Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2023, 17(2), 258–267
https://doi.org/10.12913/22998624/161591
ISSN 2299–8624, License CC-BY 4.0

Received: 2022.12.22
Accepted: 2023.03.15
Published: 2023.04.01

Evaluation of Wear Resistance of Functional Composite Polymeric Materials and Durability of Metal-Polymer Bearings

Myron Chernets[1], Antoni Świc[2*], Anatoliy Kornienko[1] AlinaYurchuk[1]

[1] Aerospace Faculty, National Aviation University, Ukraine Liubomyra Huzara Ave, 1, Kyiv, 03058 Ukraine
[2] Mechanical Faculty, Lublin Technical University, ul. Nadbystrzycka 38D, 20–618 Lublin, Poland
* Corresponding author's e-mail: a.swic@pollub.pl

ABSTRACT

A method of tribological testing of models with such sliding friction using a simple pin-on-disc mechanism was presented. Wear resistance indicators of unfilled polyamides PA6, PA66 and composites based on polyamide PA6+30GF, PA6+30CF, PA6+MoS_2, PA6 and oil coupled with steel C45 are determined. They, as polymeric materials with the property of self-lubrication, they are often used in metal-polymer dry friction bearings. Based on them, wear resistance characteristics of these polymeric materials at sliding friction are established. They are used as basic parameters for developed by authors mathematical model of material wear kinetics at sliding friction and analytical research method of metal-polymer sliding bearings research. For comparative assessment of wear resistance of the investigated polymeric materials, their wear resistance diagrams are constructed. Thef show the functional dependence of wear resistance on specific friction forces. It is proved that the wear resistance of materials nonlinearly depends on specific pressure, i.e., the specific friction forces. Qualitative and quantitative influence of the type and structure of fillers (which improve the tribological properties of the base polymer PA6) on their wear resistance has been established. The forecast estimation of durability of metal polymer bearings made of the specified polyamides by the author's method of calculation taking into account their various wear resistance, characteristics of elasticity and conditions of dry friction is carried out. The research results are presented graphically, which facilitates their understanding and analyses.

Keywords: polyamides, wear resistance, composites, dry sliding friction, metal-polymer plain bearings, durability.

INTRODUCTION

To manufacture metal-polymer (MP) bearing bushings working with dry friction various polyamides are used, namely PA6, PA66, and their composites filled with fiberglass (GF), carbon fiber (CF), molybdenum disulfide (MoS_2), lubricant (oil), and other components. This significantly improves the properties of the base polymers by making them stronger, increasing wear resistance, and reducing the coefficient of sliding friction.

In friction systems testing mode of experimental metal-polymer hybrid pairs, PoD is widely used. The conditions of research using this scheme are described in the standard ISO 7148–2 [1]. This friction scheme is the most appropriate as it provides constant friction conditions (contact pressure, sliding speed, temperature) and wear throughout the experiment. The results of such tests objectively reflect the consumption patterns of materials and enable their comparative assessment. Quantitative results of experimental studies on the tribological properties of polyamides used for MP plain bearings, using the pin-on-disc system in dry friction, are available in the literature. [2–11].

The work [2] presents the results of friction and wear tests of 18 different unfilled and filled polymers and their composites on AISI steel under dry friction conditions. This includes PA6, PA6+PTFE, PA6+GF. The wear of polyamide PA6 – AISI O2 steel was tested in [3]. The tribological behavior of PA6 over stainless steel was studied in particular in [4]. In the work [5], the coefficients of friction and wear of several PA6 composites after 40CrMnNiMo8 stainless steel were determined. The article presents the results of research on 21 types of polymers and their composites intended for tribotechnical applications [6]. The tribological behavior of polyamide PA6 on steel under various test conditions, including dry friction, was investigated [7–10]. In the work [11], the results of the tests using the ball-on-disk layout are presented: PA6+oil, PA6+MoS2, polyacetal (POM)+Al, polyethylene terephthalate (PET)+PTFE, polyetherketone PTFE+bronze, PTFE+graphite.

The literature also contains studies on the tribological behaviour of various metal-polymer bearings under dry friction, mainly with regard to their wear [12–15]. It should be noted that in experimental studies of metal-polymer bearings based on PA6 polyamides, in addition to the wear of the polymer sleeve and the sliding friction coefficient, the temperature in the bearing and its influence on certain tribotechnical characteristics are also evaluated. In [12], the tribological behaviour of various bearings with polymer sleeves was investigated, showing that friction and wear depend on speed, load, temperature and operating time. The tribological properties of bearings with different types of polymers were investigated in [13]. In [14], the effects of sliding speed, pressure and temperature on friction and wear of metal-polymer bearings made of PA66, PA66+18%PTFE and PA66+20%GF+25%PTFE composites were determined. The pendulum bearing for wear was tested in [15].

These results of wear studies of these polymeric materials are carried out, as a rule, at a single load, as required by ISO 7148–2. Therefore, it is impossible to establish the characteristics of their wear resistance, suitable for use in the calculation methods of MP plain bearings, where the range of workloads is different than in ISO 7148–2 for wear testing of materials. For this purpose, we would like to conduct model triboexperimental studies in a wide range of load and to use these results to establish wear resistance characteristics to be used in the mathematical model of sliding tribosystems wear kinetics [20, 21]. Such a need arises for our calculation methods of plain bearings made of metallic materials [20, 21] and metal-polymer bearings [22, 23].

The use of metal-polymer bearings began more than 90 years ago. Their active use in modern conditions is associated with a number of positive properties, which, first of all, include the possibility of their use in dry friction. In addition, they are needed in special technological and extreme operating conditions, where contamination by wear particles is not allowed. Also during their operation, the noise level is minimal and the damping capacity is high and they are able to operate in a wide range of temperatures, both low and high. However, for such a long period of their use in mechanical engineering, instrument making, automotive, aerospace, rocket and space technology; in food, pharmaceutical, textile, cellulose, chemical and other industries; in household, computer, office, medical, measuring equipment, effective methods of their calculation are not developed. In a few studies of MP bearings [24, 25] Acrhard's law of abrasion/adhesive wear is used, which is not dominant even in dry sliding friction, but concomitant. Instead, the above-mentioned author's methods of bearing wear research rely on the fatigue mechanism as the dominant one.

The article presents the results of wear resistance studies using model triboexperiments [20, 22] to determine the indicators and characteristics of wear resistance of unfilled (PA6, PA66) and reinforced (PA6+30GF, PA6+30CF, PA6+MoS_2, PA6+oil) polyamides. Accordingly, with their use, the calculation was performed according to the author's method of durability of MP bearings with a bushing made of these polymeric materials.

Materials and the investigation procedure

To study the wear resistance of these polymeric materials used double pin-on-disk friction layout (two polyamide rods on a steel disk), which provides constant conditions of friction during the experiment. The design of used tribotester is presented in Figure 1. In this test setup, the 4–5 cylindrical pins 4 have flat surfaces, resulting in contact pressures remaining constant throughout the experiment regardless of wear.

Test conditions:

Contact pressure: p_i = 2, 4, 6, 8 MPa; slip speed: v = 0.4 m/s; test duration: t = 5–10 h; pin diameter: d = 3 mm; ambient: dry air with temperature T = 293 K; surface roughness: steel disc – R_z = 0.8–0.9 µm, face of the flat pin – R_z = 0.7–0.9 µm. The wear was estimated based on the linear wear h_i of pins.

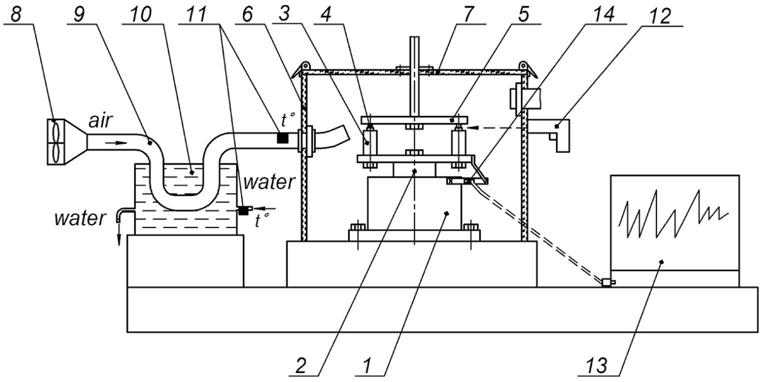

Fig. 1. The design of pin-on-disk tribotester: 1 – bearing casing; 2 – movable axis with sample holders; 3 – specimen holder; 4 – samples – cylindrical pins; 5 – steel disc – counterpart; 6 – isolated chamber; 7 – removable cover; 8 – air pump; 9 – air manifold; 10 – heat exchanger; 11 – thermocouple; 12 – contactless pyrometer; 13 – computer, 14 – friction moment sensor

For this type of polymeric materials the ISO 7148–2 standard gives the following test conditions: contact pressure p = 3 MPa, speed v = 0.4 m/s, temperature of the polymer pin sample near the joint with the metal counterdisk T = 293K ± 10K at relative humidity 50 ± 5% in an isolated chamber. The standard value of contact pressure is within the range of pressures selected for the model experiment.

The specified standard air temperature in chamber is controlled by the water temperature in the heat exchanger using temperature sensors 11. When the temperature of the samples and the counterbody is exceeded, it is lowered to the required values by accelerating the air flow inside the chamber 6.

Figure 2a shows a fragment of disc 5, showing the trace of contact with polyamide patterns. Accordingly, Figure 2b shows the surface of the PA66 standard before the experiment, and Fig. 2c – after the experiment. After wear, no noticeable change in the roughness of the rubbing surfaces of the system elements was observed.

No noticeable changes in the surface condition of polyamide samples, including roughness, were observed during the tests (Fig. 2b, c). Other types of polyamides in metal-polymer pairs behaved similarly. Since the wear resistance of C45 steel was up to 3000 times higher than that of polyamides, the initial roughness of the countersample did not change. The Young's modulus of polyamides was 64–125 times smaller than that of steel. During wear, the roughness of the polyamide samples was similar to the roughness of the steel surface.

During the wear process, delicate adhesive polymer films could have formed on the steel, which were destroyed after some time (Fig. 2a – visible remaining fragments of the PA66 polymer). Only in the case of the PA6+30GF tribopair (glass fibres) the smoothing of the steel surface of the disc could occur with increasing pressure and the adhesive film disappeared. Such a course of polymer wear shows clear signs of the friction-fatigue mechanism as the leading (dominant) one.

The wear of polymers in sliding friction is usually a combination of three types of wear (adhesive, fatigue and abrasive) [16, 17]. Which of them will be the main one depends on the properties of the polymer, friction conditions and the course of wear. Under certain conditions, in particular with dry friction, the polymeric material will be transferred to the metal antibody, forming a permanent adhesive layer, this is an indication of adhesive wear as the main process [17, 28]. If the transfer layer does not set on the steel surface and is removed as small wear particles, then frictional-fatigue wear takes place as the main process. With sliding friction coefficients greater than 0.3 (Table 1), which is typical for metal-polymer dry friction pairs, surface wear of polymers follows the mechanism of surface fatigue under the influence of friction forces [17–19]. Adhesive or abrasive wear can also occur as a minor accompanying process.

The classification and description of various types of wear of materials by sliding friction are presented in [21]. Depending on the load conditions, sliding speed, external temperature, environment, tribopair materials and other factors, the following main types and mechanisms of wear are distinguished:

1. Adhesive wear, in which the surface layers of the materials of the friction pair are damaged

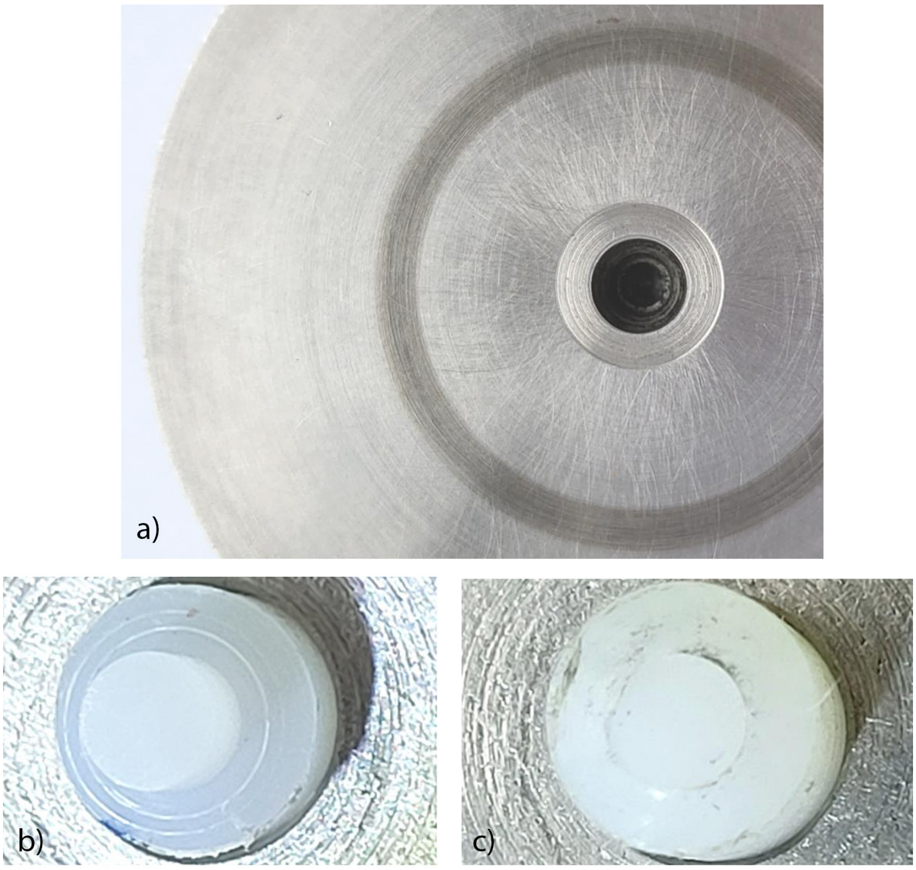

Fig. 2. The appearance of the friction surfaces of the elements of the tribological test system: (a) C45 steel disc (2:1 scale); (b, (c) PA66 sample (8:1 scale)

due to the destruction of the adhesive bonds. The wear mechanism is multi-cycle friction fatigue.

2. Fatigue wear, in which surface layers of materials of tribosystem elements are destroyed under the influence of variable friction forces (sliding friction) or cyclical contact stresses (rolling friction). The wear mechanism is multi-cycle friction fatigue.
3. Abrasive wear, in which there is local destruction of the material by micro-abrasive particles with a number of load cycles ranging from one to several hundred. The mechanism of dry abrasive wear is low-cycle frictional fatigue caused by micro-cutting and plastic deformation (furrowing) of the material.

Abrasive wear can take place dry, in the presence of lubricants and as a result of the action of a liquid or gas stream containing abrasive particles (hydro- and gas-abrasive wear). In the case of hydro- and gas-abrasive wear, the dominant mechanism of material destruction is frictional fatigue (medium and multi-cycle). It arises mainly as a result of elastic deformation of the material by abrasive particles and partly by scratching the surface, i.e. as a result of low-intensity micro-cutting.

4. Oxidative wear, in which, after a certain number of impacts, the oxide films formed on the rubbing surface are destroyed. The wear mechanism is frictional fatigue of varying intensity.
5. Corrosive and mechanical wear that occurs in the presence of an aggressive environment in the tribotechnical system.
6. Erosion wear, which consists in the local destruction of the surface layer of the material as a result of the mechanical and corrosive action of a stream of solid particles or liquids with considerable kinetic energy.
7. Cavitation wear, in which local destruction of the material occurs under the influence of liquid with gas bubbles formed. They disintegrate with increasing pressure, which causes very strong impacts of liquid particles upon impact with the surface.

The analysis of the literature on the kinetics of various types of wear confirms the cumulative nature of this type of surface destruction of materials. Therefore, it is quite reasonable to treat different types of wear as surface fatigue processes with different rates of destruction of local volumes of the surface layer material. Friction-induced wear of materials can be defined as frictional fatigue processes with a different number of failure stress cycles (tangential or normal), as indicated above.

According to the measured values of samples' linear wear, the relative characteristics of their wear resistance – wear resistance indicators – are calculated as follows:

$$\Phi_i = L_i / h_i \tag{1}$$

where: $L = v\,t$ – sliding distance,
v – sliding speed,
t – time of triboexperimental research.

The next step is to determine experimental indicators of wear resistance and their wear resistance characteristics, which are the basic input values of mathematical model used to study the kinetics of materials wear at sliding friction [20, 21, 27]. In this phenomenological model we assumed that wear intensity is a function of specific friction occurring in the tribocontact. To determine it, we used the Amonton-Coulomb formula:

$$\tau_i = f_i p_i \tag{2}$$

where: $\tau = \tau_i$ – values of specific friction forces arising at nominal contact pressure p_i,
f_i – the experimental value of coefficient of sliding friction.

To use the results of model triboexperimental studies in the author's calculation method [20, 21] of MP sliding bearings and gears, the basic wear resistance characteristics of materials of the mathematical model of material wear during friction [20, 21, 23, 30]. That is, by approximating the corresponding function of experimental wear resistance indicators using the method of least squares, the characteristics of materials' wear resistance are determined. The approximation function is as follows [11, 12]:

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

where: $\Phi k(\tau)$ – the characteristic wear resistance function – the basic integral parameter of the mathematical wear model;
B_k, m_k, τ_k – the characteristics of materials' wear resistance (Table 1);
$k = 1, 2$ – numbering of tribocouple elements.

The established characteristics of materials' wear resistance (Table 1) were further used in the calculation method of MP sliding bearings [22, 23, 29] to assess their durability.

CALCULATION OF DURABILITY OF RADIAL METAL POLYMER SLIDING BEARINGS

Evaluation of MP bearings made of these polyamides, the method of contact mechanics was used to calculate rotary or linear cylindrical bearings, given in [21, 23]. Accordingly, the durability t_* is determined according to the following relationship:

$$t_* = \frac{-B_2 \tau_{20}^{m_2}}{v c_h \tau_h \Sigma_2 \left(1 - m_2\right) K_t^{(2)}} \left\{ \left[\tau - \tau_{20}\right]^{1-m_2} - \right. \\ \left. - \left[\left(\tau - \tau_{20}\right) + c_h h_{2*} \Sigma_2 \tau_h\right]^{1-m_2} \right\} \tag{4}$$

where: $v = \omega R_2$ – sliding speed;
R_2 – shaft radius;
c_h – wear rate factor;
τ_h – specific friction force on the tribocontact during wear;
$\Sigma_2 = \left(K_t^{(2)} - h_2'\right)$; $K_t^{(2)} = \alpha_0 / \pi$ – coefficients of mutual overlap of the bushing;
$h_2' = \left[B_2 \tau_{20}^{m_2} \left(\tau - \tau_{10}\right)^{m_1}\right] / \left[B_1 \tau_{10}^{m_1} \left(\tau - \tau_{20}\right)^{m_2}\right]$ – relative wear in the tribosystem;
h_{2*} – acceptable bushing wear.

Table 1. Wear resistance characteristics of polymeric materials

Name	Polyamides					
	PA6	PA66	PA6 + 30GF	PA6 + MoS_2	PA6 + 30CF	PA6 + oil
$B_1 \cdot 10^8$	226	337	412	558	653	703
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
f	0.41	0.4	0.62	0.34	0.48	0.435

RESULTS AND DISCUSSION

The results of triboexperimental tests of polyamides in dry friction are shown in Figures 2–4. Calculations of the bearing durability according to relation (4) were performed with the following data: $N = 5000$ N; $D_2 = 50$ mm; $l = D_2$; $\varepsilon = 0.2$ mm; $\omega = 6.28$ rad/s; $h_{1*} = 0.5$ mm. Data on the materials of MP plain bearings: shaft – normalized steel 45, $R_a = 0.8 – 0{,}9$ µm – surface roughness, $E_2 = 210000$ MPa, $\nu_2 = 0.3$; $B_2 = 10^{13}$, $m_2 = 2$, $\tau_{20} = 0.1$ MPa; bushing – polyamides (Table 2).

Figure 2 presents diagrams of wear resistance of the above-mentioned polyamides. The markers show the experimental indicators of wear resistance function Φ_i of polyamides at each value of $\tau_i = fp_i$.

In Figure 3a, 3b, 3c experimental indicators of wear resistance of the respective polymeric materials, calculated according to the data of [26]. As a result of approximation of experimental values Φ_i using equation (2), wear resistance characteristics B, m, τ_0 of polymeric materials (listed in Tab. 1) are calculated and their wear resistance diagrams are constructed (graphs $\Phi : \tau$).

Figure 4 shows combined wear resistance diagram of studied polyamides and polyamide-based composites.

It is clearly seen that the experimental indicators of wear resistance of different polymers at the same contact pressures are differently located along the τ axis. These wear resistance diagrams of materials, as their graphic indicators, allow to compare wear resistance of several investigated polyamides at different values of specific friction forces. The lowest wear resistance is for unfilled polyamide PA6, and the highest – for PA6+oil. The dependence of wear resistance on the specific friction force τ is nonlinear. This behavior for different polyamides is almost identical.

For example, the results of the comparative assessment of the abrasion resistance of composites based on PA66, PA6 with different fillers (PA6+30GF, PA6+30CF, PA6+MoS_2, PA6+oil) with respect to the least wear-resistant material (unfilled polyamide PA6) at 2 MPa (certain value of the specific friction force) are given in Figure 5.

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. Oil, carbon fiber (CF) and MoS_2 are known to have varying degrees of lubricating properties. On the other hand, fiberglass (GF) has abrasive properties.

In the literature to characterize the wear resistance of materials is widely used the Acrhard's coefficient (indicator) of wear k_A, which is expressed as follows:

$$k_A = \frac{V}{NL} \text{(mm}^3\text{/N·м)} \tag{5}$$

where: V – the volumetric wear of the sample.

Given the obvious dependence that, $V = hS$ where s is the contact area of the finger sample with the disk counter-sample, and the pressure $p = N / S$, the formula (5) taking into account (1) will take the form

$$k_A = \frac{hS}{NL} = \frac{I_h}{p} = \frac{1}{p\Phi}\left(\frac{\text{mm}^3}{\text{Nm}}\right) \tag{6}$$

At a pressure of 2, 4 and 6 MPa, the Acrhard's wear rate k_A was determined, which are given in Table 3. As the contact pressure increases, the k_A decreases.

The results of the durability calculation of MP bearings with different polymeric materials are shown in Figure 6. There is no increase in the durability of bearings (Fig. 6) in the order of increasing their wear resistance (Fig. 5), although the linear characteristic B of wear resistance is increasing (Table 1). This order is not observed either in the coefficients of sliding friction or

Table 2. Mechanical properties of studied polymeric materials and composites

Property of polymeric material	Polyamides					
	PA6 (Sustamid 6 Rochling)	PA66 (Sustamid 66 Rochling)	PA6+30GF (Sustamid 6 GF30 Rochling)	PA6+MoS_2 (Sustamid 6 MO Rochling)	PA6+30CF (Sustamid 6 ESD 60 Rochling)	PA6+oil (Sustamid 6 OL Rochling)
Young's modulus 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
Compression strength R_m, MPa	80	80	100	78	80	78

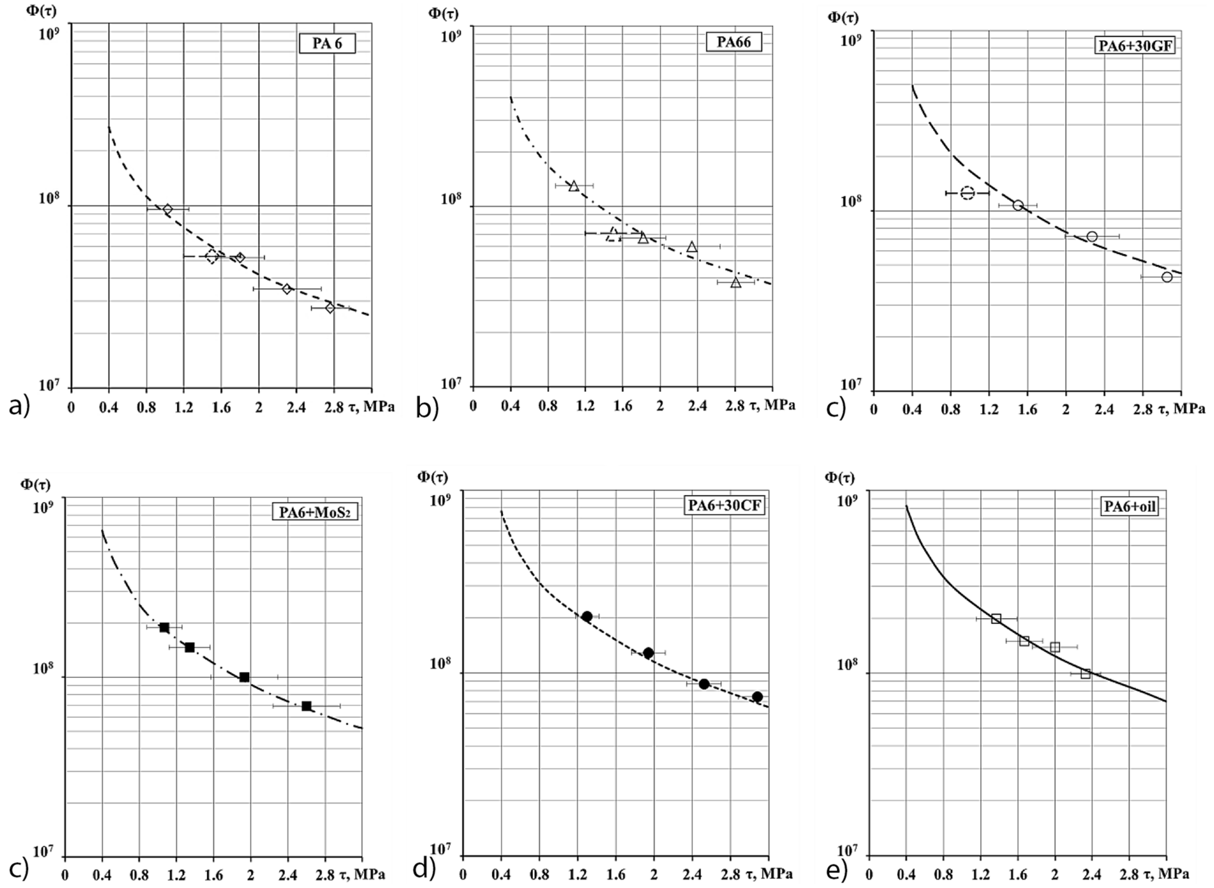

Fig. 3. Wear resistance diagrams of polyamides

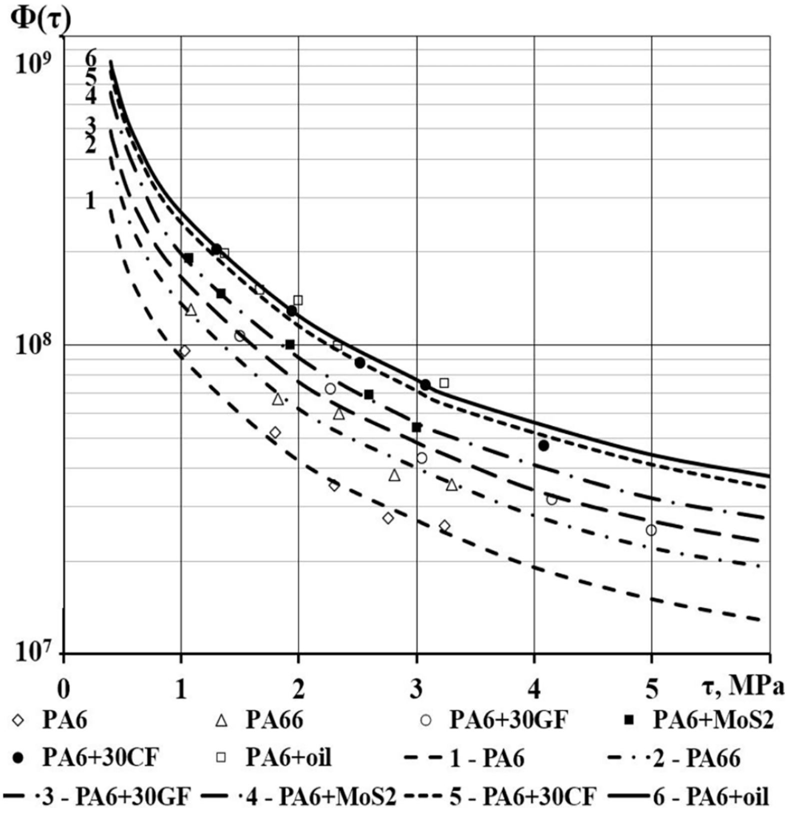

Fig. 4. Combined wear resistance diagrams of studied materials

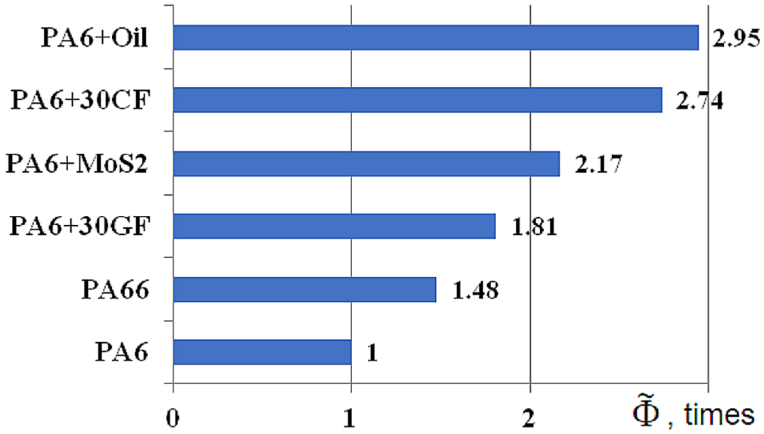

Fig. 5. Relative wear resistance $\tilde{\Phi}$ of polyamides relative to wear resistance of as fabricated (unfilled) PA6 at $\tau = 2$ MPa

Table 3. Acrhard's wear rate

Property of polymeric material	Polyamides					
	PA6	PA66	PA6+30GF	PA6+MoS_2	PA6+30CF	PA6+oil
Wear resistance indicator $\Phi \cdot 10^8$	0.52	0.67	0.72	1.47	1.29	1.50
	0.96	1.30	1.07	1.90	2.04	1.98
	0.35	0.60	0.43	1.00	0.87	1.39
Wear rate $k_A \cdot 10^{-9}$, $mm^3/N \cdot m$	5.22	3.85	4.67	2.63	2.45	2.53
	4.80	3.20	3.90	1.70	1.94	1.67
	4.76	2.78	3.47	1.67	1.92	1.12

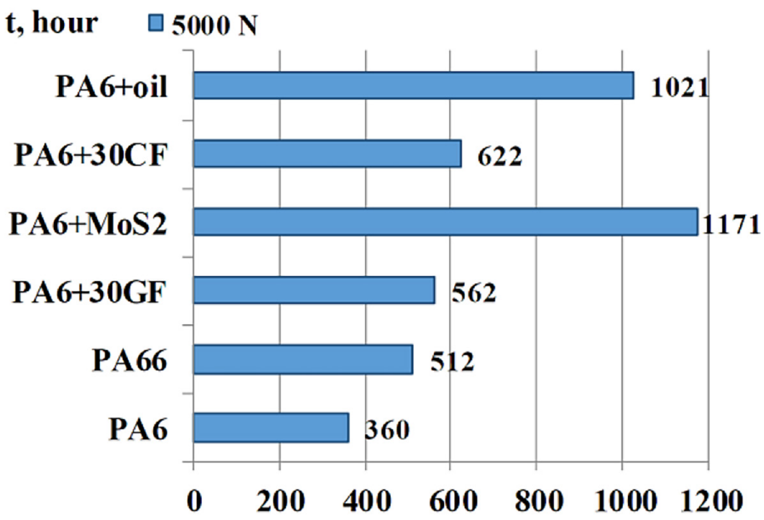

Fig. 6. Durability of MP bearings

in the value of the Young's moduli (Table 1). Therefore, the MP bearing with a polymer bushing made of a more durable material (PA6+oil) will not have the highest durability. Instead, it has a bearing with PA6+MoS_2 composite. Therefore, the durability of the bearing depends on the complex effect of these three characteristics. Figure 7 shows the relative durability of bearings from the studied materials.

CONCLUSIONS

According to the results of wear tests of polyamides (PA6, PA66 and composites PA6+30GF, PA6+30CF, PA6+MoS_2, PA6+oil coupled with steel 45, dry sliding friction) using developed by authors triboexperimental method we may say:

1. Using experimental model wear resistance indicators and their functional approximation the

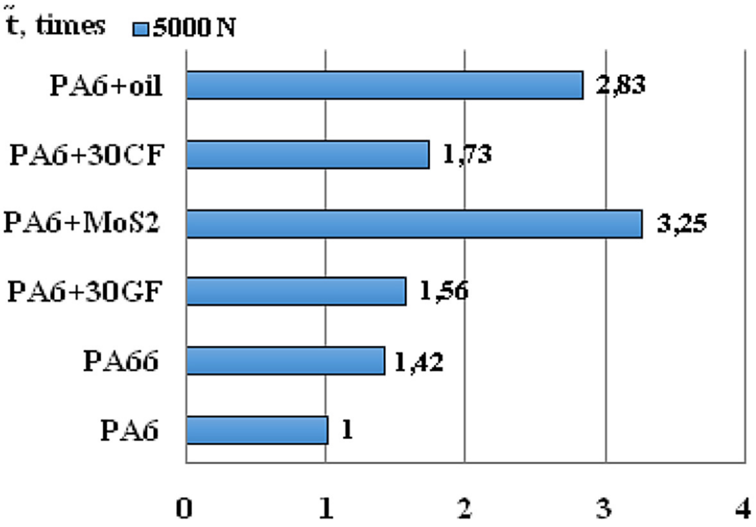

Fig. 7. Relative durability of MP bearings

wear resistance characteristics of these polymeric materials are determined.

2. The used fillers significantly affect the wear resistance of PA6-based composites, increasing it almost three times at 2 MPa. The lowest wear resistance is for polyamide PA6, and the highest – for PA6+oil composite.
3. Wear resistance of the studied polyamides is presented in the form of diagrams of wear resistance as their graphic indicators as its dependence on different values of specific friction forces. They reflect the qualitative and quantitative interdependencies of wear resistance of materials on the specific friction forces arising in tribocontact. The constructed wear resistance diagrams allow to compare wear resistances of the investigated materials in broad range of specific friction forces.
4. The estimated durability of MP bearings with bushings made of composites depends on the type of fillers and can increase 3.25 times in the case of using PA6+MoS_2 compared to the base polyamide PA6. It is comprehensively affected by the wear resistance of the polymer, its Young's modulus and coefficient of friction.

REFERENCES

1. International Standard ISO 7148–2. Plain bearings – testing of the tribological behaviour of bearings matrials. Part 2. Testing of polymer – based bearing materials. 10.01.2012.
2. Mens, J.W.M., de Gee, A.W.J.: Friction and wear behaviour of 18 polymers in contact with steel in environments of air and water, Wear 1991; 149: 255–268. https://doi.org/10.1016/0043–1648(91)90378–8
3. Palabiyik, M. and Bahadur, S.: Tribological studies of polyamide 6 and high-density polyethylene blends filled with PTFE and copper oxide and reinforced with short glass fibers, Wear 2002; 253: 369–376. https://doi.org/10.1016/S0043–1648(02)00144–8
4. Seabra, C.L., Babtista, M.A. Tribological behaviour of food grade polymers against stainless steel in dry sliding and with sugar, Wear 2002; 253: 394–402. https://doi.org/10.1016/S0043–1648(02)00138–2
5. Zsidai, L., De Baets, P., Samyn, P., Kalacska, G., Van Peteghem, A.P., Van Parrys, F.: The tribological behaviour of engineering plastics during siliding friction investigated with small scale specimens, Wear 2002; 53: 673–688. https://doi.org/10.1016/S0043–1648(02)00149–7
6. Kalácska, G. An engineering approach to dry friction behaviour of numerous engineering plastics with respect to the mechanical properties, eXPRESS Polymer Letters 2013; 7(2): 199–210.
7. http://dx.doi.org/10.3144/expresspolymlett.2013.18
8. De Almeida Rosa, A.G., Moreto, J.A., Manfrinato, M.D., Rossino, L.S. Study on friction and wear behavior of SAE 1045 steel, reinforced nylon 6.6 and NBR rubber used in clutch disks, Mat. Res., 2014; 17(6): 1397–1403. https://doi.org/10.1590/1516–1439.282714
9. Mithun, V., Kulkarni, K., Elagovan, K., Hemachandra, R. and Basappa, S.J.: Tribological bechaviours of ABS and PA6 polymer metal sliding combinations under dry friction, waterabsorbed and elektroplated conditions, Journal of Engineering Science and Technology, 2016; 11(1): 68–84.
10. Kulkarni, M.V., Elangovan, K., Reddy Hemachandra, K. and Basappa, S.J.: Tribological behaviours

of ABs and PA6 polymer metal sliding combinations under dry friction, water absorbed and electroplated conditions, Journal of Engineering Science and Technology, 2016; 11(1): 68–84.

11. https://doi.org/10.1016/j.wear.2017.01.118
12. Pogaˇcnik, A., Kupec, A., Kalin, M. Tribological properties of polyamide (PA6) in self-mated contacts and against steel as a stationary and moving body. Wear 2017; 378–379: 17–26.
13. Jozwik, J., Dziedzic, K., Barszcz, M. and Pashechko, M.: Analysis and Comparative Assessment of Basic Tribological Properties of Selected Polymer Composites, Materials 2020; 13(1): 75.
14. https://doi.org/10.3390/ma13010075
15. Feyzullahoglu, E., Saffak, Z. The tribological behavior of different engineering plastics under dry friction conditions. Materials and Design 2008; 29: 205–211.
16. https://doi.org/0.1016/J.MATDES.2006.11.012
17. Ünlü, B.S., Atik, E., Köksal, S. Tribological properties of polymer-based journal bearings, Materials and Design 2009; 30(7): 2618–2622.
18. https://doi.org/10.1016/j.matdes.2008.11.018
19. Demirci, M.T., Düzcükoglu H. Wear bechawiors of PTFE reinforced PA66, Journal bearings, International Scientific Conference, 19–20 November, GABROVO 2010; 249–253.
20. Mastan, V., Raja Kiran Kumar, V., Kiran Kumar, Ch. Study of Friction and Wear on Journal Bearings, International Refereed Journal of Engineering and Science 2012; 1(4): 63–70.
21. Myshkin, N.K., Kim, C.K., Petrokovets, M.I. Introduction to tribology. Seoul: Cheong Moon Gak Publishers, 1997.
22. Myshkin, N.K., Petrokovets M.I., Kovalev A.V. Tribology of polymers: Adhesion, friction, wear, and mass-transfer, Tribology International 2005; 38: 910–921.
23. https://doi.org/10.1016/j.triboint.2005.07.016
24. Myshkin, N., Kovalev, A., Spaltman, D., et al. Contact mechanics and tribology of polymer composites, J Appl Polym Sci. 2014; 131: 39870. https://doi.org/10.1002/app.39870
25. Myshkin, N., Kovalev, A. Adhesion and surface forces in polymer tribology–A review, Friction 2018; 6: 143–155. https://doi.org/10.1007/s40544–018–0203–0
26. Chernets, M.V., Andreikiv, O.E., Liebiedieva, N.M., Zhydyk, V.B. A model for evaluation of wear and durability of plain bearing with small non-circularity of its contours, Materials Science 2009; 2: 279–290,. http://dx.doi.org/10.1007/s11003–009–9176–5
27. Chernets, M.V. Tribocontact problems for cylindrical joints with technological roundness. Ed Lublin Polytechnic, Lublin 2013.
28. Chernets, M.V., Shil’ko, S.V., Pashechko, M.I., and Barshch, M.: Wear resistance of glass- and carbon-filled polyamide composites for metal-polymer gears, Journal of Friction and Wear 2018; 39(5): 361–364.
29. https://doi.org/10.3103/S1068366618050069
30. Chernets, M., Chernets, J., Kindrachuk, M., Kornienko A. Methodology of calculation of metal-polymer sliding bearings for contact strength, durability and wear, Tribology in Industry 2020; 42(4): 572–581. https://doi.org/10.24874/ti.900.06.20.10
31. Rezaei, A., Ost, W., Van Paepegem, W., De Baets, P., Degrieck J. Experimental study and numerical simulation of the large-scale testing of polymeric composite journal bearings: Three-dimensional and dynamic modelling, Wear 2011; 270: 431–438. http://dx.doi.org/10.1007/s11249–009–9518–3
32. Rezaei, A. et al. Adaptive finite element simulation of wear evolution in radial sliding bearing, Wear 2012; 296(1–2): 660–671,. http://dx.doi.org/10.1016/j. wear.2012.08.013
33. Wielieba, W. Bezobsługowe łożyska ślizgowe z polimerów termoplastycznych. Wyd. Politechniki Wrocławskiej, Wrocław, 2013.
34. Wojciechowski Ł., Wieczorowski M., Mathia T.G. Transition from the boundary lubrication to scuffing – The role of metallic surfaces morphology. Wear 2017; 392–393: 39–49. https://doi.org/10.1016/j.wear.2017.09.011
35. Pawlus P., Zelasko W, Reizer R., Wieczorowski M. Calculation of plasticity index of two-process surfaces. The Journal of Engineering Tribology 2017; 231(5). https://doi.org/10.1177/1350650116664826
36. Bloom P.D., Baikerikar K.G., Anderegg J. W., Sheares V.V. Fabrication and wear resistance Paul D of Al–Cu–Fe quasicrystal-epoxy composite materials. Materials Science and Engineering 2003; 360(1–2): 46–57. https://doi.org/10.1016/S0921–5093(03)00415–5
37. Zaghloul M.M.Y., Steel K., Veidt M. Wear behaviour of polymeric materials reinforced with manmade fibres: A comprehensive review about fibre volume fraction influence on wear performance. Journal of Reinforced Plastics and Composites 2022; 41: 5–6.
38. https://doi.org/10.1177/07316844211051733