

DETERMINING THE INFLUENCE OF CARBON BLACK IN OIL ON THE WEAR RESISTANCE OF ELEMENTS IN THE TRIBOLOGICAL SYSTEM "STEEL – OIL – BRONZE"

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Наведені результати експериментальних досліджень впливу концентрації вуглецевої сажі в індустріальній оливі И-30А на зносостійкість трибологічної системи «сталь-олива-бронза». Припускається, що вуглецева сажа, отримана електродуговим методом в лабораторних умовах, складається з конгломератів мікро- та наночастинок вуглецю, розміри яких знаходяться у широкому діапазоні – від нанометрів до десятих часток міліметрів.

Наведена методика, матеріали та обладнання для проведення експериментальних досліджень зносостійкості деталей трибосистеми «сталь-бронза» на машині тертя СМЦ-2. Методика досліджень передбачала варіювання двома незалежними факторами: концентрація вуглецевої сажі в індустріальній оливі И-30А та зовнішнє навантаження. Незмінними факторами залишались швидкість ковзання, контурна площа контакту та початкова температура трибосистеми.

Отриманні експериментальні данні дозволили встановити дві головні закономірності, що характеризують процес тертя та зношування в досліджуваній трибологічній системі. Перша закономірність розкриває вплив концентрації вуглецевої сажі в індустріальній оливі И-30А та зовнішнього навантаження на момент тертя в парі «сталь-бронза». Друга закономірність розкриває вплив тих самих факторів на зносостійкість деталей, що піддавались випробуванням на машині тертя. Отриманні закономірності корелюють між собою та визначають область раціональної концентрації вуглецевої сажі в індустріальній оливі И-30А, яка була застосована як мастильний матеріал у трибологічній системі, що піддавалась випробуванням.

На завершальному етапі роботи наведено дослідження поверхонь деталей тертя на атомно-силовому мікроскопі "Solver P47-Pro" фірми виробника NT-MDT. Такі дослідження дозволили розкрити механізм модифікації поверхневого шару сталі та бронзи наночастинами вуглецю при їх взаємодії в трибологічній системі під час тертя

Ключові слова: конгломерат вуглецю, наночастинка вуглецю, пара тертя, трибологічна система, індустріальна олива

1. Introduction

The experience of operation of transport-technological and energy machines (TTEM) showed that their resource

is limited to the intensity of wear of parts that operate at boundary lubrication. One of the main reasons for wear is the insufficient lubricating ability of oils. This problem occurs during the operation of hydraulic drives of track ma-

chines, construction and motor transport equipment, where industrial oils without additives are used. In particular, the analysis that was conducted in papers [1, 2] shows that 70 percent of all failures of rail transport vehicles occur due to the elements of hydraulic drives. This is due to the current state of hydraulic oil [2], as well as its lubricating ability.

The solution to this problem lies in the area of search for and application of anti-wear additives, which at low concentrations would have a high lubricating ability and contribute to the expansion of the range of normal friction and wear to the boundaries of existing loads. The substances that in small concentrations change the structure of the surface layer of metal meet the specified conditions, that is they are the concentrators and transporters of molecules of surfactants to friction surface and penetrate a softer surface, strengthening its surface layers. Such substances include: micro- and nanoparticles, which are the components of carbon black.

Most hydraulic systems of TTEM use hydraulic oils, which in their majority do not contain additives. Consequently, an increase in their lubricating ability involves finding economically grounded methods for improving the anti-wear and anti-friction properties. This method involves the addition of inexpensive but high-quality, in terms of friction and wear, carbon black that contains conglomerates of micro- and nanoparticles of carbon. The cost of carbon black is by order of magnitude lower than the cost of the net component – fullerenes and nanotubes.

That is why the search for the regularities of the influence of concentration of conglomerates of particles of graphite evaporation in hydraulic oil on the processes of friction and wear in TTEM is the relevant direction.

2. Literature review and problem statement

The appropriateness of using carbon nanoparticles as additives to the tribological systems in order to increase their wear resistance is the focus of many studies [3–9]. Thus, in paper [3], it is proposed to create nano-compositional coatings of metal-carbon nanopipe on pairs of friction, which, in turn, substantially increases their wear resistance. However, this technology can be used only at the stage of design and production of new tribosystems, rather than during the operation. Besides, the paper did not consider the interaction of carbon nano-compositional coatings with the lubricating medium. It is proposed to create on the surface of friction the coating from fullerenes C_{60} , which is a nanodispersive additive to transmission oil TAD-17 [4]. The obtained results are related to establishing a change of kinetics of microhardness of surface layers of metal depending on the existence of fullerenes in oil, which led to a decrease in the intensity of the wear of a pair of friction “steel-steel” during the operation by 45 %. However, only a couple of rolling friction was modeled in the research, and the influence of the concentration of C_{60} on the tribological properties of transmission oil was not revealed either. Sliding friction was implemented during studying the wear resistance of contact surfaces under non-stationary conditions of friction with the introduction of carbon nanoparticles C_{60} into commercial motor oil ESSO SAE 10w40 [5]. However, the industrial motor oil implies the existence of a basic package of anti-wear additives, which means that it is not possible to establish a “pure” effect of nano-dispersive component – fullerene C_{60} on the friction process in the experimental pair “steel-cast iron”.

The influence of graphite nanoparticles on the tribological characteristics of transmissive oils was studied in paper [6]. However, the dependence of these characteristics on the concentration of graphite nanoparticles was not found, an actual pair of friction was not modeled either.

The research into tribological characteristics of industrial oil with the addition of a conglomerate of carbon nanoparticles revealed a decrease in wear indicator by 11 % [7]. The wear indicator was determined on the four-ball friction machine where the point contact of metal balls was realized. That is, an actual pair of friction was not modeled, and no patterns of a change of the wear indicator depending on the concentration of conglomerate of carbon nanoparticles were established.

Paper [8] presented the results of the study of the influence of additives with the content of fullerene C_{60} in the industrial oil on the optimization of wear processes at boundary friction of metals. In this research, the parameter that characterizes the process of alignment of pairs of friction was introduced. It was shown that the magnitude of this parameter decreases by 4 times for oils with additives of fullerene C_{60} at the concentration of 5 % compared with pure oil. That is, the alignment process occurs more intensively. This result refers exclusively to the pairs of friction “steel-steel”. In addition, this parameter does reveal the process of friction in aligned pairs. Therefore, the problems of the influence of different carbon nanoparticles in different concentrations on the alignment of the pair of friction “steel-bronze”, which is the most characteristic of the units of friction of hydraulic drives, remain unresolved. In part, these problems were solved in paper [9], in particular, the dependences of friction coefficient, friction torque, wear intensity for alignment of pairs of friction “steel-steel” and “steel-copper” on the external loading and various carbon-containing additives to industrial oil were established. Carbon-containing additives in oil had the concentration of 5 % and consisted of fullerenes C_{60} and C_{70} , fullerene black, graphite and fullerene C_{60} with polystyrene. However, the effect of various concentrations and the mixture of different carbon nanoparticles on the process of friction of pairs, such as “steel-bronze” remained unrevealed. It should also be noted that particular attention in the paper was paid to high contact pressures, that is, the processes were studied in the mode of semi-fluid, semi-dry and dry friction. And this means that the research into the influence of the above-mentioned factors during boundary friction was incomplete. However, during this kind of friction, the most intensive wear occurs in the elements of the tribosystems of the hydraulic drive, consisting of pairs of friction “steel-bronze”. Therefore, this makes it possible to argue that it is appropriate to carry out the research into the influence of the concentration of carbon black in industrial oils on the processes of friction in the pair “steel-bronze”.

3. The aim and objectives of the study

The aim of this research is to establish a pattern in the influence of carbon black concentration on the tribological properties of hydraulic oils when using them in a pair of friction “steel-bronze”.

To achieve the aim, the following tasks were set:

- to determine the change in friction torque, depending on the concentration of carbon black and external loading;

- to determine the change in wear of the pair of friction “pad-roller”, depending on carbon black concentration and external loading;
- to explore the surface of friction “steel-bronze” on the atomic-force microscope after using industrial oil with carbon black.

4. Materials and methods for studying the influence of carbon black concentration on the tribological properties of industrial oils

4. 1. Studied materials and equipment used in the experiment

The industrial oil of subgroup A of I-30A brand that met the GOST (state standard) 20799-88 was selected for the studies.

This is the purest oil in terms of the availability of “additives” and is often used in hydraulic drives of various technological equipment and machines. Carbon black was made by burning graphite rods in by the electro-arc method in a specially developed setup [10–13]. Evaporation of graphite occurred in inert gas under the pressure of 0.05 MPa at current power on the rods of 90 A. Under this mode, as shown by the analysis of scientific research [14–17], the original product is fullerenes of different homologous series, single- and multi-layered carbon nanotubes, micro- and nanoparticles of graphite, which form carbon black. The concentration of carbon black in the experimental samples of oil was within 0–0.2 % [7].

A pair of friction “pad-roller” was selected because it realizes the process of sliding friction with the contact of the surface on the plane, which exists in bearings of sliding of technical systems, plunger pairs of hydraulic pumps and motors. The pad and the roller were made from similar materials that are used for manufacturing plunger pairs of the pump. That is, the roller – alloyed steel 38 X2MUA, and the pad – multi-component bronze Br AJ 9–4.

To test the samples, we used the upgraded laboratory setup (Fig. 1) consisting of the friction machine CMC-2 and the upgraded electronic system for providing the conditions to carry out research and to record the indications, specifically, of torque.

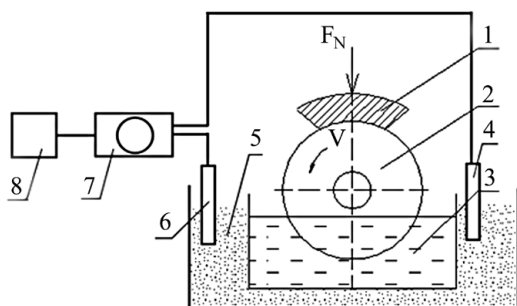


Fig. 1. Diagram of testing the friction and wear of CMC-2: 1 – pad; 2 – roller; 3 – studied oil; 4 – heater (thermoelement); 5 – tank with oil; 6 – temperature sensor; 7 – electronic thermostat; 8 – power supply unit

The roller, to 1/3 diameter of which pad 1 is pressed with the appropriate force, is immersed into tank 5 with studied oil 3. The frequency of rotation of roller 2 and the force of pressing pad 1 are regulated and supported by the elements

of controlling the friction machine. To maintain the constant temperature of studied oil 3, which arrives at the pair of friction, the setup is equipped with thermostat 7, included in the circuit of power supply of heating element 4, in this case, control signal is produced by thermal sensor 6.

- The conditions for carrying out the experiment:
 - stabilized temperature of the tank with oils, $t=40\text{ }^{\circ}\text{C}$;
 - frequency of the spindle rotation, $n=300\text{ rpm}$;
 - diameter of the roller 25 mm, thickness – 16 mm;
 - area of pad friction surface 1.56 cm^2 ;
 - duration of one testing, $t=20\text{ hours}$.

The wear of the samples was determined by the method for establishing the loss of their weight during testing during 20 hours. The samples were weighed with analytical scales BLA-200g-M with precision of 0.0005 g.

The friction surface of steel and bronze was studied on the atomic-force microscope “Solver P47-Pro” produced by company NT-MDT (Zelenograd, Russia).

4. 2. Procedure for determining the influence of concentration of carbon conglomerate on the tribological properties of industrial oils

Since the main wear of friction surfaces flows under the mode of the boundary lubrication, the primary objective was to determine the values of contact pressure in the model of a pair of friction “pad-roller”.

In order to determine the points of transition of a pair of friction to the mode of boundary lubrication to the samples, after the electrical isolation from “the ground”, the ohmmeter was connected, with the help of which the electrical resistance of the rolling contact of samples was determined. Given the fact that the hydrodynamic lubricating layer eliminates the direct contact of surfaces and is an insulator, in this mode of lubrication, electrical resistance of the moving contact of samples had the value of more than 1 ohm. During the destruction of the hydrodynamic lubricating layer, the pair of friction transfers to the mode of boundary lubrication and contact resistance drops abruptly and reaches the values of 0.2–1 Ohm, which corresponds to a dry contact of samples.

Thus, we established the values of contact pressure and sliding velocity in the pair of friction “roller-pad”, at which the transition from the hydrodynamic lubrication to the boundary one takes place. This occurs for the selected models of the samples of friction in the range of 800–1,200 N and at the velocity of 0.393 m/s. That is why external load was accepted in the range from 800 to 1,200 N (5.16–7.74 MPa). The range of fluctuations of independent factors is shown in Table 1.

Table 1

Range of fluctuations of the values of independent factors

Factor	Range
Concentration of carbon black, %	0–0.2
External loading, N (MPa)	800–1,200 (5.16–7.74)

To determine the minimal necessary repeatability of experiments, ten measuring of friction torque and wear of the pair “pad – roller” were preliminarily carried out. Industrial oil I-30A without the addition of carbon black was used in measurements. The temperature of the oil during measurements amounted to 40 °C, the external load on a pair of friction was 1,000 N (6.45 MPa), and sliding velocity was 0.393 m/s. The results of the previous tests are shown in Table 2.

Table 2

The results of preliminary tests to determine the minimal required number of experiments

No. of experiment	1	2	3	4	5
Friction torque, N·m	1.083	1.099	1.081	1.084	1.099
Wear of pad, mg	4.51	4.69	4.62	4.53	4.53
Wear of roller, mg	0.75	0.77	0.76	0.74	0.76
No. of experiment	6	7	8	9	10
Friction torque, N·m	1.096	1.084	1.067	1.115	1.097
Wear of pad, mg	4.58	4.63	4.63	4.49	4.61
Wear of roller, mg	0.74	0.77	0.76	0.77	0.75

Based on the theory of experiment planning and the methods for statistical treatment of the results of mechanical measurements [18, 19], the calculation of the required minimal number of experiments, the results of which are shown in Table 3, was carried out.

The minimal required repeatability of the experiments was determined from dependence:

$$n_{\min} \geq \frac{\sigma^2 \cdot t_{kp}^2}{\Delta^2 \cdot m_{cp}^2}, \tag{1}$$

where σ is the arithmetic mean deviation of measurements; t_{kp} is the tabular value of the Student coefficient at the assigned confidence of measurement results $P=0.9$ and the number of experiments $n=10$, $t_{kp}=1.81$ [18]; Δ is the admissible relative measurement error ($\Delta=0.02$ [19]); m_{cp} is the arithmetic mean of the value of measurement results.

Table 3

Results of calculation of the minimal number of experiments on the friction machine CMC-2

	Mean quadratic deviation of measurements, σ	Arithmetic mean value of measurement results, m_{cp}	Minimal necessary repeatability of experiments, n_{\min}
Friction torque	0.0133354	1.0905	1.22
Wear of pad	0.0646013	4.582	1.63
Wear of roller	0.0115758	0.757	1.92

Thus, the minimal repeatability of experiments, $n_{\min}=2$.

The program of conducting experimental studies implied the implementation of two 2-factor experiments, where friction torque and wear in pairs “pad-roller” were the response function (Table 4).

To get the dependences in the form of equations of regression, the orthogonal plan of the experiment, which made it possible to determine coefficients of equations at the assigned confident probability at the minimal number of experiments, was selected.

According to recommendations [18], the levels of variation of the factors (Table 5) were chosen and the orthogonal plan of the two-factor experiment was designed, Table 6.

Table 4

Program of carrying out the experimental research into the change of friction torque and wear of a pair of friction “pad –roller” of friction machine CMC-2

No. of experiment	Response function	Brand of oil	Additive, %	External loading
1	Friction torque, Nm	I-30A	Concentration of carbon black (0–0.2 %) in oil	800–1200N
2	Wear of pad and roller, mg			

Table 5

Levels of variation of the factors

Level	Code	External loading, N (MPa) X_1	Concentration of carbon black, % X_2
Lower level	-1	800 (5.16)	0
Zero level	0	1,000 (6.45)	0.1
Upper level	+1	1,200 (7.74)	0.2

Table 6

Orthogonal plan of the two-factor experiment

No. by order	Coded values		Natural values	
	X_1	X_2	External loading, N	Concentration of carbon black, %
1	0	1	1,000	0.2
2	1	0	1,200	0.1
3	-1	-1	800	0
4	-1	0	800	0.1
5	1	1	1,200	0.2
6	0	-1	1,000	0
7	1	-1	1,200	0
8	-1	1	800	0.2
9	0	0	1,000	0.1

Therefore, two two-factor experiments were conducted to determine the impact of the concentration of carbon black and the external loading on the change of friction torque and wear the pair “pad-roller”. 9 studies, each of which was repeated twice, were conducted in each experiment.

After conducting the tests on the friction machine CMC-2, the surfaces of friction of the tribological pair “pad-roller”, were explored by means of atomic-force microscopy.

5. Results of studying wear at the friction machine CMC-2

Results of the experimental research at the friction machine CMC-2 are shown in Table 7.

Based on the results of the conducted studies, we obtained regression equations that describe the pattern of a change of torque of friction between the pad and the roller and the wear of a pair of friction “pad-roller”, depending on the selected factors with the use of oil I-30A:

– torque of friction between the pad and the roller

$$M_{TP} = 6,2333334c^2 + 0,0000002p_H^2 - 1,8533334c - 0,0002496p_H + 0,000375c \cdot p_H + 1,149278; \tag{2}$$

– wear of the roller

$$U = 27,7501c^2 + 0,0007p_H - 8,3834c + 0,0009c \cdot p_H + 0,0701, \quad (3)$$

where c is the concentrations of carbon black in industrial oil I-30A, %; p_H is the external loading, N;

– wear of the pad

$$U = 125,1667c^2 + 0,0048p_H - 31,1501c - 0,0038c \cdot p_H - 0,1467. \quad (4)$$

Table 7

Results of experimental studies for determining a change in friction torque and wear of a friction pair “pad-roller” on the concentration of carbon black in oil I-30A and external loading

No. by order	Friction torque, N·m			Wear of roller, mg			Wear of pad, mg		
	$M_{TP(1)}$	$M_{TP(2)}$	$M_{TP(3)}$	U_1	U_2	U_{CP}	U_1	U_2	U_{CP}
1	1.05	1.028	1.039	0.44	0.37	0.405	2.51	2.59	2.55
2	1.045	1.054	1.0495	0.46	0.52	0.49	3.21	3.27	3.24
3	1.081	1.065	1.073	0.67	0.63	0.65	3.58	3.64	3.61
4	0.957	0.985	0.971	0.16	0.11	0.135	1.58	1.44	1.51
5	1.084	1.097	1.0905	0.5	0.56	0.53	3.46	3.37	3.415
6	1.096	1.086	1.091	0.77	0.73	0.75	4.57	4.63	4.6
7	1.128	1.11	1.119	0.93	0.89	0.91	5.53	5.47	5.5
8	0.997	1.032	1.0145	0.18	0.22	0.2	1.78	1.87	1.825
9	0.987	1.025	1.006	0.25	0.28	0.265	2.29	2.2	2.245

Reproducibility of the experiments was checked using the Cochran criterion [18, 19], and the adequacy of the model was verified using the Fisher criterion [18].

The results of testing the reproducibility and adequacy are shown in the following equations:

– determining the torque of friction between the pad and the roller

$$G_K = 0,269856 \leq 0,6385, \quad F_{\Phi} = 0,710784 \leq 6,1631;$$

– determining the wear of the roller

$$G_K = 0,365672 \leq 0,6385, \quad F_{\Phi} = 0,5005 \leq 6,1631;$$

– determining the wear of the pad

$$G_K = 0,275668 \leq 0,6385, \quad F_{\Phi} = 3,067873 \leq 6,1631.$$

The obtained regression equations are adequate to the obtained results of the experimental research, so they can be used for the analysis of the research.

The graphic image of the results of testing a pair “pad-roller” on the friction machine CMC-2 regarding a change in friction torque, depending on the concentration of carbon black and the external load at the temperature of oil of 40 °C are shown in Fig. 2, 3.

According to the obtained results regarding the influence of the concentration of carbon black on a change of friction torque in the pair “pad-roller” (Fig. 2, 3), the decrease in friction torque by 7–8.4 % at the increase in

the concentration from 0 to 0.1 % at the external load from 800 N to 1,200 N is observed. Upon further increase in the value of the concentration, friction torque begins to increase.

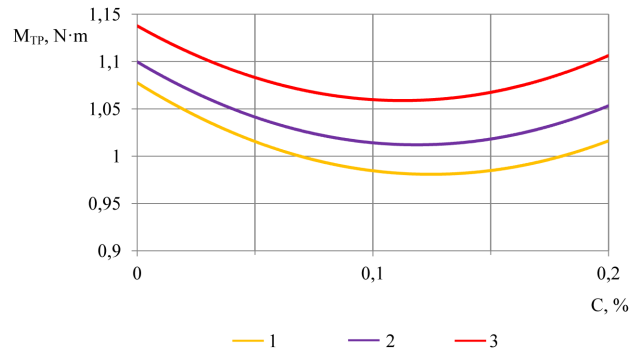


Fig. 2. Change of torque of friction between the roller and the pad, depending on the concentration of carbon black in the industrial oil I-30A: 1 – external loading $P_H=800$ N (5.16 MPa); 2 – $P_H=1000$ N (6.45 MPa); 3 – $P_H=1200$ N (7.74 MPa)

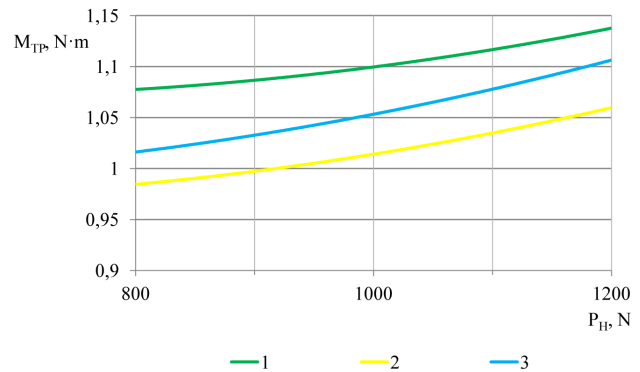


Fig. 3. Change of torque of friction between the pad and the roller, depending on external loading at various concentrations of carbon black in the oil: 1 – industrial oil I-30A without the application of carbon black; 2 – 0.1 % concentration of carbon black in the oil; 3 – 0.2 % concentration of carbon black in the oil

The results of testing for establishing the influence of the concentration of carbon black on the change of the wear of a pair of friction “pad-roller” at the external loading (800–1,200 N) on the machine CMC-2 are shown in Fig. 4, 7.

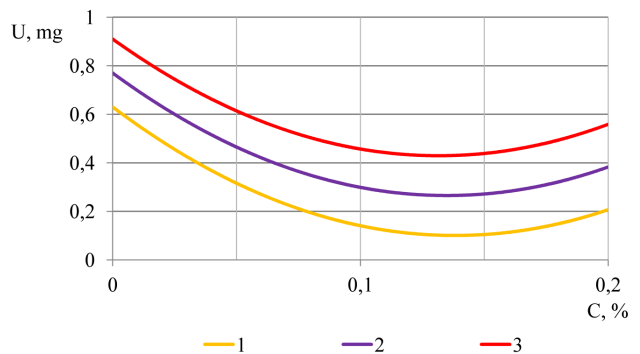


Fig. 4. Change in the magnitude of wear of the roller, depending on the concentration of carbon black in industrial oil I-30A: 1 – external loading $P_H=800$ N (5.16 MPa); 2 – $P_H=1,000$ N (6.45 MPa); 3 – $P_H=1,200$ N (7.74 MPa)

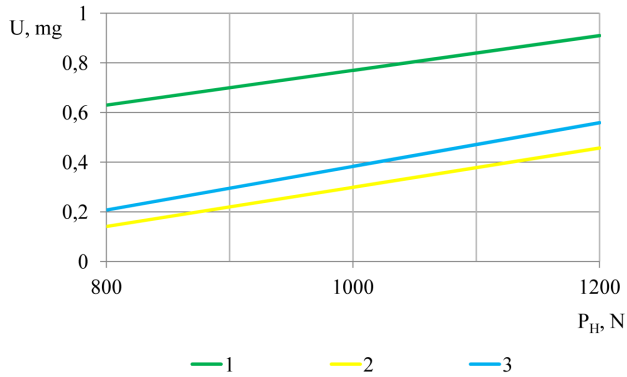


Fig. 5. Change in the magnitude of wear of the roller, depending on external loading at various concentrations of carbon black in the oil: 1 – industrial oil I-30A without the application of carbon black; 2 – concentration of carbon black in the oil – 0.1 %; 3 – concentration of carbon black in the oil – 0.2 %

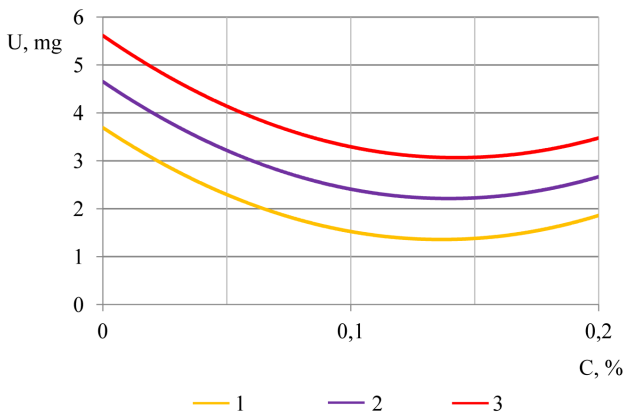


Fig. 6. Change of the magnitude of the wear of the pad, depending on the concentration of carbon black in industrial oil I-30A: 1 – external loading P_H=800 N (5.16 MPa); 2 – P_H=1,000 N (6.45 MPa); 3 – P_H=1,200 N (7.74 MPa)

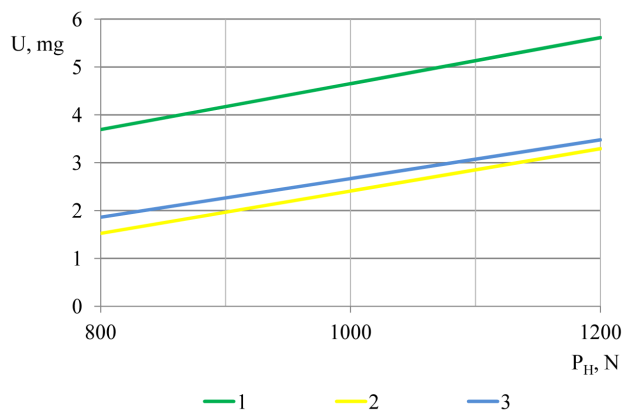


Fig. 7. Change of the magnitude of the wear of the pad, depending on external loading at various concentrations of carbon black in the oil: 1 – pure industrial oil I-30A; 2 – concentration of carbon black in the oil – 0.1 %; 3 – concentration of carbon black in the oil – 0.2 %

Based on the research results (Fig. 4, 5), the dependence of the change of the wear of the roller on the concentration of carbon black in the oil and on external loading was es-

tablished. It was revealed that at the increase in the concentration from 0 to 0.2 % at external loading from 800 N to 1,200 N, a decrease in the wear of the roller was observed. The values of the concentration of carbon black are rational values of the minimum wear at these loadings.

The results of the wear of the pad (Fig. 6, 7) at the same loadings and the studied range of concentrations showed minimum wear at the concentration of carbon black of 0.12–0.13 %.

The results of studying the surfaces of friction of steel and bronze on the atomic-force microscope “Solver P47-Pro”, manufactured by NT-MDT company (Zelenograd, Russia), after testing the industrial oil with carbon black are shown in Fig. 8, 9.

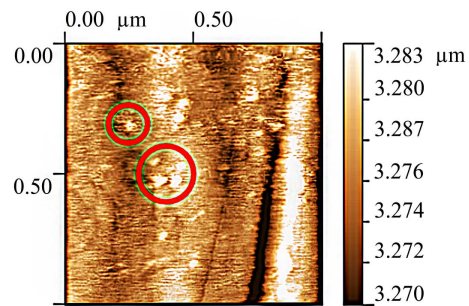


Fig. 8. Surface of the roller after testing

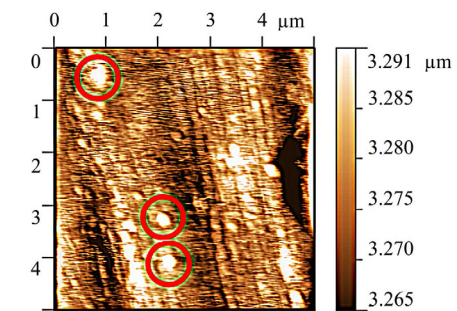


Fig. 9. Surface of the pad after testing

Fig. 8, 9 show the surfaces of friction of the studied samples after testing. There are inclusions of dimensions from 40 nm to 250 nm on the surfaces of the roller and the pad.

6. Discussion of results from studying the influence of concentration of carbon black on the tribological properties of industrial oils

The conducted experimental research is the part of the scientific direction studying the impact of micro- and nanoparticles of various forms of carbon on the processes occurring in tribological systems, specifically, the change of the tribological characteristics of industrial oils.

A decrease in friction torque in the pair “steel-bronze” at the concentration of carbon black in oil from 0–0.13 % is related to the influence of abrasive particles of carbon on the equilibrium roughness of friction surfaces, specifically, on its decrease, which leads to a decrease in the mechanical component of friction.

The region of the rational concentration of carbon black within 0.12–0.13 %, at which there is minimal wear under certain loads, is related to the fact that two types of wear are

realized in this pair of friction. One type is elastic-plastic and the other is abrasive. At an increase in the concentration of carbon black, elastic-plastic kind of wear decreases, while abrasive kind increases. And at the concentration of 0.12–0.13 %, these kinds of wear become equal. Upon further increase in the concentration of carbon black, there occur a further increase in abrasive and a decrease in elastic-plastic wear. That is why the total wear in the found region is minimal.

The research on the atomic-force microscope showed that there are inclusions that vary in size from 40 nm to 250 nm. Given the fact that carbon particles are stronger than particles of steel, the roller is made of, carbon nanoparticles are the inclusions on the surface of the roller. Nanodimensionality of the particles is observed with the use of a scale ruler. As far as the bronze pad is concerned, given the dimensions of the inclusions, it is possible to state about the existence of both carbon particles and wear products. Such inclusions strengthen the surface layers of metals and decrease their wear.

The results of the study prove the findings of earlier scientific research [9, 20–26], regarding the positive use of carbon nanoparticles of different shapes as “additives” and friction modifiers to lubricants. However, it should be noted that in papers [4, 5, 8, 25], there were used the pure forms of carbon, mainly fullerenes, the cost of obtaining of which is by an order of magnitude higher than that of obtaining conglomerate of carbon of this study.

Regarding the shortcomings of this research, it is necessary to note that the structure of carbon black was not considered. That is, what is the percentage of such forms of

carbon as fullerenes, nanotubes, micro- and nanoparticles of graphite, etc. There is also a question about the impact of change in the percentage composition of carbon black in a lubricating material on the friction and wear processes. The problems that have not been addressed are to be dealt with in the further research.

7. Conclusions

1. According to the conducted experimental research on the friction machine CMC-2, it was found that the content of carbon black in industrial oil I-30A contributes to a decrease in the wear of the friction pair “pad-roller”. At an increase in the concentration of carbon black from 0 to 0.13 %, the intensity of wear of the bronze pads decreases by 48.5–65.2 % and that of the steel roller by 52–84 % at the external loading of 800–1,200 N. At a further increase in the concentration, the wear begins to increase, which is explained mainly by abrasive wear. Minimum wear in the whole range of external loadings is observed at the value of the concentration of carbon black of 0.12–0.13 %. This range can be considered rational for the given tribological system.

2. Research at the atomic-force microscope revealed the presence of nanodimensional particles of the elements of carbon black on the friction surfaces, both on steel and on bronze. This suggests that nanoparticles of carbon black are immersed in the surface layer, which leads to its discrete strengthening and contributes to a decrease of its wear at a certain concentration.

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