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Tribomonitoring of the quality of aviation hydraulic oils according to lubricity and rheological indicators

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Abstract

The study proposes a diagnostic control method for assessing the quality of commercial batches of hydraulic oils based on the kinetics of changes in the thickness of lubricating layers, shear stresses of the lubricating material, and effective viscosity in tribotechnical contact. Timely and high-quality tribomonitoring of lubricants provides a perspective on their rational use and reduced wear of equipment parts. The developed methodology simulates the operation of gears in rolling conditions with a slip of 30% using a roller analogy. Samples of AMG-10 oil from two manufacturers were analyzed. For "Bora B" AMG-10 oil (sample 1) with gradients of the sliding speed of the lubricating layer in contact from $5.63 \cdot 10^3$ to $5.73 \cdot 10^5$ c^{-1}, the effective viscosity is set at the level of 4249 and 5039 Pa·s at a bulk oil temperature of 20 and 100 ºC, respectively, which indicates the resistance of oil components to destruction under conditions of increasing shear rate gradient. For AMG-10 oil (sample 2), the effective contact viscosity decreases by 1.53 times both at an oil temperature of 20 ºC and at 100 ºC and is 2764 Pa·s (at 20 ºC) and 3309 Pa·s (at 100 ºC), which indicates the destruction of the components of the lubricant. For "Bora B" AMG-10 oil, effective lubricating properties have been established both during the start-up period and at maximum revolutions in conditions of rolling with slipping. It was shown that at start-up, regardless of the temperature of the lubricant, the mixed lubrication mode dominates. At the maximum revolutions of the tested samples, the hydrodynamic lubrication mode dominates, which indicates the effective lubricating properties of the Bora B AMG-10 oil. According to the kinetics of changes in the rheological parameters of oils, it was established that the resistance of the lubricant's components to mechano-thermal destruction under non-stationary lubrication conditions contributes to the effective formation of a lubricating layer in contact with a high bearing capacity.

Key words: aviation oils, rheological properties, lubrication mode, effective viscosity, shear rate gradient.

Introduction

The reliability of tribotechnical systems is established at the design stage, ensured during production, and confirmed during the operation of machines and mechanisms. Lubricating material significantly affects reliability indicators. Modern requirements for the reliability of tribomechanical systems are related to the qualitative improvement of lubricating materials and their components. In general, they are due to an in-depth analysis of the lubricating medium's state and the metal's contact surface in the friction process. The production technology of lubricating materials and their components is intensively developing and improving. New lubricating materials on mineral and synthetic bases are being created. Serious developments are underway to optimize the component composition of oils and lubricants, improving their physical, chemical, and operational properties.

The correct selection of lubricants and triboelement materials often determines the reliability of machines and mechanisms with highly loaded friction units. Therefore, studying patterns that determine the interaction of friction surfaces and lubricants requires comprehensive laboratory research. The analysis of expert practice allows for revealing the connection between the properties (physical, chemical, consumer) and the intended purpose of specific categories of lubricants. Currently, there are two approaches to the analysis of lubricants: the analysis of lubricants during production (incoming control of basic components, additives, and commercial batches of finished products) and the analysis of operational oil (diagnostic control).

These two directions are different from each other. Thus, during production and incoming control, the quality indicators must fall within the specified, previously known limits determined by standards and technical conditions. During diagnostic control, monitoring not so much the absolute values of specific quality indicators as the change of these values over time is necessary. For each indicated area of quality control of commercial or operational lubricants, it is essential to correctly choose the most convenient methods of analyzing the indicators of interest. These indicators include viscosity, flash point, additive content, total acid/alkaline number, water content, soot, total content of ferromagnetic and other wear particles, nitration, sulfonation, and many other indicators. The correct choice of lubricants and their timely and high-quality diagnostics are among the main conditions that increase durability and efficiency and preserve the technical accuracy of machines and mechanisms for an extended period. In addition, timely and high-quality tribomonitoring of lubricants provides a perspective on their rational use, reducing the wear of equipment parts. These measures aim to reduce the cost of repairing machines and mechanisms, reduce their downtime, and reduce the cost of manufactured products.

Literature review

Due to the complexity of physicochemical processes in the zone of frictional contact, the properties of contact surfaces and lubricating material during friction are challenging to describe from the point of view of classical mechanics. Therefore, to establish regularities of tribological and rheological indicators of friction systems in the limit mode of lubrication: studies of the mechano-thermal stability of the limit film [1], the influence of the shear rate gradient on the change in the effective viscosity and shear stresses in the lubricant [2] are actively being conducted to predict the effectiveness of the formation of the thickness of the lubricating film in contact.

The resistance of the lubricating film to mechanical destruction due to an increase in the shear rate gradient is a determining factor that ensures the normal performance of friction pairs in critical conditions. The destruction of the lubricating film during friction is one of the leading factors determining the intensification of energy processes occurring in the contact zone. It manifests in violating the structural suitability of the contact surfaces and lubricant under critical friction conditions, destroying previously formed metastable structures. [3].

In structural adaptation, lubricating boundary layers of varied nature are formed on activated metal surfaces during friction. The initially created lubricating layer has a solid structure, is characterized by non-Newtonian properties, and binds to both surfaces. When stress is applied, the layer will deform in shear until the applied shear stress is large enough to overcome adhesion to the surface. According to [4], outside of this condition, the sliding lubricant layer can behave according to two schemes. According to the first scheme, the lubricant in contact behaves as a liquid or remains attached to both surfaces but "melts" in the center. According to the second scheme, the lubricating layer retains its solid structure, and interlayer sliding occurs between areas of the lubricating material. When the action of the external shear force stops, the lubricant reorganizes its structure to its original state but with a constant shift between its two surfaces (Fig. 1).

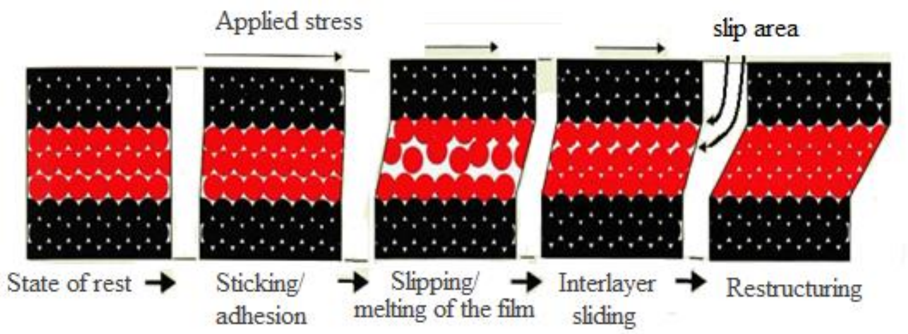

Fig. 1. The influence of shear stress on the lubricating film's deformation and its structure's reorganization [4].

According to [5], the lubricant is characterized by heterogeneity of rheological properties along the thickness of the film in frictional contact: a surface boundary layer with rheological properties different from the properties of the main part of the material in the center is formed near the wall. The lubricant flows right next to the wall as pressure is created during the system's operation. At the same time, the flow rate is zero, and the lubricant's viscosity is maximum [6]. Therefore, the material of the contact surfaces can significantly influence the rheological properties of the lubricant. The research paper [7] presents the results of studies on the formation of boundary layers in industrial lithium (LT4-C3) and calcium (STP) lubricants near the walls of six different materials: two elastomeric materials (nitrile-butadiene rubber (NBR), silicone rubber (MVQ/ VMQ)), two thermoplastic materials (polyoxymethylene (POM), polyethylene (PE)) and two metal alloys (copper C11000 and steel 304). Tests have shown that metal alloys have the most significant ability to adsorb lubricant particles on their surface. Elastomeric materials have a minor influence on the change in structural viscosity near the wall, which indicates their low capacity to form a surface layer in the tested commercial lubricants.

An experimental method for determining the interfacial shear strength based on the measured friction force and contact area during linear contact loading on coated metals has been developed [8]. It was found that the shear strength at the interface affects the overall sliding friction force under the test conditions.

In [9], the mechanism of adhesion of the boundary layer of lubricant to the surfaces forming a hydrodynamic wedge is considered. If molecules of the lubricant are in close proximity to a solid body, then their behavior is primarily determined by the influence of forces from this body. A particular rheology intermediate between the rheology of solids and liquids is characteristic of an oil film in such "boundary" conditions. With distance from the surface of the solid body, the influence of the force field created by it weakens, and its volumetric properties return to the lubricant. At the same time, boundary films have a thickness of 0.01÷0.05 μm and less.

In the mathematical modeling of the behavior of Newtonian/non-Newtonian fluids, rheological models of pseudoplastic and viscoplastic fluids and their parameters are used. For example, when building models of non-Newtonian fluids, the principle of mechanical modeling proposed by Rayner [10] is used. According to this principle, the behavior of various substances is defined as a parallel or sequential combination of elements with viscous, elastic, or plastic deformation. In [11], a general thermodynamic model of the melting of an ultrathin film of lubricant was proposed, and the value of the critical shear rate at which the lubricant melts by the shear melting mechanism was determined. It was established that the action of shear stresses leads to an increase in the volume of the lubricant, and, as a result, to an increase in the thickness of the lubricating layer in contact. The mathematical relationship between the volume and the thickness of the lubricating layer can be represented as:

$$\frac{\delta V}{V_0} = \frac{A\delta h}{Ah} = \frac{\delta h}{h}, \tag{1}$$

where δV – volume change, V_0 – initial volume, h - oil layer volume, A – contact area.

In this way, the importance of the established patterns of change of rheological indications in oily material in tribotechnical contact gives feasibility to predict the effectiveness of the formation of a boundary layer on active contact surfaces. It is especially essential in the case of boundary conditions, as the resistance of boundary melting to mechanical destruction ensures the movement of antifriction and anti-wear indicators in contact. Therefore, the actual direct assessment of the viscosity of the oily material is the analysis of its rheological characteristics under the dominance of different operating modes.

Purpose

To analyze the influence of the gradient of the shear rate, the shear stresses of the lubricating layer, and the effective viscosity in contact on the lubrication mode of commercial batches of aviation hydraulic oils.

Objects of research and experimental conditions

Oils to be studied:

- Sample 1 is oil "Bora B" AMG-10 according to TU U 19.2-38474081-010: 2016 with change 1 (produced by the LLC "Bora B", Ukraine);
- Sample 2 is oil AMG-10 according to GOST 6794-75 with changes 1 - 5 (produced by the LLC "NPP Kvalitet").

Sample 1 was developed to organize work on avoiding oil import and overcome the critical dependence of the defense industry of Ukraine on import supplies of AMG-10 oil.

The study of the samples was carried out on a software-hardware complex to evaluate the tribological characteristics of triboelements, for which a special software had been developed for stepper motor control and online visual evaluation of the kinetics of changes in the main tribological parameters of tribocontact [12]. Work of gears in the conditions of rolling with sliding was modeled using the software-hardware complex by means of a roller analogy (fig. 1).

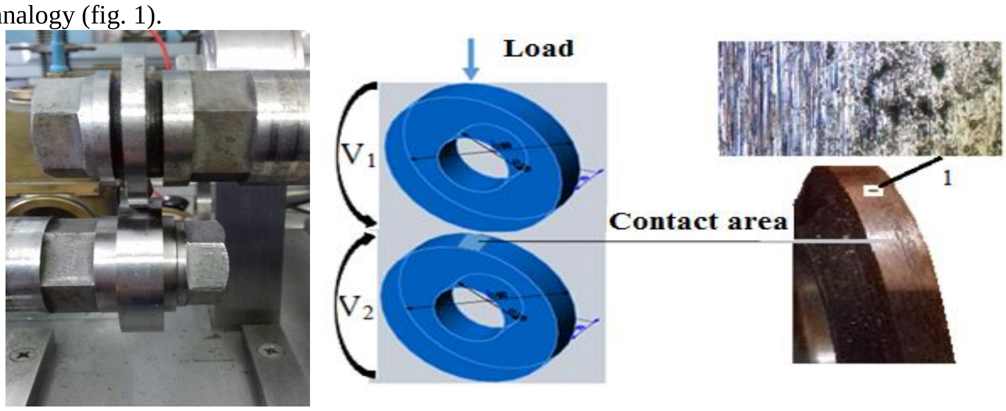

Fig. 2. The diagram of the loading node of the test samples with rotation at speeds V_1 and V_2 and the appearance of the friction tracks of the 30ChGSA steel sample; 1 – section of the contact surface of the sample.

Lubrication properties (hydrodynamic and non-hydrodynamic components of the lubricating film thickness) were determined by the method of voltage drop in the mode of normal glow discharge. Rheological characteristics of the lubricant (shear rate gradient, shear stress of lubricating layers, effective viscosity in contact) were evaluated by the kinetics of changes in the lubricating layer thickness, rotation speed of the leading and lagging surfaces and temperature of the lubricating layer.

Rollers (steel 30ChGSA, HRC 48…52, Ra 0.34 μm) were used as the material of contact surfaces. Lubrication of the contact surfaces was performed through immersing the lower roller in a bath of oil.

Testing was conducted in nonstationary conditions, which provide for the cyclicity of repetition in the start-up – stationary operation – braking – stop mode. The total duration of the cycle was 80 s.

Maximum rotation speed: 700 rpm for the leading surface and 500 rpm for the lagging surface. Sliding: 30%. Maximum contact load by Hertz: 200 MPa. Total number of cycles: 100. Temperature of oil: 20 ^{0}C (cycles 1-45), rise to 100 ^{0}C (cycles 46-50), 100 ^{0}C (cycles 51-100).

Analysis of the main results

Table 1 presents the averaged results of experimental studies of the rheological and lubricating properties of the investigated aviation hydraulic oils.

Table 1

Rheological and lubricating characteristics of aviation hydraulic oils

Parameter	Lubricant			
	Sample 1		Sample 2	
	Temperature of lubricant, °C			
	20	100	20	100
Oil layer shear stress,МПа	7,68 – 16,53	5,585 – 14,7	7,913 – 15,36	7,145 – 14,98
Effective contact viscosity, Pa·c	1836 – 8065	104,9 – 9182	1130 - 6789	78,67 - 7544
Thickness of boundary adsorption layers, µm	0,34 – 1,985	0,118– 1,992	0,118 – 1,38	0,104 – 1,57
Lubrication mode at startup	0,71 - 4,13	0,25 – 4,14	0,25 – 2,87	0,22 – 3,27
Thickness of the lubricating layer in contact, µm	3,95 – 8,768	4,65 – 9,698	3,055 – 7,8	3,454 – 7,93
Lubrication mode at maximum revolutions	8,22 – 18,24	9,67 – 20,1	6,35 – 16,22	7,18 – 16,49

Characteristics of sample 1. "Bora B" AMG-10 oil is characterized by effective rheological properties. Ensuring the hydrodynamic lubrication regime at the maximum revolutions of the cycle duration, in rolling conditions with 30% slip occurs due to the high bearing capacity of the lubricant, the formation in contact of hydro- and non-hydrodynamic components of the thickness of the lubricating layer, which are characterized by low shear stresses, on average, 9.4 MPa regardless of oil temperature (Fig. 3).

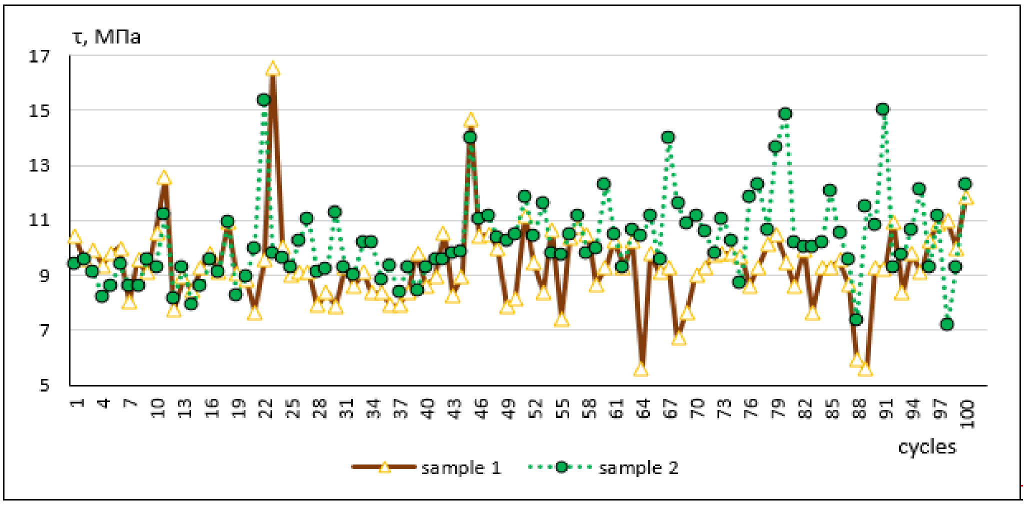

Fig. 3. Kinetics of changes in shear stress of the lubricating layer in contact (τ).

Despite the high gradients of the sliding speed of the lubricating layer in contact, from $5.63 \cdot 10^3$ to $5.73 \cdot 10^5$ c^{-1}, which occur at the maximum sliding speed of 0.71 m/s in conditions of rolling from sliding, the lubricant is characterized by effective with a viscosity at the level, on average, of 4249 and 5039 Pa·s at the volume temperature of the oil of 20 and 100 ºC, respectively (Fig. 4). This testifies to the resistance of oil components to destruction under conditions of increasing shear rate gradient. The most significant decrease in the effective viscosity in contact with 105 - 250 Pa·s occurs in the conditions of the initial increase in oil temperature (45 - 49 test cycles). This is due to a change in the nature of the boundary adsorption layers, which are characterized by effective adaptation in a wide range of temperatures.

Characteristics of sample 2 AMG-10 oil, similar to sample 1, are characterized by effective rheological properties. The shear stress of the lubricating layers is set at the level, on average, of 9.4 MPa at an oil temperature of 20 ºC, which is similar to the indicator for sample No. 1. When the oil temperature rises to 100 0C, this parameter increases to 10.82 MPa, which is slight, 1.15 times more, compared to sample 1 (Fig. 3).

Compared to sample 1, the effective contact viscosity decreases, on average, by 1.53 times at an oil temperature of 20 ºC and 100 ºC and is 2764 Pa·s (at 20 ºC) and 3309 Pa·s (at 100 ºC). However, with an increase in temperature during 45-50 cycles, a sharp decrease of this parameter was established to 78-240 Pa·s, which is due to the adaptation of the boundary layers of the lubricant to the change in the temperature regime in the frictional contact. The range of change in the gradient of the sliding speed of the lubricating layer (γ) in contact at the maximum sliding speed of 0.71 m/s in the conditions of rolling from sliding for samples 1 and 2 is from $4.51 \cdot 10^3$ to $5.73 \cdot 10^5$ c^{-1}.

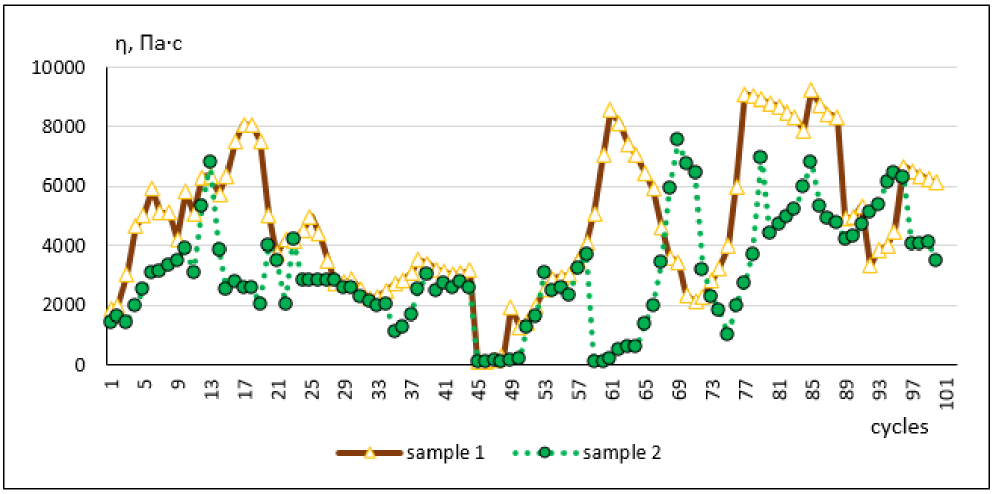

Fig. 4. Kinetics of changes in the effective oil viscosity (η) in contact.

Depending on the thickness of the lubricating layer, the lubrication mode in the frictional contact is determined according to the λ criterion:

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

where h is the thickness of the lubricating layer; R_a is the average arithmetic deviation of the profile of the contacting surfaces.

An informative indicator of the transition conditions from dry to hydrodynamic lubrication is the Hertz-Striebeck diagram. Fig.5 and Table 1 present the calculated values of the lubrication mode for the studied lubricants.

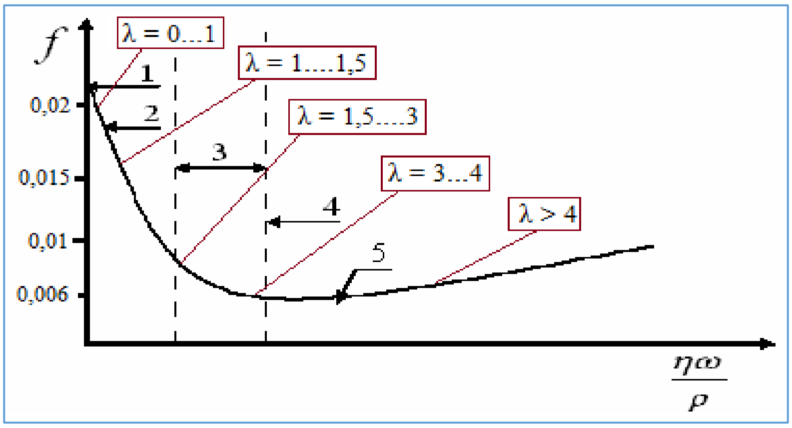

Fig. 5. Friction coefficient (*f*) and lubrication mode (λ) according to the Hersey-Striebeck diagram: 1 - dry, 2 - marginal, 3 - mixed; 4 – elastohydrodynamic; 5 - hydrodynamic lubrication modes.

The studied oil "Bora B" AMG-10 is characterized by effective lubricating properties during the start-up period and at the maximum studied revolutions. Breakdown of the lubricating layer at start-up and direct metal contact of the friction surfaces was not established. A semi-dry lubrication mode was set only for a short time during running-in and initial temperature rise. At start-up, regardless of the temperature of the lubricant, the mixed mode of lubrication dominates. At the maximum revolutions of the tested samples, the lubrication hydrodynamic mode dominates, indicating the effective lubricating properties of the oil "Bora B" AMG-10. For the tested AMG-10 oil at a bulk oil temperature of 20 and 100 ^oC, the thickness of the marginal adsorption layers is 1.44 times smaller, which leads to a deterioration of the lubrication regime in contact at start-up and the dominance of the marginal lubrication regime in 25% of the working cycles. As the temperature of the lubricant increases, long-term restoration of the protective boundary films of the oil takes place, and the period of their formation increases by 2.5 times, causing the implementation of a semi-dry lubrication mode at start-up. The total thickness of the lubricating layer is 1.27 times smaller compared to "Bora B" AMG-10 oil, regardless of the temperature of the lubricant. Thus, the resistance of the components of the studied sample 1 to mechano-thermal destruction under non-stationary lubrication conditions contributes to the effective formation of a lubricating layer in contact with a high bearing capacity, which ensures the dominance of the mixed or hydrodynamic mode of lubrication. Consequently, during the operation of the tribosystem in such conditions, optimal antifriction and antiwear characteristics of lubricants will be manifested, which is the basis for developing recommendations for the selection of commercial batches of oils for operation in conditions of rolling with slipping based on the proposed methodology for evaluating the rheological and lubricating properties of lubricants.

Conclusions

1. The conducted research on the software-hardware complex simulated gears' operation in rolling conditions with sliding using a roller analogy. Commercial AMG-10 oils from different manufacturers were studied. The errors of the obtained experimental values of the studied parameters are within 7-10%.

2. "Bora B" AMG-10 oil (sample 1) is characterized by low shear stresses, on average, 9.4 MPa, regardless of the oil temperature. For AMG-10 oil (sample 2), the shear stress of the lubricating layers is set at 9.4 MPa at an oil temperature of 20 ^oC, similar to the indicator for "Bora B" AMG-10 oil. When the oil temperature rises to 100 ^oC, this parameter increases by 1.15 times.

3. For "Bora B" AMG-10 oil (sample 1), the effective formation of the thickness of the lubricating layer in contact, resistance to the gradient of the shear rate, and effective viscosity is 4249 and 5039 Pa·s at the bulk oil temperature of 20 and 100 ^oC respectively. For AMG-10 oil (sample 2), the effective contact viscosity decreases by 1.53 times both at an oil temperature of 20 ^0C and at 100 ^oC and is 2764 Pa·s (at 20 ^oC) and 3309 Pa·s (at 100 ^oC), which indicates the destruction of the components of the lubricant.

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Ільїна О. А., Мікосянчик О. О., Ящук О. П., Мнацаканов Р.Г., Березівський Н.М. Трибомоніторинг якості авіаційних гідравлічних олив за змащувальними та реологічними показниками

Запропонована методика діагностичного контролю оцінки якості товарних партій гідравлічних олив за кінетикою зміни товщини мастильних шарів, напружень зсуву мастильного матеріалу та ефективною в'язкістю в триботехнічному контакті. Своєчасний та якісний трибомоніторинг мастильних матеріалів надає перспективу щодо їх раціонального використання та зменшення зносу деталей обладнання. В розробленій методиці за допомогою роликової аналогії моделюється робота зубчастих передач в умовах кочення з проковзуванням 30%. Проаналізовано зразки оливи АМГ-10 двох виробників. Для оливи «Бора Б» АМГ-10 (зразок №1) при градієнтах швидкості зсуву мастильного шару в контакті від $5{,}63\cdot10^3$ до $5{,}73\cdot10^5$ $с^{-1}$ встановлена ефективна в'язкість на рівні 4249 та 5039 Па·с при об'ємній температурі оливи 20 та 100 °С відповідно, що свідчить про стійкість компонентів оливи до деструкції в умовах зростання градієнту швидкості зсуву. Для оливи АМГ-10 (зразок 2) ефективна в'язкість в контакті знижується в 1,53 раз як при температурі оливи 20 °С, так і при 100 °С та становить 2764 Па·с (при 20 °С) та 3309 Па·с (при 100 ^{0}С), що свідчить про деструкцію компонентів мастильного матеріалу. Для оливи «Бора Б» АМГ-10 встановлені ефективні змащувальні властивості як в період пуску, так і при максимальних обертах в умовах кочення з проковзуванням. Встановлено, що при пуску, незалежно від температури мастильного матеріалу, домінує змішаний режим мащення, при максимальних обертах досліджуваних зразків домінує гідродинамічний режим мащення, що свідчить про ефективні змащувальні властивості оливи «Бора Б» АМГ-10. За кінетикою зміни реологічних показників олив встановлено, що стійкість компонентів мастильного матеріалу до механо-термічної деструкції при нестаціонарних умовах мащення сприяє ефективному формуванню мастильного шару в контакті з високою несучою здатністю.

Ключові слова: авіаційні оливи, реологічні властивості, режим мащення, ефективна в'язкість, градієнт швидкості зсуву.