Hindawi
Advances in Tribology
Volume 2023, Article ID 6676706, 13 pages
https://doi.org/10.1155/2023/6676706

Research Article

Dynamic Processes of Self-Organization in Nonstationary Conditions of Friction

Tareq M. A. Al-Quraan,[1] **Olha Ilina**,[2] **Mukola Kulyk**,[3] **Rudolf Mnatsakanov**,[4] **Oksana Mikosianchyk**,[2] **and Volodumur Melnyk**[2]

[1]*Al-Balqa Applied University, Ma'an College-Technical Sciences Department, 19117 Al-Balqa, Jordan*
[2]*Department of Applied Mechanics and Materials Engineering, National Aviation University, 03058 Kyiv, Ukraine*
[3]*Aerospace Faculty, National Aviation University, 03058 Kyiv, Ukraine*
[4]*Aircraft Continuing Airworthiness Department, National Aviation University, 03058 Kyiv, Ukraine*

Correspondence should be addressed to Tareq M. A. Al-Quraan; tarjorggg@bau.edu.jo

Received 28 December 2022; Revised 31 January 2023; Accepted 10 February 2023; Published 27 February 2023

Academic Editor: Lijesh Koottaparambil

Self-organization mechanisms of metastable dissipative structures during friction depending on base and oil functional additives for hypoid gears are considered. Research was conducted on a software-hardware complex with simulation of gears' operation in rolling with slipping conditions in start-stop mode. Indicators of formation of wear-resistant dissipative structures include the following: improvement of antifriction characteristics, lubricant boundary layers' formation, contact surfaces' strengthening, and formation of heterogeneous deformation microrelief with a fine-grained structure. The formation of chemically modified boundary layers on 90% of the contact area of tribo-coupling elements ensures an increase in the wear resistance of leading and lagging surfaces by 2 and 1.4 times, respectively. The sclerometry method was used to establish that the formation of dissipative structures when lubricating tribo-coupling elements with various transmission oils can reduce deformation processes in metal near-surface layers by 23%. Highly viscous flavored lubricant with distillate oil and additive composition ensures wear-resistant dissipative structures with active components, including oxygen, sulfur, and phosphorus.

1. Introduction

Machine elements are exposed to different unfriendly operating factors that decrease their service life. Friction and wear processes occupy a special place among the factors affecting the reliability of friction pairs. The evaluation of these processes is complicated since the kinetics of their flow depend on the specific pressure between the interacting surface layers, microstructural changes of the surface layer, and chemical reactions between the materials of the friction pairs [1–3].

The process of boundary lubrication is characterized by a significant influence of the chemical composition, physical parameters, and mechanical characteristics of tribo-coupling elements on the properties of the lubricant in the friction zone and, therefore, on the process of forming the lubricating layer. When changing both the material of one of the parts of the tribocombination and the type of lubricant, the process of marginal friction will proceed according to a different scenario. The process of formation of the boundary layer is dynamic in nature and the results of the self-organization of the tribosystem, with two competing processes—the formation of the layer and its destruction [4]. The thickness of the boundary layer increases over time, provided that the processes contributing to the formation of the layer proceed faster than the processes of its destruction [5, 6].

One of the most important processes taking place in the tribocontact zone at extreme friction is undoubtedly the process of supramolecular self-organization in the lubricating layer [7]. Such significant characteristics of the friction process as the wear intensity of the materials of the friction pair, the temperature in the tribocontact, and the force of friction will depend on the peculiarities of the processes of supramolecular self-organization, which determine the thickness, structure, and shielding capabilities of the boundary lubricating layer [8, 9]. Under the conditions of dominance of the limiting lubrication mode, an ordered structure of molecules or reaction products is formed on the surfaces of tribo-coupling elements, and surface friction is carried out between two weakly bonded adsorbed layers in an ordered structure. The process of the formation of a protective lubricating film over time has a nonlinear nature: the rapid growth at the initial stage of formation slows down over time, and the saturation stage occurs, at which the thickness of the boundary lubricating layer asymptotically approaches its maximum value, as permitted by the properties of the tribosystem [10]. At the same time, a certain level of thermomechanical influence in the friction zone is required to activate the process of growth of the boundary layers of the lubricant. In work [11], the formation of boundary films during normal running-in processes was established, which contributed to a decrease in friction and the wear rate. The formation of a film on the surface can occur in the first 40 seconds due to the interaction forces of the activated metal with free radicals or unsaturated bonds of organic lubricant molecules [12]. The effective formation of boundary films is triggered by the addition of polyfunctional additives to base oils [13, 14].

In the research work [15], the relationship between the relative speed of displacement of the friction surfaces and the elastic deformation in the lubricating layer was analyzed, taking into account the main provisions of the thermodynamic theory of structural states of the limiting regime of lubrication [16]. It was established that an increase in the external load (the absolute value of the normal stresses) leads to a forced arrangement of the lubricant due to a decrease in its excess volume due to an increase in the stationary values of the density modulation order parameter and the shear modulus of the lubricant. As a result of thermomechanical external influences, an intermittent regime of limit lubrication is established in the tribosystem, in which periodic phase transitions between the solid and liquid structural states of the lubricating material occur. The melting of the structured boundary film of the lubricant occurs with an increase in temperature in the friction contact, with the growth of the elastic element of the deformation that occurs in the boundary layer during shear, as well as with a decrease in the external load.

The probability of destruction of a structured adsorption layer under the influence of critical shear stress is analyzed in [17]. It has been established that the antiwear properties of surfactants increase both with an increase in their heat of adsorption on the metal surface activated during friction and with the intensification of processes, leading to the chemical adsorption of these substances on contact surfaces.

The lubricant layer contributes to the growth of hydrodynamic pressure and the reliable separation of friction pairs, the localization of shear stresses in the lubricant layer, and the reduction of the friction coefficient. An important influence on the formation of the lubricant layer in tribocontact is the microrelief of the contact surfaces. The results of the study of friction pairs with a heterogeneity of the microrelief of 15% and a depth of 19 μm, when lubricated with lithium grease in sliding conditions, testify to the high antifriction properties of the tribosystem, the presence of a reserve of lubricant in the depressions of the microrelief, and an increase in the effective viscosity of the lubricant, which causes an increase in the antiwear indicators of the tribosystem [18]. The self-organization of tribosystems is fundamentally energetic in nature; therefore, many studies are aimed at establishing the relationship between the dissipative structures formed during friction and irreversible energy transformations in the area of frictional contact in accordance with the work performed. Friction and wear are essentially typical energy processes that convert mechanical work or kinetic energy into other types of work. Such transformations include kinetics of changes in the specific work of friction, plastic deformation of the surface layers of friction pairs, and the work of wear, which are the conversion of work into internal (thermal), chemical, potential, and other forms of energy. In the research work [19], the component equations of the energy balance of the tribosystem were analyzed using existing phenomenological (empirical) ratios that determine the specific processes that occur during friction and wear. The main factors of the irreversibility of the energy characteristics of frictional contact have been established, which primarily include the dissipation of work to overcome adhesion forces, wear processes, plastic deformation, and dissipation of work to the formation and destruction of cracks. Irreversibility factors should also include the dissipation of work associated with the processes of changing the state of matter during the course of chemical reactions, diffusion processes, and heat conduction processes.

In the research work [20], an evaluation of the evolutionary changes of the tribosystem, which occur in the presence of an additional source of energy supply to the frictional contact zone, was carried out. Mathematical models of the self-organization of the tribosystem based on its dynamic reconstruction are proposed, including bifurcations of attractive aggregates of its deformational movements in areas of increased frictional forces. The tribosystem in the process of operation undergoes evolutionary changes, which are manifested in the change in the properties and state of the components of the tribotechnical system and intensified at the bifurcation points. It was established that the growth of bifurcation points leads to an increase in the probability of the manifestation of deformation processes with the dominance of the plastic component, which accelerates the realization of the catastrophic stage of wear of the tribosystem [21]. Adhesion in frictional contact occurs when the surface volume of the metal is absorbed.

The indicators of the specific work of friction obtained in [22] in the conditions of oil starvation indicate that adhesion in frictional contact occurs when energy of the limiting value is absorbed by the surface volume of the metal, which intensifies the processes of destruction of the material of the contact surfaces. During the periods of normal operation of the tribosystem and during the formation and restoration of dissipative structures, there is an increase in the specific work of friction, but this indicator rapidly decreases during the periods of adhesion of the contact surfaces. The stage of chaotic dynamics can also be manifested in the lubricant. In the process of operation, the lubricant undergoes mechanochemical transformations and is saturated with wear products, which leads to a decrease in its lubricating properties. The consequences of the intensification of tribochemical processes at the boundary between the lubricant and activated friction surfaces can be corrosion phenomena and fatigue wear with periodic pressure changes in the friction zone [23]. For example, when diesel fuel gets into engine oil, its tribological characteristics deteriorate, the degradation of the lubricant accelerates, and the degree of its oxidation increases [24].

The analysis of the tribotechnical indicators of the tribosystem when lubricated with plastic lubricants established the greatest influence on steel wear of such parameters as contact load, specific work of friction, and the thickness of the lubricating layer [25]. The authors proposed an empirical dependence of the wear of tribo-coupling elements on the specified factors, which allows predicting their intensity of wear in critical conditions, which include the conditions of the transition of the tribosystem to the semidry lubrication mode with a limited supply of lubricant to the friction zone. Under these lubrication conditions, the destruction of previously formed boundary films intensifies, and the energy tension of the frictional contact increases due to the increase in elastic-plastic deformations, which leads to an increase in the intensity of wear of steel surfaces.

The analysis of the factors influencing the processes of self-organization during friction in conditions dominated by the boundary lubrication regime showed that it is difficult to predict the behavior of the boundary layers for a wide range of operating conditions in tribosystems.

2. Purpose of Research

The purpose of the work is the development of methodical and hardware means of conducting the experiment and the determination of tribological criteria for the transition of the tribosystem to a state of self-organization. The actual way of evaluating the wear resistance of parts of the tribocombination is to establish the degree of influence of thin boundary films and the dynamic effects of their formation/destruction on the tribotechnical characteristics of the friction contact in order to predict the intensity of wear of the contact surfaces depending on the processes of self-organization of the tribosystem.

3. Research Materials

Transmission oil for hypoid gears (T-Shyp) of two manufacturers was chosen as lubricants for research. T-Shyp is a universal multifunctional oil containing highly effective antiseize additives. It can be used as an all-season oil for hypoid gears of trucks and special machines operating in the conditions of a moderately temperate climate zone.

Sample 1—transmission oil “Bora B” T-Shyp (Technical Specification Ukraine 19.2-38474081-017:2018/SAE 140/API GL-5). According to the chemical composition, this oil is a mixture of a highly viscous flavored product with high-purity distillate oil and a composition of additives (Infineum C9425 (zinc dialkyldithiophosphate), poly alkyl methacrylate copolymer, and alkylamine).

Sample 2—transmission oil for hypoid gears T-Shyp (Technical Specification 38.1011332-90). Oil composition: refined mineral oil (a complex mixture of hydrocarbons (C_{24}–C_{50}) obtained by selective purification and hydrogenation of petroleum distillate) and a complex of functional additives (zinc dialkyldithiophosphate and methylene-bis).

Additives in the specified samples of lubricants are added to improve antiseize and low-temperature properties. The main characteristics of the studied oils are presented in Table 1.

Rollers were made as the material of the contact surfaces-steel 30ChGSA (HRC 48–52, Ra 0.34 μm). The composition of the main chemical elements of steel 30ChGSA is given in Table 2.

Lubrication of the experimental samples was carried out using a container with oil.

4. Methodology of the Experiment

The study of lubricants is developed on the software-hardware complex (SHC) to estimate the tribotechnical parameters of the triboelements. SHC is a complex, which includes a friction installation (FI), an electronic unit (EU), and “Friction” software (software) installed on a personal computer (PC) of the IBM PC type. The software block of mathematical data processing calculates the coefficient of friction, thickness of the lubricating layer, rheological indicators of the lubricating material, etc. The designed program has a separate channel for visual evaluation of the kinetics of changes in the main tribotechnical indicators of tribocontact in online mode. Figure 1 shows the functional diagram of the SHC for evaluating the tribotechnical characteristics of friction pairs. The SHC has two gears (5 and 6) on the output shafts, to which experimental rollers (7 and 8) are attached; the rotation of the gears is carried out by programming the control unit 2 of the stepping electric motors (3 and 4), which are connected to the power source 1. The stepping motor 3 is fixed on the motor scale, to which the tension sensor 9 registering the friction moment is attached. The lower test sample 7 is immersed in the lubricant 10 and located in the bath 11, the lower body of which includes two thermocouples 12. The thermocouple 13 is attached to the rod 14. The loading device consists of a leverage system with a load of 15 and a counterweight of 16. The SHC works as follows: The tribosystem, which consists of two moving rollers (7 and 8), comes into contact in the process of friction, and the lubricant 10 is placed in the bath 11. The tribosystem is loaded with a predetermined force P using the loading device 15, and the rollers are set in motion by rotary drives (5 and 6).

The complex simulates the operation of gears in rolling with the slipping condition (Figure 2).

Table 1: Physicochemical indicators of transmission oil for hypoid gears T-Shyp.

Parameter	Sample 1 (transmission oil “bora B” T-Shyp)	Sample 2 (transmission oil for hypoid gears T-Shyp)
Kinematic viscosity (mm^2/s) (cSt) at 100°C (GOST 33768-2015)	25.0	18.5
The content of water-soluble acids and alkalis (GOST 6307-75)	Absence	Absence
Mass fraction of mechanical impurities (%) (GOST 6370-83)	0.001	0.005
Water content (%) (GOST 2477-2014)	Traces	Traces
Mass fraction of sulfur (%) (GOST 14377-75)	2.3	2.01
Solidification temperature (°C) (GOST 20287-91)	−22	−46
Flash point (°C) (GOST 4333-2021)	225	187
Corrosive effect on plates with:		
(i) Steel grades 40 or 50 according to GOST 1050	With stands	With stands
(ii) M2 grade copper according to GOST 859	Gives darkening	Gives darkening

Table 2: Chemical composition of steel 30ChGSA in percentage according to GOST 4543-71.

C	Mn	Si	Ni	P	S	Cu	Cr	Fe
0.29–0.34	0.8–1.1	0.9–1.2	<0.3	<0.025	<0.025	<0.3	0.8–1.1	~96

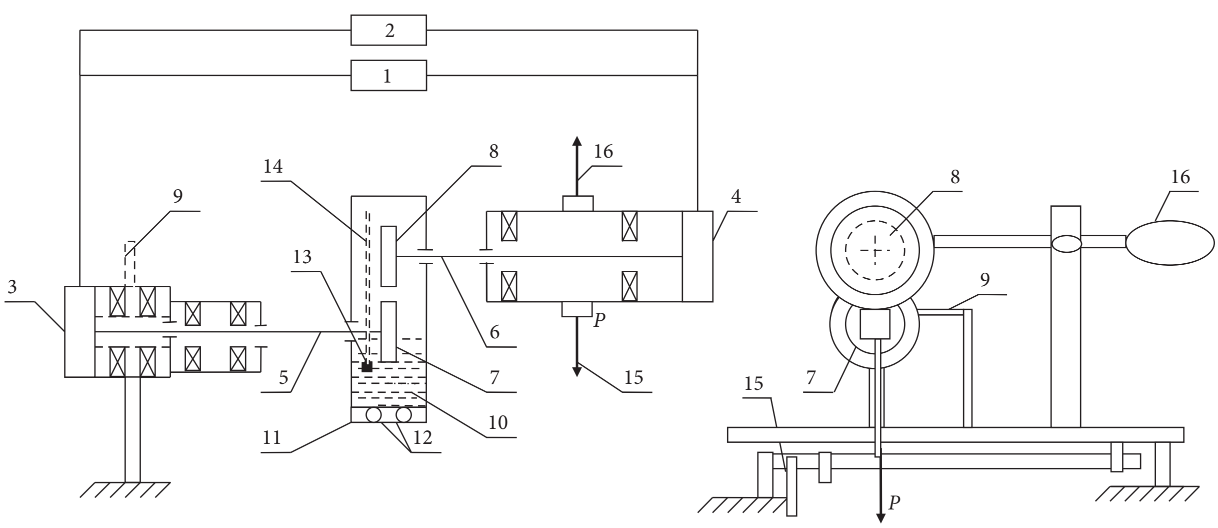


Figure 1: The scheme of the software-hardware complex for evaluating the tribotechnical characteristics of triboelements.

The electronic friction installation unit is designed for the following:

(i) Formation and transmission of control signals during the friction installation

(ii) Reception and initial processing of data from sensors during the friction installation

(iii) Transfer of results to a PC for further processing by software

The electronic unit includes a set of boards and modules. The moment of friction, the frequency of rotation of the rollers, the temperature of the lubricant, and the voltage drop in the lubricating layer in contact are recorded and processed on a PC in real time with a graphic representation of their changes.

Methods of determining the tribotechnical characteristics of the friction unit when using the investigated lubricant are as follows:

(i) Lubrication efficiency is determined by the method of voltage drop in the mode of a normal glow discharge by recording the voltage drop in the lubricating layer at a current of 2 and 4 A with further calculation of the thickness of the lubricating layer according to the calibration tables [26]

(ii) Antifriction properties of the contact are determined by the kinetics of the friction torque change and the subsequent calculation of the friction coefficient in the contact

(iii) Determination of the specific work of friction in the tribotechnical contact (this parameter is calculated

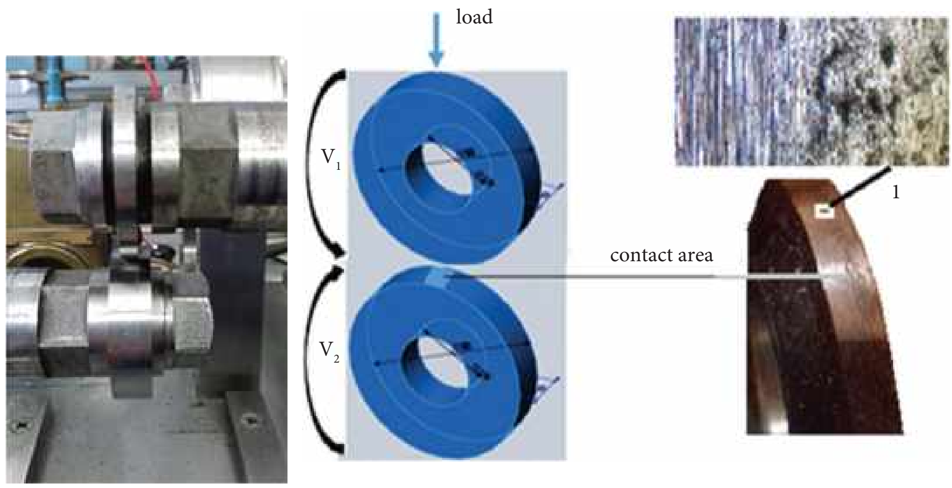


Figure 2: The scheme of the loading unit of the test samples with rotation at speeds V_1 and V_2 and the appearance of the friction tracks of the 30ChGSA steel sample; 1: section of the contact surface of the sample for structural studies.

by integrating the area along the registration curve of the friction moment in contact with the selected range of integration along the time coordinate)

(iv) Measurement of microhardness in the cross section of the central part of the contact track was carried out according to GOST 22162-76 (Method for determining microhardness) using the PMT-3 device with a load on the Vickers indenter of 0.2 N and a holding time of 10 s

(v) The antiwear properties of lubricants are determined by the results of measuring the previously applied hole by indenting the indenter of the PMT-3 device (GOST 27860-88. Parts of frictional couplings. Methods of measuring wear)

The research was carried out in nonstationary conditions, which involve the recurring operation of the engines of the research installation in the mode: start-stationary work—braking—stop with the support of the software program (Figure 3). The duration of one complete cycle was 80 seconds.

The maximum rotation frequency for the studied samples was 700 rpm or 1.83 m/s (leading surface) and 500 rpm or 1.31 m/s (lagging surface). Slippage—30%. The maximum Hertz contact load is 200 MPa. Slippage—30%. The maximum Hertz contact load is 200 MPa. The maximum number of cycles in the experiment is 100 cycles (from the 1st to the 45th cycle—oil temperature 20°C, from 46 to 50 cycle—oil heating, and from 51 to 100 cycle—oil temperature 100°C).

The structural state of the cross sections and fracture surfaces of the coatings before and after the tribological tests were studied using optical microscopy (a MIM-8M microscope with a Nikon Coolpix-4500 digital camera) and scanning electron microscopy (a TESCAN Mira 3 LMU microscope equipped with an OXFORD X-MAX 80 energy dispersive microanalyzer mm^2 for chemical micro-X-ray spectral analysis of the mass fraction of elements in the contact zone) [27].

5. Analysis of the Main Results

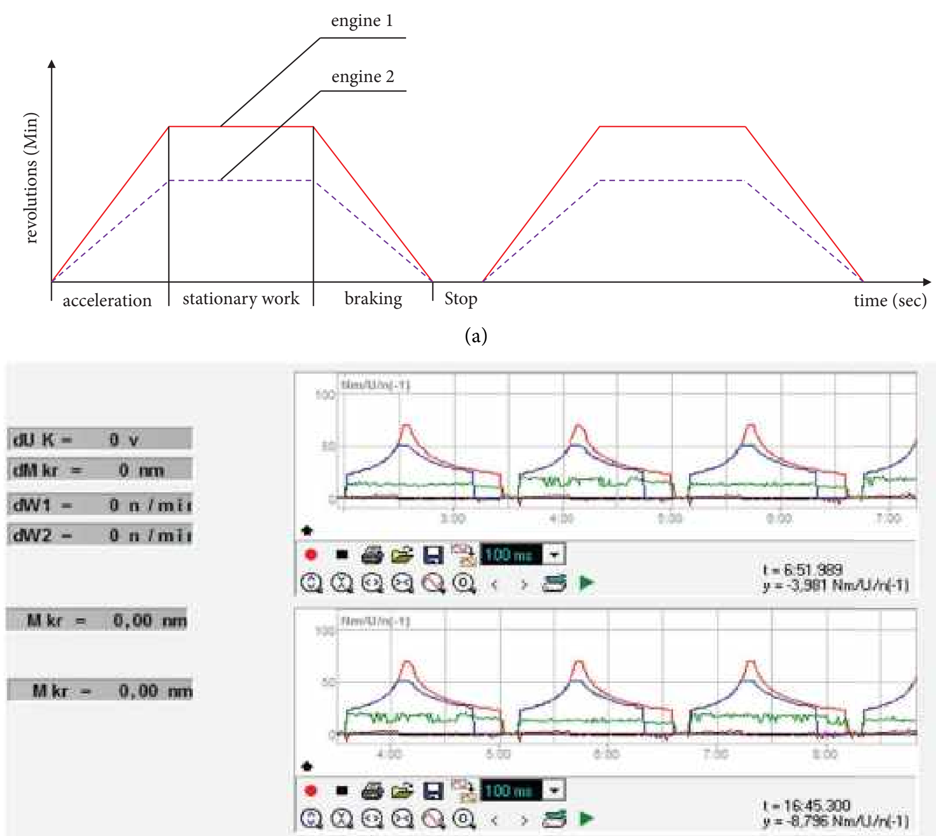
The studied oil samples are characterized by effective working-in properties, and the reduction of the friction coefficient in the initial run-in period of 7 cycles is 1.5 times for sample 1 and sample 2. A general regularity was established for the studied transmission oils regarding the increase in the friction coefficient when the temperature rises from 20 to 100°C (Figure 4).

For sample 1, the average values of the coefficient of friction are 0.009 and 0.015 at oil temperatures of 20 and 100°C, respectively. The coefficient of friction is stable, and the range of fluctuations of this parameter is within 0.006, . . ., 0.02. The increase in the friction coefficient by 1.66 times during 45–49 cycles is due to the changes in boundary layers caused by the lubricant's increased temperature.

For sample 2, the average values of the coefficient of friction are 0.012 and 0.016 at oil temperatures of 20 and 100°C, respectively, which are 1.3 times higher than the indicators established for sample 1. The coefficient of friction in the initial run-in period is 1.4 times higher, compared to sample 1. A similar pattern is maintained throughout the run-in period at an oil temperature of 20°C. Increased oil temperature leads to a two-fold increase in the friction coefficient during 45–49 working cycles.

The studied samples of lubricants are determined by effective greasing characteristics both during the start-up period and at the highest tested revolutions.

When the temperature in the tribotechnical contact for sample 1 decreases, the thickness of the boundary adsorption layers is due to the intensification of mechanical and chemical processes—the boundary layers with weak van der



(b)

FIGURE 3: The scheme of the engines' operation of the friction installation (a) and the interface of the data processing (b) during the operation of the tribosystem in nonstationary conditions.

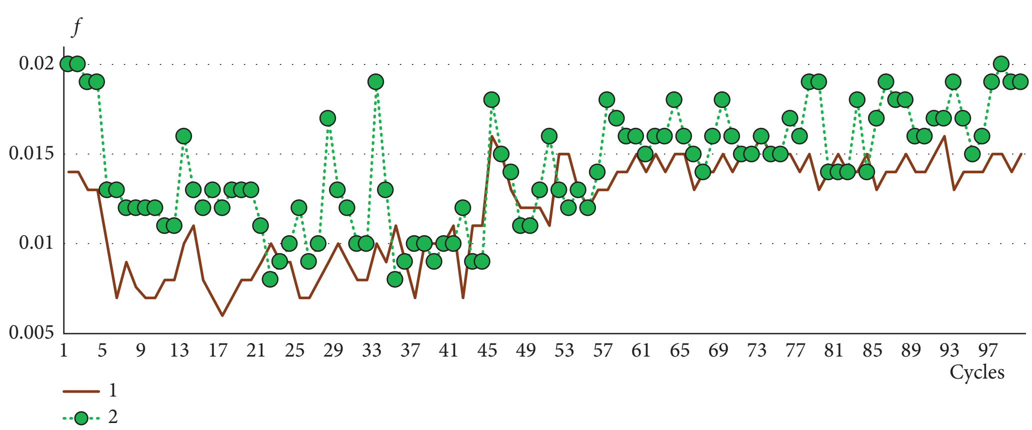


FIGURE 4: Kinetics of change in the friction coefficient: 1: sample 1; 2: sample 2.

Waals forces of interaction with the material of the contact surface are replaced by more stable adsorption chemically modified layers, which are characterized by more effective antiwear characteristics (Figure 5). The destruction of the boundary layers during start-up is not established, and semidry lubrication mode is established for up to 2% of cycles.

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

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

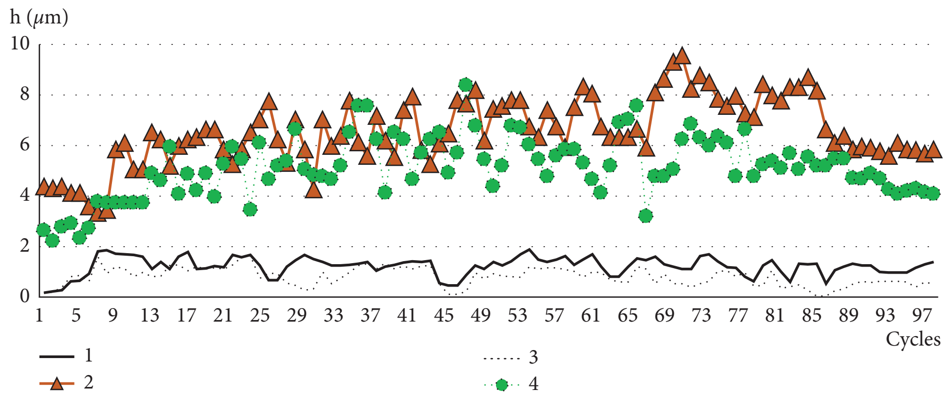


Figure 5: Formation of boundary adsorption layers (1 and 3) and the total thickness of the lubricating layer (2 and 4) in friction contact during operation: 1 and 2: sample 1; 3 and 4: sample 2.

where h is the thickness of the lubricating layer and 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–Stribeck diagram. Figure 6 and Table 3 present the calculated values of the lubrication mode for the studied lubricants.

The change in the temperature of sample 1 in a wide range does not affect the dominance of the mixed lubrication mode in the initial period of the cycle, which confirms the effective viscosity-temperature properties of the oil. At the maximum revolutions of the studied samples, which correspond to the stationary period of the working cycle, there is a significant increase in the thickness of the lubricating layer due to the hydrodynamic component, while conditions are created for the implementation of the hydrodynamic lubrication regime, ensuring reliable separation of the contact surfaces.

The patterns of the formation of boundary adsorption layers on friction-activated contact surfaces and the total thickness of the lubricating layer for sample 2 are similar to the changes considered for the sample 1. The differences are as follows: At a bulk oil temperature of 20°C, the thickness of the marginal adsorption layers is, on average, 0.96 μm, which is 1.3 times less compared to sample 1 (Figure 5). The decrease in the thickness of the boundary adsorption layers determines the dominance of the boundary mode of lubrication during the start-up period in 50% of the working cycles due to the increase in the probability of their mechanical destruction when the maximum tangential stresses are localized not in the thickness of the lubricating layer but at the boundary between the lubricating layer and the metal. When the temperature of the lubricating material increases for a short time, in 45–58 cycles, the thickness of the boundary layers decreases by 2.5 times, raising the dominance of a semidry lubrication mode at start-up.

At the highest revolutions of the studied samples, the hydrodynamic mode of lubrication dominates, regardless of the grease temperature, which indicates the effective separation of the contact surfaces due to the formation of a lubricating layer. The total thickness of the lubricating layer, which includes nonhydro and hydrodynamic components, is 1.2 times less than in sample 1, regardless of the temperature of the lubricant. During the run-in period, the total thickness of the greasing layer for sample 2 is 2 times less, compared to sample 1.

The structural adaptability of tribo-coupling elements due to irreversible mechano-chemical processes in the surface and near-surface layers of contact surfaces consists in the formation of wear-resistant dissipative structures that ensure a reduction in the energy load of frictional contact. Therefore, it is recommended to analyze the mechanisms of changes in the specific work of friction (A_{fr}) depending on the type of grease under study.

The obtained experimental values of A_{fr} for sample 1 in the range of 736, . . ., 11640 J/mm^2 characterize the operating conditions of the tribosystem with an average manifestation of energy processes in tribotechnical contact (Figure 7). With an increase in oil temperature from 20 to 100°C, the specific work of friction increases, on average, by 1.68 times, which indicates the transition of the tribosystem to more complex friction conditions. In the initial period of increasing the temperature of the lubricant, the specific work of friction increases slightly, up to 4730 J/mm^2. The breakdown of the lubricating layer is not established, and the investigated lubricant under such conditions ensures the implementation of the semidry lubrication mode in contact at start-up with a quick transition to the mixed lubrication mode.

For sample 2, the specific work of friction in contact during the initial run-in period lasting up to 13 cycles is characterized by high values at the level of 14,000–36,000 J/mm^2, which, on average, is 10 times higher than the similar parameter established for sample 1. With further working at 20°C, the specific work is, on average, 3191 J/mm^2, which is 1.37 times higher compared to sample 1. With an increase in the volume temperature of the oil to 100°C, the specific work of friction doubles and is, on average, 6213 J/mm^2, which is 1.6 times higher compared to sample 1. Periodic rapid periods of increase of A_{fr} in contact by 3, . . ., 5 times were recorded, which indicates the intensification of energy processes both at the lubricant-metal interface and in the surface layers of the metal. These processes usually lead to intensification of wear of friction pairs, which, in turn, is the main prerequisite for reducing the resource of the tribosystem.

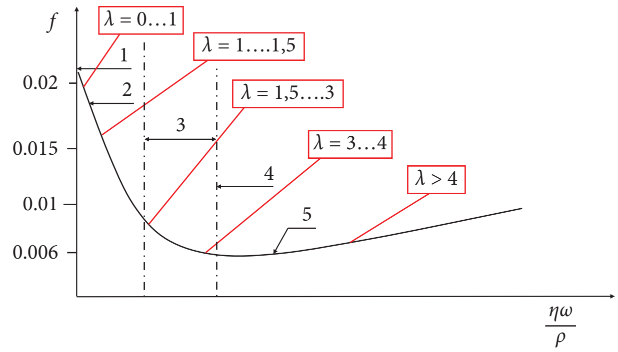


Figure 6: The friction coefficient (f) and lubrication mode (λ) according to the Hersey–Stribeck diagram. 1: dry, 2: boundary, 3: mixed; 4: elastohydrodynamic; 5: hydrodynamic lubrication modes.

Table 3: Antifriction and lubrication characteristics of transmission oils for hypoid gears.

Parameter	Lubricant			
	Sample 1		Sample 2	
	Temperature of the lubricant (°C)			
	20	100	20	100
Friction coefficient	0.006–0.016	0.011–0.02	0.008–0.02	0.011–0.02
Thickness of boundary adsorption layers (μm)	0.17–1.85	0.125–1.88	0.16–1.642	0.041–1.52
Lubrication mode at start-up	0.35–3.85	0.26–3.9	0.33–3.4	0.09–3.16
Thickness of the lubricating layer in contact (μm)	3.321–10.76	4.65–9.7	2.22–8.37	3.188–9.7
Lubrication mode at maximum revolutions	6.9–22.4	9.67–20.17	4.6–17.4	6.63–20.17

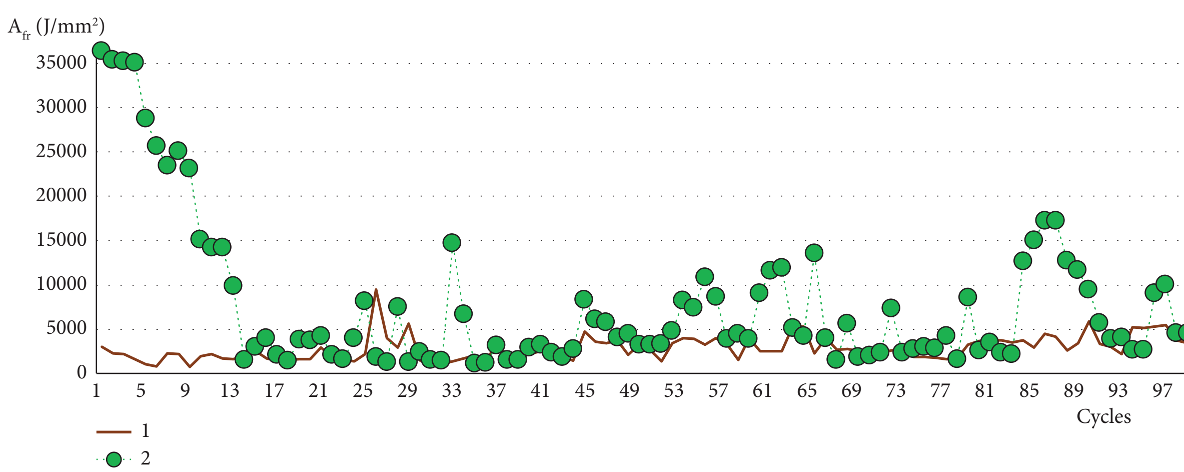


Figure 7: Kinetics of changes in the specific work of friction (A_{fr}) during working.

The total linear wear of rollers made of 30ChGSA steel is 3.259 μm and 5.21 μm when the friction pairs are lubricated with oil, respectively, in samples 1 and 2 (Table 4). The wear of the lagging surface is 2.14 (sample 1) and 1.47 (sample 2) times higher than the wear of the leading surface, which is caused by a decrease in the endurance limit of the lagging surface as a result of the increase in the rate of fatigue failure in the conditions of different directions of friction forces in contact on leading and lagging surfaces [28, 29].

The wear of contact surfaces is significantly affected by both the formation of protective chemically modified boundary layers of the lubricant and the formation of dissipative structures on the surface of the metal with increased hardness.

The change in the microhardness of the surface layers of 30ChGSA steel during work depends on the type of material under study and differs in the implementation of opposite processes.

When the friction pairs were lubricated with sample 1, strengthening of the leading (ΔH = +425 MPa) and lagging (ΔH = +705 MPa) surfaces was recorded (Table 4). When lubricating the friction pairs with sample 2, the weakening of the surface layers of the metal was established—a decrease in microhardness after working was recorded for the leading (ΔH = −300 MPa) and lagging (ΔH = −100 MPa) surfaces.

Microscopic examination of the friction surface showed that when samples 1 and 2 were used as lubricants, the

Table 4: Indicators of wear and microhardness of friction pairs.

Parameters	Lubricating material			
	Sample 1		Sample 2	
	Leading surface	Lagging surface	Leading surface	Lagging surface
Wear (micron)	1.039	2.22	2.11	3.1
Microhardness of the surface before the experiment (initial) (MPa)	6082	6438	6476	7717
Microhardness of the surface after the experiment (MPa)	6507 strengthening	7143 strengthening	6176 loss of strength	7618 loss of strength

friction surface was 90% and 50% covered with lubricant films, respectively, for the specified oils (Figure 8).

Since the studied transmission oils contain antiseize additives, the active components of which, upon activation of the surface layers of the metal during friction, form protective chemically modified layers on their surface. The surface area covered by these films is a leading indicator of the antiwear properties of the oil since the formed boundary layers of the lubricant protect friction pairs from direct contact in harsh lubrication conditions, which include the investigated nonstationary processes. This is confirmed by the correlation between the area of the surface covered with protective films and the wear resistance of the friction pairs when sample 1 is used as a lubricant. The wear resistance of the leading and lagging surfaces increases by 2 and 1.4 times, respectively, compared to a similar indicator when using sample 2.

To evaluate the strength characteristics of dissipative structures formed during friction, the method of sclerometry of the contact surface after friction under a load of 20 N was applied [30]. The depth of introduction of the indenter during sclerometry is the main parameter by which it is possible to establish the degree of resistance of the near-surface layers of the metal under the action of the load.

The formation of dissipative structures during the lubrication of tribo-coupling elements with sample 1 due to the strengthening of the surface layers of the metal during friction leads to a decrease in the spread of elastic-plastic deformations in the near-surface layers of the metal in depth by 23% compared to the dissipative structures formed when using sample 2 as a lubricant (Figure 9).

When sample 1 is used as a lubricating material at 60% and 30%, respectively, for the leading and lagging surfaces, the formation of a nonuniform deformation microrelief is established, which is manifested in the uneven distribution of thin slip marks in zones with a fine-grained structure. When lubricating the friction pairs with sample 2, the degree of inhomogeneous plastic deformation for the leading surface is up to 30% of the length of the indenter scanning path, and the formation of a fine-grained structure was not recorded for the lagging surface.

The formation of a fine-grained dissipative structure under friction provides increased wear resistance of tribo-coupling elements since the coatings, films, and nanoscale multilayer structure formed on the surface can show a shielding effect for mobile dislocations, which makes it difficult for them to go outside; as a result, the strength and creep limit, as well as the fatigue life of the subsurface layer, increase [31, 32].

The established positive effect of the formation of near-surface layers with a fine-grained structure on the wear resistance of friction pairs and the reduction of specific work of friction during operation in nonstationary conditions can be explained by the shielding properties of the boundary films of the lubricant due to the manifestation of the plasticizing effect of surface-active substances on the surface layers of investigated steel surfaces with their subsequent strengthening under an increase in the density of dislocations. Work [33] observed a decrease in energy absorption rates of metals with a decrease in their grain volume (in the range from tens to several micrometers), which is due to a decrease in the level of internal friction.

In the process of mechano-chemical reactions, the near-surface layers of 30ChGSA steel undergo a structural transformation, the result of which is the formation of metastable dissipative structures with an increased number of active components of the lubricant, which include oxygen, sulfur, and phosphorus (Figure 10 and Table 5).

When lubricating the friction pairs with lubricant sample 1, the concentration of the specified active elements in the near-surface layers of the metal at a depth of up to 10 μm is 2 times higher compared to the friction pairs that were lubricated with sample 2. The two used transmission oil samples contain a multifunctional (antiwear, antioxidant, and anticorrosion) zinc dialkyldithiophosphate additive, which is the main source of active phosphorus and sulfur elements. According to ideas about the mechanism of action of antiwear additives, zinc dialkyldithiophosphates initiate polymolecular adsorption of hydrocarbon molecules of the lubricant [34]. At the same time, the conventional thickness and mechanical properties of the adsorption layer depend both on the properties and concentration of the additive and on the parameters of the hydrocarbon molecules. When additives are introduced into base oils containing hydrocarbon components with a higher molecular weight, the antiwear properties of the additives are stronger than in oils consisting of hydrocarbons with a lower molecular weight. Unlike sample 2, which contains only high-purity distillate oil as a base, sample 1 contains up to 15% of a highly viscous flavored product that enhances the activity of zinc dialkyldithiophosphate. Effective tribological characteristics of lubricant additives are explained by the synergistic effect of long aliphatic chains and highly active elements of

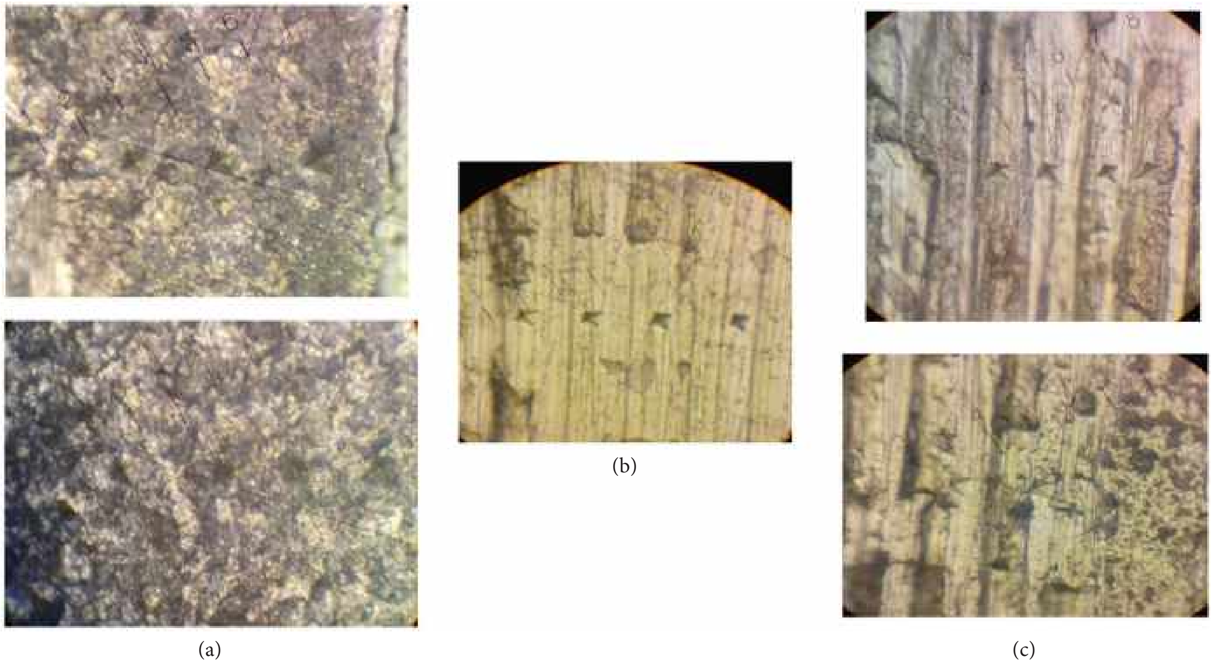


Figure 8: Photographs of areas of frictional contact: (a) when lubricated with lubricant sample 1, (b) the starting surface, and (c) when lubricated with lubricant sample 2.

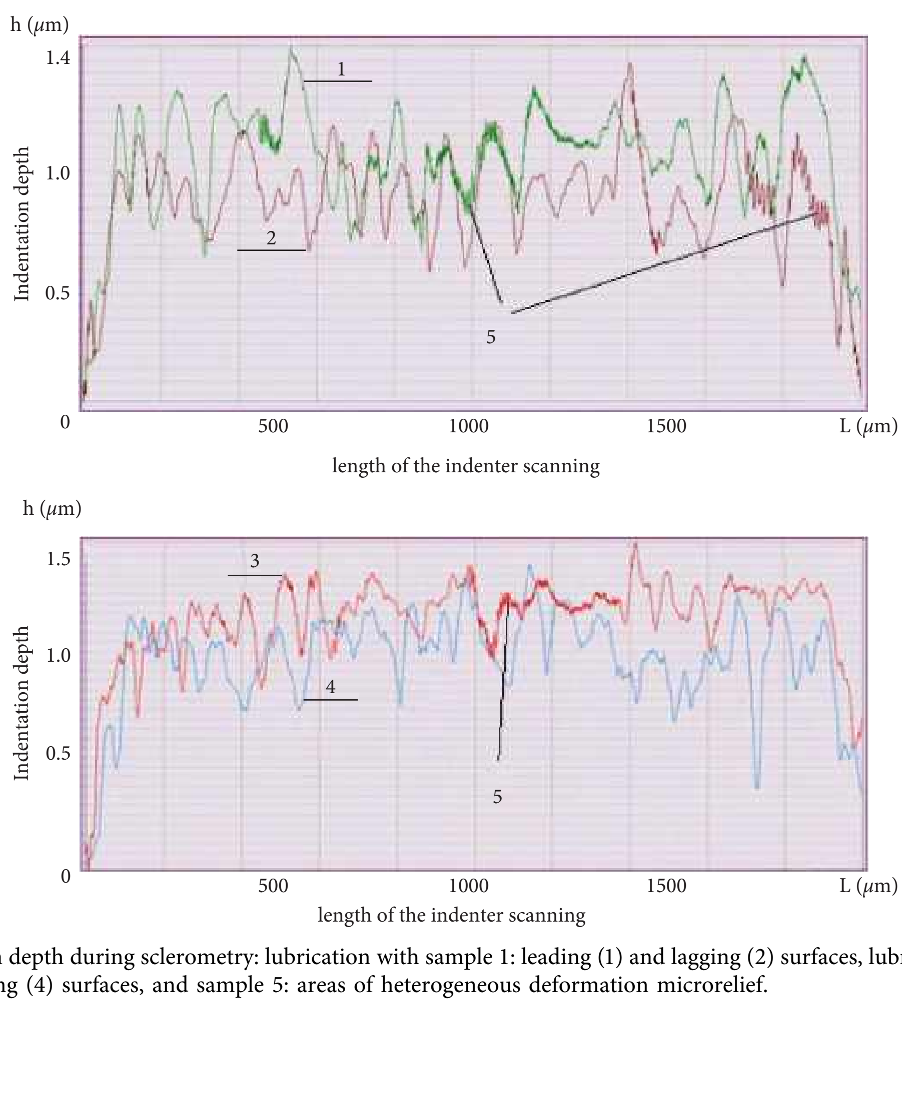
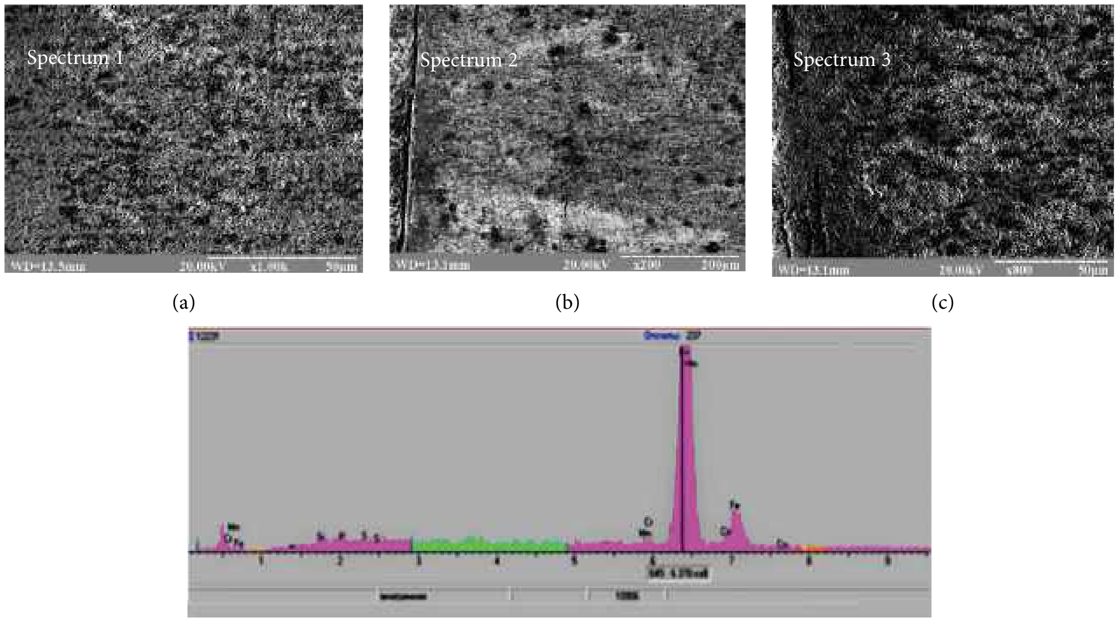


Figure 9: Indentation depth during sclerometry: lubrication with sample 1: leading (1) and lagging (2) surfaces, lubrication with sample 2: leading (3) and lagging (4) surfaces, and sample 5: areas of heterogeneous deformation microrelief.



(a) (b) (c)

(d)

Figure 10: The scanning electron microscopic image in backscattered electrons of the microstructure of the cross-sections of the 30ChGSA steel samples before (a, d) and after tribological tests during lubrication with sample 1 (b) and sample 2 (c). The rectangular zones indicate the areas of micro-X-ray spectral analysis of the chemical composition.

Table 5: Chemical composition (at %) of the selected microstructural elements of the cross-section of samples of steel 30ChGSA.

Spectrum	Element									
	C	Mn	Si	Ni	P	S	Cu	Cr	Fe	O
1	0.28	1.08	1.23	0.10	0.02	0.01	0.21	1.01	~95.88	~0.18
2	0.30	1.05	1.20	0.08	0.07	0.12	0.23	1.10	~94.83	1.02
3	0.31	1.03	1.19	0.08	0.03	0.05	0.20	0.99	~95.54	0.58

phosphorus and sulfur, which form a tribochemical boundary lubricating film [17, 35].

The presence of an alkylamine corrosion inhibitor, which ensures the formation of an oxygen-enriched tribo-film, also contributes to the increase in the antiwear properties of the dissipative structures formed when using sample 1 [36]. The formation of thin oxide layers as a result of mechano-chemical oxidation reactions can probably be considered the formation of a gradient oxide layer several hundreds of nanometers deep, consisting mainly of amorphous oxides [27, 37].

Thus, the formation of wear-resistant dissipative structures during friction must be considered a combination of mechanical activation processes in the upper surface layers of the tribo-coupling elements and chemical modification of the friction surfaces with active components of the lubricant, the rational choice of which will provide an opportunity to increase the durability of the friction pairs in operational conditions.

6. Conclusions

(1) The use of transmission oils manufactured according to different formulations allows to increase the antifriction characteristics of tribocontact, increase the thickness of the marginal adsorption layers, and create conditions for the implementation of mixed or hydrodynamic lubrication modes.

(2) Due to the rational choice of the lubricant, it is possible to reduce the intensification of energy processes both at the lubricant-metal interface and in the surface layers of the metal. In nonstationary lubrication conditions, with an increase in the oil temperature to 100°C, the specific work of friction increases, on average, by 1.68 times, which indicates the transition of the tribosystem to more complex friction conditions.

(3) Increasing the wear resistance of the elements of the tribosystem is facilitated by the processes of strengthening the surface layers during operation due to the formation of a fine-grained dissipative structure, which is the result of mechano-chemical reactions between the metal surface activated in the friction process and the active components of the lubricant.

(4) The formation of wear-resistant metastable dissipative structures with an increased number of active

components of the lubricant, which include oxygen, sulfur, and phosphorus, depends both on the base of the lubricant and on functional additives that can exert a synergistic effect on improving the tribological properties of the contact.

Data Availability

The data supporting the findings of the current study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] D. A. H. Hanaor, Y. Gan, and I. Einav, "Static friction at fractal interfaces," *Tribology International*, vol. 93, pp. 229–238, 2016.

[2] P. Sędłak, B. Białobrzeska, T. Stawicki, and P. Kostencki, "Effect of polypropylene modification by impregnation with oil on its wear and friction coefficient at variable load and various friction rates," *International Journal of Polymer Science*, vol. 2017, Article ID 9123586, 19 pages, 2017.

[3] O. A. Mikosyanchik and R. G. Mnatsakanov, "Tribotechnical characteristics of cast iron with a steel coating in lubrication medium under unsteady modes," *Journal of Friction and Wear*, vol. 38, no. 4, pp. 279–285, 2017.

[4] P. M. Cann, "Boundary lubrication mechanisms in artificial joints," in *Encyclopedia of Tribology*, Q. J. Wang and Y. W. Chung, Eds., pp. 259–262, Springer, Boston, MA, USA, 2013.

[5] Z. Zhang, Z. Cui, H. Wang, C. Jiang, J. Zhao, and L. Ren, "Tribological performance of microstructured surfaces with different wettability from superhydrophilic to superhydrophobic," *Biosurface and Biotribology*, vol. 6, no. 4, pp. 118–123, 2020.

[6] A. Moshkovich, V. Perfilyev, and L. Rapoport, "Effect of plastic deformation and damage development during friction of fcc metals in the conditions of boundary lubrication," *Lubricants*, vol. 7, no. 5, Article ID 7050045, 2019.

[7] C. Cafolla, W. Foster, and K. Voïtchovsky, "Lubricated friction around nanodefects," *Science Advances*, vol. 6, no. 14, p. 3673, 2020.

[8] N. Jeyaprakash and C. H. Yang, "Friction, lubrication, and wear," in *Tribology in Materials and Manufacturing-Wear, Friction and Lubrication*IntechOpen, London, UK, 2020.

[9] J. N. Sultan, E. T. Karash, T. K. Abdulrazzaq, and M. T. E. Kassim, "The effect of multi-walled carbon nanotubes additives on the tribological properties of austempered AISI 4340 steel," *Journal Européen des Systèmes Automatisés*, vol. 55, no. 3, pp. 387–396, 2022.

[10] Ph. Boure, D. Mazuyer, J. M. Georges, A. A. Lubrecht, and G. Lorentz, "formation of boundary lubricating layers with water-based lubricant in a concentrated elastohydrodynamic contact," *Journal of Tribology*, vol. 124, no. 1, pp. 91–102, 2002.

[11] Y. Zhang, A. Kovalev, and Y. Meng, "Combined effect of boundary layer formation and surface smoothing on friction and wear rate of lubricated point contacts during normal running-in processes," *Friction*, vol. 6, no. 3, pp. 274–288, 2018.

[12] M. V. Boiko, A. V. Sidashov, T. G. Boiko, I. V. Burykin, and I. E. Uflyand, "The mechanism of formation of boundary lubricating films during friction in a medium of di(2-ethylhexyl) sebacate," *Tribology International*, vol. 165, Article ID 107222, 2022.

[13] H. Abdullah Tasdemir, T. Tokoroyama, H. Kousaka, N. Umehara, and Y. Mabuchi, "Influence of zinc dialkyldithiophosphate tribofilm formation on the tribological performance of self-mated diamond-like carbon contacts under boundary lubrication," *Thin Solid Films*, vol. 562, pp. 389–397, 2014.

[14] S. M. Hsu and R. S. Gates, "Boundary lubricating films: formation and lubrication mechanism," *Tribology International*, vol. 38, no. 3, pp. 305–312, 2005.

[15] I. A. Lyashenko, "Зв'язок між Цараметрами Цорядку модуляції Ґустини і надлишковоҐо об'єму Ցри оЦисі стаціонарнич структурнич станів межовоҐо мастила," *Ukrainian Journal of Physics*, vol. 66, no. 11, pp. 993–1008, 2021.

[16] I. A. Lyashenko, A. E. Filippov, M. Popov, and V. L. Popov, "Effect of stress non homogeneity on the shear melting of athin boundary lubrication layer," *Physical Review A*, vol. 94, no. 5, Article ID 053002, 2016.

[17] I. Mukchortov, E. Zadorozhnaya, I. Levanov, and K. Pochkaylo, "The influence of poly-molecular adsorption on the rheological behavior of lubricating oil in a thin layer," *FME Transactions*, vol. 43, no. 3, pp. 218–222, 2015.

[18] X. Hua, J. Puoza, P. Zhang, X. Xie, and B. Yin, "Experimental analysis of grease friction properties on sliding textured surfaces," *Lubricants*, vol. 5, no. 4, Article ID 5040042, 2017.

[19] M. Banjac, A. Vencl, and S. Otović, "Friction and wear processes – thermodynamic approach," *Tribology in Industry*, vol. 36, no. 4, pp. 341–347, 2014, http://www.tribology.rs/journals/2014/2014-4/1.pdf.

[20] V. L. Zakovorotny and V. E. Gvindjiliya, "Self-organization and evolution in dynamic friction systems," *Journal of Vibro engineering*, vol. 23, no. 6, pp. 1418–1432, 2021.

[21] V. L. Zakovorotnyi and V. S. Bykador, "Cutting-system dynamics," *Russian Engineering Research*, vol. 36, no. 7, pp. 591–598, 2016.

[22] O.O. Mikosyanchyk, R. H. Mnatsakanov, L. . A. Lopata, V. E. Marchuk, and O. E. Yakobchuk, "Wear resistance of 30KhGSA steel under the conditions of rolling with sliding," *Materials Science*, vol. 55, no. 3, pp. 402–408, 2019.

[23] J. Lubas, W. Szczypiński-Sala, P. Wo´s, E. Zieli´nska, and K. Miernik, "Experimental analysis of tribological processes in friction pairs with laser borided elements lubricated with engine oils," *Materials*, vol. 13, no. 24, Article ID 13245810, 2020.

[24] R. Kuti, F. Könczöl, L. Csapó, L. Földi, and Á. D. Toth, "Detection of the possible engine damages in case of a continuous track military vehicles with tribological investigations," *FME Transactions*, vol. 50, no. 3, pp. 526–534, 2022.

[25] R. G. Mnatsakanov, O. A. Mikosianchyk, O. E. Yakobchuk, and B. D. Khalmuradov, "Lubricating properties of boundary films in tribosystems under critical operation conditions," *Journal of Machinery Manufacture and Reliability*, vol. 50, no. 3, pp. 229–235, 2021.

[26] T. M. A. Al-Quraan, "A manifestation of non-hydrodynamic factors in steady-state conditions of friction," *Journal of Mechanical Engineering*, vol. 14, no. 2, pp. 111–126, 2017, https://ir.uitm.edu.my/id/eprint/21124.

[27] B. N. Mordyuk, O. O. Mikosyanchik, and R. G. Mnatsakanov, "Structure-phase state and wear of Ni–Cr–B–Si–c coating on steel 1045 under friction conditions with the shear load

component," *Metallofizika I Noveishie Tekhnologii*, vol. 42, no. 2, pp. 175–195, 2020.

[28] I. Goryacheva and A. Meshcheryakova, "Modelling of delamination in rolling and sliding contacts," *Procedia Structural Integrity*, vol. 41, pp. 220–231, 2022.

[29] X. J. Zhao, Q. Chen, Y. S. Liu, X. Y. Qiu, E. Meli, and A. Rindi, "Effects of slip ratio and contact stress on rolling contact fatigue of defected rail materials," *Engineering Failure Analysis*, vol. 131, Article ID 105817, 2022.

[30] M. Khoma, C. Vasyliv, V. Vynar, V. Zakiev, B. Datsko, and M. Golovchuk, "Influence of heat treatment of 30MnB5 steel on its micromechanical properties and resistance to abrasion wear," *Tribology in Industry*, vol. 44, no. 1, pp. 310–321, 2022.

[31] V. P. Babak, V. V. Shchepetov, and S. D. Kharchenko, "Wear resistance of self-lubricating coatings due to the formation of carbide graphite," *Mechanics and Advanced Technologies*, vol. 89, no. 2, pp. 99–105, 2020.

[32] V. M. Beresnev, O. V. Maksakova, S. V. Lytovchenko et al., "Correlating deposition parameters with structure and properties of nanoscale multilayer (TiSi)N/CrN coatings," *East European Journal of Physics*, vol. 2, pp. 112–117, 2022.

[33] A. I. Ustinov, V. S. Skorodzievskii, and N. S. Kosenko, "A study of the dissipative properties of homogeneous materials deposited as coatings. Part 2. Copper condensates with different microstructural characteristics," *Strength of Materials*, vol. 40, pp. 275–281, 2008.

[34] S. Berkani, F. Dassenoy, C. Minfray et al., "Model formation of ZDDP tribofilm from a mixture of zinc metaphosphate and goethite," *Tribology International*, vol. 79, pp. 197–203, 2014.

[35] H. Ding, X. Yang, L. Xu et al., "Analysis and comparison of tribological performance of fatty acid-based lubricant additives with phosphorus and sulfur," *Journal of Bioresources and Bioproducts*, vol. 5, no. 2, pp. 134–142, 2020.

[36] T. Massoud, R. P. De Matos, T. Le Mogne et al., "Effect of ZDDP on lubrication mechanisms of linear fatty amines under boundary lubrication conditions," *Tribology International*, vol. 141, Article ID 105954, 2020.

[37] C. Florian, R. Wonneberger, A. Undisz et al., "Chemical effects during the formation of various types of femtosecond laser-generated surface structures on titanium alloy," *Applied Physics A*, vol. 126, no. 4, p. 266, 2020.