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STUDYING THE TRIBOLOGICAL PROPERTIES OF MATED MATERIALS C61900-A48-25BC1.25BNO. 25 IN COMPOSITE OILS CONTAINING GEOMODIFIERS

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З розвитком дисперсних систем в трибології створилась можливість ефективно використовувати функціональні добавки до мастильних матеріалів у вигляді геомодифікаторів. При впровадженні композиційних олив з геомодифікаторами не потрібно виконувати конструктивні зміни спряжень деталей машин, але їх зносостійкість і припрацьовуваність збільшується. Це потребує проведення експериментальних трибологічних досліджень.

Запропоновано використання геомодифікатора KGMF-1+олеїнової кислоди в якості функціональної добавки до моторної оливи, а для порівняння обрано свіжу оливу Monnol TS-5 UHPD 10W40 та композиційну оливу Monnol TS-5 UHPD 10W40+XADO HighWay for Diesel Truck (2,0...2,3 %). Зменшення моменту сили тертя різних спряжень зразків в досліджуваних оливах фіксували на машині тертя моделі 2070 СМТ-1 з додатковим модулем "кільце-кільце". Визначення інтенсивності зношування зразків в досліджуваних оливах проводили методом вимірювання амплітуди акустичного сигналу безпосередньо із зони тертя за допомогою приладу фірми Brüel&Kjear.

Виявлено, що зростання ефективності мастильних композицій спостерігається у наступному порядку: Monnol TS-5 UHPD 10W4, Monnol TS-5 UHPD 10W40, Monnol TS-5 UHPD 10W40+XADO HighWay for Diesel Truck, Monnol TS-5 UHPD 10W4+KGMF-1+олеїнова кислота. Показник зносу металевих зразків, в середовищі модифікованої оливи Monnol TS-5 UHPD 10W4+KGMF-1+олеїнова кислота, у порівнянні з базової оливою зменшився на 11,5...14,3 %. Значення критичного навантаження збільшилось на 17,2 %, а навантаження зварювання збільшилось на 19,3 %. відповідно. В свою чергу, зафіксовано, що максимальна інтенсивність зношування зразків при використанні модифікованої оливи Monnol TS-5 UHPD 10W4+KGMF-1+олеїнова кислота зменшилась в 3,4...6,0 рази..

Отримані дані необхідні для формування композиційних олив та обґрунтування умов їх подальшої експлуатації в період форсованого припрацювання трибоспряжень деталей

Ключові слова: трибоспряження зразків, геомодифікатор, композиційна олива, момент тертя, зносостійкість, акустична емісія, зона тертя, присадка, бронза, сірий чавун

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1. Introduction

The use of composite lubricants and geomodifiers is one of the ways to increase wear resistance and alignment of the tribojunction of machine parts. Lubricating properties of oils are improved mainly by introducing industrially designed complexes of additives into them. Today, additives based on natural mineral after their preliminary treatment are actively used. This is so-called geomodifiers. The study of the effect of the use of geomodifiers shows that surface-active substances of a metal-ceramic reducing agent, when getting on the friction surface together with oil, initiate the process of formation of the metal ceramic coating with high wear resistance and low friction coefficient on the surfaces of mated samples and parts. In the presence of additives in the lubricating medium, there occurs texturing of friction surfaces and strengthening of basic material of samples and parts at considerable depth. In the course of operation of mated parts, the rational microrelief can be gradually formed on friction surfaces, which will meet the actual operating conditions.

The difference between friction geomodifiers and other additives lies in the fact that substances that initiate self-organization processes are introduced into mated samples and details. While introducing additives and additions to oils, one mainly tries to separate mated surface by finely dispersed particles, long hydrocarbon chains and a synthetic film. This contributes to the formation of an optimal surface structure, especially in the contact areas with the maximum number of free bonds, which ensures elevated oil-retaining ability and equilibrium roughness. At the same time, the development of the problem of using geomodifiers for lubricating compositions enables increasing wear resistance and alignment of parts tribojunction. It is possible to obtain various positive effects in the operation of machines during the subsequent technological adaptation in the mass use of composite oils. The urgency of the paper is the development of lubricating compositions with geomodifiers, which makes it possible to increase the wear resistance of heavy-loaded tribojunction of machine parts.

2. Literature review and problem statement

Increased requirements for the efficiency of machines, with a high level of reliability and limited financial costs for their operation require that tribological research should focus on searching for more effective new ways to increase wear resistance of different types of mated parts. The study of the technical condition of oils, which operate in power units of transport machines, showed that there is no full compliance with the manufacturer's stated norms of the run [1]. The processes of rapid aging of working oil are identified by a significant contact temperature that leads to its oxidation [2]. In the future, lubricants should be developed to improve tribo-technical properties of parts tribojunction. Diagnosis of lubricant medium both continuous and periodic is also extremely necessary [3] especially for aviation equipment. This ensures the necessary level of reliability. Various tests for researching and specifying the characteristics of tribojunction during liquid friction and viscous resistance were developed [4]. These tests are required for theoretical description of the friction process in the contact area in the presence of oil medium and description of the processes of interaction of oil with the working surface of parts. The classification of additives to oils and development of the methodical complex of selection of necessary additives to them is covered in article [5]. At the same time, it is necessary to study separate complexes of additives for their increasing wear resistance of parts tribojunction. In order to reduce internal friction and control of the patterns of external friction of materials of mated samples and parts, it is possible to use soft metals [6] and their derived coatings [7] with the subsequent highly efficient thermal treatment [8]. At this time, these coatings do not create the possibility of dynamic regulation of wear resistance and can be supported only under certain operating conditions. Dissimilar additives and additives of synthetic and natural origin change the physical thermal oxidizing ability of oil due to the formation of the surface layers of materials. This helps reduce friction coefficient and ensure additional dissipation of friction energy [9]. The lubricating capacity of oil increases, but wear resistance in this case may change insignificantly, so it is necessary to look for new compositions with greater potential of positive properties for parts tribojunction. Provision of the required level of values of tribological characteristics and formation of renewable additives to oils containing the elements of geological origin occurs with the participation of powder with serpentine inclusions [10]. However, the obtained results did not reflect the comparative pattern of wear with existing synthetic analogues of additives. In turn, the authors of paper [11] presented some theoretical substantiation for using lubricant compositions with some friction geomodifiers of this type. By this moment, the issue of destroying these additives in the oil working medium has not been highlighted. This is due to insufficient quantity of research into colloidal friction products of friction of lubricating media, as the friction process has a significant number of processes of thermal, electromagnetic and contact-power nature, influencing the destruction of colloid particles of additives. It is therefore possible to draw a parallel with the studied model of destruction of surface layers [12]. It is also necessary to specify viscous and lubricating characteristics of oil. Development and research into geomodifiers are required based on the model of estimation of sticking of surface layers to the working surface of materials [13]. In this case, it is important to specify the nature and impact of tribo-electrization on the particles of additives and the lubricating medium.

Geomodifiers promote mechanic and chemical reactions, pyrolysis of components of oil and tribocatalytic carbonization, graphitization, and the formation of solid carbon-containing compounds from oils [14]. The conditions of formation of coatings, low coefficient of friction and thermal conductivity, high strength and corrosion resistance of geomodifiers were found. It follows from the results of the research into the properties of $Mg_6Si_4O_{10}(OH)_8$ geomodifiers [15]. It was determined that friction geomodifiers are based on a large group of minerals [16] that have similar chemical composition, where magnesium can be replaced with iron and nickel [17]. Serpentine rock includes several types of serpentine, magnetite and chromic inclusions, and the variation of chemical elements used as a mixture of geomodification compositions [18]. Development of the algorithms for the assessment of lubricating medium is possible with the help of additional calculation using analytical models and regression analysis [19]. This requires additional tribological experiments to create the required databases. The influence of the temperature field of the local regions of working surfaces of mated samples and parts makes it possible to increase the tribo-electrization in their materials [20], which causes an increase in the rate of activation of serpentine additives in the lubricating medium. The formation of coatings by galvanic methods increases their tribological properties, but they are costly, environmentally harmful and effective [21] under homogeneous operating conditions. These coatings do not ensure a significant economic effect and prevent self-organization during operation. The study of various geomodification compositions was highlighted in paper [22], but the nature of destruction of working surfaces during critical load was not described. The main recommendations for the efficient use of composite oils in the development of tribotechnologies for restoration of bearing units during operation of machines were given. It was desirable to highlight the issue of wear of the bearing node in the presence of a geomodifier [23]. Development of the apparatus for analysis of each component of the unit of the studied sample or parts is possible using optimality coefficients and round-grams of functionality of the studied systems [24]. At the same time, in the analysis of tribotechnical properties, it is necessary to generate a database of the change in wear intensity and friction momentum. If we consider the optimum technical systems, the tribojunctions in them play a significant role, providing reliability and resistance to random impacts [25]. This should be additionally considered in functioning of parts tribojunction with composite oil and determine the appropriate regularities of changing the lubricating ability.

The important place of the use of composite oils in mechanical engineering is high-speed rotors [26], as well as for calculations of empirical criteria of occurrence of auto-balancing, indicating that friction force acts as a destabilizing factor [27]. In these types of mated parts, it is important to introduce highly effective additives and additions, as well as to substantiate their operating boundaries and operating conditions.

The chemical component of the formation of a metal-ceramic layer of geomodifiers was to some degree developed in work [28], but it contains no information on the physical-mechanical and rheological properties of these layers. There are virtually no such developments. In published works, the writers suggest the possibility of elastic-hydrodynamic effect [29], which is characterized by high pressure in the oil blade, causing elastic deformation of materials of the samples and parts in contact. As a result, the magnitude of the gap between parts increases. This takes place during the work of the layer that is formed in the presence of geomodifiers in oils, which additionally protects the working surface from corrosion [30]. Profound studies of surface and surface layers, formed on the samples and parts when treating by geomodifiers have not been found in the available literature. Until now, there are no studies on the dynamics of the process of increasing the enhancement the wear resistance of lubricating compositions with friction modifiers. Wear resistant coatings certainly have dissipative and metastable structures [31], which constantly need to be monitored and detected. However, the formation of microdimensional films in the area of friction with the help of geomodifiers was not described from the tribological point of view. Contactless detection of the friction process in bearing nodes is most rational using acoustic emission [32]. This method was not considered in the case of the presence of the lubricating medium that has its own dissipating ability [33], and for different types of tribojunction. The description of the tribocontact revealed significant opportunities for the formation of new dissipative structures [34], but the possibility to expand this region with the use of composite oils modified by friction geomodifiers was created.

The low level of research and systematization of friction modifiers is associated with technological difficulties of their cleaning and pre-treatment, as well as the existence of the complex chemical composition and its impact on the friction process. Lubricating compositions of oils based on geomodifiers were not systematized and require additional research into their efficient use for tribojunctions of samples and parts in terms of improving the tribological properties.

3. The aim and objectives of the study

The aim of this work is to study the process of friction in the presence of lubrication compositions with geomodifiers of friction. This will enable an increase in wear resistance and alignment of mated samples in the oil medium with the addition of the Kateryniv geomodifier of friction – 1 (KGMF-1). Comparison of the tribotechnical characteristics of this composition is basic and composite oil with the addition of the industrial sample of additive XADO HighWay for Diesel Truck will give an opportunity to assess the tribological efficiency of a geomodifier of friction more accurately.

To accomplish the aim, the following tasks have been set:

– to study, at the four-ball friction machine FBM, the indicator of wear, critical load and welding load for basic oil Monnol TS-5 UHPD 10W40 and lubricating compositions Monnol TS-5 UHPD 10W40+XADO HighWay for Diesel Truck and Monnol TS-5 UHPD 10W40+KGMF-1;

– based on the obtained results, analyze a lubricating ability of the composite oil with the addition of geomodifier KGMF-1 in comparison with composite oil Monnol TS-5 UHPD 10W40+XADO HighWay for Diesel Truck;

– to identify the patterns of a change in friction momentum and wear intensity of different types of mated samples with the use of lubricating composition Monnol TS-5 UHPD 10W40+KGMF-1 with alignment on the friction machine 2070 CMT-1 by scheme “ring – ring”.

4. Materials and methods to study the tribotechnical characteristics of different types of mated samples in the medium of composite oil

Cast iron A48-25BC1.25BNo. 25 (HRC 40) and bronze C61900 (HB 95) were used as the material of the samples. When choosing the materials of the samples, we took into account their maximum use and similarity in the mated parts in internal combustion engines and hydraulic units of the KamAZ trucks, which are widely represented in the central region of Ukraine.

As the lubricating medium, we used basic motor oil Monnol TS-5 UHPD 10W40 – No. 1, which was selected by company ATE 2004, the city of Kropyvnytskyi (Ukraine) during the operation of the KamAZ and Renault trucks and composite oils: Monnol TS-5 UHPD 10W40+KGMF-1 (5.1...5.5 %)+oleic acid (1.4...2.5 %) – No. 2, preliminary results of the KGMF-1 content were presented in paper [11]. The most well-known additives in the market of Ukraine are represented by the preparations of the XADO trade mark, which earned good reputation for power units of transport machines. For comparative studies we used oil composition Monnol TS-5 UHPD 10W40+XADO HighWay for Diesel Truck (made in Ukraine) – No. 3. The concentration of this additive (2.1...3.2 %) was formed according to the requirements of the manufacturer. We will note that the mixture of geomodifier KGMF-1 (chemical composition: 11Na – 0.525±0.178; 12Mg – 0.950±0.118; 13Al – 32.680±0.137; 14Si – 55.287±0.168; 16S – 0.942±0.035; 20Ca – 0.899±0.053; 22Ti – 4.842±0.046; 23V – 0.042±0.02; 24Cr – 0.052±0.006; 26Fe – 3.178±0.018; 28Ni – 0.117±0.002; 29Cu – 0.015±0.001; 30Zn – 0.049±0.001; 31Ga – 0.042±0.001; 37Rb – 0.004±0.001; 38Sr – 0.037±0.001; 39Y – 0.010±0.001; 40Zr – 0.241±0.002; 41Nb – 0.026±0.001; 49In – 0.018±0.003; 82Pb – 0.043±0.002) was obtained by the author from clay-based natural substances. For comparative studies, the oil composition Monnol TS-5 UHPD 10W40+XADO HighWay for Diesel Truck (production Ukraine) was used-Number 3. The concentration of this additive (2.1... 3.2 %) was formed in accordance with the manufacturer’s requirements. It should be noted that a mixture of GEOMAMF-1s (chemical composition: 11Na – 0.525±0.178; 12Mg – 0.950±0.118; 13Al – 32.680±0.137; 14Si – 55.287±0.168; 16S – 0.942±0.035; 20Ca – 0.899±0.053; 22Ti – 4.842±0.046; 23V – 0.042±0.02; 24Cr – 0.052±0.006; 26Fe – 3.178±0.018; 28Ni – 0.117±0.002; 29Cu – 0.015±0.001; 30Zn – 0.049±0.001; 31Ga-0.042±0.001; 37Rb – 0.004±0.001; 38Sr – 0.037±0.001; 39Y – 0.010±0.001; 40Zr – 0.241±0.002; 41Nb – 0.026±0.001; 49In – 0.018±0.003; 82Pb – 0.043±0.002) was obtained by authors from natural substances based on clay.

Due to the point contact of the balls, the four-ball friction machine (FBM) serves as a reliable tool to determine the lubricating ability of oils and their compositions, effectiveness of additives and additions in them. The research into efficiency of using in base oil No. 1 of the renewable mixture KGMF-1 was carried out on the ball samples by point or linear contacts. As comparative studies, we performed testing on basic oil No. 1 and oil composition No. 3. FBM, in which the oil tribojunction medium from the balls is collected to the pyramid of four balls, the three lower balls of which are fixed motionless in the cup, which is filled with experimental oil, and the upper ball rotates in a vertical spindle. In the process of the study we determined the average values of critical load, welding load, wear rate, characterized by the diameter of a spot of wear from critical load applied to corresponding lubricating media. Testing and determining the characteristics of lubricating media on the FBM was conducted in accordance with the unified standards of GOST 9490-75, in Germany – DIN 51350, in the USA – ASTM D2783.

To study the patterns of changes in friction momentum and intensity of wear of the mated samples at lubricating with the composite oil, by which it is possible to reveal enhancement of their alignment and wear resistance. To prove the efficiency of using composite oils with the addition of a geomodifier, for example, KGMF-1+oleic acid, a friction machine 2070 CMT-1 with a test module of samples by the "ring – ring" scheme was used, Fig. 1, *b*. Basic and composite oils were fed to the friction zone by the gear pump through the nozzle. To avoid the impact of wear particles on the parameters of friction and wear, the filter with fine cleaning up to particles of dimensions of 100 microns was established in the lubricating system.

a *b*

Fig. 1. Overall view of friction machines: *a* – four-ball friction machine; *b* – friction machine 2070 CMT-1 with the additional module "ring – ring"

This scheme was implemented on the additional module of samples testing. The overall view of the samples is presented in Fig. 2.

Before studying, the samples were rubbed to each other until the full contact of contact areas. It ensured the roughness of surface $Ra = 0,2$ micron, which corresponds to aligned resource-determining junction of power units of transport and hydraulic machines. Roughness was measured according to GOST 27964-88, using a profilometer of model 283. The samples were studied with the mutual overlap coefficient K_{mo}=0.5, which was predetermined by including the large number of types of mated samples. Sample sizes and test methods correspond to GOST 23.210.

a *b*

Fig. 2. Physical appearance of experimental samples for tests according to the "ring-ring" scheme on friction machine 2070 CMT-1: *a* – C61900 (HB 95); *b* – A48-25BC1.25BNo. 25 (HRC40)

Research into tribotechnical characteristics of junctions of different types in the lubricating medium was performed at load of 200 N and the slip velocity of 0.7 m/s., which practically corresponds to the contact area of the samples according to GOST P 51860-2002 of friction machine 2070 CMT-1. The samples in line with the "ring – ring" scheme had the outer diameter of 12 mm, and the inner diameter of 6 mm.

For more accurate reflection of the process, changes in wear resistance of mated samples, which function in the basic and modified oil, it was proposed to divide them by the features of samples. For friction machine 2070 CMT-1, the samples' junctions were divided into four types by characteristic features: mobility, hardness of material and area of friction zone, Table 1.

Table 1

Types of tribojunction of samples and characteristic features of their properties

Characteristic features of properties of tribojunction of samples				
Type of junction	Movable sample		Non-movable sample	
	Hardness of material, H_m	Area of friction zone, S_m	Hardness of material, H_f	Area of friction zone, S_f
I	$H_m>H_f$	$S_m>S_f$	$H_f<H_m$	$S_f<S_m$
II	$H_m<H_f$	$S_m>S_f$	$H_f>H_m$	$S_f<S_m$
III	$H_m>H_f$	$S_m<S_f$	$H_f<H_m$	$S_f>S_m$
IV	$H_m<H_f$	$S_m<S_f$	$H_f>H_m$	$S_f>S_m$

A widely spread structure is the first type of tribojunction of the samples, in which the material of the movable sample (a part) has higher hardness (H_m) and greater area (S_m), and the material of the non-movable sample – lower hardness (H_f) and lower area of friction zone (S_f). For tribojunction of the second type, it is characteristic that $H_m<H_f$, $S_m>S_f$, for that of the third type – $H_m>H_f$, $S_m<S_f$ for the fourth type – $H_m<H_f$, $S_m<S_f$.

The first type of junction is the junction from the solid shaft and soft insert, which is widely used in the systems and units of mobile agricultural and road transport machinery and is well-proven in operation. The tribojunction of solid cylindrical samples and soft movable disc belong to the second type of tribojunction. The hydraulic cylinder and the mated piston from solid material – in this case the cylinder is made of softer material – form the third type of tribojunction. Tribojunction "cylinder plunger – piston" represents the fourth type.

In the course of research, a change in friction momentum was determined by friction force and the sample size, and wear intensity by the amplitude of acoustic signal from the friction zone.

The processes of wear of tribojunction of samples were studied by the method of acoustic emission. In this paper, the acoustic-emission complex (Fig. 3), which consisted of a serial device of the Brüel&Kjear company (Type 2511), was used.

Fig. 3. A complex for studying wear intensity according to measurement of the amplitude of the acoustic signal

The piezo element produced by this company was used as a sensor. The sensor was fixed on the non-movable sample. This complex makes it possible to record a change in the acoustic signal from the mated samples during testing. It is important for tribological research to choose the parameters of the acoustic emission, which adequately reflects the processes of wear in friction zones taking into consideration the specificity of signal formation. The amplitude of the signal from the friction zone, which correlates with the magnitude of wear intensity, was chosen as the information characteristic of acoustic emission of studying the dynamics of formation and destruction of the surface wear resistance layer. To determine the value of intensity of wear of the mated samples, the amplitude of acoustic emission of the signal was used, the corresponding calculation was carried out from formula:

$$I_u = k \cdot A \cdot 10^{-9}, \quad (1)$$

where k=0.4 mV^{-1} is the transition coefficient that is determined by calibration chart for device of the Brüel&Kjear company (type 2511) (Germany); A – amplitude of acoustic signal, mV.

Normalization of the device of Brüel&Kjear company (type 2511) (Germany) was carried out by selecting the frequency of acoustic signal that most adequately reflects the wear processes of the studied mated samples. This normalization included acoustic estimation of moving tribojunctions and elements of the hydrosystem of the friction machines 2070 CMT-1 without establishing the samples in contact, and the obtained results of the amplitude of acoustic signals were rejected as noises. The values of their amplitudes were established as a threshold value and, therefore, when assessing wear intensity using the Brüel&Kjear complex (type 2511), they were not taken into consideration. The rational frequency of estimation of sample wear intensity due to the formation and destruction of surface layers in the medium of basic and modified oils of the studied samples, put in contact, was 4 kHz. This value of frequency corresponds to the maximum amplitude of an acoustic signal in the frequency range of 3...6 kHz of the acoustic spectrum without taking into consideration of noise. At this frequency of acoustic signals, the most accurate and adequate results of determining wear intensity of the studied samples by acoustic emission in comparison with the weight method were obtained.

Experimental research of different types of mated samples was carried out with obtaining the values of wear intensity I_u and friction momentum M_{fr} in the oils: basic Monnol TS-5 UHPD 10W40 and composite Monnol TS-5 UHPD 10W40+KGMF-1+oleic acid. The total duration of the experiment at every repetition made up 100...110 min. In every case, the diagram of the change in the amplitude of the acoustic system and the friction momentum were recorded at a self-recording machine.

Reliability of the readings and experimental data on determining the wear indicator, critical load, welding load, friction momentum and wear intensity was verified according to three corresponding experiments. In this case, absolute and relative errors were determined. To process the results of the study, we used the software "Excel 2007", in which average quadratic deviation, correlation coefficient, regression factor and mean approximation error were calculated.

Studying the basic and composite oils in line with the given procedures is important for technical service of enterprises that use transport machinery. That is why their selection and formation were performed so as to ensure minimum duration and maximum effectiveness of experiments

5. Results of studying the tribotechnical characteristics and changes in wear resistance of mated samples of different types in the basic and composite oils

The influence of composition oil No. 2 was compared with basic oil No. 1 and with the lubricant composition No. 3. In the process of testing, the lubricating ability of the studied oils samples was determined on the FBM by the following indicators: wear, critical load, and welding load. The results of corresponding experimental studies are shown in Table 2.

According to the study results at the four-ball friction machine FBM, the histograms of change in average diameter of spots of wear of lower ball from applied load were constructed (Fig. 4). The time of single research, according to GOST 9490-75, equaled 10 s.

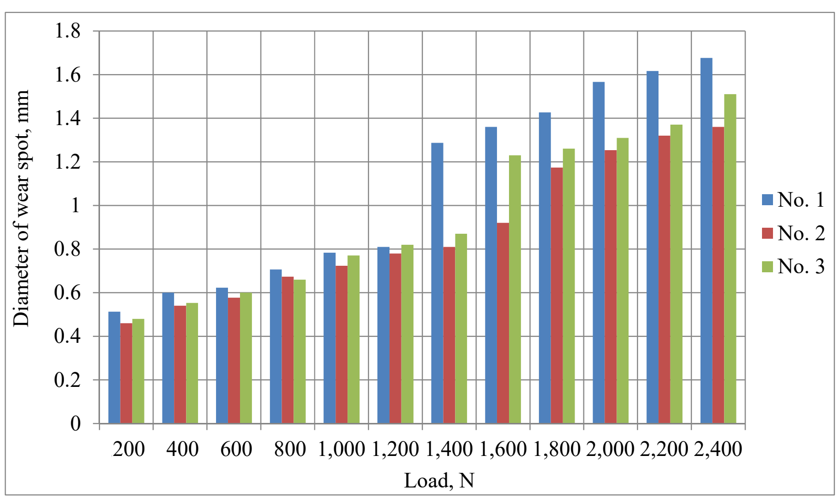

Fig. 4. Histograms of change in the average diameter of spots of wear of lower balls from applied load for various tested lubricating media

Regression analysis was performed using the tools "Data analysis" and the tool "Regression" in the applied software Excel 2010. The experimental results were averaged over three repetitions. The use of the formed database makes it possible to obtain the equation for a change in average diameter of wear spots on FBM (Table 3).

Since corresponding determination coefficients of regression equations in Table 3–5 are not more than the value of 0.95 and corresponding estimated values of the Fisher criterion are higher than the tabular values of the Fischer criterion, it is possible to state about the adequacy of obtained equations.

The results of the study of the patterns of changes in friction momentum on the friction machine 2070CMT-1 (Table 6) and wear intensity (Table 7) are presented for different types of tribojunctions of the samples based on basic oil No. 1 and oil compositions No. 2, 3. C61900 (HB95) and A48-25BC1.25BNo. 25 (HRC40) were used as the material of the mated samples.

To have a more detailed display of the overall picture and visual representation of the energy (Fig. 5) and material-consuming (Fig. 6) components of the friction process in tribojunctions, these components can be analyzed by the area corresponding to pie charts. Results presentation in this form increases the possibility of their systemic analysis, specifically, identifying the nature of alignment of different types of mated samples, working in the studied environment.

Table 2

Averaged results of the tests on the four-ball friction machine FBM in various lubricating media

Averaged indicators	Lubricating compositions		
	No. 1	No. 2	No. 3
Wear indicator, mm	0.53±0.05	0.47±0.05	0.49±0.02
Critical load, N	1,348±0.6	1,626±2.5	1,548±1.7
Welding load, N	1,874±12.4	2,327±19.5	2,232±8.5

Table 3

Regression analysis of dependence of the diameter of ball wear spot during friction on load on friction machine FBM in the presence of lubrication composition No. 1

Output variables of experiment function, mm											
1	2	3	4	5	6	7	8	9	10	11	12
0.51	0.60	0.62	0.71	0.78	0.81	1.29	1.36	1.42	1.57	1.62	1.68
+0.017 -0.013	±0.01	+0.017 -0.013	+0.013 -0.017	+0.007 -0.003	±0.01	+0.003 -0.007	±0.01	+0.007 -0.013	+0.013 -0.007	+0.013 -0.017	+0.003 -0.007
Input variables of experiment factor, N											
1	2	3	4	5	6	7	8	9	10	11	12
200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000	2,200	2,400

Equation of regression of a change of function from the experiment factor, mm	Determination coefficient	Variances of residues	Estimated value of the Fisher criterion	Table value of the Fisher criterion
Y=0.3+6.0·10^{-4}·X	0,95	0.012	173.6	2.2

Table 4

Regression analysis of the dependence of diameter of ball wear spot during friction on load of the FBM friction machine in the presence of lubricant composition No. 2

Output variables of experiment function, mm											
1	2	3	4	5	6	7	8	9	10	11	12
0.46	0.54	0.58	0.67	0.72	0.78	0.81	0.92	1.17	1.25	1.32	1.36
±0.01	±0.01	+0.003 -0.007	+0.013 -0.017	+0.017 -0.013	±0.01	±0.01	±0.01	+0.007 -0.003	+0.007 -0.003	±0.01	±0.01
Input variables of experiment factor, N											
1	2	3	4	5	6	7	8	9	10	11	12
200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000	2,200	2,400

Equation of regression of a change of function from the experiment factor, mm	Determination coefficient	Variances of residues	Estimated value of the Fisher criterion	Table value of the Fisher criterion
Y=0.319+4.33·10^{-4}·X	0,96	0.004	244.5	2.2

Table 5

Regression analysis of the dependence of diameter of ball wear during friction on the load on friction machine FBM in the presence of lubricating composition No3.

Output variables of experiment function, mm											
1	2	3	4	5	6	7	8	9	10	11	12
0.48	0.55	0.6	0.66	0.77	0.82	0.87	1.23	1.26	1.31	1.37	1.51
±0.01	+0.007 -0.003	+0.003 -0.007	+0.013 -0.007	±0.01	±0.01	±0.01	+0.007 -0.013	+0.007 -0.013	±0.01	+0.013 -0.017	±0.01
Input variables of experiment factor, N											
1	2	3	4	5	6	7	8	9	10	11	12
200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000	2,200	2,400

Equation of regression of a change of function from the experiment factor, mm	Determination coefficient	Variances of residues	Estimated value of the Fisher criterion	Table value of the Fisher criterion
Y=0.312+4.93·10^{-4}·X	0,96	0.006	242.1	2.2

Table 6

Friction momentum M_{fr} (10^{-3} N·m) of different types of mated samples based on basic oil No. 1 and oil compositions No. 2, 3.

Junction type	Oil	Duration of testing, min.									
		10	20	30	40	50	60	70	80	90	100
I	No. 1	3.1±0.09	3.7±0.10	4.5±0.12	4.6±0.08	4.7±0.11	4.2±0.08	3.6±0.09	3.3±0.14	3.2±0.10	3.2±0.13
	No. 2	2.4±0.12	3.4±0.10	3.6±0.08	3.3±0.11	3.1±0.12	2.9±0.09	2.5±0.14	2.4±0.09	2.4±0.12	2.3±0.11
	No. 3	2.7±0.10	2.8±0.09	3.2±0.12	3.6±0.09	3.4±0.13	2.6±0.07	2.3±0.08	2.1±0.11	2.1±0.13	2.0±0.12
II	No. 1	3.5±0.09	3.7±0.12	3.8±0.09	4.0±0.12	4.3±0.08	4.1±0.11	3.8±0.12	3.5±0.10	3.3±0.12	2.9±0.14
	No. 2	2.4±0.11	3.1±0.10	3.3±0.12	3.6±0.09	3.7±0.11	3.4±0.12	3.1±0.10	3.0±0.14	2.9±0.08	2.9±0.12
	No. 3	2.5±0.09	3.3±0.12	3.5±0.08	3.7±0.11	3.8±0.12	3.7±0.09	3.5±0.10	3.3±0.08	3.2±0.11	3.2±0.08
III	No. 1	1.8±0.13	2.5±0.11	2.8±0.09	3.3±0.12	3.6±0.08	3.2±0.12	3.1±0.11	2.9±0.14	2.5±0.07	2.5±0.12
	No. 2	1.7±0.10	2.3±0.11	2.4±0.09	2.5±0.10	2.3±0.08	2.2±0.12	2.2±0.11	2.2±0.08	2.2±0.12	2.2±0.11
	No. 3	1.9±0.12	2.5±0.09	2.6±0.11	2.7±0.12	2.9±0.11	2.5±0.13	2.4±0.09	2.3±0.10	2.3±0.09	2.2±0.02
IV	No. 1	3.6±0.14	4.8±0.12	4.9±0.09	4.9±0.11	4.7±0.08	4.5±0.14	4.2±0.10	3.6±0.13	3.2±0.11	3.2±0.11
	No. 2	2.4±0.10	2.6±0.15	2.7±0.11	3.2±0.09	3.8±0.12	3.9±0.11	3.4±0.13	3.1±0.09	2.8±0.08	2.8±0.08
	No. 3	2.8±0.09	2.9±0.12	3.1±0.07	3.5±0.12	4.1±0.07	4.2±0.10	4.3±0.08	4.0±0.12	3.2±0.12	3.0±0.09

Table 7

Wear intensities I_u (10^{-9}) of different types of mated samples on basic oil No. 1 and oil compositions No. 2, 3

Type of junction	Oil	Duration of testing, min									
		10	20	30	40	50	60	70	80	90	100
I	No. 1	0.12±0.01	0.36±0.02	0.48±0.04	0.49±0.03	0.51±0.01	0.47±0.02	0.45±0.03	0.43±0.02	0.42±0.03	0.42±0.01
	No. 2	0.15±0.01	0.18±0.02	0.24±0.04	0.19±0.03	0.17±0.01	0.14±0.02	0.13±0.03	0.12±0.02	0.11±0.01	0.11±0.02
	No. 3	0.13±0.02	0.24±0.01	0.25±0.03	0.26±0.02	0.23±0.04	0.21±0.01	0.15±0.02	0.14±0.03	0.14±0.03	0.14±0.01
II	No. 1	0.24±0.02	0.36±0.01	0.48±0.03	0.60±0.03	0.68±0.04	0.7±0.05	0.73±0.04	0.69±0.06	0.68±0.04	0.68±0.03
	No. 2	0.13±0.01	0.24±0.03	0.27±0.02	0.36±0.04	0.39±0.03	0.48±0.01	0.49±0.02	0.51±0.02	0.51±0.03	0.51±0.02
	No. 3	0.15±0.02	0.27±0.01	0.28±0.03	0.34±0.05	0.42±0.02	0.53±0.01	0.56±0.02	0.55±0.01	0.54±0.03	0.53±0.02
III	No. 1	0.36±0.01	0.49±0.02	0.72±0.03	0.68±0.04	0.65±0.01	0.64±0.03	0.63±0.05	0.62±0.02	0.62±0.03	0.62±0.04
	No. 2	0.21±0.01	0.25±0.02	0.36±0.03	0.14±0.02	0.12±0.04	0.11±0.05	0.11±0.03	0.11±0.02	0.11±0.03	0.11±0.04
	No. 3	0.25±0.04	0.27±0.03	0.38±0.02	0.28±0.01	0.26±0.02	0.24±0.01	0.22±0.04	0.21±0.01	0.18±0.03	0.16±0.02
IV	No. 1	0.18±0.02	0.45±0.03	0.61±0.05	0.72±0.02	0.76±0.03	0.84±0.04	0.83±0.03	0.81±0.04	0.78±0.01	0.75±0.03
	No. 2	0.20±0.03	0.48±0.04	0.60±0.01	0.64±0.03	0.72±0.02	0.64±0.04	0.62±0.03	0.60±0.01	0.58±0.03	0.51±0.04
	No. 3	0.27±0.05	0.44±0.03	0.51±0.02	0.62±0.04	0.73±0.05	0.74±0.06	0.73±0.04	0.71±0.02	0.62±0.04	0.61±0.03

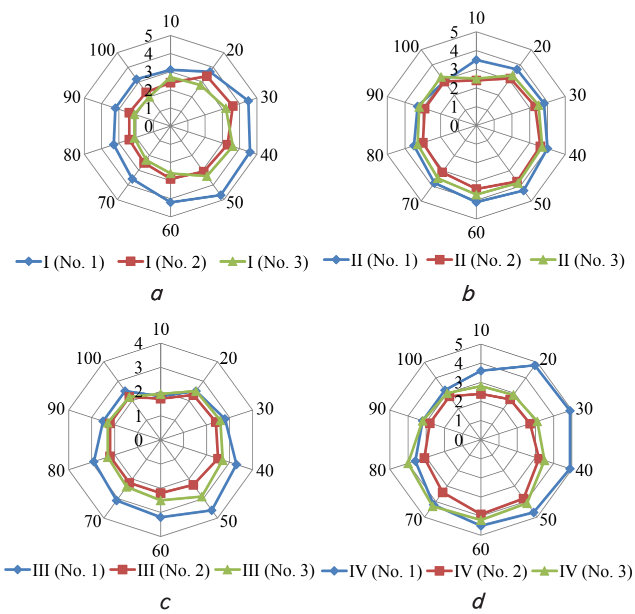

Fig. 5. Regularities of change in energetic component of the friction process of tribojunction by friction momentum M_{fr} (10^{-3} N·m) in different types of the mated experimental samples (materials of samples C61900 (HB95) and A48-25BC1.25BNo. 25 (HRC40)) over time: *a* – type I; *b* – type II; *c* – type III; *d* – type IV

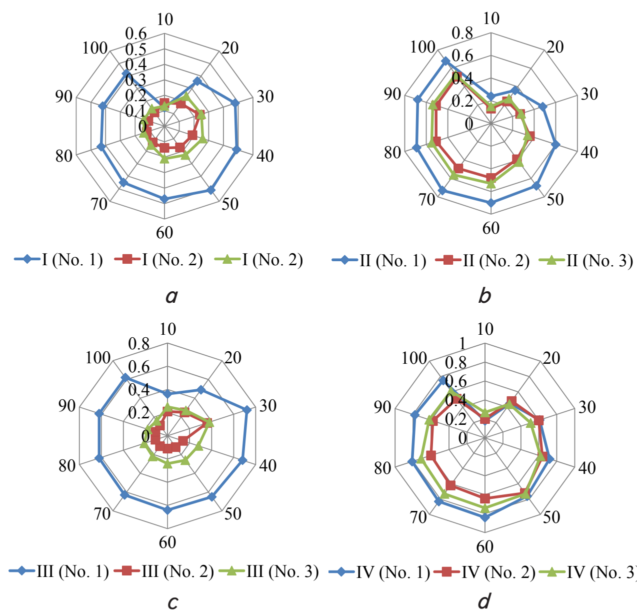

Fig. 6. Regularities of change in material consumption component of friction process in tribojunction at wear intensities I_u (10^{-9}) in different types of the mated experimental samples (materials of samples C61900 (HB95) and A48-25BC1.25BNo. 25 (HRC40)): *a* – type I; *b* – type II; *c* – type III; *d* – type IV

The regularities of changing in wear intensity and friction momentum in the junction of parts of different types make it possible to identify the main advantages and disadvantages of using geomodifiers in comparison with the production analog.

6. Discussion of results of studying a change in the tribological properties of mated parts of different types with the geomodifier KGMF-1

The conducted testing of the lubricating ability of the studied oils on the four-ball friction machine FBM (Table 1) revealed that the composite oils No. 2, 3 show the best tribological results compared to basic oil No. 1. In the case of using composite oils, wear indicator decreased, while the value of critical load and welding load increased. It was found that composite oil No. 2 showed the best result compared to the basic oil: the wear indicator decreased by 11.5...14.3 %, and critical load increased by 17.2 %. The anti-scruff properties, which are determined by welding load, increased by 19.3 %. This is explained by the fact that geomodifier KGMF-1 contributes to an increase in lubrication ability of composite oil. This is possible due to the fact that its particles in oil on the surface of the ball samples perform an additional function of solid lubrication. Oleic acid in the tribological contact reacts to contact interaction of materials due to an increase in tribo-electrization of the local contact areas.

Improved tribological properties of composite oils No. 2, 3 in comparison with basic oil No. 1 may be observed in Fig. 4. This is evidenced by the curves of a change in the diameter of the wear spots of the lower balls with an increase in applied load on the FBM. It was found that most additives, such as XADO HighWay for Diesel Truck; KGMF-1 and oleic acid (Fig. 4) increase welding load. Thus, when adding such additives to the basic oil, one will observe an increase in the anti-scruff properties of the oil medium in comparison with the basic oil. In addition, all of the above listed additives increase the value of critical load, which characterizes the range of operation of anti-wear additives. In general, the proposed additive KGMF-1+oleic acid is similar to additive XADO HighWay for Diesel Truck by anti-scruff properties, but provides the efficiency of operation of composite oil which is by 4.7...5.8 % higher by critical load (Table 2).

The studies revealed that an increase in effectiveness of lubricating ability of the basic and composite oils can be represented by the following range: Monnol TS-5 UHPD 10W40, Monnol TS-5 UHPD 10W40+XADO HighWay for Diesel Truck, Monnol TS-5 UHPD 10W40+KGMF-1+oleic acid. In addition, the obtained results require subsequent determining of the tribotechnical characteristics of mated samples in the media of basic oil No. 1 and composite oils No. 2, 3.

It was discovered that the wear process changes on composite oil in medium No. 1 with the addition of geomodifier KGMF-1+oleic acid. Friction momentum in different types of mated samples from materials C61900-A48-25BC1.25BNo. 25 have values that are by 5...57 % lower compared with the basic oil (Fig. 5, 6) for different types of junctions, which may indicate the best energy indicators of tribojunctions of parts during the operation. It was determined that the use of composite oil No. 2 reduces wear intensity by 3.4...4.1 times for mated samples of type I (Fig. 6); by 3...1.8 times for mated samples of type II (Fig. 6) and type IV (Fig. 6), respectively; by 5.0...6.0 times for mated samples of type III (Fig. 6).

This nature of a change in the wear process is explained by the fact that microparticles of geomodifier KGMF-1 charge into the soft surface of sample, Fig. 7.

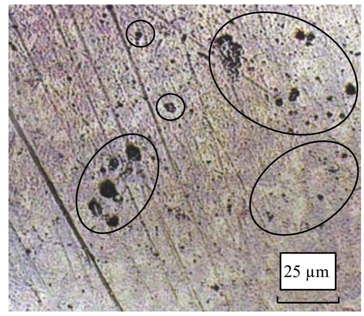

Fig. 7. Inclusion of microparticles into surface of sample from material A48-25BC1.25BNo. 25 (HRC40)

The corresponding results may be observed in determining the impact of the geomodifier on the physical-chemical parameters of the oils and samples during testing [9]. As the microparticles of the geomodifier KGMF-1 have a significant content of serpentine, oleic acid forms the ability to hold and deliver these particles to the friction surface under the influence of tribo-electrization. When the process of charging is completed, the magnitude of friction momentum decreases. Further development of this process corresponds to a change in friction momentum relative to the basic oil but with a lower magnitude. The wear intensity of mated samples during the operation on basic oil and composite oil with KGMF-1 differs dramatically. This requires additional study of the patterns of formation of protective coatings on the working surfaces of movable mated samples and parts.

Based on the results of tribotechnical characteristics, using the geomodifier KGMF-1+oleic acid in oil, it is possible to develop the technology of formation of functional additives, where special attention should be paid to the process of crushing their fractions to prevent the sedimentation process. The use of geomodifiers is a promising direction for the operation of heavy-loaded mated parts of machines.

7. Conclusions

1. Studying the lubricating ability of the basic and composite oils Monnol TS-5 UHPD 10W40+KGMF-1+oleic acid, Monnol TS-5 UHPD 10W40+XADO HighWay for Diesel Truck on materials C61900 - A48-25BC1.25BNo. 25 revealed their positive effect in comparison with basic oil Monnol TS-5 UHPD 10W40. This is proved by the enhancement of such characteristics as welding load and critical load, as well as the nature of dependence of the diameter of spots of wear of lower FBM balls on the load applied to them. These composite oils can be used to increase wear resistance of tribojunction of machine parts.

2. It was found that among the studied oils Monnol TS-5 UHPD 10W40+KGMF-1+oleic acid, Monnol TS-5

UHPD 10W40+XADO HighWay for Diesel Truck, composite oil with geomodifier KGMF-1+oleic acid demonstrated the best result in comparison with the basic oil: wear indicator decreased by 11.5...14.3 %, and critical load increased by 17.2 %. The anti-scruff properties, which are determined by welding load, increased by 19.3 %.

3. It was determined that the patterns of changing friction momentum and wear intensity of the samples over time of testing on the friction machine 2070 CMT-1 depend both on their material, type of junction and the lubricating medium. When geomodifier KGMF-1+oleic acid is used in basic oil Monnol TS-5 UHPD 10W40, friction momentum decreases on the mated samples from materials C61900-A48-25BC1.25BNo. 25 by 5...57 %, compared to the basic oil. In addition, it was determined that wear intensity decreases by 3.4...6.0 times for the mated samples of type I and type III, and by 1.3...1.8 times for the mated samples of type II and type IV.

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