Determination of measurement errors for the tribological properties of the carbon-carbon composite in aircraft brakes

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Abstract. The article is focused on the accuracy of quantification for the tribological properties of a frictional carbon-carbon material during braking. The experiments were performed with the IM-58 frictional testing machine when the rotating shaft with a previously established flyweight was in the braking mode. The tests for frictional heat resistance were performed with 2168 UMT. The research deals with the changes in friction and wear properties under the conditions of sample heating. The paper describes accuracy characteristics for the measured tribological properties. The maximum permissible temperature of frictional heating in terms of wear was established for reliable operation of the brake unit.

1. Introduction
Carbon-carbon materials (CCM) constitute one of the groups of the most promising materials for mass application in friction knots of brake units for vehicles. This paper studies the CCM modification [1] which has successfully passed the tests on aircrafts and holds a considerable potential for the magnet and levitation transport of the future. Since the material properties depend on the braking unit parameters, therefore, the experimental conditions were supposed to be as close to the actual operating conditions as possible. The principal tribological properties of the braking units include the friction coefficient, linear wear per a single braking and frictional heat resistance of the material, the latter depend on a variety of factors that determine the spread in performance. The increase in the experimental data reliability through statistical processing requires determination of the measurement accuracy indicators [3, 4].

Prediction of the friction knot engineering status is based on statistical methods for processing experimental findings [5, 10]. While the production technology is being improved and the cost of materials reduced, a more detailed study of the CCM properties is required. Tribological, physical, chemical and thermal studies of friction of carbon-carbon composites were carried out under different conditions of braking [16, 17, 19]. A range of papers [6, 11, 12, 18] studies the CCCM texture impact on tribological properties under a various loads and speeds while braking, the effect of the carbon fiber [7, 9, 20] or carbon nanotubes [8, 15] introduction on the frictional properties were also under consideration. The wear mechanism of the CCCM friction surfaces while braking was explored in some studies [13, 14] as well. It has been established that the resulting spherical wear particles produce a significant lubricating effect due to simplification of the particle rotation on the interface region.

The study is aimed at establishing the actual tribological properties of samples produced of Termar-ADF nanomodified carbon-carbon composite material while braking.
2. Equipment and materials
The IM-58 [1] friction machine designed for model experiments and tests of friction material samples in the braking mode established the linear wear (µm/brake) and the friction coefficient. The normal load and the angular velocity of the stand shaft rotation while braking were taken at the level of 160 kgf while the angular velocity of the stand shaft rotation at braking was 6000 rpm. The rotating mass moment of inertia is 0.505 kg·m².

The frictional heat resistance of the material was determined with the 2168 UMT (UNITRIB) frictional testing machine [2], designed to assess the frictional heat resistance during frictional heating based on different sliding speeds. Rotating and stationary ring samples of the studied material combination were placed coaxially with their end working surfaces pressed against each other at a specific axial force, the temperature of frictional heating was modified through stepwise frequency change for the moving sample and the wear rate and (or) friction coefficient for each step of the frictional heating temperature were established while the frictional heat resistance of the material is quantified proceeding from the dependence of these values on temperature.

3. Experiment results and discussion

3.1. Determination of the friction coefficient and linear wear
The samples is made in the shape of a ring with an outer diameter of 75 mm, an inner diameter of 53 mm, and a thickness of 14 mm. Sample preparation for testing included the division of a non-working end surface into six sectors to determine the locations subject to linear wear. The accuracy of the sample positioning on the test table is ensured owing to the specialized instruments (table 1).

The tests consisted of running-in and test braking by the method of random sampling which is aimed at choosing one of the three pairs of samples provided by the client. Before testing, the friction surfaces were washed with alcohol, the roughness and hardness parameters were checked for compliance with the drawings. The number of 4 braking activations within the running-in process was chosen according to paragraph 4.2.2. of the manufacturer’s test procedures. There were 15 test braking activations undertaken.

The limit of permissible error in measuring the drive spindle rotation frequency as a percentage of the measured value shall not exceed ± 5.

The permissible mean square deviation of the random component within the reduced error characteristic of the frictional torque meter under a static load shall not exceed 1%.

The permissible mean square deviation of the random component within the reduced error of the meter of clamping pressure applied to the tested samples under a static load cannot be more than 2%.

The linear wear of the friction pair is calculated as the sum of the linear wear values for each sample. The linear wear of each sample was established as the difference between the sample thickness before and after the test braking.

Table 1. List of measurement instruments.

| №  | Measurement instrument                        | Accuracy and calibration of the instruments                                      |
|----|-----------------------------------------------|----------------------------------------------------------------------------------|
| 2  | Profile testing instrument, model 130         | Accuracy degree 1 (TU 3943-001-70281271)                                          |
|    |                                               | RF Pattern Approval Certificate Ru.C.27.004. №26057 as of 15.12.2006, valid till 01.01.2012 |
|    |                                               | №33319-06 in the RF National Register of Measuring Equipment.                    |
| 3  | Optical caliper IZV 1                         | Accuracy 1 µm (optical head OMC-5).                                              |
|    |                                               | Regular calibration is not required.                                             |
Digital planimeter PLANIX 5 Tamara

Accuracy: not worse than ±0.2% (±2/1000 pulses)

Roughness measurement under GOST 27964-88 and GOST 2789-73 with the profile testing instrument, model 130. λ Limit of the permissible intrinsic error Δ for the profile close to a trapezoid with a roughness increment not exceeding 0.25, is:

- parameter Ra: \( \Delta = 0.02P + 0.04I \)
- parameters Rz, Rmax, Rp: \( \Delta = 0.03P + 0.05I \)
- parameter Sm, S: \( \Delta = 0.02P + 0.10I \)
- parameter \( t_r \): \( \Delta = 0.08P + 0.02I \)

where \( I \) is the effective (measured) value of the corresponding parameter, \( P \) is the upper limit of the corresponding parameter subrange.

Table 2 and table 3 show the results of the tests and the assessment of accuracy with which linear wear measurements are determined.

The calculation results for indirect measurements of a random value are recorded as follows:

\[ E_{p} = E \pm \Delta E, \]

where \( \Delta E \) is the absolute error of the calculated value \( E \). The relative error in the determination of the friction coefficient \( \delta E_f \) of the calculated value \( E_f \) is calculated as follows:

\[ \delta E_f = \frac{\Delta E_f}{E_f} = \frac{\Delta (\Delta F_x)}{\Delta F_x} + \frac{\Delta (F_z)}{\Delta F_z} + \frac{\Delta (\Delta R_{mp})}{\Delta R_{mp}} \]

where \( \Delta F_x, \Delta F_z, \Delta R_{mp} \) are the values used to calculate the friction coefficient; \( \Delta (\Delta F_x), \Delta (\Delta F_z), \Delta (\Delta R_{mp}) \) are absolute measurement errors.

Table 2 shows the relative \( \delta E_f \) and absolute \( \Delta E_f \) errors in determination of the friction coefficient through diagram planimetricing of the braking moment

Table 2. Assessment of the measurement error in determination of the friction coefficient.

| Sample material | Relative error, \( \delta E_f \) | Absolute error, \( \Delta E_f \) | \( \Delta M_p \) | \( \Delta F_x \) | \( \Delta F_z \) | \( \Delta R_{mp} \) | \( \Delta (\Delta F_x) \) | \( \Delta (\Delta F_z) \) | \( \Delta (\Delta R_{mp}) \) |
|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|-----------------|-----------------|----------------|
| FM 1.1          | 0.133           | 0.032           | 12.7 (Nm)      | 396.9          | 1600           | 32 mm          | 0.05 N          | 0.5 N           | 0.05 mm        |

where: \( \Delta M_p = 12.7 \) (Nm) is the arithmetic mean value of the frictional torque; \( \Delta F_x = 396.9 \) (N) is the arithmetic mean value of the frictional force; \( \Delta F_z = 1600 \) (N) is the arithmetic mean value of the normal load; \( \Delta R_{mp} = 0.032 \) is the radius of the friction path.

The friction coefficient is determined on the basis of the frictional torque (table 2).

Table 3. Results of a single frictional torque measurement.

| Braking No. | Braking time (s) | Braking moment (Nm) | Friction coefficient |
|-------------|------------------|---------------------|---------------------|
| 1           | 50.5             | 10.3                | 0.201               |
The arithmetic mean value of the braking time \( t = 38.9 \) s.

The arithmetic mean value of the frictional torque \( M_{fr} = 12.7 \) Nm.

The arithmetic mean value of the frictional torque \( f_{av} = 0.248 \) Nm.

The linear wear is measured for each of the sectors. The properties of the 15th braking activation are shown in Table 4, where \( \sigma_{x,1} \) is the root-mean-square deviation; \( x_{av} \) is the arithmetic mean value, \( \Delta H \) is the linear wear per a single braking.

**Table 4.** Results of a single linear wear measurement (\( \mu m/\)braking).

| Friction pair | \# braking | linear wear (\( \mu m/\)braking) for 6 sectors of each of the samples | \( \sigma_{x,1} \) | \( x_{av} \) | \( \Delta H \) |
|---------------|------------|----------------------------------------------------------------------------|---------|---------|---------|
| initial       | 1          | 13,90 13,91 13,91 13,91 13,91 13,90 | 5,89*10^-3 | 13,91   |
|               | 5          | 5 5 2 8 6 4 | 2          | 2       |
|               | 8          | 3 4 4 9 0 | 8 7       | 8 7     |
| initial       | 15         | 13,92 13,91 13,91 13,91 13,94 13,96 | 1,96*10^-2 | 13,93   |
|               | 4          | 1 4 8 1 6 | 1 7       | 1 7     |
| rotating      | 0          | 13,92 13,91 13,90 13,91 13,93 13,95 | 1,91*10^-2 | 13,92   |
|               | 4          | 0 4 7 3 3 9 | 4 7       | 4 7     |

where \( \sigma_{x,1} \) is the root-mean-square deviation; \( x_{av} \) is the arithmetic mean value, \( \Delta H \) is the linear wear per a single braking.

The assessment of errors in the determination of linear wear intensity is shown in Table 5.

**Table 5.** Errors in the wear quantification.

| Sample material | Relative error, \( \delta E_f \) | Absolute error, \( \Delta E_f \) | \( \Delta Z_{ycm} \) | \( \Delta (\Delta Z_{ycm}) \) |
|-----------------|---------------------------------|-------------------------------|--------------------|-----------------------------|
| FM 1.1          | 3.7*10^-3                       | 1.0                           | 270                | 1                           |
| FM 1.2          | 2.1*10^-3                       | 1.5                           | 470                | 1                           |

\( \Delta Z_{ycm} = 12.7 \) nm – arithmetic mean value of the linear wear after 15 breaking actions.

3.2. **Determination of frictional heat resistance**

Preparation for testing consists of the following stages: sample running-in in the course of which the sample adjacency is visually controlled to be at least 90% of the nominal contact area.

A thermocouple with a thermoelectrode diameter of not more than 0.5 mm is tightly fixed in the hole at a distance of no more than 1 mm and no less than 0.5 mm from the friction surface of the motionless sample, so that its head reached the material at the bottom of the hole. The ambient temperature is controlled.

The tests are performed under a load stated in paragraph 2 and at the following rotational speeds of the moving sample: 50, 100, 300, 700, 1000, 1500, 2000, 2500 rpm.

In case of stepwise testing of rotary speeds, the test duration at each step reaches 15 ± 0.1 min. The friction moment \( (M_{fr}) \) and temperature are continuously recorded at each step of testing. Wear, friction and temperature are measured according to the method described in Annex 1 RD 50-662-88 (mandatory).
The friction moment is expressed with the friction coefficient \( f_{av} \) according to the following formula

\[
F_{av} = \frac{M_{fr}}{rN},
\]

where: \( r \) is the sample radius of the friction path; \( N \) is the normal load for a sample.

The test results serve as the basis for a graph plotted depending on the friction coefficient temperature \( f \) and the wear rate.

The normal load is selected proceeding from equality of the contact pressure taken for the purposes of braking tests and reached 24 kgf. For the 2168 UMT frictional testing machine, the limit of the permissible error for the measurement of the spindle speed of the drive as a percentage of the measured value shall not be more than ± 5. The permissible root-mean-square deviation of the random component within the reduced error of the friction moment meter in the static load mode does not exceed 1%. The permissible root-mean-square deviation of the random component within the reduced error of the clamping pressure meter for the tested samples in the static load mode shall not exceed 2%.

The measuring system provides for continuous recording of the following testing parameters:

The permissible root-mean-square deviation of the random component within the reduced error of the friction moment meter in the static load mode shall not exceed 1% of the measured value.

The material temperature up to 800 °C at the friction surface of a motionless sample is measured with a potentiometer of 0.5 accuracy class.

Accuracy of the friction moment measurement through planimetering of the braking torque diagrams (nm): \(-0.78; 0.72; 0.76\); Average \( \{X_1\} = 0.753 \) nm; The root-mean-square deviation of a single measurement \( S_m = 0.030 \) nm; The root-mean-square deviation of the arithmetic mean value \( S = 0.017 \) nm for the adopted probability \( P = 0.95 \), the Student’s coefficient is 4.3 (at \( n=3 \)), the random error \( \Delta = 0.07 \) nm; systematic (rated 1%) measurement error \( \Delta_e = 0.01\)nm the combined error of a single friction moment measurement \( \Delta_c = (\Delta_{com}^2 + \Delta^n)^{1/2} = 0.071 \) nm.

The friction coefficient is calculated indirectly under formula (1) where the path is a constant value. To determine the error, the logarithms of this function are determined, partial derivatives are further calculated; if the rated error of the load is 1%, the relative error of the friction coefficient is 0.047, consequently, the absolute error of the friction coefficient is \( \Delta f = 0.035 \).

Graphs reflecting the inter dependence of the arithmetic mean value of the friction coefficient and the total intensity of linear wear for each of the tested pairs of samples at the appropriate step of testing are presented in figures 1 and 2.

The friction coefficient grows with an increase in temperature according to the parabolic law (figure 1).

![Figure 1. Dependence of the friction coefficient on the surface temperature.](image-url)
The wear rates manifest no significance difference till a critical surface temperature is achieved (figure 2).

The graph reflecting dependence of the total linear wear intensity on temperature shows that the wear rate is growing sharply at a surface temperature of over 500 °C.

4. Conclusions
The check tests of the frictional material produced the following findings:

1. the results of 15 test braking activations showed the following values for the linear wear and friction coefficient for the frictional material samples:
   - for a non-rotating sample \(0.27 \pm 0.02\) (μm / braking),
   - for a rotating sample \(0.47 \pm 0.03\) (μm / braking);
   - friction coefficient \(-0.248 \pm 0.032\).
2. The temperature of frictional heating (frictional heat resistance) was determined to reflect the values at which the tribocoupling is stable while the wear rates are acceptable. According to the results, the maximum permissible heating temperature of the test material is 300 °C with the acceptable wear rates \((8.69\times10^{-9} \pm 1.74\times10^{-9})\) and the friction coefficient \((0.278\div0.035)\); the material is functional at increased linear wear rates in the temperature range of 300÷500 °C, operation at higher temperatures is unacceptable from the point of view of wear resistance.

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