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Static friction of normal and reversed metal–polymer sliding pairs

Mariusz Opalka[1,*]

[1]Wroclaw University of Science and Technology, Faculty of Mechanical Engineering, Lukasiewicza 5, 50-371 Wroclaw, Poland

The frictional cooperation of materials with different hardnesses occurs in machine elements in one of the following two variants: simple or reversed friction pairs. For a simple sliding pair, the sliding materials' deformation area (contact area) does not move over the surface of the polymeric element during their interaction. In the case of reversed pairs, the contact surface changes its position as it moves over the surface of the polymer element. Tribological tests of selected sliding pairs (polymer on steel or steel on polymer) in static friction were carried out on a tribotester for tests in a reciprocating motion. The polymers selected for the research were popular sliding materials in engineering applications: ultra-high molecular weight polyethylene (PEUHMW), polyoxymethylene (POM) and polytetrafluoroethylene (PTFE). These materials cooperated with the C45 steel at different unit pressure ($P = 0.5$; 1; 2 [MPa]) in dry friction conditions. The measurement results showed a significant influence of the material combination variant (metal–polymer, polymer–metal) on the value of the friction coefficient. In all tested material combinations in which the steel sample (pin) slid over the polymer plate, the friction coefficient was higher than when the polymer sample worked with the steel plate.

Keywords: *polymers, reversed friction pair, static friction, PTFE, POM, PE-UHMW*

1. Introduction

Static friction is a major contributor to the frictional resistances arising during the starting of machines and equipment. Also in the case of reciprocating motion and swinging motion, static friction determines the resistances in the dead centres of the motion. Benabdallah [1] in described the effect of lubrication on the coefficient of static friction. Static friction resistances in metal–rubber contacts are extensively discussed in the doctoral thesis [2], which also contains numerical simulation results. The effect of unit pressure on the friction resistances of metal–polymer sliding pairs for the most commonly used thermoplastics is demonstrated in Ref. [3]. Results of the numerical modelling of static friction in rubber-metal contact are reported in Ref. [4]. Jerrams [5] in his paper presents the results of the numerical modelling of static contact with adhesion between the rigid surface and nitrile rubber. Persson et al. [6] report the results of modelling the contact between rigid bodies in boundary friction conditions with creep taken into account. Such studies usually deal with elastomeric materials or solely with thermoplastics interacting with steel under dry friction conditions. In most cases, the authors note a considerable contribution of adhesion to static friction resistances for PA6 [7], and for PP, PET, and polyethylene with an ultrahigh molecular weight (PE-UHMW) [8].

The materials used in polymer–metal friction pairs differ widely in their hardness and stiffness. Figure 1 shows two basic variants of sliding interaction between materials characterised by different deformability [9]:

(a) **variant I:** a normal (polymer-on-metal) friction pair; in this case, the area of contact between the slidingly interacting materials does not shift on the surface of the polymer element during motion;

(b) **variant II:** a reversed (metal-on-steel) friction pair; in this case, the contact area on the surface of the polymer material changes its location during motion.

* E-mail: mariusz.opalka@pwr.edu.pl

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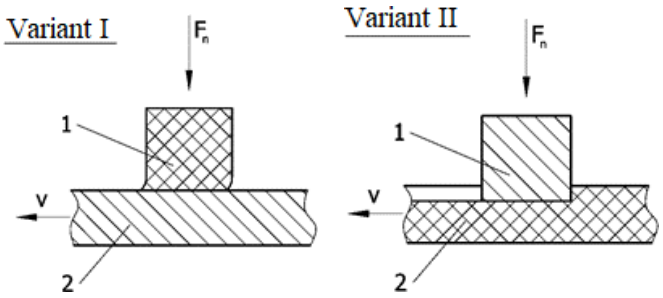


Fig. 1. Variants of sliding pairs for materials characterised by different deformability [15]: variant I (normal sliding pair) – (1) polymer sample, (2) steel counter body; variant II (reversed sliding pair) – (1) steel sample, (2) polymer counter body

Depending on the sliding pair variant, differences in the deformation mode and in the friction process, and consequently, in the wear of the polymer material are observed [10]. This is mainly due to a considerable difference between the deformation of the polymer material and that of the metal material, determining the time of dwell of a given surface in the contact. This affects how a polymer film forms on the surface of the metal element [11]. During the interaction of such sliding pairs, there occur not only adhesion and mechanical interactions between the contacting surfaces but also frictional resistances resulting from the deformation of the polymer material [12]. This means that in tribological investigations the choice of a sliding pair has a bearing on the recorded resistance-to-motion and tribological wear values.

Wieleba and Opałka [13] present test results for the coefficient of static friction for metal–polymeric elastomer sliding pairs under dry friction conditions and at mixed friction. In the whole test range, the resistances to static friction of the normal pairs were found to be lower than those of the reversed pairs, for both dry friction and mixed friction. The values are about 20%–60% lower, depending on the friction conditions (lubrication and pressure per unit area). Wieleba et al. [14] are based on normal and reversed friction pairs, but it concerns the polymer–polymer contact. It is interesting to note that also for this type of contact, a normal friction pair and a reversed friction pair can be distinguished. The deciding factor in this case is the difference in the hardness and stiffness of the interacting polymer materials. The largest differences in the static friction coefficient were found for the polytetrafluoroethylene (PTFE)–PEUHMW friction pair. In the case of the normal sliding pair, the resistances were 40%–50% lower (μ_{stat} = 0.12 for PTFE–PEUHMW; μ_{stat} = 0.05 for PEUHMW–PTFE at pressure P = 0.1 [MPa]).

The aim of the tests presented in the present paper was to determine the effect of unit pressure on the static friction coefficient under technically dry friction and mixed friction, depending on the variant of the friction pair (a normal or reversed pair) for materials characterised by different deformability.

2. Methods and materials

Static friction tests on selected material sliding pairs were carried out on a test stand for investigating friction at rolling-sliding motion [16]. The test stand had been adapted to measurements of the static friction force during reciprocating motion, and its schematic is shown in Figure 2.

A sample in the form of pin (6) was mounted in a holder, and the counter body in the form of plate (5) was placed on table (4) and fixed to carriage (3) via rollers. The load was applied via weights (8) pressing the sample against the counter body. The reciprocating motion was forced by an electric actuator (11) connected to the carriage using a flexible connector. Friction force F_t was measured by a force sensor (10) connected to the table mounted on the carriage. The force sensor was hooked up to a system recording the signal with a frequency of 100 Hz. Figure 2A also shows: a replaceable head

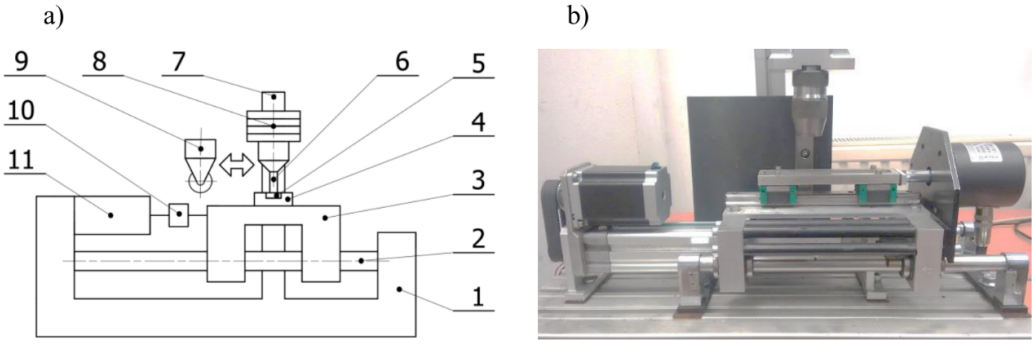


Fig. 2. Test stand for tribological investigations at reciprocating motion: **(A)** schematic, **(B)** photo of the test stand

Table 1. Mechanical parameters of polymers selected for tests [18]

	Density [g/cm^3]	**E-modulus [MPa]**	**Glass transition temperature [°C]**	**Melting point [°C]**	**Softening point [°C]**
PE-UHMW	0.93	730	−100	135	80
POM	1.41	2400	−240 to 180	167	150
PTFE	2.6	750	−97	327	-

PE-UHMW, polyethylene with an ultrahigh molecular weight; POM, polyoxymethylene; PTFE, polytetrafluoroethylene

(9) with a roller, lead screw (2), arm (1) and holder guide (7).

Since the tested polymeric materials were the plastics most commonly used for sliding applications in machine joints, the tests were conducted under technically dry friction conditions.

PE-UHMW (hardness 65 Sh A), polyoxymethylene (POM) (hardness 70 Sh A) and PTFE (hardness 60 Sh A) were used in the tests. The materials interacted with samples made of steel C45 with a hardness of 40 HRC and surface roughness Ra = 0.5 μm. The unit pressures adopted for the tests were followed by the compressive strength of the selected materials. According to various sources [17], the compressive strength of PTFE amounts to 2–4.5 [MPa]. Therefore the maximum pressure of 2 [MPa] was assumed, while the other values were matched so that general tendencies in the influence of the unit pressure on the static friction resistances and on the differences between the particular friction variants could be determined (Table 1).

The tests were carried out under the following friction conditions:

- average unit pressure

$$P = 0.5, 1, 2 \text{ MPa},$$

- time of dwell under load

$$t_p = 2 \text{ s},$$

- ambient temperature

$$\text{To} = 22^{\circ}\text{C},$$

- air humidity

$$\varphi = 40\% - 45\%,$$

- friction conditions: technically dry friction.

Before the measurements each of the tested friction pairs had been subjected to grinding-in. This had been done by mounting the tested pair in the measuring device, loading it with a pressure of 1 MPa, and putting the carriage (element 3 in Figure 2) in reciprocating motion with a velocity of 10 mm/s over a unit distance of 50 mm. Each friction pair had been ground in for 10 min.

Table 2. The static friction coefficient of tested steel-polymer friction pairs as a function of unit pressure p. Reversed sliding pairs

Counterbody material	Unit pressure p [MPa]		
	0.5	1.0	2.0
PE-UHMW	**0.12** $\pm$ 0.001	**0.11** $\pm$ 0.001	**0.11** $\pm$ 0.001
POM	**0.16** $\pm$ 0.002	**0.14** $\pm$ 0.002	**0.12** $\pm$ 0.002
PTFE	**0.09** $\pm$ 0.002	**0.08** $\pm$ 0.001	**0.06** $\pm$ 0.001

PE-UHMW, Polyethylene with an ultrahigh molecular weight; POM, polyoxymethylene; PTFE, polytetrafluoroethylene

Table 3. The static friction coefficient of tested polymer–steel friction pairs as a function of unit pressure p. Normal sliding pairs

Sample material	Unit pressure p [MPa]		
	0.5	1.0	2.0
PE-UHMW	**0.10** $\pm$ 0.002	**0.09** $\pm$ 0.001	**0.08** $\pm$ 0.001
POM	**0.09** $\pm$ 0.001	**0.08** $\pm$ 0.001	**0.07** $\pm$ 0.001
PTFE	**0.05** $\pm$ 0.001	**0.06** $\pm$ 0.001	**0.05** $\pm$ 0.001

PE-UHMW, Polyethylene with an ultrahigh molecular weight; POM, polyoxymethylene; PTFE, polytetrafluoroethylene

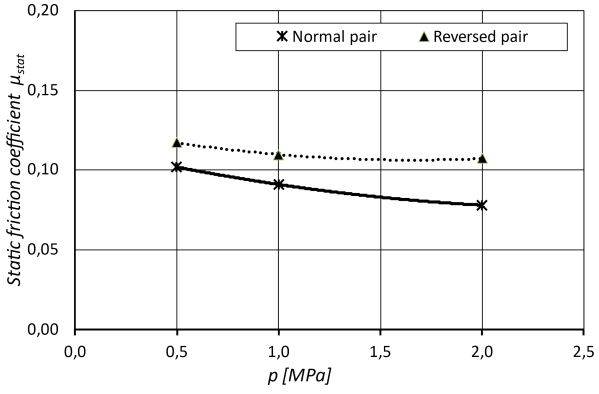


Fig. 3. Average values of static friction coefficient of tested PEUHMW-C45 contact in normal and reversed sliding pair. PE-UHMW, Polyethylene with an ultrahigh molecular weight

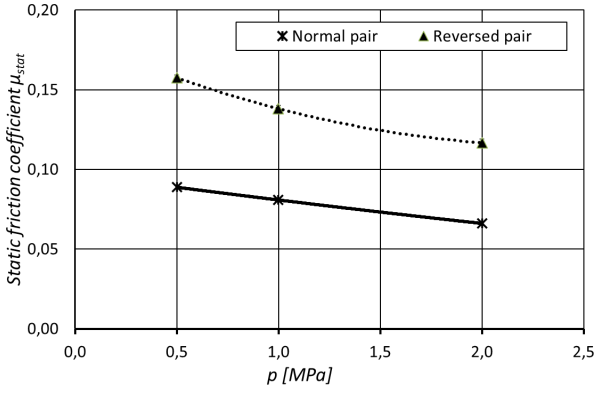


Fig. 4. Average values of static friction coefficient of tested POM-C45 contact in normal and reversed sliding pair. POM, polyoxymethylene

3. Results

The set of the tested sliding pairs and the test results (average static friction coefficient values obtained from a series of at least 40 measurements) are presented in Tables 2 and 3. Moreover, confidence levels at a significance level $\alpha = 0.05$ are given. For comparison purposes and to facilitate the analysis of the test results the latter are presented as graphs in Figures 3–5 where the results obtained for the normal pairs (polymer-on-steel) and the reversed pairs (steel-on-polymer) are compared.

Table 4 shows percentage changes in static friction coefficient values for the normal sliding pair in comparison with the reversed pair. For the different contact variants and unit pressures the normal sliding pairs are characterised by static friction resistances lower by as much as 44% than those characterising the reversed pairs.

Figures 3 and 4 graphically present the results for the normal and reversed PEUHMW-C45 and

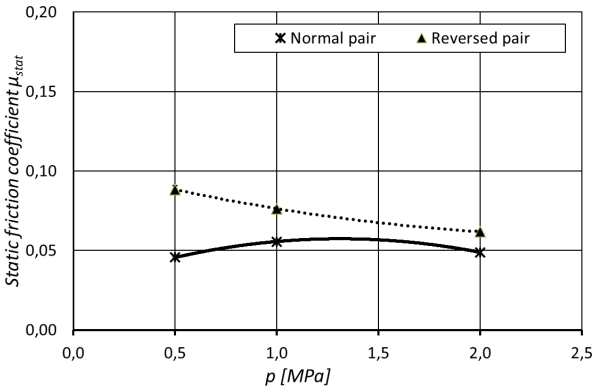


Fig. 5. Average values of static friction coefficient of tested PTFE-C45 contact in normal and reversed sliding pair. PTFE, polytetrafluoroethylene

Table 4. Percentage changes in static friction coefficient values for normal sliding pair in comparison with reversed pair

	Unit pressure p [MPa]			
	0.5	**1**	**2**	**Average**
PE-UHMW (%)	−16.7	−18.2	−27.3	−20.7
POM (%)	−43.7	−42.8	−41.7	−42.7
PTFE (%)	−44.4	−25.0	−16.7	−28.7

PE-UHMW, Polyethylene with an ultrahigh molecular weight; POM, polyoxymethylene; PTFE, polytetrafluoroethylene

POM-C45 friction pairs, showing a clear tendency for the value of the static friction coefficient to decrease with the increase in unit pressure. This is connected with the increase in contact surface in the case of an elastic contact [19]. No clear tendency for the value of the static friction coefficient to change with the increase in load is visible for the normal PTFE-C45 sliding pair in Figure 5.

Figure 6 shows microscopic images of the surface of the polymer samples, coming from normal and reversed sliding pairs, after the friction tests.

4. Discussion

The lowest static friction resistances were observed for the interaction of the normal pairs in which the PTFE material slid on the steel element. The coefficient of static friction for this pair ranged from 0.05 to 0.06, depending on the unit pressure value.

The test results show that the static friction resistances are lower than the ones in the reversed pairs. This is evidence of a considerable share of the deformation component of friction in the case when the friction of the steel element takes place on a less rigid material. This also indicates that the adhesion component does not contribute significantly to the friction resistance of the tested polymeric materials.

The test results indicate that the deformation of the interacting elements can contribute to an uneven distribution of pressure between the slidingly interacting elements, and consequently to a change in friction resistance values, as schematically shown in Figure 7. As the polymeric material exhibits viscoelastic properties, it is subject to creep. Under static load at rest it begins to deform and conform to the micro asperities of the metallic material. This mechanism occurs for both the normal sliding pair and the reversed one.

In the case of the normal sliding pair, under the friction force, the sample (pin) deflects. As a result, the metal's surface asperities and their impressions on the surface of the polymer no longer interlock, whereby the contact surface area and the resistance to motion decrease.

In the case of the reversed sliding pair, the rigid sample does not undergo such deflection. During starting, the mechanical interlocking between the contacting and viscoelastically deformed surfaces persists. In addition, the metal sample sunk into the polymer plate causes material macro deformations which further contribute to the resistance to motion. This phenomenon is described in the study [21]. Figure 6 shows that the surfaces of the polymer samples coming from the reversed sliding pairs have no so distinct grooves as the ones visible on the surfaces of the samples coming from the normal sliding pairs. They have, however, traces of the smearing of some of the polymer material (particularly clearly visible in POM).

The influence of unit pressure on friction resistances varies. For the friction pairs: C45-PEUHMW and PTFE-C45 this influence is slight, with differences in the friction coefficient amount-

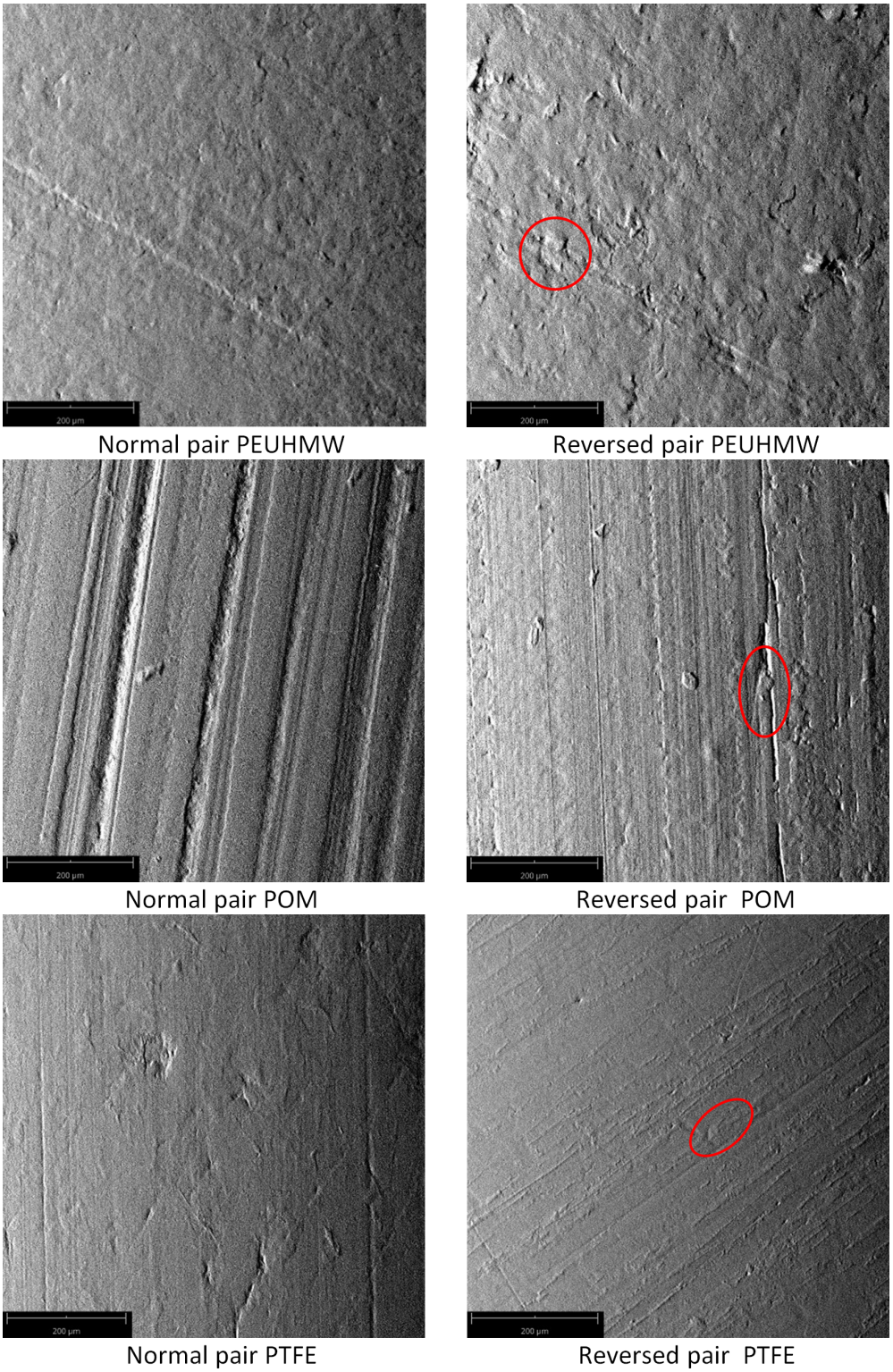


Fig. 6. Microscopic images of polymer samples' surface after friction tests. Red circles mark smeared (macrodeformed) material on the surface. SEM, magnification: ×400, topography BSD, 15 kV. PE-UHMW, Polyethylene with an ultrahigh molecular weight; POM, polyoxymethylene; PTFE, polytetrafluoroethylene

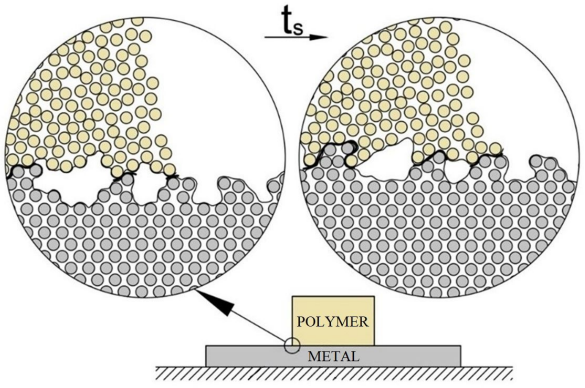


Fig. 7. A phenomenon which takes place in friction pair's contact area: increase in contact surface due to material creep at rest under load over time t_s, contributing to an increase in static friction force [20]

ing to ±0.01. The largest differences in the friction coefficient were observed for the C45-POM friction pair. As the unit pressure was increased, the static friction coefficient would decrease from 0.16 (for $P = 0.5$ [MPa]) to 0.12 (for $P = 2$ [MPa]). The changes in the friction coefficient were observed for both the normal pair and the reversed pair. In the case of this contact, as the unit pressure increased, the friction coefficient would decrease.

Practically, unit pressure only to a small degree affected the value of the static friction coefficient of the tested pairs. The exception was reversed pair C45-POM in the case of which a marked decrease in the value of the friction coefficient was observed as the unit pressure increased.

5. Conclusions

The following conclusions and observations emerge from the above tribological investigations:

- Static friction resistances in the normal sliding pairs are lower than the ones in the reversed pairs. The resistances are determined by the friction's deformation component stemming from the considerable deformability of the polymeric element. Since in the normal pairs, the zone of the deformed material in the plastic practically does not shift, the deformation component is smaller than in the reversed pairs.
- The best-sliding pair as regards the lowest friction resistances ($\mu_{stat} < 0.06$) under dry friction conditions was found to be the normal PTFE-steel pair. It should be noted that the average value of the friction coefficient would change only slightly with the changing friction conditions.
- In the case of the reversed pairs (steel-on-polymer), the test results showed a larger scatter and the average value of the friction coefficient would change with the changing friction conditions. This was probably because the structure of the polymer material in the place of its contact with the metal element would change with the successive measurements.
- To explain the static friction test results in more detail, additional investigations of the pressure distribution and the adhesion interactions between the tested materials need to be carried out.

References

[1] Benabdallah HS. Static friction coefficient of some plastics against steel and aluminium under different contact conditions. *Tribol. Int.* 2007;40: 64–73. doi:10.1016/j.triboint.2006.02.031.

[2] Deladi EL. *Static friction in rubber-metal contacts with application to rubber pad forming processes*, 2006. Available from: http://doc.utwente.nl/57594/. Access: 18.11.2022

[3] Dobrowolska A, Kowalewski P, Ptak A. Wpływ nacisku jednostkowego na współczynnik tarcia statycznego wybranych par ślizgowych metal–polimer. *Tribologia.* 2014;45(4):21–32.

[4] Deladi EL, de Rooij MB, Schipper DJ. Modelling of static friction in rubber-metal contact. *Tribol. Int.* 2007;40: 588–94. doi:10.1016/j.triboint.2005.11.007.

[5] Jerrams SJ. Friction and adhesion in rigid surface indentation of nitrile rubber. *Mater. Des.* 2005;26: 251–8. doi:10.1016/j.matdes.2004.02.012.

[6] Persson BNJ, Albohr O, Mancosu F, Peveri V, Samoilov VN, Sivebaek IM. On the nature of the static friction, kinetic friction and creep. *Wear.* 2003;254: 835–51. doi:10.1016/S0043-1648(03)00234-5.

[7] Voyer J, Klien S, Velkavrh I, Ausserer F, Diem A. Static and dynamic friction of pure and friction-modified PA6 polymers in contact with steel surfaces: influence of

surface roughness and environmental conditions. *Lubricants.* 2019;7(2):17. doi:10.3390/lubricants7020017.

[8] Cho DH, Bhushan B, Dyess J. Mechanisms of static and kinetic friction of polypropylene, polyethylene terephthalate, and high-density polyethylene pairs during sliding. *Tribol. Int.* 2016;94: 165–75. doi:10.1016/j.triboint.2015.08.027.

[9] Friedrich K. Polymer composites for tribological applications. *Adv. Ind. Eng. Polym. Res.* 2018;1: 3–39. doi:10.1016/j.aiepr.2018.05.001.

[10] Putignano C, Reddyhoff T, Dini D. The influence of temperature on viscoelastic friction properties. *Tribol. Int.* 2016;100: 338–43. doi:10.1016/j.triboint.2016.03.018.

[11] Lawrowski Z. *Tribologia: tarcie, zużywanie i smarowanie.* Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej; 2009.

[12] Wieleba W, Gidziński W. Opory tarcia w parach ślizgowych metal–polimer, pracujących w układzie odwróconym. *Tribologia.* 2008;4: 185–93.

[13] Wieleba W, Opałka M, Static friction of reverse steel-elastomer sliding pairs, *Tribologia.* 2018;3: 147–51.

[14] Wieleba W, Kowalewski P, Opałka M. Opory tarcia podczas montażu elementów z tworzyw sztucznych, *Uszczelnienia i Tech. Uszczelniania Masz. i Urządzeń Międzynarodowa XII Konf. Nauk.* Wrocław, 2016.p.271–7.

[15] Bhushan B. Modern tribology handbook, two volume set. CRC Press; Ohio, 2000.

[16] Wieleba W, Kowalewski P. Urządzenie do badania tarcia w ruchu toczno-ślizgowym, 2013.

[17] Żuchowska D. *Polimery konstrukcyjne: przetwórstwo i właściwości.* Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej; 1993.

[18] Wieleba W. *Bezobsługowe łożyska ślizgowe z polimerów termoplastycznych*. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej; 2013. Available from: `https://www.dbc.wroc.pl/dlibra/docmetadata?id=31367&from=pubindex&dirids=107&lp=161`. Access: 18.11.2022

[19] Wieleba W. The mechanism of tribological wear of thermoplastic materials. *Arch. Civ. Mech. Eng*. 2007. doi:10.1016/S1644-9665(12)60236-2.

[20] Bowden FP, Tabor D. *Wprowadzenie do trybologii*. Wydawnictwa Naukowo-Techniczne; 1980.

[21] Kowalewski P. *Tarcie polimerów termoplastycznych w warunkach złożonego ruchu*. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej; 2019.

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