Improving the antifriction properties of the housing-rotor coupling in axial turbomachines

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Abstract. The article discusses the frictional interaction of carbon-carbon composite material on steel. Antifriction properties and wear resistance of the material under dry friction at speeds up to 100 m/s are investigated. The effect of velocity and contact pressure on the friction coefficient and wear resistance of a carbon composite is analyzed. The regularities of the change in the coefficient of friction are determined depending on the load-speed factors. The assumption is substantiated that the high thermal stability of the carbon composite, its low hardness, good antifriction properties and high wear resistance allow the material to be used in friction units operating at very high speeds and temperatures. In order to improve the reliability and reduce gas flows in axial turbomachines, on the basis of the study carried out, it is recommended that instead of heat-resistant coatings, a lining of the gas duct casing should be made of carbon composite.

1. Introduction
Air leaks from the gas path in axial engines reduce the efficiency of the turbomachine. Reducing parasitic leaks between the casing and the blade is achieved by reducing the clearance. In aircraft engines, the clearance can be up to 300 microns. Under operating conditions, due to an increase in the load on the rotor, additional loads from vibration, the initial clearance become inadequate and the touch of blades and casing at high speeds and temperatures may occur. Mechanical clearances can also occur in turbines and compressors, depending on the operating time. Deterioration of engine components negatively affects performance [1]. The work [2] analyzes the turbine impeller damage in an aircraft. As a result of the impeller blades friction against the housing, damage arose, which led to the failure of the rear bearing. The work [3] investigated the influence of various factors modeling to assess the energy of the gas flow and the efficiency of the seal, taking into account the friction against the walls, as well as the work performed by the rotating disk of the turbine. In [4], a greater influence of various options for increasing the thermal efficiency of the engine is noted. In [5], a new algorithm is proposed based on the analysis of the degree of relationship between probable and specific faults to achieve fault diagnosis. Real-time simulation for aircraft gas turbine engines is widely used [6] to improve engine performance and reliability. The research established the requirements for high-precision on-board modeling during the life cycle of the engine, especially critical for safety parameters of gas flow control. Much attention is paid to the improvement of the antifriction properties of materials during the friction of the blade against the casing and to the study of the friction of materials during high-speed sliding. The friction of titanium alloys was investigated in the sliding friction mode at a low applied load of 2 N
and a very high sliding speed of 300 m/s corresponding to the condition of the blade touching the turbomachine casing. It was found that in the process of evolution of the microtexture of the surface layers of friction surfaces, layers of ultradispersed grains with an average grain size of <1 μm are formed. These changes have resulted in a significant reduction in wear losses. There are very few studies of the behavior of materials under friction at sliding speeds of more than 40 m/s, although interest in this field of tribology has existed for more than half a century, and in connection with the development of aviation and high-speed rail transport, the relevance of studying the friction of materials at high speeds has increased significantly. The first results were obtained on Beam centrifuges and similar centrifuges of the YЦ-2А type (Czechoslovakia), in which the ball was spun up in a vacuum in an electromagnetic suspension. A great contribution to the development of the high-speed friction tribology was made in the fundamental research of V.A. Balakina, V.M. Goryunova, N.L. Golego, in which the behavior of metals was studied under conditions of sliding speeds up to 100 m/s and more. Solid lubricants are used to improve the antifriction properties. It was established in [8] that the use of monolayers of transition metal dichalcogenide WS2, MoSe2, and WSe2, deposited by chemical vapor deposition, is effective. The friction coefficient did not depend on the sliding speed within the analyzed range. In [9], the phenomena of contact interaction at an ultrahigh rotor speed are investigated. It has been found that high rotational speeds do not significantly affect the peak temperature. Much attention is paid [10] to brake materials for high-speed trains, the wear resistance of which is greatly influenced by the coefficient of friction and surface vibration. In the study [11], some approaches are considered using the example of non-lubricated contact of a silicon nitride ball on a steel disk operating in humid air at a contact pressure of about 1.5 GPa with a variable high sliding speed in the range from 1 to 16 m/s. It was found that the tribochemical behavior of high-speed sliding contacts is associated with the transitions of the friction coefficient from high to low values and was accompanied by a transition from oxidative wear to the formation of a complex tribofilm at speeds above 4.5 m/s. The work [12] investigated the phenomena of contact interaction at an ultrahigh speed of rotation of the rotor. It has been found that high rotational speeds do not significantly affect the peak temperature. Much attention is paid to the problem of mass transfer of the materials and surface seizure. The influence of the initial roughness on the process of changing the roughness parameters during the running-in of the surface is discussed [13]. The work [14] studied the relationship between the kinetic force of dry friction and the sliding speed depending on the interacting materials, load and speeds. It is shown that different friction mechanisms take place at different load-force factors. At present, carbon composite materials are of interest for use in the coatings of the casing of the gas path of aircraft engines. The mechanical properties of carbon-carbon composites have been studied quite extensively, and the tribological properties of materials under conditions of sliding at high speeds have been little studied.

The aim of this work is to study the tribotechnical properties of heat-resistant composite carbon materials under conditions of high sliding speeds (up to 100 m/s) on steel.

2. Materials
For tribological tests, the following materials were selected: carbon-carbon composite material TERMAR and counterface made of steel with chemical composition in%: (0.42 - 0.5) C; (0.17 - 0.37) Si; (0.5 - 0.8) Mn; 0.25Ni; 0.04S; 0.035P; 0.25Cr; 0.25Cu; 0.08 As; ~ 97Fe.

3. Equipment and technologies
To carry out high-speed tests, the working part of the YMT-1 machine was modernized in terms of installing an additional stage in the drive to double the number of rotations. The experiments were carried out according to the pin-on-disk scheme. The machine is equipped with a steel disc with a diameter of 320 mm, the typical size of a square section pin is 5 mm. The speed has been increased to 6000 rpm. Three crystalline pin samples were installed at an angle of 1200 relative to each other in the seats of the disk-holder. The wear of the samples was determined by the gravimetric method on an electronic balance Shinko Vibra HTR-220 CE (Japan) with an accuracy of 0.0001 g. with subsequent conversion to linear wear.
The determination of mechanical properties was carried out by the kinetic indentation method. The surface was photographed with an optical microscope during micromechanical tests in accordance with GOST 27860-88. The tests were carried out on a microhardness tester MNT_Z_AE_000 from CSM Instruments in accordance with the international standard ISO / DIS 14577-1: 2002.

4. Results

The structure of the friction surface of the samples is isotropic (figure 1), which is due to the specifics of the location of the fibrous carbon filler (reinforcing frame) in the volume of this carbon-carbon composite.

Figure 1. Friction surface of a carbon composite prior to tribological tests.

The carbon matrix is uniformly formed throughout the volume, without a marked direction. There are no visible inclusions of pores in the photographs, which indicates good wettability of carbon fibers by the binder and good adhesive bonding at the interface between the matrix and the CCCM filler. These factors determine the high frictional heat resistance of the test specimen and its resistance to repeated thermal impulse loading.

The most important characteristics of the mechanical properties of the surface layers of friction parts are hardness and modulus of elasticity. Table 1 shows the mechanical properties of the samples, measured by the kinetic microindentation method at a load of 1N.

Table 1. Comparison of mechanical properties of CCCM and zirconium ceramics.

| Composition          | Density, g/cm³ | E, GPa | HV, Vickers |
|----------------------|---------------|--------|-------------|
| CCCM                 | 1.78          | 22     | 41          |
| Ceramics based on ZrO₂ | 5.8          | 214    | 1620        |

The estimated wear resistance index (GOST 23.001-2004) was taken as a dimensionless wear resistance index G, calculated by the formula

\[ G = \frac{L}{h}, \]

where \( L \) is the interval of the friction path; \( h \) - linear wear increment.

Samples of the carbon-carbon composite were tested as supplied. Conversion of weight loss to linear wear after the completion of tribological tests is carried out according to the specific gravity of the material. Many types of composite carbon-carbon material are known, the production technology and properties of which differ significantly, therefore the specific gravity of the test material was determined in accordance with GOST 15139-69. The results of measurements of the arithmetic mean of three parallel measurements are shown in table 2.
Table 2. The results of calculating the density of the CCCM sample.

| №  | $X_1 + \Delta X_1$ (mm) | $X_2 + \Delta X_2$ (mm) | $X_3 + \Delta X_3$ (mm) | $X_4 + \Delta X_4$ (cm³) | $X_5 + \Delta X_5$ (g) | $X_6 + \Delta X_6$ (g/cm³) |
|----|-------------------------|--------------------------|--------------------------|--------------------------|-------------------------|---------------------------|
| 1  | 28.02 ±0.046            | 19.86 ±0.046             | 15.04 ±0.046             | 4.615±0.066              | 8.215±5·10⁻⁴           | 1.7802±0.026              |
| 2  | 27.99±0.046             | 19.82±0.046              | 15.04±0.046              | 8.215±5·10⁻⁴            | 1.7805±0.026           |
| 3  | 28.03±0.046             | 19.87±0.046              | 15.03±0.046              | 4.614±0.066              | 8.2151±5·10⁻⁴          | 1.7805±0.026              |
|    |                         |                          |                          |                          |                         | 1.7804±0.026              |

Remarks: the dimension of units is interpreted in terms of the clause 2.3 of GOST 15139-69.

The designations used in the table:

- $X_1$ is the outer diameter of the sample;
- $X_2$ is the inner diameter of the sample;
- $X_3$ is the height of the sample;
- $X_4$ - sample volume,
- $X_5$ is the mass of the sample;
- $X_6$ is the density of the sample, determined by the formula $X_6 = X_5 / X_4$.

It has been experimentally established that the density of the test sample is: $\rho = 1.78 + 0.026$ g/cm³. The relative error for volume is: $\Delta x_4 / x_4 = 0.013$. Relative error for density: $\Delta x_6 / x_6 = 0.014$. The discrepancy between three parallel measurements is less than 0.003 g/cm³, which meets the requirements of GOST 15139-69 (no more than 0.005 g/cm³ is allowed).

Tribological tests were carried out using the step-stress test. In accordance with the accepted experimental procedure, the sample-disk was brought to a given speed mode and a normal load was applied. Calculated dependencies for determining the average contact pressure $p$ (MPa), sliding speed $v$ (m/s), sliding friction coefficient $f$ and wear resistance index of materials $G$ will have the following form:

$$p = 4 N_i / (\pi d^2); \quad v = \pi n / 30; \quad f = M / \rho N; \quad G = L / \Delta h,$$

where $N$ is the load per pin sample; $d$ is the diameter of the pin sample; $\rho$ is the distance from the axis of rotation of the sample - disk 7 to the axis of the pin sample 6; $n$ is the rotation frequency of the sample-disk 7 (min⁻¹); $M$ is the frictional moment per sample.

Contact pressure is one of the main factors affecting the wear resistance of materials. Figure 4 shows the change in the wear resistance index $G$ with increasing load. Quantitatively, the wear resistance indicator is characterized by very large values, therefore the experimental curve is plotted as a function of log $G$ on the contact pressure. Figure 2 shows the results of tests to determine the dimensionless wear resistance index $G$ with dry friction on steel at a speed of up to 100 m/s.

![Figure 2. Influence of contact pressure on the wear resistance index.](image-url)
Figure 3 shows the results of tests to determine the friction coefficient for dry friction on steel at a speed of up to 100 m / s.

In the entire range of speeds, the friction coefficient varied in the range of 0.16 - 0.28, the average value \( f = 0.21 \pm 0.07 \). A decrease in the coefficient of friction with an increase in sliding speed to 60 m / s is explained by a decrease in the actual pressure at the touching areas due to a decrease in hardness, which is caused by surface heating. The contact approach of the surfaces is relatively small and the deformation component of the friction coefficient is negligible. With an increase in the speed of more than 60 m / s, an increase in the deformation component of the friction coefficient affects. Figure 4 shows the effect on the coefficient of friction of contact pressure in sliding conditions at constant speed.

Figure 5 shows the structure of a carbon composite after tribological tests.
Figure 5. Friction surface of a carbon composite after tribological tests.

No significant changes in the structure of the carbon composite were found. The effect of contact pressure on the friction coefficient shown in the experiment obtained corresponds to the concepts of the molecular-mechanical theory of friction. Molecular bonds at the contact are of electrical nature, therefore, the shear strength of molecular bonds does not depend on temperature and the value of the friction coefficient is determined by the value of the contact pressure, the higher the contact pressure, the lower the coefficient of friction.

5. Discussion
The improvement of thermal engines of the future, including aircraft engines, is proceeding in the direction of increasing the efficiency, which is possible only with an increase in the temperature of the gas flow. Accordingly, the thermal clearances increase and the rigidity of the rotor suspension in axial machines is likely to decrease.

Modern thermal protection coatings of the gas path body are made of temperature-resistant composite materials with a ceramic matrix, for example, based on zirconium and aluminum oxides, which are materials with high hardness. Touching ceramic coatings with a rapidly rotating blade can be disastrous. The increase in clearances significantly reduces the economic performance, and the increase in the rigidity of the rotor suspension in the engine leads to a significant increase in production costs associated with tightening tolerances in the manufacture of parts. Carbon-carbon composites have high heat resistance and low hardness. The experiments carried out to study the tribological properties of CCCM indicate a lower coefficient of friction in comparison with ceramics and good wear resistance, which makes carbon composites promising for the manufacture of the lining of the gas path body. The blade is safer to touch the carbon composite lined body than the ceramic composite.

6. Summary
The developed methodology for friction and wear high-speed tests (up to 100 m/s) makes it possible to efficiently perform express-evaluation of the tribotechnical properties of structural materials.

At high-speed sliding (up to 100 m/s), the use of carbon-carbon composite materials has significantly better (more than 30 times) indicators in terms of antifriction properties and the criterion of wear resistance of samples in comparison with ceramic thermal protection coatings.

In terms of the combination of thermal stability and tribological properties, carbon-carbon materials are promising for the manufacture of the lining of the casing of the gas path of axial machines in order to increase the reliability and reduce gas leaks.
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