual layers of fabric are presented. In Figs. 7c and 7d surface profiles are shown along the drawn secant lines. It should be noted that, as with the first friction scheme, the surface of materials annealed at low temperatures has a similar character to materials annealed at high temperatures, so their images are not shown in the figure. Analysis of profilograms shows that due to the peculiarities of twill weaving, characteristic of a composite based on PAN fiber (Fig. 7a), its surface has more extensive depressions in places where individual threads are intertwined compared to a viscose-based composite. In this case, almost all fibers are located at small angles to the friction surface. Material based on viscose fibers (Fig. 7b) demonstrates a fairly uniform surface topography. Due to the peculiarities of the plain weave of the fabric, the taken profilograms contain areas with both parallel fibers and fibers at an angle close to direct to the friction surface. However, as stated above, viscose fibers, when positioned perpendicular to the contact surface, form smooth cuts with low roughness, which leads to the formation of a more uniform surface film, which helps reduce the wear of materials based on viscose fiber (TV and TVG).

Thus, the structure of the fibers and their location relative to the friction surface significantly influence the nature of their surface destruction and the formation of the TB film under frictional interaction conditions, which, in turn, determines the value of the friction coefficient and wear rate at different test schemes (Fig. 3).

CONCLUSIONS

The research carried out in this work allows us to conclude that the tribological characteristics (wear resistance and coefficient of friction) of carbon–carbon composites on a fabric basis are largely determined by the following processes:

— Formation of a film of wear products (TBs) on the surface of the material. This film can significantly reduce wear and friction, while its thickness and continuity is determined to a greater extent by the properties of the fiber (viscose fiber produces a thicker film than PAN) and to a lesser extent by the orientation of the reinforcing fabric. As a result, materials based on viscose fiber are characterized by lower wear and friction coefficient. At the same time, heat treatment has practically no effect on the film.

— Destruction of the material at the boundaries of threads and layers of fabric. This process is mainly determined by the orientation of the tissue layers relative to the friction surface. As a consequence, the friction scheme in which the fabric layers are parallel to the contact surface (second test scheme) is characterized by less wear and friction coefficient. It should be noted that this process is typical specifically for materials with a carbon matrix, since for composites with similar reinforcing fabrics and a polymer matrix (in which there is no noticeable destruction at the boundaries of structural elements during friction), the first friction scheme shows greater wear resistance.

The listed processes (interlayer destruction and formation of a surface film) take place at different scale levels (~10^{-3} m for interlayer destruction and ~10^{-6} m for the surface film) and for this reason practically do not affect each other.

Analysis of the results of tribological tests allows us to conclude that heat treatment at high temperatures (>2000°C) slightly reduces the coefficient of friction, but can cause an increase in wear in the second contact pattern (layers of fabric are located parallel to the friction surface), so its feasibility for antifriction materials is ambiguous. Thus, of the materials considered, the optimal one in terms of low values of friction coefficients and wear intensity is a composite based on viscose fiber, annealed at a temperature <1000°C, with the arrangement of fabric layers parallel to the contact surface (Hardcab-TV, second test scheme). Moreover, all the materials studied show a fairly low coefficient of friction (0.06–0.12) and high wear resistance (1.5–4.3 μm/km) when paired with a ceramic counterbody characterized by high surface hardness. This makes them promising materials for use in plain bearings operating without lubrication or with limited lubrication. The high tribological characteristics of the materials are maintained in a limited temperature range, which does not allow the evaporation of absorbed moisture from the carbon film on the surface of the composite, which imposes restrictions on the load-speed friction conditions. However, these restrictions can be significantly weakened in the case of friction in a liquid medium [6]. Considering the significant destruction of materials at the interface of threads and layers of fabric during friction, a promising way to increase the wear resistance of the materials under consideration is to increase the packing density of layers of fabric and individual threads, as well as to increase the mechanical strength of the connection between structural elements. It should also be noted that the manufacturing technology of the materials under study makes it possible to vary the direction of the fabric layers relative to the friction surface for different contact configurations (flat, cylindrical, conical, etc.), achieving optimal values of friction coefficients and reducing wear intensity under given operating conditions of a particular tribocoupling.

Thus, the results of the research can be used in the development of new carbon fabric composites for various friction units and control of their tribological characteristics by selecting the type of reinforcing fabric, its orientation relative to the working surface, and heat treatment modes of the material.

NOTATION

PAN	polyacrylonitrile
T	temperature, °C
F	load, N
P	pressure, MPa
V	sliding speed, m/s
SEM	scanning electron microscopy
I_h	wear rate, μm/km
μ	coefficient of friction

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. Khtet, V.A., Sheshin, E.P., and Vei, Z.Kh., Main properties of carbon fibers based on polyacrylonitrile, *Elektron. Mikroelektronika SVCh*, 2019, no. 1, pp. 265–267.
2. Hu, Zh., Tong, Yu., Wang, M., Xu, J., and Yang, Ch., Rapid and low-cost carbon/carbon composites by using graphite slurry impregnated prepregs, *J. Eur. Ceram. Soc.*, 2023, vol. 43, no. 10, pp. 4363–4373. https://doi.org/10.1016/j.jeurceramsoc.2023.04.002
3. Farfan-Cabrera, L.I., Tapia-Gaspar, M., and Pérez-González, J., *Tribology of polymer matrix composites within the automotive industry, Encyclopedia of Materials: Composites*, Brabazon, D., Ed., Elsevier, 2021, vol. 1, pp. 970–982. https://doi.org/10.1016/B978-0-12-819724-0.00029-X
4. Kabir, S., Shahed, Ch.A., Ador, Md.S.H., Choudhury, I.A., and Ahmad, F., Review of the developments in compo-site materials over the last 15 years, *Reference Module in Materials Science and Materials Engineering*, Elsevier, 2023. https://doi.org/10.1016/B978-0-323-96020-5.00044-3
5. Karger-Kocsis, J., Mahmood, H., and Pegoretti, A., All-carbon multi-scale and hierarchical fibers and related structural composites: A review, *Compos. Sci. Technol.*, 2020, vol. 186, p. 107932. https://doi.org/10.1016/j.compscitech.2019.107932
6. Su, H., Zhang, Ch., and Sun, Sh., Research on the wear model of carbon/carbon composite finger seal, *Wear*, 2021, vol. 476, p. 203682. https://doi.org/10.1016/j.wear.2021.203682
7. Mezrin, A.M., Morozov, A.V., Sachek, B.Ya., Goryacheva, I.G., Kiryukhin, D.P., Biryukova, M.I., Buznik, V.M., Anisimov, A.V., Lishevich, I.V., and Bakhareva, V.E., Tribological characteristics of epoxy carbon-fiber-reinforced plastics modified by solution of polytetrafluorethylene telomers, *J. Frict. Wear*, 2013, vol. 34, no. 5, pp. 368–373. https://doi.org/10.3103/s1068366613050097
8. Cheng, H., Xue, N.J., and Hou, W.Q., The application and development of carbon/carbon composites in aircraft and high-speed train braking systems, *Carbon*, 2020, vol. 184, pp. 30–33.
9. Su, F.-H., Zhang, Zh.-Zh., Wang, K., Jiang, W., and Liu, W.-M., Tribological and mechanical properties of the composites made of carbon fabrics modified with various methods, *Compos. Part A: Appl. Sci. Manuf.*, 2005, vol. 36, no. 12, pp. 1601–1607. https://doi.org/10.1016/j.compositesa.2005.04.012
10. Morozov, A.V., Sachek, B.Ya., and Mezrin, A.M., Investigation of tribological properties of modified carbon fibers in the flowing water, *Vopr. Materialoved.*, 2012, no. 4, pp. 58–65.
11. Shikunov, S.L. and Kurlov, V.N., SiC-based composite materials obtained by siliconizing carbon matrices, *Tech. Phys.*, 2017, vol. 62, no. 12. https://doi.org/10.1134/S1063784217120222
12. Gomes, J.R., Silva, O.M., Silva, C.M., Pardini, L.C., and Silva, R.F., The effect of sliding speed and temperature on the tribological behaviour of carbon–carbon composites, *Wear*, 2001, vol. 249, nos. 3–4, pp. 240–245. https://doi.org/10.1016/s0043-1648(01)00554-3
13. Shpenev, A.G., Muravyeva, T.I., Shkalei, I.V., Kulakov, V.V., and Golubkov, A.K., The study of the surface fracture during wear of C/C fiber composites by SPM and SEM, *Procedia Struct. Integr.*, 2020, vol. 28, pp. 1702–1708. https://doi.org/10.1016/j.prostr.2020.10.145
14. Shpenev, A.G., Muravyeva, T.I., Shkalei, I.V., and Bukovskiy, P.O., Influence of the surface film (third body) on the friction and wear process of carbon-fiber composites, *J. Surf. Invest.: X-Ray, Synchrotron Neutron Tech.*, 2022, vol. 16, no. 3, pp. 397–401. https://doi.org/10.1134/S1027451022030326