ISSN 2079-1372 Problems of Tribology, V. 30, No 3/117-2025, 69-75

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2025-117-3-69-75

The effect of polyimide fibre on the tribological properties of polytetrafluoroethylene

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Received: 15 August 2025: Revised 10 September 2025: Accept: 20 September 2025

Abstract

The article investigates the effect of discrete polyimide fibre on the tribological properties of polytetrafluoroethylene under friction conditions without lubrication, using the “disk-pad” scheme. It was found that the introduction of 2.5-12.5 vol% filler contributes to a significant increase in the wear resistance of polytetrafluoroethylene, up to 370 times. At the same time, the friction coefficient increases slightly, reaching a maximum value at a fibre content of 7.5 vol%. The decrease in the linear wear intensity of polytetrafluoroethylene is due to an almost twofold increase in hardness. We can explain the improvement in wear resistance by the formation of strong intermolecular bonds at the “matrix-fibre” interface, increased structural uniformity, and the formation of a stable transfer film during friction. Morphological analysis of the friction surfaces confirmed a reduction in the intensity of damage for the filled composites. On the surface of pure polytetrafluoroethylene, traces of plastic deformation, numerous plowing grooves, and signs of micro-cutting were observed, indicating the prevalence of the adhesive-fatigue wear mechanism. In contrast, the composite surfaces are characterized by a smaller number and depth of defects, which suggests a reduced influence of the adhesive component of the friction force and a transition to a pseudo-elastic wear mechanism. However, when the fiber content exceeds 10 vol.%, the material properties deteriorate due to the non-uniform distribution of the filler and the formation of structural defects. For polymer composite materials with an effective fibre content of 7.5 vol%, a set of tribological tests was conducted to determine the critical values of sliding speed and load that affect the linear wear intensity.

Keywords: polytetrafluoroethylene, polyimide fibre, volume percentage, linear wear intensity, friction coefficient, hardness

Introduction

Modern agricultural, metallurgical, and machine-building industries face an acute shortage of tribotechnical materials capable of operating effectively under conditions of high loads, sliding speeds, temperatures, and especially limited or complete absence of lubrication. Such materials must be manufactured using accessible and economically feasible technologies, cheap and environmentally safe raw materials, and meet safety requirements for human health and the environment. In this regard, the development of new tribotechnical materials that meet the specified criteria is an extremely urgent scientific and technical task. One of the promising areas in this field is the use of polymer composite materials (PCMs). Depending on the type of polymer matrix, shape, nature, content, and arrangement of the filler (Fl), such materials can provide the necessary functional properties. When creating tribotechnical materials with high tribological properties, polytetrafluoroethylene (PTFE) is often used as a polymer matrix [1–3].

In its pure form, PTFE usually does not provide a sufficient level of functional properties, so various dispersed (for example, graphite, molybdenum disulfide, boron nitride, shungite) and fibrous (for example, fibreglass, carbon and organic fibres) Fls are introduced into its composition. These materials are characterised by high wear resistance under friction conditions without lubrication, a low coefficient of thermal linear expansion, resistance to the influence of many aggressive environments, as well as stable operation in a wide temperature range (from 203 to 543 K). Experience proves that replacing serial materials with composites based on polytetrafluoroethylene allows increasing the resource of effective operation and reliability of operation of tribological connections of the agricultural, metallurgical, and machine-building equipment. Therefore, the search for new PCMs based on polytetrafluoroethylene is relevant and promising [4-6].

The purpose of the work

Considering the above, the purpose of this work is to study the effect of the percentage of fibrous filler – polyimide fibre – on the tribotechnical characteristics of polytetrafluoroethylene under friction conditions without lubrication.

Objects and methods of research

PTFE manufactured by Shandong Dongyue Polymer Material Co., Ltd (China) was chosen as a polymer matrix for the PCM. PTFE is obtained by polymerisation of tetrafluoroethylene ($C2F_4$) – a colourless, odourless gas [7], which is formed when chlorodifluoromethane ($CHClF_2$) is heated in the temperature range of 873–973 K. Chlorodifluoromethane, in turn, is synthesised by the reaction of hydrogen fluoride (HF) with chloroform ($CHCl_3$). The resulting tetrafluoroethylene monomers (small monoatomic molecules) are suspended or emulsified in water, and then polymerised – connected into high-molecular chains – under high pressure in the presence of free radical reagents. The main chain of PTFE consists of carbon atoms (C), each of which is connected to two fluorine atoms (F). Fluorine atoms, surrounding the carbon chain, act as a membrane, forming a chemically inert and relatively dense molecule with very strong C-F bonds [8].

A discrete (3 mm) polyimide (PI) fibre was chosen as a filler. It has excellent mechanical and thermal properties (see Table 1), and it is resistant to corrosion and ultraviolet radiation. Due to this, PI fibres have advantages over other high-quality polymer fibres in harsh operating conditions and have broad prospects for application in the aerospace field, environmental protection, and other industries [9, 10].

Table 1

Properties of polyimide fibre

Index	Value
Density, g/cm^3	1,3
Melting, inflection, decomposition or chemical transformation temperature, K	873
Elongation during stretching, %	6-8
Tensile strength, GPa	0,62-2,0
Tensile modulus, GPa	9-20

The production of samples of pure polytetrafluoroethylene and PCMs based on it, containing 2.5-12.5 vol% PI fibres, was carried out by compression moulding [11]. The study of the tribological properties of PTFE and PCMs based on it under friction conditions without lubrication was studied in rotational motion (ν=580 rpm) using a “disk-pad” scheme in a pair with a steel cylindrical counterbody (steel 45, ø25 mm, hardness 45-48 HRC, and surface roughness R_a=0.32 μm) at a constant sliding speed of 1.5 m/s and a load of 1.5 MPa on the SMC-2 friction machine. The determination of the actual density of PTFE and PCMs based on it was carried out by the hydrostatic weighing method, which is based on the principle of liquid displacement by an immersed body according to Archimedes’ law. We chose this method because the measurement error is ±1.5%. We studied the morphology of the friction surfaces of PTFE and PTFE-based PCMs using a BIOLAM-M microscope. The hardness of PTFE and PTFE-based PCMs samples was determined using a dynamic hardness tester of the TD-42 modification on the Rockwell scale (HRC).

Results analysis and discussion

From the data presented in Fig. 1, it is clear that the introduction of 2.5–12.5 vol% PI fibre leads to a decrease in the wear intensity of polytetrafluoroethylene by almost 370 times, reaching a minimum value at 7.5 vol%. The increase in wear resistance of PTFE is due to the increase in the resistance of the friction surface to deformation because of the increase in the hardness of PCMs by almost 2 times (see Fig. 2). The improvement of these indicators at a fibre content of 2.5-7.5 vol% is due to the formation of strong intermolecular bonds at the " polytetrafluoroethylene -PI fiber" interface, which contributes to an increase in the structural uniformity of the composition and, accordingly, a decrease in local stress concentrators. In addition, polymer composite materials during friction on a steel counterbody form a stable transfer film (so-called antifriction layer), formed from finely dispersed wear products, which performs the function of a natural dry lubricating layer [12].

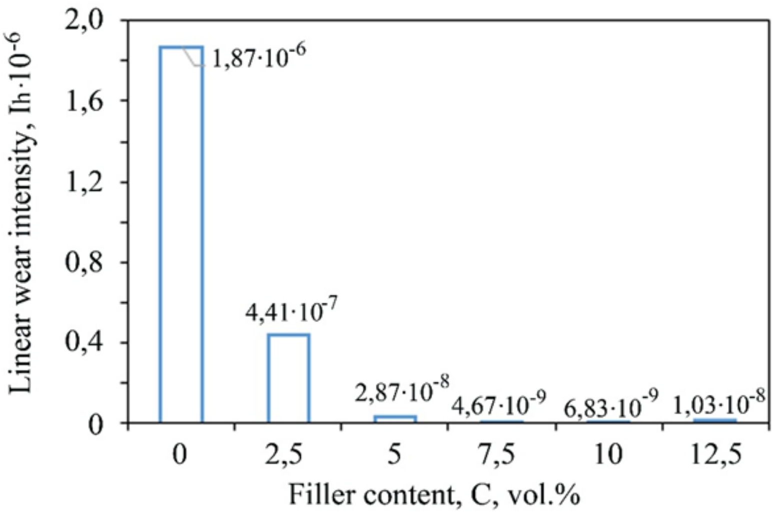

Fig. 1. Dependence of the polytetrafluoroethylene linear wear intensity (I_h) on the volume content of polyimide fibre (C, vol%)

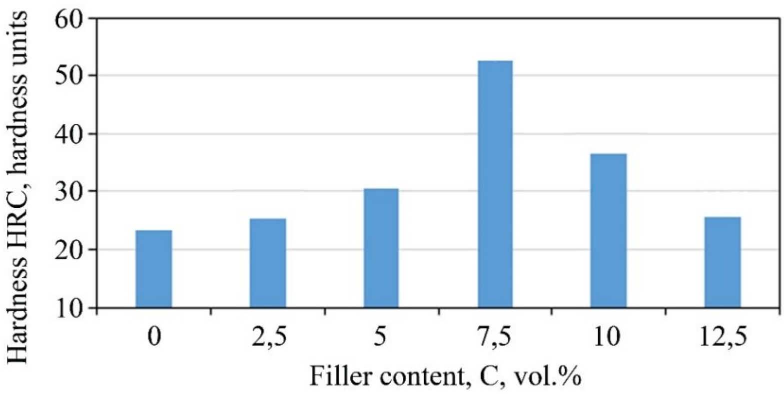

Fig. 2. Dependence of hardness (HRC, hardness units) of polytetrafluoroethylene on the volume content of polyimide fibre (C, vol%)

Morphological analysis of the friction surfaces of the samples after testing confirmed the increase in wear resistance. Comparing the obtained micrographs (Fig. 3), we can see a significant difference in the pattern of surface damage of pure polytetrafluoroethylene and PCMs filled with PI fibre. Thus, we observe signs of plastic deformation, multiple furrows, and traces of microcutting (Fig. 3, a) on the friction surface of pure PTFE. This indicates the predominance of the adhesive-fatigue wear mechanism. In contrast, the friction surfaces of PCMs (Fig. 3, b-e) are characterised by a smaller number of defects, a reduced depth of damage, and a more homogeneous microstructure. This indicates a decrease in the adhesive component of the friction force and a transition to a predominantly pseudoelastic wear mechanism [11].

We investigated the influence of the formation of a transfer film on the linear wear intensity for PCMs with an effective filler content (7.5 vol%). It can be seen from the data presented in Fig. 4 that the wear resistance of PCMs increases by almost 1.5 times with an increase in the test path. This can be explained by the fact that during the friction process, a stable transfer film forms on the surface of the counterbody, reducing the contact between it and the test sample [13]. Additionally, we observe an increase in the friction coefficient (Fig. 5), reaching a maximum value of ~0.135 at a filler content of 7.5 vol%. This can be explained by the fact that the polyimide fibre is characterised by high mechanical rigidity, which results in a more microrough friction surface. The latter contributes to an increase in mechanical adhesion between the contact surfaces during sliding. This, accordingly, increases the friction force. On the other hand, the increase in the friction coefficient of PCMs can also occur due to the low thermal conductivity of the PI fibre (0.1–0.35 W/m K), which leads to insufficient heat removal from the contact zone. The accumulation of heat in the friction zone contributes to a local increase in temperature, which causes an increase in the friction force [8].

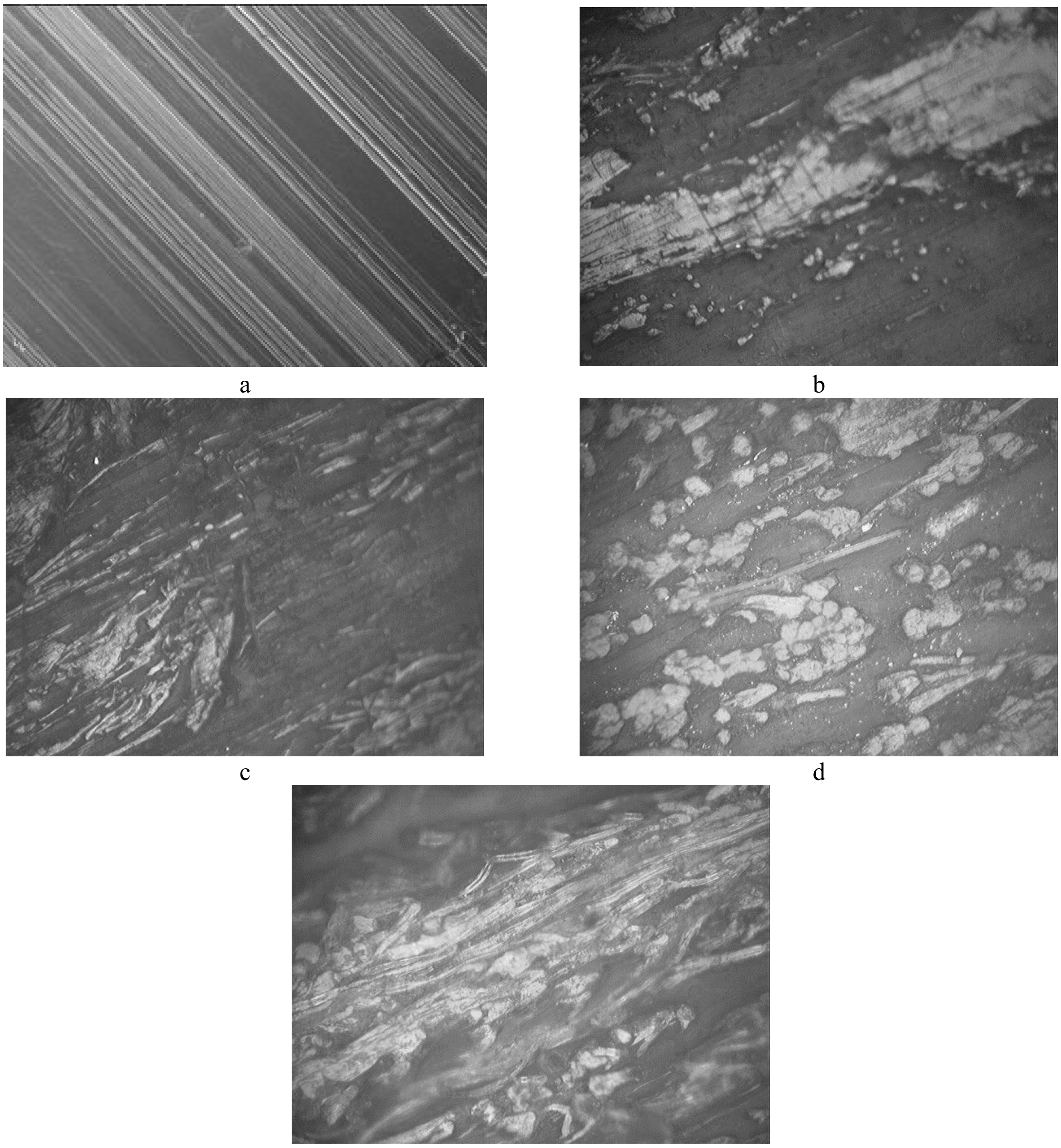

Fig. 3. Friction surfaces of pure PTFE (a) and composites based on it containing 5 (b), 7.5 (c), 10 (d), 12.5 (e) vol% polyimide fibre

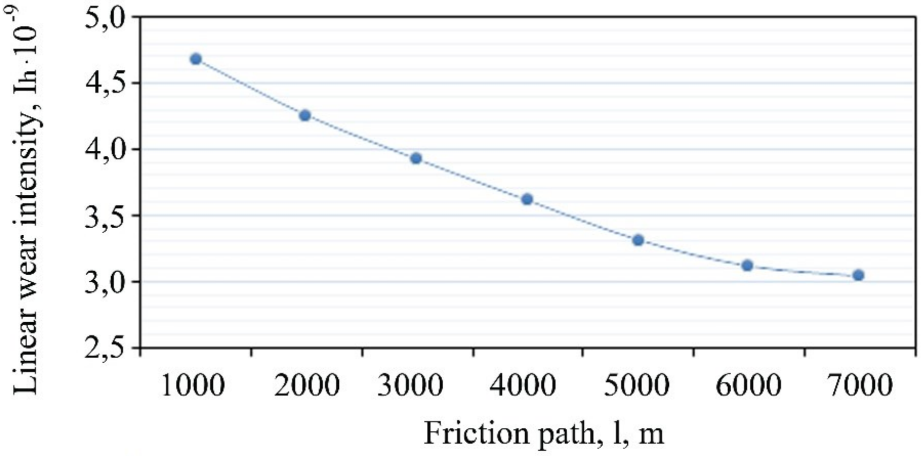

Fig.4. The influence of the length of the friction path (l, m) on the linear wear intensity of a polymer composite with a fibre content of 7.5 vol%.

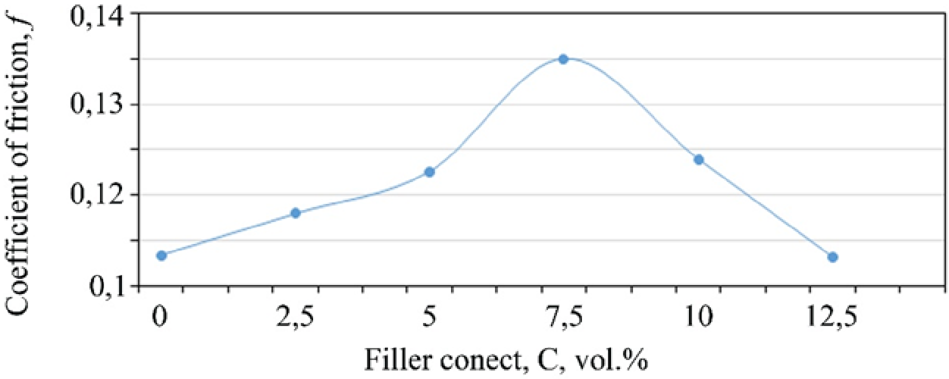

Fig.5. Dependence of the coefficient of friction (*f*) of polytetrafluoroethylene on the volume content of polyimide fiber (C, vol%)

We should note that with an increase in the PI fibre content to 12.5 vol%, a decrease in the wear resistance and hardness of the PCM is observed. This is likely due to the difficulty in uniformly distributing the filler throughout the PTFE volume, which results in a decrease in the interfacial adhesion between the polymer and the fibre. As a result, microcracks, cavities, and other defects form in the PCMs structure, negatively affecting its functional properties [14].

For PCM with an effective fibre content of 7.5 vol%, we conducted a set of tribological tests to determine the critical values of the sliding speed (υ, m/s) and load (P, MPa) that affect the linear wear intensity. From the data shown in Fig. 6, it is clear that their increase leads to a decrease in the wear resistance of the PCM.

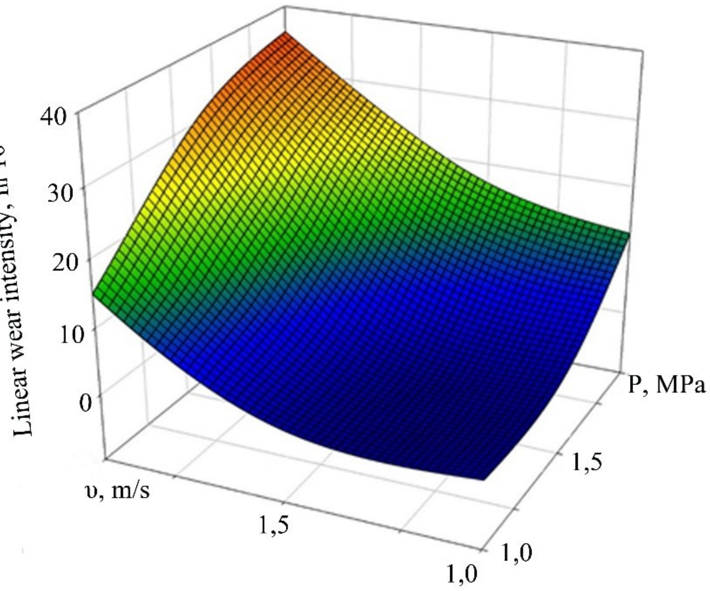

Fig.6. Dependence of the linear wear intensity index (I_h) of a composite containing 7.5 vol% PI fibre on the sliding velocity (υ, m/s) and load (P, MPa)

We can explain this dependence by the thermomechanical processes occurring in the friction zone, particularly the increase in temperature. For example, at a load of P=1.5 MPa and a sliding speed of *υ*=1.5 m/s, the temperature reached T=423 K, while at P=2.0 MPa and *υ*=2.0 m/s, it was already T=473 K, which brings it closer to the maximum operating temperature of PTFE (533 K). This increase in temperature causes a deterioration in the functional properties of the PCMs friction surface and a violation of the adhesive bond between polytetrafluoroethylene and the fibre [15].

Conclusions

Analysis of the conducted studies revealed that the introduction of polyimide fibre into the PTFE composition in amounts of 2.5-12.5 vol% results in a significant decrease in linear wear intensity by almost 370 times, with an optimal effective content of 7.5 vol%. The increase in wear resistance occurs because of a nearly twofold increase in the hardness of the PCMs, which enhances the resistance of the friction surface to deformation. This is due to the formation of strong intermolecular bonds at the "PTFE-PI fibre" interface and an increase in the structural homogeneity of the material. The formation of a stable transfer film on the counterbody surface during friction additionally increases the wear resistance of the PCMs by 1.5 times. The introduction of the fibre leads to an increase in the friction coefficient, which is due to its high rigidity and insufficient thermal conductivity, which complicates the effective removal of heat from the friction zone. Increasing the fibre content to 10-12.5 vol% leads to a decrease in the wear resistance and hardness of the PCMs due to the difficulty in uniformly distributing the Fl, a decrease in interfacial adhesion, and the formation of structural defects (microcracks and cavities). Tribological tests under various operating conditions revealed that an increase in sliding speed and load results in a corresponding rise in temperature within the friction zone. This, in turn, deteriorates the functional properties of the surface and leads to the degradation of the adhesive bond between PTFE and PI fibre, thereby reducing the wear resistance of the PCMs.

References

1. A.S. Kobets Application of polymer composites in the agricultural industry. Monograph. Dnipro: Zhurfond, 2022. 356 p.

2. O. Kabat, V. Sytar, K. Sukhyy Antifrictional polymer composites based on aromatic polyamide and carbon black. Chem. Chem. Technol. 2018. Vol.12, No.3. P. 326–330.

3. Kabat O.S., Sytar V.I., Yermachenok D.V., Davydov S.O., Heti K.V. Polymer composite materials for friction units of space and aviation equipment. System Design and Analysis of Aerospace Engineering. 2017. Vol. XXIII. P. 40–48.

4. Myshkin N.K., Pesetskii S.S., Grigoriev A.Ya. Polymer composites in tribology. VIII International scientific conferene «BALTTRIB 2015».Kaunas, 2015. P.152–1565.

5. K.V. Berladir; T.P. Hovorun, O.A. Bilous, S.V.Baranova The modeling of the composition and properties of functional materials based on polytetrafluoroethylene. Functional Materials. 2018. Vol.25, No2. P. 342–347.

6. O. Burya, Ye. Yeriomina, O. Lysenko, A. Konchits, A. Morozov, Polymer composites based on thermoplastic binders, Dnipro: Srednyak T. K. Press. 2019. 239 p.

7. K.V. Berladir, V.A. Sviderskiy Designing and examining polytetrafluoroethylene composites for tribotechnical purposes with activated ingredients. Eastern-European Journal of Eenterprise Technologies. 2016. Vol.84. No.6. P. 14–21.

8. O. Yeromenko, A.-M. Tomina, I. Rula Effect of discrete basalt fiber on operational properties of polytetrafluoroethylene. Problems of Tribology. 2022. Vol. 27. No. 4/106. P. 39–44.

9. J. Dong, C. Yin, W. Luo, et al. Synthesis of organ-soluble copolyimides by one-step polymerization and fabrication of high performance fibers. Journal of Materials Science. 2013. No.48 (21). P. 7594–7602.

10. X. Dai, F. Bao, L. Jiao, et al. High-performance polyimide copolymer fibers derived from 5-anino-2-(2-hydroxy-4-aminobenzene)-benzoxazole: preparation, structure and properties. Polymer. 2018. Vol.150. P. 254–266.

11. K.R. Voloshina, A.-M.V. Tomina, Yu.E. Hranitskyi The influence of polyamide fiber on the wear intensity of polytetrafluoroethylene. Comprehensive quality assurance of technological processes and systems (KZYATPS -2025): materials of the abstracts of the XV International Scientific and Practical Conference (Chernihiv, May 22–23, 2025): in 2 vols. / National University "Chernihiv Polytechnic" [et al.] ; editor: Prystupa Anatoliy Leonidovych [et al.]. – Chernihiv: NU "Chernihiv Polytechnic", 2025. Vol. 2. P.136.

12. O.I. Burya, S.V. Kalinichenko, A.-M.V. Tomina, I.I. Nachovniy The impact of organic tanlon fiber on performance indicators of polychlorotrifluoroethylene. Journal Problems of Tribology. 2019. Vol.92. No.2. P. 61–66.

13. Buria O.I., Tomina A.-M.V. Organoplastics of tribotechnical purpose. Prospects and priorities of research in science and technology: collective monograph. Riga, Latvia: «Baltija Publishing». 2020. Vol.2. P. 240–257.

14. M.A. Ibrahim, H. Çamur, M. Savaş, S.I. Abba. Optimization and prediction of tribological behaviour of filled polytetrafluoroethylene composites using Taguchi Deng and hybrid support vector regression models. Scientific Reports. 2022. Vol.12. No.1. P. 10393

15. S. Kolhe, A. Deshpande, K. Wangikar. Wear behavior of polytetrafluoroethylene composites: A review. In: Smart Technologies for Energy, Environment and Sustainable Development. 2019. P. 571-584.

Томіна А-М.В., Волошина К.Р., Predrag Dašić, Граніцький Ю.Є. Вплив поліімідного волокна на трибологічні властивості політетрафторетилену

У статті досліджено вплив дискретного поліімідного волокна на трибологічні властивості політетрафторетилену в умовах тертя без змащення за схемою «диск-колодка». Встановлено, що введення наповнювача у кількості 2,5-12,5 об.% сприяє зростанню зносостійкості політетрафторетилену до 370 разів. При цьому коефіцієнт тертя дещо підвищується, досягаючи максимального значення за вмісту волокна 7,5 об.%. Зменшення інтенсивності лінійного зношування політетрафторетилену обумовлено підвищенням твердості майже в два рази. Покращення зносостійкості можна пояснити формуванням міцних міжмолекулярних зв'язків на межі поділу «матриця–волокно», підвищенням структурної однорідності та утворенням стабільної плівки переносу в процесі тертя. Морфологічний аналіз поверхонь тертя підтвердив зменшення інтенсивності пошкоджень для наповнених композитів. На поверхні тертя чистого політетрафторетилену виявлено сліди пластичної деформації, численні борозни проорювання та ознаки мікрорізання, що свідчить про переважання адгезійно-втомного механізму зношування. Натомість поверхні композитів характеризуються меншою кількістю та глибиною дефектів, що свідчить про зменшення впливу адгезійної складової сили тертя та перехід до псевдопружного механізму зношування. При збільшенні вмісту волокна понад 10 об.% спостерігається погіршення властивостей матеріалу через нерівномірний розподіл наповнювача та формування структурних дефектів. Для полімерних композиційних матеріалів із ефективним вмістом волокна 7,5 об.% проведено комплекс трибологічних випробувань з метою визначення критичних значень швидкості ковзання та навантаження, що впливають на інтенсивність лінійного зношування. Отримані результати досліджень дозволяють встановити граничні умови експлуатації, за яких полімерний композит із вмістом волокна 7,5 об.% може успішно застосовуватися у виробництві деталей трибологічних з'єднань різноманітної техніки без використання мастильних матеріалів.

Ключові слова: політетрафторетилен, поліімідне волокно, об'ємні відсотки, інтенсивність лінійного зношування, коефіцієнт тертя, твердість