The effect of humidity on the tribological behavior of the carbon-carbon composite in brakes

V V Alisin

Blagonravov Institute of Mechanical Engineering, Russian Academy of Sciences (IMASH RAN), 4, M. Kharitonyevskiy lane, Moscow, 101990, Russia
E-mail: vva-imash@yandex.ru

Abstract. The article is devoted to the study of the humidity effect on the antifriction properties of a carbon-carbon composite material under the brake-applied mode. The effect of friction coefficient reducing due to the hygroscopic properties of this carbon composite is justified. The change in the friction coefficient and the composite structure during braking is investigated. In a macro scale it is shown that the structure of the samples working surface is isotropic both in the initial condition and after friction, which is due to the specific location of the fibrous carbon filler (reinforcing frame) in the volume of this carbon-carbon composite material. Based on the theory of errors, metrological assurance for evaluating the reproduction of experimental data was performed. Based on the obtained quantitative data on the reduction of the friction coefficient and the “drying” time of wet friction surfaces, practical recommendations are defined to ensure the effectiveness of vehicle braking arrangements.

1. Introduction

The advantages of carbon-carbon composite materials (C/C) include a high permissible operating temperature, resistance to thermal shock, and the ability to absorb a large amount of energy, which opens prospects for the applying of these materials in braking arrangements. Therefore, there is a constant increase in the applying of friction C/C in brakes, especially in the aeronautical industry [1]. The main disadvantage of C/C is the high labor-intensive characteristics of manufacturing, which makes them an expensive material. This disadvantage can be considered temporary and surmountable. Researches of C/C in the field of manufacturing technology and the study of their mechanical properties are performed massively. With regard to brakes, the most important are the tribological characteristics and compressive strength.

The improvement of the C/C mechanical properties by applying a catalyst in the form of chemical vapor (fallow) was studied in the paper [3]. The obtained composites showed a low wear rate and a stable coefficient of friction, which is due to the high physical and mechanical properties. In paper [4], the efficiency of appending the graphene and polytetrafluoroethylene (PTFE) to increase tribological characteristics was studied. Tribological tests have shown that the friction coefficient and wear rate are significantly reduced. In paper [5], brake friction materials containing multi-walled carbon nanotubes (CNT) were studied to determine their effect on braking action. Physical and tribological properties were significantly affected by the content of CNTs in the friction material. In particular, frictional Additives of nanoparticles of various materials [6] were appended into C/C using ultrasound. Si and SiC nano-additives were used; materials containing two different concentrations of each nano-additive in isopropyl alcohol were obtained. Samples tested for friction showed a positive effect according to
tribological characteristics. The attempts to increase the frictional properties of a carbon composite material using ultrasonic vibrations [7] are known. Based on experimental results, it was found that ultrasonic vibration provides higher tribological properties. An obvious decrease in the friction force and surface damages is achieved with ultrasonic vibration. Materials with the addition of CNTs have shown increased fastness to bleaching and friction resistance. To simplify the process of obtaining an antioxidative coating, bonderization (phosphating) of C/C and C/ SiC disks by immersion of a phosphate solution was applied [8]. The coating effect on the frictional characteristics of C/C and C/SiC was investigated. In the dry condition, the results showed that the friction-surface phosphate coating seriously reduces the average coefficient of friction. In paper [9], the physical, mechanical and tribological properties of hybrid fiber reinforced friction composites were compared with steel fiber, rock wool fiber, and fiberglass. Friction composites were manufactured using compression molding equipment and tested using a constant speed friction test machine. It was found that the friction coefficients of all samples decrease with increasing test temperature. Comparative tribological tests of various friction materials showed [10] that the friction coefficient and specific wear rate decrease with increasing contact pressure and sliding speed. In paper [11], the operating conditions of aviation brakes with frictional C/C during takeoff and landing were simulated. The results showed that the composites have stable friction coefficients, friction curves and acceptable wear losses. In paper [12], C/C bench running were performed according to the “disk-disk” pattern, which made it possible to simulate various energy conditions for landing a Boeing 737 aircraft at 50% and 90% relative air humidity. Dependencies between the microstructure, hardness of individual components of composites, and wear resistance under various operating conditions are obtained. The paper [13] is devoted to the study of the tribological properties of the C/ SiC – C/C pair. It has been established that the friction pair C/ SiC – C/C meets the requirements of high efficiency and low weight of aeronautical brakes. In paper [14], the braking efficiency of carbon/ceramic pairs suitable for high-speed trains and cars was considered. In paper [15], the structure of wear products was studied after braking tests. It was found that the graphite layers formed as a result of interlayer shearing deformation are the main elements of pyrolytic carbon during sliding, while the carbon fiber tends to wear into small fragments along the fiber axis at the initial stage of friction. It has been suggested that the detected nano-sized carbon particles participate in the friction process as a solid lubrication. In paper [16], comparative tests of carbon materials were performed on a friction test machine according to the “pin-finger” pattern, during which morphological and structural features were studied. The formation of a stable tribological film at the phase interface, which causes a decrease in friction, has been experimentally confirmed. The friction and wear of three carbon composites was studied [17] when simulating normal conditions for landing brake rotors of aircrafts. Temperature fields were also simulated by the finite element method. The matrix carbon structures had a significant effect on temperature fields. A sample with coarse layered pyrolytic carbon is the best choice for an aircraft brake rotors due to its excellent frictional, wear-resistant and thermal properties and lower temperature at the friction boundary. In paper [18], tests were performed in water splashes. A significant drop in the coefficient of friction to the level of 0.1 is shown. In paper [19], the effect of humidity on the friction and wear of a carbon composite under conditions of the joint appending of graphene and molybdenum disulfide was studied. A significant decrease in the coefficient of friction and wear rate has been established. In paper [20], the influence of relative air humidity on the tribology and emission of particles in the air of three commercial materials of railway brakeblocks was studied. Moisture adsorption by an organic composite leads to a decrease in the coefficient of friction and the emission of particles with increasing humidity.

C/C possesses high hygroscopic properties that affect the coefficient of friction and are little studied, although they have a great influence on the efficiency of the braking process. The purpose of the paper is to study the effect of humidity on the friction coefficient in brake-applied mode.
2. Materials and equipment
A pair of friction is made up of samples made of the same material. Samples are manufactured in the form of disks from one material, in the amount of 3 pairs of friction. Friction and wear tests were performed on an ИМ-58 friction test machine, under conditions simulating the taxiing operation mode of an airplane: rotation speed of a rotating sample is 2500 rpm, moment of flyweights inertia is 2.35 kgf-cm\(^2\), thrust force is 160 kgf. The moment of friction was recorded by a light-beam recording oscillograph. The tests are performed after exposure for 12 hours at a relative humidity of at least 90% and room temperature. Control tests consisted of break-in process and performing test braking. Braking is performed without interruption for sample cooling. During the braking process, a moment of friction is recorded. Before the braking test, the samples are aged in a Dycometal 2008 vck-300 series climate test chamber according to the standard test method at elevated humidity values without water condensation. The limit of permissible tolerance of measuring the spindle rotational speed, %, is not more than ± 5 from the measured value. The permissible mean square deviation of the random component of the reduced error of the friction torque meter in the static loading mode is not more than 1 %. The permissible mean square deviation of the random component of the reduced error of the clamping force measuring instrument of the test samples in the static loading mode is not more than 2%.

The coefficient of friction was determined by the following formula

\[ F = \frac{M_{\text{тр}}}{rP} \]

where: \( M_{\text{тр}} \) is the friction torque (N*cm), \( r \) is the average radius of the sample (m), \( P \) is the thrust force (N).

3. Results and discussions
The duration of the tests in the climate test chamber was 22 hours and 30 minutes. Relative humidity in the chamber was maintained within 97 ± 3%.

The oscillograph charts of braking operations are shown in fig. 1.

![Figure 1. Photograph of the oscillograph chart of the friction torque during the 1st and 2nd braking.](image_url)

At the beginning of the braking the C/C surfaces soaked (exposed) in the climatic test chamber show the friction coefficient \( f = 0.175 \), which remains almost constant for 1.4 seconds from the start of braking. This time interval corresponds to the “drying” of the friction surfaces due to the heat released during friction. Dry C/C surfaces have an almost constant coefficient of friction until stopping \( f = 0.258 \). As a result of the control measurements of the friction material, it was found that the structure of the samples working surface both in the initial condition (fig. 2 and fig. 3) and after friction is isotropic, due to the specific location of the fibrous carbon filler (reinforcing frame) in the volume of this carbon-carbon composite material (C/C).
Figure 2. A snapshot (x50) of the working surface of the discs (rotors) before friction tests (fixed sample).

The carbon matrix is uniformly formed according to volume, without a strongly marked direction.

Figure 3. A snapshot (x50) of the working surface of the discs (rotors) after friction tests (movable sample).

There are no visible pore inclusions in the photographs, which indicate a good wettability of the carbon fibers with an adhesive agent and a good adhesive bonding at the boundary between the matrix and the C/C filler. These factors determine the high frictional heat resistance of the test sample and its resistance to repeated heat impulse loadings. The results of tribological braking tests are shown in table 1.

Table 1. Results of friction coefficient measurements.

| Test No. | Braking time (second) | Brake torque (N*m) | Friction coefficient |
|----------|-----------------------|--------------------|---------------------|
| 1        | 12.7                  | 11.9               | 0.232               |
| 2        | 12.3                  | 12.6               | 0.246               |
| 3        | 12.0                  | 13.2               | 0.258               |
Metrological assurance of measurements. The arithmetic average of the friction coefficient $f_{ср} = 0.248$. The calculation result for indirect measurements of a random value is written in the form:

$$E_p = E \pm \Delta E,$$

where $\Delta E$ is an absolute uncertainty of calculated value $E$. The relative accuracy in determining the friction coefficient $\delta E_f$ of the calculated value $E_f$ is calculated by the formula:

$$\delta E_f = \frac{\Delta E_f}{E_f} = \frac{\Delta(F_x)}{F_x} + \frac{\Delta(F_z)}{F_z} + \frac{\Delta(R_{mp})}{R_{mp}},$$

where $\Delta F_x$, $\Delta F_z$, $\Delta R_{mp}$ are the values with the help of which the friction coefficient is calculated; $\Delta F_x$, $\Delta F_z$, $\Delta R_{mp}$ are the absolute errors relatively the following values: $\Delta F_x$, $\Delta F_z$, $\Delta R_{mp}$. Errors were estimated according to the data in table 2. The relative $\delta E_f$ and absolute $\Delta E_f$ error in determining the coefficient of friction is obtained by the method of braking torque diagrams planimteration.

The results of measuring the area of the 1st braking oscillograph charts (cm2):
- Average value of $\{X1\} = 33.03$;
- The standard error of an individual measurement is $S = 0.32$;
- The standard error of the mean is $S = 0.143$ for the accepted probability $P = 0.95$, Student’s coefficient is 2.8 (at $n = 5$), a random error is $\Delta x = 0.40$;
- the total error of an individual measurement is $\Delta x = 0.40$.

The relative accuracy of an individual measurement of the oscillograph charts area and, accordingly, the friction torque is 0.012 (1.2%)

| Friction pair | Relative accuracy, $\delta E_f$ | Absolute uncertainty, $\Delta E_f$ | $\Delta M_p$ | $\Delta F_x$ | $\Delta F_z$ | $\Delta R_{mp}$ | $\Delta (\Delta F_x)$ | $\Delta (\Delta F_z)$ | $\Delta (\Delta R_{mp})$ |
|---------------|-------------------------------|-----------------------------------|-------------|-------------|-------------|-------------|----------------|----------------|----------------|
| ΦМ 2.1-ΦМ 2.2-| 0.029                         | 0.038                             | 396.9       | 1600        | 32          | 4.7         | 1              | 0.03            |

Where: $\Delta F_x = 390.6$ (N) is the arithmetic mean value of the friction force; $\Delta F_z = 1600$ (N) is the arithmetic mean value of the normal loading; $\Delta R_{mp} =$; 0.032 (m) is the radius of the friction runway.

The repeatability of the test is shown in table 3.

| Test No. | samples | $T$, s | $f$ | Remark                  |
|----------|---------|--------|-----|-------------------------|
| 1        | ΦМ 2.1-ΦМ 2.2- | 12.7   | 0.232± 0.007 | Soaking (exposure) in the chamber |
| 2        | ΦМ 2.1-ΦМ 2.2- | !x,3  | 0.246±0.007 | Without moisture   |
The metrological assurance of the performed tribological tests confirms the effect of decreasing the friction coefficient of C/C wet surfaces during braking process. The scope and consequences of the effect have different meanings for different types of vehicles.

4. Conclusions
1. Experiments proved that the friction coefficient of C/C wet surfaces is approximately 5 times lower than for dry surfaces. The heat released during braking “dries” the friction surface under the experimental conditions in 1.4 s.
2. With regard to aeronautical and railway transport, this time is negligible in comparison with the braking time of an airplane or train.
3. With regard to automobile, especially passenger (light motor vehicle), transport, a decrease in the braking force by 1.5 times for 1 to 2 seconds threatens with catastrophic consequences. The effect of reducing the braking performance of C/C wet surfaces should be taken into account at the stage of designing brake devices of vehicles.

References
[1] Xu Y, Zhang P, Lu H and Zhang W 2015 Composite Structures 133 148-56
[2] Ma X, Fan S, Sun H, Luan C and Cheng L 2020 Tribology International 142 105981
[3] Deng H, Li K, Cui H, Li H and Song G 2018 Tribology International 121 231
[4] Zhao B and Bai T 2019 Carbon 144 481
[5] Hwang H J, Jung S L, Cho K H, Kim Y J and Jang H 2010 Wear 268(3–4) 519
[6] Policandriotes T and Filip P 2011 Wear 2 71
[7] Lutao Yan L, Qinjian Zhang Q, Jinhai Wang J and Yu J 2019 Tribology International 136 469
[8] Fan S, Yang C, He L, Deng J and Cheng L 2017 Tribology International 114 337
[9] Yunhai Ma Y, Yucheng Liu Y, Lidong Wang L, Jin Tong J and Jia H 2018 Tribology International 119 262
[10] Wei L, Choy Y S and Cheung C S 2019 Tribology International 138 99
[11] Hao E M, Luo R, Hou Z, Yang W and Yang C 2014 Wear 319(1–2) 145
[12] Soydan Ozcan S and Filip P 2013 Carbon 62 240
[13] Xu X, Fan S, Zhang L, Du Y and Cheng L 2014 Tribology International 77 7
[14] Samyn P 2016 Tribology International 99 127
[15] Wu S, Liu Y, Ge Y, Ran L and Yi M 2016 Tribology International 102 497
[16] Faga M G, Casamassa E, Iodice V, Sin A and Gautier G 2019 Tribology International 140 105889
[17] Xu H, Huang B, Yi M, Xiong X and Lei B 2011 Tribology International 44(1) 18
[18] Bian G and Wu H 2015 Tribology International 92 1
[19] Upadhyay R K and Kumar A 2019 Carbon 146 717
[20] Lyu Y, Bergseth E, Tu M and Olofsson U 2018 Tribology International 118 360