



Lubricating effect of oils by controlling the concentration of chemical components of the additives

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Abstract

A proposed and substantiated multifactorial approach to assessing the lubricating effect of oils, considering the influence of physicochemical factors and rheological characteristics on the evolution of the creation and adaptation of chemically modified boundary layers (CMBLs) to real operating conditions in conditions of the partial EHD lubrication mode. Comparing the results of the anti-wear and anti-friction properties of the studied oil samples, while complying with the additive manufacturer's conditions for the mass fraction of sulfur, which is 1.488–1.9662%, a necessary condition for the best results in terms of the combined action of the anti-wear and anti-friction properties of the oils is to establish a total additive concentration of 3.9–4.9% with a phosphorus mass fraction of 0.046–0.057%. In the series of samples studied, *sample 4* with a concentration of 4.9% additive shows the best universal properties, especially for the operation of units with combined engine and transmission systems (universal STOU oils for agricultural machinery).

Key words: the lubricating effect of oils, physicochemical factors and rheological characteristics, chemically modified boundary layers (CMBLs), the partial EHD lubrication mode, the anti-wear and anti-friction properties, the concentration of chemical components of the additives, chemically active substances (CAS), manganese-iron-phosphate coating (MIP).

Introduction. Analysis of recent research and publications

Improving the reliability and energy efficiency of machines and vehicles is directly related to the intensity of friction and wear processes in friction units. According to international tribological reviews [1–3], up to 25–30% of energy losses in technical systems are due to friction processes, and more than 40% of equipment failures are tribological in nature. In this context, the improvement of lubricants (oils) as one of the most cost-effective means of reducing energy consumption due to friction and wear in machines is of particular importance.

Modern oils for various technical purposes are produced on the basis of compounding base stocks and multi-component additive packages that provide the main operational properties: anti-friction, anti-wear, anti-seize, antioxidant, anti-corrosion properties, etc. At the same time, research results from leading global additive manufacturers such as Afton Chemical (USA), Lubrizol (USA), BASF (Germany), indicate that the effectiveness of the respective additive packages is determined not only by their qualitative properties, but primarily by the quantitative properties (concentration) of active chemical components or chemically active substances (CAS), which are often in the range of hundredths and thousandths of a percent. The technical regulations of these companies indicate that exceeding or underestimating the concentration of anti-wear and anti-friction CAR at the level of 0.01–0.05% of the mass fraction may lead to a significant reduction in the protective properties of the modified layer, which are formed as a result of chemical modification of contact surfaces during friction, an increase in the intensity of wear up to the rupture of the lubricating layer [1–3].

Recent experimental studies published in renowned international journals included in the Scopus and Web of Science scient metric databases indicate that the concentration of active chemical components in additives plays a critical role in the formation of strong and stable chemically modified boundary layers (CMBLs).

In particular, study [4] found that adding titanium oxide (TiO₂) nanoparticles to motor oil at a concentration of 0.01–0.075% by mass reduces the friction coefficient from 0.112 to 0.05, i.e., by more than 55%, and at the optimal value of 0.075% — to a level of about 0.01, which corresponds to a reduction in friction of almost 90%



relative to the base oil without additives. With a further increase in the concentration of the additive, the reduction in the friction coefficient stabilizes or even increases, indicating the presence of a narrow optimal range. Similar patterns were also obtained for copper and iron oxides.

Studies [5] have shown that the use of copper oxide (CuO) nanoparticles at a concentration of 0.25% by mass reduces the friction coefficient by 11–54% and the wear intensity by 30–45% compared to the base oil without additives. At the same time, at concentrations above 1.0–1.3%, the reduction in the friction coefficient and wear intensity not only does not increase, but in some cases is accompanied by a deterioration in colloidal stability and an increase in contact wear due to particle agglomeration. Similar results were obtained for hybrid nanodispersed systems (CuO–TiO₂), where the optimal concentration range was within 0.05–0.15% by mass to ensure a 35–60% reduction in the friction coefficient and a 40–55% reduction in linear wear.

These results are consistent with the technical regulations of Afton Chemical and Lubrizol [1,2], which state that the optimal concentration of phosphorus- and sulfur-containing anti-wear additives within ± 0.01 – 0.02% allows for a simultaneous reduction in wear by 20–35% in internal combustion engines (ICE).

Outline of unresolved issues

From an economic point of view, the problem of optimal additive formulation is no less significant. According to industry reviews, the cost of functional additive packages can be up to 40–60% of the cost of commercial oil, while their mass fraction exceeds 3–7%. At the same time, even a 0.1% reduction in the concentration of active components without loss of performance properties can reduce the cost of lubricant production by 5–8%, which, on a mass production scale, corresponds to a significant economic effect. In addition, a 30–50% reduction in friction wear, as reported in [4, 5], correlates with a 15–25% increase in machine maintenance intervals, thereby significantly improving the technical and economic efficiency of vehicle and industrial system operation.

Thus, an analysis of current scientific publications and technical regulations of leading additive manufacturers convincingly demonstrates that the lubricating effect of oils is determined not by the absolute amount of additives introduced, but by the precision of controlling the concentration of active chemical components, with a narrow range of hundredths and thousandths of a percent.

At the same time, most modern studies devoted to optimizing the qualitative and quantitative composition of chemical components of additives are carried out empirically without taking into account the mechanism of evolution of CMBLs formation under real friction conditions, thus limiting the possibilities of scientifically based forecasting of the resource and lubricating efficiency of oils. In this regard, it is important to develop a method for controlling the concentration of active chemical components of additives based on experimentally established patterns of the evolution of modified layers and changes in the friction coefficient in the contact zone under real operating conditions.

In addition, by solving the problem of increasing the lubricating effect of oils by controlling the concentration of active chemical components of additives, both from a scientific and applied point of view, the results obtained create the prerequisites for the development of energy-saving lubricating compositions with specified tribological properties that ensure a simultaneous reduction in friction losses, increased machine life, and optimized costs for expensive functional additives, which must correspond to current trends in sustainable development, energy conservation, and increased competitiveness of automotive and machine-building products.

Taking into account the multifactorial nature of the task of improving the lubricating effect of oils, it was necessary to use a comprehensive approach to assess the main tribological patterns and changes in tribotechnical characteristics—the evolution of the thickness of the modified layer and changes in the friction coefficient at all stages of real-time friction and wear processes depending on the mileage (friction path) according to the physicochemical factor.

Problem statement

An important role in the experimental study is the analysis of the qualitative and quantitative composition of active chemical components in the lubricant to improve the lubricating effect of oils by adapting the modified layers to the real operating conditions. Chemically active substances (CAS) create strong and stable CMBLs under high temperature conditions through chemical interaction and exchange of valence electrons of metal surface atoms with lubricant components in the form of metal salts: sulfides, phosphides, chlorides, and other compounds to increase anti-wear, anti-scuffing, and anti-friction characteristics.

Therefore, when analyzing the beneficial effect of CAS, it became necessary to study the analysis of CAS concentration and develop scientific and applied methods for improving the lubricating effect of oils for conditions as close as possible to the actual operating conditions of non-conforming friction units.

To conduct the relevant comprehensive experimental studies, it was necessary to use modern, specialized, and high precision tribotechnical equipment with simulation of the operation of bearing friction units of various classes in real operating conditions in two stages:

- 1) The first stage involved determining the presence of active chemical elements and measuring the concentration of the additives under study in neutral base oil using an energy-dispersive X-ray fluorescence spectrometer (EDXRF);

2) The second stage involved determining the best sample from the list of additives studied in neutral base oil by measuring the thickness of the formed modified layer or linear wear by the depth of the wear impression of the counterbody (anti-wear properties) and the friction coefficient (anti-friction properties) for a specified mileage on a CSM tribometer.

Method for determining the concentration of active chemical components of additives in EDXRF

A mixture of BS150 hydrocracked base oil and SN500 petroleum-based base oil (hereinafter referred to as “base oil”) was used as a neutral oil. Subsequently, using the compounding method based on base oil, five samples of mixtures were produced containing the studied tribo-package of additives, which contains active chemical elements of sulfur and phosphorus in various concentrations, which are used in modern transmission oils for lubricating transmission components and universal (engine-transmission) oils for lubricating combined engine and transmission systems of military and agricultural equipment.

Neutral base oil was used as a sample in its pure form without additives to compare its results with other mixtures under study.

The sample preparation method was as follows:

- in the first stage, a tribo-package of additives was added in various concentrations to neutral base oil;
- the finished mixture was kept at a temperature of 70°C with constant stirring using a laboratory vibrating mixer, after which a sample of the appropriate concentration was obtained (see Fig. 1).

The program of comprehensive laboratory studies included:

- 1) conducting a series of measurements:
 - the presence of active chemical elements and the concentration of test samples on EDXRF (mass fraction of sulfur and phosphorus in percent);
 - conducting a physicochemical analysis to measure kinematic viscosity at 40°C and 100°C, viscosity index, and density at 20°C;
 - thickness of the modified layer (depth of linear wear mark) from the mileage of test samples on a tribometer.
 - coefficient of friction from the mileage of test samples on a tribometer.
- 2) establishing the following dependencies:
 - changes in the thickness of the modified layer (depth of linear wear impression) from the mileage of test samples at different concentrations.
 - changes in the friction coefficient from the mileage of test samples at different concentrations.



Fig. 1. General view of the laboratory vibration mixer

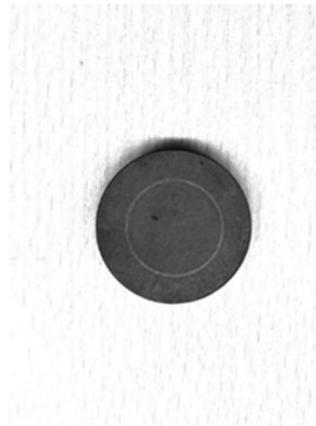


Fig. 2. Friction pair indenter with manganese-iron-phosphate coating

To simulate the operating conditions of friction bearing assemblies of various classes, the following tribotechnical pairs were proposed: as a counterbody — a 6 mm diameter ball made of SHX-15 steel (AISI E 52100, HRC 67, roughness class 10b); as an indenter — 25 mm diameter disc made of SHKH-15 steel coated with manganese-iron-phosphate salt (roughness class 10a), see Fig. 2. The test was conducted at a temperature of 70°C, humidity of 75%, linear speed of 8.5 cm/s, maximum load of 50N, with a total mileage of up to 2,000 m.

Manganese-iron-phosphate coating (MIP) belongs to the class of conversion chemical coatings, which are formed directly on the metal surface as a result of chemical interaction with phosphate solutions. The resulting phosphate layer is a complex microcrystalline structure containing manganese and iron phosphates and characterized by high adhesion to the base material. Such coatings are widely used in mechanical engineering as a tribomodifying material that improves the running-in of contact friction surfaces and in tribology as a means of improving the modification of the surface of hard alloys in the composition of the additives under study.

In tribological laboratory studies, MIP coatings are used as a model surface that allows reproducing the operating conditions of real friction units, in particular in bearing friction units or in non-conforming units of the

cylinder-piston group of an ICE. The use of such a coating as a sample for a tribometer ensures the reproducibility of test results and the stability of the initial surface condition, which is of fundamental importance in the comparative analysis of the studied samples of additives dispersed in neutral base oils and in the study of the influence of the chemical composition of oils on the tribological characteristics of contact.

The use of MIP coating on the inner walls of internal combustion engine cylinders is associated with the need to improve the tribological conditions of the cylinder-piston group, especially during engine start-up and running-in. Under these conditions, boundary and mixed (partial the EHD) lubrication modes are mainly implemented, in which the efficiency of the unit is largely determined by the condition of the surface and its ability to interact with oils. The phosphate MIP coating formed on the inner surfaces of the cylinders creates a microcrystalline layer with a developed porous structure, which helps to retain oil and stabilize friction processes between the cylinder surface and compression piston rings.

From the point of view of interpreting the experimental results, the use of MIP coating reduces the influence of random factors associated with the microstructural heterogeneity of the metal surface. Thus, the main focus is on studying the lubricating properties of oils, taking into account the physicochemical factor influencing the creation of CMBLs, rather than on the random characteristics of the sample material. This is especially important when conducting serial experiments and statistical processing of the obtained data. EDXRF is one of the widely used methods of physical and chemical analysis of materials, based on the registration of characteristic X-ray radiation of atoms of the substance under study. The method allows determining the elemental composition of materials in a wide range of concentrations without significant destruction of the sample, which makes it particularly suitable for analyzing surface layers, coatings, and wear products [6]. In tribological studies, XRF is used for qualitative and quantitative assessment of the elemental composition of modified surfaces, protective films, friction and wear products, as well as for analyzing the distribution of active chemical components in the surface layers of materials. This allows establishing a connection between friction conditions, lubricant composition, and structural and chemical changes in the surface.

A typical energy-dispersive X-ray fluorescence spectrometer design includes a primary X-ray source, a beam shaping and collimation system, a sample chamber, a characteristic radiation detector, and a signal processing system. An X-ray tube with an anode made of molybdenum, rhodium, or silver is usually used as the primary radiation source, the choice of which is determined by the range of elements being analyzed [6]. The detector in modern XRF spectrometers is a semiconductor detector (Si-PIN or SDD), which provides high energy resolution and allows spectra to be recorded with sufficient accuracy even for elements with close energy lines. Signals from the detector are transmitted to a multichannel analyzer, where the energy spectrum of X-ray radiation is formed.

EDXRF method is particularly valuable when analyzing surfaces that have been subjected to tribological influences. During friction, secondary structures, modified tribochemical layers, and wear products can form on surfaces, the composition of which directly affects the thickness of the modified layer, the intensity of wear, and the friction coefficient. The use of EDXRF allows the identification of the elements that make up such films and the evaluation of their relative quantitative composition (concentration) [7]. The method is particularly effective for analyzing CAS added to lubricants in the form of additives, such as zinc, phosphorus, sulfur, calcium, or molybdenum. The detection and quantitative assessment of these elements in the surface layers after friction tests allows conclusions to be drawn about the mechanisms of formation of protective modified layers and the effectiveness of controlling the concentration of active components.

To perform elemental analysis of surfaces after tribological tests, this work uses an ElvaX Light energy-dispersive X-ray fluorescence spectrometer (see Fig. 3), which belongs to the class of universal laboratory EDXRF systems. The device is designed for qualitative and quantitative determination of the elemental composition of solid, powdery, and liquid materials, as well as surface deposits and modified layers. A distinctive feature of ElvaX Light is the combination of a compact design with sufficiently high sensitivity to elements of a wide periodic range. This makes it suitable for use in materials science and tribological research, where it is necessary to analyze both the main elements of the sample material and the active components of lubricant additives involved in the formation of tribochemical films.



Fig. 3. General view of the ElvaX Light EDXRF spectrometer

Methodology for determining the anti-wear and anti-friction properties of oils from mileage on the CSM tribometer

Determining anti-wear properties (modified layer thickness and linear wear) is one of the key stages in a comprehensive assessment of the physical and chemical factors influencing the formation/wear of modified layers and their wear resistance. In laboratory conditions, such studies are carried out using high precision tribometric devices, in particular CSM tribometers, which provide controlled friction conditions and the ability to continuously record process parameters [8].

The CSM tribometer (see Fig. 4) is used in this study and is designed to perform tests in rolling with slippage, sliding, and reciprocating motion modes according to the “ball-disc” or “pin-disc” schemes. The device allows you to set the normal load, sliding speed, displacement amplitude, and total mileage, which ensures the reproducibility of experimental conditions. The high rigidity of the structure and the accuracy of the measuring sensors ensure the correct recording of both force and geometric wear parameters [9].

The reciprocating motion module (see Fig. 5) is used to simulate model tests close to real operating conditions, where it is necessary to reproduce rolling friction with slippage or sliding according to kinematic characteristics, which are typical for bearing friction assemblies of various classes.

Main characteristics of the module:

- Maximum torque: 450 N·mm;
- Maximum load 50 N;
- Frequency: from 0.005 to 1.6 Hz (1.6 Hz over the entire stroke length, up to 10 Hz possible with limited stroke length);

- Linear speed range: from 0.3 to 100 mm/sec;

- Working stroke: up to 60 mm;

- Test time: up to 40 days with 10 Hz data acquisition sampling.

Main characteristics of the module:

- Heating up to 120°C

- Indenter sample size, diameter - 25 mm;

- The heating module uses liquid to heat the sample when testing in the presence of oil;

- The external electronic unit guarantees temperature control accuracy of 0.1°C.

The heating module (see Fig. 6) allows you to select a convenient intermediate solution for the temperature factor (selected temperatures - up to 120°C, which are characteristic of the maximum temperatures of bearing friction units and non-conforming internal combustion engine units). The typical configuration of the CSM tribometer (see Fig. 7) includes a movable plate or sample (indenter) that performs linear or rotational movement relative to another contacting element of the counterbody (ball or pin). The system is equipped with high-precision force sensors that allow recording changes in friction force during testing, as well as recording the thickness or wear parameters of both contacting surfaces. In configurations with linear movement, the device measures the formation of a modified layer in terms of thickness or linear wear in terms of depth of contact surfaces under load and movement, simulating conditions of prolonged friction in real time at specified parameters of high loads and shear rates up to $10^6 \cdot s^{-1}$ for the studied oil samples with different viscosity stability (rheology) and physicochemical properties [10]. During measurement on a tribometer (see Fig. 8), the counterbody (ball) is fixed in the holder and immersed in a steel bowl filled with the oil sample under test, pressing down on the movable indenter (a disc coated with MIP) with a specified contact load. The indenter is fixed on a spring lever and connected to an LVDT inductive sensor. During the rotation of the indenter, a frictional force arises between it and the counterbody, which is measured by the minimum deflection of the spring lever in the vertical and tangential directions by the LVDT sensor.



Fig. 4. The CSM tribometer diagram: 1 - Tribometer; 2 - Reciprocating motion module; 3 - Protective cover; 4 - Heating module

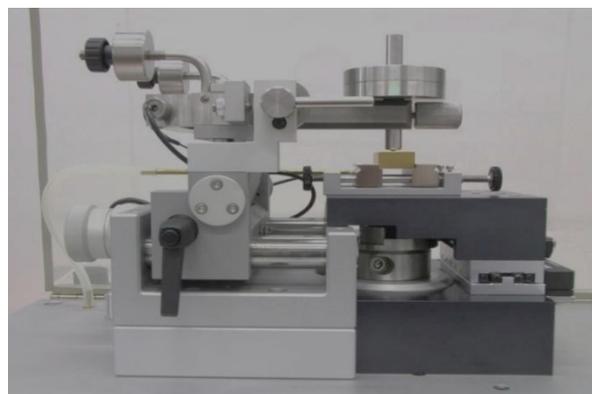


Fig. 5. Reciprocating motion module of the CSM tribometer

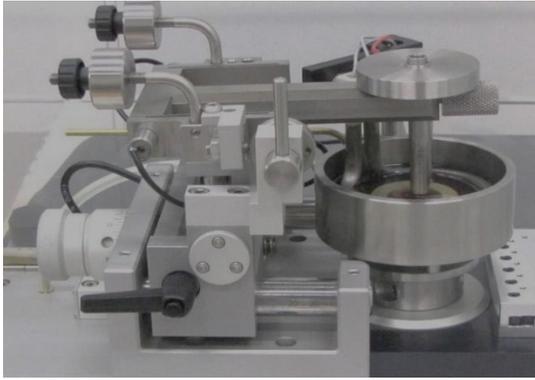


Fig. 6. The CSM tribometer heating module

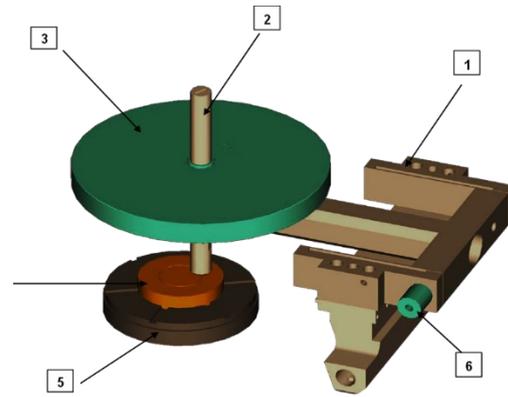


Fig. 7. Typical measurement diagram on the reciprocating motion module of the CSM tribometer: 1 - Elastic lever; 2 - Counterbody holder (ball or pin); 3 - Load; 4 - Indenter (disc with MIP coating); 5 - Indenter mounting chuck; 6 - LVDT micro-displacement sensor

As the mileage of the contacting surfaces increases, material is gradually formed/removed, accompanied by a change in the position of the contact pair depending on whether a modified layer is being formed, whether the corresponding modified layers are wearing out, or whether the surface layers of the metal are wearing out. These changes are recorded by a highly sensitive LVDT displacement sensor, which allows the total amount of modified layer thickness formation or linear wear to be determined with high accuracy depending on the mileage, which in our study is $L = 2000$ m. The obtained dependence of the thickness of the modified layer/linear wear on the mileage, taken from the vertical displacements of the LVDT sensor, allows us to evaluate the anti-wear properties of the studied oil samples, taking into account the physicochemical factor for the conditions of partial EHD contact in real-time testing. At the initial stages of the test, the modified layer is modified and adapted if the wear curve increases and stabilizes, and linear wear occurs if the wear curve decreases relative to the initial position, indicating a transition to wear of the base material. Thus, the nature of the change in thickness/linear wear from mileage allows determining the effective thickness of the modified layer, taking into account the rheological properties and physicochemical factors of the studied oil samples [10].

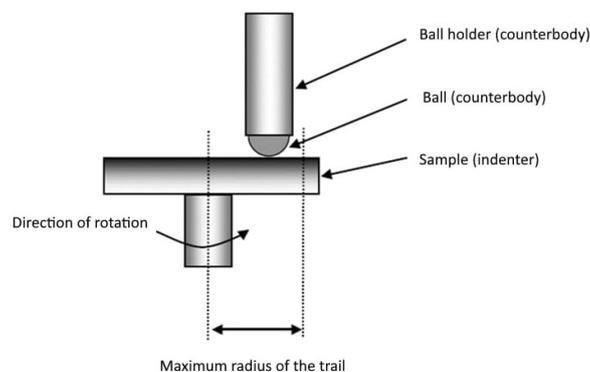


Fig. 8. Diagram of the position of the tribo-pair (indenter + counterbody) when taking measurements on the CSM tribometer

The anti-friction properties (friction force or coefficient) of the oil samples studied are one of the main tribological parameters characterizing the interaction of contacting surfaces during relative motion in the tangential direction. In tribological systems, the friction coefficient is defined as the ratio of friction force to applied normal load and allows quantitative assessment of the strength of the lubricating film, anti-friction properties of oils, and lubrication conditions. Determining the dependence of the friction coefficient on mileage is an important step in analyzing the behavior of a contact pair during running-in, wear-in, and subsequent stable operation.

On the CSM tribometer, the friction coefficient is determined in real-time friction force recording mode during testing. The design of the device includes an LVDT inductive sensor that records the tangential component of the force, including in the tangential direction, which characterizes the friction force. The normal load is set separately and maintained at a constant level throughout the test cycle. The ratio of the measured friction force to the normal load is used to calculate the instantaneous value of the friction coefficient. The dependence of the friction coefficient on mileage is usually analyzed in the form of a graphical curve $\mu(L)$, where L is the friction path or mileage of the contact pair. At the initial stage of the test, which corresponds to the run-in period, unstable

behavior of the friction coefficient is observed, which is due to the adaptation of the modified layers, smoothing of micro-irregularities, and the formation of the contact friction zone. During this period, both increased and decreased friction coefficient values are possible, depending on the surface condition and the presence of modified layers. A further increase in mileage is usually accompanied by the transition of the system to a steady-state friction mode, which is characterized by a relative stabilization of the friction coefficient values. In this mode, changes in the friction coefficient from mileage are insignificant and reflect the stable nature of the tribological system. The friction coefficient value in the steady state is often used for comparative evaluation of different olive samples under study, taking into account rheological properties and physicochemical factors, as it is less sensitive to random factors and the initial surface condition.

Analysis of the dependence of the friction coefficient on mileage on the CSM tribometer also allows identifying possible changes in the lubrication regime during the test, which is especially important for the partial EHD lubrication regime, which is a borderline lubrication regime from EHD to the limit in mixed friction and proceeds spontaneously. An increase or sharp fluctuation in the friction coefficient values may indicate the destruction of protective or modified layers, a change in lubrication conditions, or the appearance of lubricant layer breaks. At the same time, a decrease in the friction coefficient may be associated with the formation of strong and stabilized CMBLs in the sensitive zone of partial EHD contact.

The experimental data obtained on the friction coefficient are analyzed simultaneously with the results of measuring the thickness of the modified layer/linear wear. This approach allows for a comprehensive assessment of the tribological behavior of the contact pair, since the friction coefficient reflects the energy characteristics of the friction process, while the thickness/linear wear characterizes the geometric consequences of the tribological system's operation. A joint analysis of these parameters provides a more complete picture of the lubricating mechanisms of oils and wear processes under the influence of modification by CAS and the rheology of the samples under study.

Thus, the use of the CSM tribometer to determine anti-wear properties (modified layer thickness and linear wear) and anti-friction properties (friction coefficient) ensures high reliability and accuracy of experimental studies and allows for a comprehensive assessment of the lubricating effect of oils, taking into account the rheological properties and physicochemical factors of the studied oil samples in sensitive areas of partial EHD contact.

Results of the assessment of the anti-wear properties of the studied oil samples

The graphical interpretation of the results of the anti-wear properties of the studied oil samples was compiled into a single graph (see Fig. 9).

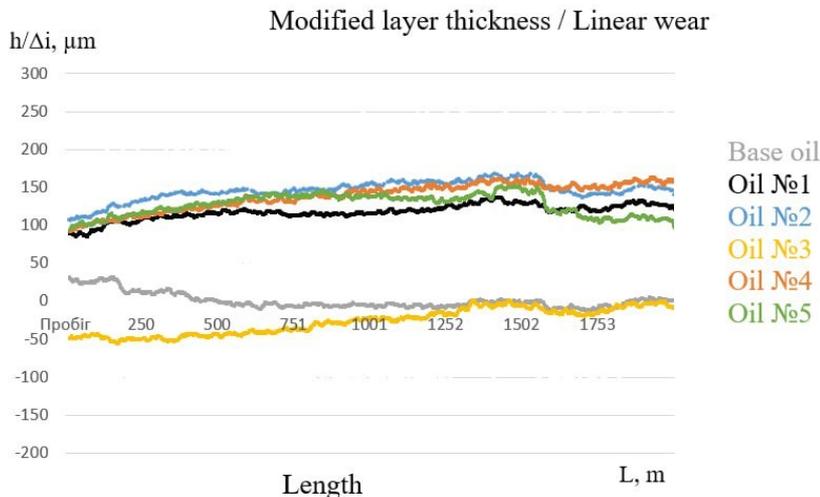


Fig. 9. Anti-wear properties for all samples studied

The results of the combined analysis of the anti-wear properties (see Fig. 9) of the oil samples studied showed the following:

- base oil is characterized by the destruction of the lubricating layer until cracks appear, which is reflected as linear wear, where the depth of the wear mark h reaches negative values below zero throughout the entire run L ;

- sample 3 is characterized by the slow formation of modified layers with a predominance of intensifying wear friction processes, starting from negative values of linear wear. This is explained by the unexpressed anti-wear properties associated with an insufficient percentage (0.04%) of phosphorus mass fraction to ensure optimal anti-wear properties;

- unlike samples of base oil and 3, samples 1, 2, 4, and 5 are characterized by the formation and adaptation of modified layers with an average thickness of up to 30 μm at a maximum load of 50 N. Moreover, instantaneous

formation and adaptation of modified layers is observed during the running-in period, followed by an increase in the thickness of the modified layer, which lasts for approximately 1600 km of length;

– after 1600 m of length, for samples 1, 2, 4, 5, some stabilization is observed in the formation of the modified layer thickness, but with different thickness values. Samples 2 and 4 create thicker modified layers during the corresponding period.

Thus, after two periods: formation (running-in) and stabilization (adaptation) of the modified layer thickness, two best samples can be selected in terms of anti-wear properties: samples 2 and 4. Moreover, sample 2 adapts better in running-in conditions, forming and building up thicker modified layers during this period. Sample 4 is slightly inferior to sample 2 in terms of thickness during the running-in period, but during the stabilization period it retains the most negative value of the modified layer thickness, which indicates the ultra-high strength of the film during this period under all equal test conditions.

Based on the above analysis of the research results, to ensure optimal anti-wear properties, transmission and universal oils should contain a concentration of 0.046–0.057% by mass of phosphorus, which will allow the creation of strong CMBLs, quickly adapting to high loads during the running-in and stabilization period in the process of forming, building up, and wearing down modified layers.

Results of the evaluation of the anti-friction properties of the oil samples studied

A graphical interpretation of the results of the anti-friction properties of the studied oil samples was compiled into a single graph (see Fig. 10).

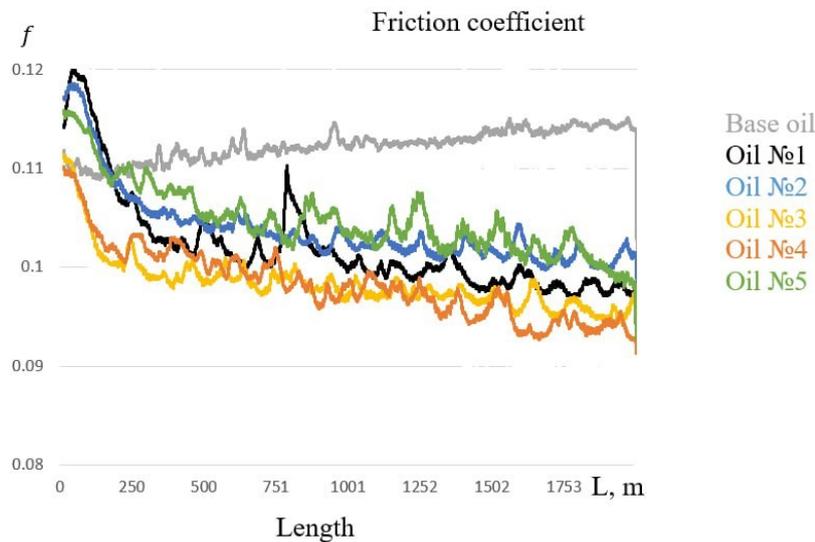


Fig. 10. Anti-friction properties for all samples studied

The results of the combined analysis of the anti-friction properties (see Fig. 10) of the oil samples studied showed the following:

– the base oil sample is characterized by an increase in the friction coefficient throughout the entire run, since the lubricating layers do not provide anti-friction properties in the absence of CMBLs;

– unlike the base oil sample, samples 1, 2, 3, 4, and 5 are characterized by an initial significant reduction in friction to 200 m of the test run by an average of 30%, and then after 200 m throughout the entire test run, by a gradual reduction in friction by an average of 10%;

– for the initial friction coefficient value during the running-in period and the stabilization period, samples 3 and 4 have the minimum value, which indicates pronounced anti-friction properties with a sulfur mass fraction in the range of 1.488-1.9662%, i.e., across the entire range of selected samples studied.

Thus, it can be stated that to ensure high anti-wear and anti-friction properties, it is not so much the mass fraction of sulfur, which must be within a certain range guaranteed by the manufacturer, that is important, but rather the mass fraction of phosphorus, which requires additional tribotechnical research.

Comparing the results of anti-wear (see Fig. 9) and anti-friction (see Fig. 10) properties of the studied oil samples, while complying with the additive manufacturer's conditions for the mass fraction of sulfur, which is: 1.488 - 1.9662%, a necessary condition for the best results in terms of the combined action of anti-wear and anti-friction properties of oils is to establish a total additive concentration of 3.9-4.9% with a mass fraction of phosphorus of 0.046-0.057%. In the series of samples studied, sample 4 with a concentration of 4.9% additive shows the best universal properties, especially for the operation of units with combined engine and transmission systems (universal STOU oils for agricultural machinery). The corresponding universal properties make it possible to modify friction surfaces with durable CMBLs for high load conditions and to adapt more quickly to extreme friction conditions when operating temperature and load conditions change significantly, for example, when

operating in the engine and transmission simultaneously.

Conclusion

A multifactorial approach to assessing the lubricating effect of oils has been proposed and justified, taking into account the influence of physicochemical factors and rheological characteristics on the evolution of the creation and adaptation of CMBLs to real operating conditions in conditions of partial EHD lubrication mode. The substantiated choice of modern spectral and tribometric equipment made it possible to comprehensively evaluate the tribological behavior of the contact pair, since the friction coefficient reflects the energy characteristics of the friction process, while thickness/linear wear characterizes the geometric consequences of the tribological system's operation. Thus, a joint analysis of these parameters provides a more complete understanding of the mechanisms of the lubricating action of oils and the wear processes under the influence of modification by CAS and the rheology of the studied samples.

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Міланенко О., Бобро А. Мазильна дія оливи шляхом керування концентрації хімічних компонентів присадок.

Запропоновано та обґрунтовано багатофакторний підхід щодо оцінки мазильної дії оливи з урахуванням впливу фізико-хімічного фактору та реологічної ознаки на еволюцію створення та адаптації хімічно модифікованих граничних шарів (ХМГШ) до реальних умов експлуатації в умовах часткового ЕГД режиму мащення. Порівнюючи результати протизношувальних і антифрикційних властивостей досліджуваних зразків оливи, при дотриманні умов виробника присадок щодо масової частки сірки, яка становить 1,488–1,9662%, необхідною умовою для досягнення найкращих результатів з точки зору комбінованої дії протизношувальних і антифрикційних властивостей оливи є встановлення загальної концентрації присадок в діапазоні 3,9–4,9% з масовою часткою фосфору 0,046–0,057%. Для досліджуваного ряду зразків, зразок 4 з концентрацією присадки 4,9% показує універсальні властивості, які особливо важливі при експлуатації в суміщених системах двигуна і трансмісії (універсальні оливи STOU для сільськогосподарської техніки).

Ключові слова: мазильна дія оливи, фізико-хімічний фактор та реологічна ознака, хімічно модифіковані граничні шари (ХМГШ), частковий ЕГД режим мащення, протизношувальні й антифрикційні властивості, концентрація хімічних компонентів присадок, хімічно активні речовини (ХАР), марганцево-залізо-фосфатне покриття (МЗФ).