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EXPERIMENTAL ESTIMATION OF WEAR RESISTANCE OF POLYAMIDE COMPOSITES, REINFORCED BY CARBON AND GLASS FIBRES USED IN METAL-POLYMER GEARINGS

Myron CHERNETS,[*] Myroslav KINDRACHUK,[*] Anatolii KORNIENKO[*], Alina YURCHUK[**]

[*]Aerospace Faculty, Department of engineering, standardization and certification,
National Aviation University, 1, Liubomyra Huzara ave., Kyiv, Ukraine, 03058
[*]Aerospace Faculty, Department of computerized electrotechnical systems and technologies,
National Aviation University, 1, Liubomyra Huzara ave., Kyiv, Ukraine, 03058

myron.czerniec@gmail.com, nau12@ukr.net, anatoliy_k@ukr.net, pruner@ukr.net

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Abstract: The method of model triboexperimental studies to determine the basic mathematical model parameters of materials wear resistance at sliding friction is considered. The quantitative relative experimental characteristics of wear resistance of glass fibre and carbon fibre reinforced polyamide used in metal-polymer gear couple have been determined. Wear resistance functions of these functional polymeric composites have been established as the basic ones in the tribokinetic mathematical model of material wear for sliding friction conditions. Also, according to the conducted researches, wear resistance diagrams were constructed. They may be used as graphical indicators of wear resistance in the required range of specific friction forces. The dependences that connect the characteristic functions of wear resistance of these materials (obtained by the developed mathematical tribokinetic wear model) with linear wear and gearing service life are presented.

Keywords: Method for determining the characteristics and functions of wear resistance, reinforced polyamide, dispersed glass and carbon fibres, metal-polymer gears

1. INTRODUCTION

New developments in industrial technologies require constant improvements of materials used (Kindrachuk et al, 2018). New hardfacing and advanced materials are always introduced, and many of them will find their application much later (Pashechko et al., 2018, Gorokh et al., 2018). A very important task here is the prediction of wear loss, or service life of mechanisms and machines, but most scientists predict durability of materials only. Various methods and power schemes of triboexperimental studies to evaluate the wear resistance of materials are used. Here, it is possible to determine the absolute and relative characteristics of the studied tribocouple's materials under the given conditions. They can be used to make a comparative assessment of materials' wear resistance under identical test conditions. The most common of these include linear, mass and volume wear loss (absolute characteristics) and the intensity and rate of wear (relative characteristics). It is more convenient to use relative wear characteristics. These quantitative characteristics of materials' wear resistance are traditionally determined under specified normal loading in tribocouple. However, the calculation methods for estimating wear using them are not adequate as far as they are, as a rule, calculated for one value of specific load. Therefore, it is necessary to perform numerical triboexperimental studies of tribocouples in a sufficiently wide range of specific loads, the results of which should establish the characteristics of wear resistance. These characteristics will become the basic ones in mathematical models of wear kinetics of sliding (or rolling with slippage) tribocouples. Polymeric materials have some peculiarities if they operate in couple with steels, and we should take this into account (Kindrachuk et al., 2019 a, b,).

This paper presents the results of the studies on the method of model triboexperiments (Chernets and Lenik, 1997, Chernets, 2019) with sliding friction to establish the wear resistance characteristics of reinforced polyamide composites paired with steel used in metal-polymer gear couple.

2. STATE OF THE ART

As it is known, during the operation of gears under the influence of friction forces acting on the gear in the torque transmission, tooth wear occurs inevitably. The wear rate is the practical criterion that determines the gears' lifespan (Zarkoa et al., 2019, Greco et al., 2011). However, despite the obvious necessity at the design stage of carrying out the predicted calculation of gears' durability according to the criterion of acceptable linear wear of the teeth, effective and reliable methods of calculation have not yet been developed. There are several methods of calculation of this kind in the literature. In the 1970s and 1980s, Drozdov Yu.N. has been working on this problem in USSR. (Drozdov, 1969, 1975, Drozdov and Nazhestkin, 1990, Pronikov, 1978, Grib, 1982). There is no continuation of these studies by other investigators in the countries of the former USSR. Since the late 1990s, several scientists have been developing such methods to calculate certain types of gears. Among them, there are: Bajpai et al., (2004), Brauer and Andersson, (2003), Flodin, (2000), Flodin and

Andersson (1997, 1999, 2000, 2001), Kahraman et al., (2005), Kolivand and Kahraman (2010), Mao (2007), Pasta and Mariotti (2007), Wu and Cheng (1993). Archard's law of abrasive wear is used in all simplified calculation methods to evaluate wear of teeth. According to him, the wear rate is linearly dependent on the friction path and contact pressure. In closed gearings operated with lubrication, abrasive wear does not occur and the use of these methods is therefore unreasonable. Besides, other factors are not covered by these methods, which will be discussed below. This fact makes it impossible to use them in engineering practice. Even in open gear drives, abrasive wear is also uncommon, because in the presence of an abrasive medium, gears quickly lose their performance.

The estimation of service life of gearings is a very important task. Reasons of gearings failure may vary a lot. Basically, teeth may fail due to fatigue or sudden rupture (Gębura et al., 2019), surface fatigue (Brandao et al., 2014), fretting-fatigue (Wei et al., 2020), contact-fatigue (Liu et al., 2020) or may be worn out (Brethee et al.). In problem of lifespan estimation, scientists focus their attention to particular reasons of failure. Brandao et al. (2014) did a study of pitting and fatigue influence on gears wear. They developed a numerical model that involves simulation of micropitting and fatigue wear. But, these two processes were modelled separately and combined later. DIN 20MnCr5 steel was used as gear material. Bravo et al. (2015) were solving the task of gear couple deterioration until the final failure. They point out the complexity of this task. Both gears were manufactured of plastic materials. Authors succeeded a lot in developing effective means to extend the time for plastic gear applicability.

Hegadekatte et al. (2010) studied the wear in miniature gear mechanisms made of ceramics or cemented carbides. The Archard's wear model was selected as the most appropriate. Simulation was done using FEM method. This time, the lifespan prediction by this method for macrogears is questionable. To determine wear coefficient, they used experimental pin-on-disk and twin-disc wear data. Wang et al. (2019) made a numerical model and simulations of wear process of heavy loaded helical gears based on the modified Archard's wear model for elastohydrodynamic lubrication. They also found relations between load factors, gear geometric parameters and wear rate of tooth contact surface. These data, unfortunately, were not checked experimentally.

The surface condition and gear modification also influence simulation; besides, the roughness effect during simulations is also an important factor. Bodach et al. (2012) studied the numerical simulation of positively modified gears' roughness influence on lubrication and wear process. Results showed that tooth geometry change influences much more than change in roughness during operation. Guilbault and Lalonde (2019) made a significant effort to predict tooth roughness change with high accuracy (1.27 μm predicted compared to 1.3 μm measured). They proved that micropitting failure starts on the surface, while pitting crack initiates at some depth under the surface. But, both these studies cannot spot the method to predict lifespan of the gear.

Raadnui (2019) studied the wear and other deterioration processes of gears, including contamination and corrosion influence on gears conditions. He deduced the relationships between operating conditions, wear debris size, morphology and failure mode. This work's results can't be used directly to predict the lifespan of gear trains, but may be used for quantitative prediction of wear loss. For wear tests, he used a test set with two industrially produced gears engaged.

The dynamic wear prediction model established by Liu et al., (2016) has a task to connect surface wear process and gear dynamics. At low rpm, the effect of initial tooth wear is negligible, but as rpm rises, the wear effect becomes more significant. But, the question about experimental studies still requires a solution. Feng et al. (2019) updated the dynamic model by taking into account vibrations occurring during operation, and vibration-wear bias. Tooth wear was monitored continuously and corrected tooth shape (as a result of wear) continuously being added to the model. All the results were checked by laboratory gear test rig. This model may predict the wear of gears with acceptable accuracy.

3. WEAR TEST PROCEDURE

When conducting model triboexperimental studies, they usually use plane friction contact. In this case, the conditions of wear are unchanged throughout the experiment. A pin-on-disc tribometer is a very good solution for that.

To study the polymer composite-steel couple's wear, a friction PoD layout was used (composite pin – AISI 1045 steel disk).

In the current work, tribological tests were conducted using a pin-on-disk test layout (composite pin – steel disk), which ensures that the conditions of friction and wear are constant during the experiment. The following research program was used: contact pressure P = 1, 2, 5, 10, 20 MPa, sliding speed v = 0.4 m/sec, wear path = 2000 m, diameter of pin d = 2 mm. Friction factor measured for materials was 0.3.

For wear test, we used Anton Paar tribometer TRB³ (Fig. 1).

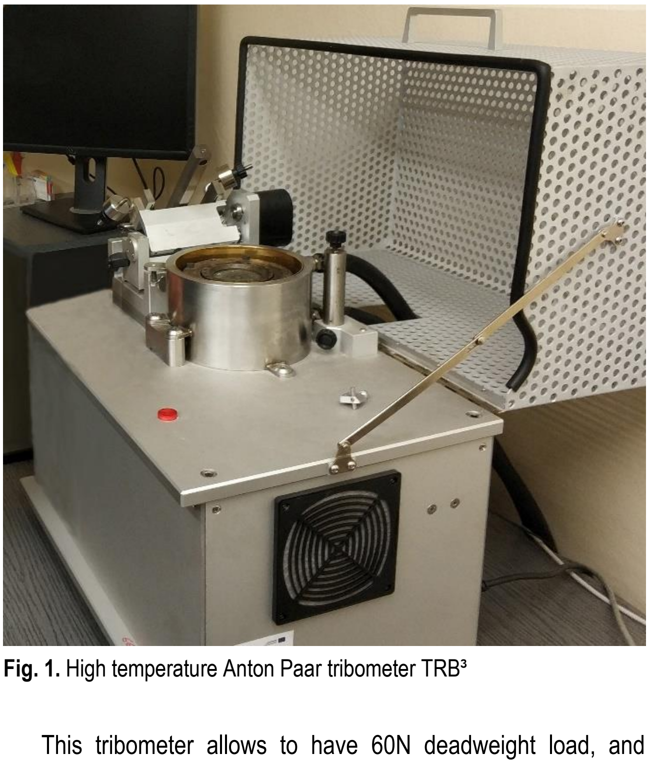

Fig. 1. High temperature Anton Paar tribometer TRB³

This tribometer allows to have 60N deadweight load, and combined with standard specimen, 20 MPa contact pressure may never be achieved. But, to meet the requirements of the test, a modified pin specimen was manufactured (Fig. 2). The contact area of the modified specimen with cone section is 3 mm², which gives 20 MPa at 60N load. Reduced pin diameter section length is about 2 mm, and no plain contact distortion was observed. Mass

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wear loss was measured by electronic balances with accuracy 0.001 g Axis model ANG 200 C.

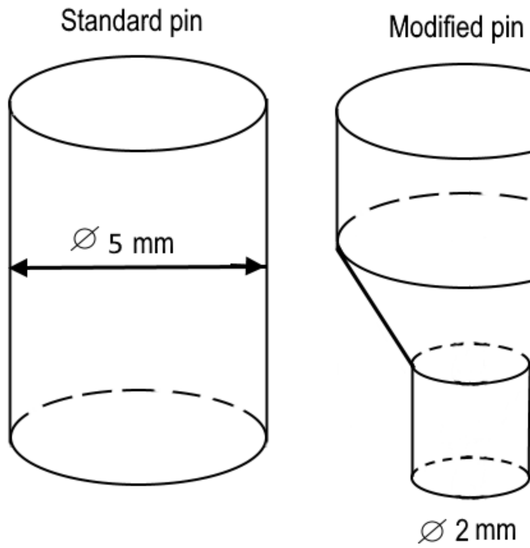

Fig. 2. Standard and modified pin for TRB³ tribometer

4. RESULTS AND DISCUSSION

After the wear test, mass wear loss ΔM of specimens was determined, and their average linear wear h was calculated by the formula:

$$h = \frac{\Delta M}{\rho S}, \quad (1)$$

where ρ is the density of polyamide composite with 30 wt. % of fibre reinforcement; S is the nominal contact area.

The next stage of data processing of triboexperimental studies was the establishment of experimental wear resistance model characteristics, in particular wear resistance functions Φ_i at certain levels of specific friction forces τ_i in friction contact

$$\Phi_i = L_i / h_i, \quad (2)$$

where $L_i = vt$ is friction path, v – friction velocity, t is the duration of the experiment, h_i– linear wear of samples, τ_i is the discrete value of specific friction force at contact pressure i. We should note that the friction forces can be significantly different with the same contact pressure in the tribomechanical system. They depend on the sliding friction coefficient, which can be in a wide range (from 0.005 to 0.01 for mixed friction, from 0.05 to 0.1 for boundary friction, from 0.1 to 1.0 for dry friction) (Kurdi et al., 2018, Bongaerts et al., 2018, Wand and Wang, 2013). The specific friction force, the value of which determines the wear rate of tribosystem elements, in tribotechnology is calculated by Amonton – Coulomb formula:

$$\tau = fP, \quad (3)$$

where f is friction coefficient; P is nominal contact pressure.

The final stage of processing experimental data is to determine the basic characteristics of wear resistance for a mathematical model of the study of materials wear kinetics at sliding friction (Chernets and Lenik, 1997, Chernets et al., 2011). Using the established by (2) discrete experimental characteristics of wear resistance – wear resistance functions. Their approximation is performed according to the following relation (Chernets, 2019a, Chernets et al., 2011):

$$\Phi_k(\tau) = C_k \left(\frac{\tau_{sk}}{\tau}\right)^{m_k}, \quad (4)$$

where C_k, m_k – are nonlinear and exponential wear resistance characteristics of tribocouple materials, which are determined by formula (4) through approximation by the method of least squares through several iterations based on the experimental values of wear resistance functions Φ_i determined earlier by formula (2), τ_S – shear strength of materials, k = 1; 2 – designation of tribocouple elements. The characteristic function of wear resistance is the basic integral parameter of the developed mathematical wear model (Chernets and Lenik, 1997, Chernets et al., 2011, Chernets, 2019b).

The above procedure was used to determine the wear resistance characteristics C_k, m_k of polyamide composites with a filler volume fraction of 30% coupled with steel (calculated by formula (4)):

carbon fibre reinforced polyamide PA6 + 30CF (UPA – 6130 UV): = C_{CF}= 3.1·10^5, m_{CF}= 2.3, τ_{SCF}= 48 MPa; glassfibre reinforced polyamide PA6 + 30GF (PA6-L-CB30-1): = C_{GF}= 1.26·10^5, m_{GF}= 1.9, τ_{SGF}= 52 MPa.

On Fig. 3, points show the experimental discrete values of the calculated wear resistance functions $\Phi_i = \Phi_i(\tau_i)$ of both the composites, and the lines show their wear resistance diagrams $\Phi(\tau) \sim \tau$ as indicators of their wear resistance in the studied range of friction forces.

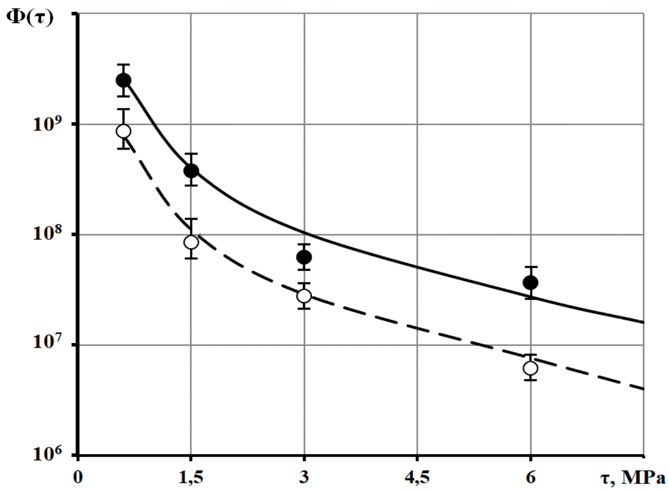

Fig. 3. Diagram of wear resistance of polyamide composites: solid line – carbon fibre reinforced composite, dashed line – fiberglass reinforced composite; dark circles – experimental values of wear resistance function for carbon fibre composite, light circles – for fi -breglass reinforced composite. Each point is an average value of 3 wear tests

The above mentioned material's wear resistance diagram (WRD) allows to visually evaluate the material's wear resistance over the entire range of specific friction force change. In addition, when studying the wear of several materials, it is easy to compare their wear resistance under different loading conditions.

Based on the results of triboexperimental studies and WRD of these polymeric composites, the comparative wear resistance was evaluated, and we found that carbon fibre-reinforced composite would be C_{CF}/C_{GF} = 2.46 times more wear resistant than fibreglass reinforced composite.

Wear resistance is inverse to wear intensity. Therefore, respectively, experimental inverse function of linear wear resistance will be the experimental function of the intensity of linear wear $\mathrm{I_{hi}}(\tau_\mathrm{i})$ for corresponding values of specific friction force τ_i:

$$\frac{1}{\Phi_i(\tau_\mathrm{i})} = \frac{h_i}{L_i} = I_{hi}(\tau_i), \tag{5}$$

Also, wear resistance function $\Phi_i(\tau_\mathrm{i})$ is related to the linear wear rate $\gamma_{hi}(\tau_i)$ by the following formula:

$$\Phi_i(\tau_\mathrm{i}) = v/\gamma_{hi}(\tau_i), \tag{6}$$

and inverse:

$$\gamma_{hi}(\tau_i) = v/\Phi_i(\tau_i) = vI_{hi}(\tau_i), \tag{7}$$

So, these experimental evaluation results of materials' wear resistance may be compared with the results of other authors obtained under similar wear conditions, first of all, at the same range of specific friction force and sliding speeds.

Basic wear characteristics may be used to calculate the total linear wear of tribomechanical sliding system if wear characteristics of one of its elements are known. This is especially important in case of dissimilar wear resistance of coupled materials and dissimilar tribocontact conditions. Total linear wear of tribosystem h_Σ can be calculated as follows:

$$h_\Sigma = h_1 + h_2 = h_1(1 + h'_1) = h_2(1 + h'_2), \tag{8}$$

where h'_1, h'_2 – relative linear wear of coupled elements (pinion 1 and gear 2).

They are calculated as $\Phi_k(\tau)$ taking into account (4) according to the following dependencies:

$$h'_1 = \frac{h_2}{h_1} = \frac{\Phi_1(\tau)}{\Phi_2(\tau)} = \frac{C_1\tau_{S1}^{m_1}\tau^{m_2}}{C_2\tau_{S2}^{m_2}\tau^{m_1}}K_t^{(2)},$$

$$h'_2 = \frac{h_1}{h_2} = \frac{\Phi_2(\tau)}{\Phi_1(\tau)} = \frac{C_2\tau_{S2}^{m_2}\tau^{m_1}}{C_1\tau_{S1}^{m_1}\tau^{m_2}}K_t^{(1)}, \tag{9}$$

where $K_t^{(1)}, K_t^{(2)}$ – coefficients of elements mutual overlapping at tribological contact.

Correspondingly, in a gearing:

$$h_\Sigma = h_k\left(K_t^{(k)} + h'_k\right);$$

$$h_\Sigma = h_1\left(-K_t^{(1)} + h'_1\right);$$

$$h_\Sigma = h_2\left(K_t^{(2)} - h'_2\right);$$

$$K_t^{(1)} = 1,$$

$$K_t^{(2)} = z_1/z_2, \tag{10}$$

where z_1, z_2 are respectively the number of teeth of pinion and gear.

Linear wear h_k of gears teeth are interrelated, so:

$$h_1 = \frac{h_2h'_2}{K_t^{(2)}}; \quad h_2 = \frac{h_1h'_1}{K_t^{(1)}}, \tag{11}$$

Taking into account (2):

$$vT_1 = \Phi_1h_1;\ vT_2 = \Phi_2h_2, \tag{12}$$

where T_1 and T_2 – are the durabilities of the studied tribocouples. Accordingly, relative durabilities T'_1 and T'_2 of tribomechanical system elements will be determined as:

$$T'_1 = \frac{T_2}{T_1} = \frac{\Phi_2(\tau)h_2K_t^{(2)}}{\Phi_1(\tau)h_1K_t^{(1)}} = \frac{\Phi_2^2(\tau)}{K_t^{(1)}\Phi_1^2(\tau)}$$

$$T'_2 = \frac{T_1}{T_2} = \frac{\Phi_1(\tau)h_1K_t^{(1)}}{\Phi_2(\tau)h_2K_t^{(2)}} = \frac{\Phi_1^2(\tau)}{K_t^{(2)}\Phi_2^2(\tau)} \tag{13}$$

Then,

$$T_1 = \frac{T_2\Phi_1^2(\tau)}{\Phi_2^2(\tau)K_t^{(2)}} = T_2T'_2;$$

$$T_2 = \frac{T_1\Phi_2^2(\tau)}{\Phi_1^2(\tau)K_t^{(1)}} = T_1T'_1. \tag{14}$$

5. CONCLUSIONS

The method of triboexperimental studies of materials at sliding friction according to pin-on-disk friction layout provides the correct determination of relative wear resistance characteristics Φ_i of materials due to the invariance of tribocontact conditions throughout the experiment. The developed method's efficiency is confirmed by an example of the tests given here of the two types of polyamide-based composite materials PA+30%CF and PA6+30%GF under the studied range of specific friction forces.

Obtained experimental values of Φ_i were used to construct wear resistance diagrams of the studied materials. They graphically display their wear resistance (Fig. 3).

These wear resistance diagrams of materials, as graphical indicators of their wear resistance, allow to determine the comparative wear resistance of the studied composites for any required value of specific friction force.

Determined as a result of approximation of experimental wear resistance indicator values (functions Φ_i) and material's wear resistance characteristics C_k, m_k are required for the assessment of wear and durability of metal-polymer gears by the developed method of gears calculation (Chernets et al, 2011, Chernets, 2019, Chernets and Chernets, 2017) or by the corresponding numerical methods used in problems of contact mechanics (Kindrachuk and Galanov, 2014).

Using the characteristics of material's wear resistance C_k, m_k in tribocouple, it is possible to determine the relative linear wear of tribosystem elements h'_1, h'_2, their total wear resistance h_Σ and durabilities T_1 and T_2 of tribosystem elements.

This methodology allows transforming wear rates, friction force values, and friction factors, available from scientific literature, into wear resistance functions. Thus, any of the results obtained with dissimilar test methods may be used as a database for further research.

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