***ISSN 2079-1372 Problems of Tribology**, V. 31, No 2/120-2026, 52-59*

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

DOI: https://doi.org/10.31891/2079-1372-2026-120-2-52-59

The effect of load and sliding speed on the wear rate of a metal-polymer composite containing an Al-Co filler

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Received: 12 April 2026: Revised 25 April 2026: Accept: 15 May 2026

Abstract

The paper presents the results of a study on the tribotechnical behaviour of a polymer composite material based on ultra-high-molecular-weight polyethylene, filled with 25 wt.% of a rapidly quenched binary alloy of the Al–10 wt.% Co system. The relevance of the study is due to the need to improve the wear resistance of tribological joints operating under conditions of intensive wear, high loads, and insufficient lubrication. The aim of the study is to develop a mathematical model describing the influence of sliding speed and applied load on the intensity of linear wear of the composite under dry friction conditions using a disk–pad configuration. The study was carried out using a full factorial experiment and a first-order regression model, which made it possible to quantitatively evaluate the influence of the experimental factors and their interaction. It was established that with increasing load, the intensity of linear wear increases significantly, while the influence of sliding speed is less pronounced and becomes evident in interaction with load. A synergistic effect of the combined action of the investigated factors on the linear wear intensity of the polymer composite was identified. The developed mathematical model was validated using statistical criteria and adequately describes the experimental data. The obtained results can be used to predict the wear resistance of the material and to determine rational operating conditions for tribological joints, thereby improving their durability and reliability.

Keywords: ultra-high-molecular-weight polyethylene, binary alloy of the Al-Co system, sliding speed, applied load, linear wear rate, mathematical model

Introduction

The development of modern technology directly depends on the stable and efficient operation of lightly and heavily loaded tribological components of equipment. Under aggressive operating conditions, particularly in the presence of abrasive particles (e.g. sand and crop-processing products) and moisture, as well as under friction conditions with insufficient or no lubrication, bearings and other friction elements are subject to severe wear. This leads to loss of performance, equipment downtime, and significant financial costs associated with the repair and replacement of machine components. One common solution to this problem is using polymer composite materials (PCMs) based on thermoplastics containing dispersed fillers (FLs) of various types, including graphite, aluminosilicate microspheres, carbides, and metal powders. Using them as an alternative to traditional materials reduces manufacturing labour intensity, including for components of complex geometry, as well as reducing operating costs associated with the maintenance of tribological systems [1, 2].

Literature Review

The main factors affecting the wear resistance of polymer composite materials are the sliding speed (υ, m/s) and the applied load (P, MPa). Knowledge [3] of the critical values of these parameters makes it possible to determine rational operating conditions for PCM-based components, predict their tribological behaviour, and extend the service life of tribological systems [4]. The application of design of experiments methods and the development of a mathematical model make it possible to determine these critical parameters without conducting a large number of resource-intensive experiments, including bench and full-scale tests, while ensuring high informativeness and reliability of the obtained results [5]. One of the most widely used materials for PCM production is ultra-high molecular weight polyethylene (UHMWPE), which is characterized by a low coefficient of friction and high resistance to wear and aggressive environments. Studies have shown that the incorporation of dispersed metallic nanoparticles [6], in particular aluminium-based binary alloys [7, 8], can significantly improve its functional properties by increasing stiffness, wear resistance, and thermal conductivity of UHMWPE. Despite the large number of studies, the combined effect of sliding speed and load on the wear rate of PCMs filled with such nanoparticles remains insufficiently investigated. In particular, there is a lack of generalized mathematical models capable of predicting the tribological behaviour of these materials over a wide range of operating conditions.

In works [7, 8] it was established that the PCM containing 25 wt.% of a rapidly quenched binary alloy of the Al-10 wt.%Co system exhibits an effective combination of tribological properties. A rapidly quenched binary alloy of the Al–Co system containing 10 wt.% Co was selected as a dispersed filler (particle size 50–100 μm) for the polymer matrix. As shown by X-ray diffraction studies, the structure of these alloys contains single-phase highly supersaturated substitutional solid solutions based on Al, which provide these binary alloys with unique functional properties. These properties are caused by a high level of crystal lattice microstrains in the alloys. The difference in the atomic radii of the elements (r_{Al}=0,143 nm, r_{Co}=0,143 nm) causes lattice microstrain (Δa/a) at the level of $2{,}7\cdot10^{-3}$. In particular, the introduction of this FL contributes to an increase in the wear resistance of UHMWPE (manufactured by Jiujiang Zhongke Xinxing New Material Co., Ltd., China) under various operating conditions, including the action of firmly embedded abrasive particles and friction without lubrication, as well as to improved heat dissipation from the contact zone, which is critically important for tribological materials.

At the same time, an analysis of the literature indicates that the combined effect of sliding speed and applied load on the wear rate of such materials remains insufficiently studied, particularly in terms of quantitative description and prediction of their tribological behaviour. In this regard, there is a need to apply mathematical modeling approaches that make it possible to establish relationships between friction regime parameters and material wear resistance. With this in mind, the present study employs a full factorial design with subsequent development of a first-order regression model to investigate the effect of sliding speed and load on the linear wear rate of the PCM. This approach makes it possible not only to evaluate the individual contributions of these parameters, but also to identify the synergistic effects of their interaction [7, 8].

In study [7], it was established that the coefficient of friction of the composite changes insignificantly. Therefore, the linear wear rate was selected as the main optimization parameter, since it directly characterizes the durability and performance of tribological joints.

The purpose of the work

In view of the above, the aim of this work is to develop a mathematical model describing the effect of load and sliding speed on the linear wear rate of a polymer composite based on ultra-high molecular weight polyethylene containing 25 wt.% of a rapidly quenched binary alloy of the Al-10 wt.% Co system as a filler.

Objects and methods of research

The tribological properties of the developed PCM under dry contact conditions were investigated using an SMC-2 testing machine in a «disk–pad» configuration. This configuration was selected because it simulates real friction conditions in tribological systems across various engineering applications The samples were fabricated in the form of cylinders with a diameter of 30 mm and a height of 10 mm. The counterbody was made of medium-carbon steel (grade 45) with a diameter of 25 mm, a hardness of 45–48 HRC, and a surface roughness of R_a=0,32 μm. To ensure the reliability of the results, error estimation was performed based on the variance of parallel measurements using the Cochran, Student's t-, and Fisher's F-tests. This made it possible to confirm the reproducibility of the experiments, the statistical significance of the model coefficients, and the adequacy of the developed model. The linear wear rate was calculated using the following equation:

$$I_h = \frac{\lambda}{\rho_{exp}} \cdot \frac{\Delta m}{S \cdot L},$$

where λ=1 indicates that all points of the friction surface of the specimen are in contact with the counterbody;

ρ_{exp} is the experimental density of the specimen, determined by hydrostatic weighing, g/cm^3;

Δm is the mass loss, g;

S is the contact area between the specimen and the counterbody, cm^2;

L is the sliding distance (friction path) of the specimen [8].

The morphology of the friction surfaces was investigated using a BIOLAM-M binocular microscope.

Results analysis and discussion

For PCMs with an effective content of 25 wt.% of the FL in the Al-Co system, the linear wear rate (I_h) was selected as the optimisation parameter. This parameter depends on two factors: sliding speed (x_1) and load (x_2):

$$I_h = f(x_1, x_2),$$

To simplify the calculations, the experimental factor values were transformed to a coded scale (−1, 0, +1) using the following formula:

$$x_i = \frac{X_i - X_{io}}{n},$$

where X_i is the current value of the factor, X_{io} is the baseline level, and n is the variation step [9]. The transformation from natural factor values to coded variables was performed as follows:

$$x_1 = \frac{v - v_0}{\Delta v},$$
$$x_2 = \frac{P - P_0}{\Delta P},$$

where υ is the sliding velocity, m/s; P is the applied load, MPa; υ_0=1,0 m/s and P_0=1,0 MPa are the baseline factor levels; Δυ=0,5 m/s and ΔP=0,5 MPa are the variation intervals. The coded values of the experimental factors are presented in Table 1. The selected ranges of load and sliding speed were determined taking into account the expected operating conditions of lightly and moderately loaded tribological joints of agricultural machinery, in which UHMWPE-based composites can be used.

Table 1

Initial data for experiment design

Factors	Symbol, unit of measurement	Conventional symbol	Variation step (n)	Level of variation		
				-1	0	+1
Sliding speed	υ, m/s	x_1	0,5	0,5	1,0	1,5
Load	P, MPa	x_2	0,5	0,5	1,0	1,5

In accordance with the experimental design, N = 9 experiments were conducted, each repeated three times (k=3), thereby increasing the reliability of the results and minimising the influence of random measurement errors (Table 2).

Table 2

Experimental design matrix with calculated factor interaction terms

№ of the experiment	Variable values on the coded scale				Variable values on the natural scale	
	x_0	x_1	x_2	x_1x_2	υ, m/s	P, MPa
1	+1	+1	+1	+1	1,5	1,5
2	+1	+1	0	0	1,5	1
3	+1	+1	-1	-1	1,5	0,5
4	+1	0	+1	0	1	1,5
5	+1	0	0	0	1	1
6	+1	0	-1	0	1	0,5
7	+1	-1	+1	-1	0,5	1,5
8	+1	-1	0	0	0,5	1
9	+1	-1	-1	+1	0,5	0,5

To describe mathematically the influence of the studied factors on the linear wear rate, a first-order regression equation was used:

$$y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_{12},$$

where y is the calculated value of the optimisation parameter; b_0 is the intercept term corresponding to the value of the response function at the center of the experiment; b_1, b_2 are coefficients describing the effects of sliding velocity and load, respectively; b_{12} is a coefficient accounting for the interaction between the factors. The mean values of the response function ($\bar{y}_j$) were determined from the results of parallel experiments [10, 11]:

$$\bar{y}_j = \frac{1}{k}\sum_{i=1}^{k} y_{ji}, \qquad j=1,2,\ldots,N$$

where k = 3 is the number of repetitions and N = 9 is the total number of experiments according to the experimental design (Table 3). The mean square errors of the parallel experiments were calculated using the following expressions:

$$S_j^2 = \frac{S_r^2}{\sum_{J=1}^{N} x_i},$$

$$S_j^2 = \frac{\sum_{j=1}^{N}(y_i - \tilde{y}_j)}{k-1}.$$

The homogeneity of variances obtained in the parallel experiments was assessed using Cochran's criterion:

$$G_p = \frac{\max S_j^2}{\sum_{i=1}^{k} S_j^2}.$$

A comparison between the calculated value of Cochran's criterion and the tabulated value was conducted for the number of degrees of freedom $f_1 = k-1$ and the number of experiments N, at a confidence level of P=0,95. Since the calculated value of Cochran's criterion G_p is lower than the tabulated value G_{tab}, the dispersions are considered homogeneous. The error in determining the regression coefficients was estimated using the following expression:

$$S_{bi} = \frac{S_y}{\sqrt{N \cdot k}}.$$

Table 3

Experimental and calculated values of linear wear rate

№ of the experiment	y_1	y_2	y_3	mean	calculated
				$\tilde{y}_j$	$y_j{}^p$
1	$4{,}86 \cdot 10^{-6}$	$5{,}00 \cdot 10^{-6}$	$5{,}12 \cdot 10^{-6}$	$4{,}99 \cdot 10^{-6}$	$3{,}68 \cdot 10^{-6}$
2	$4{,}58 \cdot 10^{-6}$	$4{,}63 \cdot 10^{-6}$	$4{,}52 \cdot 10^{-6}$	$4{,}58 \cdot 10^{-6}$	$2{,}50 \cdot 10^{-6}$
3	$1{,}8 \cdot 10^{-7}$	$3{,}57 \cdot 10^{-7}$	$5{,}72 \cdot 10^{-7}$	$3{,}7 \cdot 10^{-7}$	$1{,}76 \cdot 10^{-6}$
4	$2{,}79 \cdot 10^{-6}$	$2{,}85 \cdot 10^{-6}$	$2{,}74 \cdot 10^{-6}$	$2{,}79 \cdot 10^{-6}$	$2{,}28 \cdot 10^{-6}$
5	$3{,}56 \cdot 10^{-7}$	$3{,}59 \cdot 10^{-7}$	$3{,}6 \cdot 10^{-7}$	$3{,}58 \cdot 10^{-7}$	$1{,}52 \cdot 10^{-6}$
6	$1{,}91 \cdot 10^{-8}$	$1{,}1 \cdot 10^{-8}$	$1{,}05 \cdot 10^{-8}$	$1{,}35 \cdot 10^{-8}$	$7{,}60 \cdot 10^{-7}$
7	$1{,}26 \cdot 10^{-7}$	$2{,}89 \cdot 10^{-7}$	$1{,}61 \cdot 10^{-7}$	$1{,}26 \cdot 10^{-7}$	$9{,}20 \cdot 10^{-7}$
8	$9{,}75 \cdot 10^{-9}$	$1{,}35 \cdot 10^{-8}$	$9{,}82 \cdot 10^{-9}$	$1{,}16 \cdot 10^{-8}$	$5{,}40 \cdot 10^{-7}$
9	$9{,}74 \cdot 10^{-9}$	$9{,}6 \cdot 10^{-9}$	$9{,}74 \cdot 10^{-9}$	$9{,}69 \cdot 10^{-9}$	$2{,}00 \cdot 10^{-7}$

The regression coefficients were calculated using analytical dependencies derived from the full factorial experiment results.

$$b_0 = \sum_{i=1}^{N} \frac{\tilde{y}_j x_0}{N},$$

$$b_i = \sum_{i=1}^{N} \frac{\tilde{y}_j x_i}{N},$$

$$b_{ij} = \sum_{i=1}^{N} \frac{\tilde{y}_j x_{ij}}{N}.$$

Based on the calculated data, a first-order regression equation was obtained. It describes the influence of the studied factors on the response function.

$$y(I_h) = 1{,}47 \cdot 10^{-6} + 1{,}08 \cdot 10^{-6} x_1 + 8{,}35 \cdot 10^{-7} x_2 + 5{,}00 \cdot 10^{-7} x_{12}.$$

To obtain the regression equation in natural variables, the coded variables were substituted using the following relationships:

$$x_1 = \frac{v - 1{,}0}{0{,}5},$$
$$x_2 = \frac{P - 1{,}0}{0{,}5}.$$

Substituting these expressions into the regression equation, the following equation in natural variables (P, υ) was obtained:

$$I_h = (-0{,}36 + 0{,}16 \cdot \upsilon - 0{,}33 \cdot P + 2{,}00 \cdot \upsilon \cdot P) \cdot 10^{-6}.$$

The analysis of the obtained coefficients shows that an increase in sliding velocity and load is accompanied by an increase in wear intensity, as confirmed by the positive values of coefficients b_1 and b_2. The positive value of the interaction coefficient b_{12} indicates the presence of a synergistic effect, whereby the simultaneous action of both factors intensifies the wear process.The statistical significance of the regression coefficients was assessed using Student's t-criterion by constructing confidence intervals, taking into account the corresponding degrees of freedom and a confidence level of 0,95.

$$|b_{cr}| = t_{cr} \cdot S_{bi}.$$

A coefficient was considered statistically significant if its absolute value exceeded the critical value. The results of the analysis showed that all coefficients were significant according to Student's criterion and were therefore retained in the mathematical model. As a result, a regression equation was obtained. It adequately describes the influence of the studied factors on the response function. The adequacy of the developed model was evaluated by comparing the experimental and calculated values of the response function [12, 13]. For this purpose, the dispersion of adequacy was determined:

$$S_{ad}^2 = \frac{1}{N - B} \sum_{j=1}^{N} \left(\bar{y}_j - y_j^P\right)^2,$$

where B is the number of statistically significant coefficients. Accordingly, the number of degrees of freedom for the adequacy assessment is $f_{\text{ад}}$=N – B. The calculated values of wear intensity are presented in Table 4. To assess the adequacy of the mathematical model, Fisher's criterion was applied, defined as the ratio of the adequacy variance to the reproducibility variance [11].

$$F_p = \frac{S_{ad}^2}{S_y^2}.$$

Table 4

Calculated data for assessing model adequacy using Fisher's criterion

S_y^2	Regression coefficients				S_{ad}^2
	b_0	b_1	b_2	b_{12}	
$1{,}07 \cdot 10^{-14}$	$1{,}47 \cdot 10^{-6}$	$1{,}08 \cdot 10^{-6}$	$8{,}35 \cdot 10^{-7}$	$5{,}00 \cdot 10^{-7}$	$3{,}10 \cdot 10^{-14}$

At a confidence level of 0,95 and corresponding degrees of freedom f_1=3 and f_2=5, the calculated value of Fisher's criterion (F_p = 2,89) is lower than the tabulated value (F_{tab} =5,05). This confirms the adequacy of the mathematical model for describing the studied process.

Based on the simplified and statistically significant first-order regression equation, a response surface of the linear wear rate of the PCM was constructed as a function of sliding speed and applied load (Fig. 1).

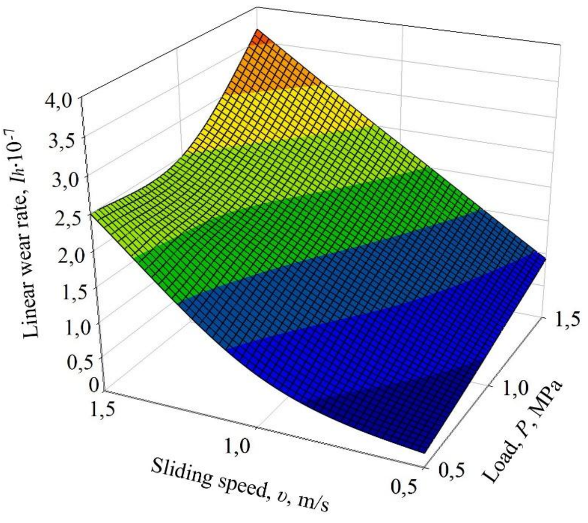
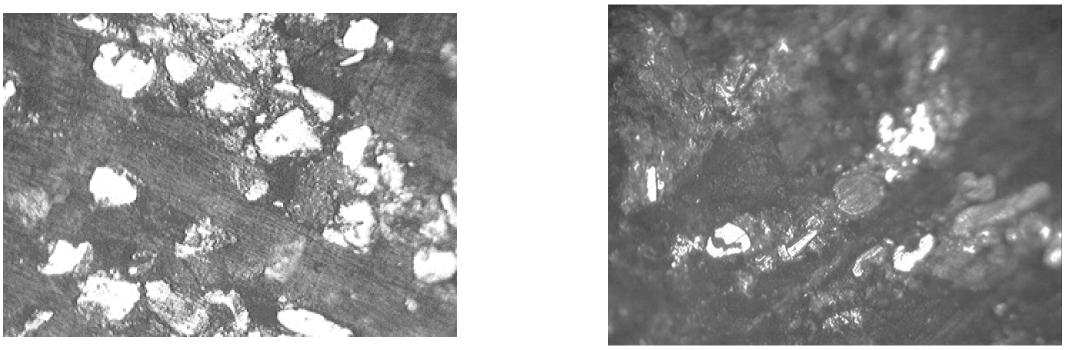


Fig. 1. Response surface of the linear wear rate (I_h) of the composite as a function of sliding speed (υ, m/s) and applied load (P, MPa)

Analysis of the response surface (Fig. 1) shows that the linear wear rate of the PCM is strongly influenced by both sliding speed and applied load. As the load increases, a monotonic increase in wear rate is observed, which can be attributed to higher contact stresses and intensified degradation processes in the surface layer. The effect of sliding speed is nonlinear: as it increases, the wear rate changes less markedly; however, when combined with high loads, a sharp decrease in wear resistance is observed. This indicates the presence of interaction effects between the factors, as evidenced by the shape of the response surface.

The obtained dependences of the linear wear rate on sliding speed and load are determined by the peculiarities of the stress-strain state of the surface layer of the PCM during friction. The introduction of the metallic FL contributes to the redistribution of contact stresses in the surface layer and limits excessive plastic deformation of UHMWPE during friction. Under relatively low loads and sliding speeds, this ensures stabilization of the tribocontact and high wear resistance, which is confirmed by the morphology of the friction surfaces (Fig. 2a), characterized by a less damaged surface relief and insignificant traces of plastic deformation. This indicates that an adhesive-fatigue wear mechanism is realized between the tested specimen and the steel counterbody. At the same time, an increase in the applied load leads to an increase in the real contact area and contact stresses, which is accompanied by intensified deformation and destruction processes in the surface layer of the PCM. Under such conditions, friction-induced heating becomes more pronounced, especially at high sliding speeds. Despite the fact that the Al–Co FL promotes efficient heat dissipation from the contact zone, as confirmed by the increase in the thermal conductivity of the PCM reported in [14], under the simultaneous action of high loads and sliding speeds the amount of generated thermal energy exceeds the ability of the tribosystem to stabilize the friction process. This results in intensified wear processes, which is confirmed by the experimentally established increase in the linear wear rate of the PCM. Analysis of the friction surface morphology showed that at high values of load and sliding speed, pronounced deformation regions, local damage, and traces of material removal are observed on the friction surface of the PCM. This indicates the predominance of mechanical destruction processes in the surface layer (Fig. 2b) and the transition to a pseudoelastic wear mechanism.



a b

Fig. 2. Morphology of the friction surface (×150) of the polymer composite containing 25 wt.% of the binary alloy under friction conditions: P = 1,0 MPa and υ = 1,0 m/s (a), and P = 1,5 MPa and υ = 1,5 m/s (b)

The positive interaction coefficient obtained in the regression equation indicates a synergistic effect of the applied load and sliding speed on damage accumulation in the surface layer of the PCM. This indicates that the simultaneous increase in these parameters promotes intensification of degradation processes compared with their individual influence. Such behaviour is consistent with current concepts of dry friction of PCMs, according to which the applied load primarily determines the stress state of the tribological interaction, whereas the sliding speed significantly affects the thermal conditions of friction.

Moreover, the presence of highly supersaturated substitutional solid solutions and a high level of crystal lattice microstrains in the Al–Co binary alloy may contribute to increasing the resistance of the PCM surface layer to microcutting and local plastic deformation during friction. In addition, the metallic nature of the binary alloy promotes more efficient heat dissipation from the friction zone, which partially suppresses the development of thermally activated wear processes under dry friction conditions. Minimum values of the linear wear rate are observed in the region of low sliding speeds and low applied loads, whereas the maximum values occur under their simultaneous increase.

Analysis of the results shows that the minimum wear rate values are achieved at lower load levels, whereas an increase in load leads to a rise in wear rate, which is consistent with the result of regression analysis. Thus, the obtained experimental results and the developed regression model consistently describe the influence of sliding speed and applied load on the linear wear rate of the investigated polymer composite. The model adequately reflects both the individual effects of the factors and their interaction, which is confirmed by statistical analysis and graphical interpretation of the response surface.

Therefore, the relationships established in this study regarding the increase in wear intensity with increasing applied load are consistent with the results of other studies on PCMs [4, 9], which demonstrate the decisive role of contact stresses in the wear process. It was also found that the less pronounced effect of sliding speed and its interaction with the load are in agreement with current understanding of PCM wear mechanisms, where sliding speed determines the thermal conditions at the contact, while the applied load governs the intensity of surface layer degradation. Similar approaches to analyzing the influence of these factors and to developing mathematical models using design of experiments methods are presented in [12]. Thus, the obtained results not only confirm previously reported data but also extend them by providing a quantitative description of the interaction between factors affecting the linear wear intensity of PCM based on UHMWPE containing 25 wt.% of a binary Al–Co alloy as a filler.

Conclusions

1.In this study, quantitative relationships describing the effect of sliding speed and applied load on the linear wear rate of a UHMWPE-based PCM filled with 25 wt.% of a rapidly quenched Al–10 wt.% Co alloy were established for the first time.

2.Based on the experimental data and using a full factorial design, an adequate mathematical model of the wear process was developed, accounting for both the individual effects of the studied factors and their interaction. A synergistic effect of the combined action of sliding speed and load on the linear wear rate was identified, which has not been sufficiently reported previously for this class of materials.

3.The developed mathematical model made it possible to determine the range of rational operating parameters at which minimum values of the linear wear rate of the PCM are achieved. The model can be used to predict the wear resistance of the composite and to substantiate optimal operating conditions under various friction regimes in tribological systems.

4.Semi-helical moldboards made of the developed PCM were manufactured and tested at LLC «Dnipro Metal Structures Plant». The field test results demonstrated increased wear resistance, reduced soil adhesion, and improved plow efficiency. These results support the recommendation of this PCM for implementation in industrial production.

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Микита К.А. Вплив навантаження та швидкості ковзання на інтенсивність зношування металополімерного композиту з наповнювачем системи Al-Co

У роботі наведено результати дослідження триботехнічної поведінки полімерного композиційного матеріалу на основі надвисокомолекулярного поліетилену, наповненого 25 мас.% швидкозагартованого бінарного сплаву системи Al-10 мас.% Co. Актуальність дослідження обумовлена необхідністю підвищення зносостійкості трибологічних з’єднань, що працюють в умовах інтенсивного зношування, підвищених навантажень і недостатнього змащення. Метою дослідження є розробка математичної моделі впливу швидкості ковзання та прикладеного навантаження на інтенсивність лінійного зношування композити в умовах тертя без змащення за схемою «диск-колодка». Дослідження виконано із застосуванням методу повного факторного експерименту з використанням регресійного рівняння першого порядку, що дозволило кількісно оцінити вплив дослідних факторів та їх взаємодії. Встановлено що зі зростанням навантаження інтенсивність лінійного зношування суттєво підвищується, тоді як вплив швидкості ковзання є менш вираженим і проявляється при взаємодії з навантаженням. Виявлено синергетичний ефект спільної дії дослідних факторів на інтенсивність лінійного зношування даного полімерного композиту. Побудована математична модель перевірена за статистичними критеріями та адекватно описує експериментальні дані. Отримані результати можуть бути використані для прогнозування зносостійкості матеріалу та визначення раціональних режимів експлуатації трибологічних з’єднань, що сприяє підвищенню їх довговічності та надійності.

Ключові слова: надвисокомолекулярний поліетилен, бінарний сплав системи Al-Co, швидкість ковзання, прикладене навантаження, інтенсивність лінійного зношування, математична модель