***Problems of Tribology**, V. 28, No 3/109-2023, 49-55*

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2023-109-3-49-55

Mechanisms of formation of wear-resistant dissipative structures in non-stationary lubrication conditions

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Received: 20 August 2023: Revised:15 September 2023: Accept:25 September 2023

Abstract

The work aimed to determine the influence of the processes of supramolecular self-organization in the lubricating layer on the patterns of wear of friction pairs. The mechanisms of structural adaptability of tribocoupler elements were analyzed, and the regularities of the manifestation of a large-scale and energy jump, which characterizes the transition of the tribosystem to a metastable state, were determined. An evaluation of the tribotechnical characteristics of commercial transmission oils was carried out on a software-hardware complex that, using a roller analogy, simulates the operation of gears in conditions of rolling with slipping. It was established that the activation of contact surfaces in the mode of frequent starts and stops leads to active interaction of the lubricant's components and the metal's surface layers with the gradual formation of boundary adsorption layers. For transmission oil 'Bora B' T-Shyp, an increase in anti-friction properties has been established due to the effective lubricating ability of the oil when forming the hydro- and non-hydrodynamic components of the lubricating layer thickness. The effect of the chemical activity of the zinc dialkyl dithiophosphate antiwear additive and the hydrocarbon components of the base of transmission oils on the effectiveness of the formation of boundary films is considered. It was determined that the formation of stable boundary films of the lubricant is the leading process in manifesting their damping properties concerning the localization of elastic-plastic deformation along the depth of the metal. When boundary films are formed on 90-95% of the contact area, the change in the microstructure of the near-surface layers is fixed at a depth of up to 20 microns; when boundary films are formed on 20...50% of the surface area, the spread of elastic-plastic deformation reaches a depth of up to 50 microns. The kinetics of the formation of boundary films by the lubricant and the indicators of the specific work of friction in contact are correlated with the intensity of wear of the contact surfaces.

Key words: wear, microhardness, specific work of friction, lubrication, deformation, microstructure.

Introduction

The improvement of machines and mechanisms, the expansion of their operating conditions in the load-speed and temperature range put forward stricter requirements for lubricant quality and tribotechnical properties of lubricants. A critical aspect affecting the operational properties of lubricants is their ability to change the surface properties of triboelements by forming ordered structures as a result of the internal restructuring of the tribosystem. In each specific case, self-organization manifests itself differently. It depends on the complexity and nature of the tribotechnical system. The process of ordering in the system takes place with the help of internal factors, without external specific influence. Self-organization primarily reduces entropy production of processes occurring within the surface layers [1]. The lubricant is the most critical element in any tribological system, which ensures the modification of the surface layers of the metal due to such processes as passivation, the formation of boundary layers of lubricant of different nature, weakening or strengthening of the metal surface due to the manifestation of external or internal effects of Rebinder et al. The processes of self-organization of the lubricant and the mechanical system, which includes friction nodes, largely depend on the base's hydrocarbon composition and the additive package's functional properties. The essence of the self-organization of the tribotechnical system is that the interaction of the tribocoupling elements' surface layers and the lubricant's activated components is localized in thin near-surface layers. Such interaction causes the formation of secondary friction structures that protect the tribotechnical system from external influences.

Determining the mechanisms of the formation of boundary films of lubricant on contact surfaces activated by friction, the kinetics of changes in the specific work of friction, the patterns of changes in antifriction, and rheological indicators of frictional contact will expand the vision about the ways of ordering secondary protective structures. That will make it possible to control the processes of self-organization of the tribosystem due to the selection of a lubricant with a specific base and multifunctional additives, which will ensure increased wear resistance of friction pairs by localization of adaptation processes in surface metastable structures.

Literature review

One of the most common manifestations of friction in mechanical systems is the release of heat in the area of contacting surfaces. The main activating factor of triboprocesses in the zone of frictional contact is elastoplastic deformation. According to [2, 3], from a thermodynamic point of view, the work of friction forces can be conditionally divided into two components. The first part of the friction work measures material damage and relates to the change in the deformed volumes of materials in the latent (potential) energy of various elementary defects and damages that originate and accumulate in the near-surface layers of materials. The second part of the friction work is related to microscopic mechanisms of the dissipative type. It is related to dynamic recovery processes, during which latent energy and heat of friction are released. There are many contradictions regarding the quantitative indicators of stored energy during friction. According to [4, 5], most of the energy spent on deformation is converted into heat, and only a few percent of this energy is stored to form crystal lattice defects. In [6], it is noted that more than 90% of all stored energy is concentrated inside the surface films, which are stable zone with increased internal energy.

Since the surface layer of tribocoupler elements is an open thermodynamic system, friction, and wear processes can be described by energy balance or entropy balance equations. The total production of entropy in the tribosystem always increases. However, instead of the expected chaos and degradation, self-organization processes dominate the vast majority of tribosystems, which creates prerequisites for the tribosystem to remain in an equilibrium state for a long time. The level of the equilibrium state is determined not by the entire entropy but only by its small part, which is related to the substance of the tribostructure. At a constant temperature, it is proportional to the volume and can increase and decrease [7]. The competition of free energy and entropy gives rise in conditions far from equilibrium to stable periodic processes. As a result of such processes, the formation of dissipative structures is possible, leading to the tribosystem's self-organization. Dissipative structures are characterized by processes producing negative entropy [8]. Due to the occurrence of processes with negative entropy production, the total entropy production in a system with dissipative structures is lower than in a similar system without them. The formation of dissipative structures leads to decreased entropy production and wear rate.

According to [9], the maximum production of entropy is a condition for initiating the self-organization process in tribofilms, capable of significantly reducing the wear rate. The authors consider applying friction body run-in in rigid regimes close to seizure. In such conditions, the activation of triboprocesses is accelerated, and there is a correlative decrease in the run-in period and the time of the start of self-organization, which leads to a decrease in overall wear. In [6], a new technology for selecting wear-resistant materials, based on the selection of materials that accelerate the formation of dissipative structures, is considered. The authors show that the intensity of the wear process for the formation of dissipative structures is lower than for the formation of equilibrium surface structures. Presented in [10, 11], the method of studying self-organization processes based on the parameters of thermo-oxidative stability of lubricants with cyclic temperature changes allows to determine the quantitative indicators of self-organization processes, in which excessive thermal energy is transferred to lower energy levels with the formation of oxidation and evaporation products, according to which the temperature range is established performance of lubricants and their resource. In [12], it was found that when steel is rubbed in a lubricating medium (transmission oils based on pentaerythritol esters and organosiloxane liquids), protective surface films of sulfur and silicon compounds are formed on the surface of the steel. It is noted that the presence of unoxidized iron on the friction track promotes catalytic reactions that form surface films of lubricant molecules that reduce the friction coefficient by 70–80%. The leading indicators characterizing the formation of wear-resistant dissipative structures when lubricating steel with oils for hypoid gears include an increase in antifriction characteristics, the formation of boundary layers of lubricant, strengthening of contact surfaces, and the formation of a heterogeneous deformation microrelief with a fine-grained structure [13]. The formation of chemically modified boundary layers on 90% of the contact area of the tribo-coupling elements ensures an increase in the wear resistance of the leading and trailing surfaces in rolling with slipping by 2 and 1.4 times, respectively.

Thus, establishing the mechanisms of structural adaptability of tribo-coupling elements, determining the patterns of manifestation of a large-scale and energy jump, which characterizes the transition of the tribosystem to a metastable state, will allow determining the ways of controlling dynamic recovery processes in the zone of frictional contact.

Purpose

To determine the influence of the processes of supramolecular self-organization in the lubricating layer on friction pairs' wear patterns.

Objects of research and experimental conditions

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 anti-seize additives. It can be used as an all-season oil for hypoid gears of trucks and special machines operating in the conditions of a moderate 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-dialkylditiophosphate), poly alkylmethacrylate copolymer and alkylaminemine). Sample 2 - transmission oil for hypoid gears T-Shyp (Technical Specification 38.1011332-90). Oil composition: refined mineral oil (a complex mixture of hydrocarbons (C24-C50), obtained by selective purification and hydrogenation of petroleum distillate) and a complex of functional additives (zinc dialkyldithiophosphate and methylene-bis).

Rollers were made as the material of the contact surfaces - steel 45 (HRC 38 - 42, Ra 0.37 µm).

The study of lubricants is developed on the Software-Hardware Complex (SHC) to estimate the tribotechnical parameters of the triboelements [14]. The complex simulates the operation of gears in rolling with slipping condition.

The research was carried out in non-stationary 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 (Fig. 1). The duration of one complete cycle was 80 seconds.

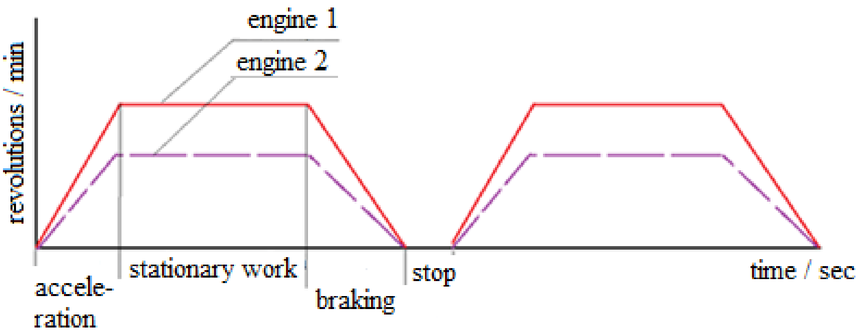

Fig. 1. Scheme of the engines' operation of the friction installation during the operation of the tribosystem in non-stationary conditions [13].

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 ^{0}C, from 46 to 50 cycle - oil heating, from 51 to 100 cycle - oil temperature 100 ^{0}C).

Analysis of the main results

Table 1 presents the averaged results of the tribotechnical parameters of the frictional contact in conditions of rolling with slipping.

Table 1

Tribotechnical characteristics of the contact

Indicator	**Lubricant**			
	Sample 1		Sampl 2	
	Lubricant temperature, ^{0}C			
	20	100	20	100
Coefficient of friction	0.009	0.015	0.013	0.021
The minimum thickness of boundary layers, µm	0.12	0.09	0.1	0.038
The total thickness of the lubricating layer, µm	5.14	4.7	4.5	3.95
Specific work of friction, J/mm2	12569	15440	39100	19000
Effective viscosity in contact, Pa·s	490.9	58.21	190.4	41.71

The increase in the antifriction properties of tribocontact by 30% when using sample 1 as a lubricant is due to the greater bearing capacity of the lubricating layer. The total thickness of the lubricating layer, which consists of hydro- and non-hydrodynamic components, is on average 12...14% higher for sample 1.

Activation of contact surfaces in the mode of frequent starts and stops leads to active interaction of the lubricant components and metal surface layers, which is manifested in the formation of boundary adsorption layers (Fig. 2).

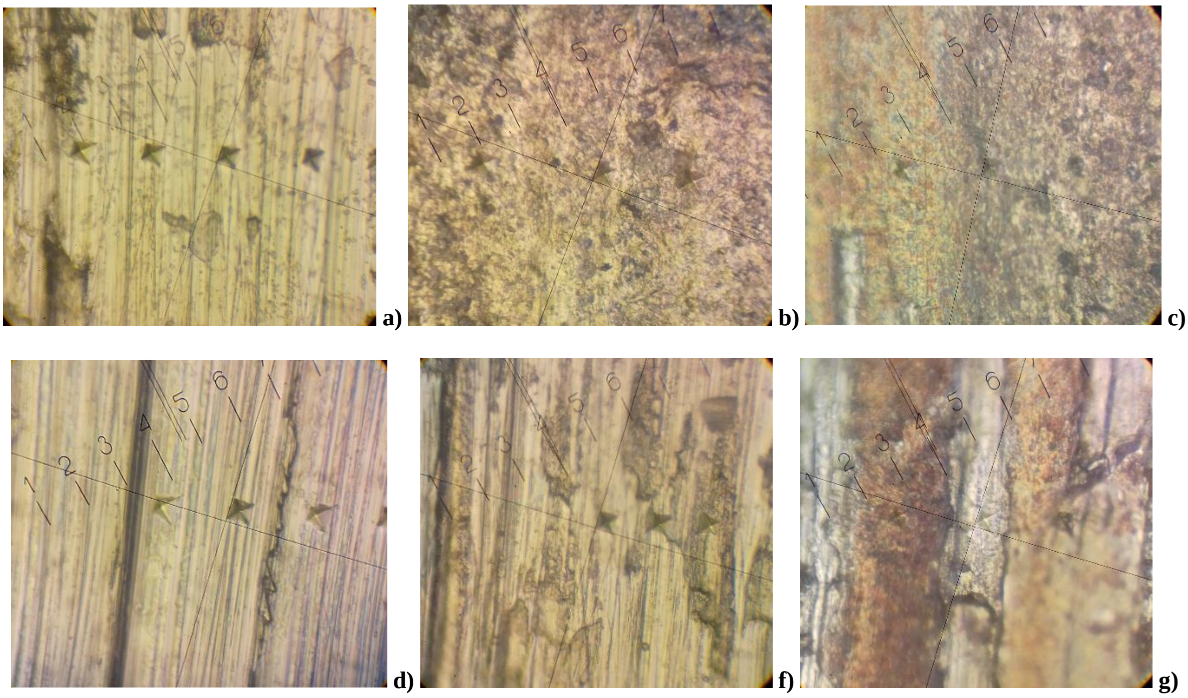

Fig. 2. The initial surface of steel 45 (a, d) and after 100 cycles of lubrication by sample 1 (b, c) and sample 2 (f, g).

However, the mechanism of formation of the non-hydrodynamic component of the lubricating layer thickness is significantly different for the two oils under study. Let us consider this mechanism with the energy parameter of contact-specific friction work. The activation of the surface layers of steel 45 due to elastic-plastic deformation causes the chemical activity of the anti-wear additive zinc dialkyl dithiophosphate and hydrocarbon components of the base of the tested gear oils, which form boundary films on the metal surface. Unlike sample 2, which contains only high-purity distillate oil as a base, sample 1 contains up to 15 % of a highly viscous aromatic product that enhances the activity of zinc dialkyl dithiophosphate [13, 15]. The use of sample 1 ensures the formation of stable boundary films on 90-95% of the contact area (Fig. 2, b, c) with a thickness of 0.09...1.2 μm, which effectively shields the surface from the propagation of elastic-plastic deformations to the upper surface layers. The change in microstructure is recorded at a depth of up to 20 μm and indicates structuring (Fig. 3, b). The values of specific friction work range from 12000...16000 J/mm^2.

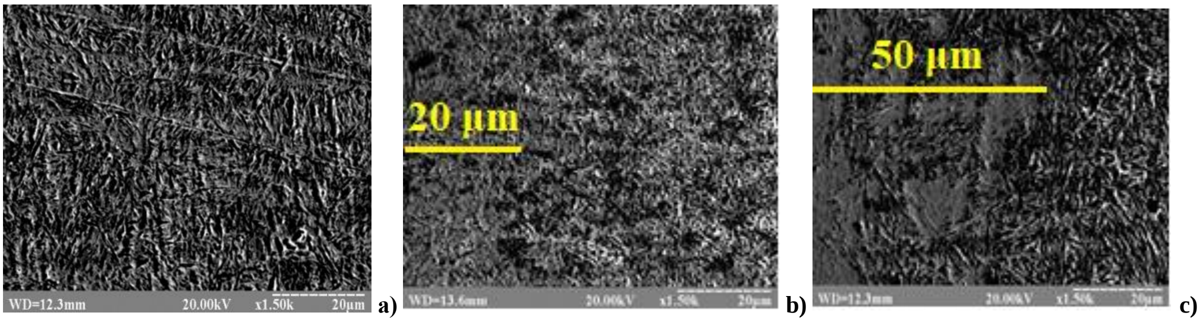

Fig. 3. Microstructure of the surface layers of steel 45 (× 1500) before friction (a) and after 100 cycles of lubrication with sample 1 (b) and sample 2 (c).

When using sample 2, boundary layers of lubricant with a thickness of 0.038....1.2 μm are formed on 20...50% of the surface area (Fig. 2, f, g). Suppose the maximum thickness of the boundary layers is similar to the values established for sample 1. In that case, their minimum value is 1.2 and 2.37 times less, respectively, at an oil temperature of 20 and 100 ^{0}C. Destruction of boundary layers occurs in 10-15% of cycles. Accordingly, the less effective shielding effect of the boundary film of sample 2 causes the propagation of elastic-plastic deformation at the third to a depth of 50 μm. At the same time, the values of the specific friction work are 3.11 and 1.23 times higher than those for sample 1, respectively, at an oil temperature of 20 and 100 ^{0}C.

The kinetics of the formation of boundary films by the lubricant and the indicators of specific friction work in contact correlate with the intensity of wear of the contact surfaces.

The total linear wear of 45 steel rollers is 3.97 μm and 7.6 μm when friction pairs are lubricated with oil samples 1 and 2, respectively (Table 2).

Table 2

Indicators of linear wear and microhardness of friction pairs

Indicators	**Lubricant**			
	Sample 1		Sample 2	
	Leading surface	Lagging surface	Leading surface	Lagging surface
Wear, μm	1.4	2.57	3.1	4.5
Surface microhardness before the experiment (initial), MPa	4382	4380	4376	4385
Surface microhardness after 100 operating cycles, MPa	5100 (strengthening)	4590 (strengthening)	4116 (weakening)	3890 (weakening)

The wear of contact surfaces is significantly affected by both the formation of protective 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 (ΔH) of the surface layers of steel 45 during working depends on the type of the material under study. If when lubricating the friction pairs with sample 1, the leading (ΔH = + 718 MPa) and lagging (ΔH = + 210 MPa) surfaces are strengthened, then when using sample 2, the weakening of the metal surface layers is established for the leading (ΔH = - 260 MPa) and lagging (ΔH = - 495 MPa) surfaces (Table 2).

Thus, the formation of stable boundary films of the lubricant on friction-activated contact surfaces is the leading process in the manifestation of their damping properties concerning the localization of elastic-plastic deformation along the depth of the metal and anti-wear properties in harsh lubrication conditions, which include the investigated non-stationary processes.

Conclusions

1. The study was carried out on a hardware and software complex using a roller analogy to model the operation of gears under rolling and slipping conditions. The tribotechnical characteristics of commercial gear oils from different manufacturers were studied.
2. Compared to the T-Shyp gear oil for hypoid gears (sample 2), a 30% reduction in the coefficient of friction was observed for the T-Shyp gear oil 'Bora B' (sample 1), due to the oil's effective lubricating ability in forming the hydrodynamic and non-hydrodynamic components of the lubricating film thickness.
3. The correlation between the linear wear of steel and the kinetics of the formation of boundary films by the lubricant, the indicators of the specific friction work in contact, and the formation of dissipative structures on the surface of a metal with increased hardness were established.

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Ільїна О. А., Мікосянчик О. О., Мнацаканов Р.Г., Костюннік Р. Є., Ящук О П., Штейник М. А. Механізми формування зносостійких дисипативних структур в нестаціонарних умовах мащення

Метою роботи було визначення впливу процесів надмолекулярної самоорганізації в мастильному шарі на закономірності зношування пар тертя. Проаналізовано механізми структурної пристосованості елементів трибоспряження, визначено закономірності прояву масштабного і енергетичного стрибка, що характеризує перехід трибосистеми до метастабільного стану. Проведена оцінка триботехнічних характеристик товарних трансмісійних олив на програмно-апаратному комплексі, який за допомогою роликової аналогії моделює роботу зубчастих передач в умовах кочення з проковзуванням. Встановлено, що активація контактних поверхонь в режимі частих пусків – зупинок призводить до активної взаємодії компонентів мастильного матеріалу та поверхневих шарів металу з поступовим формуванням граничних адсорбційних шарів. Для transmission oil 'Bora B' T-Shyp встановлено підвищення антифрикційних властивостей за рахунок ефективної змащувальної здатності оливи при формуванні гідро- та негідродинамічної складової товщини мастильного шару. Розглянуто вплив хімічної активності протизношувальної присадки диалкілдитіофосфат цинку та вуглеводневих компонентів базової основи трансмісійних олив на ефективність формування граничних плівок. Визначено, що утворення стійких граничних плівок мастильного матеріалу є ведучим процесом щодо прояву їх демпфуючих властивостей стосовно локалізації пружно-пластичної деформації по глибині металу. При формуванні граничних плівок на 90-95% площі контакту зміна мікроструктури приповерхневих шарів фіксується на глибині до 20 мкм, при формуванні граничних плівок на 20…50% площі поверхні розповсюдження пружно-пластичної деформації при терті сягає глибини до 50 мкм. Кінетика формування граничних плівок мастильним матеріалом та показники питомої роботи тертя в контакті корелюють з інтенсивністю зношування контактних поверхонь.

Ключові слова: знос, мікротвердість, питома робота тертя, змащування, деформація, мікроструктура.