DOI: 10.5604/01.3001.0015.5861

Magdalena LEMECHA*, Krzysztof LIGIER, Jerzy NAPIÓRKOWSKI*****

ASSESSMENT OF ABRASIVE WEAR RATE FOR PTFE-BASED COMPOSITES IN COMBINATION WITH STEEL

OCENA INTENSYWNOŚCI ZUŻYCIA ŚCIERNEGO KOMPOZYTÓW NA OSNOWIE PTFE W SKOJARZENIU ZE STALĄ

Key words: polymer-steel sliding friction, abrasive wear, PTFE composite, polymer film.

Abstract: This paper presents a study of the tribological wear rate for PTFE-based composites in combination with C45 steel. PTFE composites with the addition of glass fibre, bronze, carbon fibre, and graphite were selected for the study. Tribological tests were conducted in a roller-block combination over an expanded contact area with no lubrication, using an SMC-2 machine. The study assessed the mass and volumetric wear for the test materials and the wear rate index. The highest wear values were noted for the PTFE composite with the addition of bronze, while the lowest was for the PTFE composite with the addition of glass fibre. For all the test materials, the formation of a polymer film on the steel counter specimen was noted.

Słowa kluczowe: tarcie ślizgowe polimer–stal, zużycie ścierne, kompozyt PTFE, film polimerowy.

Streszczenie: W pracy przedstawiono badania intensywności zużycia ściernego kompozytów na osnowie PTFE w skojarzeniu ze stalą C45. Do badań wytypowano kompozyty PTFE z dodatkiem włókien szklanego, brązu i włókna węgla oraz grafitu. Badania tribologiczne prowadzono w skojarzeniu rolka–klocek w styku rozwiniętym bez smarowania z wykorzystaniem maszyny SMC-2. Ocenie poddano zużycie masowe oraz objętościowe badanych materiałów oraz dokonano oceny wskaźnika intensywności zużycia. Najwyższe wartości zużycia zaobserwowano dla kompozytu PTFE z dodatkiem brązu. Najniższe wartości zużycia zaobserwowano dla kompozytu PTFE z dodatkiem włókna szklanego. W przypadku wszystkich badanych materiałów zaobserwowano tworzenie się filmu polimerowego na przeciwpróbce stalowej.

INTRODUCTION

The materials currently used in friction assemblies should be primarily characterised by reduced resistance to motion and increased reliability and functionality. This is particularly important for maintenance-free friction assemblies operating under conditions of under-lubrication or technically dry lubrication **[L. 1, 2, 3, 4, 5]**. Plastics, especially thermoplastic polymers and their composites, have found relatively wide use in this area **[L. 6, 8, 9]**. Of the many thermoplastic polymer grades, only some of them are used on friction assemblies, for example, polyamide (PA), polyethylene (PE), polyoxymethylene (POM), or polytetrafluoroethylene (PTFE) and their composites **[L. 10, 11]**.

The interest in polymers as sliding materials arises from their numerous advantages, including low density, easy shaping of parts (e.g., by injection moulding, pressing, casting), resistance to corrosion, mechanical vibration damping capability, self-

* ORCID: 0000-0003-3414-4099. University of Warmia and Mazury in Olsztyn, Faculty of Technical Sciences, Departament of Building of Vehicles and Machines, M. Oczapowskiego 11 Street, 10-719 Olsztyn, Poland.
** ORCID: 0000-0003-1348-7068. University of Warmia and Mazury in Olsztyn, Faculty of Technical Sciences, Departament of Building of Vehicles and Machines, M. Oczapowskiego 11 Street, 10-719 Olsztyn, Poland.
*** ORCID: 0000-0003-2953-7402. University of Warmia and Mazury in Olsztyn, Faculty of Technical Sciences, Departament of Building of Vehicles and Machines, M. Oczapowskiego 11 Street, 10-719 Olsztyn, Poland.

lubrication, resistance to seizure in interaction with steel without lubrication, and chemical resistance **[L. 12, 13]**. The main disadvantages of the materials concerned include low thermal conductivity, high thermal expansion, hygroscopicity, and changes to the mechanical properties under the influence of temperature **[L. 14]**. These disadvantages, however, can be reduced by an appropriate polymer modification. One of the modification methods is a mechanical modification that involves the introduction of fillers into the polymer. Two- or multi-component composites are formed in this manner. The composite matrix is the base polymer, and the fillers can be made from various types of materials differing in terms of the type (metals and non-metals), the form (dispersible or fibrous), and the particle size **[L. 4]**. The composites obtained in this way can differ significantly in mechanical and tribological properties. PTFE is one of the materials that are least sensitive to the interaction conditions in a friction assembly **[L. 3, 6]**. Polytetrafluoroethylene (PTFE) is a semi-crystalline thermoplastic obtained in the process of radical suspension or emulsion polymerisation of tetrafluoroethylene (TFE), characterised by a large proportion of the crystalline phase (approx. 92–96%) and a linear structure of the monomer chain. In view of its relatively poor mechanical properties (e.g., susceptibility to creeping or tearing even under light load), the construction sector uses the PTFE modified with different additions, e.g., glass fibre, graphite, carbon, bronze, steel, and molybdenum disulphide.

The aim of the study is to assess the wear rate for PTFE-based composites in combination with steel.

STUDY MATERIALS

For the study, C45 steel in a normalised state, which is characterised by a pearlitic-ferritic microstructure, was used as a counter specimen. Four PTFE-based composites were selected for the study as specimens:

- PTFE BZ40 – PTFE with bronze added at 40% by volume,
- PTFE G15 – PTFE with graphite added at 15% by volume,
- PTFE CF25 – PTFE with carbon fibre added at 25% by volume, and
- PTFE GF25 – PTFE with glass fibre added at 25% by volume.

PTFE modification with bronze is used in mechanical engineering to manufacture guide rings in hydraulic cylinders and slide bearings which are exposed to mechanical loads. PTFE modification with bronze improves resistance to compressive loads, reduces creeping, and ensures good thermal conductivity.

The addition of graphite contributes to an improvement in the sliding properties as well as the thermal and electrical conductivity of PTFE. For this reason, the material is used to produce sliding films that enable the discharge of an electrical charge.

PTFE modification with carbon fibre reduces polymer creeping, thus ensuring very high resistance to abrasive wear, and improved thermal conductivity. This composite is used for manufacturing slide bearings and other parts exposed to abrasive wear **[L. 8]**.

PTFE modified with glass fibre was selected as the last study material. This composite is characterised by increased compressive strength, resistance to abrasive wear, and higher thermal conductivity. It is used for manufacturing valve faces and bearing parts in sliding pairs.

The density of the test composites was determined by the hydrostatic method, i.e. by measuring the weight of the specimens in the air and in ethyl alcohol using a laboratory balance. The density was determined based on five measurements using the following formula:

$$\rho_k = \frac{m_k}{m_k - m_{kc}} \rho_c \tag{1}$$

where:
ρ_k – composite density, ρ_c – liquid density, m_k – composite specimen weight in the air, m_c – measured weight of the composite specimen immersed in a liquid.

Hardness was measured by the Brinell method, according to the standard PN-EN ISO 6506, using an Innovatest Nexus 703A hardness tester, with a load of 132 N applied for 10 s. The test was repeated three times. Measurements of roughness were conducted using a HOMMEL TESTER T1000 contact profilometer. The measurements were conducted according to the standard PN-ISO 4288.

The results of measurements of the test material parameters are provided in **Table 1**.

Table 1. Test material parameter measurement results
Tabela 1. Wyniki parametrów badanych materiałów

Material	Density [g/cm^3]	Hardness [HB]	Roughness Ra [µm]
PTFE-BZ40	3.08	27.24	5.08
PTFE-G15	2.14	26.85	6.78
PTFE-CF25	2.07	35.98	5.74
PTFE-GF25	2.24	31.12	5.45

METHODOLOGY OF THE STUDY

The study was conducted in a roller-block combination over an expanded contact area, using an SMC-2 universal wear machine. The material was taken from semi-finished products in the form of extruded rollers with a diameter of 65 mm, from which specimens were made in the form of a ring section with an external diameter ϕ of 60 mm, an internal diameter ϕ of 40 mm, and a width of 10 mm (**Fig. 1a**). The counter specimen was a disk made from C45 steel in a normalised state, with a diameter of 40 mm and a width of 12 mm (**Fig. 1b**). The specimens were placed in a holder mounted on the shaft of the wear machine, while the counter specimen was placed on the second shaft (**Fig. 2**).

The specimen was gravitationally loaded with a mass placed on the specimen holder's arm. The friction assembly diagram is shown in **Fig. 2**.

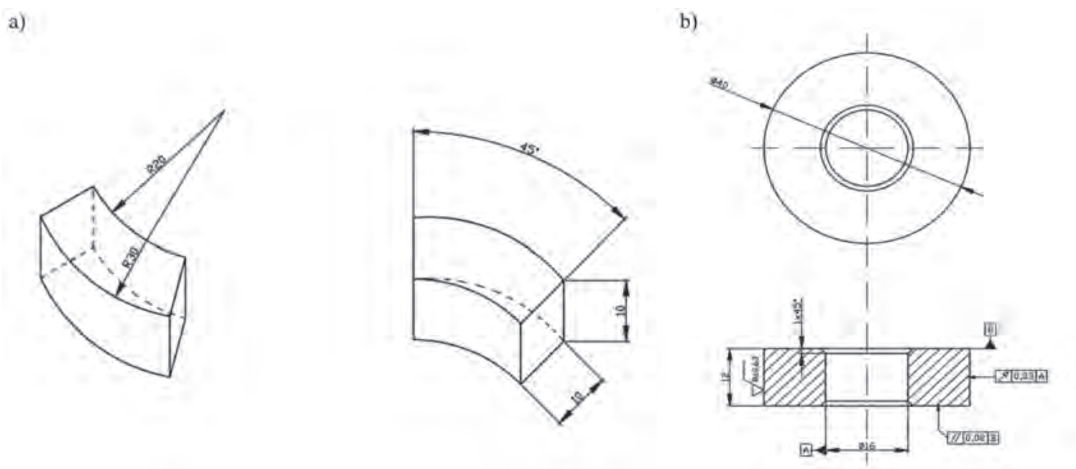

Fig. 1. The shape of the PTFE composite specimen (a) and the steel counter specimen (b) used in the study
Rys. 1. Kształt próbki kompozytu PTFE (a) i przeciwpróbki stalowej (b) użytych do badań

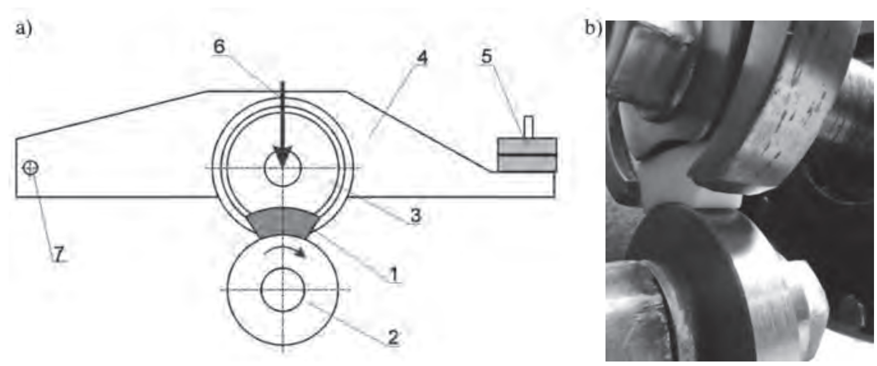

Fig. 2. Test stand: a) test stand diagram: 1 – specimen, 2 – counter specimen, 3 – specimen holder, 4 – arm, 5 – loading mass, 6 – friction assembly load, 7 – pin; b) a view of friction assembly
Rys. 2. Stanowisko badawcze: a) schemat stanowiska badawczego: 1 – próbka, 2 – przeciwpróbka, 3 – uchwyt próbki, 4 – ramię, 5 – masa obciążająca, 6 – obciążenie węzła tarcia, 7 – sworzeń; b) widok węzła tarcia

The following friction parameters were applied:

- Counter specimen rotational speed – 300 min^{-1},
- Angular velocity: 31.4 rad/s,
- Friction assembly load – 40 N,
- Friction distance – 226 m,
- Experimental run duration – 6 min.

Volumetric wear, calculated based on the weight loss and the density of test composites, according to the following formula, was used as the measure of wear:

$$z_v = \frac{m_1 - m_2}{\rho_k} \tag{2}$$

where:
z_v – volumetric wear, m_1 – initial specimen weight, m_2 – final specimen weight,
ρ_k – composite density.

The wear rate was determined using the wear index W_r calculated according to the following formula:

$$W_r = \frac{z_v}{S \cdot N} \tag{3}$$

where:
z_v – volumetric wear, S – friction distance, N – specimen load.

The surfaces of the test materials were assessed using a Kayence VHX7000 digital optical microscope.

STUDY RESULTS

Figure 3 presents a comparison of the test composite wear indices. The composite containing bronze (PTFE-BZ40), which lost over 20 mm^3 in volume, exhibited the highest wear rate. The loss of other composites was considerably smaller and amounted to approx. 3.5 mm^3 for PTFE G15 and to approx. 2 mm^3 for PTFE CF25. On the other hand, the PTFE GF25 composite exhibited the smallest loss of approx. 1 mm^3. The wear value for this composite type was 20-fold lower than that for PTFE BZ40.

After conducting tribological tests, the surfaces of the test materials and of the associated counter specimens were analysed in order to identify the wear patterns, which are shown in **Figs. 4–7**. A transferred polymer layer was observed on the surfaces of the counter specimens operating in combination with all the test composites. The formation of a polymer film (marked with No. 2 on counter specimen microphotographs) on the metal surface of the metal-polymer pair is a typical phenomenon occurring in the abrasive wear process **[L. 7]**, which is due to the Van der Waals force interaction between the metal and the polymer. On the other hand, the most commonly found wear marks on the counter specimen surfaces include material tear-ups (**Fig. 4b1**) and scratching (**Fig. 4b1**).

As for the interaction between PTFE and the chemically active materials (e.g., iron), this layer is strongly bonded to the substrate, and its displacement is hindered and polymer-

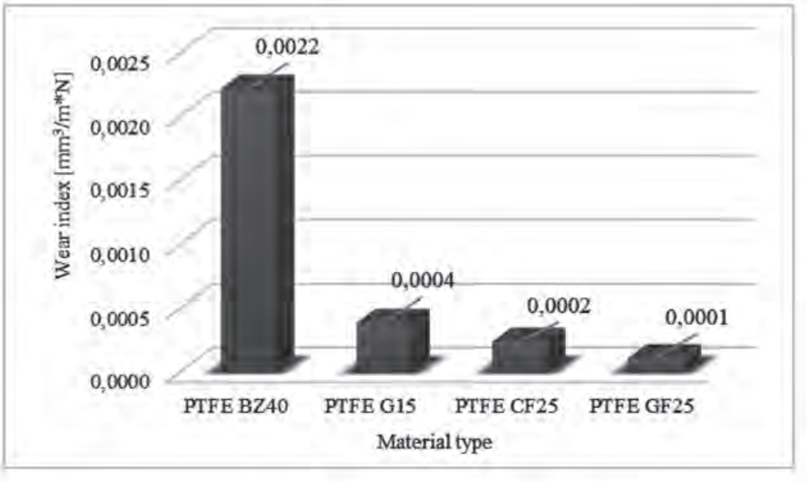

Fig. 3. A comparison of the test material wear indices
Rys. 3. Zestawienie wskaźnika zużycia badanych materiałów

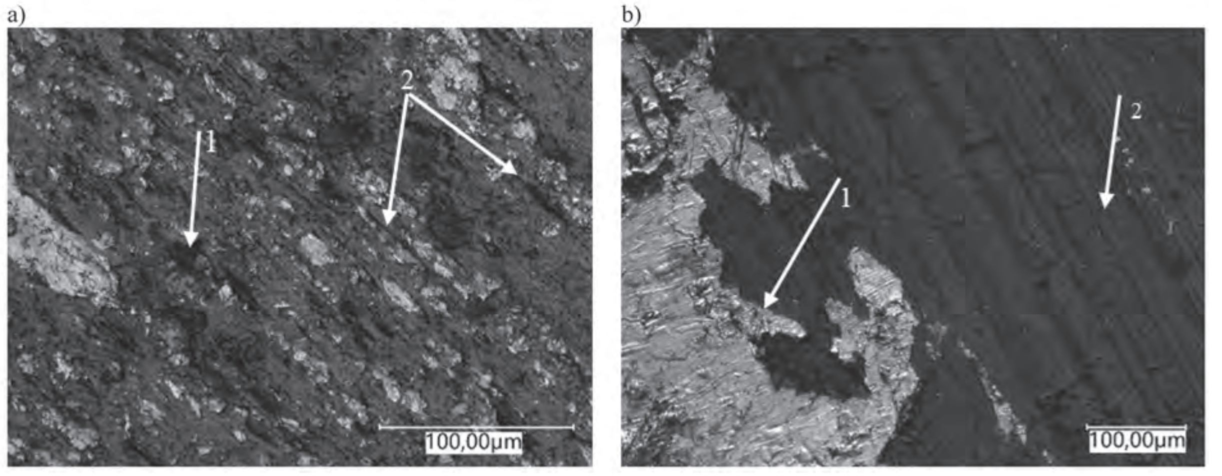

Fig. 4. The surface of: a) PTFE G15 composite specimen, b) steel counter specimen
Rys. 4. Powierzchnia: a) próbki kompozytu PTFE G15, b) przeciwpróbki stalowej

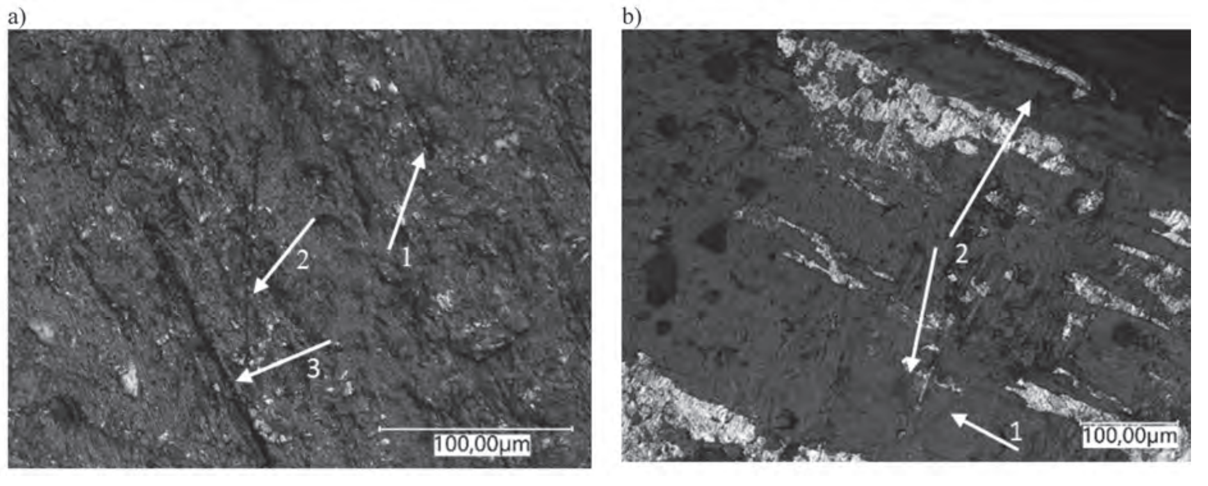

Fig. 5. The surfaces of: a) PTFE CF25 composite specimen, b) steel counter specimen
Rys. 5. Powierzchnia: a) próbki kompozytu PTFE CF25, b) przeciwpróbki stalowej

polymer friction occurs. PTFE fillers in the form of flake graphite and carbon fibres reduced the wear of the composites containing them (**Figs. 4** and **5**). This could be related to the anti-slip effect of graphite and the improvement of PTFE mechanical properties by the addition of carbon fibres **[L. 9]**. On the surfaces of the specimens with graphite and carbon fibre added, material tear-ups (**Fig. 4a1**; **Fig. 5a1**), scratches (**Fig. 4a2**) and ridging (**Fig. 5a3**) were identified.

The addition of glass fibres (**Fig. 6a1**) also improves the mechanical properties of PTFE, which is confirmed by the lowest wear value noted for the tested composites. Partially exposed filler fibres that limited the PTFE contact with the counter specimen surface can be noted on the PTFE GF25 composite surface. Moreover, wear products transferred from the counter specimen can be identified (**Fig. 6a2**). Additionally, the sharp edges of the protruding hard filler fibres caused accelerated wear of the counter specimen surface (**Fig. 6b1**) **[L. 4]**.

As regards the PTFE-BZ40 composite, the wear value was the highest. This is due to the fact that bronze particles exhibit greater adhesion to steel than PTFE particles **[L. 15]**. Therefore, the exposed bronze particles (**Fig. 7a1**) coming into contact with steel formed material build-up on its surface (**Fig. 7b1**), which, in turn, intensified the ridging (**Fig. 7a2**) and scratching (**Fig. 7a3**) processes occurring on the specimen surface. On the other hand, bronze particle fragments, transferred from

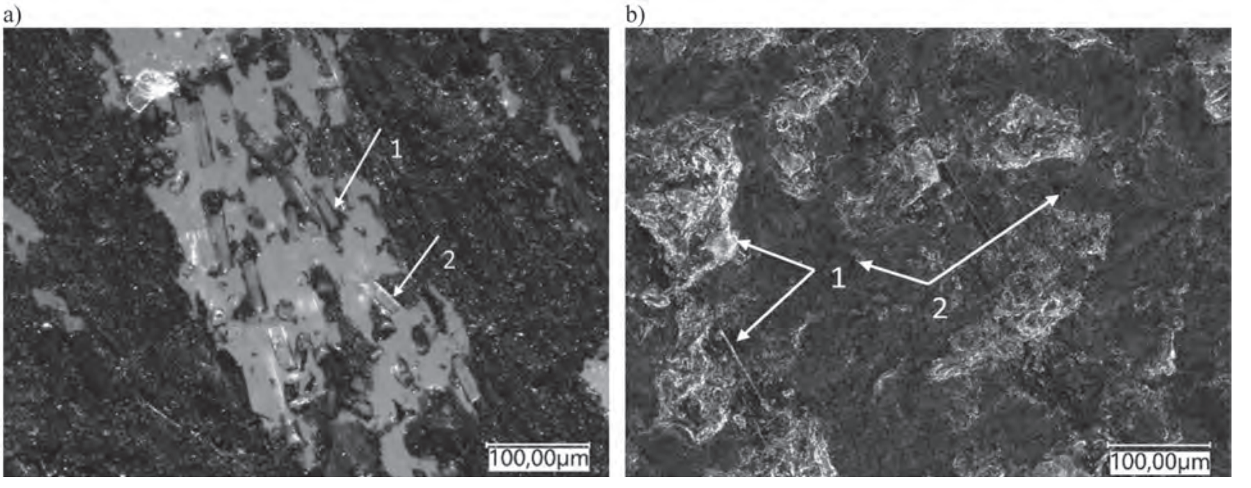

Fig. 6. The surfaces of: a) PTFE GF25 composite specimen, b) steel counter specimen
Rys. 6. Powierzchnia: a) próbki kompozytu PTFE GF25, b) przeciwpróbki stalowej

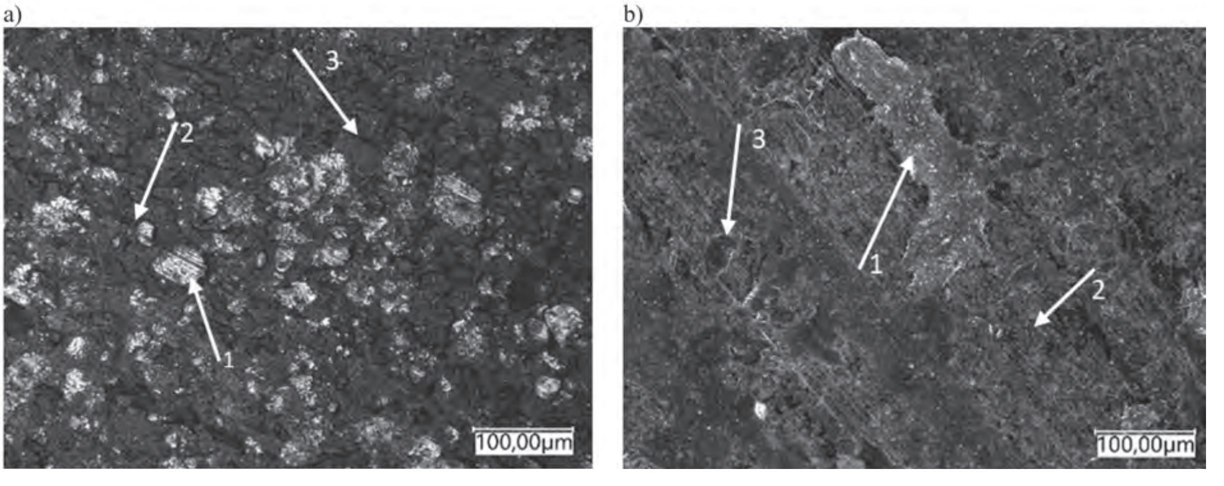

Fig. 7. The surfaces of: a) PTFE BZ 40 composite specimen, b) steel counter specimen
Fig. 7. Powierzchnia: a) próbki kompozytu PTFE BZ 40, b) przeciwpróbki stalowej

the specimen and coated with a polymer film, were identified on the counter specimen surface (**Fig. 7b3**).

It was observed that the wear marks are not distributed uniformly over the entire contact area, which is related to its geometry which represents the interaction between the shaft neck and the slide bearing sleeve. What is typical of the interaction of such parts is the uneven wear of the sleeve, caused by uneven load distribution due to rotational motion of the shaft. The contact geometry adopted by the presented study better represents the operating conditions of the slide bearing sleeve than the "pin-on-disc" geometry, commonly described in the literature and used to assess the wear resistance of materials used for manufacturing slide bearings.

CONCLUSIONS

1. The lowest wear rate was exhibited by the PTFE composite with the 25% addition of glass fibre (PTFE GF25). The highest wear rate was observed for the PTFE BZ40 composite: it was 20-fold higher than that of PTFE GF25.
2. It was observed that the addition of both glass fibre and carbon fibre filler to PTFE increased the composite hardness and its resistance to abrasive wear.
3. The surfaces of the composites under study show scratching, ridging, and adhesive wear marks. The rate of particular wear forms was determined by the filler type in the composite. The surface of the composite with bronze filler

was characterised by the highest proportion of adhesive wear. As regards the PTFE GF25 composite, it was observed that, after the removal of the polymer matrix from the material surface due to friction, the filler fibres, which reduced the rate of wear impact of the counter specimen on the material, were exposed.

4. For all tested polymers, transfer of the composite material onto the counter specimen surface was noted. This process proceeded particularly intensely for the bronze-reinforced PTFE, which can be linked to the strong adhesion between steel and bronze. This process resulted in bronze particle build-up formed on the steel counter specimen surface, which intensified the composite wear process.

REFERENCES

1. Lawrowski Z.: Bezobsługowe łożyska ślizgowe, Oficyna Wydawnicza Politechniki Wrocławskiej, 2001.
2. Szczerek M.: Badania tribologicznych własności materiałów, “Tribologia, Teoria i Praktyka” 1993. Rok XXIV, No. 43–70.
3. Wieleba W.: Bezobsługowe łożyska ślizgowe z polimerów termoplastycznych, Oficyna Wydawnicza Politechniki Wrocławskiej 2013.
4. Capanidis D.: Mechanizm tarcia i zużywania wieloskładnikowych kompozytów na osnowie polioksymetylenu, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2013, pp. 7–10.
5. Zwierzycki W.: Zagadnienia identyfikacji procesów zużywania w styku tarciowym, 2000.
6. Yu L., Yang S., Wang H., Xue Q.: An investigation of the friction and wear behaviors of micrometer copper particle and nanometer copper particle filled polyoxymethylene composites, “Journal of Applied Polymer Science” 2000, 77(11), pp. 2404–2410.
7. Królikowski W.: Polimerowe kompozyty konstrukcyjne, Wydawnictwo Naukowe PWN, Warszawa 2012.
8. Wieleba W.: The statistical correlation of the coefficient of friction and wear rate of PTFE composites with steel counterface roughness and hardness, “Wear” 2002, 252(9–10), pp. 719–729.
9. Capanidis D., Wieleba W., Woźniak J., Wierciak M.: Właściwości tribologiczne wybranych materiałów polimerowych wytworzonych z recyklatu, “Tribologia” 2007, (2), pp. 117–126.
10. Krawiec S.: On the mechanism of the synergistic effect of PTFE and copper in a lithium grease lubricant, “Industrial Lubrication and Tribology” 2011.
11. Salunkhe S., Chandankar P.: Friction and Wear Analysis of PTFE Composite Materials. In Innovative Design, Analysis and Development Practices in Aerospace and Automotive Engineering (I-DAD 2018), Springer, Singapore 2019, pp. 415–425.
12. Rymuza Z.: Trybologia polimerów ślizgowych, WNT, Warszawa 1984.
13. Campbell K.L., Sidebottom M.A., Atkinson C.C., Babuska T.F., Kolanovic C.A., Boulden B.J., Krick B.A.: Ultralow wear PTFE-based polymer composites – the role of water and tribochemistry, “Macromolecules” 2019, 52(14), pp. 5268–5277.
14. Szczerek M., Wiśniewski M. (eds.): Tribologia i tribotechnika, Wydaw. Instytutu Technologii Eksploatacji, Radom 2000.
15. Deli G., Qunji X., Hongli W.: Physical models of adhesive wear of polytetrafluoroethylene and its composites, “Wear” 1991, 147(1), pp. 9–24.