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A. – M. TOMINA, K. MYKYTA, Ye. YERIOMINA, O. NABEREZHNAYA, D. FROLOV

Dniprovsk State Technical University, Dnipro, Ukraine

RESEARCH ON THE INFLUENCE OF TECHNOLOGICAL FORMING PARAMETERS ON THE TRIBOLOGICAL PROPERTIES OF A COMPOSITE BASED ON ULTRA-HIGH-MOLECULAR-WEIGHT POLYETHYLENE

The article presents the results of a study on the influence of technological parameters of moulding on the abrasive wear index of a polymer composite based on ultra-high-molecular-weight polyethylene containing 25 wt.% dispersed binary alloy of the Al–10 wt.%Co system as a filler. We applied the method of a full factorial experiment of type 2^3 to reduce the volume of experimental tests and establish quantitative relationships between technological parameters of moulding and tribological properties of the material. We obtained an adequate mathematical model that reflects the influence of processing temperature, holding time under load, and load magnitude on the abrasive wear index. We established optimal pressing conditions which allow the wear resistance of the composite to reach its maximum value.

Keywords: *ultra-high-molecular-weight polyethylene, abrasive wear index, full factorial experiment, binary alloy of the Al-Co system*

Introduction. Using thermoplastic materials in modern production is becoming increasingly relevant due to their combination of high functional properties and the possibility of multiple processing methods. This provides high economic efficiency and complies with the principles of sustainable development, particularly, it contributes to reducing waste and greenhouse gas emissions. Ultra-high-molecular-weight polyethylene (UHMWPE) takes a special place among high-performance polymers. It is used to manufacture durable, wear-resistant products [1,2].

At the same time, even UHMWPE does not always provide the required level of durability under conditions of intense abrasive wear, typical of transportation systems and agricultural machinery. This necessitates improving its performance characteristics by introducing fillers of various natures and shapes. Using dispersed inorganic fillers is an effective approach. Thus, [3] shows that the addition of boron nitride reduces the intensity of wear, while the introduction of Al_2O_3 helps to increase mechanical and tribological properties [4]. The authors [5] found that using metal sulfides (MoS_2, SnS_2) increases the wear resistance of UHMWPE up to 62%. This improves the mechanical and thermomechanical characteristics of the material, too.

It is known [6] that the moulding mode has a significant impact on the functional properties of composites, including those based on UHMWPE. The main technological parameters that determine the structure and operational characteristics of the material include the pressing temperature, the holding time under load, and the magnitude of the applied load.

Methods of mathematical experimental planning were used for a rational selection of these parameters and a decrease in the number of experimental tests. This allows obtaining quantitative relationships between the composition, technological modes of moulding, and operational properties of composites (wear index, friction coefficient, etc.). The works of domestic researchers (Burya O.I., Aulin V.V., Rula I.V., Diadchenko N.K.) and foreign authors (Boon Peng Chang, Hazizan Md Akil, Predrag Dašić) have confirmed the effectiveness of mathematical modelling for optimising the tribological characteristics of polymer composites [6–9].

Materials and research methods. In [10], the authors established that the best set of tribological properties is characterised by a composite based on UHMWPE, containing 25 wt.% alloy of the Al–10 wt.%Co system, rapidly quenched from the liquid state, as a filler. Based on this material, we decided to manufacture semi-screw blades for the plough of the «Sirius-10» pneumatic cultivator for «Dnepr Metal Structures Plant» LLC since its operation occurs under the influence of abrasive particles. As noted above, the moulding mode has a significant impact on the tribological properties of composites, so we decided to conduct a full factorial experiment of type 23, which allows to evaluate the influence of the main factors and their combinations on the abrasive wear index of a composite based on UHMWPE with an effective content of Al–Co filler in the amount of 25 wt.% [11]. The effectiveness of the experiment largely depends on the correct choice of controlled parameters and the determination of the ranges of their change. Table. 1 shows the initial values used to build the experimental plan. For each of the studied factors, three levels of variation were determined: minimum (–1), nominal (0) and maximum (+1), which ensures coverage of the full range of parameter changes.

We performed the study with a three-level variation of each factor, which made it possible to conduct a detailed analysis of their influence on the abrasive wear index of the composite. To determine the optimal parameters of the system, an analytical dependence was used in the form:

$$y= f(x_1 , x_2 , x_3),$$

where y is the response function characterising the abrasive wear index.

Table 1

Initial data for experiment planning

Parameter		Symbol	Basic level	Variation step	Levels of variation	
					+1	-1
Processing temperature	X_1	T, K	185	5	463	453
Holding time under load	X_2	τ, s	12,5	2,5	15	10
Load	X_3	P, MPa	7,5	5	10	5

In order to simplify the processing of results and further calculations, the natural values of the factors were converted into a coded form. In this form, each level of the variable corresponds to a conditional value: minimum – (-1), average – (0) and maximum – (+1), according to the dependence:

$$x_i = \frac{X_i - X_{I0}}{h},$$

where x_i is the coded value of the factor; X_{i0} is the nominal (basic) level of variation; h is the step of changing the parameter.

Using coded values allowed us to create a unified scale for all the factors under study, which significantly facilitated the further analysis of the experimental data. Table 2 shows the experimental planning matrix in a conventional and full scale. Using it provided the possibility of a comprehensive study of the interaction between factors, assessment of their impact on target indicators and determination of optimal conditions for material formation.

Table 2

Full factorial experiment design matrix

Experiment number	Conventional scale							Full scale		
	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	T, K	τ, s	P, MPa
1	1	1	1	1	1	1	1	463	15	10
2	1	-1	1	1	-1	-1	1	453	15	10
3	1	1	-1	1	-1	1	-1	463	10	10
4	1	-1	-1	1	1	-1	-1	453	10	10
5	1	1	1	-1	1	-1	-1	463	15	5
6	1	-1	1	-1	-1	1	-1	453	15	5
7	1	1	-1	-1	-1	-1	1	463	10	5
8	1	-1	-1	-1	1	1	1	453	10	5

Results analysis and discussion. According to the approved experimental plan, $N=2^k=8$ experiments were performed, where k is the number of experimental factors. We performed each experiment three times ($n=3$) in a random sequence, which made it possible to minimise the influence of systematic errors.

Table 3

Experimental, averaged, and calculated values of the abrasive wear index

Experiment number	Abrasive wear index, V_i, mm^3/m			Value: Averaged	Value: Calculated	Error
	y_1	y_2	y_3	$\bar{y}_i$	y_i^p	δ, %
1	0,7140	0,7900	0,8640	0,789	0,729	-8,29
2	1,2450	1,1510	1,0130	1,136	1,177	3,48
3	1,0730	0,9600	1,1700	1,068	1,128	5,36
4	1,1200	1,3500	1,2200	1,230	1,189	-3,44
5	1,2400	1,5500	1,4400	1,410	1,451	2,82
6	1,1200	1,2500	1,1700	1,180	1,120	-5,40
7	1,5800	1,4800	1,3800	1,480	1,439	-2,84
8	0,5900	0,7200	0,6700	0,660	0,720	8,39

We conducted mathematical modelling of the dependence of the abrasive wear index on the processing temperature, holding time under load, and load value according to the method of a full factorial experiment. During the analysis, the average values of the response function (equation 1) were calculated using the experimental data from Table 3.

$$\bar{y}_i = \frac{1}{n}\sum_{i=1}^{n} y_{ji}, \tag{1}$$

where $j=1, 2,\ldots, N$.

Table 3 presents the experimental (y_i^p) and averaged values of the results () obtained while studying the influence of the processing temperature, holding time under load, and load value on the abrasive wear index of the developed composite. The reproducibility variance was calculated using the formula (2), and the dispersion of parallel experiments (3).

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

$$S_j^2 = \frac{\sum_{j=1}^{N}(y_i - \bar{y}_j)^2}{(k-1)}, \tag{3}$$

The homogeneity of the variances obtained in parallel experiments was checked by the Cochrane criterion:

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

We compared the calculated and tabulated values of the criterion under the conditions of degrees of freedom $f_1 = k–1 = 2$ and $N = 8$ with a confidence probability of P=0.95.

The calculated value of the Cochrane criterion is G□=0.47, which is less than the tabulated G□$_{\alpha\beta}$□=0.516. Therefore, the obtained variances can be considered homogeneous.

The coefficients of the regression equation have the same error, which is calculated by the formula:

$$S_{bi} = \frac{S_y}{\sqrt{N \cdot K}}, \tag{5}$$

Using the analytical expressions obtained in the process of the full factorial experiment, the coefficients of the regression equation were determined:

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

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

$$b_{ij} = \sum_{i=1}^{N} \frac{\bar{y}_j x_{ij}}{N}, \tag{8}$$

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

$$y(V_i) = 1{,}1192 + 0{,}0676x_1 + 0{,}0098x_2 - 0{,}0633x_3 - 0{,}0968x_{1,2} - 0{,}1949x_{1,3} - 0{,}1028x_{2,3}$$

We assessed the statistical significance of the coefficients of the regression equation b_0 , b_1 , b_2 , b_3 , $b_{1\ 2}$, $b_{1\ 3}$, $b_{2\ 3}$ by calculating confidence intervals that took into account the variance caused by the errors in determining these coefficients.

We calculated confidence intervals using the t-Student’s criterion, taking into account the given degrees of freedom (f_1, f_2) and a confidence probability of 0.95.

The formula for calculating the confidence interval is as follows:

$$\Delta b_i = t_{кр} \cdot S_{bi}, \tag{9}$$

The critical value of the Student's t-test tcr was determined according to the number of degrees of freedom *N (n–1)*=16 and the selected significance level of 0.95.

The regression coefficient was considered statistically significant if the inequality $t_{кр} < t.$ was fulfilled. After checking the statistical significance of the coefficients according to the Student's t-test (formula 9), it was found that one of the obtained coefficients can be neglected, so the structure of the equation will change:

$$y(V_i) = 1,1192 + 0,0676x_1 - 0,0633x_3 - 0,0968x_{1,2} - 0,1949x_{1,3} - 0,1028x_{2,3} \qquad (10)$$

The adequacy of the obtained equation was checked by comparing the theoretical values of the optimisation parameter calculated according to equation (10) with the corresponding experimental results for each experiment conducted. This allowed us to determine the variance of the adequacy of the equation according to the following formula:

$$S_{ад}^2 = \frac{1}{N-B}\sum_{j=1}^{k}(\bar{y}_j - y_j^p)^2, \qquad (11)$$

In this case, B means the number of statistically significant coefficients of the regression equation. Accordingly, the number of degrees of freedom to check the adequacy of the model was determined as $f_{ad} = N–B = 2$. The calculated values of the optimisation parameter are given in Table 4.

Table 4

Calculated data for determining the adequacy of the mathematical model using Fisher's criterion

S_y^2	Regression coefficients							S_{ad}^2
	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	
0,0108	1,1192	0,0676	0,0098	-0,0633	-0,0968	-0,1949	-0,1028	0,0106

To assess the extent to which the mathematical model (10) reflects the real nature of the relationship between the input and output parameters, we used Fisher's criterion [12]. It is defined as the ratio of the adequacy variance to the reproducibility variance (see Table 4) and is calculated by the formula:

$$F_p = \frac{S_{ad}^2}{S_y^2}, \qquad (12)$$

Therefore, with a confidence probability of 0.95 and degrees of freedom f_1=1 and f_2=2, the calculated value of Fisher's criterion F_r=0.98 appeared to be less than the tabular one. This indicates the adequacy of the constructed mathematical model in reflecting the studied process.

The relationship between the coded and natural values of factors that affect the optimisation parameters is determined by the following ratio:

$$x_1 = \frac{T-458}{5},$$

$$x_2 = \frac{\tau - 12,5}{2,5},$$

$$x_3 = \frac{P-7,5}{2,5}.$$

The transition from coded factors (x_1, x_2, x_3) to natural ones (T, τ, P) made it possible to build a mathematical model of the dependence of the abrasive wear indicator on the influence of processing temperature, holding time under load, and load magnitude.

$$V_i = -104,2871 + 0,2271T + 3,6701\tau + 7,3214P - 0,0077T\tau - 0,0156TP - 0,016\tau P$$

Conclusion. The resulting mathematical model made it possible to determine the conditions under which the minimum level of wear is ensured and the durability of the material increases. The developed model was used during the design and manufacture of semi-screw blades for the plough of the «Sirius-10» pneumatic cultivator for «Dnepr Metal Structures Plant» LLC to conduct production tests. During operation, it was established that these semi-screw blades are characterised by increased wear resistance to abrasive particles, less tendency to soil sticking, and increased efficiency of the plough in the field.

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Anna-Mariia Tomina – Candidate technical of Sciences, associate professor of Department of Condensed State Physics, Dniprovsk State Technical University, Dniprobudivska St., 2, Kamianske, Ukraine, 51918, tel.number: +380569560667, E-mail: an.mtomina@gmail.com https://orcid.org/0000-0001-5354-0674

Kateryna Mykyta – Candidate for higher education «Doctor of Philosophy» in specialty 132 «Materials Science» educational and scientific program «Materials Science» of Department of Condensed State Physics, Dniprovsk State Technical University, Dniprobudivska St., 2, Kamianske, Ukraine, 51918, tel.number: +380569560667, E-mail: mikita2703@gmail.com https://orcid.org/0009-0001-1307-4434

Yekaterina Yeriomina – Candidate technical of Sciences, associate professor, associate professor of Department of Condensed State Physics, Dniprovsk State Technical University, Dniprobudivska St., 2, Kamianske, Ukraine, 51918, tel.number: +380569560667, E-mail: eka.yeriomina@gmail.com https://orcid.org/0000-0001-8595-5735

Olga Naberezhnaya – Candidate technical of Sciences, associate professor, associate professor of Department of Condensed State Physics, Dniprovsk State Technical University, Dniprobudivska St., 2, Kamianske, Ukraine, 51918, tel.number: +380569560667, E-mail: o.naberezhnaya@gmail.com https://orcid.org/0000-0003-1302-4098

Danylo Frolov – 4rd-year Bachelor’s degree student in speciality 132 «Materials Science», Educational Program «Materials Science», Department of Condensed Matter Physics, Dniprovsk State Technical University, Dniprobudivska St., 2, Kamianske, Ukraine 51918, tel.number: +380569560667, E-mail: ndj95582@gmail.com https://orcid.org/0009-0005-9057-8555

А.-М. В. ТОМІНА, К.А. МИКИТА,, К. А. ЄРЬОМІНА, О. О. НАБЕРЕЖНА, Д. А. ФРОЛОВ

ДОСЛІДЖЕННЯ ВПЛИВУ ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ ФОРМУВАННЯ НА ТРИБОЛОГІЧНІ ВЛАСТИВОСТІ КОМПОЗИТУ НА ОСНОВІ НАДВИСОКОМОЛЕКУЛЯРНОГО ПОЛІЕТИЛЕНУ

У статті представлено результати дослідження впливу технологічних параметрів формування на показник абразивного стирання полімерного композиту на основі надвисокомолекулярного поліетилену, що містить як наповнювач 25 мас.% дисперсного бінарного сплаву системи Al–Co, із відсотковим вмістом останнього 10 мас.%. Для скорочення обсягу експериментальних випробувань і встановлення кількісних залежностей між технологічними параметрами формування та трибологічними характеристиками матеріалу застосовано метод повного факторного експерименту типу 2^3. Отримано адекватну математичну модель, що відображає вплив температури переробки, часу витримки під навантаженням і величини навантаження на показник абразивного стирання. Встановлено оптимальні умови пресування, за яких зносостійкість композиту досягає максимального значення.

Ключові слова: надвисокомолекулярний поліетилен, показник абразивного стирання, повний факторний експеримент, бінарний сплав системи Al-Co

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Томіна Анна-Марія Вадимівна – канд. техн. наук, доцент кафедри фізики конденсованого стану, Дніпровський державний технічний університет, вул. Дніпробудівська, 2, м. Кам'янське, Україна, 51918, тел.: +380569560667, E-mail: an.mtomina@gmail.com https://orcid.org/0000-0001-5354-0674

Микита Катерина Андріївна – здобувач вищої освіти ОС «Доктор філософії» спеціальності 132 «Матеріалознавство» ОНП «Матеріалознавство», кафедри фізики конденсованого стану, Дніпровський державний технічний університет, вул. Дніпробудівська, 2, м. Кам'янське, Україна, 51918, тел.: +380569560667, E-mail: mikita2703@gmail.com https://orcid.org/0009-0007-3612-6659

Єрьоміна Катерина Андріївна – канд. техн. наук, доцент, доцент кафедри фізики конденсованого стану, Дніпровський державний технічний університет, вул. Дніпробудівська, 2, м. Кам'янське, Україна, 51918, тел.: +380569560667, E-mail: eka.yeriomina@gmail.com https://orcid.org/0000-0001-8595-5735

Набережна Ольга Олександрівна – канд. техн. наук, доцент, доцент кафедри фізики конденсованого стану, Дніпровський державний технічний університет, вул. Дніпробудівська, 2, м. Кам'янське, Україна, 51918, тел.: +380569560667, E-mail: o.naberezhnaya@gmail.com https://orcid.org/0000-0003-1302-4098

Фролов Данило Артемович – здобувач вищої освіти 4-го курсу ОС «Бакалавр» спеціальності 132 «Матеріалознавство» ОПП «Матеріалознавство» кафедри фізики конденсованого стану, Дніпровський державний технічний університет, вул. Дніпробудівська, 2, м. Кам'янське, Україна, 51918, тел.: +380569560667, E-mail: ndj95582@gmail.com https://orcid.org/0009-0005-9057-8555