The influence of thermocyclic effects on the tribological properties of a carbon-carbon composite under braking conditions

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Abstract. The article considers the issues of the influence of repeated thermal shock on the frictional properties of a carbon-carbon composite material. For thermal loading, the heat-pulse method was applied, in which the energy of rotating masses is absorbed by a friction couple from samples of the material being studied. The change in the friction coefficient during braking is analyzed. Based on the results of repeated braking, conclusions are drawn about the resistance of the material to thermal cyclic behaviours. Particular attention is paid to the maximum temperature that occurs on friction surfaces and the temperature change during thermal loading. The dependence of the average friction coefficient in each test on the number of loading cycles was obtained. Based on the study, the number of thermal loads at which the frictional properties of the material are stable was established.

1 Introduction

The prospects for the use of carbon-carbon composites in high-temperature friction units are due to their good mechanical properties, ability to operate at high temperatures, low specific gravity and low thermal expansion. The disadvantage of carbon composites is the rapid oxidation of carbon-carbon composites at temperatures above 500°C. Much attention is paid to combating ablation. Work [1] studied oxidation resistance, microstructure evolution and mechanical strength, and the mechanism of destruction at elevated temperatures. In [2], the durability of a ZrO2 coating applied by thermal plasma spraying onto a carbon composite during firing with a gas-flame burner is studied. The heat treatment smoothed the rough surface of the sprayed ZrO2 coating and effectively eliminated the defects. Without heat treatment, after 8 thermal cycles the coating peeled off. It was found in [3] that the mass ablation rate of C/C composites was 0.39 mg cm2 s–1. Thermal shock testing of SiC-coated C/C composites was carried out in an acetylene torch at 1873 K and cooled to room temperature. After 10 thermal cycles, no gaps between the coating and the substrate or penetrating cracks were observed in the coated SiC C/C composites. In [4], ZrO2 coatings with different contents (0, 15, 30.40 wt%) of ZrB2 were applied to C/C composites by plasma spraying to create thermal conductivity inside the formed coating. The work [5] describes a

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technology for improving the mechanical properties of a carbon composite by introducing carbon nanotubes (CNTs), which were uniformly distributed over the surface of spherical copper powder (Cu), and then sintered by hot pressing. The high efficiency of the technology has been established. To improve the mechanical properties of carbon composites, reinforcement with copper wire is used [6]. C/C-Cu composites are said to have more advantages than pure carbon tape in terms of mechanical properties. A CCCM with a tin-modified surface, which has a structure with high-quality carbon coatings, has been developed [7]. [8, 9] studied a new technological approach to improve the mechanical properties of carbon composites, including the addition of nickel, for the manufacture of carbon fiber-reinforced composites for temperature control and operational control. It has been shown [9] that at high temperatures \((T > 500 \, ^\circ\text{C})\) the main mechanism of degradation of carbon composites is carbon oxidation. Work [10] studies the effect of temperature on the oxidation of a carbon composite by heating in a furnace and electric arc heating. The work [11, 12] is devoted to optimizing the structure of a carbon composite. Structural materials must have good heat transfer properties. Finite element modeling revealed that the heterogeneous structure has a beneficial effect on surface heat transfer when the surface is locally heated. The effect of ablation of carbon composite materials on tribological properties is felt during repeated heating. Thermocyclic loading is typical for the operation of braking devices. However, the effect of thermal cycling on brake performance has not been sufficiently studied.

The purpose of the work is to study the patterns of changes in the tribological properties of carbon composites in the process of thermal shock and the influence of thermocyclic effects on the stability of the friction coefficient.

2 Materials

The test objects were samples of a carbon-carbon composite based on discrete fibers of the Termar_ADF brand [13]. The samples are ring-shaped with outer and inner diameters of 75 and 53 mm, thickness 10 mm.

3 Equipment and testing methods

Model braking tests of samples of carbon composite friction couples of the same name were carried out on an ИМ-58 friction machine [14], the operating principle of which is to convert the kinetic energy reserve of rotating flywheel masses into heat from the friction of the samples. The emerging thermal area is characterized by a large temperature gradient, and therefore represents a thermal shock. Model test mode: angular speed of rotation of the stand shaft at the moment of braking is 6000 rpm, the normal load value is 160 kgf, the moment of inertia of the rotating masses is 0.505 kg.m².

The mechanical properties of materials were determined by the method of kinetic indentation with a Vickers pyramid on a microhardness tester MNT_ZAE_000 from CSM Instruments in accordance with the ISO/DIS 14577_1:2002 standard according to the method [15].

4 Results

The force impact on the material during machining operation and the influence of the environment affect the physical and mechanical properties of the friction surfaces of materials. The kinetic indentation method allows to evaluate the characteristics of the elastic
and plastic properties of materials in thin surface layers. Fig. 1 shows a diagram of the load and unloading of the indenter when pressed into a carbon composite sample.

![Diagram of load and unloading](image)

**Fig. 1.** Kinetic microindentation of a carbon composite diagram

Table 1 shows the results of testing carbon-carbon composite material samples on a microhardness tester: HV – Vickers hardness; E – elastic modulus; \( A_e \) – elastic deformation work; \( A_p \) – plastic deformation work; nIT – elastic deformation work to the total work proportion.

**Table 1.** Test results on a microhardness tester at a load of 1H.

<table>
<thead>
<tr>
<th>Material</th>
<th>HV</th>
<th>E, (GPa)</th>
<th>( A_e ) (mkJ)</th>
<th>( A_p ) (mkJ)</th>
<th>nIT, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-carbon composite material</td>
<td>80</td>
<td>21.7</td>
<td>1.41</td>
<td>0.77</td>
<td>64.6</td>
</tr>
</tbody>
</table>

To illustrate the braking mode fig. 2 shows point-by-point oscillograms of the friction coefficient values in the model friction mode.

![Oscillograms of friction coefficient](image)

**Fig. 2.** Change in friction coefficient during braking
After testing, the surface roughness is characterized by the following parameters: \(Ra = 2.4 \, \mu m\) (arithmetic mean deviation); \(Rz = 46.1 \, \mu m\) (height of irregularities at 110 points); \(R_{\text{max}} = 81.6 \, \mu m\) (maximum height of irregularities); \(S_{\text{m}} = 23.1 \, \mu m\) (average pitch of irregularities). Deep grooves remain on the friction surface (Fig. 3).

**Fig. 3.** Profilogram of the sample surface after testing

In repeated experiments, instability of tribological characteristics which is associated with anisotropy of the material structure is observed. During the tests, the following were continuously recorded over time: pressure, sliding speed, braking torque and volumetric temperature, from which the average temperature of the sample friction surface was calculated. To determine the maximum surface temperature \(T_{\text{max}}\) during the relative sliding of samples, the temperature summation hypothesis was used

\[
T_{\text{max}} = T_0 + T_c + T_B,
\]

where: \(T_0\) – ambient temperature; \(T_c\) – average bulk temperature of the surface layer; \(T_B\) – flash point.

At each moment of speed, the maximum surface temperature was calculated in steps of 2 seconds. The average volumetric temperature of the surface layer was measured with a thermocouple mounted in the sample. The flash point was determined by calculation according to the method [13]. Fig. 4 shows the change in maximum surface temperature during braking.

**Fig. 4.** Change in maximum surface temperature during braking

Structural changes in the material are reflected in tribological properties. The influence of the heating and cooling mode is shown in Fig. 5.
Fig. 5. The effect of temperature on the coefficient of friction

The sample temperatures in the heating and cooling modes are different. The influence of thermocyclic effects on the stability of the friction coefficient can be assessed by comparing experimental data on friction coefficients. 50 experiments on braking of carbon composite samples were carried out. The experiments were carried out under the same experimental conditions. Fig. 6 shows the dependence of the friction coefficient on repeated thermal effects.

Fig. 6. Number of braking influence on the friction coefficient

As a result of the friction material tests, it was established that the structure of the working surface of the samples, both in the initial state (Fig. 7a) and after friction (Fig. 7b), is isotropic, which is due to the specific location of the fibrous carbon filler (reinforcing frame) in the volume of this carbon-carbon composite material.
The carbon matrix is formed uniformly throughout the volume, without a clearly defined direction. There are no visible pore inclusions at the photos, which indicates good wettability of the carbon fibers by the binder and good adhesive bond at the interface between the matrix and the carbon-carbon composite filler. These factors determine the high frictional heat resistance of the test sample and its resistance to repeated thermal pulse loading. After repeated thermal shocks, no microcracks were found on the friction surfaces of the specimens.

5 Conclusion

It has been experimentally established that a carbon composite can withstand up to 30 thermal shocks without significant changes in the average friction coefficient. With an increase in the number of braking, the friction coefficient decreases, but does not reach critically low values. In conditions of limited space, for example in braking devices, the operation of products is limited only by wear indicators. In open-space applications, such as boiler equipment rotating valves operating in high-temperature gas flows, require increased attention to maintaining strength properties, changes in which are caused by structural transformations in the carbon composite and weakening due to high-temperature ablation.
References

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