Встановлені закономірності зміни антифрикційних властивостей контакту від міцнісних характеристик фізичних та хемосорбційних граничних плівок. Визначено вплив градієнту швидкості зсуву змащувальних шарів на кінетику їх руйнування та реологічні характеристики. Розглянуті механізми, які призводять до підвищення адгезійної складової коефіцієнта тертя при порушенні суцільності змащувального шару або до її зниження при плавленні твердокристалічного змащувального шару

Ключові слова: коефіцієнт тертя, напруга зсуву, ефективна в'язкість, проковзування, граничні плівки змащувального матеріалу

Установлены закономерности изменения антифрикционных свойств контакта от прочностных характеристик физических и хемосорбционных граничных пленок. Определено влияние градиента скорости сдвига смазочных слоев на кинетику их разрушения и реологические характеристики. Рассмотрены механизмы, обусловливающие повышение адгезионной составляющей коэффициента трения при нарушении сплошности смазочного слоя либо ее снижение при плавлении твердокристаллического слоя смазки

Ключевые слова: коэффициент трения, напряжение сдвига, эффективная вязкость, проскальзывание, граничные пленки смазочного материала

UDC 621.891
DOI: 10.15587/1729-4061.2016.75857

INFLUENCE OF THE NATURE OF BOUNDARY LUBRICATING LAYERS ON ADHESION COMPONENT OF FRICTION COEFFICIENT UNDER ROLLING CONDITIONS

O. Mikosyanchyk
PhD, Associate Professor
Department of Life Safety*
E-mail: oksana.mikos@bk.ru

R. Mnatsakanov
Doctor of Technical Science, professor
Department of organization of aviation works and services*
E-mail: mnatsakanov@bk.ru

A. Zaporozhets
Doctor of Technical Science, professor
Educational and Research Institute of Ecological Safety*
E-mail: zap@nau.edu.ua

R. Kostynik
PhD, Senior Researcher
Research laboratory technology nanotribo*
E-mail: kostunik@ukrpost.net

*National Aviation University,
Kosmonavta Komarova ave., 1, Kyiv, Ukraine, 03058

1. Introduction

One of the directions of increasing reliability of modern machines and mechanisms is the development and creation of such operating modes, with which the dominating manifestation of the conditions of external friction is ensured. The integral approach to the solution of problems in this direction should imply analyzing and considering many factors, the change in kinetics of which predetermines antifriction and anti-wear properties of a contact. First of all, external friction is determined by the structure and properties of the surface layers of metal [1], by the stress-strained state of contact surfaces [2, 3], by the structure of boundary lubricant layers [4], by the operation modes of the elements of tribointegration, etc. An inherent component of a tribotechnical system is the lubricating material, the self-organization of which under different load-speed modes is an important condition of the manifestation of external friction in contact and an increase in its operational reliability.

Development of means and methods of checking the lubricating power of oils in the operation process is a relevant direction in studying the processes of self-organization of a tribosystem, which makes it possible to forecast its operational reliability.

2. Literature review and problem statement

Tangent stresses, caused by intermolecular interaction of surfaces in the zones of actual contact, produce essential influence on the threshold of external friction [5]. The presence of a lubricant in the zone of contact, oxide films, adsorbed vapors and gases implies a considerable decrease in the adhesive component of the friction coefficient both due to the viscous flow in the volume of the third body and due to the reduction in the area, on which metallic contact of the surfaces occurs during transfer of tribosystem to the boundary condition of lubricating action [6, 7]. However, the problems connected with the formation of boundary films of different chemical composition on the surfaces of metal, which are essentially different in shear stress and antifriction characteristics, are not examined in the given works. The existing rheological models of a lubricant under slipping conditions make it possible to consider the influence of shear stress of boundary layers on the frictional force at high pressures and temperatures [8, 9]. Comprehensive studies of rheological properties of lubricants do not cover the conditions of rolling with different degree of slippage characteristic for the gear transmissions.

The effective viscosity in the temperature range of 130–180 °C and the gradient of shearing rate of 10^5–10^7 s^{-1}, the properties of boundary layers and the ability to chemically modify the surface layers of metal are the important indicators for predicting operating characteristics of oil [10]. The thin surface layers of the products of reaction of active components of a lubricant with the materials of contact surfaces possess lowered shear strength and are characterized by a higher temperature and mechanical durability [11]. The phase transition of the lubricant, physically adsorbed into the chemisorbed layer with the toughening of the load mode of a lubricant testing, was established in the work [12], which provides an increase in the strength properties and reduction in the antifriction indicators of boundary lubricant layers. It should be noted that in the indicated works the study of the boundary layers of lubricants was carried out under conditions of abundant oil feed to the contact zone. This contributes to forming the thickness of the lubricant layer, which includes two components — hydrodynamic and non-hydrodynamic. The volumetric, antifriction and rheological properties of boundary layers differ significantly from the analogous indicators of the liquid phase of a lubricant. Therefore, creation of experimental conditions, which exclude the influence of the hydrodynamic component of the thickness of the lubricant layer on the tribotechnical properties of a contact, is an important direction in studying boundary layers.

The value of the adhesive component of the friction coefficient, determined by molecular interaction of the contact surfaces, depends on shearing stresses on the boundary of the division of solid bodies [13]. Shearing stresses are localized at a certain depth in the case of poor lubrication, which leads to crack occurrence under a surface layer of the metal [14]. However, sufficient amount of a lubricant creates prerequisites for the passage of tangential stresses onto the surface; in this case, the start of the cracks development occurs in the cavities of rough surfaces. Nevertheless, the given papers do not contain criteria for evaluation of localization of the vector of tangential stresses during a tribosystem transfer from the hydrodynamic to the boundary condition of lubricating action.

Based on the above given material, the effect of the structure of boundary lubricant layers and their rheological properties on the durability of friction pairs with the local form of contact is not sufficiently explored. In connection with this, there is a need for developing comprehensive methods of tribotechnical tests, which would cover a variety of effects of interaction of the lubricants' components with activated surface of a metal. The study of the process of forming the lubricant layer as the main elasto-hydrodynamic and boundary aspect is undoubtedly of interest for an increase in reliability and bearing capacity of modern machines and mechanisms.

3. The aim and the tasks of the study

The purpose of the studies was to establish the dependence of the kinetics of a change in the friction coefficient under conditions of cutting off a lubricant feed on the lubricating and rheological properties of the boundary films, formed on the surface layers of a metal, activated by friction.

To achieve the set purpose, the following tasks were solved:

— determining the influence of slippage on the lubricating power of oil;

— identification of a change in antifriction properties of contact under conditions of pure rolling and rolling with the slippage;

— determining a change in the gradient of the shear rate, shear stress and effective viscosity of a lubricant layer with friction under conditions of cutting off the regular feed of a lubricant to the contact zone;

— identification of the nature of the boundary films of a lubricant by the character of changing their rheological properties;

— establishing the interrelation between the kinetics of the destruction of boundary lubricant layers and the antifriction characteristics of contact.

4. Materials and methods of studying tribotechnical characteristics of boundary films under conditions of cutting off the lubricant feed to contact zone

The study of lubricating, antifriction and rheological properties of boundary films was conducted at the device for evaluation of tribotechnical characteristics of triboelements [15]. Friction moment, rotation frequency of rollers, temperature of a lubricant, voltage drop in the lubricant layer in contact were recorded and processed by the PC (software package ProfiLab) in real time scale with graphic representation of their changes.

The studied non-stationary friction conditions implied cyclic recurrence of conducting the experiments in the mode «start — stationary work — braking — stop» (Fig. 1).

Section I corresponds to the initial operating cycle of friction pairs and is characterized by a gradual increase in the rolling speed of rollers, in this case $V_{sl} = 0$. The assigned maximum slippage of rollers is reached in section II, the rolling speed of friction pairs in this operating cycle is constant. Section III corresponds to braking, which consists of two periods: an initial decrease in rolling speed of rollers with retention of the assigned slippage at point A and a gradual decrease to zero in the slippage degree at point B (IIIa). Further braking occurs under conditions of simultaneous decrease in the rolling speed of both rollers with maintaining the condition $V_{sl} = 0$ (IIIb). Section IV corresponds to a stop. If we project the selected cycle to involute gearing, the polar zone of gearing corresponds to sections I and IIIb, circumpolar zone corresponds to section IIIa and extreme points of gearing with the maximum slippage corresponds to section II.

The maximum rotation frequency for the advancing surface amounted to 1000 r/min. The slippage 3 %, 10 %, 20 %, 30 % and 40 % was imitated in the work. The maximum contact stress according to Hertz was 250 MPa.

The rollers made of steel 45 (HRC 38, Ra 0,57 microns) were used as the samples. The lubrication of contact surfaces was achieved by dipping the lower roller into a tray with oil. Mineral transmission oil for mechanical gearboxes and main drives of passenger cars and trucks Okko GL-4 80w/90 was used as the lubricant. The volumetric temperature of oil was 20 °C.

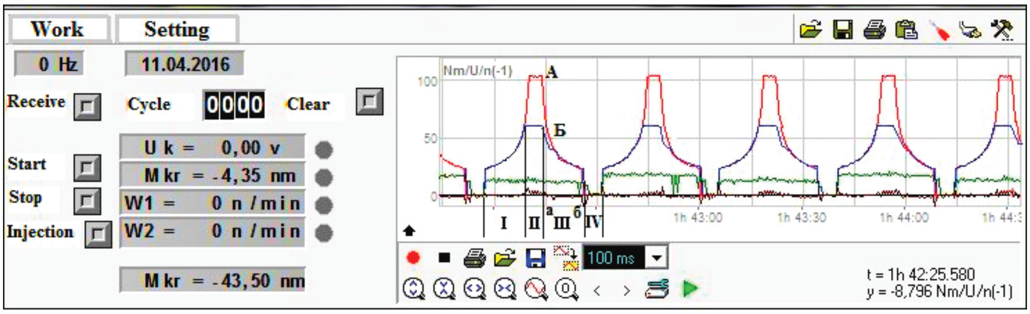


Fig. 1. Schematic of tribosystem operation under non-stationary friction conditions: section I — start; section II — stationary work; section III — braking; section IV — stop

The thickness of lubricant layers was measured by the method of voltage drop in the mode of a normal smouldering discharge [16], microhardness of the surface layers of metal was measured at the instrument PMT-3.

Rheological characteristics of a lubricant were determined with the use of the methods [17, 18].

The alignment of contact surfaces, including 100 cycles and subsequent operation of friction pairs during 400 cycles, was achieved under conditions of rich oiling, after which the feed of lubricant was cut off. The total number of cycles in each experiment comprised: 500 (rich oiling by dipping the lower roller into the tray with oil), 400 (imitation of the mode of oil deficiency due to the cut off regular feed of the lubricant from the tray to the contact zone), 100 (forced removal of the lubricant from the contact surfaces by wiping rollers with cleaning cloth).

5. Results of the study of lubricating, rheological and antifriction properties of boundary films, formed by active componentss of transmission oil

Under operating conditions of contact surfaces without the feed of a lubricant, the effectiveness of the lubricating properties of contact is determined exclusively by the durability of the boundary layers, formed on the contact surfaces, activated by friction under conditions of rich oiling. Up to the 400th alignment cycle, the 0.5–2 mkm increase in the thickness of the lubricant layer was observed at the start due to the spare lubricant, which is spread throughout the contact area because of its adhesive and cohesive forces of interaction. The hydrodynamic mode of lubricating action was realized under conditions of rich oil feed to the contact zone. The cutoff of the lubricant feed creates prerequisites for the tribosystem transfer to tougher operating conditions. In this case, different modes of lubricating action — from half-dry to hydrodynamic — are manifested (Table 1).

Table 1

Effectiveness of lubricating action at a different slippage degree of contact surfaces

Slippage, %	Thickness of lubricant layer, microns	Mode of lubricating action by parameter $\lambda = \frac{h}{\sqrt{R_1^2 + R_2^2}}$
Up to 3	0.2–5.1	0–10.86 (half-dry — hydrodynamic)
10	0.35–4.0	0.5–7.2 (half-dry — hydrodynamic)
20	0.2–3.8	0.5–6.7 (half-dry — hydrodynamic)
30	0.15–2.1	0.5–5.4 (half-dry — hydrodynamic)
40	0–1.9	0–2.7 (half-dry — mixed)

The decrease in the hydrodynamic component of thickness of a lubricant layer, on the average by 70 %, affects antifriction properties of contact differently.

In section I, at the start under conditions of pure rolling, f does not change for the surfaces with further slippage of 10–20 %, f increases by 1.8 and 1.2 times for the contact surfaces with the subsequent slippage of 30 % and 40 % respectively. A more considerable increase in the friction coefficient (by 1.22–2.4 times) was established after the 400th alignment cycle with the forced removal of spare lubricant from the contact zone. The exceptions are the contact surfaces, working subsequently with the minimum slippage of 3 %: the decrease in thickness of the lubricant film does not produce any effect on antifriction properties of contact. The friction coefficient is in the range of 0.006–0.008, similar to it under conditions of rich oiling.

A sharp increase in the friction coefficient, on average by 3 times, for the conditions of slippage of 10–40 % was established under operating conditions of contact surfaces during rolling with slippage in section II. Again, the contact surfaces with minimum slippage were an exception; the antifriction properties of contact remain unchanged (Fig. 2).

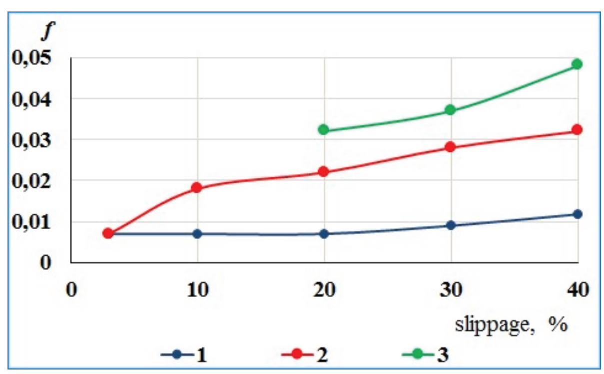


Fig. 2. Dependency of friction coefficient on the degree of slippage under conditions of limited lubrication: 1 — mode of pure rolling at the start; 2 — mode of rolling with slipping; 3 — moment of setting in the mode of rolling with slipping

The absence of additional lubricant does not substantially influence the gradient of shearing rate (γ) — increase γ amounted to 1.02–1.1 times, irrespective of the degree of slippage of the contact surfaces. An increase in the slippage from 3 % to 40 % predetermines the growth of the gradient of the shearing rate of lubricant layers by 4.6 times (Fig. 3, *b*). It is this parameter that influences the durability of the formed boundary films: the increase γ from $1{,}0\cdot10^5$ to $2{,}3\cdot10^5\ s^{-1}$ during the growth of slippage from 20 % to 40 % leads to the full abrasion of the formed boundary layers in 30 % of alignment cycles on the surfaces with maximum slippage (Fig. 4).

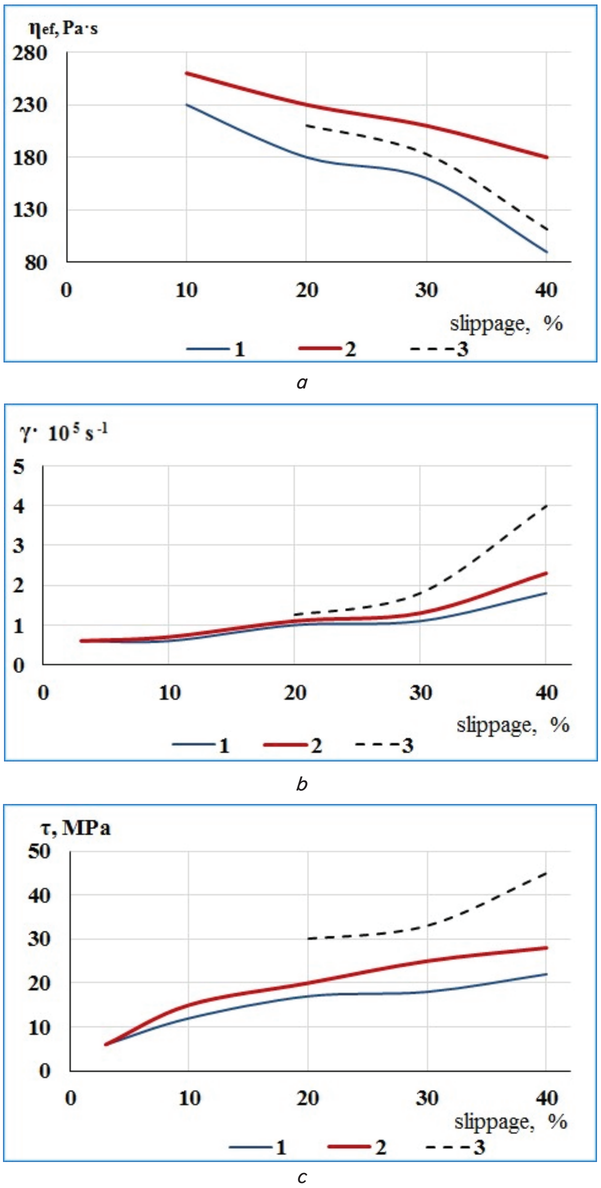


Fig. 3. Influence of the degree of slippage on rheological characteristics of lubricant: 1 — rich oiling; 2 — limited amount of lubricant; 3 — forced removal of lubricant; *a* — change in effective viscosity (η) in contact; *b* — change in the gradient of shearing rate (γ) of lubricant layers; *c* — change in shear stresses (τ) of lubricant

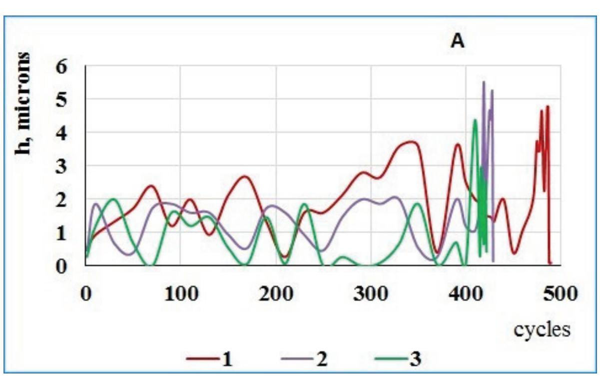


Fig. 4. Kinetics of the change in lubricant layer thickness in the rmode «start — stop» during rolling with slippage of 20 % (1), 30 % (2), 40 % (3). At point A — forced removal of lubricant

With the increase in the degree of slippage from 10 % ($\gamma = 0{,}5 \cdot 10^5\ s^{-1}$) to 40 % ($\gamma = 2{,}3 \cdot 10^5\ s^{-1}$), effective viscosity in contact is decreased from 260 Pa·s to 180 Pa·s (Fig. 3). Up to 400 alignment cycles, when the oil was not forcedly removed from the studied surfaces, the shear stress of lubricant layers (τ) under conditions of slippage of 10–40 % increases on average by 1.25 times in comparison with the rich feed of a lubricant. The increase in the effective viscosity of a lubricant, which comprised 1, 13:1, 27:1, 31:2 times for the slippage of 10 %, 20 %, 30 % and 40 %, respectively, was established under conditions of the limited lubricating action, which leads to the decrease in thickness of the lubricant layer in contact (Fig. 3).

After the 400th alignment cycle, the lubricant was forcedly removed from the friction surfaces by wiping the rollers. Normal operation of triboitegration was established for the contact surfaces with the slippage of 3 % and 10 % up to the 500th alignment cycle, the friction coefficient was stable, which testifies to high antifriction properties of boundary lubricant films. An increase in the degree of slippage to 20 %, 30 % and 40 % leads to reduction of the period of normal operation of contact surfaces, the first signs of the setting appear, which correspond to the 490th, 430th and 415th alignment cycles, respectively. Abrupt change in the antifriction characteristics of contact was observed under such extreme conditions, which is manifested by periodic increase and decrease in the friction coefficient (Fig. 5).

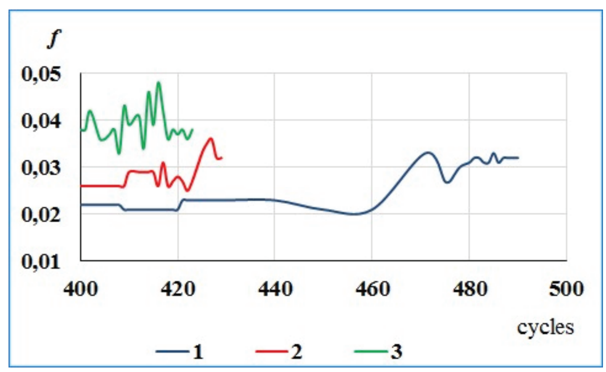
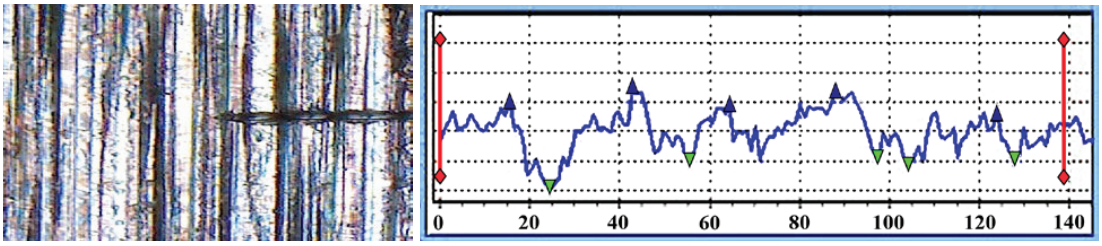


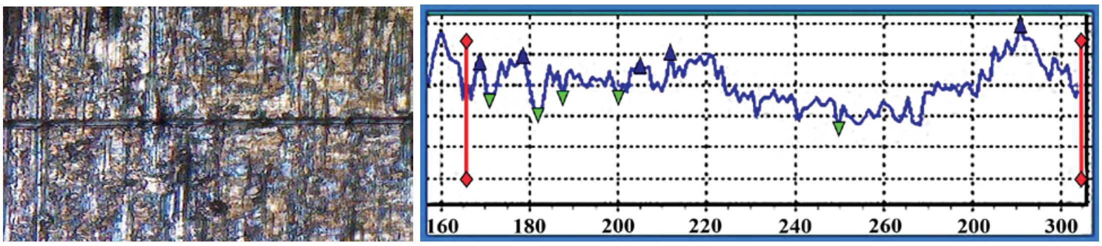
Fig. 5. Change of friction coefficient in the period of forced removal of lubricant during rolling with slippage of 20 % (1), 30 % (2), 40 % (3)

For the contact surfaces, working in section II under conditions of minimum slippage of 3 %, substantial changes in rheological properties of boundary lubricant layers during the tribosystem transfer to the mode of cutting off supply of the lubricant feed were not observed: the stability of shear stresses of lubricant layers testifies to the weakness of cohesive forces of the interaction.

However, in the alignment of 400<N<500 cycles, under conditions of forced lubricant removal, the signs of setting of contact surfaces were not established, despite the formation of boundary layers of physical nature by the transmission oil during structural adaptability. Two factors contribute to normal operation of triboitegration. Firstly, because of the reserve of a lubricant on rough contact surfaces (operational $R_a = 0.39$ microns, $R_z = 1.71$), the thickness of the lubricant layer starts increasing from the 430th alignment cycle to 3 microns with subsequent cycle oscillation of 0.2–3 microns, which prevents the setting of friction surfaces (Fig. 6).



a



b

Fig. 6. Roughness of the contact surfaces: *a* — initial (R_a = 0.57 microns, R_z = 2.33); *b* — operational (R_a = 0,39 microns, R_z = 1.71)

Secondly, because of the plasticizing Rehbinder effect, the surface layers of metal that lost their strength are characterized by low indicators of resistance to tangential shear stresses. The microhardness of surface layers decreases on average by 1000 MPa, and the depth of the amorphized layer that lost its strength reaches 60 mkm. Thus, the manifestation of the given processes in contact contributes to retention of the stability of adhesive component of the friction coefficient at the level of the indicators, established at a sufficient feed of a lubricant to the contact zone.

6. Discussion of results of studying antifriction properties of lubricating boundary films under non-stationary friction conditions

The friction coefficient is equal to the sum of two components: adhesive, determined by the molecular interaction of solid bodies in the actual area of contact, and deformational, caused by deformation of the surface layers of solid bodies at friction [19]. Therefore, the analysis of the kinetics of change in antifriction properties of contact must be based on considering the problems concerning both the lubricating power of the used materials and changes occurring during friction in the surface layers of metal. Results of the studies represented in this article describe only a part of the obtained dependencies, which affect the change in rheological properties of a lubricant during formation of the boundary films of different nature and thickness on the contact surfaces activated by friction. Accordingly, the value of the adhesive component of the friction coefficient will be determined by tangential shear stresses mainly in the lubricant layer.

Let us examine the kinetics of change in antifriction properties of the transmission oil from the position of self-organization of lubricating boundary films during the tribosystem transfer to extreme working conditions, which imply the lack of a lubricant reserve. During the start, under conditions of pure rolling in section I, with an increase in the speed, tangential shear stresses (τ) are localized in the central part of thickness of the lubricant layer since there is no gradient of shearing rate ($V_{sl.} = 0$). With the alignment of 400 cycles, shearing stresses are localized mainly in this layer due to an increase in the thickness of a lubricant film because of the presence of spare lubricant on the contact surfaces. Since the lubricant amount is sufficient for full separation of the contact surfaces, the change τ in section I for the surfaces with further slippage of 3–20 % was not observed, τ = 6–7 MPa, similar to the conditions of rich oiling. The indicated processes contribute to domination in contact of the hydrodynamic mode of lubricating action, with which the friction coefficient is determined by the volumetric properties of the liquid smectic or nematic phase of a lubricant [20]. Localization of tangential shear stresses under conditions of pure rolling in a liquid phase, as a result of the minimum influence of a solid body surface, ensures the best antifriction characteristics of contact with the minimum friction coefficient at the level of 0.006–0.008 (Fig. 2).

Intensive spraying of a lubricant was established on the contact surfaces working in section II at the slippage of 30 % and 40 %, where the maximum speed of slip reaches 0.85 m/s and 1.5 m/s, respectively. This leads to the reduction in an increase in the thickness of film at the start by 2 times on average, as a result of which the mixed mode of lubricating action is mainly realized. However, shear stress of lubricant layers in the operating cycle in section I increases insignificantly (by 1.2 times on average) in comparison with the conditions of rich oiling. With the decrease in the thickness of lubricant film in contact, the influence of the solid phase of metal on the components of a lubricant grows, which ensures the decrease in antifriction properties; the friction coefficient increases to 0.01–0.013 (Fig. 2).

In section II, under conditions of slippage, the slip rate reaches maximum values, which leads to occurrence of the gradient of the shearing rate of lubricant films in contact throughout the thickness of the lubricant film. As a result of the decrease in the hydrodynamic component of thickness of the lubricating film, the vector of tangential shear stresses is localized mainly in the boundary layer of the lubricant [21]. Since the boundary layers are characterized by structurization and are exposed to strong influence of the solid phase of a metal, we will analyze the influence of rheological properties of a lubricant on the kinetics of change in adhesive component of the friction coefficient.

The analysis of lubricating power of the examined transmission oil under conditions of rich oiling revealed formation of the boundary lubricant films of different nature. On the contact surfaces with the minimum slippage of 3 %, physically adsorbed boundary films with weak van der Waals forces of interaction are mainly formed, which are characterized by low shear stresses, analogous for a volumetric phase. With the slippage of 10–40 %, active components of the lubricant form chemisorption films and chemically modified layers on the contact surfaces, which possess somewhat larger shear stresses than a volumetric phase due to the cohesive forces of interaction.

For the contact surfaces with the slippage of 3 %, the change in the adhesive component of the friction coefficient under conditions of limited lubrication was not established, in comparison with the rich lubricant feed to the contact zone. First of all, this is connected with low activation of the surface layers of metal at the insignificant slip rate ($V_{sl.}$ = 0.07 m/s). Domination of rolling speeds creates prerequisites for minimum mechanical and thermal effects from the speed gradient [22], as a result of which physically adsorbed boundary films are formed. The absence of strong adhesion bonds of the components of a lubricant with the surface of metal predetermines frequent disorientation of boundary layers that is manifested in the cycle variations of the thickness of lubricant film from 0.2 to 3–5 microns during 50 alignment cycles. Rheological properties of the volumetric liquid phase of oil are characteristic for such boundary layers: shear stress and effective viscosity in contact are analogous to the parameters, observed under conditions of rich oiling.

However, a further increase in the degree of slippage and, respectively, the gradient of shearing rate, creates prerequisites for forming the boundary lubricant films of chemisorption nature.

According to [23], the gradient of shearing rate of the order of $10^5...10^7$ s^{-1} causes destruction of the components of lubricants, which is manifested by the decrease in their viscosity. Similar results were obtained in the conducted studies: effective viscosity in contact is decreased by 1.45 times with an increase in the degree of slippage from 10 % to 40 %. However, the conducted analysis of rheological characteristics of the structured boundary lubricant films revealed a different pattern of the kinetics of change in effective viscosity under conditions of cutting off the feed of a lubricant. Effective viscosity increases, in this case the degree of its increase correlates with the slip rate (Fig. 3). These layers are characterized by an increase in shear stresses as a result of an increase in the force of cohesive interaction with the formation of a more dense stressed structure. According to [17], polymorphism of organic molecules of lubricants during their structurization on the surface of a solid body is the source of formation of boundary layers by the type of lattice (reticular) heterogeneous structures. Reconstruction of molecular structure occurs under the action of high pressures in this boundary layer, with the formation of more tight packages during the change in the structure of chain molecules as a result of the axial compression of chains due to the deformation of tetrahedral angles between the atoms of carbon.

The studied mineral transmission oil is made on the base of residual oil, low-viscous distillate and the package of polyfunctional additives. Thus, it contains molecules of different stoichiometric structure. Under the action of high gradients of shearing rate, as a result of mechanical destruction of a lubricant components, formation of reticular boundary layers occurs, with multiple cross links between active centers of molecules. In this case, single planes of easy slip, which are oriented in the plane of action of the tangential vector of shear stresses, are formed in the thickness of the boundary layer. Such a formed laminar reticular structure serves as a special reservoir for chaotic arrangement of free inactive molecules in it. The presence of such molecules is characteristic for the fractions of saturated and non-polar compounds, available in the basic foundation during compounding of mineral transmission oil.

Thus, the ordered solid crystalline reticular structures are formed on the contact surfaces activated by friction; they are similar to the arrangement of dispersed phase of lubricants, which contain a different quantity of free oil molecules, analogous to dispersion constituent of lubricants. Moreover, a quantity of inactive free components in such structures decreases with the growth of the degree of ordering and density of the body. Accordingly, the tighter the arrangement of a strong crystalline structure, the higher its shear stress is, which is manifested during maximum slippage (Fig. 3).

The kinetics of the change in the thickness of boundary lubricant films after the 400^{th} alignment cycle serves as a proof to this assumption, with the forced removal of spare lubricant from the contact surfaces. For the contact surfaces with the slippage of 10 %, the thickness of boundary lubricant films varies from 0.5 to 3.2 microns, rheological characteristics of chemisorption films remain constant. Stable indicators of the gradient of shearing rate and shearing stress testify to strong adhesive and cohesive bonds. The vector of tangential stresses is localized in the boundary layer of a lubricant, the strength properties of which are sufficiently effective, since a stable solid crystalline structure of boundary layers is maintained. This structure of boundary films ensures their high antifriction and anti-wear properties. Normal operation of friction pairs was established up until the 500^{th} alignment cycle; the signs of the setting of contact surfaces were not observed.

Similar regularity was also established with the slippage of 20 % up to the 450^{th} alignment cycle. Then the thickness of lubricant film abruptly increased by 2.5 times, shear stresses — by 1.5 times, the gradient of shearing rate — by 1.25 times. This is connected to the destruction of cohesive and adhesion bonds of solid crystalline boundary layer, which leads to its disordering, fusion and transition to the smectic phase. Then the decrease in effective viscosity in contact by 1.2 times and a sharp increase in the friction coefficient from 0.008 to 0.017 occur with the availability of a lubricant in the friction zone, the friction coefficient increases to 0.032 in the moments of disruption in the continuity of the lubricating layer and the first signs of the setting of contact surfaces appear at the alignment of 490 cycles (Fig. 5).

A more intensive destruction of boundary layers and the occurrence of the first signs of the setting were established with the 430th and 415th alignment cycles under conditions of slippage of 30 % and 40 %, respectively, during forced removal of spare lubricant from the friction zone. Thus, the durability properties of boundary chemisorption layers directly depend on the slip rate in contact, the increase of which creates high gradients of shearing rate, which lead to mechanical and thermal destruction of the formed films of lubricant. For example, at the moment of the setting of contact surfaces with the slippage of 40 %, the gradient of shearing rate increases by 2 times, shear stress of lubricant films – by 1.6 times, and the decrease of effective viscosity in contact was established from 180 to 112 Pa·s. In this case, the abrupt fluctuations of the thickness of lubricant film were observed, their increase may reach 4 microns, ensuring low friction coefficient at the level of 0.006, in comparison to 0.014 at the minimum thickness of lubricant film. The mechanism of this process comes down to the disorientation of boundary lubricant films under the action of shear stresses and temperature increment in contact due to an increase in the slip rate, which leads to melting of solid crystalline layer due to mechanical and temperature action. A lubricant again acquires Newtonian properties, it becomes liquid, the cohesive and adhesive forces of interaction weaken, a volumetric liquid phase of lubricant in contact increases, which leads to a short-term manifestation of hydrodynamic mode of lubricating action, which is characterized by high antifriction properties of a lubricant. The obtained data are in line with the main conditions of models of the phase transitions of the first order [24, 25] between the solid and liquid states. According to the postulates of these models, an abrupt change in the frictional force occurs in the moment of an abrupt change in the properties of a lubricant with the transition from a solid crystalline phase to the liquid one. Melting of the boundary layers of a lubricant can be achieved at the limit values of shearing strain; in this case, the lubricant, independent of the temperature, will be in a liquid state [26–28]. In the moments of disruption of the continuity of the lubricating layer, the friction coefficient increases sharply to 0.038 and 0.047 during the slippage of 30 % and 40 %, respectively (Fig. 5).

Thus, sharp fluctuations of the friction coefficient at the occurrence of the first signs of the setting of contact surfaces are caused by the destruction of boundary lubricant films. These processes are characterized by manifestation of two opposite effects. One of them causes an increase in the adhesive component of the friction coefficient as a result of an increase in the degree of direct metallic contact of surfaces. The other one causes the decrease in the friction coefficient and manifestation of short-term hydrodynamic effects in contact as a result of the focal melting of boundary layers.

7. Conclusions

1. The decrease in lubricating power of the mineral transmission oil was established with an increase in the slippage of contact surfaces from 3 % to 40 % under conditions of cutting off the lubricant feed to the contact zone. This is connected to a decrease in the thickness of oil film by 1.43 times during the tribosystem transition to more tough operation conditions, which correspond to the mixed and boundary lubricating action.

2. Under conditions of pure rolling, high antifriction properties of contact are caused by localization of tangential shear stresses in the liquid phase of a lubricant film. Under conditions of rolling with the slippage, the vector of tangential stresses is localized in the boundary structured chemisorption films, which decreases the antifriction characteristics of contact.

3. The boundary layers of physical nature, formed on the contact surfaces at the slippage of 3 %, are characterized by identity of rheological properties with the volumetric liquid phase of a lubricant. Such structures produce strong plasticizing influence on the surface layers of metal, which is manifested by a decrease in the adhesive component of friction coefficient.

4. An increase in the slippage degree from 10 % to 40 % predetermines creation of high gradients of the shearing rate of lubricant films and increases activation of contact surfaces. These factors create prerequisites for the formation of chemisorption films on the friction surfaces, which present ordered solid crystalline reticular structures of laminate type.

5. An increase in the slippage between contact surfaces leads to the acceleration of period of occurrence of the first signs of the setting, which is manifested by an increase in the adhesive component of friction coefficient during desorption of the boundary layers.

References

1. Zaporozhets, V. V. Dinamicheskie harakteristiki prochnosti poverhnostnyih sloev i ih otsenka [Text] / V. V. Zaporozhets // Trenie i iznos. – 1980. – Vol. 1, Issue 4. – P. 602–609.
2. Surface effects in adhesion, friction, wear, and lubrication. Tribology Series 5 [Text] / D. H. Buckley. – Elsevier Science, New York, NY, 1981. – 630 p.
3. Heuberger, M. Topographic information from multiple beam interferometry in the surface forces apparatus [Text] / M. Heuberger, G. Luengo, J. Israelachvili // Langmuir. – 1997. – Vol. 13, Issue 14. – P. 3839–3848. doi: 10.1021/la960942a
4. Luengo, G. Generalized effects in confined fluids: new friction map for boundary lubrication [Text] / G. Luengo, J. Israelachvili, S. Granick // Wear. – 1996. – Vol. 200, Issue 1–2. – P. 328–335. doi: 10.1016/s0043-1648(96)07248-1
5. Rice, J. R. Off-fault secondary failure induced by a dynamic slip pulse [Text] / J. R. Rice, C. G. Sammis, R. Parsons // Bulletin of the Seismological Society of America. – 2005. – Vol. 95, Issue 1. – P. 109–134. doi: 10.1785/0120030166
6. Offner, G. A Generic Friction Model for Radial Slider Bearing Simulation Considering Elastic and Plastic Deformation [Text] / G. Offner, O. Knaus // Lubricants. – 2015. – Vol. 3, Issue 3. – P. 522–538. doi: 10.3390/lubricants3030522
7. Wang, Y. Wet Friction-Elements Boundary Friction Mechanism and Friction Coefficient Prediction [Text] / Y. Wang, B. Wei, X. Wu // Tribology in Industry. – 2012. – Vol. 34, Issue 4. – P. 198–205.
8. Garg, H. C. Thermohydrostatic analisis of capillary compensated Asymmetric holes-entry hybrid journal bearing operating with non-Newtonian lubricant [Text] / H. C. Garg, V. Kumar, H. B. Sharda // Industrial Lubrication and Tribology. – 2009. – Vol. 61, Issue 1. – P. 11–21. doi: 10.1108/00368790910929485
9. Muhortov, I. V. Usovershenstvovannaya model reologicheskih svoystv granichnogo sloya smazki [Text] / I. V. Muhortov, N. A. Usoltsev, E. A. Zadorozhnaya, I. G. Levanov // Trenie i smazka v mashinah i mehanizmah. – 2010. – Vol. 5. – P. 8–19.

10. Shram, V. G. Issledovanie vliyaniya produktov temperaturnoy destruktsii i nagruzki na protivoiznosnyie svoystva chastichno sinteticheskogo motornogo masla TNK Super 5w-40SL/CF. Chast 2 [Text] / V. G. Shram, B. I. Kovalskiy, Yu. N. Bezborodov et. al. // Vestnik KuzGTU. — 2012. — Vol. 6, Issue 94. — P. 67–74.
11. Kovalskiy, B. I. Rezultatyi ispyitaniya mineralnogo motornogo masla na temperaturnuyu stoykost [Text] / B. I. Kovalskiy, S. B. Kovalskiy, A. V. Berko, N. N. Malyisheva // Izvestiya Tomskogo politehnicheskogo universiteta. — 2010. — Vol. 316, Issue 2. — P. 46–50.
12. Korotkevich, S. V. Samoorganizatsiya smazochnyih sloev pri granichnom trenii [Text] / S. V. Korotkevich, S. M. Martyinenko, V. V. Kravchenko, M. V. Paramonov // Vestnik GGTU im. P. O. Suhogo. — 2004. — Vol. 4, Issue 17. — P. 13–16.
13. Pravednikov, I. S. Kontaktnoe vzaimodeystvie tverdyih tel s uchetom davleniya, temperaturyi i tverdosti [Text] / I. S. Pravednikov // Electronic scientific journal «Oil and Gas Business». — 2005. — Vol. 1. — Available at: http://ogbus.ru/article/kontaktnoe-vzaimodejstvie-tverdyx-tel-s-uchetom-davleniya-temperatury-i-tverdosti/
14. Ognyanovic, M. Progressive Gear Teeth Wear and Failure Probability Modeling [Text] / M. Ognyanovic // Journal of the Serbian Tribology Society. — 2004. — Vol. 26, Issue 3&4. — P. 44–49.
15. Patent na korysnu model #88748, MPK G 01 N 3/56 Prystrij dlya ocinky trybotexnichnyx xarakterystyk tryboelementiv [Text] / Mikosyanchyk O. O. — u 2013 13450, declared: 19.11.13; published: 25.03.14, Byul. 6. — 4 p.
16. Rayko, M. V. Issledovanie smazochnogo deystviya neftyanyih masel v usloviyah rabotyi zubchatyih peredach [Text] / M. V. Rayko. — Kyiv: KIIGA, 1974. — 369 p.
17. Ahmatov, A. S. Molekulyarnaya fizika granichnogo treniya [Text] / A. S. Ahmatov. — Moscow: Fizmatgiz, 1967. — 472 p.
18. Porohov, V. S. Tribologicheskie metodyi ispyitaniya masel i prisadok [Text] / V. S. Porohov. — Moscow: Mashinostroenie, 1983. — 183 p.
19. Trenie, iznashivanie i smazka: Spravochnik. Kn. 1 [Text] / I. V. Kragelskiy, V. V. Alisin (Eds.). — Moscow: Mashinostroenie, 1978. — 400 p.
20. Voronin, S. V. The research of tribological characteristics of smectic layer of boundary film [Text] / S. V. Voronin, V. O. Stefanov // Problems of Tribology. — 2014. — № 2(72). — P. 58–64.
21. Yanzhong, W. Wet Friction-Elements Boundary Friction Mechanism and Friction Coefficient Prediction [Text] / W. Yanzhong, W. Bin, W. Xiangyu // Tribology in Industry. — 2012. — Vol. 34, Issue 4. — P. 198–205.
22. Gurskiy, B. E. Teplovaya zadacha treniya i ee razvitie. Chast 2. Rol teplovyih yavleniy v razrushenii zubchatyih koles tsilindricheskih evolventnyih peredach realnyih razmerov [Text] / B. E. Gurskiy, A. V. Chichinadze // Trenie i iznos. — 2007. — Vol. 4, Issue 28. — P. 418–425.
23. Klamann, D. K. Smazki i rodstvennyie produktyi [Text] / D. K. Klamann. — Himiya, 1988. — 488 p.
24. Thompson, P. A. Origin of stick-slip motion in boundary lubrication [Text] / P. A. Thompson, M. O. Robbins // Science. — 1990. — Vol. 250, Issue 4982. — P. 792–794. doi: 10.1126/science.250.4982.792
25. Robbins, M. O. Critical velocity of stick-slip motion [Text] / M. O. Robbins, P. A. Thompson // Science. — 1991. — Vol. 253, Issue 5022. — P. 916. doi: 10.1126/science.253.5022.916
26. Lemaître, A. Boundary lubrication with a glassy interface [Text] / A. Lemaître, J. Carlson // Physical Review E. — 2004. — Vol. 69, Issue 6. doi: 10.1103/physreve.69.061611
27. Popov, V. L. Termodinamika i kinetika plavleniya sdvigom tonkogo sloya smazki, zaklyuchennogo mezhdu tverdyimi telami [Text] / V. L. Popov // Zhurnal tehnicheskoy fiziki. — 2001. — Vol. 71, Issue 5. — P. 100–110.
28. Lemaître, A. Rearrangements and dilatancy for sheared dense materials [Text] / A. Lemaître // Physical Review Letters. — 2002. — Vol. 89, Issue 19. doi: 10.1103/physrevlett.89.195503