



## Tribological information of contact electrical resistance parameters in the study of oxidation and metal plating processes

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### Abstract

The work investigates the regularities of the change in contact electrical resistance in heavily loaded tribosystems under the conditions of transition from oxidation processes to the formation of adaptive metal-clad tribofilms. It is proposed to consider contact electrical resistance as an integral kinetic criterion of the structural and energy state of the frictional contact, which reflects the processes of destruction of oxide and metal-clad layers, activation of friction surfaces, formation of electrically conductive adaptive tribostructures and transition to adhesive contact. The research was carried out according to a scheme that models the contact "camshaft cam - roller pusher" using 42CrMo4 and 16MnCr5 steels, typical for modern heavily loaded components of the gas distribution mechanism of internal combustion engines. It is established that the change in contact electrical resistance has a pronounced kinetic nature and reflects structural and phase transitions in the surface layers of the tribosystem. It is shown that high values correspond to the presence of oxide and tribochemical insulating layers, stable minimum values characterize the formation of adaptive electrically conductive metal-cladding tribofilms, and a sharp decrease in contact electrical resistance indicates the destruction of adaptive tribolayers and the transition to direct metal contact. Critical regimes of force loading and sliding speed are determined, under which the most stable conditions of structural and energy self-organization of surface layers are realized.

**Keywords:** contact electrical resistance, structural-energetic self-organization, metal plating, adaptive tribofilms, adhesive friction, Cu-containing additives, cam-roller pusher contact

### Introduction

In modern heavily loaded tribosystems of transport vehicles, friction processes are accompanied by complex structural and energetic transformations of surface layers, which determine the stability of frictional contact, wear intensity and durability of friction units. Particularly complex processes are implemented in the contacts of the gas distribution mechanism of internal combustion engines, where under conditions of high contact loads, variable sliding speeds, cyclic nature of loading and transient lubrication regimes, the processes of oxidation, tribochemical self-organization, metal plating and adhesive destruction of surface layers simultaneously occur.

It has been established that during the friction process in the friction contact zone, adaptive tribochemical structures in the form of oxide and metal plating films can form, capable of stabilizing contact, locally compensating for wear and ensuring structural and energetic stability of the tribosystem. In this case, the metal plating processes play the role of a positive autocompensator of wear, while adhesive friction is the main antagonist of self-organization processes, which is accompanied by the destruction of adaptive tribolayers, the development of microscratches and the transition to direct metal contact.

However, the regularities of kinetic transitions between oxidative, mechanochemical, metal plating and adhesive mechanisms of friction remain insufficiently studied, as well as the relationship between the structural and energy state of surface layers and the parameters of the electrophysical state of frictional contact. The search for an integral criterion that would allow real-time assessment of the kinetics of friction processes, self-organization processes and structural degradation of surfaces is especially relevant.



A promising direction for solving this problem is the use of the contact electrical resistance parameter  $R$  as an integral indicator of the structural and energy state of the tribosystem. The change in  $R$  reflects the processes of destruction of oxide and lubricating films, activation of friction surfaces, formation of electrically conductive adaptive tribolayers, and transition to adhesive contact.

### **Purpose of work**

The aim of the work is to establish a correlation between the kinetics of friction processes in heavily loaded tribosystems and the contact electrical resistance index as an integral criterion of structural and energetic processes in the frictional contact zone. To achieve this goal, it is necessary to investigate the regularities of the change in contact electrical resistance during the transition from oxidation to metal plating and adhesive destruction of surface layers, as well as to establish the influence of loading modes, sliding speed, lubrication conditions, concentration of Cu-containing components and the state of the initial surface on the processes of self-organization of adaptive tribofilms in the contact "camshaft cam - roller pusher".

### **Analysis of recent research and publications**

In modern research, considerable attention is paid to the use of nanodispersed additives in lubricants, since they are able to reduce the friction coefficient, wear intensity and form protective tribofilms on friction surfaces. The work of M. Waqas et al. summarized the influence of various nanoadditives on the friction characteristics of lubricants and showed that the effectiveness of such compositions largely depends on the type of particles, their concentration, dispersion and stability in the lubricating medium [1]. A separate direction is the study of copper-containing nanoadditives. Y. Choi et al. established that the addition of copper nanoparticles to oil reduces the friction coefficient and reduces surface wear, which is explained by the formation of a protective layer on the friction surface [2]. Similar results were obtained by H. L. Yu et al., where it was shown that Cu nanoparticles can form a thin copper film directly during friction, improving the antifriction and antiwear properties of the lubricating medium [3]. In the work of M. Scherge et al. it is shown that copper-containing additives in motor oils can implement a multi-stage mechanism of formation of protective films on metal surfaces. This is of great importance for explaining the processes of metal plating and the formation of adaptive tribolayers in heavily loaded contacts [4]. Also relevant are studies related to the electrophysical control of friction processes. In works devoted to contact electrical resistance, it is shown that the electrical parameters of the contact can be used to assess the state of the lubricating film, the degree of metal contact, the formation of tribofilms and the transition between lubrication modes [5, 6]. This directly corresponds to the idea of using the contact electrical resistance  $R$  as an integral criterion of the structural and energy state of the tribosystem. Important for this topic are the works of H. A. Spikes, who considered the influence of electric potentials on friction, wear and tribochemical processes. The author emphasizes that electrical influences can change the kinetics of tribochemical reactions, film formation and frictional contact behavior [7]. This confirms the feasibility of combining tribological and electrophysical approaches in the study of adaptive tribofilms. Recent studies of electrified tribocontacts show that the formation of tribofilms can significantly depend on the electrical state of the contact. In particular, N. Siddique et al. investigated the formation of polymer tribofilms at different electric current densities and used impedance spectroscopy to evaluate their electrical properties [8]. This is an important methodological analogue for works where contact electrical resistance is used as a diagnostic parameter. The work of J. A. Cao-Romero-Gallegos et al. is devoted to the effect of electric current on the thickness of the lubricating film in boundary and mixed lubrication regimes. The authors showed that the electrical contact conditions affect the change in the lubricating layer, which is important for explaining the transitions between hydrodynamic, elastohydrodynamic and boundary lubrication regimes [9]. General reviews of recent years confirm that the modern development of tribology is aimed at creating functionally doped lubricating compositions capable of forming self-organized adaptive tribolayers. Particular attention is paid to metal nanoparticles, oxides, graphene structures, h-BN, MoS<sub>2</sub> and ionic liquid components [10, 11]. The results obtained are consistent with the data of works [12,13], where it is shown that the tribological behavior of surface layers is determined by complex structural-energy processes, which include the formation of secondary structures, tribochemical transformations and the development of material damage mechanisms. The established patterns confirm that the processes of self-organization of surface layers have a direct impact on the parameters of friction, wear and stability of the functioning of tribosystems. Thus, the analysis of recent studies shows that a promising direction is the combination of nanomodified lubricating compositions, metal plating processes and electrophysical monitoring of the state of the frictional contact. At the same time, the patterns of the transition from oxidative and mechanochemical secondary structures to electrically conductive adaptive tribofilms in heavily loaded automotive tribosystems, in particular in the contact "camshaft cam - roller pusher", remain insufficiently studied. This is precisely what determines the relevance of further use of the contact electrical resistance parameter  $R$  for diagnosing the structural and energy state of surface layers.

### **Research materials and methodology**

The functioning of tribocouplings of the gas distribution mechanism of internal combustion engines is accompanied by complex non-stationary processes of interaction of surface layers, which occur under conditions of high specific loads, cyclic nature of contact and variable lubrication modes. In the contact "camshaft cam - roller pusher" mechanical, thermal and tribochemical processes are simultaneously implemented, which determine the nature of the evolution of surface structures and the durability of the friction unit. When moving from the hydrodynamic to the limit lubrication mode, the role of structural and phase transformations in the surface layers associated with the destruction of oxide films, activation of contact surfaces and the development of local adhesive interactions significantly increases. In the process of friction, the surface layers of the tribosystem are in a non-equilibrium state, which creates conditions for the emergence of self-organization processes and the formation of secondary tribochemical structures. Under certain load conditions and sliding speeds, adaptive metal-cladding tribofilms can form in the contact zone, which are characterized by reduced shear resistance and the ability to stabilize frictional contact. Such structures perform the function of local wear compensation, reduce the concentration of contact stresses and prevent the development of destructive processes in the friction zone. However, when the structural stability of tribolayers is violated, their destruction occurs, which is accompanied by a transition to adhesive contact and intensive wear of surfaces.

One of the main problems of modern tribology is the establishment of a parameter that would allow assessing the kinetics of structural and energy changes in the tribosystem directly during the operation of the friction unit. Traditional tribotechnical indicators do not always make it possible to promptly record the initial stages of destruction of adaptive tribolayers or the moment of transition to adhesive friction. In this regard, the use of  $R$  as a sensitive parameter reflecting the change in the physical state of the surface layers and the nature of the interaction between them is promising.

To study the kinetic indicators  $R$ ,  $I$ ,  $T$  and  $\mu$ , a specialized tribometer was used (Fig. 1), which simulated the operating conditions of the gas distribution mechanism of an automobile engine. The tribometer was formed from 42CrMo4 steel (EN 1.7225), which simulated the working surface of the camshaft cam, and cemented steel 16MnCr5 (EN 1.7131), which corresponded to the material of the roller pusher. The tests were carried out in a wide range of force parameters of loads and sliding speeds using alloyed lubricating compositions modified with Cu-containing functional components.

The increased rigidity of the tribometer frame structure, friction unit, and loading mechanism minimizes the occurrence of vibration during the research process and its negative impact on the objectivity of the obtained results.



**Fig. 1. General view of the tribometer**

*Source: created by the author based on experimental data using artificial intelligence tools*

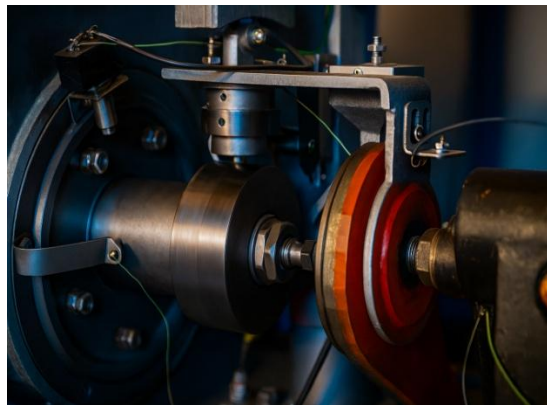
General view of the friction unit in Fig. 2. The friction unit of the studied tribocoupling modeled the contact of the pair "camshaft cam - roller pusher". For experimental studies, the studied sample was used in the form of a cylindrical roller, the working surface of which imitated the surface of the roller pusher, and a countersample in the form of a cam, the working surface of which modeled the profile of the camshaft cam. The geometric parameters of the samples and the contact conditions were chosen in such a way as to ensure the reproduction of the nature of the contact interaction, load and speed regimes of a real tribocoupling. Both parts were manufactured to the sixth quality of accuracy. The roughness of the working surfaces after running-in was  $R_z = 0.125-0.250 \mu\text{m}$ .

Experimental studies were carried out under normal load on the sample within 100–600 N, which ensured the formation of contact pressures close to the operating conditions of the tribocoupling "camshaft cam - roller pusher". The sliding speed was varied in the range of 0.2–3.0 m/s, which allowed to reproduce the operating modes of the cam mechanism at different camshaft rotation frequencies. The main controlled parameters during the tests were normal load, sliding speed, friction duration, temperature in the contact zone, friction coefficient, wear intensity and parameter R. The main parameters and modes of experimental studies of the tribocoupling "camshaft cam - roller pusher" are given in Table 1.

Table 1

**Main parameters of experimental studies of tribocoupling "camshaft cam - roller pusher"**

Parameter	Value
Normal load, N	100; 200; 300; 400; 500; 600 N
Contact pressure, $p$	4–12 MPa
Sliding speed, $v$	0.2; 0.5; 1.0; 1.5; 2.0; 3.0 m/s
Test duration	300–600 min
Surface roughness after running-in, $R_a$	0.125–0.250 $\mu\text{m}$
Temperature in the contact zone	40–120 °C

**Fig. 2. General view of the friction unit**

*Source: created by the author based on experimental data using artificial intelligence tools*

The open design of the friction unit is convenient for visual control of its operation, lubrication mode, natural cooling of the friction contact zone, replacement of tribocoupling parts, connection of measuring equipment.

To intensify the processes of structural and energy self-organization of surface layers and the formation of adaptive metal-cladding tribofilms, the base lubricating medium was subjected to functional alloying with a complex of micro components. The selection of materials was carried out taking into account their tribochemical activity, ability to form secondary structures and influence on the electrophysical state of the friction contact.

As a base lubricating medium, SAE 10W-40, API CI-4/SL class motor oil for heavy-duty diesel engines was used, which is characterized by high thermal-oxidative stability, sufficient anti-wear properties and a wide range of operating modes. Shell Rimula R6 M 10W-40 was chosen as the base oil, to which functional Cu-containing alloying components were introduced at a concentration of 5, 10 and 20% by weight of the additive.

The preparation of alloyed lubricating compositions was carried out by mechanical dispersion using ultrasonic treatment at a frequency of 22 kHz for 20...30 min, which ensured uniform distribution of particles in the lubricating medium and prevented their agglomeration. To stabilize the dispersed system, surface-active components were used at a concentration of 0.5...1.0%.

### Research results and discussion

The introduced functional components were involved in tribochemical reactions in the contact zone during the friction process and participated in the formation of self-organized electrically conductive adaptive tribolayers. The effectiveness of the processes of structural-energy self-organization was assessed by the change in R, which was considered as an integral kinetic indicator of the structural state of the surface layers of the tribosystem.

Structural-energy transitions and the relationship between the processes of oxidation, self-organization, and metal plating in the frictional contact zone of heavily loaded tribosystems are shown in Fig. 3.

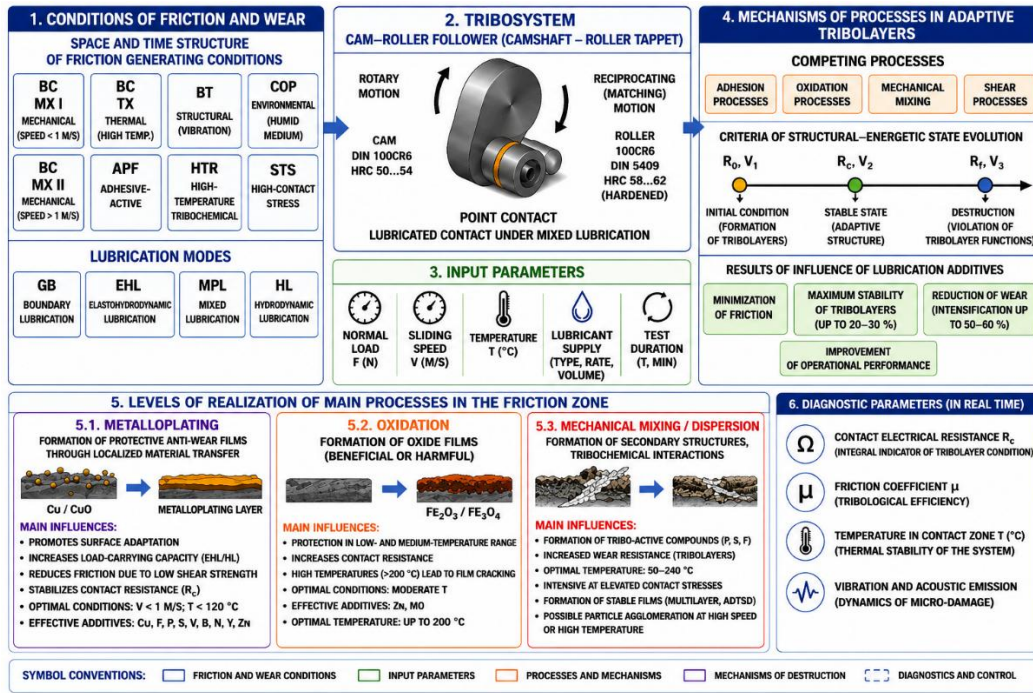


Fig. 3. Structural and energy scheme of the implementation of the processes of self-organization, oxidation, metal plating and adhesive wear in heavily loaded tribosystems of the gas distribution mechanism: VS MX I, II - secondary structures of mechanochemical type I and II, VS TX - secondary structures of thermochemical type, VP - selective transfer structures, SOP - self-organized organic tribofilms, ATP - adaptive tribofilms, NKTSh - nanocomposite tribochemical layers, STS - self-organized dissipative tribostructures, HD - hydrodynamic lubrication regime, EHL - elastohydrodynamic lubrication regime, BNL - boundary nanolubrication regime, MPP - metal-cladding films, Cu/CuO - copper-containing tribochemical components, P1-P3 - critical loads of structural-energy transitions, V1-V3 - critical sliding velocities of structural-energy transitions, R - contact electrical resistance of frictional contact, μ - friction coefficient, AE - acoustic emission parameters, T - temperature in the frictional contact zone.

Source: created by the author based on experimental data using artificial intelligence tools

The regularities of the evolution of surface structures and the transition between different stages of the structural and energy state of the tribosystem are shown in Fig. 4.

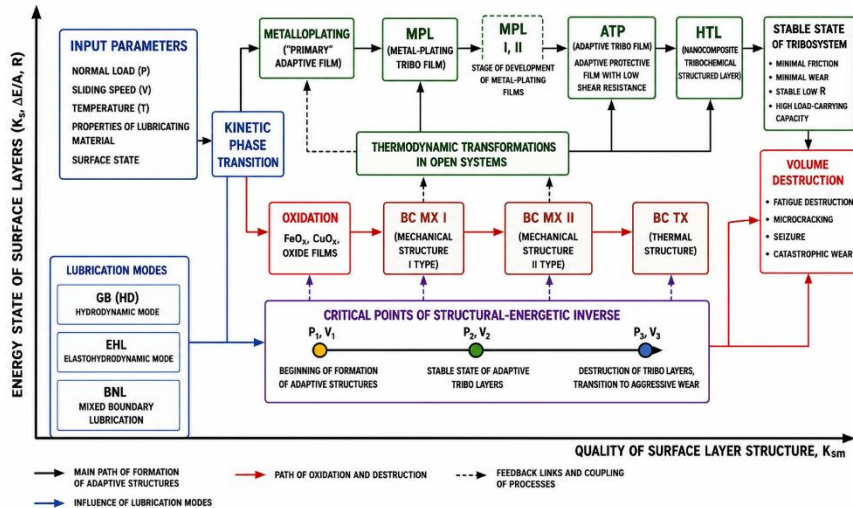


Fig. 4. Evolution of the structure of materials of surface layers of technical tribosystems: VS MX I, II - secondary structures of mechanochemical type I and II, VS TX - secondary structures of thermochemical type, MPP - metal-plating films, ATP - adaptive tribofilms, NKTSh - nanocomposite tribochemical layers, HD - hydrodynamic lubrication mode, EHL - elastohydrodynamic lubrication mode, BNL - boundary nanolubrication mode, FeOx, CuOx - oxide tribochemical structures, Kz - energy storage coefficient by surface layers, Kzm - strengthening coefficient of surface layers, ΔE/At - ratio of stored energy to the work of friction forces, R - contact electrical resistance of frictional contact, P1-P3 - critical loads of structural-energy transitions, V1-V3 - critical sliding velocities of structural-energy transitions

Source: created by the author based on experimental data using artificial intelligence tools

This figure reflects the structural-energy model of the evolution of surface layers in heavily loaded tribosystems and demonstrates the relationship between the processes of oxidation, metal plating, the formation of adaptive tribofilms and the destruction of surface layers during friction.

The vertical axis shows the energy state of the surface layers, which is characterized by the parameters  $K_z$ ,  $\Delta E/AT$  and  $R$ . With an increase in the energy activation of the surface layers in the contact zone, tribochemical and structural-phase transformations are intensified. The horizontal axis shows a change in the quality of the structure of the surface layers, which is characterized by the coefficient  $K_{zm}$ , which reflects the degree of strengthening, stabilization or degradation of the surface tribolayers.

At the initial stage, the input parameters of the tribosystem — load, sliding speed, temperature, lubrication mode, properties of the lubricant and surface condition — determine the nature of the course of structural-energy processes in the frictional contact zone. When critical conditions are reached in the tribosystem, a kinetic phase transition is realized, after which two main mechanisms begin to compete: oxidation of surface layers and metal plating processes.

The lower branch of the scheme reflects the oxidative direction of the evolution of surface structures. First, oxide films of  $FeO_x$  and  $CuO_x$  are formed, after which secondary structures of mechanochemical type I and II (BC MX I, BC MX II) appear. Further accumulation of energy and increase in temperature leads to the formation of thermochemical structures (BC TX). When the system goes beyond the limits of structural stability, volumetric destruction of surface layers occurs, which is accompanied by microscratches, seizing, fatigue failure and catastrophic wear.

The upper branch of the scheme describes the processes of metal plating and self-organization of adaptive tribolayers. After the phase transition, in the presence of Cu-containing components in the contact zone, a metal plating film (MP) is formed, which goes through several stages of development. Further thermodynamic transformations in the open tribosystem lead to the formation of adaptive tribofilms (AT) and nanocomposite tribochemical layers (NCTL). These structures have reduced shear resistance, stabilize the friction process, reduce the friction coefficient and wear intensity, and increase the bearing capacity of the contact.

The figure also shows the critical points of structural-energy inversion  $P_1, V_1$ ;  $P_2, V_2$ ;  $P_3, V_3$ . At point  $P_1, V_1$ , the formation of adaptive structures begins. In the range  $P_2, V_2$ , stabilization of adaptive tribolayers and the most effective implementation of self-organization processes are observed. When  $P_3, V_3$  is reached, the destruction of tribofilms begins and the transition to adhesive wear and destructive processes occurs.

Lubrication modes significantly affect the direction of evolution of surface structures. In the hydrodynamic mode (HD), stable separation of surfaces by a lubricating film prevails. In the elasto-hydrodynamic mode (EHL), the conditions for the formation of adaptive tribofilms are realized. The boundary nanolubrication mode (BNL) is characterized by high activation of surface layers, the development of tribochemical reactions and the most intensive self-organization processes.

Using the parameter  $R$ , the ranges of structural and energetic stability of the processes of formation of secondary tribochemical structures, metal-cladding films and adaptive nanocomposite tribolayers in the contact zone “camshaft cam – roller pusher” were established. Analysis of the change in contact electrical resistance allowed us to determine the critical transition modes between oxidative, mechanochemical and metal-cladding mechanisms of self-organization of surface layers. The existence of critical points of structural and energetic inversion of tribological processes ( $P_1, V_1$ ;  $P_2, V_2$ ;  $P_3, V_3$ ) was established, within which the transition from unstable oxidative and mechanochemical secondary structures to the formation of electrically conductive adaptive tribofilms with a reduced critical shear stress and high structural stability occurs (Fig. 5).

It is shown that in the range  $P_1$ – $P_2$  and  $V_1$ – $V_2$  the most favorable conditions for the processes of metal plating and the formation of self-organized nanocomposite tribolayers are realized, capable of stabilizing frictional contact, localizing the energy of plastic deformation and reducing the intensity of adhesive wear. When reaching the critical parameters  $P_3$  and  $V_3$ , a violation of the structural equilibrium of the tribosystem, destruction of adaptive tribofilms and a transition to destructive friction modes are observed, which is accompanied by the development of microscratches, seizure of surfaces and a sharp increase in the friction coefficient.

The change in the value of  $R$  allowed us to evaluate in real time the kinetics of destruction of surface oxide layers, the degree of activation of friction surfaces, the formation and stabilization of electrically conductive metal plating structures, as well as the processes of self-organization of adaptive tribofilms in the frictional contact zone. It has been established that the parameter  $R$  is a sensitive integral criterion of the structural and energy state of the tribosystem and can be used to diagnose transitions between the regimes of oxidation, boundary lubrication, metal plating, and adhesive destruction of surface layers, which is accompanied by the transition from unstable oxidative structures to the formation of adaptive metal plating tribolayers (Fig. 3).

The graph reflects the influence of the initial surface state on the nature of the transition processes from oxidation to metal plating in heavily loaded tribosystems. At the initial stage, surfaces with high oxidation and roughness are characterized by high values of  $R$ , which corresponds to the formation of unstable oxide structures. With an increase in the load  $P$  and the sliding speed  $V$ , the destruction of oxide films, activation of surfaces and a transition to the formation of mechanochemical structures occur. In the range from  $P_2, V_2$  to  $P_3, V_3$ , the most favorable conditions for metal plating processes and the formation of adaptive metal plating films (MPF) are realized, which is accompanied by a sharp decrease in contact electrical resistance due to the formation of electrically conductive tribolayers. It is shown that pre-finished surfaces quickly transition to the stable metal

plating mode, while untreated surfaces remain in the region of oxidative processes longer and are characterized by a less stable course of structural and energy self-organization.

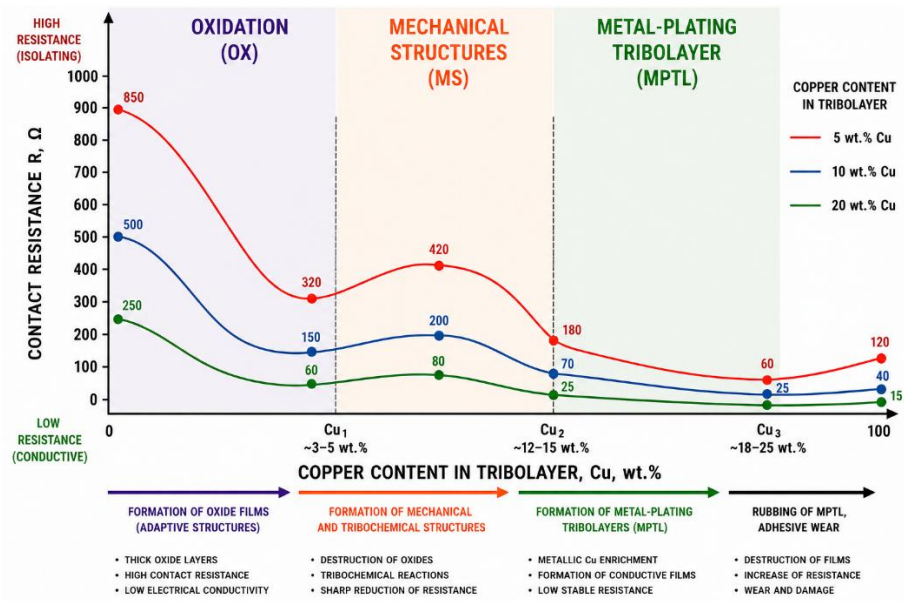


Fig. 5. The influence of the initial surface condition on the nature of the oxidation (OS) - metal plating (MPP) transient processes

Source: created by the author based on experimental data using artificial intelligence tools

To establish the relationship between the processes of structural and energetic self-organization of surface layers and changes in tribotechnical characteristics, a comparative analysis of the kinetics of R, the friction coefficient and the wear intensity at different contents of the functional alloying component Cu in the tribosystem was carried out. Particular attention was paid to determining the range of loads and sliding speeds within which the most stable conditions for the formation of adaptive metal-clad tribolayers are realized and the positive self-compensation effect of metal-clad is manifested (Fig. 6).

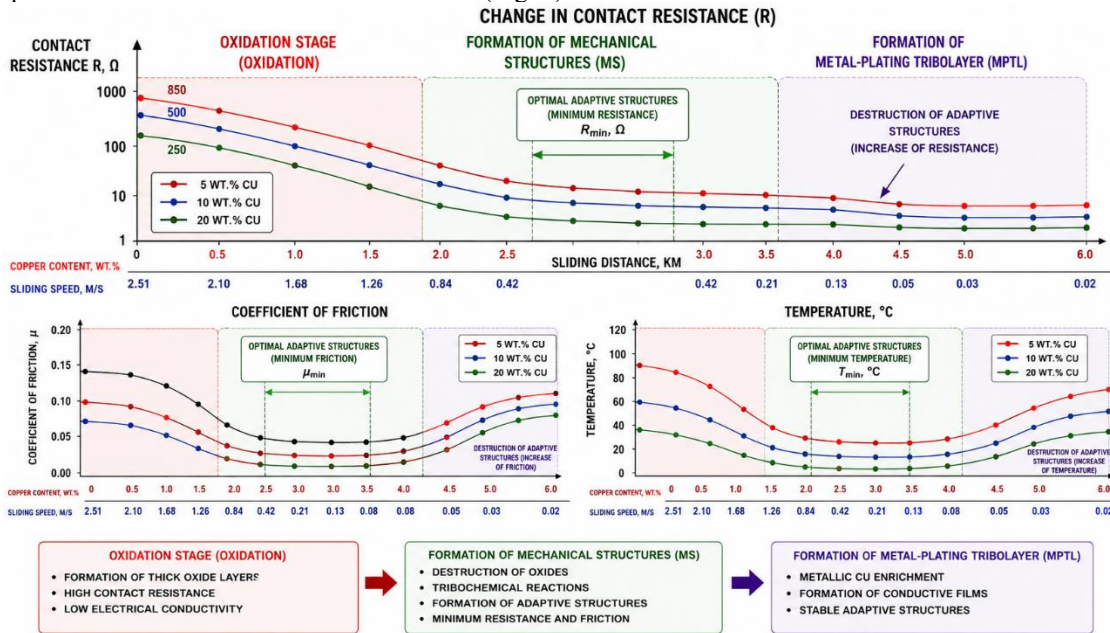


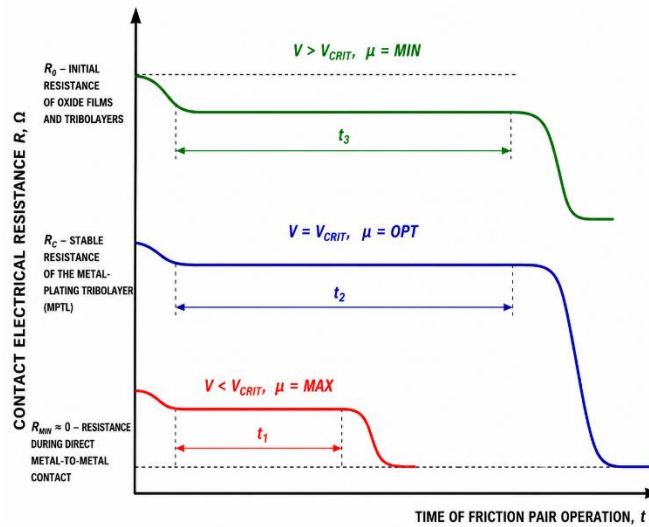
Figure 6. Correlation between contact electrical resistance (CER), friction parameters, and structural-energetic transformations of adaptive tribolayers under different Cu concentrations in the lubricating medium

Source: created by the author based on experimental data using artificial intelligence tools

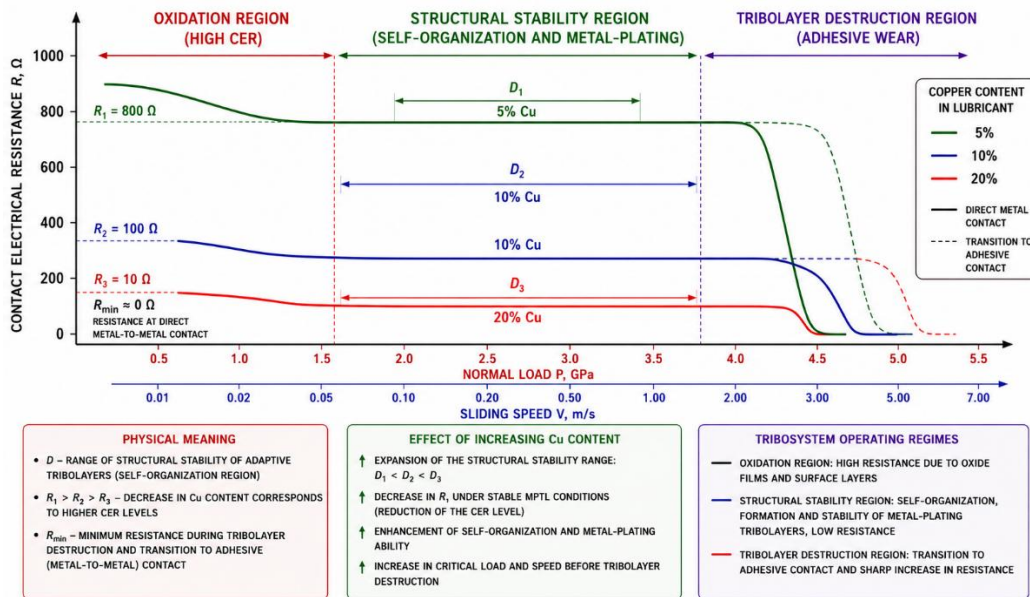
As can be seen from Fig. 6, doping the tribosystem with Cu-containing components significantly affects the nature of the change in R, the friction coefficient and the wear intensity. In the zone of optimal values R of the load and sliding speed, R is stabilized at a minimum level, which indicates the formation of electrically conductive adaptive metal-clad tribolayers. In the same range, the friction coefficient and wear intensity are minimized, which

confirms the implementation of the processes of structural and energy self-organization of surface layers and the positive self-compensation effect of metal plating. A further increase in the specific load and sliding speed leads to a violation of the structural stability of adaptive tribolayers, the development of adhesion processes and a transition to destructive friction modes. This is accompanied by a sharp decrease in R, which corresponds to the transition to direct metal contact, as well as an intensive increase in the friction coefficient and wear rate of surfaces. The obtained results confirm the existence of a correlation between the kinetics of change of R and the main tribotechnical indicators of the tribosystem.

The nature of the change and the value of the main tribotechnical indicators, the parameters of adaptive tribofilms and the processes of structural and energetic self-organization of surface layers are significantly affected by the volume and periodicity of the supply of alloyed lubricant to the frictional contact zone (Fig. 7), the concentration, dispersion and stability of functional micro- and nanodispersed additives in the lubricating medium (Fig. 8). It has been established that the change in load modes, sliding speed and contact cyclicly directly affects the kinetics of formation and destruction of adaptive tribochemical layers, the stability of the lubricating film, the value of R, the friction coefficient and the intensity of wear of surface layers.



**Fig. 7.** Correlation between R and the existence time of adaptive MPPs on lubrication conditions:  $t_1, t_2, t_3$  - time of structural stability (“lifetime”) of the MPP;  $R_0$  - initial resistance of oxide and tribochemical layers;  $R_c$  - stable contact electrical resistance of adaptive metal-clad tribolayers;  $R_{min} \rightarrow 0$  - resistance at direct metal contact;  $V$  - volume of lubricant at a single supply;  $V_{crit}$  - critical volume of supply of lubricating medium;  $\mu_{min}$  - minimum value of the friction coefficient;  $\mu_{opt}$  - optimal friction coefficient;  $\mu_{max}$  - maximum friction coefficient  
 Source: created by the author based on experimental data using artificial intelligence tools



**Fig. 8.** Effect of the concentration of alloying elements of the lubricant additive (Cu) on R and the range of structural self-organization of surface layers D  
 Source: created by the author based on experimental data using artificial intelligence tools

According to the results of the research, it was found that an increase in the concentration of Cu-containing functional components in the lubricating medium significantly affects the kinetics of R change and the structural stability of adaptive tribolayers. It is shown that with an increase in the Cu content, a decrease in the stable level of R is observed, which indicates the formation of more electrically conductive metal-clad tribofilms with an increased ability to structural and energetic self-organization. At the same time, the range of structural stability D ( $D1 < D2 < D3$ ) expands, within which the most effective metal-clad processes and frictional contact stabilization are implemented. It is established that Cu-containing components shift the critical transition to the destruction of adaptive tribolayers to the region of higher specific loads and sliding speeds, which indicates an increase in the resistance of surface layers to adhesive destruction. A sharp decrease in contact electrical resistance corresponds to the destruction of metal-clad tribolayers and the transition to direct metal contact, which is accompanied by the development of adhesion processes and intensive wear of friction surfaces. The obtained results confirm the existence of a correlation between the concentration of alloying components, R, and the structural and energetic stability of tribosystems.

### Conclusions

It was found that the thickness of adaptive tribofilms formed when using alloyed lubricating compositions with functional micro- and nanodispersed additives is heterogeneous and depends on the concentration, dispersion and tribochemical activity of the alloying components. In the course of research, the formation of stable nanocomposite tribolayers with a thickness of hundreds of nanometers to tens of micrometers was revealed, which provide a reduction in the friction coefficient by 15–30% and a significant reduction in the intensity of wear of the contacting surfaces of the tribosystem "camshaft cam - roller pusher". The obtained effect is explained by the formation in the frictional contact zone of self-organized tribochemical structures with a reduced critical shear stress, capable of stabilizing the friction process and localizing the energy of plastic deformation in the surface layers.

It has been established that the geometric, structural-energy and tribotechnical parameters of adaptive tribofilms depend on a complex of interrelated factors, the main of which are: the surface energy of the tribocoupling materials; the magnitude and nature of the load change in the "cam - roller pusher" contact; the state of the initial friction surface, in particular the presence of secondary mechanochemical or thermochemical structures, surface roughness, the degree of activation of surface layers and the presence of abrasive particles; kinematic parameters of motion, the overlap coefficient of contact surfaces, load cyclicality, as well as the amount and periodicity of lubricant supply to the frictional contact zone.

Analysis of the research results showed that the formed adaptive tribofilms are characterized by high antifriction, antiwear and anti-seize properties. The formation of stable tribochemical layers occurs in a relatively narrow range of critical loads and sliding speeds, characteristic of the modes of boundary and mixed lubrication of the gas distribution mechanism of the internal combustion engine. In this range, the friction coefficient, wear intensity and contact electrical resistance parameters are characterized by stable values, which indicates the formation of electrically conductive self-organized tribolayers with high structural stability. The processes of structural and energy self-organization are most effectively implemented with a cyclic nature of the load, a smooth change in sliding speeds and the use of alloyed lubricating compositions with high tribochemical activity of functional nanoadditives.

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**Гупка А.Б., Ляшук О.Л., Міронов Д.В., Хорошун Р.В., Алексевиц Я.Р., Фурса В.А., Гинда Т.Ю.** Трибологічна інформативність параметрів контактного електроопору при дослідженні процесів окислення та металоплакування

У роботі досліджено закономірності зміни контактної електроопору у важконавантажених трибосистемах в умовах переходу від окислювальних процесів до формування адаптивних металоплакуючих трибоплівків. Запропоновано розглядати контактний електроопір як інтегральний кінетичний критерій структурно-енергетичного стану фрикційного контакту, який відображає процеси руйнування оксидних і металоплакуючих шарів, активацію поверхонь тертя, формування електропровідних адаптивних трибоструктур та перехід до адгезійного контакту. Дослідження проводили по схемі яка моделює контакт «кулачок розподільного вала – роликівий штовхач» із використанням сталей 42CrMo4 та 16MnCr5, характерних для сучасних важконавантажених вузлів газорозподільного механізму двигунів внутрішнього згорання. Встановлено, що зміна контактної електроопору має виражений кінетичний характер та відображає структурно-фазові переходи у поверхневих шарах трибосистеми. Показано, що високі значення відповідають наявності оксидних та трибохімічних ізолюючих шарів, стабільні мінімальні значення характеризують формування адаптивних електропровідних металоплакуючих трибоплівків, а різке зниження контактної електроопору свідчить про руйнування адаптивних трибошарів і перехід до прямого металевого контакту. Визначено критичні режими силового навантаження та швидкості ковзання, за яких реалізуються найбільш стабільні умови структурно-енергетичної самоорганізації поверхневих шарів.

**Ключові слова:** контактний електроопір, структурно-енергетична самоорганізація, металоплакування, адаптивні трибоплівки, адгезійне тертя, Си-вмісні добавки, контакт «кулачок – роликівий штовхач»