ISSN 0208-7774 TRIBOLOGIA 6/2018 p. 89–95

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DETERMINATION OF THE FRICTION COEFFICIENT IN THE FOIL-ROLLER COMBINATION

WYZNACZANIE WSPÓŁCZYNNIKA TARCIA W SKOJARZENIU FOLIA–ROLKA

Key words: friction coefficient, foil bearing, friction, top foil.

Abstract In order to verify and select the appropriate materials for cooperation in high-speed foil bearings in the particular tribological pair, a series of friction and wear tests of selected material pairs were carried out. This paper presents a method for determination of the friction coefficient, a basic quantity characterizing two materials cooperating frictionally in an atypical tribological combination of the foil-roller type. Laboratory tests, necessary to determine the friction factor value in the mentioned friction junction and in a low-boiling liquid environment, were carried out on a specially prepared test stand using the T-27 apparatus.

Słowa kluczowe: współczynnik tarcia, łożysko foliowe, tarcie, folia ślizgowa.

Streszczenie W celu weryfikacji i doboru odpowiednich materiałów do współpracy w szybkoobrotowych łożyskach foliowych w określonym węźle tribologicznym przeprowadzono szereg badań tarcia i zużycia wybranych par materiałowych. W niniejszej pracy przedstawiono sposób wyznaczania współczynnika tarcia, podstawowej wielkości charakteryzującej dwa materiały współpracujące ciernie w nietypowym skojarzeniu tribologicznym typu folia–rolka. Badania laboratoryjne, niezbędne do wyznaczenia wartości współczynnika tarcia we wspomnianym węźle tarcia w środowisku cieczy niskowrzącej, przeprowadzono na specjalnie do tego celu przygotowanym stanowisku badawczym z zastosowaniem aparatu T-27.

INTRODUCTION

Each use of foil bearings requires an individual approach to solve the problem of their construction. Such bearings increasingly work in machines with operating speeds that may exceed 100.000 rpm and temperatures reaching 800°C – compare [**L. 1**]. In addition, they are used in machines that, within the conditions of operation, generate a specific working environment for foil bearings. For the purpose of the energy microturbine bearing system construction with the use of foil bearings, tests were carried out, among others, to select the most optimal material pairs of materials at the disposal of the research team for the individual working elements of such bearings.

In foil bearings, the friction phenomenon plays a particularly important role. Its complete elimination is not possible. However, it is always aimed at reducing the effects of friction as much as possible, which directly translates into the durability of the foil bearing. Various methods of friction reduction in a foil bearing are used, including the following: by covering the frictionally cooperating surfaces with properly selected solid-lubricant coatings [**L. 2**], or by using lubrication factor in the form of liquid or gas [**L. 3**]. Moreover, the selection of materials for different part of the foil bearing is not a random procedure. On the other hand, entire bearing systems for rotating machines are tested on specially designed stands. Their use always results from individual research goals. It can be noted, however, that

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the majority of these devices collect information about bearing loads, operating rotational speed, displacements, and temperature distributions [**L. 1, 4**].

Using a wide range of both material and operational tests, materials were also associated for the sliding foil – shaft journal tribological node. To make this choice, one should carry out tests, inter alia, of friction and wear. A special test stand constructed around the T-27 tribometer was constructed for this purpose [**L. 5**]. The unique T-27 device allows for model friction and wear tests of materials, which, when using in combination type of sliding foil – shaft journal, will operate in the low-boiling liquid environment. With particular interest, presented in this paper, attention was drawn to the method of determining the coefficient of friction of such a tribological node, which was modelled with a foil-roller association. Such a bearing node model, which represents the cooperation of the shaft journal with the sliding foil, mainly during start-up and rundown of the rotor machine, is placed in a closed test chamber. The set, prepared for tests, of metal foil strip dedicated for the sliding foil in the bearing and a roller made of the material proposed for the bearing journal of the turbine shaft, in the test chamber of the T-27 device, is additionally located in the low-boiling liquid environment, which acts as the lubricant of the target foil bearing. A view of the foil-roller combination prepared for testing in the test chamber is shown in **Fig. 1**. The test chamber is closed during the test run, and over the test node there is a nozzle supplying the low-boiling liquid to the inside of the test chamber, spraying it directly on the tribological node.

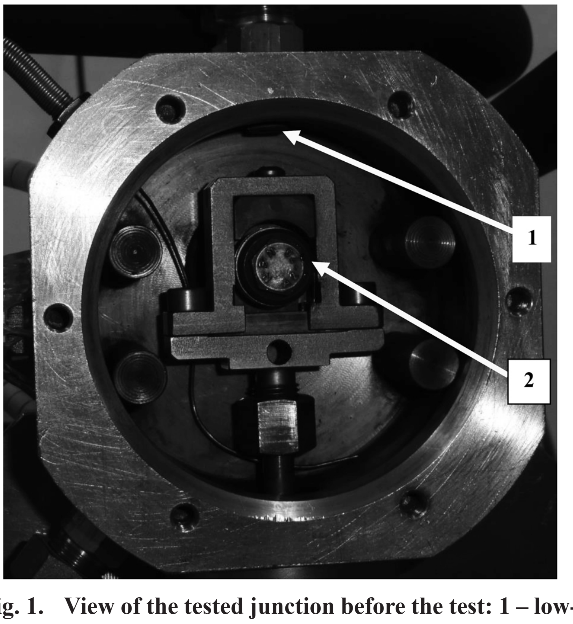

Fig. 1. View of the tested junction before the test: 1 – low-boiling liquid spray, 2 – tested tribological node

Rys. 1. Widok badanego węzła przed biegiem badawczym: 1 – natrysk cieczy niskowrzącej, 2 – badany węzeł tribologiczny

During the test, the T-27 tribometer allows the monitoring and recording of parameters necessary for further analysis of tribological properties. The basic parameter obtained from test run is the moment of friction. Its value is then used to determine the coefficient of friction of a selected material pair working in a foil-roller combination. The sliding friction coefficient determination, on the basis of the classical law of sliding friction and measured values of friction torque, give values far in excess of unity. Such results may be misinterpreted by designers of such bearings.

In this paper, an attempt to verify determined coefficients of friction was made and the method of their determination is given, taking into account the nature of metal foil strip cooperation with a rotating roller.

Determination of friction coefficient

On the test stand for the study of friction and wear in the foil-roller combination, the friction torque M_t is measured. Distribution of forces on the roller and foil, between which the coefficient of friction is determined, is shown in **Fig. 2**.

Forming the equilibrium equation of moments for the entire system (**Fig. 2a**) with respect to the O point, in the form

$$M_t - R_C \cdot h = 0 \tag{1}$$

the R_C reaction can be determined in the seal point C:

$$R_C = \frac{M_t}{h} \tag{2}$$

For the system of forces acting on the roller having the radius of R (**Fig. 2b**), the equilibrium equation of moments in relation to the point O can be written as follows:

$$M_t + S_2 \cdot R - S_1 \cdot R = 0 \tag{3}$$

It shows that the difference between the belt tension forces on the tight and slack side can be determined as follows:

$$S_1 - S_2 = \frac{M_t}{R} \tag{4}$$

As it is easy to check, the same relation (4) will be obtained from the equilibrium equation of moments with respect to the point O for the forces shown in **Fig. 2c** in which Equation (2) will be taken into consideration.

From conditions of the force equilibrium in relation to the x and y axes for the force system from **Fig. 2a**, the following was obtained:

$$\begin{cases} R_{ox} = R_C \\ R_{oy} = G \end{cases} \tag{5}$$

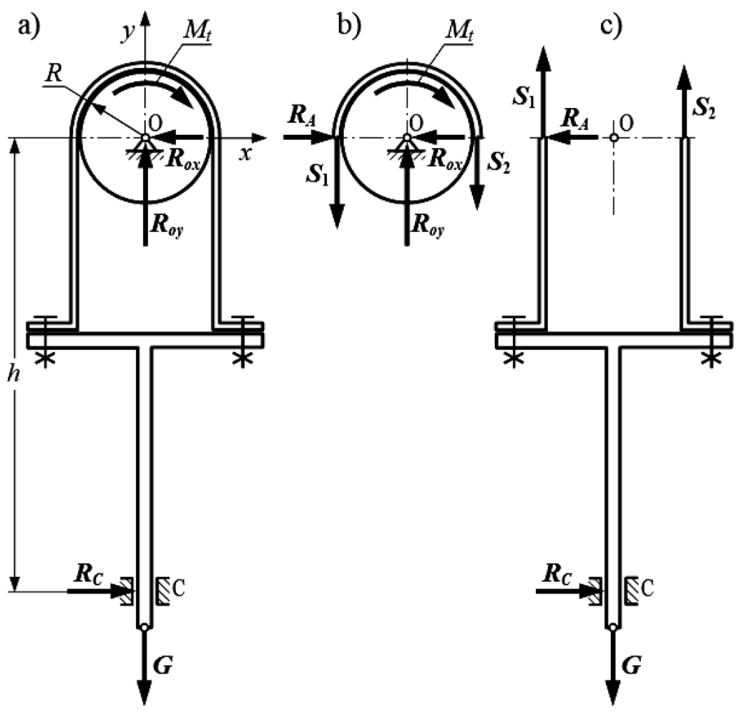

Fig. 2. Distribution of forces in elements of the measuring device
Rys. 2. Rozkład sił w elementach urządzenia pomiarowego

where G – is a given weight, loading the friction node of a foil-roll type.

However, from the equilibrium of the force projections on the x and y axes for the force systems presented in **Fig. 2.b** and **2.c**

$$R_A = R_{ox} = R_C \tag{6}$$

and

$$S_1 + S_2 = G \tag{7}$$

were determined.

Substituting the S_2 force calculated from Equation (7) into Relation (4), simple transformations give tension forces of the foil strip as a function of a given weight G and the measured moment of friction M_t.

$$\begin{cases} S_1 = \dfrac{1}{2R}\left(G \cdot R + M_t\right) \\ S_2 = \dfrac{1}{2R}\left(G \cdot R - M_t\right) \end{cases} \tag{8}$$

As the foil is thin and flexible and wraps the roller on the half of its circumference, i.e. the angle equal to π [rad], to determine friction conditions, the equilibrium conditions for elementary arc segment of the foil strip with $d\varphi$ opening angle according to the **Fig. 3** should be formulated. The dimension, $h>>R$, and measured moments of friction are relatively small, so it was assumed, that $R_A \cong 0$.

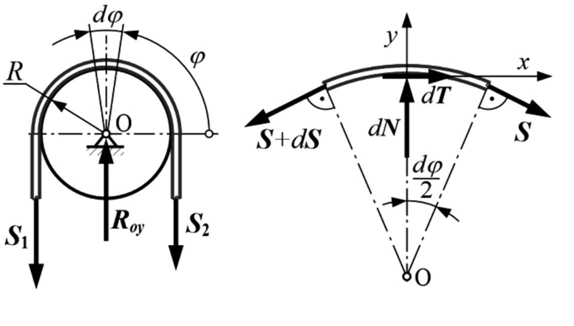

Fig. 3. Distribution of forces in the elementary section of the foil
Rys. 3. Rozkład sił w elementarnym wycinku folii

The condition of moment equilibrium for the elementary arc section with respect to the point O has the following form:

$$(S + dS) \cdot R - dT \cdot R - S \cdot R = 0 \tag{9}$$

where S – is the tension force of the elementary foil section, dS – is its increment, dT – is the friction force, and dN – the pressure between the foil and the roller.

After transformations, it follows from dependence (9) that the elementary increase in the foil strip tension is equal to the increase in the friction force

$$dS = dT \tag{10}$$

The condition of force equilibrium in relation to the y-axis is formulated as follows:

$$dN - (S + dS)\sin\frac{d\varphi}{2} - S \cdot \sin\frac{d\varphi}{2} = 0 \tag{11}$$

After reduction, the following was derived:

$$dN - 2S\sin\frac{d\varphi}{2} - dS \cdot \sin\frac{d\varphi}{2} = 0 \tag{12}$$

Assuming that the product of the two calculations is infinitely small and negligible, and elementary angle $d\varphi$ expressed in radians $\sin\frac{1}{2}d\varphi \cong \frac{1}{2}d\varphi$ can be assumed, then, from Equation (12), the following dependence results:

$$dN = S \cdot d\varphi \tag{13}$$

The relation between the elementary friction force and the pressure on the foil with roller contact area, according to the law of sliding friction is in the form:

$$dT = \mu \cdot dN \tag{14}$$

where μ – is searched dimensionless sliding friction coefficient of the foil on the roller.

Having regard to Equations (10) and (13) in the law of friction (14), the following differential equation is obtained:

$$\frac{dS}{S} = \mu \cdot d\varphi \tag{15}$$

which, after integration, takes the following form:

$$\ln S\Big|_{S_2}^{S_1} = \mu \cdot \varphi\Big|_0^{\pi} \tag{16}$$

After substituting limits of integration and determining the coefficient of friction, the result is the following:

$$\mu = \frac{1}{\pi} \cdot \ln\frac{S_1}{S_2} \tag{17}$$

By introducing Equation (8) into Relation (7), the final formula was derived for the calculation of the coefficient of sliding friction of foil on the roller using a predetermined weight G and the total moment of friction M_t, measured at the laboratory stand, in the following form:

$$\mu = \frac{1}{\pi} \cdot \ln\frac{G \cdot R + M_t}{G \cdot R - M_t} \tag{18}$$

Experimental research

In order to determine the coefficient of friction in the theory presented in the previous chapter, it is necessary to conduct a series of experimental runs and collect data mainly about the friction moment occurring in the tested node during each test.

Fig. 4. View of the T-27 apparatus for testing friction and wear of materials in foil-roller combination
Rys. 4. Widok aparatu T-27 do badania tarcia i zużycia materiałów w skojarzeniu folia–rolka

The experimental run with the use of T-27 tribometer, which is shown in **Fig. 2,** should be carried out in accordance with the operating instructions prepared by the manufacturer – the Tribology Department of the Institute for Sustainable Technologies – National Research Institute in Radom. It includes activities related to the preparation of the tribometer itself for the test performance and also the whole range of activities regarding the preparation of samples and counter-samples for testing. Due to the prototype character of the device, unit production and the lubricant used, the correct operation of a T-27 device is learned during detailed on-the-job training, while the methodology of testing with the mentioned apparatus is presented in **[L. 6]**.

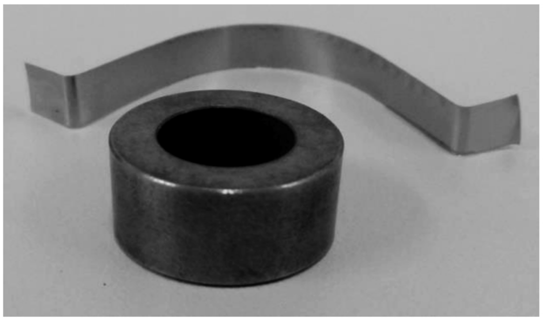

Fig. 5. Example of tribological foil-roller combination
Rys. 5. Przykładowe elementy skojarzenia tribologicznego folia–rolka

The experimental tests were carried out assuming the following parameters of the friction contact and course of tests:
- Tribological combination – foil and roller,
- Type of motion – continuous sliding,
- Type of friction contact – distributed,
- Friction node load – 20 N,
- Spindle rotational speed – 10 000 rpm,
- Running time – 3600 s,
- Number and type of cycles – 1, continuous,
- Lubricant – HFE-7100,
- Lubrication – circulating,
- Medium temperature – adjustable, max. 50°C.

Samples for tests, made of chromium alloy with nickel called Inconel 600 (Ni – 72%, Cr – 14–17%, Fe – 6–10%, Mn – 1%, Cu – 0.5%, Si – 0.5%, C – 0.15%, S – 0.015%), were prepared as a thin metal foil strips measuring 90×6×0,1 mm. Counter-samples are rollers with a diameter of 20 mm made of 100Cr6 bearing steel characterized by high resistance to abrasion, good machinability, and hardenability (**Fig. 5**). Before testing, samples and counter-samples were measured and purified in isopropyl alcohol with the use of an ultrasonic cleaner. The sample, which was a metal foil ready for test formed in a special device, was mounted in a holder (**Fig. 1**), and the counter-sample, which was a roller mounted in the tribometer test chamber, formed the friction node, which was loaded as planned.

The applied lubricant (HFE-7100) is a transparent low-boiling substance with the chemical name methoxy-nonafluorobutane and the molecular formula $C_4F_9OCH_3$, characterized by a slight colour and odour. The HFE-7100 medium has beneficial properties for the natural environment and does not damage the ozone layer [**L. 7**]. It is practically used, among others, as an industrial solvent or heat carrier with a boiling point of 61°C, which is thermally resistant, non-flammable, and slightly toxic. However, it is known from our own experience that excessive human exposure in conditions of evaporating HFE-7100 causes symptoms of fainting, headache, and nausea. Therefore, people operating a test stand with a T-27 tribometer should ensure adequate ventilation of the room in which tests are carried out.

The HTE+7100 substance has two functions in the T+27 device: It is a lubricant brought to the tested friction joint and it has the task of removing heat from a sealed test chamber. For this reason, the agent is working in a closed circuit and is continuously discharged from the test chamber, then cooled and re-supplied to the test chamber. The temperature inside the test chamber is monitored from the beginning of the test run, and its maximum value can be set.

During experimental runs of the T-27 tribometer, the value of frictional moment, which arises in the frictional node, was primarily monitored. During the test of one tribological pair, the frictional moment generated by the internal resistance of the test machine, starting from the engine driving the entire system up to the test chamber, was measured first. At this stage of the test, the metal foil was moved away from the roller rotating at the certain speed and in no way was in contact with it. This eliminates contact of both tested elements of the friction junction and the sum of frictional resistance of all elements of the machine rotational speed transmission system was recorded in the device memory. The value of this sum was recorded as the frictional moment without the load of the examined foil-roller combination. An example of changes of internal friction resistance recorded during tests is shown in **Fig. 6**.

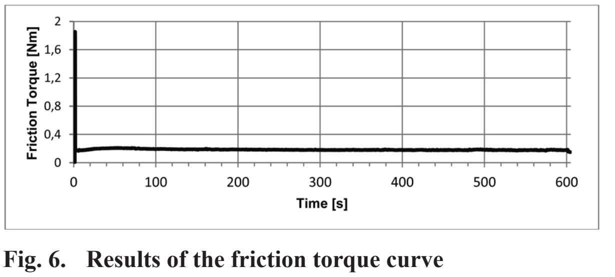

Fig. 6. Results of the friction torque curve
Rys. 6. Przebieg momentu tarcia bez obciążenia w funkcji czasu

Then the tested metal foil was based on a roller, the whole friction node was loaded with the given weight, and the main part of the test run with the measure of the total friction resistance of the rotating device was carried out, taking into account the frictional resistance occurring as a result of wrapping the counter-sample with the metal foil strip in the foil-roller test combination. The course of changes in the total friction torque of test Number 5 (**Table 1**) registered by the measuring system of T-27 tribometer is shown in **Fig. 7**.

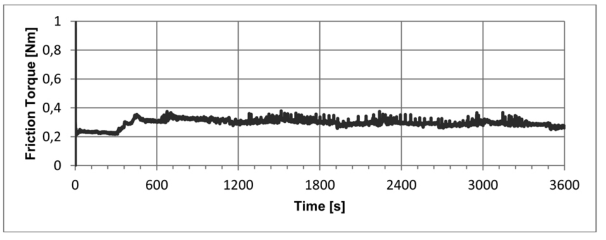

Fig. 7. Results of the total moment of friction curve
Rys. 7. Przebieg całkowitego momentu tarcia w funkcji czasu

Stored in memory, measurement results of friction moments from individual test runs for tested 100Cr6 steel – Inconel 600 material pair were averaged and determined mean values of friction moments are presented in **Table 1**.

Table 1. Values of friction torque from tests
Tabela 1. Wartości momentów tarcia z badań

Friction moment test number	Without load [Nm]	With a load [Nm]	M_t [Nm]
1	0.171	0.220	0.049
2	0.177	0.227	0.050
3	0.110	0.320	0.210
4	0.103	0.294	0.191
5	0.198	0.298	0.100

Analysis of results

Mean values of friction moments presented in **Table 1**, respectively, without load and with a load, were calculated from data obtained in individual test runs. However, with longer observation, it was noticed that values of friction moments without load should be determined after about 1 to 2 minutes of the run. After this time, there were no significant deviations from previously determined values. This is why it was decided to limit the duration of the run determining internal friction resistance of the system driving the counter-sample in the test chamber in each test run for up to 10 minutes.

Analysing values of individual moments, one can notice a large discrepancy between the results of friction moment of the testing device without the load of the tested friction node. The maximum difference between designated numbers is 0.095 Nm, while the standard deviation in the mentioned set of numbers is equal to 0.043 Nm. For the friction moments with a load, the situation is similar. The largest difference between designated values is 0.1 Nm, and the standard deviation is 0,045 Nm. Unfortunately, not all results are serviceable, and they could not be used to determine the coefficient of friction.

When calculating the coefficient of friction based on the data presented in **Tab. 1** and using Relation (18), a positive result will not be obtained in the case of test Number 3, because the logarithmic number has a negative value; therefore, it does not include in the domain of the natural logarithm function. It is therefore necessary to reject this test when determining the coefficient of friction.

Moreover, the data from test Number 4, for which the determined moment of friction M_t is equal to 0.191 Nm. After using it in Equation (18), it results in the coefficient of friction equal to 1.2, which is much larger than the other values, which are listed in **Tab. 2**.

Table 2. Calculated values of the coefficient of friction in the foil-roller combination
Tabela 2. Obliczone wartości współczynnika tarcia w skojarzeniu folia–rolka

Friction moment test number	Friction coefficient *m*
1	0.159
2	0.163
3	–
4	*1.200*
5	0.350
Mean from 1, 2 and 5	**0.224**

Using Equation (18) and the data of the other three test runs, an attempt was made to determine the coefficient of sliding friction in the model tribological combination of the foil-roller type for Inconel 600 – 100Cr6 steel material pair. Its average value is equal to $\mu = 0.224$ with a standard deviation $\sigma = 0.109$.

Mention should also be made of the necessity of rejecting a large number of test runs (6 runs) for which the data on friction moments differ significantly from the values presented in this study. Therefore, they were considered errors and were not considered in the above analysis.

CONCLUSIONS

A method of determining the coefficient of friction of tribological foil-roller type combination was proposed in this study. The presented method is applicable in the model study of tribological characteristics of friction node occurring in foil bearings with a unique test apparatus developed at the Institute for Sustainable Technologies – National Research Institute in Radom.

The friction node used in the device models the strip of metal foil that wraps the roller on the half of its circumference. Such a system suggests the application of wrapping friction theory to determine the sliding friction coefficient at the mentioned node.

Unfortunately, for this reason, the proposed method has mathematical limitations, because the final dependence on the coefficient of friction is the function of natural logarithm.

At the same time, in order to evaluate the coefficient of friction, test runs are carried out, determining the moment of friction on their basis, the value of which must be used in the proposed calculation algorithm. It is important to precisely take into consideration the presence of internal friction resistance of the test apparatus itself, which is why their direct cooperation and operating condition that are close to the real working environment of the target elements of foil bearings are crucial in calculating the coefficient of friction of tested material pairs, and the accuracy of the calculated values is much higher.

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