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STUDY OF RESISTANCE TO ABRASIVE WEAR OF MULTICOMPONENT POLYOXYMETHYLENE COMPOSITES

BADANIA ODPORNOŚCI NA ZUŻYCIE ŚCIERNE WIELOSKŁADNIKOWYCH KOMPOZYTÓW NA OSNOWIE POLIOKSYMETYLENU

Key words:

abrasive wear, POM composites, powder of PEEK, powder of bronze, chopped glass fibres, glass microballs

Słowa kluczowe:

zużycie ścierne, kompozyty POM, proszek PTFE, proszek brązu, włókna szklane cięte, mikrokulki szklane

Abstract

The article presents the results of the comparative tribological study of the resistance of multicomponent polyoxymethylene (POM) composites to abrasive wear. The fillers for the studied POM matrix composites were a PTFE powder, the bronze powder, chopped glass fibre, and glass microballs, which were used both individually and in various combinations. Quantities of the composites were developed based on the simplex plan of the experiment. For the research, a Tester T-07 was used as a test stand. The study was conducted in the presence

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of loose abrasive, electrocorundum F90, subjected to the same conditions of friction for all the tested composites. The study has shown that the most effective compound in increasing resistance to the abrasive wear of the POM composites is the powder of bronze and the hybrid glass filler; whereas, the PTFE powder caused a slight reduction in the resistance to abrasive wear. In order to explain the mechanism of the abrasive wear of the studied composites, a microscopic examination of their friction surface before and after friction was conducted. Based on that study, the effect of particular fillers on the abrasive wear resistance of the tested POM composites was determined.

INTRODUCTION

Polyoxymethylene (POM) is widely used in various elements of machines and devices, such as gears, pulleys, chains, chain wheels, slide bearings sleeves, guide rolls, wheels, as well as housings and bodies **[L. 1–3]**. The elements are, in many cases, exposed to intensive abrasive wear that is caused by hard particles of dirt in the friction area or the excessive roughness of the friction surface of a collaborating rigid metallic element **[L. 4–5]**. In these situations, it is the resistance to the abrasive wear that is the determinant for selecting the suitable polymeric material for the making of such machine and device elements that will provide them with the required durability and operational reliability **[L. 6–7]**. The abrasive wear is caused by the loss of the polymeric material in the top layer as a result of separating the particles resulting from microcutting, scratching, or ridging **[L. 5]**. In order to improve the abrasive wear resistance of the polymers, various technological measures are taken, including their physical modification **[L. 8]**. Numerous researchers have tried to define the factors that primarily determine the abrasive wear resistance of polymeric materials, but so far they have failed to clearly establish this relationship. In their study on the abrasive wear of selected polymer types, Rajesh, Bijwe, and Tewari **[L. 9]** found that the abrasive wear showed a relatively good correlation with some mechanical properties, such as the coefficient of plasticity, crack initiation stress, fracture surface energy, the critical crack length, the tensile modulus, the cracking velocity, etc. However, a full linear correlation was not observed, because other physical properties, such as crystallinity, molecular weight, or microstructure also influence the mechanical properties. They also showed that the abrasive wear of the polyamids does not depend on one material property. Budinski, on his part **[L. 10]**, showed that plastics that are easier to deform by the impact of loose abrasive particles are less prone to generating material wear products by scratching and present a higher resistance to abrasive wear. This behaviour is connected with the energy required for the plastic deformation of the polymeric material. A similar pattern was observed in **[L. 3]** that the higher yield polymers, such as PE or PP, are more resistant to abrasive wear than the higher rigidity polymers, such as PS. This is explained by the fact that during friction, the loose particles of the abrasive material result in the chipping of the surface layer material in the high rigidity polymers, while in the higher yield polymers, the elastic-plastic deformation is observed, which does not cause the chipping of the plastic material. Furthermore, it was observed that an increase in the size of the abrasive grains reduces the abrasive wear resistance of the polymers under investigation.

THE TRIBOLOGICAL RESEARCH OBJECTIVES

The aim of the tribological research was to determine the effect of selected fillers used in various combinations in the POM composites on their resistance to abrasive wear and to clarify the mechanism of the effect of particular fillers on the process of abrasive wear of the studied composites.

TESTED MATERIALS

The tribological comparative tests of resistance to abrasive wear included an unmodified POM and POM matrix composites with three types of fillers: the PTFE powder, the bronze powder and the hybrid glass filler (cut glass fibre and glass microballs in an equal weight relation) **[L. 8]**. Particular fillers in the composites were used both separately and in various combinations. Quantities of particular composites were prepared using the simplex plan of the experiment **[L. 8, 11]** and are given in **Table 1**.

Table 1. The share of individual fillers [% by volume]
Tabela 1. Udział poszczególnych napełniaczy [% objętościowo]

Composite	POM matrix	PTFE powder	Bronze powder	Glass filler
Nr 1	100	0	0	0
Nr 2	64	36	0	0
Nr 3	40	0	60	0
Nr 4	76	0	0	24
Nr 5	82	18	0	0
Nr 6	70	0	30	0
Nr 7	88	0	0	12
Nr 8	52	18	30	0
Nr 9	70	18	0	12
Nr 10	58	0	30	12
Nr 11	68	12	20	0
Nr 12	80	12	0	8
Nr 13	72	0	20	8
Nr 14	60	12	20	8
Nr 15	70	9	15	6

A view of the samples used in the abrasive wear resistance research is presented in **Figure 1**.

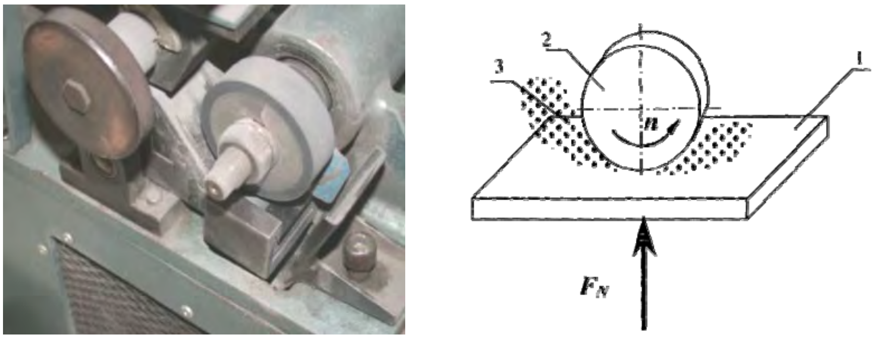
Fig. 1. Samples for abrasive wear resistance test: 1 – unmodified POM, 2–7 – two-component composites POM, 8–9 – three-component composites POM, 14–15 – four-component composites POM

Rys. 1. Próbki do badań odporności na zużycie ścierne: 1 – niemodyfikowany POM, 2–7 – dwuskładnikowe kompozyty POM, 8–9 – trójskładnikowe kompozyty POM, 14–15 – czteroskładnikowe kompozyty POM

The components of each composite were mixed by repeated rolling on heated rolls up to the point when a satisfactory homogenization of the mixture was achieved, and then, the material was crushed in a mill to form small particles (chips) which, by means of injection moulding, were used for the making of blocks - discs of 110 mm in diameter and 12 mm in thickness **[L. 8]**. Next, from the blocks, samples were cut out for the abrasive wear resistance tests. The samples were 30x20x3 mm plates that were then polished on both sides in order to obtain flat surfaces involved in the friction.

METHOD OF THE TRIBOLOGICAL STUDY

The tribological study of the polymers' resistance to abrasive wear was carried out on a T-07 test stand **[L. 13, 14]**. In paper **[L. 12]**, Tester T-07 proved useful for that type of research on polymer materials. Views of the friction couple as well as a diagram of the research method are shown in **Figure 2**.



a) b)

Fig. 2. View of the friction couple – a) diagram of the test of resistance to abrasive wear – b); 1 – sample of composite material, 2 – rubber roll, 3 – abrasive [L. 3]

Rys. 2. Widok pary ciernej – a) schemat metody badania odporności na zużywanie ścierne – b); 1 – próbka z badanego materiału, 2 – rolka gumowa, 3 – ścierniwo **[L. 3]**

The method is compliant with the Russian norm GOST 23.208-79, which includes guidelines for the examination of the abrasive wear resistance of materials and of the abrasive wear protection coatings. A sample of the tested material (1) during the test is pressed with a force of $\boldsymbol{F_N}$ = 44.4 N to a rubber disc (2) (diameter d = 50 mm) rotating at a constant rotational speed N = 60 rev/min. Between the rotating disc and the fixed sample, loose abrasive (3) is continuously supplied causing the abrasion of the sample. The abrasive recommended in this method is electrocorundum F90 (according to DIN ISO 8486:1998). The reference sample was made of standardized steel C45 of approx. 200 HB hardness. In the experiments, the weight wear of $\boldsymbol{Z_{wb}}$ sample occurring after number $\boldsymbol{N}_b$ = 150 rpm of revolutions of the rubber roller assumed for the tested materials featuring hardness lower than 400 HV was defined.

In the case of the standard steel sample $\boldsymbol{N_w}$ = 600 rpm assumed for materials of the hardness equal to or higher than 400 HV, based on the weight wear measurement, the abrasive wear resistance ratio $\boldsymbol{K}_b$ from the equation (1) was derived, which is defined as the volumetric wear ratio of standard sample $\boldsymbol{Z}_{Vw}$ to the volumetric wear of the studied materials Z_{Vb}.

$$K_b = \frac{Zv_w / N_w}{Zv_b / N_b} = \frac{Z_{ww} \cdot \rho_b \cdot N_b}{\rho_w \cdot Z_{wb} \cdot N_w} \tag{1}$$

where: $\boldsymbol{Z}_{ww}$ – weight wear during the test of the standard steel sample (C45 steel), $\boldsymbol{Z}_{wb}$ – weight wear during the test of of the studied material, $\boldsymbol{\rho}_w$ – material density of the standard sample, $\boldsymbol{\rho}_b$ – material density of the tested sample, $\boldsymbol{N}_w$ – number of revolutions of the standard sample friction path, $\boldsymbol{N}_b$ – number of revolutions of the tested sample friction path.

RESULTS AND ANALYSIS OF THE TRIBOLOGICAL RESEARCH

The test results of the weight abrasive wear $\boldsymbol{Z}_{wb}$ are presented in **Table 2**.

Table 2. The results of tribological tests of POM composites
Tabela 2. Wyniki badań tribologicznych kompozytów POM

Material number	Average weight wear $\boldsymbol{Z}_{wb}$ [g]	Density ρ_b [g/cm^3]	Abrasive wear resistance ratio $\boldsymbol{K}_b$	Confidence interval for $\boldsymbol{K}_b$
1	0.06	1,404	0.054	0.00082
2	0.076	1,668	0.052	0.00978
3	0.191	5,893	0.073	0.01193
4	0.053	1,553	0.069	0.00340
5	0.077	1,497	0.046	0.01024
6	0.133	3,740	0.066	0.00574
7	0.049	1,434	0.069	0.00457
8	0.142	3,621	0.060	0.00648
9	0.066	1,582	0.056	0.00096
10	0.118	3,857	0.077	0.00995
11	0.136	2,918	0.051	0.01066
12	0.059	1,548	0.064	0.01010
13	0.096	3,041	0.075	0.00866
14	0.117	2,949	0.06	0.01
15	0.102	2,774	0.064	0.01

The same table also shows the experimentally determined density ρ_b of the studied composites, calculated as the average of 6 measurements, and the average values of abrasive wear resistance rates $\boldsymbol{K}_b$ of the tested materials and their confidence intervals determined on the basis of the t-Student distribution at a $\alpha = 0.05$ significance level. In order to facilitate the analysis of the impact of the studied POM composites on the value of rate $\boldsymbol{K_b}$, the research results have been presented in the following graphs including the two and three-component composites **(Fig. 3, 4, 5)**.

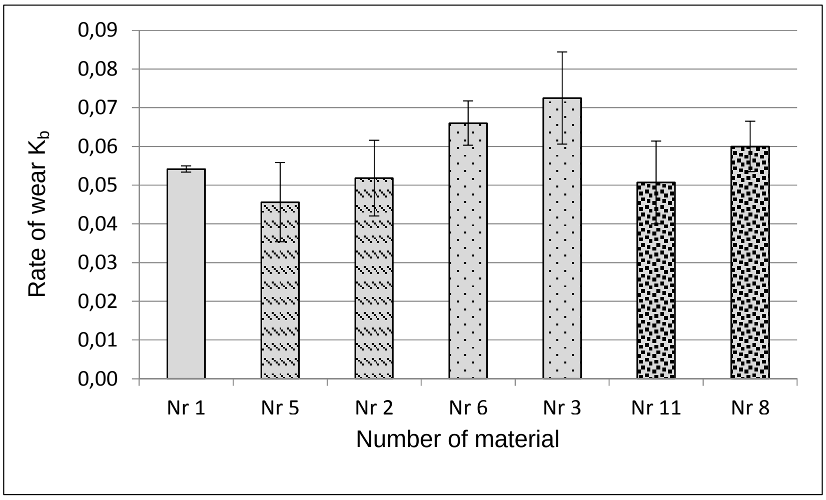


Fig. 3. The rate of abrasive wear resistance K_b of POM composites containing PTFE powder or/and bronze powder

Rys. 3. Wskaźnik odporności na zużywanie ścierne K_b kompozytów POM zawierających proszek PTFE lub/i proszek brązu

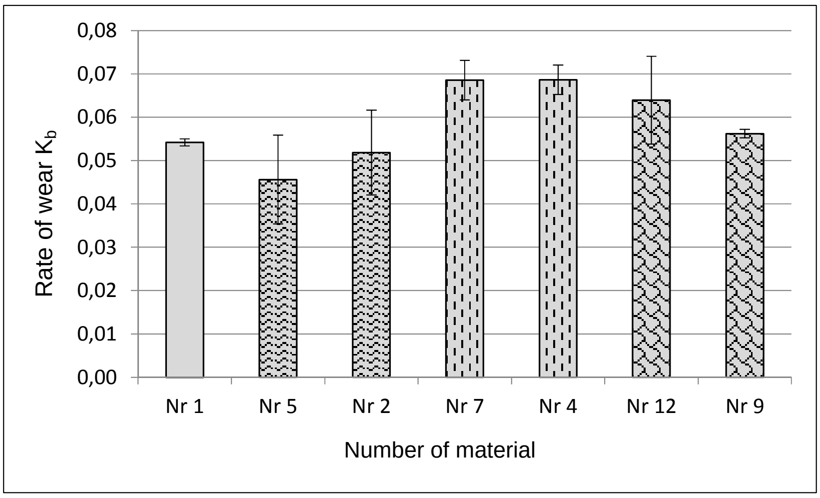


Fig. 4. The rate of abrasive wear resistance K_b of the two-component POM composites containing PTFE powder or/and glass filler

Rys. 4. Wskaźnik odporności na zużywanie ścierne K_b dwuskładnikowych kompozytów POM zawierających proszek PTFE lub/i napełniacz szklany

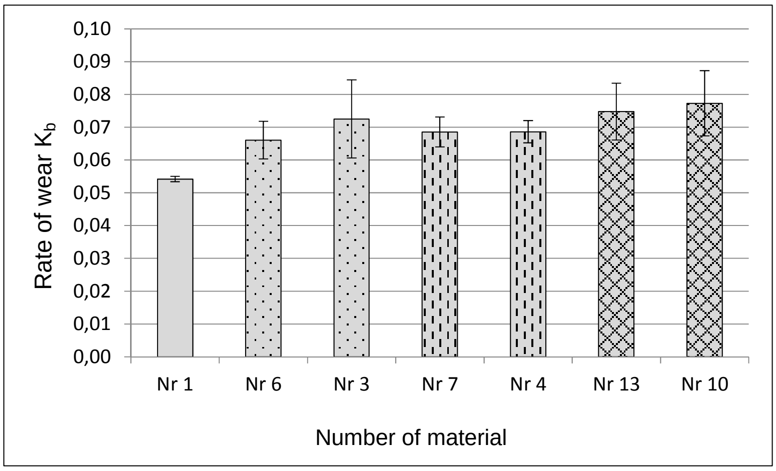


Fig. 5. The rate of abrasive wear resistance K_b of POM composites containing the bronze powder or/and glass filler

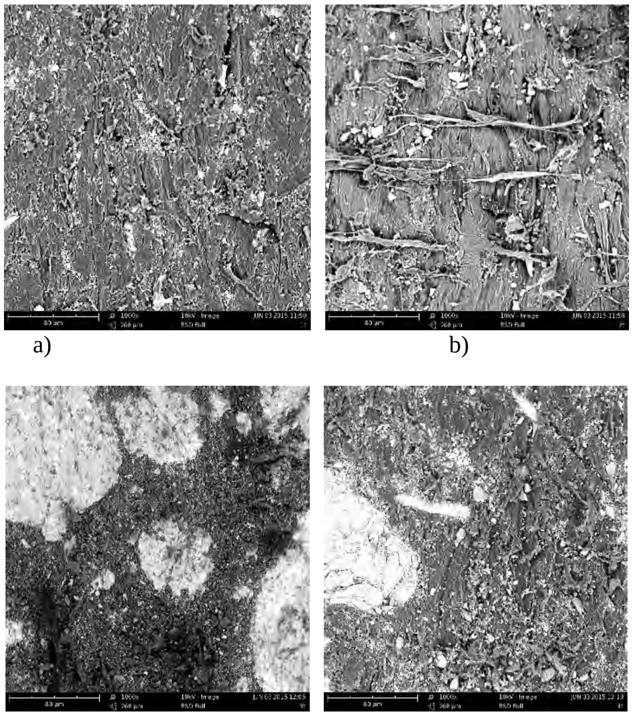
Rys. 5. Wskaźnik odporności na zużywanie ścierne K_b kompozytów POM zawierających proszek brązu lub/i napełniacz szklany

The tribological research results show that the PTFE, as a POM filler used individually, caused a minor decrease in the abrasive wear resistance of such composites (Numbers 5 and 2, **Figs. 3** and **4**), while the POM composites containing hard particles of the fillers, bronze powder (Numbers 6 and 3), and of the hybrid glass filler (Numbers 7 and 4) presented higher abrasive wear resistance (**Figs. 5, 3,** and **4**) compared to the unmodified POM.

In the case of the three-component composites, the highest abrasive wear resistance was presented by the composite combining the bronze powder and the hybrid glass filler (Numbers 10 and 13), the abrasive wear resistance rate of which increased by over 42% compared to the unmodified POM (Number 1, **Fig. 5**). The PTFE powder used in POM composites combined with other fillers (Numbers 12 and 9, as well as 11 and 8) caused an increase in the abrasive wear resistance of the composites (**Figs. 3** and **4**) compared to the unmodified POM, similar to the four-component composites (Numbers 13 and 14, **Tab. 2**).

RESULTS AND ANALYSIS OF THE MICROSTRUCTURAL RESEARCH

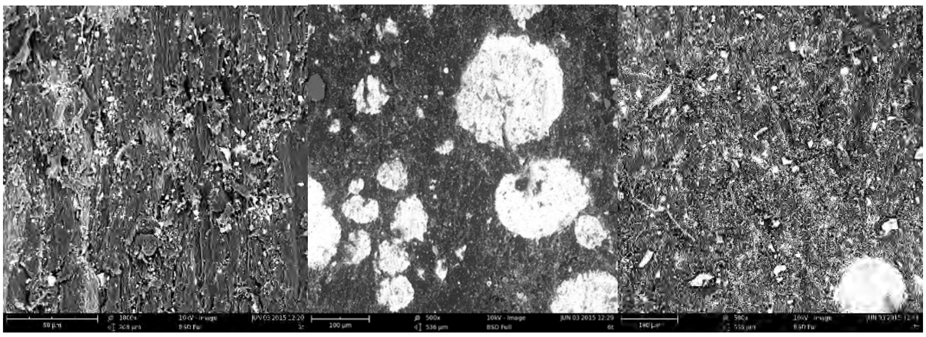
The microscopic studies were carried out by means of the ProX Phenom scanning electron microscope. Figure 6 shows micrographs of the surface after the friction process of the unmodified POM and POM composites with individually applied fillers of their maximum content assumed for the studies, and **Figure 7** presents micrographs of the same type of composites, but with half the content of the fillers.



a) b) c) d)

Fig. 6. The friction surface after the abrasive wear process: a – Number 1: POM, b – Number 2: POM + 36% PTFE powder, c – Number 3: POM + 60% bronze powder, d – Number 4: POM + 24% glass filler

Rys. 6. Powierzchnia ślizgowa po procesie tarcia; a – nr 1: POM, b – nr 2: POM + 36% proszku PTFE, c – nr 3: POM + 60% proszku brązu, d – Nr 4: POM + 24% napełniacza szklanego



a) b) c)

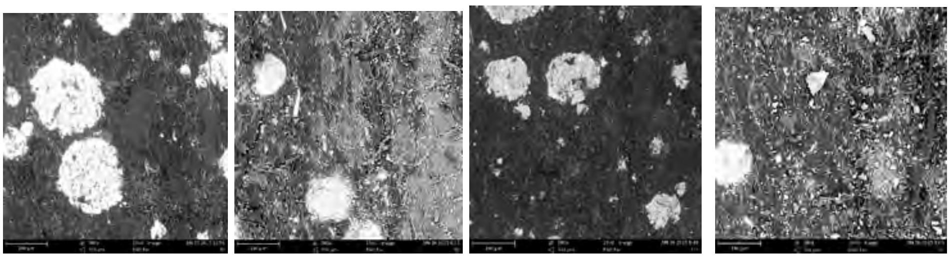
Fig. 7. The friction surface after the abrasive wear process: a – Number 5: POM + 18% PTFE powder, b – Number 6: POM + 30% bronze powder, c – Number 7: POM + 12% glass filler

Rys. 7. Powierzchna ślizgowa po procesie tarcia; a – nr 5: POM + 18% proszku PTFE, b – nr 6: POM + 30% proszku brązu, c – nr 7: POM + 12% napełniacza szklanego

The area of the unmodified POM after friction (**Fig. 6a**) is characterized by distinct traces of microcutting, scratching, and ridging by the electrocorundum grains, proving its intensive abrasive wear. On the surface of the POM composite with the PTFE powder (**Figs. 6b** and **7a**), there are numerous strips of the PTFE drawn from the top layer, as well as traces of the surface damage caused by the interaction with the grains of the abrasive. The POM composite with the bronze powder (**Figs. 6c** and **7b**) has a relatively smooth surface with only a few traces of interactions typical of the abrasive wear process. The surface of the POM composite with the hybrid glass filler composite (**Figs. 6d** and **7c**) can be characterized similarly, but, in that case, it is more damaged due to the activity of the loose abrasive and of the crashed glass filler particles.

Figure 8 shows micrographs of the surface after the friction tests in the presence of the loose abrasive of the three-component POM composite featuring the PTFE powder and the bronze powder (**Figs. 8a** and **8c**) or the glass filler (**Figs. 8b** and **8d**), differing in the quantity of particular fillers. The composites containing relatively hard filler particles (of the bronze and glass filler) together with the powder PTFE show considerably more visible traces of the surface damage, resulting not only from the interaction with the loose grains of the electrocorundum, but also with the hard filler particles ripped out of the composites' matrix, which was not observed in the composites without the PTFE powder (**Figs. 6** and **7**).

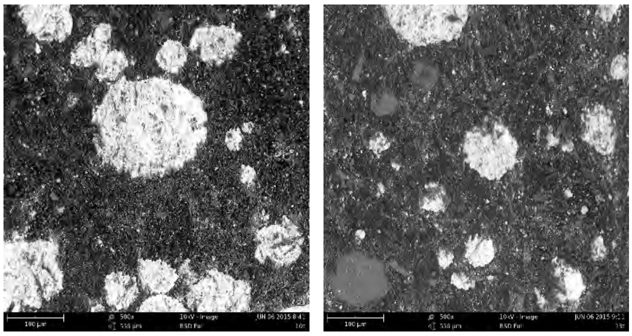
This observation was also confirmed by micrographs of the surface after the friction process of the composites containing both the bronze powder and the glass filler (Numbers 10 and 13) but without the PTFE powder (**Fig. 9**). These surfaces are less damaged and have hardly any ripped out particles of the fillers, which confirms the PTFE's role in the weakening of the combination of those fillers with the POM matrix.



a) b) c) d)

Fig. 8. The sliding surface after the friction process; a – Number 8: POM + 18% PTFE + 30% bronze, b – Number 9: POM + 18% PTFE + 12% glass filler, c – Number 11: POM + 12% PTFE + 20% bronze, d – Number 12: POM + 12% PTFE + 8% glass filler

Rys. 8. Powierzchnia ślizgowa po procesie tarcia; a – nr 8: POM + 18% PTFE + 30% brązu, b – nr 9: POM + 18% PTFE + 12% napełniacza szklanego, c – nr 11: POM + 12% PTFE + 20% brązu, d – nr 12: POM + 12% PTFE + 8% napełniacza szklanego



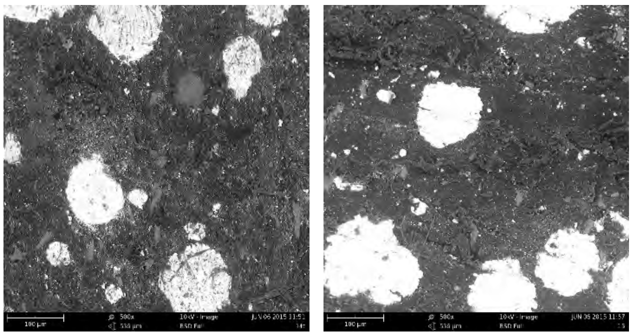
a) b)

Fig. 9. The friction surface after the abrasive wear process; a – Number 10: POM + 30% bronze powder + 12% glass filler, b – Number 13: POM + 20% bronze powder + 8% glass filler

Rys. 9. Powierzchnia ślizgowa po procesie tarcia; a – nr 10: POM + 30% proszku brązu + 12% napełniacza szklanego, b – nr 13: POM + 20% proszku brązu + 8% napełniacza szklanego

Figure 10 shows micrographs of the surface of the POM composites containing all types of the fillers used, but differing in their quantitative content. The surfaces of those composites are more damaged by the abrasive action compared to the surface of the composites which did not contain the PTFE, which is another proof confirming the conclusion about the role of this filler in the POM composites.

The composite containing a lower percentage of the fillers (Number 15, **Fig. 10b**), including a lower content of the PTFE powder, namely 9%, had a less damaged surface than composite Number 14 (**Fig. 10a**) containing 12% of the PTFE powder and showed a slightly greater resistance to the abrasive wear.



a) b)

Fig. 10. The friction surface after the abrasive wear process; a – Number 15: POM + 12% PTFE powder + 20% bronze powder + 8% glass filler, b – Number 15: POM + 9% PTFE powder + 15% bronze powder + 6% glass filler

Rys. 10. Powierzchnia ślizgowa po procesie tarcia; a – nr 14: POM + 12% proszku PTFE + 20% proszku brązu + 8% napełniacza szklanego, b – nr 15: POM + 9% proszku PTFE + 15% proszku brązu + 6% napełniacza szklanego

The least damaged surface after the friction process was observed in the POM composites that did not contain the PTFE powder. They also proved to be more resistant to the abrasive wear, which was higher proportionally to the percentage of the hard filler particles, like in the case of composite Number 10 or composite Number 13, for instance (or, alternatively, Numbers 3 and 4).

CONCLUSIONS

Based on the study, the following conclusions have been drawn:
1. Among the tested POM fillers, the highest efficiency increasing the abrasive wear resistance of the POM composites were featured by the powder of bronze and, only slightly lower, the hybrid glass filler.
2. The PTFE powder used individually as a POM filler resulted in a minor decrease in the abrasive wear resistance of the composites.
3. The greatest resistance to the abrasive wear, of all the test materials, was presented by the POM composite combining the bronze powder and the hybrid glass filler, the wear rate of which increased by more than 42% compared to the unmodified POM.
4. The POM composites containing hard filler particles, the bronze powder, and the hybrid glass filler were characterized by a higher mechanical strength, causing an increase in the abrasive wear resistance of the POM composites.
5. The PTFE powder, used in the POM composites in combination with other fillers, caused a weakening of the combination of the bronze powder and glass filler particles with the POM matrix, which reduced the abrasive wear resistance of those composites.

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Streszczenie

W artykule przedstawiono wyniki tribologicznych badań porównawczych odporności na zużywanie ścierne wieloskładnikowych kompozytów na osnowie polioksymetylenu (POM). W badanych kompozytach na osnowie POM użyto następujących napełniaczy: proszek PTFE, proszek brązu, włókna szklane cięte i mikrokulki szklane, które stosowano oddzielnie i w różnych zestawieniach. Składy ilościowe kompozytów opracowano na podstawie planu sympleksowego eksperymentu. Do badań wykorzystano stanowisko badawcze Tester T-07. Badania prowadzono w obecności luźnego ścierniwa, którym był elektrokorund F90, z zachowaniem jednakowych warunków tarcia dla wszystkich badanych kompozytów. Badania te wykazały, że największą efektywność zwiększającą odporność na zużywanie ścierne kompozytów POM wykazał proszek brązu oraz hybrydowy napełniacz szklany, natomiast proszek PTFE powodował nieznaczne zmniejszenie odporności na zużywanie ścierne. W celu wyjaśnienia mechanizmu zużywania ściernego badanych kompozytów przeprowadzono badania mikroskopowe ich powierzchni trących przed i po procesie tarcia. Na podstawie tych badań określono wpływ poszczególnych napełniaczy na odporność na zużywanie ścierne testowanych kompozytów POM.