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DETERMINATION OF OPTIMAL OPERATING MODES TO INCREASE THE SERVICE LIFE OF GRAPHITE PLASTIC

The article presents the results of scientific research on the processes of operation of graphite plastic in a tribological unit. The effect of sliding speed and load on the intensity of wear and coefficient of friction of graphite plastic was determined, and mathematical models describing the tribotechnical behavior of graphite plastic depending on the load and sliding speed of the friction unit were developed. The research carried out in the paper made it possible to reveal the influence of the technological parameters of the operation process on the intensity of linear wear and the coefficient of friction of graphite plastic. The obtained mathematical dependencies make it possible to reliably predict the duration of the developed graphite plastic in tribological units of modern technology, which is important for ensuring the efficiency and reliability of machines and mechanisms.

Key words: *intensity of wear, coefficient of friction, load, sliding speed, graphite plastic.*

Introduction. One of the main problems characterizing the direction and stages of modern technology development (agricultural, automotive, metallurgical, etc.) is an increase in the reliability and service life of tribological units. As part of the measures aimed at solving this problem, the increase in the efficiency of the parts of tribological units is an issue of particular importance. It is especially relevant for serial rolling and sliding bearings, seals, gears, and impellers, which operate under the conditions of the most common types of wear, in particular abrasive, fretting corrosion, and corrosion-technical [1] and limited lubrication. It is known [2] that the increase in the working resources of modern mechanisms and machines can be achieved by several approaches:

- the development of innovative designs of machines with a significantly changed principle and mechanism of their functioning;
- the creation of new functional materials for structural and tribotechnical purposes with an improved set of functional properties in compared with the existing ones.

However, the innovative structure development with significantly modified principles and mechanisms of operation is a complex and resource-intensive process that requires a large amount of time and significant financial costs. Therefore, using this approach is not effective. Nowadays, a higher priority is given to the machines and mechanisms modernization because of this. This process includes the replacement of serial metal structural and tribotechnical parts with composite ones [2], including those on a polymer basis, with improved properties.

When creating new polymer composite materials for tribological units of modern technology, it is difficult to predict the conditions of their stable and trouble-free operation, due to the influence of variable loads and sliding speeds. Forecasting the long-term stability of polymer composite materials requires a comprehensive approach that includes testing at various stages of production and real operating conditions.

However, it is known [3] that field and bench research require much time and financial costs. Given this, many domestic and foreign material scientists [4-7] use mathematical models that reflect the operational dynamics of tribological units of modern technology. Taking into account the above, the work aimed to study the modes of effective operation of polymer composite materials in a tribological unit.

Materials and research methods. An organosilicon (OS) polymer polyorganosiloxane) was chosen as a polymer matrix for the creation of graphite plastic (GP), which includes silicon (Si) atoms in its molecules, together with organic radicals and groups. This polymer material is characterized by high resistance to weak acids and alkalis, and high and low temperatures. The unique properties of polyorganosiloxane, primarily its high heat resistance (653-723 K), are due to the specific nature of the Si-O bond (the energy of this Si-O bond = 422-494 kJ/mol, while for C-C = 262 kJ/mol) [8]. As a filler, hidden crystalline cast graphite was chosen, which is characterized by an incomplete texture, which may indicate insufficient crystallization of its structure, and also often contains an admixture of finely dispersed carbonaceous matter.

Preparation of GP was carried out in a horizontal mixer followed by thermoreactive crosslinking of polyorganosiloxane for 30 min. at a temperature of 393 K. Tin dibutyl dilaurate $(C_4H_9)_2Sn(OOC(CH_2)_{10}CH_3)_2$, which is a broad-spectrum organotin catalyst, was chosen as a catalyst. The introduction of graphite took place gradually until complete mixing. After the introduction of graphite, we continued mixing for another 20 minutes. During the mixing process, the size of the graphite did not change, but only its distribution by volume of the polymer material took place. Tribotechnical characteristics (friction coefficient and intensity of linear wear) under conditions of friction without lubrication according to the «disk-pad» scheme were determined on the SMC-2 friction machine at a load (P) from 0,5 to 1,5 MPa, sliding speed (υ) from 1 to 2 m/s. Steel 45 (45-48 HRC, Ra=0,32 μm) was used as a counterbody.

Before starting the research, each sample was run-in in working mode until full contact with the counterbody was achieved.

The coefficient of friction was calculated according to the formula:

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

where M is the moment of the force acting on the sample;

F is the friction force of the test sample, the accuracy of which was ±5%;

R= 25 mm is the radius of the steel counterbody.

The loss of mass (wear and tear) of the GP was determined by the weight method on VLR-200 analytical balances. We took the main engineering property of the wear process to be the intensity of linear wear I_h, which was determined by the following dimensionless ratio:

$$I_h = \frac{\lambda}{\rho} \cdot \frac{\Delta G}{A_a \cdot dL_T},$$

where ΔG is the value of mass wear, kg;

ρ is the hydrostatic density of the wearing material, kg/m^3;

A_a is the contact area of the sample with the counterbody; it was measured after each experiment, m^2;

L_T=1000 m is a friction path;

λ=1 is the coefficient characterizing the contact of the friction surface of the test sample with the steel counterbody [9].

Analysis of results and discussion. The task set in the work was achieved by using statistical methods of active experimentation, namely, using orthogonal composite planning of the second order of degree 3^2.

The intensity of linear wear and coefficient of friction were chosen as optimization parameters. The processes investigated in the paper were described by the following dependencies: $y(I_h) = f(x_1, x_2)$, $y(f) = f(x_1, x_2)$, where the sliding speed (x_1) and load (x_2) were chosen as independent factors of variation.

To facilitate calculations, the dosage values of the experimental factors were converted into representative units and adjusted so that when converted into a representative scale, they corresponded to the values of -1, 0, and +1, using 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, n is the step of factor variation (see Table 1).

The calculation results of the initial dosages of the studied components are summarized in Table 1.

Table 1

Initial data for experiment planning

Factors	Symbol, unit of measure	Symbol	Variation step (n)	Levels of variation		
				-1	0	+1
Sliding speed	υ, m/s	x_1	0,5	1	1,5	2
Load	P, MPa	x_2	0,5	0,5	1	1,5

According to the developed plan of the mathematical experiment (Table 2), 9 experiments (N) were conducted, each of which was repeated three times (k=3) in a random order to avoid systematic errors in total.

Table 2

Planning matrix with calculated columns of interaction of factors

Experiment number		The value of variables in a representative scale						Values of variables in the true scale	
		x_0	x_1	x_2	x_1x_2	x_1^2	x_2^2	υ, m/s	P, MPa
The core of the plan	1	1	1	1	1	0,333	0,333	2	1,5
	2	1	-1	1	-1	0,333	0,333	1	1,5
	3	1	1	-1	-1	0,333	0,333	2	0,5
	4	1	-1	-1	1	0,333	0,333	1	0,5
Star points	5	1	1	0	0	0,333	-0,667	2	1
	6	1	-1	0	0	0,333	-0,667	1	1
	7	1	0	1	0	-0,667	0,333	1,5	1,5
	8	1	0	-1	0	-0,667	0,333	1,5	0,5
The center of the plan	9	1	0	0	0	-0,667	-0,667	1,5	1

A mathematical description of the dependences of the wear intensity and the coefficient of friction of graphite plastic on the selected variable factors was proposed to be sought in the form of a regression equation represented by a 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 calculated value of the optimization parameter, b_i and b_{ij} are the regression coefficients of equation.

The average values of the response functions y_j were calculated on the basis of the obtained experimental data (Tables 3, 4):

$$y_j = \frac{1}{k}\sum_{i=1}^{k} y_{ji}, \quad j = 1, 2, ..., N$$

Table 3

Experimental and calculated values of intensity of linear wear

Experiment number	y_1	y_2	y_3	average y_j	calculated y_j^c
1	$8{,}30\cdot10^{-9}$	$6{,}37\cdot10^{-9}$	$6{,}96\cdot10^{-9}$	$7{,}21\cdot10^{-9}$	$6{,}97\cdot10^{-9}$
2	$8{,}97\cdot10^{-9}$	$6{,}33\cdot10^{-9}$	$7{,}65\cdot10^{-9}$	$7{,}65\cdot10^{-9}$	$7{,}78\cdot10^{-9}$
3	$8{,}74\cdot10^{-9}$	$5{,}50\cdot10^{-9}$	$6{,}98\cdot10^{-9}$	$7{,}07\cdot10^{-9}$	$7{,}17\cdot10^{-9}$
4	$9{,}23\cdot10^{-9}$	$1{,}07\cdot10^{-8}$	$6{,}70\cdot10^{-9}$	$5{,}67\cdot10^{-9}$	$6{,}14\cdot10^{-9}$
5	$7{,}56\cdot10^{-9}$	$6{,}82\cdot10^{-9}$	$7{,}11\cdot10^{-9}$	$7{,}16\cdot10^{-9}$	$7{,}31\cdot10^{-9}$
6	$8{,}26\cdot10^{-9}$	$8{,}09\cdot10^{-9}$	$7{,}06\cdot10^{-9}$	$7{,}80\cdot10^{-9}$	$7{,}20\cdot10^{-9}$
7	$7{,}70\cdot10^{-9}$	$7{,}71\cdot10^{-9}$	$6{,}69\cdot10^{-9}$	$7{,}37\cdot10^{-9}$	$7{,}48\cdot10^{-9}$
8	$7{,}41\cdot10^{-9}$	$8{,}19\cdot10^{-9}$	$6{,}38\cdot10^{-9}$	$7{,}33\cdot10^{-9}$	$6{,}76\cdot10^{-9}$
9	$6{,}97\cdot10^{-9}$	$6{,}67\cdot10^{-9}$	$7{,}12\cdot10^{-9}$	$6{,}92\cdot10^{-9}$	$7{,}37\cdot10^{-9}$

Table 4

Experimental and calculated values of coefficient of friction

Experiment number	y_1	y_2	y_3	average y_j	calculated y_j^c
1	0,21	0,26	0,26	0,24	0,24
2	0,20	0,27	0,17	0,21	0,19
3	0,39	0,28	0,28	0,32	0,33
4	0,65	0,78	0,68	0,70	0,70
5	0,28	0,25	0,25	0,26	0,24
6	0,39	0,39	0,38	0,39	0,41
7	0,29	0,19	0,21	0,24	0,26
8	0,50	0,57	0,67	0,58	0,56
9	0,34	0,39	0,39	0,37	0,37

The mean squared errors of parallel experiments were calculated using the following formulas:

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

where S_r^2 is the dispersion of reproducibility, which was calculated from experiments in the center of the plan according to the formula:

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

Table 5 shows the calculated values of variances.

Table 5

Regression equation coefficients and variance values of parallel experiments

for wear intensity		for friction coefficient	
equation coefficients	variance values of parallel experiments	equation coefficients	variance values of parallel experiments
b_j	S_j	b_j	S_j
$71{,}3\cdot10^{-10}$	$8{,}50\cdot10^{-20}$	0,37	0,00153
$-0{,}54\cdot10^{-10}$	$0{,}94\cdot10^{-20}$	-0,08	0,00017
$3{,}60\cdot10^{-10}$	$1{,}42\cdot10^{-20}$	-0,15	0,00025
$-4{,}62\cdot10^{-10}$	$2{,}13\cdot10^{-20}$	0,10	0,00038
$-1{,}10\cdot10^{-10}$	$4{,}25\cdot10^{-20}$	-0,04	0,00076
$-2{,}47\cdot10^{-10}$	$6{,}61\cdot10^{-20}$	0,04	0,00119

Cochran's Q test (G) was used to check the homogeneity of mean square errors of parallel experiments.

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

With a confidence probability of P = 0,95, degrees of freedom $f_1 = k - 1$ and N, the calculated values of the Cochran's Q test were compared with tabular values (G_{table}), and it was established that the calculated values for the obtained variances of parallel experiments are smaller than the tabular value, that is, the variances parallel experiments are homogeneous.

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

$$b_i = \frac{1}{N}\sum_{j=1}^{N} y_j x_i,$$

The calculated values of the coefficients are given in Table 5. After calculating all coefficients, the equation will take the following form:

$$y(I_h) = (71{,}3 + 0{,}54x_1 + 3{,}60x_2 - 4{,}62x_1x_2 - 1{,}10x_1^2 - 2{,}47x_2^2)\cdot10^{-10}, \quad (1)$$

$$y(f) = 0{,}37 - 0{,}08x_1 - 0{,}15x_2 + 0{,}10x_1x_2 - 0{,}04x_1^2 - 0{,}04x_2^2, \quad (2)$$

The statistical significance of the coefficients of the regression equations was checked based on the calculation of confidence intervals using the Student's t-test (t), which was determined according to the accepted degrees of freedom (f_1, f_2) and the significance level (0,95). For the orthogonal composite design of the experiment, the confidence intervals are calculated according to the following formula:

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

Determination of the critical value of the Student's t-test t_{cr} was carried out with $N(k–1)=18$ degrees of freedom, and the accepted significance level of 0,95. It is considered that the regression coefficient is significant if the condition is fulfilled: $t_{cr.}<\Delta b_i$. Since all the coefficients of the regression equations turned out to be significant, the equations that determine the dependence of the intensity of linear wear and the coefficient of friction of the GP on the selected variable factors remain unchanged. The obtained equations were checked for adequacy by evaluating the deviations of the values of the y_j^c optimization parameter, calculated according to equations (1, 2), from the experimental y_j for each of the conducted experiments. It made it possible to determine the dispersion of adequacy for the same number of parallel experiments.

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

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

The calculated values of the optimization parameters are given in Tables 3, 4. After determining the regression coefficients, Fisher's exact test (F_c) was used to check the correspondence of the obtained mathematical models (1; 2) to the theoretical form of the relationship between input and output parameters. This criterion is the ratio of the dispersion of adequacy (S_{ad}^2) to the dispersion of reproducibility of the experiment (S_r^2) (see Table 6) and is calculated according to the following formula:

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

Table 6

Calculated values for evaluating the adequacy of equations according to Fisher's exact test

for wear intensity		for friction coefficient	
S_r^2	S_{ad}^2	S_r^2	S_{ad}^2
$8{,}50\cdot10^{-20}$	$4{,}07\cdot10^{-19}$	0,0015	0,0007

When using Fisher's exact test, the condition $S_{ad}^2 > S_r^2$ must be taken into account. For the coefficient of friction, this condition is not fulfilled, so it is necessary to change the dispersions in the formula (3) according to [10].

Since at a significance level of 0,95 and degrees of freedom for the equations under consideration, $F_{c.}$ (I_h) = 4,78 and $F_{c.}$ (f) = 2,22, which is less than the table value (F_{table} = 9,55) [10], then they adequately describe the experimental process.

The coded values of the factors affecting the optimization parameters are associated with the following natural dependencies:

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

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

After making the transition from the coded values of the factors (x_1, x_2) to their natural values (P, υ), we will obtain mathematical models describing the tribotechnical properties of the GP depending on the sliding speed and load.

$$I_h = (-4,40\upsilon^2 - 9,88P^2 - 18,48P\upsilon + 32,76\upsilon + 54,68P + 14,98)\cdot 10^{-10},$$

$$f = -0,16\upsilon^2 + 0,16P^2 + 0,40P\upsilon - 0,08\upsilon - 1,22P + 1,31.$$

Conclusions. The research carried out in the paper made it possible to reveal the influence of the technological parameters of the operation process on the intensity of linear wear and the coefficient of friction of graphite plastic. The obtained mathematical models allow us not only to analyze the influence of individual parameters on wear and friction but also to predict the durability of parts using the developed GP in tribological units of modern technology at different values of sliding speeds and loads.

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ВИЗНАЧЕННЯ ОПТИМАЛЬНИХ РЕЖИМІВ ЕКСПЛУАТАЦІЇ З МЕТОЮ ЗБІЛЬШЕННЯ РОБОЧОГО РЕСУРСУ ГРАФІТОПЛАСТУ

У статті представлені результати наукових досліджень щодо процесів експлуатації графітопласту в трибологічному з'єднанні. Було визначено вплив швидкості ковзання та навантаження на інтенсивність зношування та коефіцієнт тертя графітопласту, а також розроблено математичні моделі, що описують триботехнічну поведінку графітопласту залежно від навантаження та швидкості ковзання вузла тертя. Проведені у роботі дослідження дозволили виявити вплив технологічних параметрів процесу експлуатації на інтенсивність лінійного зношування та коефіцієнт тертя графітопласту. Отримані математичні залежності дозволяють надійно прогнозувати тривалість роботи розробленого графітопласту у трибологічних з'єднаннях сучасної техніки, що є важливим для забезпечення ефективності й надійності машин та механізмів.

Ключові слова: інтенсивність зношування, коефіцієнт тертя, навантаження, швидкість ковзання, графітопласт

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