Tribological tests of frictional carbon/carbon composite in braking mode

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Abstract. The article discusses the issues of friction and wear testing of a carbon-carbon composite of tribological purpose. The experiments were performed on a bench, the work of which is based on the absorption of kinetic energy of rotating masses with materials intended for use in brake devices. The friction coefficient and wear rate of the friction carbon composite in braking mode are investigated. Ring samples are divided into 6 sectors, in each of which, after testing, the parameters of the roughness of the friction surfaces and wear during one braking are determined. The value of linear wear was determined as the average value over 6 sectors for rotating and stationary samples. Changes in the structure of friction surfaces are investigated. Metrological support of the experiments was carried out by statistical processing of the results. The errors in measuring the coefficient of friction and wear rate are determined. High resistance to energy absorption and thermal shock of the studied frictional material is established, which open up the prospects for the mass use of C/C in transport brake devices.

1 Introduction
Current trends in the development of vehicles are based on an increase in speed and traffic safety, which determines the need for improving brake devices. To increase braking efficiency, new materials are developed and existing ones are improved.

Promising friction materials include carbon-carbon composite materials (C/C) because they have unique specific strength characteristics. Much attention is paid to improving tribological properties and test methods. The wear of the friction material and its effect on tribological characteristics were examined in study [1]. To study the tribological characteristics of friction materials, laboratory friction machines operating according to the disk-finger scheme are used [2 — 4].

The structure of the friction layer of carbon-carbon composites after braking tests was studied in [5]. It has been found that carbon fiber tends to wear out into small fragments along the fiber axis. Nanosized carbon particles were discovered in the surface layer, which during friction acted as a lubricant. The use of short carbon fibers to improve the tribological properties of carbon composites was tested [6]. The study of mechanical and tribological properties showed that a composite with a fiber content of 30% demonstrates the highest bending strength (201 MPa) and shear strength (116 MPa) and has the highest wear resistance. It was established in [7] that the effect of carbon fiber on increasing toughness and thermal conductivity is more noticeable than that of aramid fiber. In [8], the influence of the surface roughness of the friction material on the tribological characteristics of disc brakes is shown.

The influence of braking pressure and braking speed on the tribological properties (C / C) of composites was studied in [9]. At higher braking pressure or braking speed, wear increases due to scaly damage to the friction film and high oxidation losses. In [10], the effect of moisture on the friction coefficient of a composite disk was experimentally established. Evidence of a possible transition to a hydrodynamic regime of friction is given. In [11], the braking characteristics of carbon composites, which are promising for high-speed trains and cars, were investigated. It was found that the introduction of a plastic phase into the brake pads favorably reduced the friction coefficient to an acceptable range and effectively increased wear resistance. In [12], a study was made of friction, wear, thermal properties, and temperature fields of three C / C composites with different matrix-carbon textures.
In [13], the tribological properties of carbon composites under dry friction and in an aqueous medium were studied. It was found that carbon composites meet the technical conditions for use in aircraft brakes. In [14], the mechanism of brake disc wear was investigated. Recommendations on hardening discs are proposed to reduce abrasive wear. In [15], studies were performed by the spectroscopic method, which made it possible to identify the physicochemical mechanisms of the degradation of composites. An important stage in the creation of new friction materials is tribological testing. More reliable and accurate tests are carried out on models as close as possible to real braking devices, especially in terms of modeling thermal fields.

The practical need for the results of tribological tests in braking mode determines the relevance of the work.

2. Purpose of work
Determine the friction-wear characteristics of the carbon composite and their compliance with the requirements of the technical conditions for materials for use in brake devices of vehicles.

3. Materials and equipment.
The samples are made of a carbon-carbon composite material in the form of ring disks with an outer diameter of 75 mm and an inner 53 mm separated by radial grooves into 6 sectors with a total of 3 friction pairs of one material.

Friction model tests were carried out on an IM-58 friction machine, which makes it possible to simulate on the samples the temperature field formed in materials during braking. The operation of a friction machine is based on the absorption of kinetic energy of rotating masses by friction materials of brake devices in braking mode. The kinetic energy of the masses is selected from the condition that the load-speed parameters approach the typical values of the friction pairs of real brakes. A feature of the braking mode is the rapid change in temperature in the surface layer of materials. The test procedure is based on the twist reduction of rotating masses with an inertia moment of 0.505 kg.m² up to 6000 rpm, then the drive is turned off and the friction pair is loaded with an axial force of 160 kgf. Previously, a friction pair is wearing-in by a 3-fold recycling of the braking. The number of wearing-in brakes is 4, the number of valid brakes is 15 brakes.

Roughness measurement according to GOST 27964-88, GOST 2789-73 on the profilometer model 130.

4. Results and Discussion
The tribological characteristics of friction pairs depend on the roughness of the friction surfaces. Figure 1 shows a typical profilogram of the wearing-in friction surface.

![Figure 1](image)

Figure 1. Profilogram of the C/C composite surface in sector 1 and the type of the reference curve.

On the profilogram, individual grooves are clearly visible, the formation of which is associated with the formation of wear products in the contact surfaces. Analysis of the state of the friction surface in all sectors (table 1) according to the accepted roughness parameters shows that the parameters are very close and the process of friction and wear is the same over the entire friction surface.
Table 1. Roughness parameters of the wearing-in surfaces

| letter designation | parameter | dimension | Sector 1 | Sector 3 | Sector 5 |
|--------------------|-----------|-----------|----------|----------|----------|
| Ra                 | Deviations of the arithmetic means | micrometr | 2.37     | 2.36     | 2.48     |
| Rz                 | Roughness height by 10 points | micrometr | 32.3     | 34.9     | 46.1     |
| Rmax               | Maximum roughness height | micrometr | 51.0     | 50.1     | 81.6     |
| Sm                 | Mean pitch of roughness | micrometr | 26.0     | 26.2     | 23.1     |
| S                  | Mean pitch of local peak of profile | micrometr | 5.78     | 5.92     | 5.59     |
| Rpk                | Height of surface asperity | micrometr | 15.6     | 17.1     | 9.13     |
| Rvk                | Depth of surface valley | micrometr | 28.0     | 30.3     | 63.2     |
| tp1                | Top of bearing surface | %         | 10.1     | 14.6     | 7.17     |
| tp2                | Bottom of bearing surface | %         | 92.8     | 89.2     | 94.0     |
| Rp                 | Height of maximum surface asperity | micrometr | 19.4     | 18.9     | 14.0     |

In the structure of the working surface of the samples both in the initial state (Fig. 2) and after friction (Fig. 3), there are no visible pore inclusions in the volume of this carbon-carbon composite material, which indicates good wettability of the carbon fibers by the binder and good adhesion bond at the interface between the matrix and C/C filler. This structure provides high stability and reproducibility of test results.

Figure 2. A picture (×50) of the working surface of the disks before friction tests (rotating sample)
During braking tests, temperature was constantly monitored. In between each test, the temperature of the cooling samples was measured (not more than 50 °C). After each control test on the samples, thickness measurements were carried out in each of the 6 sectors (table 2). The linear wear value was determined as the average value over 6 sectors for rotating and stationary samples. The linear wear of the sample was determined by the difference in thickness of the sample before the valid braking and after the test.

Table 2. The results of a single measurement of linear wear (mm) for 6 sectors and contain note a)

| № | view | 1     | 2     | 3     | 4     | 5     | 6     | the average |
|---|------|-------|-------|-------|-------|-------|-------|-------------|
| 1 | n\(^b\) | 13.905 | 13.915 | 13.912 | 13.918 | 13.916 | 13.904 | 13.912 |
|   | v\(^c\) | 13.905 | 13.915 | 13.912 | 13.917 | 13.915 | 13.902 | 13.911 |
|   | n     | 13.924 | 13.921 | 13.914 | 13.918 | 13.941 | 13.969 | 13.931 |
|   | v     | 13.924 | 13.920 | 13.914 | 13.918 | 13.941 | 13.969 | 13.911 |
| 2 | n     | 13.905 | 13.917 | 13.912 | 13.916 | 13.914 | 13.902 | 13.911 |
|   | v     | 13.926 | 13.919 | 13.913 | 13.918 | 13.941 | 13.979 | 13.933 |
| 3 | n     | 13.906 | 13.917 | 13.912 | 13.916 | 13.914 | 13.902 | 13.911 |
|   | v     | 13.924 | 13.918 | 13.912 | 13.916 | 13.941 | 13.977 | 13.931 |
| 4 | n     | 13.905 | 13.917 | 13.914 | 13.914 | 13.914 | 13.902 | 13.911 |
|   | v     | 13.924 | 13.918 | 13.911 | 13.914 | 13.941 | 13.970 | 13.930 |
| 5 | n     | 13.905 | 13.915 | 13.914 | 13.914 | 13.912 | 13.902 | 13.910 |
|   | v     | 13.922 | 13.917 | 13.911 | 13.914 | 13.932 | 13.969 | 13.928 |
| 6 | n     | 13.902 | 13.913 | 13.914 | 13.914 | 13.912 | 13.902 | 13.910 |
|   | v     | 13.922 | 13.917 | 13.912 | 13.914 | 13.934 | 13.968 | 13.928 |
| 7 | n     | 13.902 | 13.916 | 13.914 | 13.915 | 13.910 | 13.901 | 13.910 |
|   | v     | 13.922 | 13.917 | 13.912 | 13.916 | 13.937 | 13.971 | 13.929 |
| 8 | n     | 13.901 | 13.915 | 13.913 | 13.915 | 13.909 | 13.901 | 13.909 |
|   | v     | 13.922 | 13.917 | 13.911 | 13.915 | 13.936 | 13.975 | 13.929 |
| 9 | n     | 13.901 | 13.915 | 13.913 | 13.915 | 13.907 | 13.901 | 13.909 |
|   | v     | 13.922 | 13.916 | 13.911 | 13.915 | 13.935 | 13.973 | 13.929 |
| 10| n     | 13.901 | 13.915 | 13.913 | 13.914 | 13.909 | 13.901 | 13.909 |

\(^a\) Note: \(^b\) n = rotating sample, \(^v\) v = stationary sample

Figure 3. A picture (×50) of the working surface of the discs after friction tests (rotating sample)
Metrological provision is given in table 3, where the following symbols are accepted:

{Xi} - average linear size for a non-rotating sample, micrometer;
Sn is the standard deviation of an individual measurement, micrometer;
S is the standard deviation of the arithmetic mean, micrometer;
Δ is the random error for the accepted probability P = 0.95, the Student's coefficient is 2.6 (for n = 6), micrometer;
Δx is the accumulated error of an individual measurement (absolute error), micrometer;
μ - Relative error of an individual measurement of linear dimensions, %.

Table 3. The results of statistical measurement process data of wear of friction surfaces and contain note a)

| Parameter | Braking 1 | Braking 5 | Braking 10 | Braking 15 |
|-----------|-----------|-----------|------------|------------|
|           | b) 1n     | c) 1v     | 5n         | 5v         | 10n        | 10v        | 15n        | 15v        |
| {Xi}      | 13.911    | 13.932    | 13.910     | 13.914     | 13.909     | 13.928     | 13.908     | 13.924     |
| Sn        | 0.0061    | 0.0212    | 0.0055     | 0.0216     | 0.0064     | 0.023      | 0.0072     | 0.0185     |
| S         | 0.0025    | 0.0087    | 0.0022     | 0.0088     | 0.0026     | 0.0094     | 0.0029     | 0.0075     |
| Δ         | 0.0065    | 0.0225    | 0.0058     | 0.0229     | 0.0068     | 0.0244     | 0.0076     | 0.0196     |
| Δx        | 0.021     | 0.021     | 0.0208     | 0.0304     | 0.0211     | 0.032      | 0.0214     | 0.028      |
| μ         | 0.15      | 0.15      | 0.149      | 0.218      | 0.152      | 0.227      | 0.154      | 0.201      |

b) 1n – stationary sample №1.

Table 4. Evaluation of the measurement error of the coefficient of friction

| Sample material | Relative error, \( \delta E_f \) | Absolute error, \( \Delta E_f \) | \( \Delta F_x \) H | \( \Delta F_z \) H | \( \Delta R_{mp} \) mm | \( \Delta(\Delta F_x) \) H | \( \Delta(\Delta F_z) \) H | \( \Delta(\Delta R_{mp}) \) mm |
|-----------------|-------------------------------|-----------------|-----------------|-----------------|-------------------|-----------------|-----------------|------------------|
| FM 1.1          | 0.133                         | 0.032           | 396.9           | 1600            | 32                | 0.05            | 0.5             | 0.05             |
ΔМтр = 12,7 (Нм) - arithmetic mean value of the friction moment;

ΔFх = 396.9 (Н) – arithmetic mean of friction force;

ΔFz = 1600 (Н) - arithmetic mean of the normal load;

ΔRтр = 0,032 - friction groove radius.

5. Conclusion

Control tests of a friction carbon-carbon composite material on a bench simulating the distribution of heat fluxes in a real braking device showed high stability of tribological characteristics during braking. Testing the frictional heat resistance of the C/C composite showed a good reproduction of the friction coefficient, which is 0.248 ± 0.032. The C/C composite wear resistance was established with an intensity of 0.27 ± 0.02 (мкм / brake.) for a non-rotating sample, 0.47 ± 0.03 (мкм / brake.) for a rotating sample, which allows to increase the service life of the brakes. High resistance to energy absorption and thermal shock determines the prospects for mass application of C/C composite in transport brake devices. The reliability of the work is confirmed by the results of statistical processing of experimental data obtained in the braking mode.

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