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Multifactorial criterion evaluation of lubrication efficiency and wear resistance of friction units operating under extreme operating conditions

O. Milanenko[*] 0000-0002-8197-5277, **A. Bobro** 0009-0002-1193-117X

National Transport University, Kyiv, Ukraine
E-mail: milanmasla@gmail.com

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Abstract

A new multifactor criterial approach to modifying lubricants by rheological properties and chemical composition is proposed in order to increase the lubricating ability of modified layers and wear resistance of friction units from the position of mixed lubrication conditions. Prevention of micro-EHD lubricating layer is achieved by a set of measures: implementation of stable micro-EHD lubrication by the criterion of lubrication mode; optimal viscosity class with an increase in the fraction of hydrodynamic pressure of modified layers relative to the contact pressure from micro-unevenness of rough surfaces by the pressure criterion; optimal type of lubricant by the rheological criterion; assessment of the appearance of a plastically deformed state by the criterion of plasticity; selection of the qualitative and quantitative chemical composition of active components in the lubricant to create durable modified layers with high structural adaptability and thermomechanical stability by the temperature criterion. A new concept for increasing lubricity and wear resistance for friction units operating in extreme operating conditions, using an appropriate criteria approach, takes into account: non-stationary friction conditions, the shape of local contact and friction kinematics, rheological properties of lubricating layers, contact temperature, and the composition of components in the lubricant.

Key words: elastohydrodynamic lubrication, micro-EHD friction contact, film thickness**,** rheological properties, chemically active ingredients, surface-active ingredients, chemically modified boundary layers

Introduction. Analysis of recent research and publications

Most non-conformal assemblies with point or linear contact (friction bearing assemblies, gears, cams of the gas distribution mechanism, etc.) have limited areas of working surfaces. The contact load is applied to a relatively small area. These features of the contact form lead to contact fracture, which, unlike scoring, seizure, cavitation, and other types of damage, develops over time with the formation of crumbling (pitting) on the friction surfaces in the form of individual notches [1]. The initial size and shape of these pits depend on the material properties, nature and magnitude of stresses. During further operation of the assembly, their number increases, they merge and enlarge, and the fracture zone covers an increasingly large area of the surface. New stress concentrators appear, lubrication conditions and dynamic characteristics of the assembly deteriorate, the temperature rises, and a significant portion of the working surfaces lose their bearing capacity. Under conditions of a mixed lubrication regime in terms of speed and load and the material's tendency to wear, this process can slow down or even stop altogether. However, in heavily loaded bearing assemblies, high microhardness steels are used as indenter material - bearing balls made of the SHKH-15, which are poorly worked up, pitting becomes progressive, in most cases, the assembly fails prematurely [2]. Along with structural, technological, and operational factors, the root cause of such failure is the nature and level of stresses, which is influenced by the shape of the contact [3].

From the foregoing, it can be stated that the prediction of the durability of friction units operating under contact load conditions requires solving several important tasks, including

1. Depending on the calculated maximum normal and tangential loads, it is necessary to know the optimal form of contact with its equivalent mechanical properties, taking into account the position of the zones of frequent surface failure in depth and in the rolling direction, and to experimentally verify the obtained solution.
2. To take into account the influence of deformations of rolling surfaces when contact stresses change in the

process of friction.

3. Determine the necessary parameters of materials: reduced modulus of elasticity, microhardness, roughness of contact surfaces for specific friction units.

The theory of elastohydrodynamic (EHD) lubrication is used to explain the rheological and physicochemical effects of a lubricant [4, 5]. According to this theory, the thickness of the lubricating layer separating the surfaces of friction units is determined by the viscosity-pressure dependence of the lubricant. The contact of surface irregularities does not occur if it is possible to maintain a sufficient thickness of the lubricating layer - in this case, the EHD lubrication regime with long-term bearing life is ensured. If the thickness of the lubricating layer is reduced to the point where the micro-irregularities of the contact surfaces begin to touch, then as the frequency of contact increases, fatigue life will rapidly decrease. At present, there is no satisfactory explanation for how contact of surface micro-irregularities leads to fatigue damage.

The features of micro-EHD friction contact [6] are characterized by similar EHD conditions: the influence of elastic properties of the material and the characteristic dependence of viscosity on pressure and the influence of compressibility of the lubricant. However, for micro-EHD friction conditions, the influence of the mechanical properties of the surfaces (the magnitude and position of the localization of maximum tangential stresses at a certain depth) and the level of roughness of the contact surfaces is also important, since there are discrete areas of the contact pressure of the material that begin to reach the level of hydrodynamic pressure of the lubricating layers, which reduce the level of lifting force and viscous friction in the gap of the lubricating layer [7].

In [8], the rheological properties of fresh and used SAE 5W-30 diesel engine oils with a low content of sulfate ash, phosphorus, and sulfur (Low SAPS oils) were studied using an EHD tribometer and rotational viscometers of the HTHS (High Temperature High Shear) type, which provide low and high shear rates. Based on the thickness of the lubricating layer formed in the EHD contact in the range from 10 to 150 nm, two types of lubrication mechanisms were identified depending on the rolling speed. On the one hand, the classical behavior of the EHD lubrication with an optimal dynamic viscosity above a certain critical film thickness was observed. On the other hand, the authors recorded a sharp drop in film thickness, which is an indicator of the inability of polymeric viscosity modifiers to form a thin film within the contact, which was influenced by the particle size in the oil composition. The authors established a correlation between the critical film thickness and particle size and thus concluded that used oil has a more critical film thickness than fresh oil and that under certain conditions the friction properties of the oil were related to this critical film thickness. A characteristic feature of the studied oils was their non-Newtonian behavior, which was revealed in tribological experiments. These observations of the authors were related to rheological measurements made at shear rates up to $10^7 s^{-1}$ at temperatures from 25 to 150°C.

Under extreme conditions of mixed friction, the chemical action of the lubricant and its additives (chemically active ingredients, CAS or surface-active ingredients, SAS) significantly affects fatigue life [9]. This is because under mixed lubrication conditions, contact surfaces are subjected to tangential stresses of much greater magnitude. The corresponding forces cause the appearance of maximum contact stresses on the contact surfaces, which stimulate fatigue of the surfaces themselves in the near-surface layers, as opposed to fatigue developing below the surface. In addition, chemical reactions of the lubricant with the material of the metal surfaces significantly reduce the resistance to crumbling. However, some additives, on the contrary, reduce surface forces and thus reduce tangential stresses, thereby increasing fatigue life.

Finally, it should be noted that according to the “unified” theory of boundary lubrication by A. Cameron [10], in the temperature range $T_o > T > T_{cr}$, the lubricating effect occurs due to the formation of “thick” polymer films and only after their destruction does the interaction of active components of the medium with friction surfaces begin with the formation of chemically modified boundary layers (CMBL). According to the relevant theory of boundary lubrication, the increase in the lubricating ability of modified layers and the wear resistance of friction units occurs due to the formation of optimal polymer films, and only after their destruction does the interaction of active components of the medium with friction surfaces begin with the formation of boundary layers, the strength of which depends on local temperatures in the contact zone.

Thus, the study of the influence of the qualitative and quantitative composition of chemical components, taking into account the temperature factor, using modern and automated equipment and adapted methods, opens up wide opportunities for modifying lubricants. Finally, this will make it possible to increase the wear resistance of contact surfaces and improve lubricity, taking into account the control of the critical temperature (thermomechanical stability) in the local contact zone in terms of contact-mechanical, rheological, and physicochemical aspects. From a practical point of view, an appropriate integrated approach will allow managing the process of approaching real operating conditions for specific friction units and ensuring uniformity in the creation of universal lubricants in hybrid vehicles, which should have the properties of, for example, motor, transmission and hydraulic oils at the same time.

Statement of unresolved issues

Many problems of tribology associated with the operation of friction units require not only theoretical and experimental studies, but also bench and operational tests on real equipment, since many transient processes occurring in the micro-volume (micro-EHD) of the friction contact of real units make significant adjustments to the research results. The task of increasing the lubricating ability and wear resistance of friction pairs operating under extreme conditions requires systematic studies of modifying lubricating layers with optimal chemically active components as one of the effective and modern technologies for improving rheological and tribotechnical parameters, including to provide versatility to lubricants in order to reduce material and financial costs for maintenance of friction units. Carrying out relevant research and testing is impossible without the use of modern automated equipment, both in laboratory and factory conditions and on original equipment in real-time operation to ensure the accuracy and reliability of the results. Otherwise, the results will remain at the level of a phenomenological fact, for which there is either no theoretical justification or it will be contradictory from the standpoint of different scientific schools dealing with these issues.

To date, there is no consensus on how to improve lubricity and wear resistance under mixed lubrication, an intermediate mode between liquid and boundary lubrication, in which most components are operated, where the structure of the lubricating layer, its rheological and tribotechnical characteristics change. It is also added that mixed lubrication is a predominantly unstable mode due to rapidly changing processes in the friction contact zone, for example, under conditions of lubrication starvation, in which there are breaks in the EHD of lubricating layers or modified boundary layers in discrete areas of the actual contact area under high loads. Therefore, a comprehensive solution to the above issues using the results of scientific and applied research on lubricants in laboratory and factory conditions and at enterprises-operators of equipment will allow developing modern methods and technologies for increasing the lubricating ability and wear resistance of friction pairs in the friction contact zone, taking into account contact-mechanical, rheological and physicochemical aspects. The corresponding integrated approach will form the basic basis for scientifically sound approaches to the development of modern lubricants and optimized designs of friction units operating under real-world conditions in vehicles.

Thus, the scientific and technical problem is the implementation of sustainable lubrication in mixed friction conditions and the creation of modified layers with optimal lubricity and structural adaptability to extreme operating conditions in the friction contact zone of non-conformal and conformal friction units, aimed at increasing the lubrication efficiency and wear resistance of friction pairs in terms of contact-mechanical, rheological, and physicochemical aspects.

Statement of the problem

Most friction units in extreme operating conditions are operated in a mixed lubrication mode, which is characterized by micro-EHD lubrication (in foreign literature: partially elastic-hydrodynamic partial hydrodynamic lubrication), when the thicknesses of the lubricating layer become almost commensurate with the heights of micron irregularities of metal surfaces. Micro-EHD lubrication is characterized by the sensitivity of the influence of contact surface roughness, since contact pressures from discrete areas along the actual contact area arise, which begin to reach the total level of hydrodynamic pressure of the lubricating layers, which reduce the level of lifting force and viscous friction in the gap of the lubricating layer.

In the mixed lubrication regime, physical (viscous and rheological) aspects of lubrication have a significant impact, since the proportionality of the thickness of the lubricating layer with the height of the micronutrient irregularities of the contact surfaces under extreme conditions at high stresses and shear rates can lead to the manifestation of pseudoplasticity and elasticity of the lubricating layers. Since very few works have been devoted to this issue, and they are mainly generalized by hypothetical calculations, the task is to conduct not only the necessary experimental studies, but also to make appropriate calculations to take into account the rheological properties in the micro-EHD contact zone.

Under conditions of boundary lubrication, the surfaces of conformal internal combustion engine assemblies have direct contact between sections of large length. At the boundary lubrication, the lubricating ability will be characterized by the physical and chemical aspects of the structural adaptability of the modified layers adsorbed on metal surfaces. The coefficient of friction in boundary lubrication is significantly higher than in liquid lubrication, but by modifying the surfaces with surfactants that form strong CMBL at high temperatures or surfactants that form polymerization chemisorption or physically adsorbed films at moderate temperatures, it is possible to prevent type 1 adhesion (cold seizure) and significantly reduce wear of contact surfaces.

It has been established that appropriate chemical reactions of the lubricant with the material of metal surfaces can reduce surface forces and thus reduce tangential stresses, thereby increasing fatigue life. Unfortunately, such studies under mixed lubrication conditions are fragmentary in nature, since, in general, the influence of the chemical component, as well as the relationship between the rheological properties of the boundary layers and the chemical properties of the components in the lubricant that create the corresponding modified layers, are considered only from the standpoint of boundary lubrication. Thus, it is necessary to ensure an integrated approach to conducting theoretical and experimental studies, taking into account the rheological and physicochemical aspects of lubricants for friction units.

One of the effective means of creating appropriate durable modified layers on friction surfaces is adsorption and surface shielding with certain CAS or SAS, which opens up wide opportunities for modifying lubricants to increase the lubricating ability of the corresponding modified layers and the wear resistance of friction pairs, and the corresponding means will be useful in implementing a unified approach to the use of universal lubricants in modern hybrid machines.

For the friction units of internal combustion engines, the conditions of non-stationarity (start-stop) are important, which should be considered from the point of view of contact strength (contact-mechanical aspect), determination of thermomechanical stability in the friction contact zone and structural adaptability of modified layers under the conditions of the boundary lubrication regime, taking into account the mechanical component of the friction force and molecular interaction of contact surfaces. The contact-mechanical component of the friction force is ensured by taking into account the mechanical properties of materials, the level of maximum contact stresses and deformations occurring in the friction contact zone. The molecular component is provided by rheological and physicochemical aspects of the structural adaptability of the modified layers in the friction contact zone.

Taking into account the multifactorial nature of the task of increasing the lubricity and wear resistance of bearing units and ICE units, it is necessary to use an integrated approach to assessing contact-mechanical, rheological, and physicochemical aspects, and based on their results, to conduct bench and operational tests in real friction units in order to confirm the adequacy and accuracy of the multifactorial criterion approach to increasing the lubricity and wear resistance of friction units under extreme operating conditions.

The purpose of the work

Liquid, plastic, solid, and gaseous lubricants are used to increase the lubricating ability and wear resistance of friction units, depending on the operating conditions. The most widely used are liquid lubricants (oils), which additionally provide heat dissipation and protection against corrosive environmental effects. In this regard, it is very important to optimally select and modify oils for specific operating conditions in order to minimize friction, prevent adhesion of the 1st kind of contact metal surfaces under extreme (heavily loaded and unsteady) friction conditions and create strong structured and modified lubricating layers on the surfaces, which facilitate the microplastic deformation in the subsurface friction contact zone in order to inhibit the propagation of fatigue processes in depth and along the direction of movement.

Fig. 1 shows a schematic diagram of the proposed new criterion-based approach for a comprehensive assessment of modifying the physical and chemical composition of lubricants to increase the lubricity and wear resistance of friction units operating under extreme operating conditions, in which there is a transition from liquid to boundary lubrication, which allows identifying the mixed lubrication mode.

At the first stage, in order to ensure the necessary conditions for the implementation of EHD lubrication, in which the wear of contact surfaces is observed in a steady state with a small supply of wear particles, and friction is minimal, it is necessary to observe the boundary of the transition zone from EHD to mixed lubrication mode with the corresponding input characteristics of the materials of friction surfaces and lubricant, the shape of the contact and the operating parameters of friction units.

The corresponding boundary is determined by the micro-EHD lubrication regime, which is influenced by the roughness of the micro-irregularities of the contact surfaces when forming the thickness of the lubricating layer, which is estimated by the lubrication regime criterion λ according to the expression in [11]:

$$\lambda = \frac{h}{\sqrt{R_{a1}^2 + R_{a2}^2}}, \tag{1}$$

where h – the thickness of the lubricating layer in the contact area (for steady-state operation, the value of the thickness of the lubricating layer in the central contact area is used h_0; to establish a violation of the lubrication regime - the minimum value of the lubricating layer thickness at the contact outlet h_{min}), μm;

R_{a1} – arithmetic mean deviation of the indenter surface profile, μm;

R_{a2} – arithmetic mean deviation of the counterbody surface profile, μm;

$\sqrt{R_{a1}^2 + R_{a2}^2}$ – the arithmetic mean deviation of the tribopair profile under model tests, μm.

According to the criterion of lubrication regime λ, the regimes are divided: boundary, when $\lambda < 1$; mixed, when $\lambda = 1 \div 3$; the EHD, when $\lambda = 3 \div 4$; hydrodynamic, when $\lambda \geq 4$. The micro-EHD regime characterizes the boundary of the transition from the mixed to the EHD lubrication regime or vice versa, when $\lambda = 3$.

At the second stage, the influence of the contact shape on mechanical properties (maximum contact normal and tangential stresses, deformations, position of localization of tangential stresses) in the friction contact zone is taken into account, especially for non-conformal friction units, since at the boundary of the transition from the mixed to the EHD lubrication mode from the position of mixed lubrication, only part of the load is perceived by the lubricating layer for units with a limited (concentrated) contact shape. The authors of [12], as a first approximation, proposed the following ratio:

$$\frac{P_h}{P_\Sigma} = \frac{1}{\lambda} \cdot \left(\frac{h_{min}}{h_0}\right)^{6,3}, \tag{2}$$

where P_h – hydrodynamic pressure perceived by the lubricating layer;

P_Σ – total pressure in the contact;
h_0 – thickness of the lubricating layer in the central contact area;
h_{min} – minimum thickness of the lubricating layer at the contact outlet.

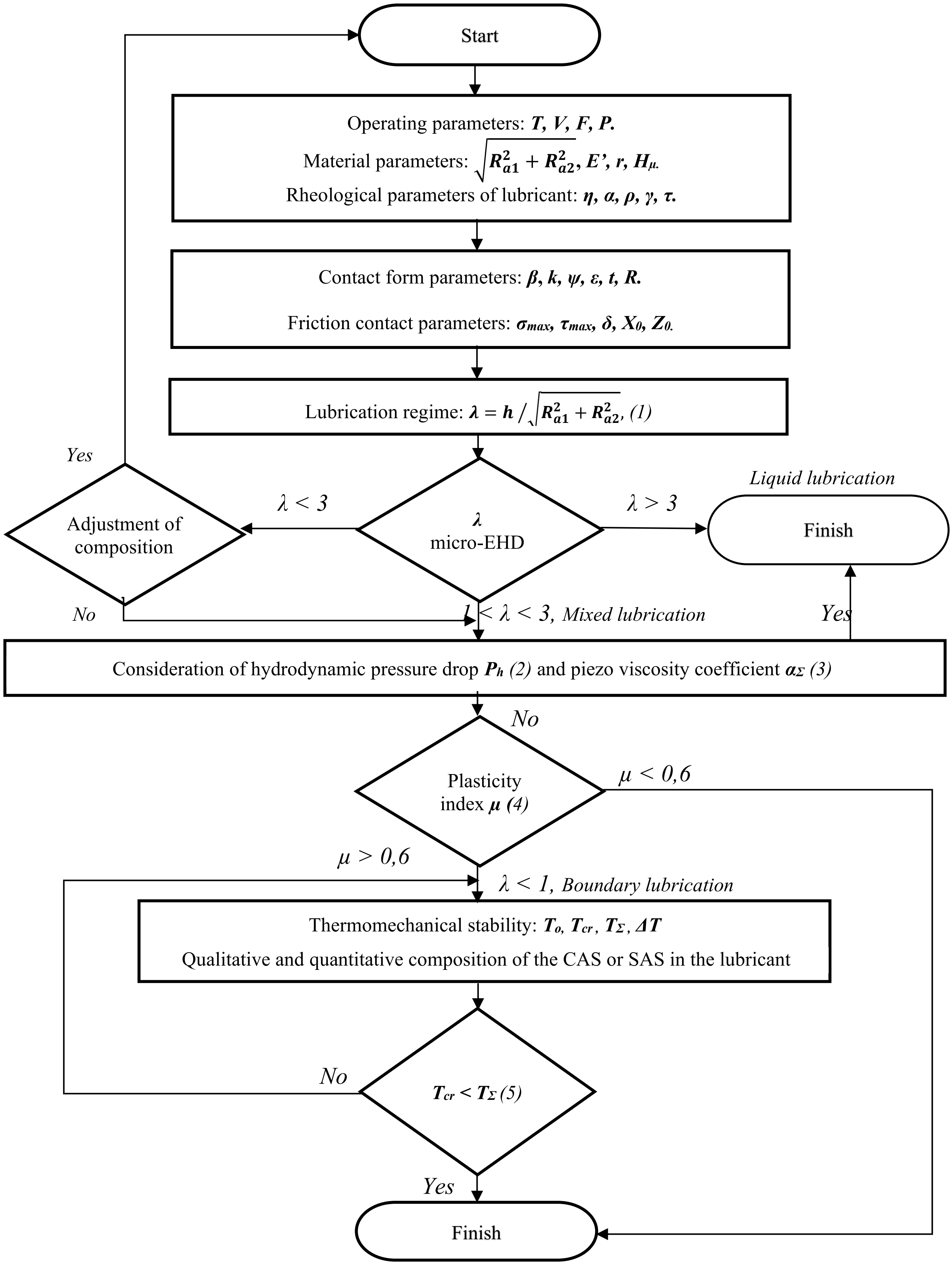

Fig. 1. Block diagram of the criterion approach to the integrated assessment of modification of the physical and chemical composition of lubricants.

At the second stage, the rheological properties of the lubricant are taken into account, i.e., ensuring optimal mechanical stability of the dynamic viscosity at high shear rate gradients of the lubricating layers in a wide range of low and high temperatures (bearing capacity). In other words, the lubricant must provide mechanical stability in terms of non-Newtonian properties at high shear rates under extreme operating conditions in a wide temperature range.

The main functionality that describes the influence of rheological properties is the calculation of dynamic viscosity with increasing load, but the corresponding definition is valid for Newtonian oils, which have a constant piezo viscosity coefficient α at low shear rates. Although, most modern oils at high shear rates, reaching $5 \cdot 10^6$ s^{-1}, can exhibit non-Newtonian properties and change the piezo viscosity coefficient α at high shear rates. Therefore, the authors of [13] proposed the definition of the average value of α_Σ that takes into account the change in this coefficient with pressure. The average value of the piezo viscosity coefficient α_Σ as a criterion for assessing rheological properties is determined as follows:

$$\alpha_\Sigma = \frac{\ln(\eta_1/\eta_2)}{P_2 - P_1}, \tag{3}$$

in which the index *1* refers to the atmospheric pressure and temperature at $T = 311K$, the index *2* to the highest pressure relative to the viscosity at $T = 311K$.

At the same time, the piezo viscosity coefficient α determines the tangent to the curve of $ln(\eta)$ versus P at atmospheric pressure, and α_Σ will determine the tangent to the same curve in the region between atmospheric and increased pressure.

At the third stage, the appearance of a plastic-deformed contact is estimated by the value of the plasticity index μ [12]:

$$\mu = \frac{E'}{H_\mu} \cdot \left(\frac{\sqrt{R_{a1}^2 + R_{a2}^2}}{r} \right)^{\frac{1}{2}}, \tag{4}$$

where E' – reduced elastic modulus, GPa;

H_μ - microhardness, determined experimentally by the method of artificial bases on the device PMT-3, Pa;

$\sqrt{R_{a1}^2 + R_{a2}^2}$ – the arithmetic mean deviation of the tribopair profile under model tests, μm;

r - average radius of microroughness vertices, μm.

At $\mu > 0.6$, a plastic-deformed contact;

at $\mu < 0.6$, elastically deformed contact under a slight thermal load.

At the fourth stage, first, the volumetric temperature of the lubricant T_o, measured by a thermocouple in the vicinity of the contact, is compared with the local temperature measured in the vicinity of the friction contact T_Σ by the thermal imaging method, which is the average of the specific points of local temperatures (thermomechanical resistance) under the same test conditions.

If the thermomechanical resistance of the studied modified layer T_Σ is higher than the thermomechanical resistance of the modified layer calculated for the nominal temperature resistance (critical temperature T_{cr}), by the difference (flash) of temperature ΔT, according to expression (5), with all initial parameters of friction and wear (tribotechnical and rheological parameters) being equal:

$$T_\Sigma = T_{cr} + \Delta T, \tag{5}$$

then the condition $T_{cr} < T_\Sigma$ will be fulfilled, which will indicate the optimal qualitative and quantitative chemical composition of the active components in the lubricant.

If the condition $T_{cr} < T_\Sigma$ is not fulfilled (see Fig. 1) with all friction and wear parameters being equal, then the corresponding physicochemical composition of the lubricant will have insufficient thermomechanical resistance of the modified layers to the corresponding operating conditions. In this case, the physicochemical composition of the lubricant is corrected by modifying the CAS or SAS with the determination of the optimal concentration. High surface activation due to changes in the physicochemical properties (modification) of the lubricant will increase the strength of the modified layers and improve the structural adaptability to specific operating conditions and hence increase the thermomechanical stability of the T_Σ. At the same time, the service life of friction units will be increased by reducing the wear rate of friction pairs.

Thus, if the condition $T_{cr} < T_\Sigma$ is not fulfilled, the lubricant is introduced into the lubricant in the form of halogen-containing compounds or sulfides in order to create strong the CMBL on the friction surfaces, or organic nano modifiers in the form of fullerenes (SAS), that modify and polymerize the surface with self-generating organic films (SGFs) that minimize friction and reduce wear (sometimes, adhesive wear is replaced by softer corrosion-mechanical wear). In addition, the appropriate modification improves the structural adaptability of the modified layers in the friction contact zone of the friction units of the internal combustion engine or bearing units to extreme operating conditions at high temperatures.

Conclusions.

The forward-looking multifactorial criterion approach to the modification of lubricants by their physical and chemical composition has been proposed to increase the lubricating ability of modified layers and the wear resistance of friction units from the standpoint of mixed lubrication conditions. Prevention of micro-EHD rupture of the lubricating layer is achieved by a set of measures: realization of stable micro-EHD lubrication according to the criterion of the lubrication mode *(λ)*; optimal viscosity class with an increase in the share of hydrodynamic pressure (lubricity) of the modified layers relative to the contact pressure from micro-irregularities of rough surfaces according to the pressure criterion ($\frac{P_h}{P_\Sigma}$); optimal type of lubricant according to the rheological criterion (α_Σ); assessment of the appearance of a plastic-deformed state according to the plasticity criterion *(μ)*; selection of the qualitative and quantitative chemical composition of active components in the lubricant to create durable modified layers with high structural adaptability and thermomechanical stability according to the temperature criterion *(T_Σ)*.

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Міланенко О., Бобро А. Багатофакторна критеріальна оцінка мастильної здатності та зносостійкості вузлів тертя, що працюють в екстремальних умовах роботи.

Запропоновано новий багатофакторний критеріальний підхід щодо модифікування мастильних матеріалів за реологічними властивостями та хімічним складом з метою підвищення мастильної здатності модифікованих шарів і зносостійкості вузлів тертя з позиції умов змішаного мащення. Запобігання розриву мікро-ЕГД мастильного шару досягається комплексом заходів: реалізації стійкого мікро-ЕГД мащення за критерієм режиму мащення (λ); оптимального класу в'язкості при збільшенні долі гідродинамічного тиску (мастильної здатності) модифікованих шарів відносно контактного тиску від мікронерівностей шорстких поверхонь за критерієм тиску (P_h/P_Σ); оптимального типу мастильного матеріалу за реологічним критерієм ($\alpha_{сер}$); оцінки появи пластично-деформованого стану за критерієм пластичності (μ); підбором якісного і кількісного хімічного складу активних компонентів в мастильному матеріалі для створення міцних модифікованих шарів з високою структурною пристосовуваністю та термомеханічною стійкістю за температурним критерієм ($T_{сер}$).

Нова концепція підвищення мастильної здатності та зносостійкості для вузлів тертя, що працюють в екстремальних умовах роботи, за відповідним критеріальним підходом, враховує: нестаціонарні умови тертя, форму локального контакту та кінематику тертя, реологічні властивості мастильних шарів, температуру контакту, склад компонентів в мастильному матеріалі.

Ключові слова: еластогідродинамічне змащення, фрикційний мікро-ЕГД контакт, товщина плівки, реологічні властивості, хімічно активні інгредієнти, поверхнево-активні інгредієнти, хімічно модифіковані граничні шари.