UDC 620.191.3:519.876.5 DOI: 10.18372/0370-2197.2(111).21337

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INVESTIGATION OF THE TRIBOLOGICAL PROPERTIES OF A METAL-POLYMER BASED ON ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE AND PREDICTION OF ITS DURABILITY IN TRIBOLOGICAL JOINTS

The article presents the results of scientific research on the processes of operation of a polymer composite material based on ultra-high molecular weight polyethylene, containing 20 wt.% binary alloy of the Al-Cr system as a filler in a tribological joint. The influence of sliding speed and load on the wear intensity and coefficient of friction of the polymer composite was determined, and mathematical models were developed. They describe its tribotechnical behaviour depending on the load and sliding speed of the friction unit. The obtained mathematical dependencies allow us to reliably predict the service life of the composite in tribological joints of equipment and mechanisms of modern machinery, which is important for increasing their efficiency and reliability.

Keywords: *wear intensity, coefficient of friction, load, sliding speed, rapidly quenched alloy, ultra-high molecular weight polyethylene*

Introduction. The continuous development of technical progress necessitates the development and creation of new materials for friction units of modern machinery with high indicators of tribological properties. A promising direction in this area is polymer composite materials (PCMs), in particular, based on ultra-high molecular weight polyethylene (UHMWPE), which contain dispersed fillers (FLs) of various nature, including talc, diamond, aluminium hydroxide, hexagonal boron nitride, graphite, metal sulfides, and zeolite [1]. Therefore, searching for new PCM compositions based on UHMWPE remains an urgent task. Mathematical planning of the experiment makes it possible to ensure the trouble-free and efficient operation of products made of new polymer composite materials without conducting an excessive number of bench and full-scale tests, which in turn allows you to save time and financial resources significantly. Thus, the mathematical models developed by Rula I. [2], Dykha O. [3], Breslavsky D. [4], Burya O. [5], Stotsko Z. [6] made it possible to perform a critical analysis of the influence of the main factors on the functional properties of PCMs, as well as to optimize their composition and operating modes of tribological joints. Thanks to these models, it became possible to predict wear, friction coefficient and other factors without the need for resource-intensive and long-term experiments, which significantly increases the efficiency of the testing stage and the introduction of new PCMs into the practice of modern industry [7].

Materials and research methods. When creating new PCM compositions, the UHMWPE of the Jiujiang Zhongke Xinxing New Material Co., Ltd. [8] was selected as a matrix. A dispersed (40-100 μm) single-phase rapidly quenched binary alloy of the Al-Cr system with 5 wt.% chromium content was selected as a filler. Significant interest in creating new PCMs based on UHMWPE is caused by rapidly quenched alloys based on aluminium. This is explained by the fact that their fine-grained structure, formed during the rapid cooling process, contributes to the production of materials with high functional properties. It was established In the work [9] that PCM with a binary alloy content of 20 wt.% has the best complex of tribological properties. The influence of friction modes on the intensity of linear wear and the coefficient of friction of this PCM under friction without lubrication was studied during rotational motion according to the “disk-pad” scheme in a pair with a steel counterbody (steel 45, hardness 45-48 HRC and surface roughness R_a=0,32 μm) at the sliding speeds of 0,5-1,5 m/s and loads of 0,5-1,5 MPa on the SMC-2 friction machine. We obtained mathematical models using the second-order orthogonal compositional planning of degree 3^2. The detailed methodology is described in [8]. The models allow us to predict the tribological properties of the composite with a filler content of 20 wt.% from the sliding speed and load.

Results analysis and discussion. The linear wear intensity and coefficient of friction were selected as optimisation parameters for the developed PCM. The following dependencies described the studied processes in the work: $y(I_h) = f(x_1, x_2)$, $y(f) = f(x_1, x_2)$, where the sliding speed (x_1) and load (x_2) were selected as independent factors. To ensure the convenience of calculations, we normalized the values of the factor dosages to a conventional scale with the levels -1, 0 and +1, using the formula:

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

where x_i is the coded value of the factor, X_i and X_{i0} are the upper and main levels of factor variation, respectively, n is the step of factor variation (see Table 1) [9].

Table 1 summarises the results of calculating the initial dosages of the studied components.

Table 1

Initial data for experiment planning

Factors	Symbol, unit of measurement	Symbol	Step of variation (n)	Levels 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

We conducted 9 experiments (N) according to the developed plan of the mathematical experiment (Table 2). Each of them was repeated three times (k=3) in random order to avoid systematic errors completely.

$$y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_{12} + b_{11}x_1^2 + b_{22}x_2^2,$$

where: y is the calculated value of the optimization parameter, b_i and b_{ij} are the regression coefficients of the equation. The average values of the response functions $\overline{y_i}$ were calculated based on the obtained experimental data (Tables 3 and 4):

$$y_i = \frac{1}{n}\sum_{i=1}^{n} y_{ji},$$

where j=1, 2,…, N.

Table 2

Planning matrix with calculated columns of factor interaction

Experiment number		Values of variables on a conditional scale						Variable values on a natural scale	
		x_0	x_1	x_2	x_1x_2	x_1^2	x_2^2	υ, m/s	P, MPa
Core of the plan	1	1	1	1	1	0,333	0,333	1,5	1,5
	2	1	-1	1	-1	0,333	0,333	0,5	1,5
	3	1	1	-1	-1	0,333	0,333	1,5	0,5
	4	1	-1	-1	1	0,333	0,333	0,5	0,5
Star points	5	1	1	0	0	0,333	-0,667	1,5	1
	6	1	-1	0	0	0,333	-0,667	0,5	1
	7	1	0	1	0	-0,667	0,333	1,0	1,5
	8	1	0	-1	0	-0,667	0,333	1,0	0,5
Centre of the plan	9	1	0	0	0	-0,667	-0,667	1,0	1

Table 3

Experimental and calculated values of linear wear intensity

№ of experiment	y_1	y_2	y_3	mean	calculated
				$\tilde{y}_j$	$y_j^{\ c}$
1	$1{,}43\cdot10^{-6}$	$1{,}03\cdot10^{-6}$	$9{,}32\cdot10^{-7}$	$1{,}13\cdot10^{-6}$	$1{,}13\cdot10^{-6}$
2	$8{,}69\cdot10^{-8}$	$7{,}05\cdot10^{-8}$	$1{,}11\cdot10^{-7}$	$8{,}94\cdot10^{-8}$	$8{,}73\cdot10^{-8}$
3	$4{,}20\cdot10^{-7}$	$3{,}40\cdot10^{-7}$	$2{,}50\cdot10^{-7}$	$3{,}37\cdot10^{-7}$	$3{,}45\cdot10^{-7}$
4	$2{,}18\cdot10^{-8}$	$4{,}22\cdot10^{-8}$	$1{,}20\cdot10^{-8}$	$2{,}53\cdot10^{-8}$	$2{,}77\cdot10^{-8}$
5	$8{,}53\cdot10^{-7}$	$8{,}42\cdot10^{-7}$	$5{,}03\cdot10^{-7}$	$7{,}33\cdot10^{-7}$	$7{,}20\cdot10^{-7}$
6	$3{,}47\cdot10^{-8}$	$3{,}20\cdot10^{-8}$	$5{,}00\cdot10^{-8}$	$3{,}85\cdot10^{-8}$	$3{,}82\cdot10^{-8}$
7	$4{,}83\cdot10^{-7}$	$7{,}65\cdot10^{-7}$	$6{,}61\cdot10^{-7}$	$6{,}36\cdot10^{-7}$	$6{,}34\cdot10^{-7}$
8	$1{,}14\cdot10^{-7}$	$2{,}47\cdot10^{-7}$	$3{,}02\cdot10^{-7}$	$2{,}21\cdot10^{-7}$	$2{,}10\cdot10^{-7}$
9	$1{,}67\cdot10^{-7}$	$3{,}51\cdot10^{-7}$	$6{,}53\cdot10^{-7}$	$3{,}90\cdot10^{-7}$	$4{,}03\cdot10^{-7}$

Table 4

Experimental and calculated values of the coefficient of friction

№ of experiment	y_1	y_2	y_3	mean	calculated
				$\tilde{y}_j$	$y_j^{\ c}$
1	0,29	0,38	0,33	0,33	0,33
2	0,38	0,39	0,28	0,35	0,35
3	0,24	0,26	0,23	0,24	0,25
4	0,27	0,22	0,25	0,25	0,26
5	0,29	0,23	0,23	0,25	0,25
6	0,26	0,33	0,28	0,29	0,27
7	0,26	0,27	0,21	0,25	0,25
8	0,22	0,18	0,13	0,18	0,16
9	0,17	0,15	0,16	0,16	0,17

The mean square errors of parallel experiments were calculated using the formulas given below:

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

where S_r^2 is the reproducibility variance. It was calculated from the experiments in the center of the plan using the formula

$$S_r^2 = \frac{1}{k-1}\sum_{i=1}^{k}(y_{9i} - y_9)^2,$$

Table 5 shows the calculated values of the variances and coefficients of the regression equation.

Table 5

Regression equation coefficients and variance values of parallel experiments

for wear intesity		For coefficient of friction	
equation coefficients	variance of parallel experiments	equation coefficients	variance of parallel experiments
b_j	S_j	b_j	S_j
$4\cdot10^{-7}$	$9{,}55\cdot10^{-15}$	0,255	$2{,}22\cdot10^{-5}$
$3{,}41\cdot10^{-7}$	$1{,}43\cdot10^{-14}$	-0,01	$3{,}33\cdot10^{-5}$
$2{,}12\cdot10^{-7}$	$1{,}43\cdot10^{-14}$	0,04	$3{,}33\cdot10^{-5}$
$1{,}82\cdot10^{-7}$	$2{,}15\cdot10^{-14}$	-0,0035	$5{,}00\cdot10^{-4}$
$-0{,}238\cdot10^{-7}$	$2{,}15\cdot10^{-14}$	0,09	$5{,}00\cdot10^{-4}$
$0{,}193\cdot10^{-7}$	$4{,}30\cdot10^{-14}$	0,03	$1{,}56\cdot10^{-4}$

We checked the homogeneity of the mean square errors of parallel experiments using the Cochrane criterion (G).

$$G = \max S_j^2 \frac{1}{\sum\limits_{i=1}^{k} S_j^2},$$

With a confidence probability of P=0.95 and degrees of freedom $f_1 = k - 1$ and N, the calculated values of the Cochrane criterion were compared with the tabular values ($G_{\text{tab.}}$). It was found that all the calculated values are less than the tabular value, which indicates the homogeneity of the variances of parallel experiments. Based on the data of the orthogonal composite experiment, we determined the coefficients of the regression equation according to the formula:

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

The equation will have the following form after calculating all the necessary coefficients:

$$y(I_h) = (4,0 + 3,41x_1 + 2,12x_2 + 1,82x_1x_2 - 0,238x_1^2 + 0,193x_2^2)\cdot10^{-7}, \qquad (1)$$

$$y(f) = 0,255 - 0,01x_1 + 0,04x_2 - 0,0035x_1x_2 + 0,09x_1^2 + 0,03x_2^2, \qquad (2)$$

We assessed the statistical significance of the regression equation coefficients by calculating confidence intervals using the Student's test (t), determined according to the given degrees of freedom (f_1, f_2) and a significance level of 0,95. The confidence intervals were calculated using the formula:

$$\square b_i = b_i \cdot S_j^2,$$

The critical value of the Student's test t_{cr} was calculated with 18 degrees of freedom ($N(k\text{-}1)$) at a significance level of 0,95. The regression coefficient was considered statistically significant when the condition $t_{\text{cr}} < \Delta b_i$ was met. In our case, all coefficients of the regression equation appear to be significant, that is, analytical expressions (1) and (2) remain unchanged. We checked the adequacy of the obtained equations by comparing the calculated values of the parameter y_j^c with the experimental $\tilde{y}_j$ in each experiment. This made it possible to calculate the adequacy variances for the same number of parallel experiments [10].

$$S_{ad}^2 = \frac{1}{N-B}\sum_{j=1}^{k}(\tilde{y}_j - y_j^c)^2,$$

where: B is the number of significant coefficients of the equation. The number of degrees of freedom $f = k(N-B) = 9$ is also associated with them.

Tables 3 and 4 present the calculated values of the optimization parameters. After calculating the regression coefficients, we used Fisher's exact test (F_p) to assess the correspondence of the obtained mathematical models (1, 2) to the theoretical relationship between the input and output parameters. This test is the ratio of the adequacy variance (S_{ad}^2) to the experimental reproducibility variance (S_b^2) (see Table 6), and is calculated by the following formula:

$$F_p = \frac{S_{ad}^2}{S_b^2} \tag{3}$$

Table 6

Estimated values or assessing the adequacy of equations according to Fisher's criterion

for wear intensity		for coefficient of friction	
S_b^2	S_{ad}^2	S_b^2	S_{ad}^2
$8{,}59\cdot10^{-14}$	$1{,}8\cdot10^{-16}$	0,0002	0,0003

Since $F_{p.}$ are less than the tabular value ($F_{tab.}$=9.55) [11] at a significance level of 0.95 and degrees of freedom for the equations under consideration, they adequately describe the process under study.

The following dependencies give the relationship between the coded and natural values of factors affecting the optimization parameters:

$$x_1 = \frac{\upsilon - 1{,}5}{0{,}5} = 2\upsilon - 3,$$

$$x_2 = \frac{P - 1{,}5}{0{,}5} = 2P - 3.$$

The transition from coded factors (x_1, x_2) to natural ones (P, υ) allowed us to obtain mathematical models of the tribological properties of the composite as functions of sliding speed and load.

$$I_h = (0{,}773P^2 - 0{,}951\upsilon^2 + 7{,}296P\upsilon - 9{,}02P - 1{,}27\upsilon + 3{,}422)\cdot 10^{-7},$$

$$f = 0{,}1316P^2 + 0{,}3612\upsilon^2 - 0{,}014P\upsilon - 0{,}02864P - 1{,}0832\upsilon + 1{,}2321,$$

Conclusion. The obtained mathematical models allow us not only to analyze the influence of individual parameters on the tribological properties of parts made of this polymer composite material, but also to predict their trouble-free and reliable operation in friction units of modern agricultural, textile, and automotive equipment under the influence of various loads and sliding speeds.

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Received: May 07, 2026
Accepted: May 15, 2026
Published: May 31, 2026

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ДОСЛІДЖЕННЯ ТРИБОЛОГІЧНИХ ВЛАСТИВОСТЕЙ МЕТАЛОПОЛІМЕРУ НА ОСНОВІ НАДВИСОКОМОЛЕКУЛЯРНОГО ПОЛІЕТИЛЕНУ ТА ПРОГНОЗУВАННЯ ЙОГО ДОВГОВІЧНОСТІ У ТРИБОЛОГІЧНИХ З’ЄДНАННЯХ

У статті представлено результати наукових досліджень щодо процесів експлуатації полімерного композиційного матеріалу на основі надвисокомолекулярного поліетилену, що містить як наповнювач бінарний сплав системи Al-Cr у кількості 20 мас.% в трибологічному з’єднанні. Було визначено вплив швидкості ковзання та навантаження на інтенсивність зношування та коефіцієнт тертя полімерного композиту, а також розроблено математичні моделі, що описують його триботехнічну поведінку залежно від навантаження та швидкості ковзання вузла тертя. Отримані математичні залежності дають змогу достовірно прогнозувати ресурс роботи композиту у трибологічних з’єднаннях машин і механізмів сучасної техніки, що є важливим для підвищення їхньої ефективності й надійності.

Ключові слова: інтенсивність зношування, коефіцієнт тертя, навантаження, швидкість ковзання, швидкозагартований сплав, надвисокомолекулярний поліетилен

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