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**Yeromenko Olexander**, post graduate student, Department of Condensed Matter Physics
**Єрьоменко О.В.**, здобувач наукового ступеня, кафедра фізики конденсованого стану
ORCID: 0009-0007-3612-6659
e-mail: eromenko81@gmail.com

**Yeriomina Yekaterina**, Candidat of Technical Sciences, Associate Professor, Department of Condensed Matter Physics
**Єрьоміна К.А.**, кандидат технічних наук, доцент, кафедра фізики конденсованого стану
ORCID: 0000-0001-8595-5735
e-mail: eka.yeriomina@gmail.com

**Tomina Anna-Mariia**, Candidat of Technical Sciences, Associate Professor, Department of Condensed Matter Physics
**Томіна А.-М.В.**, кандидат технічних наук, доцент, кафедра фізики конденсованого стану
ORCID: 0000-0001-5354-0674
e-mail: an.mtomina@gmail.com

Dniprovsk State Technical University, Kamyanske
Дніпровський державний технічний університет, Кам’янське

# SUPPLY OF OPERATION MODES ON TRIBOLOGICAL POWER TO BASALTOPLASTICS BASED ON POLYTETAFLUORORETYLENE

# ДОСЛІДЖЕННЯ ВПЛИВУ РЕЖИМІВ ЕКСПЛУАТАЦІЇ НА ТРИБОЛОГІЧНІ ВЛАСТИВОСТІ БАЗАЛЬТОПЛАСТИКУ НА ОСНОВІ ПОЛІТЕТАФТОРЕТИЛЕНУ

*The article presents the results of research into the processes of operating basalt plastic in the friction unit. The effect of sliding speed and load on the intensity of wear and friction coefficient of basalt plastic was determined, and mathematical models of the studied processes were developed. The given mathematical dependencies make it possible to reliably predict the durability of the developed basalt plastic in friction units.*

***Keywords**: basalt plastic, the intensity of wear, coefficient of friction, mathematical planning of the experiment, friction units.*

*Запропонована стаття присвячена важливому науковому завданню — збереженню показників якості вузлів тертя протягом всього періоду експлуатації останніх. Важливість зазначеного завдання пояснюється потребами промисловості у зменшенні простою обладнання та економії часу на технічне обслуговування. В даній статті поставлене завдання вирішують на прикладі використання базальтопластику у вузлах тертя робочих органів машин і механізмів сучасної техніки із застосуванням математичного планування експерименту, а саме ортогонального центрального композиційного планування 2-го порядку. В статті наведено результати експериментальних даних та, отримані за ними, математичні моделі дослідження впливу параметрів оптимізації на триботехнічні характеристики базальтопластику на основі політетрафторетилену, що містить 30 мас.% дискретного базальтового волокна. Досліджувані процеси описували функціональними залежностями: $y(I_h) = f(x_1, x_2)$, $y(f) = f(x_1, x_2)$, де варійованими незалежними факторами виступали: швидкість ковзання ($x_1$) та навантаження ($x_2$) на дослідний зразок. Отримані математичні моделі, у вигляді поліномів другого порядку, адекватно описують залежність параметрів оптимізації (коефіцієнту тертя та інтенсивності лінійного зношування) базальтопластику від незалежних факторів — швидкості ковзання та* *навантаження зразка (похибка при розрахунках не перевищує похибки експерименту). Використання зазначених математичних моделей на етапі заміни серійних підшипників ковзання та кочення на виготовлені із запропонованого базальтопластику дозволить оптимізувати роботу трибологічних з'єднань та ефективно прогнозувати довговічність роботи вузла тертя, що дозволить своєчасно проводити заміну елементів вузлів тертя та призведе не лише до економії часу на технічний огляд, а й зменшить простій технологічних систем.*

***Ключові слова**: базальтопластик, інтенсивність зношування, коефіцієнт тертя, математичне планування експерименту, вузли тертя.*

## Problem's Formulation

High indicators of tribological properties (a stable coefficient of friction and a low wear rate) of working bodies of machines and mechanisms of modern technology are an important condition for their reliable and long-lasting operation. It is known from literary sources [1, 2] that the operation of tribological units of industrial equipment of metallurgical, agricultural, and automotive machines equipped with serial metal parts is constantly accompanied by their intensive wear and tear and requires the use of lubricating materials. As a result, businesses spend a significant part of funds and material resources on repair and lubrication and greasing. Therefore, the problem of increasing wear resistance and service life of tribological units, as well as predicting stable operation, is an extremely important task.

## Analysis of recent research and publications

Forecasting the conditions of stable operation of tribological units of various machines is an urgent task. A number of domestic (Aulin V.V., Dykha O.V. [3], Tsymbal B.M. [4], Borak K.V. [5], Zagrebelnyi V. V. [6], Kashytskyi V.P., and Savchuk P.P. [7]) and foreign (Davis F.A., Korcet S., Stanly R.A. Rezaei A. [8], Erol Kilickap [9]) scientific works are devoted to this issue. Analyzing the data accumulated by them, it can be concluded that the design of mathematical models that will allow optimizing the operation of tribological units without preliminary test experiments is an urgent task. It is known [10] that the main factors of the operating conditions affecting the stable and efficient operation of tribological units are the linear sliding speed ($v$, m/s) and the load ($P$, MPa) of the parts.

## Formation of the study purpose

Taking the above, the purpose of the work was to design mathematical models of the processes of operation of tribological connectors of equipment using orthogonal central composite planning of the second order using the results of a complex of tribological studies in conditions of friction without lubrication according to the "disk-pad" scheme. At least 6 parallel tests were carried out to obtain reliable statistical data for each of the studied indicators (friction coefficient and wear intensity). The obtained mathematical models will allow us to optimize the operation of tribological units equipped with sliding and rolling bearings made of basalt plastic.

## Presenting main material

Basalt plastic based on polytetrafluoroethylene (PTFE) was chosen as the research object. The combination of high resistance to corrosion, chemical inertness, and thermal stability allows the use of PTFEs as elements of tribounits. However, the use of PTFE is limited due to the high coefficient of thermal linear expansion, low indicators of mechanical properties, and wear resistance. That makes it a promising polymer for the manufacture of composite materials. Various dispersed fillers and nanofillers are used to increase the wear resistance of PTFE, but their use does not allow to us obtain a composite with high mechanical properties and, as a result, sufficient resistance to high dynamic loads. Glass, carbon, or organic fibers are usually used to improve the mechanical properties of this polymer.

Discrete basalt fiber (produced by PJSC "Research Institute of Fiberglass and Fibers", Ukraine) was chosen as a filler. The degree of filling made 30 mass %. Basalt fiber is a promising filler for PTFE because it combines high functional properties and low cost (in contrast to glass and organic ones). The technical characteristics of this fiber are given in the Tabl. 1. The preparation of basalt plastic was carried out according to the method given in the work [11].

Tribological properties under conditions of friction without lubrication according to the "disk-pad" scheme were determined on the SMC-2 friction machine in the range of loads of 1—2 MPa, sliding speed of 1—2 m/s. Steel 45 (45—48 HRC, $Ra$ = 0,32 мм) was used as a counterbody.

*Table 1.* Properties of basalt fiber

| Indicator | Value |
|---|---|
| Density, g/cm$^3$ | 2.70 |
| The average diameter of the elementary fiber, мм | 13.6 |
| Operating temperature, K | 23–923 |
| Thermal conductivity coefficient, W/m·K:<br>- at 398 K<br>- at 573 K | <br>0.064<br>0.096 |

The coefficient of friction ($f$) was calculated according to the following formula

$$f = \frac{M}{R \cdot F},$$

where $M$ is the moment of force acting on the sample; $F$ is the friction force of the tested sample; $R$ is the radius of the steel counterbody.

The intensity of linear wear ($I_h$) was calculated according to the following formula [12]

$$I_h = \frac{\lambda}{\rho_T} \cdot \frac{dG}{A_a \cdot dL_T},$$

where $G$ is the amount of mass wear; $\rho_T$ is the density of the wearing material; $A_a$ is a nominal contact area; $\lambda = 1$ — that is we considered the wear of the body, all points of the friction surface of which are in contact with the counterbody. $L$ is the path of friction.

***Discussion of the results***. The goal set for the work was achieved by using statistical methods of setting up an active experiment, namely by using orthogonal composite planning of the 2nd order of degree $3^2$ [13].

The wear intensity and the friction coefficient were chosen as optimization parameters. The studied processes were described by functional dependencies: $y(I_h) = f(x_1, x_2)$, $y(f) = f(x_1, x_2)$, where the variable independent factors were sliding speed ($x_1$) and load ($x_2$) on the test sample.

To simplify the calculations, the dosage values of the studied factors were converted into conventional units and set so that when translated into a conventional scale, they correspond to –1; 0; +1 according to the following 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, and $n$ is the step of factor variation.

The results of the calculation of the initial dosages of the studied components are summarized in the Tabl. 2.

*Table 2.* Initial data for the planning of the experiment

| Factors | Symbol | Representation | Variability interval ($n$) | Levels of variability | | |
|---|---|---|---|---|---|---|
| | | | | -1 | 0 | +1 |
| Sliding speed | $v$, m/s | $x_1$ | 0.5 | 1 | 1.5 | 2 |
| Load | $P$, MPa | $x_2$ | 0.5 | 1 | 1.5 | 2 |

According to the accepted plan of the mathematical experiment (Tabl. 3, 4), 9 experiments ($N$) were carried out; each of them was repeated three times ($k = 3$) in a randomized order (Tabl. 5, 6) to eliminate systematic errors completely.

A mathematical description of the dependences of the intensity of wear and the coefficient of friction of basalt plastic on selected varied factors was proposed to be sought in the form of a regression equation represented by the following second-order polynomial

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

where $y$ is the estimated value of the optimization parameter, $b_i$ and $b_{ij}$ are coefficients of the regression equation.

*Table 3.* Planning matrix with calculated columns of interaction of factors on a representative scale

| Experiment number | | $x_0$ | $x_1$ | $x_2$ | $x_1x_2$ | $x_1^2$ | $x_2^2$ |
|---|---|---|---|---|---|---|---|
| The core of the plan | 1 | 1 | 1 | 1 | 1 | 0.333 | 0.333 |
| | 2 | 1 | -1 | 1 | -1 | 0.333 | 0.333 |
| | 3 | 1 | 1 | -1 | -1 | 0.333 | 0.333 |
| | 4 | 1 | -1 | -1 | 1 | 0.333 | 0.333 |
| Star points | 5 | 1 | 1 | 0 | 0 | 0.333 | -0.667 |
| | 6 | 1 | -1 | 0 | 0 | 0.333 | -0.667 |
| | 7 | 1 | 0 | 1 | 0 | -0.667 | 0.333 |
| | 8 | 1 | 0 | -1 | 0 | -0.667 | 0.333 |
| The center of the plan | 9 | 1 | 0 | 0 | 0 | -0.667 | -0.667 |

*Table 4.* Planning matrix with calculated columns of interaction of factors on the natural scale

| Experiment number | | *v*, m/s | *P*, MPa |
|---|---|---|---|
| The core of the plan | 1 | 2 | 2 |
| | 2 | 1 | 2 |
| | 3 | 2 | 1 |
| | 4 | 1 | 1 |
| Star points | 5 | 2 | 1.5 |
| | 6 | 1 | 1.5 |
| | 7 | 1.5 | 2 |
| | 8 | 1.5 | 1 |
| The center of the plan | 9 | 1.5 | 1.5 |

Based on the obtained experimental data (Tabl. 5, 6), the average value of the response function $\tilde{y}_j$ was calculated

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

*Table 5.* Experimental and calculated values of wear intensity

| Experiment number | $y_1$ | $y_2$ | $y_3$ | Average | Calculated |
|---|---|---|---|---|---|
| | | | | $\tilde{y}_j$ | $y_j^{c.}$ |
| 1 | $6.22\cdot10^{-8}$ | $7.16\cdot10^{-8}$ | $9.98\cdot10^{-8}$ | $7.79\cdot10^{-8}$ | $7.57\cdot10^{-8}$ |
| 2 | $1.42\cdot10^{-8}$ | $4.99\cdot10^{-8}$ | $3.62\cdot10^{-8}$ | $3.34\cdot10^{-8}$ | $3.26\cdot10^{-8}$ |
| 3 | $0.42\cdot10^{-8}$ | $1.11\cdot10^{-8}$ | $0.88\cdot10^{-8}$ | $0.80\cdot10^{-8}$ | $0.82\cdot10^{-8}$ |
| 4 | $0.69\cdot10^{-8}$ | $0.26\cdot10^{-8}$ | $0.34\cdot10^{-8}$ | $0.43\cdot10^{-8}$ | $0.58\cdot10^{-8}$ |
| 5 | $3.93\cdot10^{-8}$ | $1.93\cdot10^{-8}$ | $2.00\cdot10^{-8}$ | $2.62\cdot10^{-8}$ | $2.82\cdot10^{-8}$ |
| 6 | $0.64\cdot10^{-8}$ | $0.76\cdot10^{-8}$ | $0.44\cdot10^{-8}$ | $0.60\cdot10^{-8}$ | $0.55\cdot10^{-8}$ |
| 7 | $3.07\cdot10^{-8}$ | $8.46\cdot10^{-8}$ | $2.71\cdot10^{-8}$ | $4.75\cdot10^{-8}$ | $5.05\cdot10^{-8}$ |
| 8 | $0.71\cdot10^{-8}$ | $0.48\cdot10^{-8}$ | $0.33\cdot10^{-8}$ | $0.51\cdot10^{-8}$ | $0.34\cdot10^{-8}$ |
| 9 | $1.48\cdot10^{-8}$ | $1.69\cdot10^{-8}$ | $1.25\cdot10^{-8}$ | $1.47\cdot10^{-8}$ | $1.33\cdot10^{-8}$ |

*Table 6.* Experimental and calculated values of the coefficient of friction

| Experiment number | $y_1$ | $y_2$ | $y_3$ | Average | Calculated |
|---|---|---|---|---|---|
|  |  |  |  | $\tilde{y}_j$ | $y_j^c$ |
| 1 | 0.64 | 0.61 | 0.68 | 0.65 | 0.65 |
| 2 | 0.64 | 0.60 | 0.65 | 0.63 | 0.66 |
| 3 | 0.64 | 0.68 | 0.97 | 0.76 | 0.73 |
| 4 | 0.13 | 0.23 | 0.23 | 0.20 | 0.19 |
| 5 | 0.86 | 0.66 | 0.69 | 0.74 | 0.76 |
| 6 | 0.46 | 0.66 | 0.45 | 0.53 | 0.50 |
| 7 | 0.87 | 0.78 | 0.78 | 0.81 | 0.78 |
| 8 | 0.52 | 0.50 | 0.63 | 0.55 | 0.58 |
| 9 | 0.71 | 0.85 | 0.70 | 0.75 | 0.75 |

The error mean squares of parallel experiments were calculated according to the following formulas

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

where $S_r^2$ is the error mean square of reproducibility which was calculated from experiments in the center of the plan according to the formula

$$S_r^2 = \frac{1}{k-1}\sum_{i=1}^{k}(y_{9i} - \tilde{y}_9)^2.$$

The calculated values of error mean squares are presented in the tabl. 7, 8.

*Table 7.* Regression equation coefficients and the values of error mean squares of parallel experiments for wear intensity

| Coefficients of equation $b_j$ | Error mean squares of parallel experiments $S_j$ |
|---|---|
| $2.48 \cdot 10^{-8}$ | $7.99 \cdot 10^{-19}$ |
| $1.14 \cdot 10^{-8}$ | $1.20 \cdot 10^{-18}$ |
| $2.36 \cdot 10^{-8}$ | $1.80 \cdot 10^{-18}$ |
| $1.02 \cdot 10^{-8}$ | $3.60 \cdot 10^{-18}$ |
| $0.36 \cdot 10^{-8}$ | $5.59 \cdot 10^{-18}$ |
| $1.37 \cdot 10^{-8}$ | $7.99 \cdot 10^{-19}$ |

*Table 8.* Regression equation coefficients and the values of error mean squares of parallel experiments for the coefficient of friction

| Coefficients of equation $b_j$ | Error mean squares of parallel experiments $S_j$ |
|---|---|
| 0.62 | 0.00144 |
| 0.13 | 0.00216 |
| 0.10 | 0.00324 |
| -0.14 | 0.00648 |
| -0.12 | 0.01008 |
| -0.07 | 0.00144 |

The homogeneity of the obtained error mean squares of parallel experiments was checked according to the Cochrane criterion ($G$)

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

Calculated values were compared with the tabular ones ($G_{tab.}$) for degrees of freedom $f_1 = k - 1$ and $N$, with a confidence level of $P = 0.95$ [13].

For the obtained error mean squares of parallel experiments $G(I_h) = 0.457$ and $G(f) = 0.452$ that are less than $G_{tab.} = 0.48$. Accordingly, the error mean squares of parallel experiments are homogeneous.

Based on the orthogonal composite experiment, the coefficients of the regression equation were calculated according to the formula

$$b_i = \frac{1}{N}\sum_{j=1}^{N} \tilde{y}_j x_i.$$

The calculated values of the coefficients are presented in the Tabl. 6.

The equation takes the following form after calculating all coefficients

$$y(I_h) = (2.48 + 1.14\,x_1 + 2.36\,x_2 + 1.02\,x_1x_2 + 0.356\,x_1^2 - 1.37\,x_2^2)\cdot 10^{-8}, \qquad (1)$$

$$y(f) = 0.62 + 0.13\,x_1 + 0.10\,x_2 - 0.14\,x_1x_2 - 0.12\,x_1^2 - 0.07\,x_2^2. \qquad (2)$$

The verification of the statistical significance of the coefficients of the regression equations was evaluated on the basis of the calculation of confidence levels according to the Student's t-test ($t$) that was given according to the accepted degrees of freedom ($f_1$, $f_2$) and the level of significance (0.95). Confidence levels for orthogonal composite planning of the experiment are determined by the formula

$$\Delta b_i = b_i \cdot S_j^2.$$

The critical value of Student's t-test $t_{cr.}$ [4] was chosen for the number of degrees of freedom $N(k - 1) = 18$ and the accepted significance level of 0.95. It is accepted that the regression coefficient is significant if the following condition is fulfilled: $t_{cr.} < \Delta b_i$.

The equations describing the dependence of the intensity of wear and the coefficient of friction of basalt plastic on the selected variable factors remain unchanged, since all the coefficients of the regression equations turned out to be significant.

The obtained equations were checked for adequacy. For this purpose, the deviations of the values of the optimization parameter $y_j^{c.}$ calculated according to equations (1, 2) from the experimental $\tilde{y}_j$ for each of the experiments of the conducted experiment were evaluated. It made it possible to determine the dispersion of adequacy for an equal number of parallel experiments

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

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

The estimated values of the optimization parameters are presented in the Tabl. 5, 6.

After calculating the regression coefficients, the degree of compliance of the obtained models with the theoretical form of the relationship between the studied input and output parameters was checked to determine the adequacy of mathematical descriptions (1, 2). For this purpose, we used Fisher's criterion ($F_{c.}$) which is the ratio of the dispersion of the adequacy ($S_{ad.}^2$) to the error mean square of the experiment ($S_b^2$) (Tabl. 9) and is calculated according to the formula

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

*Table 9.* Calculated values for evaluating the adequacy of equations according to Fisher's criterion

| For wear intensity | | For the coefficient of friction | |
|---|---|---|---|
| $S_b^2$ | $S_{ad.}^2$ | $S_b^2$ | $S_{ad.}^2$ |
| $7.19\cdot10^{-18}$ | $8.89\cdot10^{-18}$ | 0.01297 | 0.0018 |

When calculating Fisher's criterion, the condition $S^2_{ad.} > S^2_b$ must be fulfilled. In our case, this condition is not fulfilled, so it is necessary to change the variances according to.

Since at a significance level of 0.95 and degrees of freedom for the equations under consideration, $F_{c.}$ $(I_h) = 1.24$ and $F_{c.}$ $(f) = 7.25$ which are less than tabular $F_{tab.} = 9.55$ [13], then they adequately describe the studied phenomenon.

Coded values of the factors are associated with the following natural dependencies

$$x_1 = \frac{v - 1.5}{0.5} = 2v - 3,$$

$$x_2 = \frac{P - 1.5}{0.5} = 2P - 3.$$

Switching from coded ($x_1$, $x_2$) factor values to natural ones ($P$, $v$), we obtain the dependences of wear intensity and friction coefficient on sliding speed and load

$$I_h = (1.424\, v^2 + 5.48\, P^2 + 4.08\, Pv - 8.112\, v - 17.84\, P - 1.666)\cdot 10^{-8},$$

$$f = -0.48\, v^2 - 0.28\, P^2 - 0.56\, Pv + 2.54\, v + 1.88\, P - 3.04.$$

## Conclusion

The conducted research made it possible to obtain the dependence of the influence of the technological parameters of the operation process on the intensity of wear and the coefficient of friction of basalt plastic. The obtained mathematical models allow us to predict the durability of the parts made of the developed basalt plastic in the friction units at different sliding speeds and loads; that will allow predicting the durability of the friction unit effectively.

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