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TRIBOLOGICAL CHARACTERISTICS OF AVIATION LUBRICANTS UNDER CRITICAL OPERATING CONDITIONS OF TRIBOSYSTEMS

The article presents a comparative analysis of the tribological characteristics and wear resistance of contact surfaces under critical loads. The study uses 30KhGSA steel, extensively utilized in aviation engineering for critical components. The surfaces were lubricated with two distinct lithium-based greases: a traditional synthetic hydrocarbon-based grease (VNIINP-286M) and a modern synthetic alternative (AeroShell Grease 33). The research establishes kinetic dependencies of key parameters during simulated extreme conditions, focusing on sudden lubricant starvation. The analysis investigates the relationships between heat release intensity, friction coefficient evolution, and specific work of friction. Findings demonstrate that synthetic AeroShell Grease 33 offers superior performance for heavily loaded wing high-lift devices. This synthetic grease forms and maintains highly stable boundary lubricating films under extreme stress, providing higher resistance to thermal and oxidative degradation. Consequently, it drastically reduces the probability of localized overheating, severe scuffing, and adhesive wear compared to traditional synthetic counterparts, highlighting the importance of advanced synthetic lubricants for modern aviation machinery.

Key words: *aviation greases, tribosystem, friction coefficient, wear, boundary lubrication, 30KhGSA steel.*

Introduction. Numerous fundamental and applied works by domestic and foreign scientists have been dedicated to the study of boundary lubricating layers and their fundamental role in ensuring the wear resistance of modern aviation tribosystems. As evidenced by the basic principles of the physicochemical mechanics of contact, the boundary lubricating layer is an ultrathin mesophase molecular-scale structure, the properties of which differ cardinally from the bulk rheological characteristics of the lubricant. Studies [1, 2] clearly demonstrate that the chemical nature of the lubricant, the structure of its molecular chains, and the kinetics of the formation of secondary dissipative structures directly affect the adhesion and deformation components of the friction coefficient. Complex molecular interactions occurring at the phase interface determine the formation of the orientational order of adsorption layers, creating a barrier against direct metallic contact and reducing tangential shear stresses.

In turn, recent works [3, 4, 5] consider in detail the complex physicochemical mechanisms of stabilization, destruction, and self-organization of boundary films formed by modern synthetic lithium greases in the aerospace industry. Researchers pay special attention to their tribological response under severe thermal loads, high-frequency vibrations, and critical "oil starvation". Researchers indicate that under high shear velocities, the cohesive strength of ordered molecular structures of the boundary layer and the structural stability of the three-dimensional thickener framework have decisive importance, collectively preventing local thermal destruction of the boundary film under the influence of local frictional heating.

The issues of replacing traditional, outdated aviation greases with modern synthetic analogues of a new generation have been actively studied in the domestic aircraft industry in view of updated technical specifications and strict international standards for the operational safety of aircraft [6]. The significant advantages of polyalphaolefin and ester greases over traditional lubricating products were experimentally confirmed. Due to the high polarity of the ester components and the pronounced thermal stability of the hydrocarbon skeleton of polyalphaolefins, a significant increase in the load-carrying capacity of the lubricating layer is achieved, and the operating temperature range of the friction unit is significantly expanded.

Despite this, the aspects of the energy balance in the frictional contact zone during the transition to non-stationary or critical lubrication regimes of local contacts still remain insufficiently studied. In particular, the processes of accumulation of specific friction work, the dynamics of frictional shear resistance of boundary layers, and the kinetics of step-like heat release during frictional interaction require deeper theoretical and experimental analysis. Frictional contact under critical operating conditions should be considered from the standpoint of non-equilibrium thermodynamics, where the destruction of the boundary layer is a direct consequence of the imbalance between the processes of local entropy generation and dissipation of frictional energy. An attempt at a comprehensive solution to this problem using modern tribotechnological approaches, thermodynamic criteria for surface adaptation, and evaluation of the load-carrying capacity of the residual lubricating layer thickness was highlighted in fundamental works and qualified scientific research papers of recent years [7, 8]. These works laid the scientific foundation for the energy evaluation of process wear; however, they require further development, systematization, detailed experimental confirmation, and comprehensive tribological substantiation regarding high-strength steels in non-stationary regimes of dry and semi-dry friction.

Based on the analysis of conducted research, there is a need to solve an important scientific and practical problem: determining the performance limits of boundary lubricating layers in highly loaded units of aviation equipment during the transition to extreme operating conditions. The traditional use of plastic greases such as Era VNIINP-286M in the wing mechanization and landing gear units of "An" family aircraft under conditions of significant contact pressures, vibrations, and extreme temperature drops often leads to premature destruction of the boundary film. The consequence of this is a sharp increase in the friction coefficient, intensive heat generation in the contact zone, adhesive galling, and premature wear of parts made of high-strength 30KhGSA steel.

Thus, the practical problem lies in the need to transition to a new generation of synthetic plastic greases with an improved polar structure (in particular, AeroShell Grease 33) and a detailed scientific substantiation of their tribological effectiveness. The connection of the research with important practical tasks consists in developing criteria for predicting the frictional behavior of structural materials in non-stationary "oil starvation" regimes to prevent sudden failures and increase the service life of critical friction units of aircraft.

The purpose of the study is a comparative study of the kinetics of changes in the antifriction and antiwear properties of mineral and synthetic lithium aviation greases under extreme friction conditions and the evaluation of their impact on the wear resistance of 30KhGSA steel.

Testing procedure. To model non-stationary operating regimes and evaluate the tribotechnological parameters of a local frictional contact, a test rig was used, which implements a two-roller kinematic friction scheme (Fig. 1) [7]. This scheme allows an adequate replication of the stress-strain state and real operating conditions of highly loaded cylindrical joints of aircraft structures in the rolling-with-sliding mode (for example, for the joints of wing mechanization units of the "AN" family aircraft).

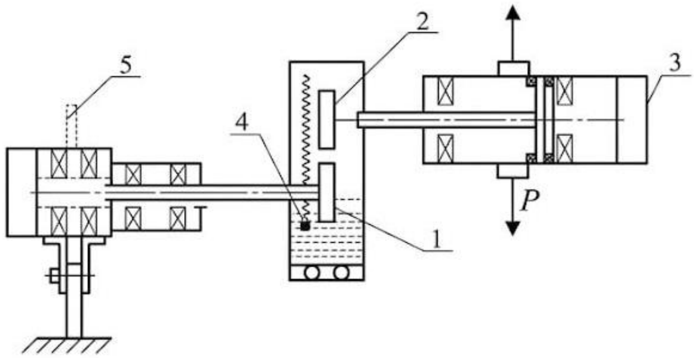

Fig. 1. Schematic diagram of the test rig: 1 – specimen (upper roller); 2 – counter-specimen (lower roller); 3 – lever-based loading system; 4 – volume temperature measurement unit (chromel-copel thermocouple); 5 – spring element with friction force strain gauges.

The lower roller (counter-specimen) was made of 30KhGSA steel with a diameter of 40 mm, quenched to a hardness of 38...42 HRC. The upper roller (specimen) with a contact area of 1.2 cm^2 was also made of 30KhGSA steel. The roughness of the working surfaces of both rollers complied with the requirements of the design documentation (Ra = 0.32...0.40 μm).

The tests were carried out at a contact pressure P = 450...500 MPa and a sliding velocity V_{sl} = 0.15 m/s with a slide-to-roll ratio of 30%. Friction force measurements were carried out by the strain gauge method with continuous signal recording on a PC. The measurement of the bulk temperature in the friction zone was performed using a chromel-copel thermocouple mounted in the upper roller at a distance of 1.5 mm from the working friction surface.

A specific feature of the methodology is the evaluation of the tribosystem behavior in the critical regime of oil starvation. The lubricant (Era VNIINP-286M or AeroShell Grease 33) in an amount of 0.1 g was initially applied directly to the working surface of the frictional contact before starting the tribometer. After 5 minutes of stable operation in the run-in mode (to form the primary boundary film), the grease supply was completely stopped, and its remnants displaced from the friction zone were removed by a special cleaning device. The parameters registration was continued until a sharp jump in the friction torque and the appearance of a characteristic metallic noise occurred, which indicated the critical destruction of the boundary film and the onset of scuffing.

For the energy evaluation of the contact state, the heat generation intensity Q (W) and the specific work of friction A_{spec} (J/m^2) were calculated according to the formulas:

$$Q = f N_l V_{sl}, \quad (1)$$

where f is the instantaneous friction coefficient; N_l is the linear load, N; V_{sl} is the sliding velocity, m/s;

$$A_{spec} = [\left|\int_0^{t_i} M_i(t) \cdot 2\pi n_i(t) d(t) - \frac{1}{2}\sum_0^{i=n_{ti}} J\Pi_i \cdot \omega_i^2\right|]/F, \quad (2)$$

where M is the torque generated by friction; n and ω denote the rotational frequency and angular velocity of the friction pair elements, respectively; t represents the duration of the operational cycle; J signifies the polar moment of inertia of the tribotester's rotating components, which determines the measurement accuracy of the contact friction torque; and *F* stands for the theoretical contact area calculated via Hertzian contact mechanics.

Processing of the obtained experimental results, filtration of high-frequency noises of strain gauge signals, approximation of thermodynamic parameters of the contact, and construction of graphical dependencies were carried out using the modern Python software environment (in particular, specialized libraries for scientific data analysis NumPy, Pandas, and visualization Matplotlib).

Research findings and their analysis To deeply understand the frictional behavior of the studied materials, it is necessary to analyze in detail the nature of their base structure. Era VNIINP-286M grease is a classic representative of the traditional school of aviation chemmotology for aircraft of the AN, TU and IL types. Its base consists of a medium-viscosity synthetic hydrocarbon oil thickened with lithium soap of stearic acid (lithium stearate). To ensure antiwear characteristics, an additive package is introduced into its composition, which includes zinc dithiophosphate and specific aminophenol antioxidants.

The main limitation of the synthetic hydrocarbon dispersion base of Era VNIINP-286M grease is the moderate binding energy of the adsorbed molecules with the juvenile metal surface. Under conditions of cyclic alternating loads and a local temperature fluctuation field in the contact zone, the molecules of the base oil undergo a process of destructive thermal decomposition and premature desorption. This significantly limits the tribotechnological resource of the boundary films of this lubricant in high-intensity aviation tribosystems.

In contrast to the traditional analogue, the modern synthetic grease AeroShell Grease 33 is developed on the basis of an improved blend of synthetic hydrocarbons – polyalphaolefins (PAO) and esters (diesters), thickened with a complex lithium soap. The use of highly polar molecules of the ester fraction allows for an extremely high adhesion energy of the grease to the metal substrate. The complex lithium thickener forms a stable fibrous three-dimensional structure that retains the dispersion medium even under significant mechanical shear deformations and high shear rate gradients inherent in aviation friction units.

The comparative physicochemical properties of both greases are presented in Table 1 [6].

Table 1

Main physicochemical characteristics of the investigated greases

Property	Era VNII NP-286M	AeroShell Grease 33
Operating temperature range, °C	from -60 to +120	from -73 to +121
Base oil type	Synthetic (hydrocarbon)	Synthetic (PAO + diesters)
Thickener type	Lithium soap (Li stearate)	Complex lithium soap
Dropping point, °C	185	236
Base oil kinematic viscosity at 40°C, mm^2/s	14.5	14.2
Colloidal stability (oil separation), %, not more than	11.0	3.0

Experimental tests revealed significant differences in wear dynamics and the kinetics of boundary lubricating layer destruction. Within the framework of this work, the generalization and systematization of the results of tribotechnological studies after 300 cycles of alternating frictional loading were carried out. It was established that the magnitude of the maximum normal contact pressure σ_{max} has a decisive influence on the stability of boundary lubricating layers on 30KhGSA steel.

With an increase in the amplitude of contact stresses σ_{max} from a moderate 250 MPa to a critical 700 MPa, an intensive decrease in the load-carrying capacity and destruction of the formed protective films is observed (Fig. 2). Specifically, when using the traditional synthetic grease Era VNII NP-286M, the thickness of the boundary lubricating layer under increasing load up to 700 MPa decreases by 15 times compared to its initial value. For the modern PAO-ester grease AeroShell Grease 33, layer destruction occurs much slower: the thickness of its boundary film decreases only by 3.5 times across the entire investigated pressure range. This confirms the exceptional mechanical stability of the structure of chemisorted ester complexes.

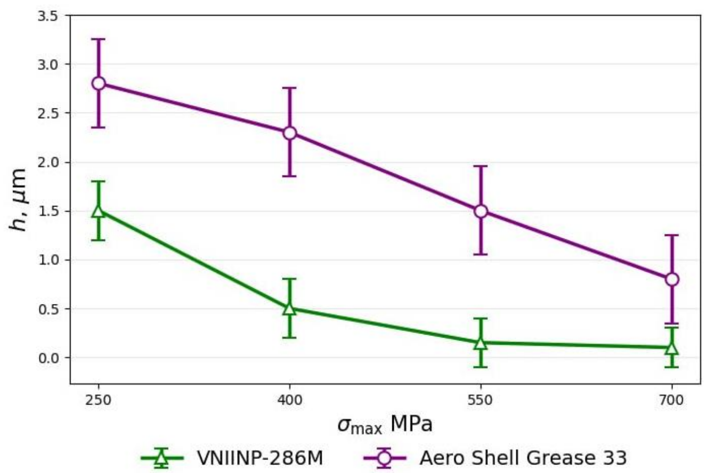

Fig. 2 Dependence of the boundary lubricating layer thickness on the maximum contact stress σ_{max} after 300 cycles of frictional operation.

AeroShell Grease 33 demonstrates significantly better lubricating properties compared to Era VNIINP-286M grease, which is especially clearly manifested at contact pressures above 400 MPa. At a relatively low pressure (σ_{max} = 250 MPa), the thickness of the boundary film formed by the components of AeroShell Grease 33 is 1.9 times greater than the thickness of the VNIINP-286M layer. However, at high loads (in the range from 550 to 700 MPa), when full displacement of weakly adsorbed molecules occurs, this difference increases significantly and ranges from 8 to 10 times in favor of the modern aviation grease AeroShell Grease 33.

Thermal processes in the contact also confirm the low resistance of the traditional lubricant to shear heating. Since the dispersion base of VNIINP-286M has lower thermo-oxidative stability, an increase in heating in the contact zone up to 80...90 °C leads to rapid thinning of the oil, loss of its load-carrying capacity, and destruction of the protective layer. This causes a sharp increase in the instantaneous intensity of heat generation Q (Fig. 3), which accelerates the adhesive processes of metal galling.

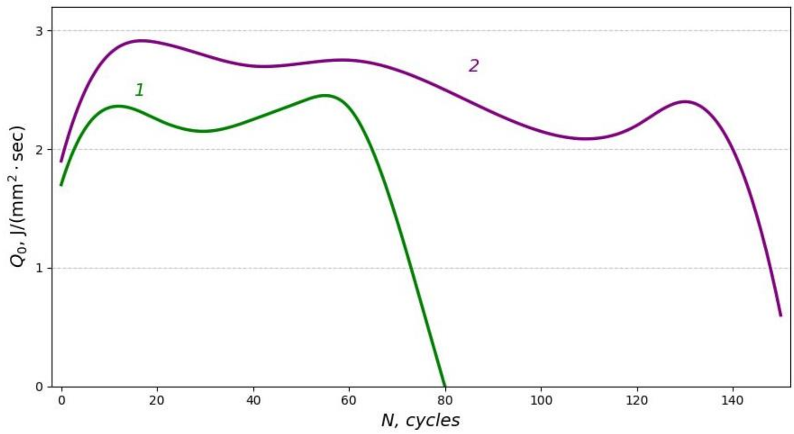

Fig. 3. Dependence of the heat generation intensity in the contact on the test time (number of cycles).

In contrast to this, the synthetic AeroShell Grease 33, due to its PAO-ester matrix, withstands significant local temperature spikes without losing dynamic viscosity, effectively dissipating friction energy and forming stable secondary metastable structures with a minimum level of entropy generation in the contact zone.

Consequently, the conducted studies and the analysis of the energy balance of the frictional contact provide grounds to assert that replacing the traditional hydrocarbon base of the grease with the highly polar PAO-ester composition of AeroShell Grease 33 cardinally changes the nature of tribochemical processes in the friction zone of 30KhGSA steel. The boundary layers formed in this case exhibit a significantly higher thermodynamic resistance to mechanical destruction and thermal desorption at high contact pressures. Thus, the formation of stable secondary structures under conditions of minimal entropy generation allows maintaining a stable level of frictional resistance and preventing local metal galling even under conditions of severe oil starvation.

Conclusions.

1. It has been established that under critical operating conditions of tribosystems, which were artificially modeled by completely stopping the supply of lubricant (oil starvation), the modern synthetic grease AeroShell Grease 33 ensures high performance and preservation of the protective boundary layer 3 times longer compared to the traditional hydrocarbon grease Era VNIINP-286M. This is achieved due to the pronounced polar structure of the ester components and the high stability of the spatial framework of the complex lithium thickener, which prevents rapid displacement and desorption of the oil under the action of high shear rate gradients.

2. The use of modern synthetic grease provides an effective reduction in the intensity of local heat generation and retards the growth of the specific friction force in the frictional contact zone of 30KhGSA steel triboelements. Preventing local temperature fluctuations beyond the critical limit of the grease's thermo-oxidative stability completely eliminates a sudden transition of the tribosystem from the boundary lubrication regime to adhesive galling and scuffing development.

3. The obtained experimental results and tribotechnological criteria for evaluating the energy balance of frictional contact serve as a reliable scientific foundation for developing practical recommendations on the complete replacement of obsolete lubricants in the friction units of aviation equipment with modern highly efficient

synthetic analogues. This will significantly increase the reliability and operational resource of highly loaded moving joints of domestic and foreign aircraft.

4. Prospects for further scientific research in this direction are related to a deeper study of the rheological behavior of AeroShell Grease 33 boundary layers under extreme low (cryogenic) temperatures (down to -70 °C). Evaluating the impact of relaxation processes in the lubricant on the preservation of adsorption and chemisorption stability at the interface of juvenile surfaces will expand the limits of predicting the frictional reliability of aviation joints under complex climatic conditions of flight operation.

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ТРИБОЛОГІЧНІ ХАРАКТЕРИСТИКИ АВІАЦІЙНИХ МАСТИЛЬНИХ МАТЕРІАЛІВ У КРИТИЧНИХ УМОВАХ ЕКСПЛУАТАЦІЇ ТРИБОСИСТЕМ

У статті представлено результати комплексного порівняльного аналізу трибологічних характеристик та зносостійкості спряжених контактних поверхонь високонавантажених деталей авіаційного призначення. Як базовий конструкційний матеріал дослідження обрано середньолеговану високомічну сталь 30ХГСА, яка широко застосовується в аерокосмічній техніці для виготовлення силових елементів кріплення, валів та осей вузлів механізації крила і шасі. Досліджено специфіку впливу традиційного мастила на синтетичній вуглеводневій основі (Ера ВНИИ НП-286М) та синтетичного аналога (AeroShell Grease 33) на літієвій основі на кінетичні закономірності тертя, температурну стабільність та зношування в умовах жорстких нестаціонарних режимів роботи, що супроводжуються масляним голодуванням фрикційного контакту. На основі експериментальних даних встановлено залежності кінетики зміни інтенсивності локального тепловиділення, коливань миттєвого коефіцієнта тертя та динаміки накопичення питомої роботи тертя безпосередньо після примусового припинення подачі мастильного матеріалу в робочу зону. Доведено, що використання синтетичного пластичного мастила AeroShell Grease 33 для високонавантажених рухомих спряжень механізмів висування крила літаків родини «Ан» гарантує значно вищу структурну стійкість граничних мастильних шарів. Унікальна здатність його синтетичної базової оливи формувати стабільні хемосорбційні шари на сталевих поверхнях ефективно нівелює прямий фрикційний дотик мікронерівностей, суттєво знижуючи ймовірність задиркоутворення (схоплювання), адгезійного виривання металу та катастрофічного зношування матеріалів вузла у порівнянні з традиційними мастильними композиціями.

Ключові слова: авіаційні мастила, трибосистема, коефіцієнт тертя, зношування, граничне мащення, сталь 30ХГСА.

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