Investigation of the effect of tribological loading parameters on the linea wear rate of a polytetrafluoroethylene-based composite reinforced with polyimide fiber

Ye.A. Yeriomina[1][0000-0001-8595-5735], **K.R. Voloshina**[1][0009-0007-8929-2191], **Predrag Dašić**[2][0000-0002-9242-274X]

[1]Dniprovsk State Technical University, Kamyanske, Ukraine
[2]Academy of Professional Studies Šumadija – Department in Trstenik, Trstenik, Serbia
E-mail: voloshina.k25.06@gmail.com

Abstract

The article presents the results of a comprehensive experimental and theoretical study of the tribotechnical characteristics of a composite material based on polytetrafluoroethylene reinforced with polyimide fiber. The main objective of the study was to determine the quantitative regularities governing changes in the intensity of linear wear as a function of external tribological loading parameters, as well as to establish optimal operating modes for the material. A mathematical modeling approach based on a full factorial design was employed to plan and conduct the experiments. During the study, the effects of sliding velocity and normal load on the linear wear intensity of the composite were analyzed. The experimental results enabled the derivation of a first-order regression equation describing the dependence of wear on the variable parameters. Statistical analysis of the model included an assessment of its adequacy and the significance of the regression coefficients. By constructing response surfaces, zones of minimum wear intensity were identified, and optimal operating conditions for the material under dry friction were determined. The study confirms the significant influence of both individual factors and their interaction on the wear resistance of the composite material. It was established that deviations of tribological loading parameters from their optimal values lead to a substantial increase in linear wear intensity. The combined use of statistical analysis methods and tribological testing allowed for a deeper evaluation of the material behavior and a significant reduction in the scope of experimental work through the development of a mathematical model. The proposed approach can be effectively applied to optimize the operating modes of composite materials based on polytetrafluoroethylene and polyimide fiber in friction units of machines and mechanisms operating under high loads and requiring enhanced wear resistance.

Keywords: polytetrafluoroethylene, polyimide fiber, composite material, tribological properties, experimental design, linear wear intensity, regression model

Introduction

Increasing the wear resistance of friction units is one of the key challenges of modern industry, especially under operating conditions involving high sliding speeds, significant mechanical loads, and limited lubrication. Under such conditions, traditional structural materials often rapidly lose their functional performance, which has led to increased interest in polymer composite materials [1]. These materials are capable of providing stable tribotechnical characteristics under severe operating conditions. Composites based on polytetrafluoroethylene (PTFE) are considered among the most promising representatives of this class of materials. PTFE exhibits a low coefficient of friction and high physicochemical stability; however, in its pure form it is characterized by insufficient wear resistance. The tribotechnical properties of PTFE can be improved by introducing fibrous fillers. Among them, polyimide (PI) fibers are particularly promising due to their high thermal stability, mechanical strength, and chemical inertness. Previous studies of PTFE–PI composite materials have shown that the optimal filler content is 7.5 vol.% of PI fibers [2]. At this filler concentration, the highest level of structural uniformity and wear resistance is achieved. Tribological tests conducted on this composite confirmed the dependence of linear

wear intensity on sliding velocity and applied load. An increase in these parameters intensifies thermomechanical processes in the contact zone, which leads to a reduction in wear resistance. Considering the need to obtain accurate experimental data while minimizing experimental costs, the application of mathematical methods for experimental design is of particular importance. Methods of experimental design are among the most effective tools for identifying regularities in complex multifactorial processes [3]. They significantly reduce the number of experiments required compared to direct empirical approaches while ensuring high accuracy of the obtained results.

The purpose of the work

Determining the quantitative relationships governing the linear wear of a polytetrafluoroethylene–polyimide composite under varying tribological loading conditions and to identify its optimal operating modes.

Objects and methods of research

To optimize the developed polymer composite material with an effective filler content of 7.5 vol.%, linear wear intensity was selected as the key performance parameter. The description of the investigated process was carried out in accordance with established mathematical relationships:

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

In this case, the sliding velocity (x_1) and the applied load (x_2) were selected as independent factors. To simplify the calculation procedure, the values of the independent factors were normalized to a dimensionless scale with corresponding levels of -1, 0, and $+1$. For this purpose, the following normalization formula was used, which allowed the experimental data to be converted into a standard form for further analysis:

$$x_i = \frac{X_i - X_{i0}}{n},$$

where x_i is the coded value of the factor, X_i and X_{i0} are the upper and central levels of factor variation, respectively and n is the step of factor variation (Table 1) [4]. The calculated values of the initial levels of the studied factors are presented in Table 1.

Table 1

Independent factors and their variation levels

Factor	Symbol	Designation	Variation step (n)	Variation levels		
				-1	**0**	**+1**
Slip speed	v, m/s	x_1	0.25	1.5	1.75	2
Load	P, MPa	x_2	0.5	1	1.5	2

According to the mathematical experimental design (Table 2), four experiments (N) were carried out, each of which was repeated twice ($k = 2$) in a random order in order to completely eliminate systematic errors.

Table 2

Planning matrix with calculated interaction columns of factors

Experiment No.	Values of variables on a coded scale				Values of variables on a natural scale	
	x_0	x_1	x_2	$x_1 x_2$	v, m/s	P, MPa
1	+1	+1	+1	+1	2	2
2	+1	-1	+1	-1	1.5	2
3	+1	+1	-1	-1	2	1
4	+1	-1	-1	+1	1.5	1

Mathematical modeling of the dependence of the linear wear intensity of the PTFE–PI composite on the selected variable factors was proposed to be carried out in the form of a regression equation represented by a first-order polynomial:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_{12},$$

where y is the calculated value of the optimization parameter; b_i and b_{ij} are the regression coefficients in the equation. Based on the experimental data presented in Table 3, the average values of the response functions were determined:

$$\widetilde{y}_J = \frac{1}{k} \sum_{i=1}^{k} y_{ji}, \qquad j = 1, 2, \dots, N. \tag{1}$$

Table 3 presents both the experimental values (y_j) and the averaged results (y_j^C) obtained in the study of the influence of sliding speed and applied load on the linear wear intensity of the developed composite material.

Table 3

Experimental and Calculated Values of Linear Wear Intensity

Experiment No.	y_1	y_2	Average Value	Calculated Value
			$\widetilde{y}_J$	y_j^C
1	$3.66 \cdot 10^{-8}$	$3.56 \cdot 10^{-8}$	$3.61 \cdot 10^{-8}$	$3.31 \cdot 10^{-8}$
2	$4.4 \cdot 10^{-8}$	$1.61 \cdot 10^{-8}$	$3.01 \cdot 10^{-8}$	$3.31 \cdot 10^{-8}$
3	$1.71 \cdot 10^{-8}$	$0.84 \cdot 10^{-8}$	$1.27 \cdot 10^{-8}$	$1.21 \cdot 10^{-8}$
4	$0.87 \cdot 10^{-8}$	$1.43 \cdot 10^{-8}$	$1.15 \cdot 10^{-8}$	$1.21 \cdot 10^{-8}$

The reproducibility variance was calculated according to formula (2), and the variance of parallel measurements was calculated according to formula (3):

$$S_y^2 = \frac{1}{N} \sum_{j=1}^{N} S_j^2, \tag{2}$$

$$S_j^2 = \frac{\sum_{j=1}^{N} (y_i - \widetilde{y}_J)}{k-1}. \tag{3}$$

The homogeneity of the variances obtained in parallel experiments was evaluated using Cochran's test:

$$G = \frac{max S_j^2}{\sum_{i=1}^{k} S_j^2}. \tag{4}$$

The calculated and tabulated values of the criterion were compared for degrees of freedom $f_1 = k - 1 = 1$ and $N=4$ at a confidence probability of $P=0.95$. The calculated value of Cochran's test was $G_C = 0.881$ which is lower than the tabulated value $G_{table} = 0.91$. Therefore, the obtained variances can be considered homogeneous. The coefficients of the regression equation have the same error, which is determined using the following formula:

$$S_{bi} = \frac{S_y}{\sqrt{N \cdot k}}. \tag{5}$$

Based on the analytical expressions obtained in the course of a full factorial experiment, the coefficients of the regression equation were calculated:

$$b_0 = \sum_{i=1}^{N} \frac{\widetilde{y}_J x_0}{N}, \tag{6}$$

$$b_i = \sum_{i=1}^{N} \frac{\widetilde{y}_J x_i}{N}, \tag{7}$$

$$b_{ij} = \sum_{i=1}^{N} \frac{\widetilde{y}_J x_{ij}}{N}. \tag{8}$$

Based on the calculations performed according to formulas (1)–(7), a first-order regression equation was obtained, describing the dependence of the response function on the experimental factors:

$$y(I_h) = 2.26 \cdot 10^{-8} + 0.18 \cdot 10^{-8}x_1 + 1.05 \cdot 10^{-8}x_2 + 0.12 \cdot 10^{-8}x_{12}.$$

The statistical significance of the regression coefficients b_0, b_1, b_2, b_{12}, was estimated by calculating confidence intervals. These intervals take into account the variance arising from errors in the determination of the coefficients. Confidence intervals were calculated using Student's t-test, considering the specified degrees of freedom (f_1, f_2) and a confidence probability of 0.95. The formula for calculating the confidence interval is as follows:

$$|b_{cr}| = t_{cr} \cdot S_{bi}. \tag{9}$$

The critical value of Student's t-criterion (t_{cr}) was determined based on the degrees of freedom $N(k–1)=4$ and the chosen significance level of 0.95. A regression coefficient was considered statistically significant if the inequality $t < t_{cr}$ was satisfied. After testing the statistical significance of the coefficients using Student's t-test according to formula (9), it was found that two of the obtained coefficients could be neglected. As a result, the structure of the regression equation was modified, and it was established that, within the studied range of sliding speeds, the applied load has the greatest influence on the linear wear intensity:

$$y(I_h) = 2.26 \cdot 10^{-8} + 1.05 \cdot 10^{-8}x_2. \tag{10}$$

The adequacy of the obtained regression equation was verified by comparing the theoretical values of the optimization parameter, calculated according to equation (10), with the corresponding experimental results for each performed experiment. This allowed the variance of the equation's adequacy to be calculated using the following formula:

$$S_{ad}^2 = \frac{1}{N-B}\sum_{j=1}^{N}(\widetilde{y}_j - y_j^C)^2. \tag{11}$$

In this case, B represents the number of statistically significant coefficients in the regression equation. Accordingly, the degrees of freedom for assessing the adequacy of the model were determined using the formula $f_{ad} = N - B = 2$. The calculated values of the optimization parameter are presented in Table 4.

Table 4

Calculated Data for Assessing the Adequacy of the Mathematical Model Using the Fisher Criterion

S_y^2	Regression Coefficients				S_{ad}^2
	b_0	b_1	b_2	b_{12}	
$1.1 \cdot 10^{-16}$	$2.26 \cdot 10^{-8}$	$0.18 \cdot 10^{-8}$	$1.05 \cdot 10^{-8}$	$0.12 \cdot 10^{-8}$	$0.09 \cdot 10^{-16}$

To assess how well the mathematical model (10) represents the actual relationship between the input and output parameters, Fisher's test [5] was used. This criterion is defined as the ratio of the adequacy variance to the reproducibility variance (see Table 4) and is calculated using the following formula:

$$F_C = \frac{S_{ad}^2}{S_y^2}. \tag{12}$$

At a confidence probability of 0.95 and degrees of freedom $f_1 = 4$ and $f_2 = 4$ the calculated value of Fisher's test, $F_C = 0.081$ was found to be lower than the tabulated value. This indicates that the constructed mathematical model is adequate for describing the studied process [6]. The relationship between the coded and natural values of the factor affecting the optimization parameters is described by the following equation:

$$x_2 = \frac{P-1.5}{0.5}. \tag{13}$$

Results analysis and discussion

Based on a properly selected regression equation, the response surface of the linear wear intensity of the PTFE–PI composite was modeled as a function of slip rate and applied load (Fig. 1). The response surface analysis results show that the minimum wear intensity is achieved at lower applied loads across the entire range of slip rates studied [7]. As the load increases, a noticeable rise in linear wear intensity is observed, confirming the findings of the regression analysis.
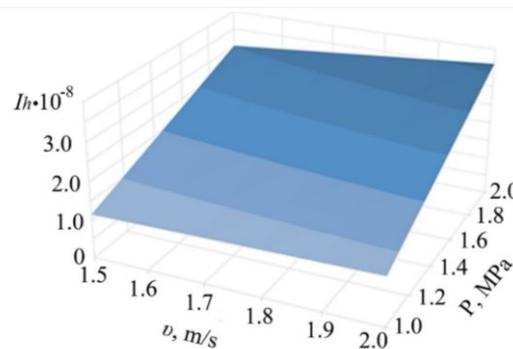

Fig. 1. Response surface of the linear wear intensity of the PTFE–PI composite as a function of slip rate and applied load

The transition from coded variables (x_1, x_2) to natural variables (v, P) made it possible to develop a mathematical model describing the dependence of linear wear intensity on the applied load.

$$y(I_h) = 0.89 \cdot 10^{-8} + 2.1 \cdot 10^{-8}P. \tag{14}$$

Conclusions

The results of a comprehensive experimental and theoretical study of the tribotechnical characteristics of a polytetrafluoroethylene-based composite reinforced with 7.5 vol.% polyimide fibers showed that:

1. It was established that within the studied speed range, the linear wear intensity of the composite significantly depends on the applied normal load. As the load increases, the wear intensity increases, which is attributed to elevated contact stresses and the activation of thermomechanical processes in the friction zone.

2. Based on a full factorial experiment, a first-order regression model was developed to describe the dependence of linear wear intensity on the key influencing factors. The results of the statistical analysis showed that the applied normal load is the dominant factor, whereas the effects of slip rate and factor interactions within the investigated range are statistically insignificant.

3. The validity of the developed mathematical model was verified using Cochran's test for homogeneity of variances and Fisher's test to assess model adequacy. The results confirmed its reliability and consistency with the actual wear behaviour of the composite material under dry friction conditions.

4. The developed model made it possible to identify the regions in which the linear wear intensity is minimal, as well as to determine the optimal operating conditions of the composite. These conditions correspond to relatively lower levels of applied load within the investigated range.

Thus, the application of experimental design methods in combination with tribological testing significantly reduced the scope of experimental studies and enabled the derivation of accurate quantitative relationships describing the wear process. The proposed high-efficiency approach can be used to optimize the operating conditions of PTFE-based composite materials reinforced with polyimide fibers in friction units of machines and mechanisms operating under elevated loads and dry friction conditions.

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Єрьоміна К.А., Волошина К.Р., **Predrag Dašić** Дослідження впливу трибологічних параметрів навантаження на лінійну інтенсивність зношування композиційного матеріалу на основі політетрафторетилену, армованого поліімідним волокном

У роботі наведено результати комплексного експериментально-теоретичного дослідження триботехнічних характеристик композиційного матеріалу на основі політетрафторетилену, армованого поліімідним волокном. Метою дослідження було визначення кількісних закономірностей зміни інтенсивності лінійного зношування як функції параметрів зовнішнього трибологічного навантаження та встановлення оптимальних режимів роботи матеріалу. Для планування та проведення експериментів застосовувався підхід математичного моделювання на основі повного факторного експерименту. Проаналізовано вплив швидкості ковзання та нормального навантаження на лінійну інтенсивність зношування композиту. Експериментальні результати дозволили побудувати рівняння регресії першого порядку, оцінити адекватність моделі та значущість її коефіцієнтів. На основі поверхонь відгуку визначено зони мінімальної інтенсивності зносу та оптимальні умови експлуатації при терті без змащення. Дослідження підтверджує значний вплив окремих факторів та їх взаємодії на зносостійкість композиту. Комбіноване використання статистичного аналізу та трибологічного тестування дозволяє глибше оцінити поведінку матеріалу та скоротити обсяг експериментальної роботи. Запропонований підхід може ефективно застосовуватися для оптимізації режимів роботи полімерних композицій у фрикційних агрегатах машин та механізмів, що працюють при високих навантаженнях і потребують підвищеної зносостійкості.

Ключові слова: політетрафторетилен, поліімідне волокно, композиційний матеріал, трибологічні властивості, математичне моделювання, інтенсивність лінійного зношування, рівняння регресії