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Structural-Energy Characteristics of Tribotechnical Contact in Unsteady Operational Modes

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Abstract

The current tribological research is intended to achieve maximum wear resistance under the structural adaptability of tribocoupling elements, which requires application of means to reduce the activation of the metal surface layers, decrease in frictional work, regulation of passivation and temperature control. The aim of this study is to identify the patterns that influence the kinetics formation of the boundary layers of lubricating mineral gear oil on activated friction contact surfaces, and the increment of the friction specific work on wear-resistant steel 42Cr4 and 100Cr6 in frequent start and stop operation mode. Due to the activation of surface layers of metal in the non-stationary operating conditions of the contact surfaces, the gradual forming of the boundary lubricant adsorption layers with increased effective viscosity in contact occurs, exhibiting high adaptation ability, and the boundary layer thickness is from 0.2 to 4 microns. This research analyzed the lubricating ability of oil at the starting maximum torque of friction, showing that the thickness of the oil layer formed in contact had a dual nature—boundary and hydrodynamic. The pure rolling conditions promote localization of shear in the lubricating layers, and the high frictional properties of the transmission oil have been identified regardless of the hardness of the investigated surfaces.

Keywords

Friction Specific Work, Kinetics Formation, Boundary Layers, Lubricating Layers, Hardness

1. Introduction

The variety of physic-chemical processes occurring on the contact surfaces under friction makes it difficult to

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choose an approach describing wear process elements of tribocoupling. Wear of the parts and durability of the tribological system at steady mode are determined by the continuous friction wear model, taking into account the kinetic patterns of wear, representing time function [1]. The literary review describes the peculiarities of many tribomechanical systems, and it was identified that non-stationery work in some corresponds to 60% - 90% of the time of system operation. The normal operation work of tribocoupling elements is characterized by changes of many physical and mechanical parameters of the lubricant and contact surfaces under friction, which are manifested in their structural adaptability [2]. The main fundamental objectives on increasing durability of tribocoupling are to set up the range of loading-speed and temperature parameters of friction pairs' operation, the selection of wear-resistant materials and an effective lubricant. At the same time, anti-wear and anti-friction properties of the lubricant must be related to peculiarities of the structure and properties of thin modified friction surface layer of the metal [3]. It was found that surfaces exposed to the effects of friction were characterized by enhanced adsorption-diffusion processes and abnormal sharp increase in chemical activity of materials [4]. The changes occurring on activated friction contact surfaces form thin films of secondary structures [5]. Lubricating adsorption layers of different natures, as a result of structural adaptability, have greater wear resistance, as compared with the starting material [6]. To achieve the maximum wear resistance of the structural adaptability of elements of tribocoupling, it is necessary to use means to reduce the activation of the surface layers of the metal, reduce the frictional work and control the passivation and temperature regulation [7]. This research is to develop a method for evaluating the effectiveness of the tribological characteristics of the contact in non-stationery conditions that is a promising direction in determining material performance range of contact surfaces and lubrication during their operation in dynamic loading conditions.

Research Objectives

The research has the following objectives:

1) To identify the patterns influencing the kinetics formation of the boundary lubricant layers on activated by friction contact surface.

2) To identify the increment of specific friction work on the wear resistance of steel in a frequent start and stop mode.

3) To reduce activation of the metal surface layers, decrease in frictional work, regulation of passivation and temperature control.

2. Materials and Methods of Research

The research of tribological parameters of friction pair was conducted with the device for evaluation the tribological characteristics of tribocoupling elements [8]. The frictional torque, rotation speed of the rollers, temperature of the lubricant, and thickness of lubricant layer are measured by the method of voltage drop during normal glow discharge which is recorded and processed on a computer in real-time with graphical representation of changes at each cycle. For example, steel rollers 42Cr4 (DIN) (HRC 38, Ra = 0.32 mcm), steel 100Cr6 (DIN) (HRC 60, Ra = 0.32 mcm) and lubricant-transmission mineral multi grade oil TAD-17i (ARI-GL-5) have been used. Examination of lubricating properties of the oil has been conducted in the start-stop mode as follows: acceleration under pure rolling of contact surfaces (12.5 s)-work in conditions of 20% slippage (4 c)-deceleration under pure rolling of contact surfaces (12.5 s). Contact load by Hertz (σ_{max}) has been 250 MPa, the total number of cycles-200, the maximum number of turns 1000 and 800 per min, respectively for the leading and trailing surfaces.

3. Results and Discussion

The study of effectiveness of the lubricating abilities of the TAD-17i transmission oil at the initial start-up period of the cycle, in a pure rolling condition has identified high load-bearing capacity of oil for all kinds of contact surfaces investigated. It should be noted that in the initial starting period, which corresponds to 0 - 2 s, the pushing contact surfaces in 200 cycles for the steel 42Cr4 is to calculate the criteria λ takes place under conditions of medium-dry (5% of cycles), boundary (20% of cycles), elasto-hydrodynamic (30% cycles) and hydrodynamic (45% of cycles) lubricating action mode [9]. For most solid steel 100Cr6 number of starts occurring in semi-dry conditions and boundary conditions of the lubricating action are increasing by an average of 20%. Due to the activation of surface layers of metal in the non-stationary operating conditions of the contact surfaces, the gradual forming in them of the boundary lubricant adsorption layers occurs, exhibiting high adaptation ability-the boundary layer thickness is from 0.2 to 4 microns. The analysis of the lubricating ability of oil at the starting maximum torque of friction showed that the thickness of the oil layer formed in contact has a dual nature—boundary and hydrodynamic. Increment of hydrodynamic component of the lubricating layer thickness under increasing of the total rolling speed up to 1.48 m/s, calculated as the difference between layer thickness measured at a given speed of the contact surfaces and the thickness of the boundary layer measured at the stand makes 1 - 3 mcm, which is under further increase of rolling speed insures the implementation of the hydrodynamic model of the lubricating action (**Figure 1**).

In these experimental conditions, pure rolling contact surfaces varied in the rolling slippage, the maximum value of which amounted to 20% at a speed of rolling of 4.8 m/s. Under this mode the analyzed lubricant exhibits effective lubrication effect, shows the realization of hydrodynamic lubrication, while the thickness of the lubricating layer is 4 - 8 mm, which correspond to similar values of the parameter in pure rolling conditions. According to [10] the results obtained in contact-hydrodynamic criteria $P_n/\mu V_{\Sigma k}$ characterizing the bearing capacity of the contact, positively evaluates the increase of rolling speed on lubricating thickness in contact. Although an increase in the sliding speed under the presence of slippage causes the decrease in the efficiency of the lubricating effect. Similar results were obtained in the current experimental conditions-stabilization of the thickness of the lubricating layer in contact, absence of correlation influence on the rolling speed parameter is the consequence of the appearance in the contact of the high shear rate of the oil layer which reaches a value of 623×10^4 - 1.84×10^5 s^{-1} under slippage increase.

The presence of the slippage in contact significantly modifies the rheological properties of the investigated mineral transmission oil. If the conditions of pure rolling effective viscosity (η_{ef}), regardless of the type of material of the contact surfaces, was on average of 2000 Pa·s, while at high speed of shear rate the decrease of this parameter was in 10 times by lubricated steel 42Cr4 and 20 times with using rollers made of steel 100Cr6 (**Figure 2**).

Dependence of η_{ef} from speed shear rate indicates obtaining of non-Newtonian properties of the lubricant in contact, which is also confirmed by other authors [11]. Conditions of the pure rolling shear contribute to localization of shear stress directly in the lubricating layer, where the frictional force is less, at the same time high viscosity TAD-17i exhibits high antifriction properties-the friction coefficient does not depend on the hardness of the investigated surface and on average constitutes 0.01. However, at high shear gradients across the lubricating layer under slippage condition, shear stress of lubricating layers increases in 2.4 times by using a softer 42Cr4

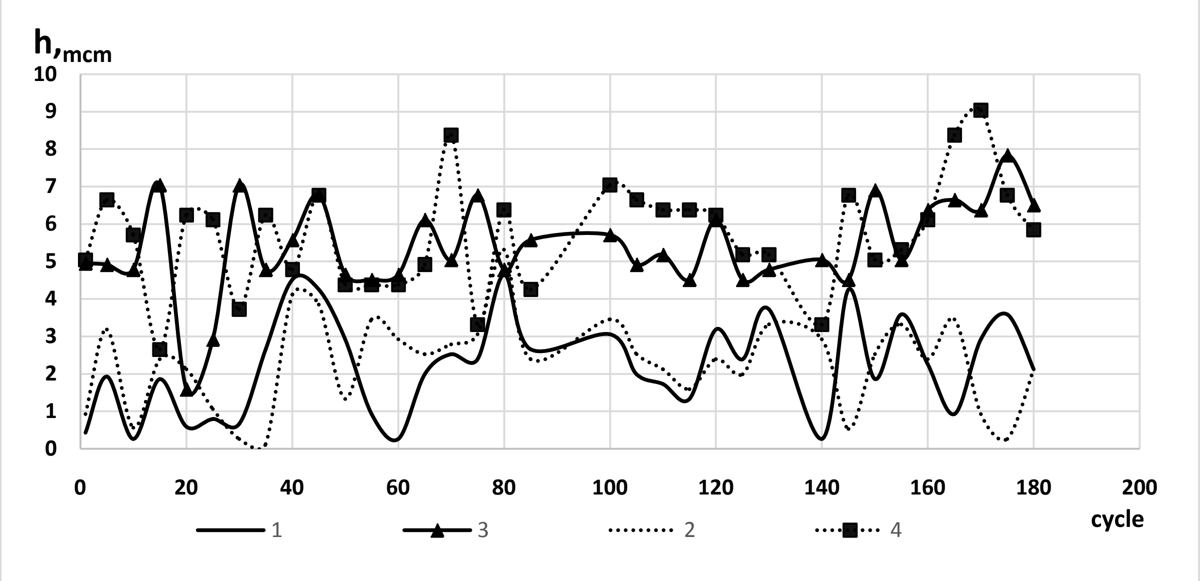
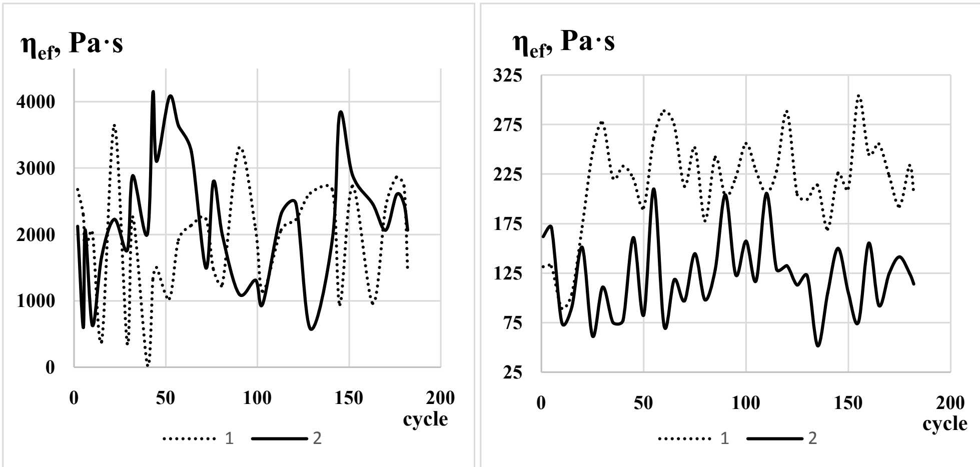


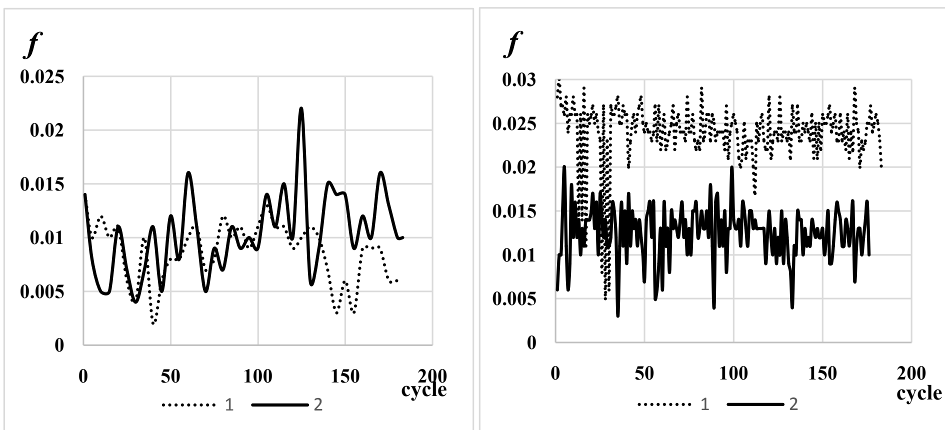
Figure 1. The change in total thickness of the lubricating layer in contact with the total rolling speed of 1.48 m/s and the thickness of the boundary lubrication adsorption layers: 1—the thickness of the boundary layer of oil on the steel 100Cr6; 2—the thickness of the boundary layer of oil on the steel 42Cr4; 3—the total thickness of the lubricant for steel 100Cr6; 4—total thickness of lubrication for steel 42Cr4.

steel, which also leads to the correlation increase of the friction coefficient, and for lubrication of steel 100Cr6 the changes in shear stress of lubricating layer and friction coefficient is not identified in **Figure 3**.

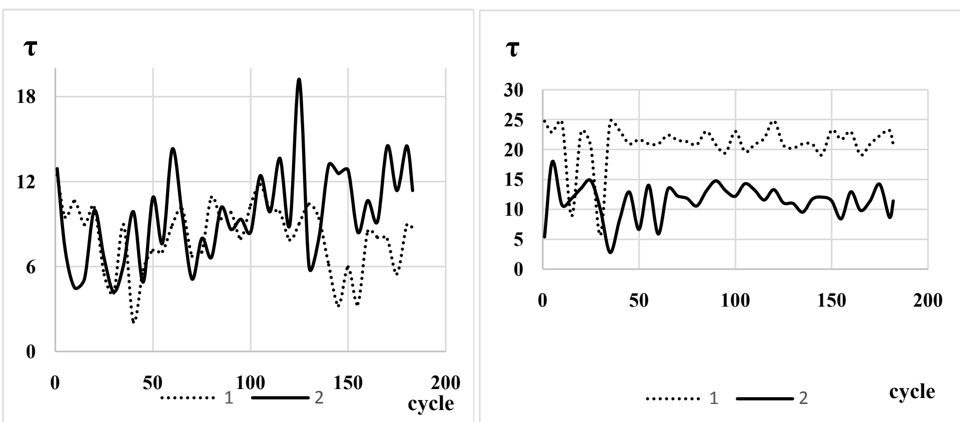


(a) rolling (b) slippage

Figure 2. The kinetics of the effective viscosity change in contact under pure rolling (a) and rolling with slippage (b): 1—for lubrication of steel 42Cr4, 2—for lubrication of steel 100Cr6.



(a) (b)



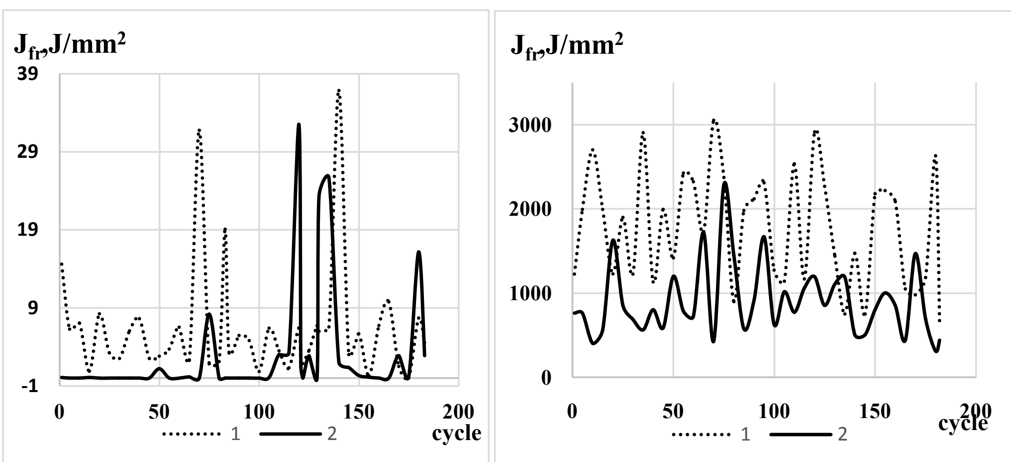
(c) (d)

Figure 3. Dynamics of the friction coefficient (a-rolling, b-slippage) and the shear stress of the lubricating layer (c-rolling, d-slippage) in non-stationary operating conditions: 1—under lubrication of steel 42Cr4; 2—under lubrication of steel 100Cr6.

It is suggested that different shear stresses in the lubricant layer in using steels 100Cr6 and 42Cr4 are conditioned by the varying nature of the boundary lubricant layers that are formed from lubricant components and participating in the formation of secondary structures on activated by friction contact surface. This assumption is based on an analysis of change in the energy parameter-specific work of friction (J_{fr}) in contact according to the methodology [9]. The specific work of friction is a complex physical criteria that comprehensively describing the process of friction and wear, as well as the surface strength of the materials [7]. At the initial starting torque of the contact surfaces of steel 42Cr4 the mounted increases of the specific work of friction in the range of 3 - 35 J/mm^2 in 95% of cycles at an operating time, and for steel 100Cr6 under similar experimental conditions, the increment of the parameter is 1 - 30 J/mm^2 at 20% cycles. Increasing of the rolling speed to 4.8 m/s under slippage presence, where the maximum slippage speed is 0.65 m/s, the power density contact sharply increases: J_{fr} is in the range 1000 - 2800 J/mm^2 and 500 - 2000 J/mm^2 for steel 42Cr4 and 100Cr6, respectively (**Figure 4**). These significant differences in the kinetics change of the energy parameter for the studied steels brands are due to their structural differences. The steel 42Cr4 is characterized by sorbitol structure. According to [12], under the friction of such steel in the surface layer, because of the low potential barrier of shear deformation, the textured structure is formed. In the current experimental conditions, physico-chemical activity of the activated by friction metal increases, resulting in an increased adsorption capacity and the formation of the contact surfaces chemosorbitol boundary layers, that characterized by increased shear stress due to the impact of the solid phase of the activated metal, which is manifested in the slippage mode. The initial stage of the formation of the boundary layers leads to an intensification of wear and adsorption plasticizing of the metal surface layers, which is manifested in their softening—micro-hardness (ΔH_{100}) leading and trailing surfaces is reduced by 260 and 490 MPa, respectively (**Figure 5**).

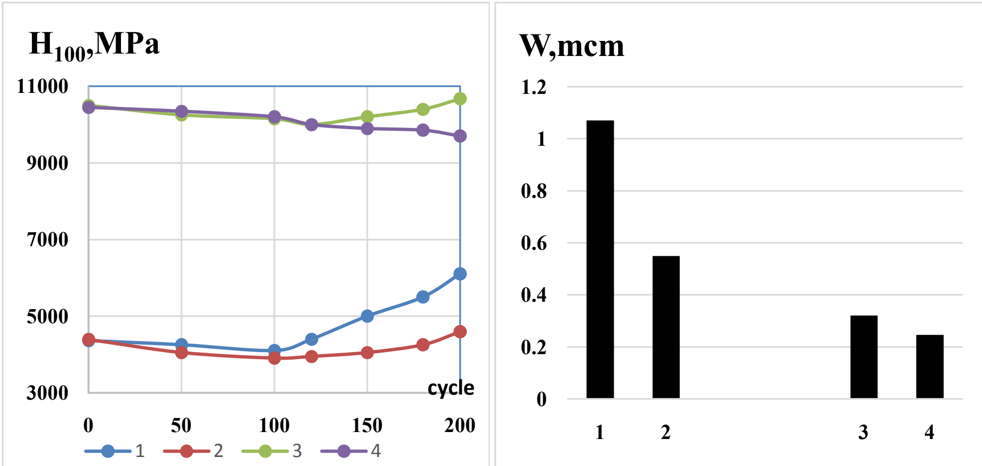
However, after 100 operating cycles, there is a gradual hardening of the surface layers of 42Cr4 steel, which also coincides with the results obtained in [12]: major type of the reinforcement of sorbitol structure in the surface layer is hardening.

The steel 100Cr6, after hardening and low temperature tempering has a structure of small-needle martensite with evenly distributed excess carbides, is characterized by high wear resistance of the contact surfaces-the wear of the trailing and leading surfaces in 3.34 and 2.23 times lower compared with those identified for steel 42Cr4 (**Figure 5**). The dispersed carbides have beneficial effects on the relaxation of the metal. In the current experiment, under the non-stationary work of the contact surfaces, the specific work of the friction is characterized by low index, observed the decrease of the influence of the solid phase in boundary lubrication layers formation, which is manifested in reducing shear stress in the lubricating layer in 2.3 times under slippage compared with τ of the boundary layers formed on steel 42Cr4 [13]. It should be noted that the effect of the adsorption plasticizing and decrease in strength of the surface layers of metal for 100Cr6 is identified under longer load cycles-for the trailing surface softening of surface layers of metal was ΔH_{100} = 800 MPa without subsequent hardening,



(a) (b)

Figure 4. Changing of the specific work of friction during the start-up in pure rolling (a) and at 20% slippage of the contact surfaces (b): 1—for steel 42Cr4, 2—for steel 100Cr6.



(a) (b)

Figure 5. Changing of the micro-hardness (a) of the metal surface layers and the wear (b) of the contact surfaces at an operating time of 200 cycles: 1—trailing surface, 42Cr4; 2—leading surface, 42Cr4; 3—trailing surface, 100Cr6; 4—leading surface, 100Cr6.

while for leading surface softening was ΔH_{100} = 500 MPa up to 120 cycles, with further operating time the contact surfaces characterized by a gradual hardening. The descriptive analysis of lubrication, anti-friction and rheological properties of the tribological contact demonstrates that the structural adaptability of the contact surfaces in non-stationery work conditions are significantly affected by the activation of the surface layers of the metal and the formation of the boundary lubricating layers by lubricating oil TAD-17i. Moreover, a material with a lower hardness is characterized by the formation of the boundary layer with high rates of effective viscosity in the contact and shears of the oil layer due to their disorientation and constant updates on the abrading surface of the metal under wear. Increasing the hardness of the steel due to its less intense activation under friction contributes to the formation of stable boundary adsorption layers, characterized by a low shear stress and profound anti-friction properties.

4. Conclusion

From the above discussion, the following conclusions can be drawn. Steel 100Cr6 increases the time of the adaptation of the boundary lubrication layers due to the minimum increment of the friction specific work in contact, which manifests itself in 20% increase of cycles in which the initial breakaway period has realized semi-dry or boundary modes of lubricant action. 20% of slippage in the contact significantly increases a shear rate gradient of lubricating layers, which reduces the effective viscosity in contact. When a shear rate gradient in the thickness of the lubricating layer is above 6.23×10^4 c^{-1} under slippage condition, the shear stress of the lubricating layers increases in 2.4 times by using a softer material of 42Cr4 steel, which also leads to correlation increase of friction coefficient, while the lubricating surfaces of steel 100Cr6-changes in shear stress of the lubricant layer and the friction coefficient have not been identified. Established indicators for increment friction specific work during start-up in pure rolling are for steel 42Cr4 up to 35 J/mm^2 at 95% of operating cycles and for steel 100Cr6 up to 30 J/mm^2 at 20% of cycles, if there is slippage that the power density of the contact increases dramatically. Structural differences of steel 100Cr6 and steels 42Cr4 after tempering substantially affect wear resistance of the metal: steel 100Cr6 has a structure of small-needle martensite with evenly distributed excess carbides characterized by high wear resistance of contact surfaces—the wear of leading and trailing surfaces in 3.34 and 2.23 times is less compared with those established for sorbitol 42Cr4 steel.

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