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RESEARCH

Investigation of Wear Resistance of Polyamide PA6 Based Composite Materials for Metal - Polymer Plain Bearings and Gears

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A B S T R A C T

Metal-polymer plain bearings and gears are becoming increasingly used in many areas of human activity. The wear resistance of one group of such materials - unreinforced polyamides PA6, PA66, and composites with fillers PA6+30GF, PA6+30CF, PA6+MoS2, PA6+Oil was studied. To determine their wear resistance indicators the author's method of model triboexperimental research according to the scheme of end friction at dry sliding friction paired with carbon steel (0.45%C) is used. According to the determined wear resistance indicators, are calculated as the basic parameters of the author's mathematical model of materials' wear kinetics at sliding friction and the analytical method of the research of specified friction units. Based to the research, polymeric materials' wear resistance diagrams are plotted as graphical indicators of wear resistance in the accepted range of specific friction forces. The qualitative and quantitative influence of the type and structure of the fillers on the wear resistance has been established. Qualitatively, the nature of the change in wear resistance of the indicated types of polyamides is similar, quantitatively the difference is significantly differentiated. It was found that PA6+Oil has the highest wear resistance compared to the PA6. It consistently increases in the following sequence: PA66, PA6+30GF, PA6+MoS2, PA6+30CF, PA6+Oil

1. INTRODUCTION

One of the common polymeric materials for bushings of metal-polymer (MP) plain bearings and MP gears are polyamides, in particular PA6, with different types of fillers (fiberglass - GF, carbon fibre - CF, molybdenum disulfide – MoS_2), oil. Filling the base polymer (matrix) with these and other fibres / particles of different type and structure with different volume content minimizes the disadvantages of unfilled polymers, improves their strength, increases wear resistance and reduces friction. To study the wear resistance of materials, in particular in hybrid tribocouples, various triboexperimental research methods and power schemes are used in practice. Conditions and schemes are described in the standard ISO 7148 - 2 [1]. One of the widely used schemes is the end friction. This is due to the fact that there are constant conditions of friction and wear throughout the experiment. Therefore, the results of such studies most objectively reflect the absolute and relative quantitative characteristics (markers, indicators) of wear of the studied tribocouples under the accepted conditions allowing their comparative evaluation. For this purpose, absolute (linear, weight and volume wear) and relative (wear intensity and rate) characteristics, and other specific indicators of wear resistance are used. Experimental studies of the tribological behaviour of various polymeric materials for MP plain bearings and gears are sufficiently covered in the literature. For materials used in MP bearings, such results on the pin-on-disk scheme and model bearings are given in [2 - 10 etc.]. In particular, the study of the pin-on-disk scheme for dry friction was conducted in [2, 3 – 5]. PA6 polyamide composites paired with AISI 02 steel were studied in [2]. In [3] the results of wear of twenty-one engineering polymers (basic and their composites) are given. In [4, 5] the regularities of friction and wear of PA6 polyamide coupled with metal under different conditions were studied. The work [6] is devoted to the study of ball-on-disk tribological behaviour in dry friction of six polymer composites: cast polyamide PA6+oil, PA6+MoS_2, polyacetal POM+Al, polyterephthalat ethylene PET+PTFE, PTFE+Bronze, PTFE+Graphite. Also, tribological properties of polymeric materials were studied on model MP plain bearings in [7 - 10]. In particular, in [7] the wear resistance of polyacetal POM, cast polyamide PA6 and others was studied. The work [8] is devoted to the assessment of wear resistance of polymers PE (polyethylene), PA, POM, PTFE (Teflon). The study [9] establishes the effect of sliding speeds on friction and wear of composites PA66, PA66+18PTFE and PA66+20GF+25PTFE. In [10] the tribostability of cast polyamide PA6 was investigated.

Regarding experimental studies of the quantitative wear resistance of various polymer composites of MP gears, there is a rather limited amount of such data in the literature. According to the pin-on-disk scheme at dry friction in [11] the wear resistance of the tribocouple PA66 - steel SAE 1045 was investigated. In [6, 12-14] the tribological behaviour of PA6 under dry friction under different conditions was studied. Instead, works [15 - 17] are devoted to the experimental study of wear of model MP gears. In particular, in [15, 16] in conditions of dry friction (at abrasive presence and without) the volumetric teeth wear of polyamide gears made of PA6-Mg, PA6-Na, PA66+30GF, polyacetal POM-C with steel gear (steel S355) was investigated. Sufficiently extensive studies of weight wear of a gear made of PA6 in pair with a steel gear in MP spur, bevel and worm gears are presented in [17].

It should be noted that according to the available results of studies of polymeric materials wear, conducted, as a rule, at one load, there is no possibility to establish the characteristics of their wear resistance, suitable for use in calculation methods of MP plain bearings and gears.

According to the standard ISO 7148-2 testing of materials wear in triboexperimental researches is carried out at the specified size of contact pressure in tribocouple. However, in the calculation methods of tribomechanical sliding systems wear, the specified numerical characteristics of wear resistance, which are determined at one standard load, cannot be used for a larger range of changes in the load of the tribocontact. For this purpose, it is necessary to carry out model triboexperimental researches in a wide enough range of change of loadings and on their results to establish the basic characteristics (indicators) of wear resistance accepted in mathematical models of tribosystems wear kinetics. In fact, such a need arises in the author's calculation methods of plain bearings and various types of gears made of metallic [18 - 22] and metal-polymer [23 - 26] materials.

The paper presents the results of wear resistance studies by model triboexperiments [17, 23, 24] to determine the indicators and characteristics of wear resistance of unreinforced (PA6, PA66) and reinforced (PA6+30GF, PA6+30CF, PA6+MoS_2, PA6+Oil) polyamides.

2. METHOD OF EXPERIMENTAL STUDY OF WEAR RESISTANCE

To study the wear resistance of these polymeric materials a scheme of end friction (two polyamide rods on a steel disk) is used, which provides constant conditions of friction and wear during the experiment.

The study of metal-polymer pairs was carried out at dry friction according to the following program: contact pressure p_i = 2, 4, 6, 8, 12 MPa, sliding speed v = 0.4 m/s, experiment duration t = 5…10 hours, finger sample diameter d = 3 mm. The linear wear of the samples is determined. In the insulated box with the experimental tribocouple air cooling to T = 23±1°C is provided at a relative humidity of 50 ± 5% (ISO 7148-2 standard).

According to the results of experimental studies, the experimental indicators of wear resistance of polymeric materials are calculated as follows:

$$\Phi_i = \frac{L_i}{h_i}, \tag{1}$$

where $L = vt$ - path of friction.

Responsible for the rate (intensity) of elements wear of the studied sliding tribosystem is the specific friction force τ, which occurs in tribocontact. The Amonton-Coulomb formula was used to determine it

$$\tau = fp, \tag{2}$$

where τ_i – discrete values of specific friction forces at levels i = 1, 2, 3, … of nominal contact pressure p_i, f – the coefficient of sliding friction established experimentally.

To use the results of model triboexperimental research in the author's calculation method [17 - 26] of MP sliding bearings and gears, the definition of the basic wear resistance characteristics for the mathematical model of the materials wear kinetics study during sliding friction [17, 18, 21-25] is performed. That is, by approximating the corresponding function of discrete experimental wear resistance indicators Φ_i using the method of least squares, the following materials wear characteristics of the studied tribocouples were determined.

The following approximation function was used for MP plain bearings [17, 18]:

$$\Phi_k(\tau) = B_k \frac{\tau_{k0}^{m_k}}{(\tau-\tau_{k0})^{m_k}}, \tag{3}$$

where $\Phi_k(\tau)$ - wear resistance characteristic function – basic integral parameter of the mathematical wear model, B_k, m_k, τ_{k0} – wear resistance characteristics of materials of the studied tribocouple under these conditions, k = 1; 2 – numbering of tribocouple elements.

For MP gears, where there are several times higher specific friction forces than in MP plain bearings, a function of another type is used [22 - 25]

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

where C_k, m_k – wear resistance characteristics of materials of the studied tribocouple, τ_S - shear strength of materials.

The general view of MP plain bearing is given in Fig. 1a, and MP gear - in Fig. 1b.

(a) (b)

Fig. 1 Metal-polymer plain bearing and gears: a) plain bearing, b) gears.

3. RESULTS AND DISCUSSIONS

Data on materials of metal-polymer tribosystems:

2.1. MP plain bearings: shaft 1 is made of normalized carbon steel 0.45%C, roughness R_a = 0.8-1 μm, Young's module E_2 = 210000 MPa, Poisson's ratio ν_2 = 0.3; bushing 2 is made of polyamides (table 1).

The results of triboexperimental studies are presented in Fig. 2 - 6. In particular Fig. 2 presents diagrams of wear resistance of the above polyamides at 4 levels of contact pressures p_i = 2, 4, 6, 8 MPa.

Table 1. Materials of plain bearings bushings.

Characteristics of polymers	Polyamides					
	PA6	PA66	PA6+30GF	PA6+MoS_2	PA6+30CF	PA6+Oil
$B_1 \cdot 10^{10}$	2.26	3.37	4.12	5.58	6.53	7.03
m_1	1.09	1.09	1.09	1.1	1.1	1.1
τ_{10}, MPa	0.05	0.05	0.05	0.05	0.05	0.05
Young's module E_1, MPa	2000	2300	2700	1660	3300	1960
Poisson's ratio ν_1	0.4	0.4	0.41	0.4	0.41	0.4

The markers show the experimental indicators of wear resistance Φ_i of polyamides at each level of $\tau_1 = fp_i$. They at the same contact pressures are located on the axis τ differently. As a result of their approximation according to function (2) the wear resistance characteristics B, m, τ_0 are determined (Table 1) and their wear resistance diagrams are plotted. These graphical indicators allow comparing the wear resistance of the studied materials at different levels of specific friction forces. The lowest wear resistance will be in unfilled polyamide PA6, and the highest - in PA6+Oil. The dependence of wear resistance on the specific friction force is nonlinear, and the qualitative nature of its change in wear resistance for different polyamides is almost the same.

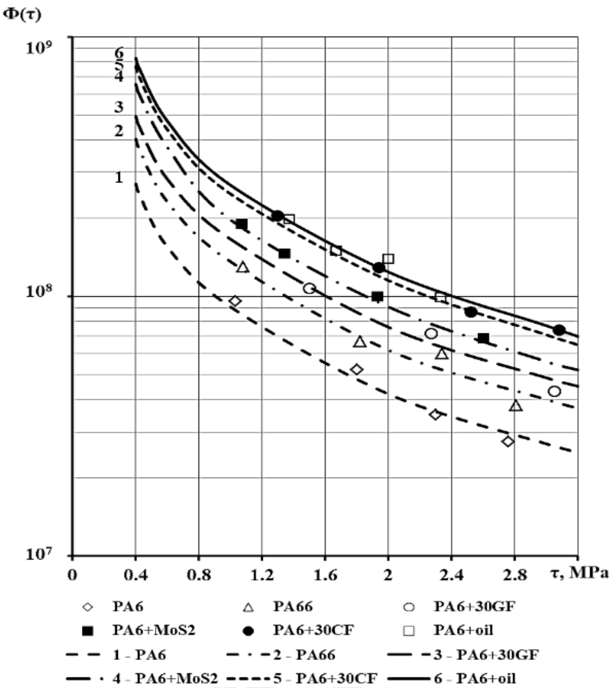

Fig. 2. Wear resistance diagrams of polyamides for MP bearings.

Accordingly, Fig. 3 shows the relative wear resistance $\tilde{\Phi}$ of the studied polyamides relative to the base unfilled polyamide PA6 at $\tau = 2$ MPa.

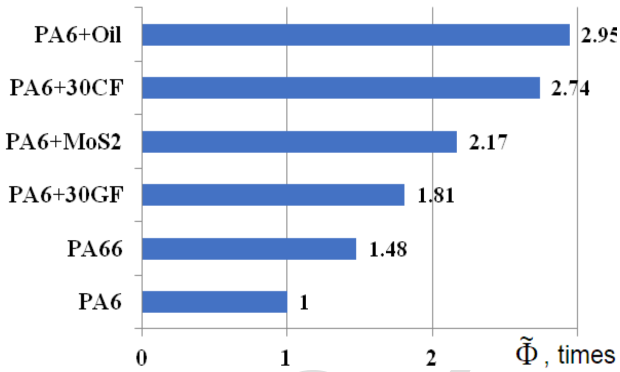

Fig. 3. Relative wear resistance of polyamides in relation to PA6.

The relative wear resistance $\tilde{\Phi}$ of polyamides PA6 and PA66 and PA6 based composites is different depending on the type of filler. That is, the fillers provide a significant increase in wear resistance of the studied polyamide composites.

2.2. MP gears: pinion 1 is made of normalized carbon steel 0.45%C, roughness R_a = 0.8-1 μm, Young's module E_2 = 210 GPa, Poisson's ratio ν_2 = 0.3; gear 2 is made of polyamides (table 2).

Fig. 4 presents wear resistance diagrams of the supplied polyamides at 5 levels of contact pressures pi = 2, 4, 6, 8, 12 MPa and a larger range of specific friction forces (up to 6 MPa).

Accordingly, Fig. 5 shows the relative wear resistance $\tilde{\Phi}$ investigated polyamides relative to the base unfilled polyamide PA6 at $\tau = 4$ MPa.

Table 2. Materials polymer gear.

Characteristics of polymers	Polyamides					
	PA6	PA66	PA6+30GF	PA6+MoS$_2$	PA6+30CF	PA6+Oil
$C_1 \cdot 10^6$	1.34	1.98	1.88	3.08	3.67	4.20
m_1	1.15	1.15	1.15	1.15	1.15	1.15
τ_{S1}, MPa	40	40	50	38	40	38

The quantitative effect of the fillers on the wear resistance of polyamide PA6 based composites is close, as found above when $\tau = 2$ MPa (Fig. 3).

The dependence of the friction coefficient f on the contact pressure p_i in experimental tribocouples is also established (Fig. 6).

With increasing contact pressure in experimental tribocouples, a decrease in the coefficient of dry friction is observed. In the region of lower pressures, it is significant, but as they increase its magnitude decreases by 2.05…2.7 times, depending on the type of tribocouple.

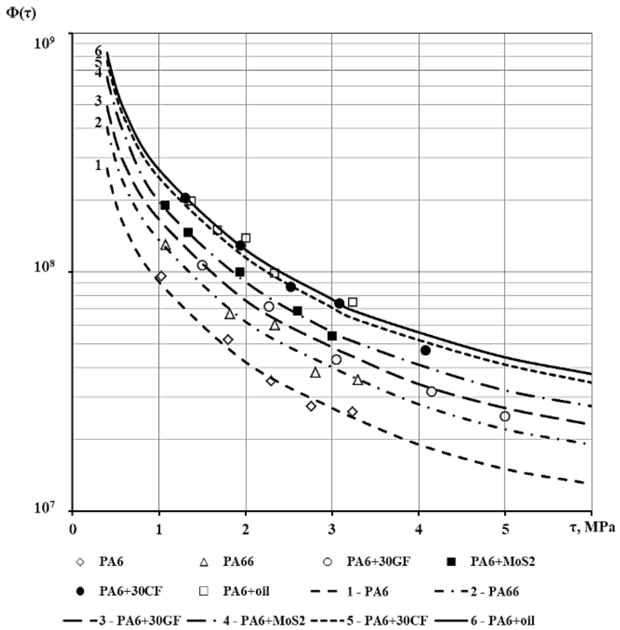

Fig. 4. Wear resistance diagrams of polyamides for MP gears.

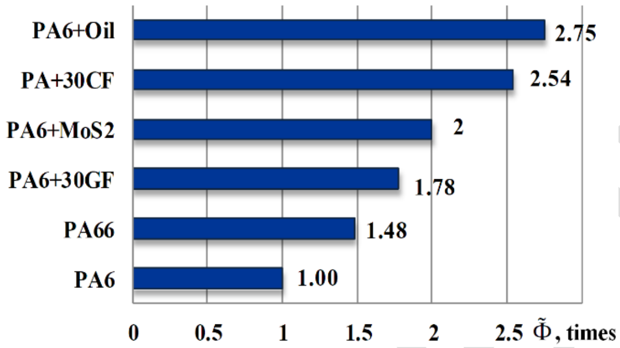

Fig. 5. Relative wear resistance of polyamides in relation to PA6.

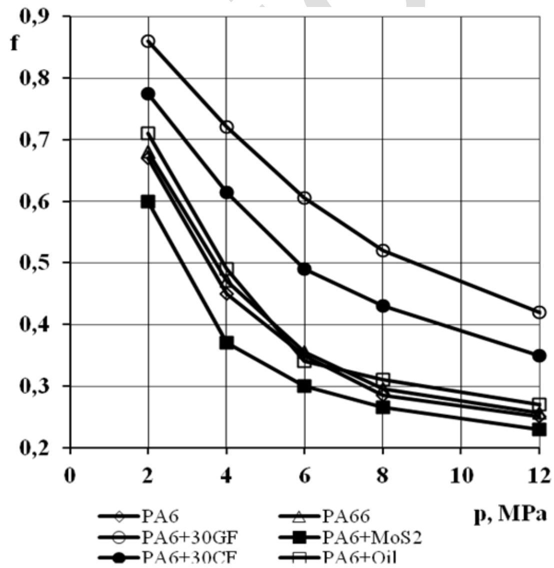

Fig. 6. Experimental dependence of the average sliding friction coefficient on the pressure in polyamide – steel tribocouples.

The highest coefficient of friction was in the pair PA6+30GF - steel, slightly lower - in the pair PA6+30CF - steel, and the lowest - in the pair PA6+MoS_2 - steel. The coefficient of friction in the pairs PA6+30GF - steel and PA6+MoS_2 - steel differs approximately twice. Filling polyamide PA6 with glass or carbon fibers leads to a significant increase in the coefficient of friction. Instead, the addition of MoS_2 in PA6 reduces it. In the case of cast composite PA6+Oil, the coefficient of friction is close as in PA6, PA66 - steel.

4. CONCLUSION

The wear resistance of polyamides (PA6, PA66 and composites PA6+30GF, PA6+30CF, PA6+MoS_2, PA6+Oil) on carbon steel 0.45%C at dry sliding friction according to the author's technique of triboexperiments is investigated and on their basis the corresponding experimental wear indicators are calculated. Using them, it is calculated by approximating the wear resistance characteristics as the basic parameters of the author's mathematical model of materials wear kinetics at sliding friction and analytical method of research of MP plain bearings and MP gears. As a result of research, it was found that:

1. Different filler types (GF, CF, MoS_2, Oil) for polyamide PA6 significantly affect the wear resistance of its composites, increasing it when $\tau = 2$ MPa up to 2.95 times (MP bearings) and when $\tau = 4$ MPa up to 2.75 times (MP gears). Unfilled polyamide PA6 has the lowest wear resistance, and its composite PA6+Oil has the highest.
2. The coefficient of dry sliding friction nonlinearly depends on the contact pressure in the experimental tribocouples. Accordingly, the qualitative and quantitative regularities of these dependences for each of the studied polymers are presented. The lowest coefficient of friction is in the pair PA6+MoS_2 - steel, and the highest - in the pair PA6+30GF – steel.

Also, the wear resistance of these studied polyamides is presented in the form of graphical indicators - wear resistance diagrams, as its dependence on different levels of specific friction forces in the tribocontact, which reflect the qualitative and quantitative interde-pendences of these characteristics. The given wear resistance diagrams provide comparison of wear resistances of the investigated materials in a considerable range of specific friction forces.

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