Władysław SKONECZNY*, Sławomir KAPTACZ*, Adrian BARYLSKI**, Tomasz KMITA*

ANALYSIS OF TRIBOLOGICAL PROPERTIES OF SELECTED PTFE-BASED POLYMER COMPOSITES IN A SLIDING INTERACTION WITH ALUMINIUM OXIDE (AL_2O_3)

ANALIZA WŁAŚCIWOŚCI TRIBOLOGICZNYCH WYBRANYCH KOMPOZYTÓW POLIMEROWYCH NA BAZIE PTFE WSPÓŁPRACUJĄCYCH ŚLIZGOWO Z TLENKIEM GLINU (AL_2O_3)

Key words: wear, friction modifiers, hardness, PTFE, surface roughness.

Abstract The paper presents the microstructure and mechanical and tribological properties of polymer composites based on polytetrafluoroethylene (PTFE) intended for use in friction couples where reciprocating motion is performed, e.g., in compressors or actuators. Micromechanical tests carried out using the Oliver-Pharr method showed that the PTFE composite with a 40% bronze content (T8B) had the most advantageous mechanical properties (hardness H, Young's modulus E). In turn, tribological tests that were conducted using a ball-on-disc tester in the linear (reciprocating) motion showed that the polytetrafluoroethylene composite with a mixture of 25% bronze powder and 15% graphite (T4GM) had the lowest tribological wear. The tribological properties of composite T5W with 25% graphite content were not much worse. Despite the most favourable mechanical parameters, the tribological wear of composites T8B and PTFE with glassy carbon (T3Ws) was nearly twice higher due to the absence of grease formed by a graphite filling. The results show that the use of composites containing a bronze-graphite filling improves the service life of lubricant-free friction couples that perform reciprocating motion.

Słowa kluczowe: zużycie, modyfikatory tarcia, twardość, PTFE, chropowatość powierzchni.

Streszczenie W artykule przedstawiono mikrostrukturę, właściwości mechaniczne i tribologiczne kompozytów polimerowych na osnowie politetrafluoroetylenu z myślą o zastosowaniu w węzłach tarcia urządzeń realizujących ruch posuwisto-zwrotny takich jak sprężarki oraz siłowniki. Technika pomiaru twardości instrumentalnej pozwoliła w oparciu o metodę Olivera-Pharra wyznaczyć twardość (H) i moduł Younga (E). Najkorzystniejsze właściwości mechaniczne miał kompozyt PTFE z 40% zawartością brązu (T8B). Badania tribologiczne przeprowadzono z kolei na stanowisku kula–tarcza w ruchu liniowym (posuwisto-zwrotnym). Testy wykazały, że najmniejszym zużyciem tribologicznym charakteryzował się kompozyt politetrafluoroetylenu z mieszanką 25% proszku brązu i 15% grafitu (T4GM). Niewiele gorsze właściwości tribologiczne miał kompozyt T5W z 25% zawartością węgla. Pomimo najkorzystniejszych parametrów mechanicznych kompozyty T8B oraz PTFE z węglem szklanym (T3Ws) charakteryzowały się blisko 2-krotnie wyższym zużyciem tribologicznym ze względu na brak obecności smaru stałego w postaci wypełnienia grafitem. Otrzymane wyniki wskazują, że zastosowanie kompozytów zawierających wypełnienie brąz–grafit sprzyja poprawie trwałości eksploatacyjnej bezsmarowych węzłów tarcia realizujących ruch posuwisto-zwrotny.

INTRODUCTION

Polytetrafluoroethylene (PTFE) is one of the most popular and most commonly used plastic materials in the machine building industry. This is due to its very low friction coefficient and the anti-adhesion of other materials to the PTFE surface [**L. 1–4**]. The basic properties of polytetrafluoroethylene are as follows:

- High thermal resistance – it can work at temperatures from –200°C to +260°C.

* University of Silesia in Katowice, Institute of Technology and Mechatronics, ul. Żytnia 10, 41-200 Sosnowiec, Poland email: tomasz.kmita@us.edu.pl.

** University of Silesia in Katowice, Institute of Materials Science, ul. 75 Pułku Piechoty 1A, 41-500 Chorzów, Poland.

- High chemical resistance – PTFE is characterized by resistance to most of chemical substances. It is affected by alkali metals, chlorine trifluoride, and fluorine.
- PTFE is not soluble in practically any solvent.
- It is resistant to environmental ageing (the effect of atmosphere and light).
- It does not absorb water.
- It is resistant to friction.
- It has self-lubricating properties.
- It has excellent dielectric and anti-adhesive properties.

The issues of friction couples relate to a number of the basic components of machines, whose functionality determines the reliability and durability of the machines and devices. A number of opposing properties are required from the materials used in friction couples: deformability and abrasion resistance, providing a maximum surface area of real shape and minimal friction, the stability of the shape and deformability, etc. Therefore, material selection is one of the basic issues in the development of friction couples. The use of lightweight, easily machinable polymer composites, with high vibration damping capability, decreases friction losses, reduces noise and vibration, extends the range of operation, and improves the reliability and durability of the mechanisms.

In certain situations, polymer sliding couples used in machines and technical appliances are the basis for the operation of some mechanisms. This happens when certain products and items cannot be contacted with some sliding materials or lubricants. Such operating conditions of sliding couples occur, among others, in the food processing, paper making, textile, pharmaceutical and medical industries. In such applications of friction couples, plastic materials, which have been used for many years as sliding materials, are of particular importance. Thermoplastic polymers are most commonly used. However, the increasing demands placed on these materials by designers and operators cause that new polymer sliding materials are still being sought. Most often, the modification of already existing plastics is used to create new sliding materials. The modification process can be carried out in different processing phases. The most commonly encountered modification methods include the filling of the base polymer with fillers (modifiers). Modification of polymers by this method, in order to improve their tribological properties, most often consists in introducing fillers, such as graphite, molybdenum disulphide (MoS_2), metal and non-metal powders, fiberglass, carbon fibre, etc. [**L. 5–11**]. These fillers can be introduced separately (two-component composites) or simultaneously, in different combinations and quantities (multi-component composites). Modification of the polymer with many types of filler at the same time is generally more effective, but it is not always possible to fully predict its effects, due to the synergy of the fillers in the polymer matrix of the composite.

EXPERIMENTAL DETAILS

Materials

PTFE is characterized by low tensile and compressive strength, flow, even at not very high loads, and low resistance to wear. Therefore, it is usually modified by introducing appropriate fillers. Fibrous fillers (fiberglass, carbon fibre) reduce creep, shrinkage, and thermal expansion, and improve wear resistance of composites. In the case of dispersion fillers, the best results were observed for composites containing bronze powder. These composites exhibit high wear resistance with a relatively low friction coefficient under different operating conditions. Other widely applied dispersive fillers are graphite and molybdenum disulphide. Their positive effect, especially of graphite, is evident at high loads of composites.

In devices where the reciprocating motion is performed, one of the weakest elements in terms of quality of work of the whole device is the sliding couples, which include, among others, technical seals. In the piston-cylinder combination in a number of modern compressors and pneumatic actuators, the sliding cooperation takes place at the contact: Al_2O_3 coating – plastic material. Such a pairing allows the operation in conditions of technically dry friction [**L. 12–13**]. Machine components made of such materials can operate without service throughout the life of the equipment in places where impurities must be eliminated for environmental or technological reasons. State-of-the-art piston rings made of PTFE composites can be used, primarily where the operating conditions have made lubrication impossible or in chemically aggressive environments.

The following PTFE-based polymer composites were the object of the tribological tests:

- Composite **T5W** with the composition: 75% of PTFE powder, 25% of prepared carbon powder.
- Composite **T4GM** with the composition: 60% of PTFE powder, 25% of bronze powder, 15% of graphite.
- Composite **T3Ws** with the composition: 85% of PTFE powder, 15% of fiberglass.
- Composite **T8B** with the composition: 60% of PTFE powder, 40% of bronze powder.

Composite materials were supplied by the Materspec Company in the form of rods, 40 mm in diameter. The selection of materials was, inter alia, the effect of positive results of tribological tests performed in the Department of Technology and Mechatronics at the University of Silesia in interaction with Al_2O_3 surface layers [**L. 14–15**]. **Figure 1** shows the microstructures of the tested composites. The tests were conducted using a NEOPHOT 2 light microscope. **Table 1** presents the physicochemical and mechanical properties of the tested polymer composites according to the manufacturer's quality certificates.

Table 1. Physicochemical and mechanical properties of the tested polymer composites
Tabela 1. Właściwości fizykochemiczne badanych kompozytów polimerowych

Physicochemical and mechanical properties		Type of material			
		T5W	T4GM	T3Ws	T8B
Apparent density	[kg/dm³]	above 2	above 2.1	above 2.25	above 3.8
Water absorption	[%]	above 1	no data available	below 0.5	no data available
Shore D hardness	[°Sh]	above 65	above 60	above 60	above 65
Mechanical tensile strength	[MPa]	no data available	min 15	no data available	above 20
Unit elongation	[%]	no data available	above 150	no data available	60 – 90
Linear thermal expansion (20°C –200°C)	[$1/°C \cdot 10^{-5}$]	no data available	9.0 – 11.0	no data available	7.8 – 10.1
Mechanical breaking strength	[MPa]	no data available	no data available	magn. 20	no data available

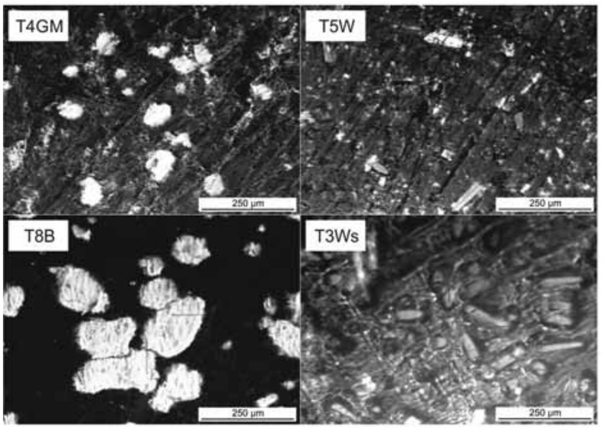


Fig. 1. Microstructures of the investigated polymer composites
Rys. 1. Mikrostruktura badanych kompozytów polimerowych

Methods

Tests of micromechanical properties of polymer composites were performed with a Micron-Gamma device (manufactured by Micron-Systema, Ukraine, Kiev). A standard Berkovich indenter was used in the tests. Micromechanical tests were carried out using the Oliver-Pharr method [**L. 16**]. The test conditions were as follows: test force – 1N, application time of test force and time taken to remove the test force – 30 s, and duration time of test force – 10 s. Additionally, the samples were placed in a self-levelling bracket. Continuous recording of the indentation parameters was applied (normal force – F_N, displacement – h). Examples of curves obtained during measurements are presented in **Fig. 2**. Hardness (H) and Young's modulus (E) were calculated averaging the values for 10 measurements.

Tribological tests of polytetrafluoroethylene with different types of filling were performed using the ball-on-disc friction couple in the linear (oscillating) motion on an Anton-Paar tribometer (TRN). For each tested case, 3 repetitions were done. Balls with a radius of 5 mm were made of Al_2O_3. The contact parameters during tribological tests were as follows: unlubricated wear, stroke length – 10 mm, oscillating frequency – 5 Hz, sliding distance – 100 m, and normal load – 25 N. Test and environmental parameters (temperature, humidity) were consistent with the ASTM G-133 standard [**L. 17**]. During tribological tests, static μ_S and dynamic μ_D friction coefficients were measured. The measurement of the static friction coefficient is crucial when designing the total resistance to the motion of elements of machines operating in cycles, especially in reciprocating motion [**L. 18**]. This is because losses due to resistance to motion during starting and changes of the direction of movement cause a significant decrease in the efficiency of the entire device. The methodology for the determination of static and dynamic friction coefficients is shown in **Fig. 3**.

The quantitative traces of wear were calculated based on the results of measurements made using the TalySurf Series 2 contact profilographometer (manufactured by Taylor Hobson, UK). The tests were performed by 3D scanning. The analysis included the following: volumetric wear – W_V, average linear wear W_L, and total area of the wear trace S_W, and was carried out using TalyMap Universal software.

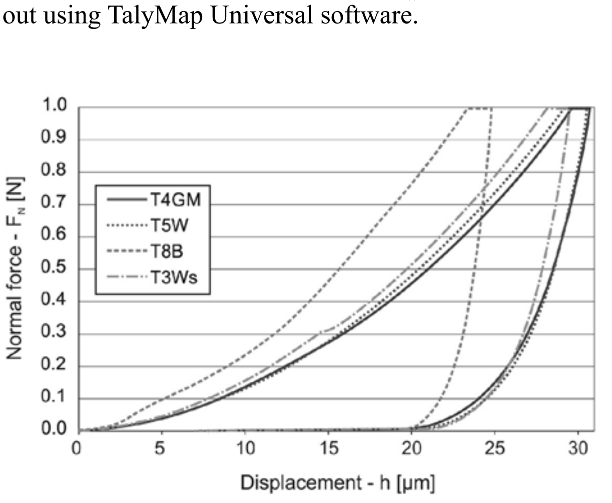


Fig. 2. Examples of loading/unloading curves
Rys. 2. Przykładowe krzywe obciążenie/odciążenie

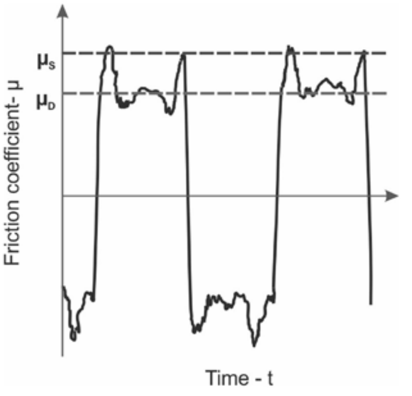


Fig. 3. The methodology for the determination of static μ_S and dynamic μ_D friction coefficients

Rys. 3. Metodyka wyznaczania statycznego μ_S i dynamicznego μ_D współczynnika tarcia

RESEARCH RESULTS

Micromechanical properties of PTFE composites

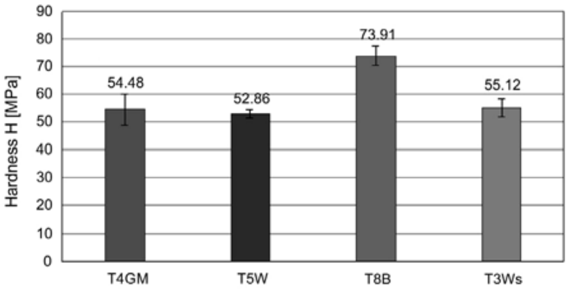
At first, the effect of various PTFE fillings on the mechanical properties was investigated. Differences in hardness and Young's modulus were observed, depending on the amount and type of filler used (**Figs. 4a, 4b**). The best results were obtained for composite T8B (H=73.9 MPa). The other composites were characterized by hardness at a similar level (52– 55 MPa), which was ca. 40% lower than for the PTFE with a bronze additive.

Much greater differences were observed for the Young's modulus (**Fig. 4b**). The highest value was again recorded for composite T8B (E = 3.17 GPa). It was by more than 2.5 times higher than for T4GM and T5W (E = 1.23 GPa and E = 1.36 GPa), and by 1.8 times higher than for composite T3Ws (E = 1.76 GPa). The observed changes in mechanical properties can have a direct effect on the service life and wear of the investigated PTFE composites.

Wear properties

The consequence of differences in the mechanical properties of the tested composites was changes in wear resistance. **Figs. 5–7** show an analysis of the area of the wear trace, the volumetric wear of the tested composites, and the adopted method of determining parameter S_W. Tribological tests showed that the smallest area of the wear trace, 27287 μm^2, and the lowest volumetric wear value, $1.09 \cdot 10^{-4}$ mm^3/Nm, were observed for the polytetrafluoroethylene composite with a mixture of 25% bronze powder and 15% graphite (T4GM). Composite T5W had tribological properties that were only slightly worse. In the case of the other two composites, T8B and T3Ws, the wear increased significantly. T3Ws worn out almost twice as much as the above-mentioned composites. In the case of ceramic counter-specimens (balls), no significant differences were observed in the surface wear after tribological interaction with the tested PTFE composites.

a)



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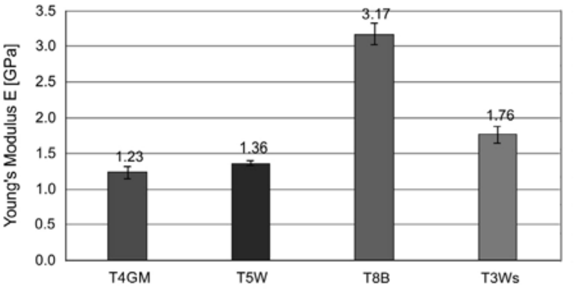
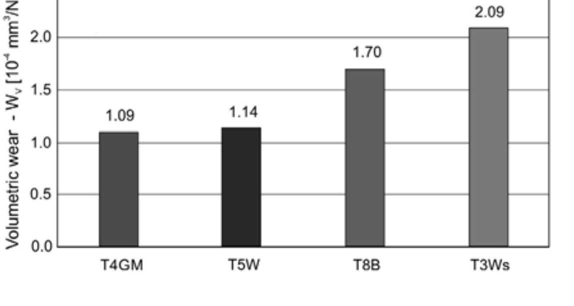


Fig. 4. Hardness (H) and Young's modulus (E) of the tested PTFE composites

Rys. 4. Twardość H (a) i moduł Younga E (b) kompozytów PTFE

a)



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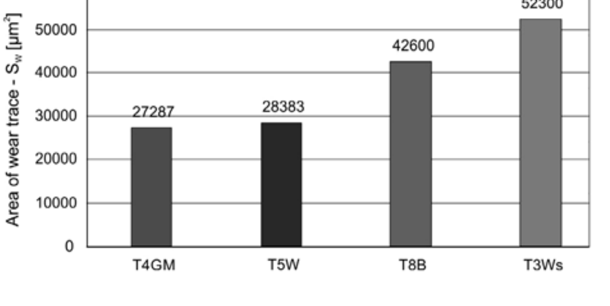

Fig. 5. Volumetric wear – W_V (a) and area of wear trace – S_W of the PTFE composites

Rys. 5. Zużycie objętościowe – W_V (a) i powierzchnia śladu wytarcia – S_W (b) kompozytów PTFE

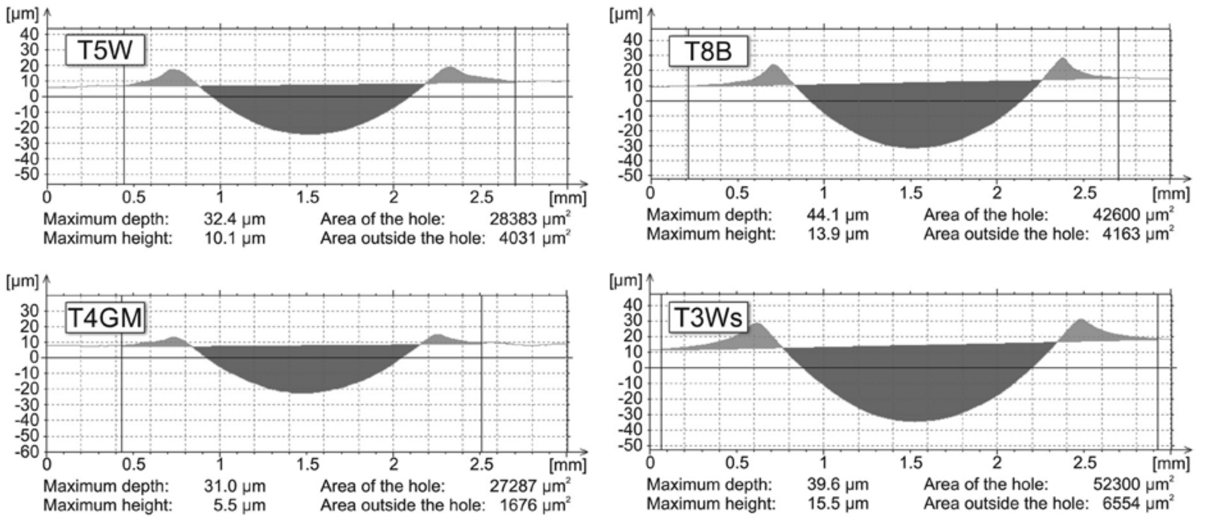

Fig. 6. Methodology of determining the area of wear trace
Rys. 6. Metodyka wyznaczania powierzchni śladu wytarcia

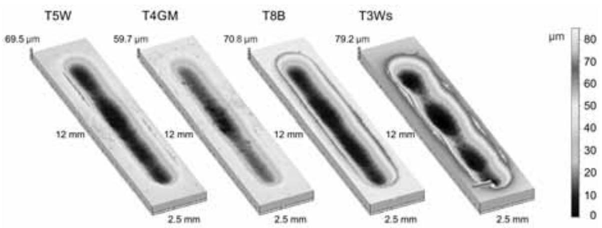

Fig. 7. Stereometric image of friction traces
Rys. 7. Obraz stereometryczny śladów tarcia

During the tribological tests, the linear wear of the investigated composites was also recorded (**Fig. 8**). Similarly to volumetric wear, the lowest linear wear was recorded for composites T4GM (29.9 μm) and T5W (30.9 μm), while T8B (41.2 μm) and T3Ws (45.5 μm) had much worse properties.

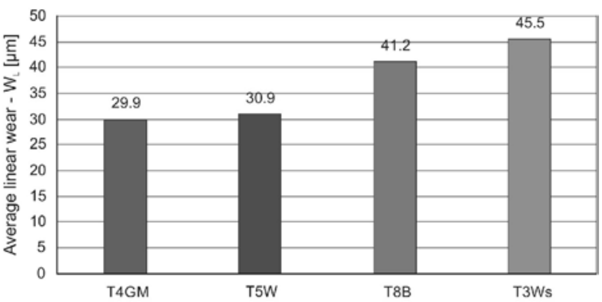

Fig. 8. Average linear wear – W_L
Rys. 8. Średnie zużycie liniowe – W_L

The tribological tests conducted in the linear (reciprocating) motion allow determining static and dynamic friction coefficients. Based on the presented results (**Figs. 9a, 9b**), it can be concluded that the most favourable coefficients of friction were recorded for the polytetrafluoroethylene with 25% carbon content (T5W) and for PTFE with 40% bronze content.

a)

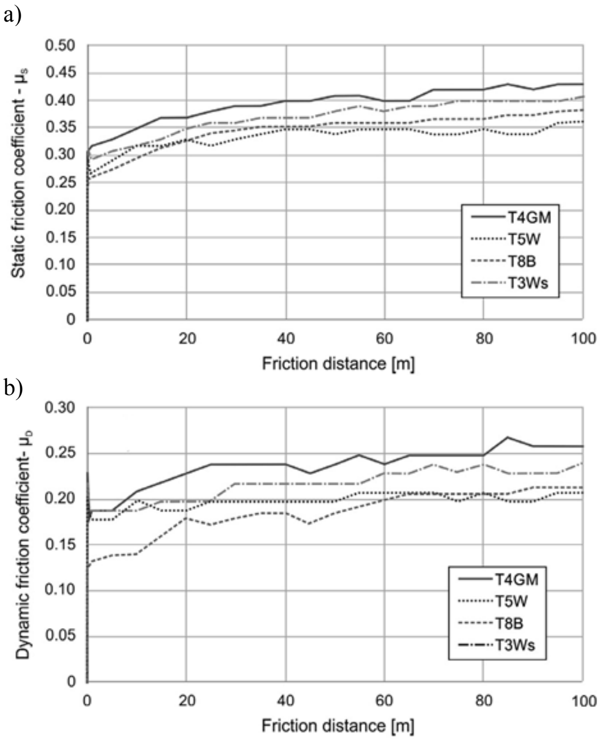

Fig. 9. Static μ_S (a) and dynamic μ_D (b) friction coefficient
Rys. 9. Statyczny μ_S (a) i dynamiczny μ_D (b) współczynnik tarcia

SUMMARY

Based on the results of research on tribological properties, a number of interesting observations can be formulated:

- Friction resistance of the tested couples, as should have been expected, decreased significantly in the presence of a lubricant (carbon powder) and in the case of PTFE modification with bronze (because

a plastic bronze film forming in the friction zone can considerably decrease friction forces), in comparison to composites with fillers in the form of glass fibre.
- Tribological properties of the tested polymer composites depend very strongly on the type and quantity of the filler, as shown by the test results for the T4GM and T8B composites.
- The tests show that it would be beneficial to conduct further research concerning the effect of unit pressure and sliding velocity, which could confirm the thesis that T8B is a very good polymeric composite material for use at high loads and high speeds.
- The functional properties of PTFE-based polymer composites are influenced by both the percentage contents of the composite material and the preparation of the composite surface, as well as a change of its internal structure, e.g., a uniform filling, which is consistent with other scientists' observations [**L. 18**].
- Modifying the polymer with multiple fillings at the same time is more effective.
- Fibres (fiberglass) increase micromechanical properties but do not improve tribological properties. Crushed glass fibre fragments can contribute to the increase in mechanical interactions (abrasive wear) between the PTFE composite and the counter-specimen's surface [**L. 18–19**]. Therefore, multi-component fillers should be used in such a case, e.g., a graphite additive.
- The use of PTFE composites containing a bronze-graphite filling significantly increases the operational durability of sliding friction nodes which perform the reciprocating motion.

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