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THE EFFECT OF LOAD AND ABRASIVE PARTICLE SIZE ON THE ABRASIVE WEAR INDEX OF A POLYMER COMPOSITE BASED ON ULTRA-HIGH-MOLECULAR-WEIGHT POLYETHYLENE

This article examines the effect of the applied load and abrasive particle size on the abrasive wear index of a polymer composite material based on ultra-high-molecular-weight polyethylene filled with 20 wt.% of the Al- 5 wt.% Cr binary alloy. The investigations were carried out at three load levels (10, 15 and 20 N) and three levels of abrasive particle size for firmly fixed abrasive particles (100, 150 and 200 μm) using a HECKERT testing machine. Design of experiments and regression analysis were employed to determine the effects of the experimental factors on the abrasive wear index of the polymer composite. The results of the studies yielded a second-order mathematical model that enables prediction of the abrasive wear index of a polymer composite based on ultra-high-molecular-weight polyethylene filled with a liquid-quenched Al-5 wt.% Cr binary alloy, depending on the applied load and abrasive particle size. The statistical significance of the coefficients and the adequacy of the mathematical model to the experimental data were assessed using the Student's and Fisher's criteria, respectively. It was established that the abrasive wear index is affected by both the applied load and abrasive particle size, as well as by their combined effect. The mathematical model obtained can be used to predict the abrasive wear resistance of a polymer composite and to determine appropriate operating conditions for structural and tribological components in agricultural, mining and automotive machinery operating under abrasive wear conditions.

Keywords: *ultra-high-molecular-weight polyethylene, liquid-quenched alloy, load, abrasive wear, abrasive particle size*

Introduction. One of the most common and severe forms of surface damage to metal components in agricultural, mining and automotive machinery is abrasive wear [1], which, in turn, leads to a reduction in the reliability and service life of the equipment, and, consequently, to increased financial costs associated with the replacement of worn parts and equipment downtime [2]. The use of polymer composite materials (PCMs), including those based on ultra-high-molecular-weight polyethylene (UHMWPE), is an effective way of improving the reliability and durability of components. UHMWPE-based PCMs containing dispersed fillers, in particular binary alloys of the Al–Ni and Al–Co systems [3], graphene oxide and aluminium oxide [4, 5], sodium alendronate [4], metallic quasicrystalline powders [6] and silicon dioxide nanoparticles [7], are characterised by high functional performance, in particular high abrasive wear resistance. Abrasive wear resistance depends significantly on the conditions of interaction with the abrasive medium, in particular on the applied load and the size of the abrasive particles. An increase in load leads to a change in the contact conditions between the PCM surface and the abrasive particles, which contributes to an increase in the intensity of abrasive particle penetration into the surface layer of the PCM and the intensification of surface degradation processes. Another important factor is the size of the abrasive particles, as this determines the nature and extent of localised damage to the material. It should be noted that the effects of these factors may be

interrelated; therefore, a comprehensive analysis of them allows for a more reliable assessment of the characteristics of abrasive wear. The use of design of experiments methods makes it possible to determine the combined effect of the factors under investigation and to establish a mathematical relationship between the abrasive wear index and operating conditions; consequently, this helps to identify effective operating conditions for PCM components and contributes to extending their service life under abrasive wear conditions [8, 9]. In view of the above, the aim of this study was to develop a mathematical model of the abrasive wear index of UHMWPE-based PCM under different loads and abrasive particle sizes.

Materials and research methods. It was established in [10] that the introduction of a liquid-quenched (LQ) Al-Cr binary alloy with a chromium content of 5 wt.% results in a twofold reduction in the abrasive wear index of UHMWPE while simultaneously improving its thermophysical properties. The effect of the applied load (10, 15 and 20 N) and the abrasive particle size (100, 150 and 200 μm) on the abrasive wear index of PCM was investigated using a HECKERT testing machine. Using a full factorial design of type 3^2 with two factors, each varied at three levels, a mathematical model was obtained that enables the prediction of the abrasive wear index of the PCM containing 20 wt.% of LH Al-5 wt.% Cr as a function of the applied load and the abrasive particle size.

Results analysis and discussion. When developing a mathematical model of the effect of operating conditions on the wear resistance of the PCM against firmly fixed abrasive particles, the abrasive wear index (y) was selected as the response variable. To describe the process under investigation, the dependence of the optimisation parameter on two independent factors was considered: particle size x_1 and load applied to the specimen x_2, i.e., $y=f(x_1, x_2)$ [11]. For convenience of calculation, the actual values of the factors were converted into a coded coordinate system with variation levels of –1, 0 and +1. The factors were normalised according to the following relationship:

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

where x_i is the coded value of the i-th factor; X_i is the actual value of the factor; X_{i0} is the basic (zero) level of the factor; n is the variation interval of the factor.

The results of the calculation of the basic levels of the factors and their variation intervals are presented in Table 1.

Table 1

Factor designation

Factors	Parameter, unit of measurement	Factors designation	Variation interval (n)	Values of variable levels		
				-1	0	+1
Particle size	D, μm	x_1	50	100	150	200
Load	P, N	x_2	5	10	15	20

According to the developed experimental design, nine experiments were conducted in accordance with a full factorial design of type 3^2 for two factors at three levels (Table 2). The value of the optimisation parameter was determined for each combination of

factors. Based on the results of the experimental studies, the mean values of the response function and the regression coefficients were calculated [11].

The mathematical model of the process under investigation can be expressed in general form by the following equation:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_{12} + b_{11} x_1^2 + b_{22} x_2^2, \quad (1)$$

where y is the parameter under investigation (abrasive wear index); b_0, b_1, b_2, b_{12}, b_{11}, b_{22} are the coefficients of the regression equation; x_1, x_2 are, respectively, the particle size and the load in coded units. Based on the experimental data obtained (Table 3), the mean values of the response variable were determined as follows:

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

where j=1, 2,…, N.

Table 2

Experimental design matrix with calculated interaction and squared factor columns

Experiment No.	Values of variables in the coded scale						Actual values of variables	
	x_0	x_1	x_2	x_1x_2	x_1^2	x_2^2	D, μm	P, N
1	+1	+1	+1	+1	+1	+1	200	20
2	+1	+1	0	0	+1	0	200	15
3	+1	+1	-1	-1	+1	+1	200	10
4	+1	0	+1	0	0	+1	150	20
5	+1	0	0	0	0	0	150	15
6	+1	0	-1	0	0	+1	150	10
7	+1	-1	+1	-1	+1	+1	100	20
8	+1	-1	0	0	+1	0	100	15
9	+1	-1	-1	+1	+1	+1	100	10

The root mean square errors of the replicate experiments were determined using the following equations:

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

where S_r^2 is the reproducibility variance. The reproducibility variance of the experiment was calculated from the experimental results using the following formula:

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

The calculated values of the regression equation coefficients and the variances of replicate experiments are presented in Tables 4 and 5, respectively.

Table 3

Experimental and calculated values of the abrasive wear rate

Experiment No.	y_1	y_2	y_3	mean value	calculated value
				$\tilde{y}_j$	$y_j{}^c$
1	7,15	6,62	6,57	6,78	6,70
2	5,31	4,63	4,45	4,80	4,97
3	3,54	3,08	3,33	3,32	3,24
4	4,98	4,38	3,90	4,42	4,37
5	3,40	3,01	3,16	3,19	3,26
6	2,22	2,42	2,09	2,24	2,15
7	2,01	1,85	1,87	1,91	2,04
8	1,84	1,80	1,80	1,81	1,55
9	0,96	0,92	0,85	0,91	1,06

Table 4

Regression equation coefficients

Regression equation coefficient	b_0	b_1	b_2	b_{12}	b_{11}	b_{22}
Value	3,26	-1,71	-1,11	0,62	-0,02	0,01

Table 5

Variances of replicate experiments

Experiment No.	1	2	3	4	5	6	7	8	9
S_j^2	0,0062	0,0011	0,0152	0,0184	0,0774	0,5856	0,1061	0,4115	0,2066

The homogeneity of the variances of the replicate experiments was tested using Cochran's *G* test.

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

For each of the nine experiments, which were conducted in triplicate, the variance S_j^2 was determined. The calculation yielded a Cochran's *G* test statistic of G=0,41. At a confidence level of P=0,95 and with the corresponding degrees of freedom $f_1=k-1$ and $f_2=N$ the calculated value of the Cochran's test statistic was compared with the tabulated value G_{tab}. The results showed that $G<G_{tab}$, indicating the homogeneity of the variances across the replicate experiments. Based on the experimental results, the coefficients of the regression equation were determined. A second-order mathematical model was used to describe the dependence of the abrasive wear index on the factors under investigation.

The values of the coefficients b_0, b_1, b_2, b_{12}, b_{11}, b_{22} were determined from the results of the experiments conducted. After calculating the coefficients, Equation (1) takes the following form:

$$y(V_i) = (3,26 - 1,71x_1 - 1,11x_2 + 0,62x_1x_2 - 0,02x_1^2 + 0,01x_2^2), \quad (2)$$

The statistical significance of the regression equation coefficients was assessed using Student's t-test. To this end, confidence intervals for the coefficients were determined using the corresponding formula. The critical value of Student's t-test was determined for f=18 degrees of freedom at a confidence level of P=0,95 [11]. A regression equation coefficient was considered statistically significant provided that:

$$|b_i| > \Delta b_i,$$

or in an equivalent form,

$$t_i = \frac{|b_i|}{\Delta b_i} > t_{cr}.$$

Based on the assessment of the statistical significance of the regression equation coefficients using Student's t-test, it was established that the coefficients b_0, b_1, b_2, b_{12} are statistically significant. The coefficients b_{11}=-0,02 and b_{22}=0,01 are not statistically significant, as their absolute values are less than the critical value b_{cr}=0,16. Therefore, the coefficients b_{11} and b_{22} were excluded from the mathematical model, resulting in the final regression equation:

$$y(V_i) = 3,26 - 1,71x_1 - 1,11x_2 + 0,62x_1x_2, \quad (3)$$

The adequacy of the mathematical model obtained was assessed using Fisher's F-test by comparing the variance of adequacy with the reproducibility variance of the experiment. The variance of adequacy was determined based on a comparision of the experimental $\tilde{y}_j$ and calculated y_j^c values of the response variable:

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

According to the calculation results, the variance of adequacy was S_{ad}^2=0,032. The agreement of the mathematical model with the experimental data was assessed using Fisher's F-test by comparing the adequacy variance with the reproducibility variance of the experiment:

$$F_{cal} = \frac{S_{ad}^2}{S_b^2}$$

The calculated value of Fisher's F-test statistic was F_{cal}=0,21. This value was compared with the tabulated value F_{tab}=2,40, determined for $f_1=k(N-B)$=15, where k=3 is the number of replicate experiments; N=9 is the number of experiments in the design; B=4 is the number of statistically significant coefficients in the regression equation; $f_2=N(k-1)$=18, at a confidence level of P=0,95. Since $F_{cal}<F_{tab}$, the mathematical model obtained was considered to be adequate to the experimental data. The relationship between the coded and actual values of the factors influencing the abrasive wear index was determined using the following relationships:

$$x_1 = \frac{D-150}{50} = 0,02D - 3,$$

$$x_2 = \frac{P-15}{5} = 0,2P - 3.$$

The conversion of the coded values of the factors x_1 and x_2 into the actual values D and P made it possible to express the resulting mathematical model in terms of actual

variables. This makes it possible to directly assess the influence of the actual abrasive particle size and load values on the abrasive wear index of the PCM under investigation:

$$V_i = 0,00296DP - 0,071D - 0,594P + 17,3.$$

It has been established that the abrasive wear index is determined both by the applied load and the size of the abrasive particles, as well as by their interaction. Using a simplified, statistically significant first-order regression equation, a response surface of the PCM abrasive wear index was constructed, reflecting the effects of the applied load and abrasive particle size (Fig. 1) [12].

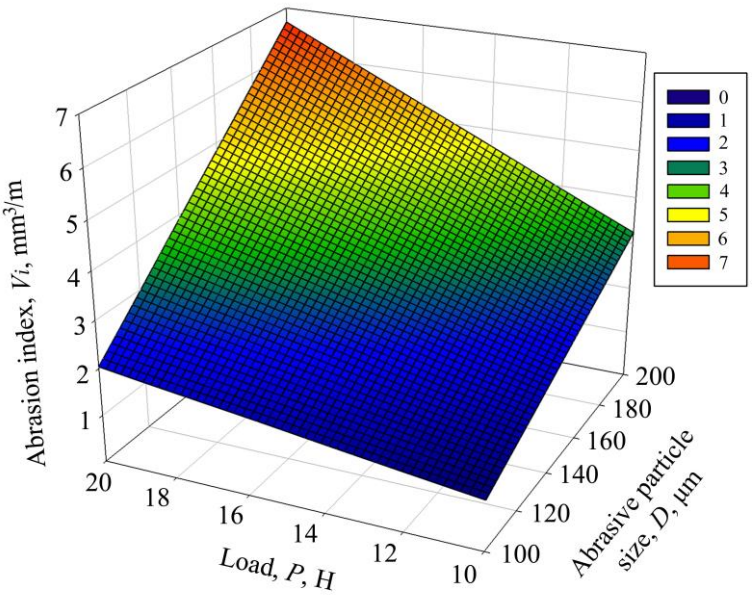
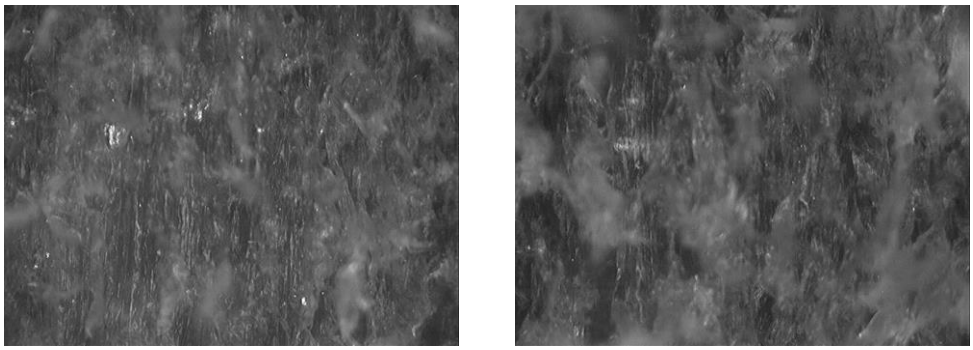


Fig. 1. Response surface of the abrasive wear index (V_i, mm^3/m) of the composite as a function of the applied load (P, N) and abrasive particle size (D, μm)

Analysis of the response surface (Fig. 1) of the test specimen of PCM showed that the abrasive wear index depends on both the applied load and the size of the abrasive particles. As the values of these factors increase, a monotonic increase in the abrasive wear rate of the PCM is observed, which is attributed to an increase in the intensity of abrasive particle penetration into the surface layer of the PCM and the intensification of its surface degradation processes. This conclusion is supported by a comparison of the friction surfaces (Fig. 2) [13]. As the applied load and the size of the abrasive particles increase, more pronounced signs of mechanical damage are observed on the friction surface of the PCM, in particular a greater number of ploughing grooves, scratches and areas of localised damage.



a b

Fig. 2. Morphology of the friction surface of the PCM (×150) containing 20 wt.% of a liquid-quenched binary Al-5 wt.% Cr alloy: *P*=10 N and *D*= 150 μm (a), and *P*=20 N and *D*=200 μm (b)

An increase in the size of the firmly fixed abrasive particles leads to their deeper penetration into the surface layer of the PCM, while an increase in the applied load intensifies the contact interaction between the abrasive particles and the surface. Consequently, the processes of micro-cutting, scratching, and removal of PCM fragments from the friction surface are intensified (Fig. 2), which, in turn, reduces the abrasive wear resistanceof the material.

Conclusion. The mathematical model developed makes it possible not only to assess the influence of load and abrasive particle size on the abrasive wear index of a polymer composite material based on UHMWPE and containing a liquid-quenched 20 wt.% Al-5 wt.% Cr as a filler, but also to predict its value under various operating conditions. This model can be used to analyse the tribological properties of components made from the material under investigation and to determine the optimal operating conditions for such components in friction assemblies of agricultural, mining, and automotive machinery under abrasive wear conditions.

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ВПЛИВ НАВАНТАЖЕННЯ ТА РОЗМІРУ ЧАСТОК АБРАЗИВУ НА ПОКАЗНИК АБРАЗИВНОГО СТИРАННЯ ПОЛІМЕРНОГО КОМПОЗИТУ НА ОСНОВІ НАДВИСОКОМОЛЕКУЛЯРНОГО ПОЛІЕТИЛЕНУ

У статті розглянуто вплив прикладеного навантаження та розміру часток абразиву на показник абразивного стирання полімерного композиційного матеріалу на основі надвисокомолекулярного поліетилену, що містить, як наповнювач, 20 мас.% бінарного сплаву Al-5 мас.% Cr. Дослідження здійснювали за трьома рівнями навантаження (10, 15 та 20 Н) та трьома рівнями розмірів жорсткозакріплених часток абразиву (100, 150 та 200 мкм) із використанням дослідної машини HECKERT. Для встановлення закономірностей впливу дослідних факторів на показник абразивного стирання полімерного композиту застосували математичне планування експерименту та регресійний аналіз. За результатами проведених досліджень отримано математичну модель другого порядку, яка дозволяє прогнозувати величину показника абразивного стирання полімерного композиту на основі надвисокомолекулярного поліетилену, наповненого рідинно-загартованим бінарним сплавом Al-5 мас.% Cr, залежно від величини прикладеного навантаження та розміру часток абразиву. Статистичну значущість коефіцієнтів та адекватність експериментальним даним математичної моделі оцінено за критеріями Стьюдента та Фішера відповідно. Встановлено, що на показник абразивного стирання впливають як прикладене навантаження та розмір часток абразив. так і їх комплексна дія. Отримана математична модель може бути використана для прогнозування показника абразивної зносостійкості полімерного композиту та визначення раціональних режимів експлуатації деталей конструкційного та триботехнічного призначення сільськогосподарської, гірничорудної та автомобільної техніки, експлуатація яких відбувається за умов абразивного зношування.

Ключові слова: надвисокомолекулярний поліетилен, швидкозагартований з рідини сплав, навантаження, показник абразивного стирання, розмір часток.

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