ISSN 1648-7788 / eISSN 1822-4180

VILNIUS TECH Vilnius Gediminas Technical University

AVIATION

2023
Volume 27
Issue 4
Pages 272–278
https://doi.org/10.3846/aviation.2023.20650

EFFICIENCY OF POLYMER MATERIALS IN HIGHLY LOADED SYSTEMS IN THE AVIATION INDUSTRY

Anita PTAK ✉, Tadeusz LEŚNIEWSKI, Michał PURZYCKI, Krzysztof PŁONKA

Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Łukasiewicza 5, 50-371 Wrocław, Poland

Article History:
received 30 November 2023
accepted 19 December 2023

Abstract. The static coefficient of friction was calculated on an inclined plane tribological stand. Different specimens and masses loading the system were used during the experiment. Surface-to-surface contact was tested in a pin-on-plate setup. The tested polymer pairs were POM on POM, PA6 on PA6 and PET on PET. The variables in the experiment were different pressures acting on the friction pair, and dry and lubricated friction was tested. Static coefficients of friction for each case was calculated and the surface quality of the pin and plate was measured by profilometer and optical microscope. The coefficient of static friction was higher for lubrication friction than the dry friction. It was also observed that the coefficient of friction decreases with increased load. POM – POM pair had the lowest coefficient of friction under dry conditions, while for lubricated friction, PA6 – PA6 had the most stable increase of friction coefficient.

Keywords: static friction, tribology, polymers, dry friction, lubrication, polymer-polymer, sliding pair.

✉Corresponding author. E-mail: *anita.ptak@pwr.edu.pl*

Introduction

Mechanically processed construction materials have been used in the aerospace and aviation industries for several decades. Their undoubted advantage is low density (which can significantly reduce the aircraft's weight) and high relative mechanical strength. In the aviation industry, it is crucial to maintain the system's stability, making it as little susceptible to external sources as possible, especially those causing excitation of the structure (Krzyzak et al., 2020). Sound absorption and the ability to dampen vibrations of polymer materials are crucial here. Additionally, they are characterized by good sliding properties, which is why they are called self-lubricating. This allows you to reduce the number of necessary service cycles of the element and the risk of failure due to seizure. However, sometimes a lubricant is required in sliding joints, or for operational reasons, the materials used come into contact with the aircraft's operating fluids – hydraulic or aviation fuel. Hence, the material must meet chemical resistance requirements while maintaining mechanical and tribological properties.

It is assumed that friction is one of the most common phenomena occurring in nature. Recently, there has been an increase in interest and research in this area aimed at eliminating or at least limiting its formation. Friction as a phenomenon occurring during the relative motion of two bodies, from the engineer's point of view, may be positive or negative. On the one hand, friction is the component responsible for the problems of tribological wear of machine and equipment components, which ultimately translates into operational efficiency and reliability. On the other hand, the presence of friction allows engineers to use a friction drive – such as belt drive (Singh et al., 2017).

The most frequently used in the aviation industry are polyamide 6.6 and polyacetal (primarily as surfaces exposed to abrasion). Due to their excellent sliding properties, they create perfect friction pairs. In this context, the self-lubrication process can cause a significant decrease in the friction coefficient than metals (Pogačnik & Kalin, 2012). Topic of polymer-steel tribological pairs have been studied throughout on unfilled polymers as well as on composites based on polymer matrix. This topic was taken up by Pogačnik and Kalin (Pogačnik & Kalin, 2012) In their work the PA6 specimen was mated with POM and steel countersurface in the pin-on-disc arrangement. They showed that the coefficient of friction in the PA6-POM pair was lower than in the PA6-steel pair. Those coefficients of friction were respectively in the range of 0.41–0.54 and 0.46–0.68. Kinetic friction was researched also by Mens and de Gee (1991), in that work 18 different polymers were tested those were unfilled as well as reinforced with the glass fiber. Dependency of the friction coefficient and temperature was shown and the work in humid environment. Increased humidity correlated with decreased coefficient of friction. In the case of static friction Benabdallah tested composites based on polyoxymethylene matrix mated with AISI 1045 steel and 6061 aluminum (Benabdallah, 2007) In his research the centrifugal force based stand was used to carry out the research. Benabdallah showed that the coefficient of static friction was decreasing with increase of load and surface roughness. Ötzürk et al. (2018) examined the static coefficient of friction between POM and and steel in a spherical mating setup meant to emulate the contact in bearings. In this work the correlation of decreasing static friction coefficient with increased load was confirmed up to load equal to 450 N. Upon exceeding this value the coefficient stabilizes. However the polymer-polymer friction pair still leaves room for further research. Jia et al. (2007) researched kinematic friction of PA6-PA6, PTFE-PTFE and PPS-PPS friction pairs in dry and lubricated friction conditions. Pin-on-disc setup was tested. The results showed that in dry conditions there were significant differences in friction coefficient. PPS-PPS pair had coefficient equal to 0.8 while PTFE's pair coefficient was equal to 0.25. Adding the lubricant the lowered the friction coefficients of all pairs below 0.1. Chaudri et al. (2015) tested friction in reciprocated movement in which the pin made out of PBT slid against POM countersurface. This work also confirmed the correlation of friction coefficient and the load applied to the specimen. Tests showed that even after 2000 meters travel of the specimen the friction didn't stabilize. Temperature reading of POM countersurface was also recorded. It was shown that the temperature increased linearly with applied load. Martin et al.researched the friction between the polymers during thermoforming (Martin et al., 2012). They tested two testing apparatures setup. First one was according to the ASTM D1894-08 and ISO 8295:2004. Second method allowed to conduct tests under elevated temperature by utilising moving sled along with universal tensile tester. The work concluded by stating that both methods are able to obtain credible data and can be used interchangeably. Unal and Findik tested dry friction of commercially used polyamides in electric industry (Unal & Findik, 2008). PA46 reinforced with glass fiber had the best friction characteristics out of the polymers tested. Unal et al.tested also kinetic friction of polymers on the pin-on-disc setup under different loads and speeds (Unal et al., 2013). PA6 with added 10% graphite had the lowest wear rate. PV coefficient was insignificant with regards to wear rate more important was selection of friction pairs and their reinforcement. Dai et al. (2011) simulated mechanism of PE-PE friction based on dynamic molecule simulation. Those simulations differentiated the friction into 3 stages depending on the speed of friction. The phenomenon of polymer-polymer friction is important, because the constructional polymers such as POM or PA6 are used as gears or pistons (Miler et al., 2019).

Developments in the aerospace industry have been significant in recent years. The common occurrence of tribological phenomena, especially in these areas, requires careful analysis. Due to the many possibilities of using polymer materials for construction solutions, determining tribological properties is important, considering the significant impact of friction and wear on the efficiency and reliability of machines and devices (Policandriotes & Filip, 2011). This work contributes to creating tribological characteristics of polymer structural elements that can replace metal elements in many sliding places of tribological nodes, including in the aviation industry.

1. Sliding evaluation of highly loaded polymeric materials

In this work three different friction pairs were used: polyoxymethelene (POM), polyamide (PA6) and polyethylene terephthalate (PET). POM is characterized by a low tendency to creep and high fatigue strength. A critical advantage from the designer's point of view is the high stiffness of this material and the surface hardness with an appropriate degree of crystallization. It should also be noted that the Izod notched impact strength remains unchanged in the temperature spectrum. Polyacetals are more resistant to repeated impacts than aluminium and zinc alloys (Żuchowska, 2000). Polyamide 6 (PA6, polycaprolactam) is a structural thermoplastic from the polyamide group. PA6 is a linear polymer capable of crystallization. The degree of crystallinity of the polyamides used is 30–50%, depending on the processing conditions. Polyamides are characterized by water absorption. Its participation in polyamides changes their properties. Polyamides with a low water content are brittle and have low impact strength with an equally high resistance to bending (Żuchowska, 2000) and tensile stresses. As the water content increases, the polymer's elasticity and impact strength increase, but its strength decreases. As an engineering thermoplastic, PET is characterized by prolonged crystal growth compared to other thermoplastics. This means that the crystallization rate is about 40 times slower than that of polyacetals and 500 times lower than the crystallization rate of high-density polyethene. The result of this feature is the difficulty of processing, but on the other hand, this property is used when forming bottles using the injection method (Żuchowska, 2000). Table 1 shows a comparison of the properties of tested materials. The materials were injection moulded into pins with the dimensions of Ø8 mm × 20 mm and countersurface in the form of a plate with the dimensions 100 × 10 × 3 mm. The HLP 68 hydraulic grease was used to test lubricated friction. Its properties are shown in Table 2. The lubricant used for testing was applied to the contact zone using a 1 ml pipette for each repeated measurement. The surface roughness of the specimens before tribological tests was equal to Sa = (3.5 – 4) μm. Tests were carried under five different loads: 25, 50, 55, 70 and 75 N, which resulted in 0.64, 1.15, 1.54, 1.63, and 1.82 MPa. Ten tests were carried out for each friction pair and the results were statistically analyzed. All testing parameters are presented in Table 3.

Table 1. Review of selected properties of the tested polymer materials (Dobrzański, 2006; Erhard & Thompson, 2006; Żuchowska, 2000)

Property category	Property	Polymer		
		PET	PA6	POM
Processing	Glass transition temperature Tg [°C]	69	50	–85
	Melting point TT [°C]	265	215	175
	Processing temperature [°C]	260–300	240–290	180–230
	Pre-drying [°C/h]	120/4	80/(8–15)	110/2
	Mold temperature [°C]	130–150	40–120	60–120
	Processing shrinkage [%]	1.6–2	0.8–2.5	1.5–2.5
Mechanical properties	Density [g/cm^3]	1.38	1.13	1.41–1.42
	Tensile strength [MPa]	47	70–85	62–70
	Elongation at break [%]	50–300	200–300	25–70
Thermal properties	Minimum continuous use temperature [°C]	–20	–30	–60
	Maximum continuous use temperature [°C]	100	80–120	90–110
	Linear expansion coefficient [10-6/K]	70	80	90–110
	Thermal capacity [kJ/kg*K)	1.05	1.7	1.46

Table 2. The basic properties of hydraulic oil HLP 68

Properties	
Viscosity index	99
Pour point	–30 °C
Flashpoint	228 °C
Kinematic viscosity at 40 °C	66.2 mm^2/s
Corrosion action on copper plates (100 °C/3 h)	1a degree of corrosion
Deemulsibility, time to oil/water emulsion separation: 40–43 ml of oil 37–40 ml of water 0–3 ml of emulsion	25 min. at 54 °C
Ability to release air at 50 °C	8 min.
Ability to transfer loads with the FZG, breaking load, minimum	10

Static friction coefficient tests were carried out on a specially designed stand that mimicked inclined plane behaviour (Figure 1). The test stand allows pin-on-plate testing. The experiment consisted of increasing the plane's angle until the specimen's movement was observed. The angle at which the specimen moved was named the friction angle and was used to calculate the friction coefficient by the dependency shown below:

$$\mu = \hat{u} \quad \alpha = \frac{H}{L}. \qquad (1)$$

Table 3. Tribological test parameters

Experimental parameters	
Polymer sliding pair	POM-POM
	PET-PET
	PEEK/BG
Range of unit pressure p	0.64; 1.15; 1.54; 1.63; 1.82 [MPa]
Friction pair	pin-on-plate
sample dimensions – plate	100 × 10 × 3 mm
sample dimensions – pin	Ø8 mm × 20 mm
Environment	Dry friction Mixed friction – HLP 68 hydraulic oil in place of contact

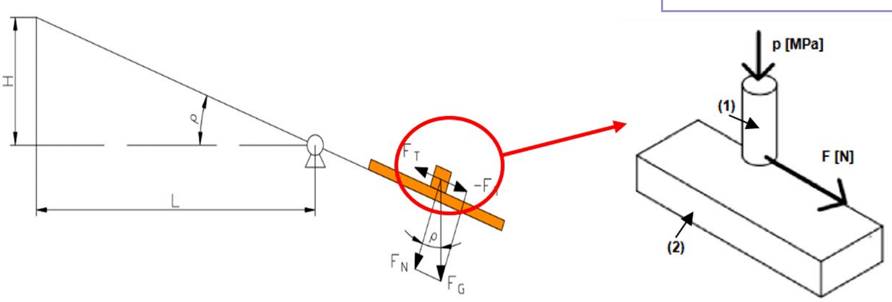


Figure 1. Test stand for testing the coefficient of static friction: a) diagram of the stand, b) combination used on the stand, (1) polymer pin, (2) polymer plate

2. Tribological characteristics of polymer-polymer sliding pairs

Tests carried out on the tribological stand allowed to calculate the static friction coefficient for each friction pair. Figure 2 and Figure 3 show the correlation of friction coefficient with relation to unit pressure and compare the friction coefficient of friction pairs under the same load. The surface of specimens was also tested using a profilometer, which allowed to check the surface quality after the tribological test, those results are shown in Figure 4.

Comparing the friction pairs under the same loads, the PA6-PA6 and POM-POM pairs characterize themselves by a lower static friction coefficient than PET-PET for each load under dry friction. Under the inclusion of HLP-68 lubricant PA6-PA6 had a significantly lowered friction coefficient for loads from 25 N to 55 N, while for loads 70 N and 75 N the friction coefficient is similar. An increase in the load meant reducing the friction coefficient for each pair under the dry friction conditions. It's worth to note that the PET-PET pair had the highest difference in static friction coefficient. The difference was equal to 25% from a friction coefficient equal to 0.2 to 0.15. PA6-PA6 pair had the lowest difference of 8%, while for the POM pair, this difference was 13%. Under the lubricated friction condition, POM and PA6 had similar characteristics as in dry friction – the differences were equal to 10 and 15%, respectively. PET showed abnormal behavior – with the load increase under lubricated friction, the friction coefficient increased by 5.5%.

3. Characteristics of friction surfaces

The friction surfaces were analyzed using a Leica DCM8 optical profilometer. The tests were performed using the confocal measurement method. The surface roughness was examined before and after the friction process, and microscopic images were taken. The surface Sa index (arithmetic mean height) was used to assess surface roughness. The measurement results are in Table 4, and their graphical interpretation of the topography layer before and after the friction process is from Figure 4 to Figure 6.

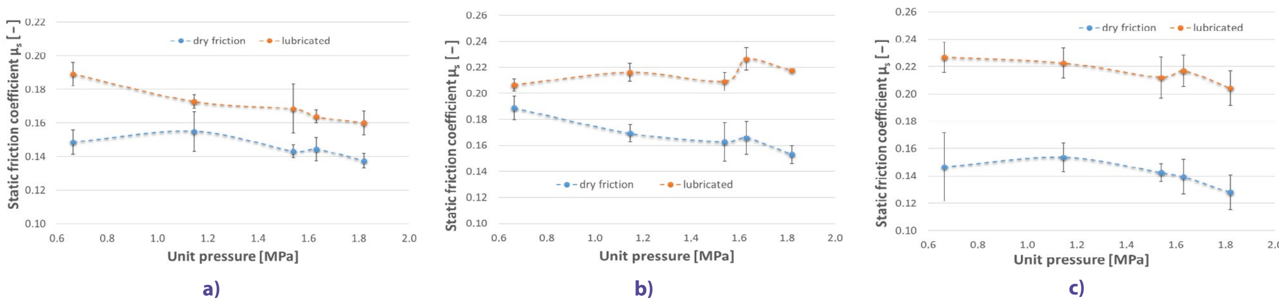


Figure 2. The friction coefficient for dry and lubricated friction of sliding pair: a) PA6-PA6, b) PET-PET, c) POM-POM

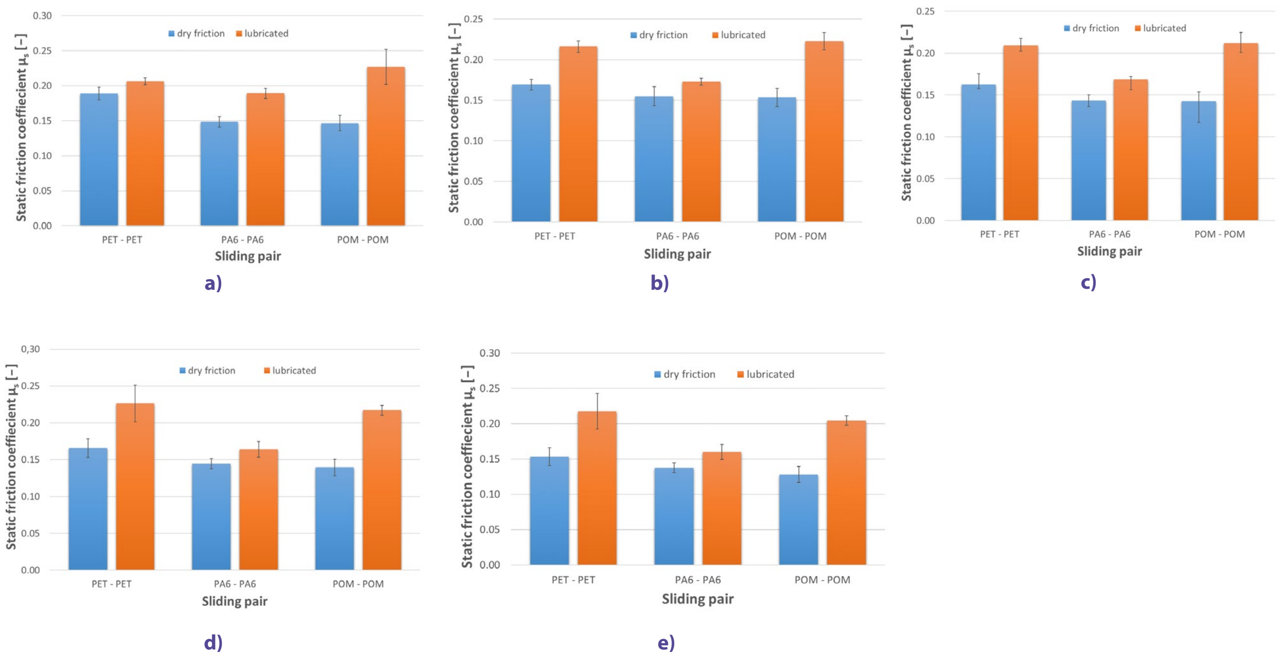
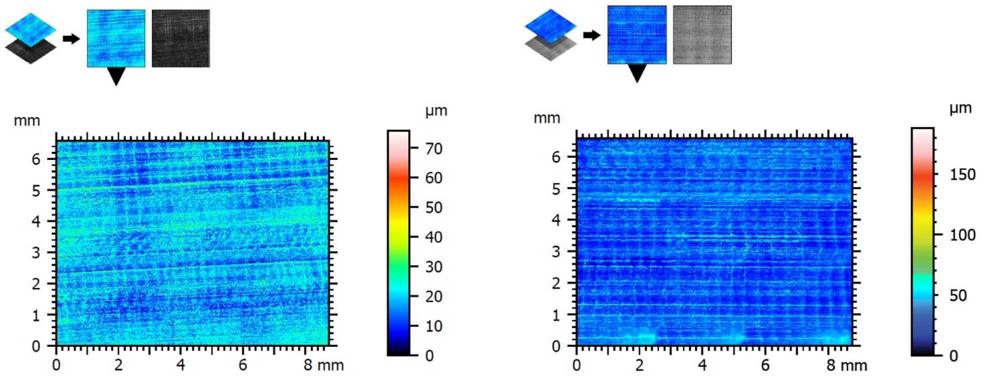


Figure 3. Values of the static friction coefficient for each tested polymer-polymer sliding pair at different unit loads: (a) 25 N, (b) 50 N, (c) 55 N, (d) 70 N, (e) 75 N

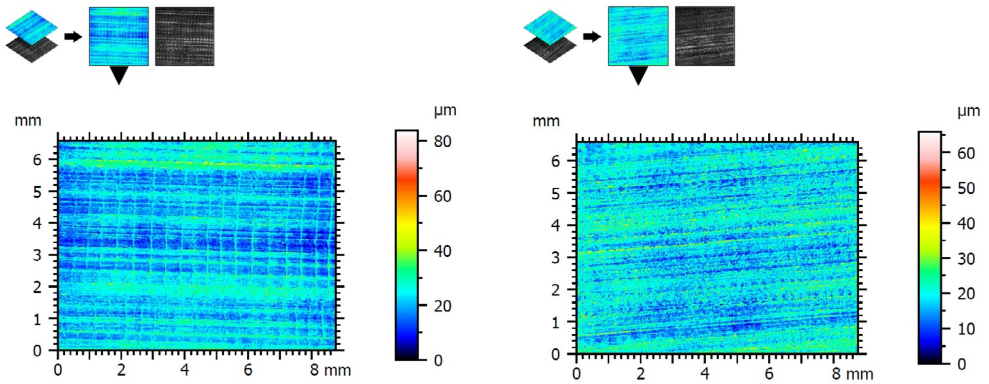
Table 4. The parameters of surface texture

Roughness [μm]	PA6		PET		POM	
	before	after	before	after	before	after
Sq	4.85782	8.52130	4.97345	5.74064	12.1442	20.4471
Ssk	0.588231	0.867826	0.720909	0.462999	0.595325	0.548989
Sku	4.46936	6.05741	4.84924	4.00062	2.91881	2.21148
Sp	57.3713	155.302	47.2627	61.8919	79.4539	124.484
Sv	18.4434	32.5057	18.6578	21.9116	78.0093	35.1163
Sz	75.8147	187.807	65.9205	83.8035	157.463	159.600
Sa	3.75110	6.61229	3.79373	4.48950	10.1435	17.4859



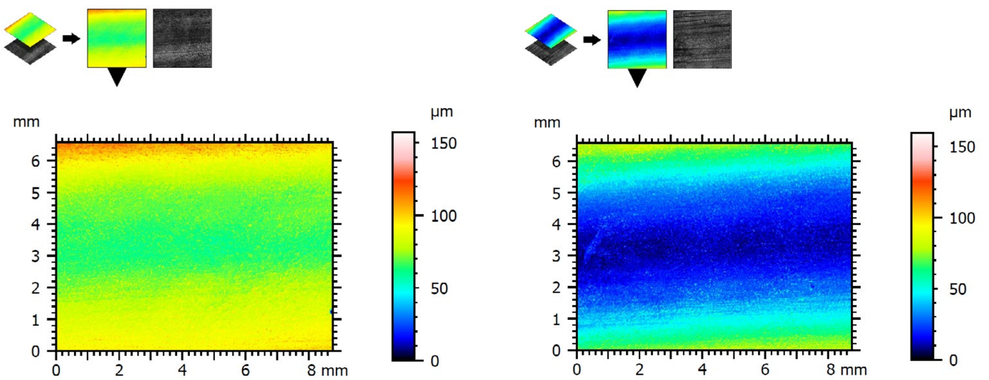
a) b)

Figure 4. The axonometric image of PA6 surface texture: a) topography layer before the friction process, b) topography layer after the friction process



a) b)

Figure 5. The axonometric image of PET surface texture: a) topography layer before the friction process, b) topography layer after the friction process



a) b)

Figure 6. The axonometric image of POM surface texture: a) topography layer before the friction process, b) topography layer after the friction process

Figure 4–Figure 6 shows a 2D view (surface map) of the surface topography before the friction process (Figures 4a–6a) and after the friction process (Figures 4b–6b). The analysis used the advanced MountainsMap9 Expert software (Digital Surf). The image obtained using the non-contact method was made with an accuracy of the measured points above 99.5%. The surface of the samples prepared for testing was characterized by lower Sa roughness values than after the experiment. PA6 and POM recorded as much as approx. 75% increase in Sa roughness, while in the case of PET, an increase of less than 20% can be observed. During the preparation of the sample surfaces, the problem was encountered in obtaining similar values during the preparation of the sample surfaces. Hence, the reasoning focused on the impact of friction on the percentage change in the roughness of a given surface rather than on a direct comparison of the results.

The surface of PA6 and PET (Figure 5 and Figure 6) has characteristic marks along the direction of friction. Additionally, before the experiment, the PET had visible traces placed across the path of friction, which could have caused a small share of the stick-slip phenomenon to appear during the tests. This is also believed to explain the highest value of the friction coefficient for this material. For POM (Figure 6), on the other hand, no clear directed friction traces are observed. However, a precise wide groove is visible, which may indicate wear despite the use of lubricant.

Conclusions

Research of polymer-polymer friction pairs is a complex problem. The authors performed a comparative analysis on three different friction pairs made out of the most common engineering polymers used in mechanical engineering – PA6, PET and POM. Tribological characteristics analysis was considered when the specimens started to move concerning each other and showed that it depended on the load applied to the material. The introduction of lubricant to the friction pair significantly increased the static coefficient of friction, the most considerable increase in coefficient of friction had POM – 31% increase in the case of the biggest load applied compared to dry conditions. This is also confirmed in the case of the kinetic friction coefficient. The increase may correlate with additional surface tension on the lubricant interfaces and specimens. For the PET-PET pair, the lowest load applied correlated with only an 8% increase in friction coefficient. Other loads meant an increase of friction coefficient between 21 and 29%. The PA6-PA6 pair showed the greatest stability of friction coefficient regardless of the load applied, increasing it between 10 and 15%. The results presented in the research constitute a starting point for further scientific research on polymer pairs working in sliding systems. Especially since they raised further questions that could open new directions of research, namely the influence of loading time before the experiment and the influence of lubricant contact time on the chemical, mechanical and tribological properties of the samples.

Funding

The presented research was carried out as part of the research task "Tribological tests of polymer-polymer sliding pairs in various operating conditions" funded from the pro-quality subsidy for the development of the research potential of the Faculty of Mechanical Engineering of Wrocław University of Science and Technology in 2023 under the "Excellence Initiative" – Research University (IDUB) program.

Author contributions

Anita Ptak was responsible for Conceptualization, Methodology, Investigation, Validation, Data Curation, Formal analysis, Visualisation, Writing – original draft, Writing – review and editing, Project Administration and Funding Acquisition. Tadeusz Leśniewski provided Conceptualization, Methodology and Writing – review and editing. Michał Purzycki provided for Formal analysis, Visualisation, Writing – original draft preparation. Krzysztof Płonka provided Investigation, Validation, Data Curation.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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