Wear in combustion engines: experiment and simulation on a basis of movable cellular automaton method

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The presented model is based on experimental data of the role of a thin nanolayer (10–70 nm) forming on surfaces of cylinders and pistons in combustion engines. The nanolayer mostly consists of carbon and iron oxides. It is shown that experimentally observed values of wear rate (from a fraction of a nanometer to several ones per hour) can be explained interpreting a wear process as “extrusion” of the surface nanolayer from a friction zone. Processes of plastic deformation and mass mixing in the nanolayer with modified chemical composition are simulated using the movable cellular automaton method. Based on the analytical models the simulation results were analyzed. A comparison of the calculated results and experimental data was carried out.

1. Introduction

It is widely believed that processes in combustion engines at a stage of running-in wear are related with changing a surface relief of contacting elements, such as cylinder and piston ring walls. However, the recent experimental investigations revealed that on frequent occasions a degree of running-in wear is no more than 100 nm, which is much less than a characteristic height of surface roughness of a cylinder and a piston ring. Such degree of wear results in no substantial surface-relief adaptation. What is more surface roughness can increase or decrease at the stage of running-in wear depending on the initial roughness characteristics, whereas wear rate generally decreases. In the recent papers [1, 2] Kehrwald and Gervé supposed that possible factor responsible for properties of tribological system during and after running-in wear is change of chemical composition of the surface layer. In these papers the change in chemical composition of the surface layer ranging in thickness from several nanometers to several tens of nanometers is given the name of tribomutation. In the present paper mechanical behavior of the contacting surface layers is simulated using the movable cellular automaton method. Experimental data obtained for production engines with using a special tribometer are compared with the numerical simulation and analytical results.

2. Structure and properties of nanolayers (experimental data)

In this section a brief review of experimental data on wear process and surface-layer properties for production engines is presented. In the paper [1] the experimental procedures were described in detail. The experimental data show that a thin nanolayer (as a rule, from 10 to 70 nm thick) is formed on a surface of grey iron cylinder of combustion engines at the stage of running-in (during the first hours of operation). After many thousands of hours of operation layer thickness and composition are essentially unaffected. By this is meant that the surface layer constantly wears out and forms again. Layer thickness depends on the conditions of running-in wear. As a rule, the higher the running-in power, the thinner the layer. Thin layers are more wear resistant than thick layers. Notice that the surface
roughness is several orders of magnitude larger than the thickness of the tribomutated layer. In the initial state a magnitude of surface roughness is usually about 3.8–4.8 µm. After 15 hours of running-in wear it is 0.9–2.2 µm [1]. At the stage of running-in wear roughness can increase or decrease depending on the initial roughness characteristics and applied pressure. It seems likely that wear rate, governed by properties of the surface nanolayer, is unaffected by roughness of micron scale [1].

Experimental study [1] of distribution of chemical elements and compounds in the surface layer show that the key process in the surface layer is carbon deposition (Fig. 1). It seems likely that fuel and oil lubricant are carbon sources. At a depth the concentration of oxidized iron as FeO-compound peaks. A structure of the compound is similar to that of NaCl and usually unstable in the free state. As it will be indicated below, the possible mechanism of surface layer formation is heterogeneous deformation and mass mixing (mechanical alloying).

Wear rate in high-quality production engines is between 0.2 and 2.5 nm/h. Size of debris is varied from several nanometers to micrometers. In the experiments with nucleopore filters, size of most wear debris is in the range from 10 to 120 nm and diameter of around 50 % of particles is less than 40 nm [2].

3. Numerical model

When the cylinder wall and the piston are subjected to moderate normal pressure, their surfaces contact just in several contact patches. Patch area, is as a rule, a few square microns. Investigation of the cylinder and piston surfaces at the lower scale level with using atomic force microscope shows that essential roughness occurs in the microcontact regions. The characteristic roughness amplitude was of the order of 100 nm [1]. Below we will study processes taking place at two “nanorough” microcontacts of the cylinder and piston surfaces which are subjected to a normal pressure and move relative to each other with tangential velocity about 10 m/s.

The method of movable cellular automata [3–5] is used for computer-aided simulation of deformation and mass mixing within surface layers. In the framework of the method a medium is described as an ensemble of discrete elements (movable cellular automata) that are characterized by continuous variables, position of center of gravity, degree of plastic deformation and rotation pseudovector as well as by discrete variables characterizing bonds between neighboring automata. The basic principles of deriving the equations of motion for a system of cellular automata and of specifying inter-automata interactions are described in [3].

In the case being considered a simulated object consists of four parts (Fig. 2). The upper row of automata is a perfectly rigid body moving in the horizontal direction with velocities from 1 to 16 m/s in various numerical experiments. Two intermediate layers with nanoscale initial roughness simulate the surface regions of the cylinder and the piston. The lower row is rigidly fixed.

The upper row is subjected to a constant normal force corresponding to pressure from 0.5 to 8 MPa. Automaton
diameter is 10 nm. Automaton elastic properties correspond to those of steel with Young’s modulus 200 GPa, Poisson’s ratio 0.3, shear yield stress 170 MPa and average shear strength 300 MPa. The value of statistical straggling of parameters was 15 %. It was assumed that unbonded but contacting automata affect to “viscous” force that is proportional to relative velocity of motion. The constant of proportionality corresponds to the effective medium viscosity $\eta = 0.41 \text{ Pa} \cdot \text{s}$. Initial roughness was preassigned in the explicit form. Nevertheless, the simulation results are unaffected by initial roughness. The periodic boundary conditions were given on the left and right boundaries of the simulated system. The schematic representation of the system at an initial time point is shown in Fig. 3(a).

4. Nanolayer dynamics at friction

*Quasi-liquid layer formation.* Even within the first nanoseconds following the onset of tangential motion rough edges of the contact surfaces were intensively deformed and failed and after approximately 100 nanoseconds a dynamic equilibrium was established in the system. A pronounced layer containing a great number of voids was formed. Motion in the layer was similar to turbulent motion in liquid (Fig. 3(b)). Notice that in reality this layer has no liquid properties. Processes at work in the layer are deformation, rupture of inter-automata bonds and their rebonding, “welding”. The turbulent layer was named as a quasi-liquid one to emphasize distinction of its properties from liquid ones in a thermodynamic sense. As a short time passes processes of failure and recovery of layer integrity come to dynamic equilibrium and hereafter the layer properties are considered as statistically invariable. Notice that the quasi-liquid layer is localized close to the initial friction surface and is not developed deep into the contact bodies. A characteristic value of layer thickness depends on system parameters and mainly on an effective viscosity of ensemble of automata. In the present calculations viscosity was used as an adjustable parameter and was chosen so that a layer thickness corresponds to the experimental values. Initial roughness is not affected on quasi-liquid layer formation that is explained by its equilibrium nature. In other set of numerical experiments, processes in a contact region of a deformed body and a perfectly rigid layer was examined. In this case, too, the quasi-liquid layer is formed (Fig. 4), but turbulent motion occurs only in the deformed layer.

*Dependence of friction force on normal pressure and sliding velocity.* The fact that the quasi-liquid layer is not true liquid is illustrated more emphatically by consideration of a friction force in the tribological contact. A horizontal component of a total force acted on the upper (rigid) row of automata was averaged over the simulation time from the instant of dynamic equilibrium establishment. Dependences
Fig. 4. Cellular automaton positions after 8 ns (a) and 400 ns (b) deformation. Normal pressure $P = 2 \text{ MPa}$, sliding velocity $v_0 = 4 \text{ m/s}$

Fig. 5. Dependence of time average value of tangential force (friction force) acting on the upper layer of automata on normal pressure. Sliding velocity $v_0 = 4 \text{ m/s}$

Fig. 6. Friction force dependence on sliding velocity. Pressure $P = 4 \text{ MPa}$
of the friction force on normal pressure and sliding velocity are shown in Figs. 5 and 6, respectively. Friction force increases linearly with pressure (coefficient of friction is 0.3) and does not essentially depend on sliding velocity. Hence we are dealing here with a typical case of dry friction. This result sheds light on a nature of interactions in the turbulent layer which is not evident from direct consideration of spatial configuration of the system depending slightly with pressure. Part of automata in the turbulent layer is always contacted forming so-called “elastic bridges” joining both bodies. Configuration of the bridges constantly changes. They are failed during several nanoseconds and new bridges arise. Nevertheless, at each instant of time just they withstand normal pressure and resist to tangential movement. Number of such “nanobridges” increases in proportion to applied pressure because each “bridge” can bear only a certain load defined by material strength. This leads to linear dependence of friction force on applied pressure. Notice that such a mechanism of force load transfer in the quasi-liquid layer is similar to the results in [6] where coefficient of friction is determined as a ratio between shear strength and indentation resistance of the microcontacts. In the present model dynamically formed nanocontacts in quasi-liquid layer play a role of the microcontacts.

Influence of pressure on thickness of quasi-liquid layer. To investigate influence of pressure on thickness of the quasi-liquid layer, the set of numerical experiments with constant sliding velocity 4 m/s and different applied pressure (0.5, 1.0, 2.0, 4.0, and 8.0 MPa) was carried out. Fig. 7 shows dependence of quasi-liquid layer thickness on normal pressure. Layer thickness decreases, when pressure increases, and at pressure ≥ 4 MPa the thickness is practically invariant. Changing in pressure essentially affects on density of voids in the quasi-liquid layer. At low pressure void density can exceed 90 %. At higher pressure motion is more laminar and there are only small fluctuations. The notions of “low” and “high” pressures will be discussed in Section 6 in more detail.

Influence of sliding velocity on thickness of quasi-liquid layer. To determine a dependence of layer thickness on sliding velocity six numerical experiments were carried out for pressure 4 MPa and velocities ranging from 2 to 16 m/s. The simulation results are presented in Fig. 8. At velocities ≥ 4 m/s the layer thickness increases monotonically.

5. Diffusion and mass mixing in quasi-liquid layer
As is seen from Fig. 4, in the quasi-liquid layer intensive mechanical mass mixing occur. Since in practice residual fuel and oil lubricant are present in contact regions, these matters will penetrate inside walls of cylinder and piston rings due to mass mixing process. Along with mass mixing, diffusion of elements from a surface layer inside a material is possible. To investigate the mutual roles of convective and diffusion processes in nanolayers, the following simulation was carried out. It was assumed that all automata with at least one ruptured inter-automata bond (in other words, automata located in the quasi-liquid layer or on the walls of microcracks) are in a contact with carbon source (fuel or oil lubricant). Change of carbon concentration within single automaton and in bonded automata was found from solution of the diffusion equation:

\[ \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \]  

where \( D \) is diffusion constant; \( C \) is admixture (carbon) concentration. As a boundary condition, a carbon concentration on a free surface of the material is assumed to be equal to carbon concentration in fuel. It was deemed that carbon diffusion is independent on concentration of the latter and defined by the equation:

\[ D = D_0 e^{-Q/RT} \]

At low pressure motion is more laminar and there are only small fluctuations. The notions of “low” and “high” pressures will be discussed in Section 6 in more detail.
Fig. 9. Schematic representation of carbon distribution in the “wall of cylinder”. Carbon concentration in an automaton presented by thickness of a black border is proportional to exceeding of carbon concentration over the average value

where \( D_0 = 2.0 \cdot 10^{-6} \text{ m}^2/\text{s} \), \( Q = 80 \text{ (kJ \cdot K)/mole} \) at \( T = 300 \text{ K} \). Each automaton was characterized by iron and carbon concentrations. Fig. 9 shows carbon distribution in the surface layers of the contact bodies (carbon concentration in an automaton is graphically presented by thickness of a black border). Taking into account that diffusion process is characterized by other characteristic time period (hours) as compared to mechanical mixing (tens and hundreds nanoseconds), we used the following way. We proceed from the fact that after the short running-in stage the system reaches a state of stationary movement. Since all the system configurations in this state are statistically equivalent, let us substitute the total configuration set by the lesser but statistically representative set of configurations which are realized during a smaller time interval. In other words, it is suggested that we have the right to substitute approximately \( 10^{12} \) configurations occurring within 10 hours by statistically representative 600 configurations observed within about 600 ns. For every configuration the diffusion equation is solved for one-minute time interval. So, the total diffusion process corresponds to the process lasting 10 hours. Similar calculations were carried out also for oxygen diffusion. Here oxidation intensity is assumed to be proportional to viscosity work at relative movement of automata. This phenomenological dependence takes into account the fact that during friction oil lubricant and oxidized layer are scratched from the contact surface and the surface has been prepared for oxidation. Fig. 10 shows theoretical and experimental dependences of carbon and oxygen concentrations on depth after 11 (theoretical curves) and 15 (experimental curves) hours of wear process. Peak oxygen concentration on the depth of the order of 30 nm is apparently governed by the fact that viscous friction force is of maximum value at the interface of the quasi-liquid layer and the basic material.

The results of simulation of diffusion and convective flows show that fuel and oil-lubricant elements penetrate inside the material mainly by mechanical mass mixing in the surface layer. So, an experimentally measured thickness of the tribomutated layer can consider as a thickness of the quasi-liquid layer.

6. On physical nature of quasi-liquid layer

Let us discuss physical nature of the quasi-liquid layer and dependence of its characteristics (in particular, thickness) on material parameters and loading conditions. Consider a qualitative model schematically presented in Fig. 11. Experimental data and theoretical analysis of micromechanisms of plastic deformation show that upon overcoming a elastic limit the plastic deformation can develop at the lower stress [7]. Situation, when a stress required for plastic flow
maintenance is approximately two times smaller than stress required for its initiation, is typical. In the presented below discussion for the sake of simplicity we assume that a stress needed for plastic flow maintenance is zero (it is not affected on the qualitative relations). Since dissipative stresses are less than stresses in the system at an instant of stability loss, accelerated relative movement of the contact bodies starts. It is easy to estimate that relative velocity reaches 5 m/s in the material with yield stress 300 MPa. At such values of velocity, excitation of phonon and electron systems starts to play a significant role. This effect shows itself as a certain effective viscosity of the material arising from the onset of plastic flow. For rough estimation of stresses in the quasi-liquid layer under high normal pressure (when the layer has a few voids only), let us assume that in a region in the state of plastic flow solely a viscous stress acts:

$$\sigma_{vis} = \eta \frac{\partial v}{\partial x},$$ \hspace{1cm} (2)

where $\eta$ is viscosity of solid in the state of plastic flow.

Fig. 10. Theoretical ($a, b$) and experimental ($c, d$) curves of carbon and oxygen distribution in the surface layer of the cylinder at the initial state ($a, c$) and after 11 hours ($b$) and 15 hours ($d$) running-in wear.
It is easy to see that in the state of dynamic equilibrium the viscous stress has to be of the same order as yield stress \( \sigma_0 \) of the underlying layers of the material. Actually, if the viscous stress in the quasi-liquid layer will be higher than the yield stress \( \sigma_0 \) of the underlying layers, then these layers will be also involved in plastic flow. As a result a thickness of the quasi-liquid layer increases, the viscous stress decreases, and further increase of layer thickness stops. So, for the equilibrium state the following equation can be written:

\[
\frac{\eta \nu}{h} = \sigma_0. \tag{3}
\]

It follows that thickness of the quasi-liquid layer in the course of plastic flow can be found as:

\[
h = \frac{\eta \nu}{\sigma_0}. \tag{4}
\]

Notice that the described physical conceptions are in complete correlation with the model of interactions among movable cellular automata. Particularly, in the framework of the numerical model only the “viscous” force proportional to relative velocity of movement is assumed to act on the unbonded but contacting automata. Estimated value of deformed layer thickness is 7 nm at viscosity \( \eta = 0.41 \text{ Pa} \cdot \text{s} \) (this value was used in the numerical calculations), velocity \( \nu = 5 \text{ m/s} \) and stress \( \sigma_0 = 300 \text{ MPa} \).

**Fluctuations of velocity in plastic layer.** Discussed above dynamics of the surface layer is based on an assumption about its laminar flow. In reality, flow of the surface layer is non-uniform and characterized by large fluctuations of velocity. Value of fluctuation at low sliding velocities can exceed an average velocity of ordered motion. Even particles inside the layer “stick” at times and then again start to move. To a particle starts movement, it is necessary to overcome critical stress \( \sigma_0 \). At this moment the particle is in a strained state with the energy density:

\[
E = \frac{\sigma_0^2}{2\mu}, \tag{5}
\]

where \( \mu \) is shear modulus. In the case of fracture when all potential energy transfer into kinetic one of movement with the velocity \( \nu_0 \), we can write:

\[
\frac{\sigma_0^2}{2\mu} = \rho \frac{\nu_0^2}{2}, \tag{6}
\]

and, hence,

\[
\nu_0 = \frac{\sigma_0}{\sqrt{\rho \mu}}. \tag{7}
\]

Notice that using parameters from the numerical calculations we obtain \( \nu_0 = 5 \text{ m/s} \). Viscous stress induced by the particle moving with such velocity is defined by the expression:

\[
\sigma_{\text{vis}} \approx \frac{\eta \nu_0}{h} = \frac{\eta \sigma_0}{h \sqrt{\rho \mu}}. \tag{8}
\]

The underlying layers are involved in motion only if \( \sigma_{\text{vis}} > \sigma_0 \). It follows that thickness of the quasi-liquid layer, \( h \), is defined by the expression:

\[
h = \frac{\eta \nu_0}{\sqrt{\rho \mu}}. \tag{9}
\]

It is evident that the characteristic velocity (7) specifies a value of sliding velocity such that a flow with high fluctuations, when viscous forces are governed by a fluctuation value of sliding velocity, is changed by a laminar flow, where viscous forces depend on macroscopic velocity. Starting from this velocity value, layer thickness linearly increases with sliding velocity in accordance with Eq. (4). The numerical simulation results depicted in Fig. 8 reinforce this conclusion.

**Characteristic pressure in quasi-liquid layer.** Let us denote an average density of the quasi-liquid layer by \( \rho' \). An average velocity of particle movement in the layer at low sliding velocities is defined by Eq. (7). At high velocities the only characteristic velocity in the system is sliding velocity. Sliding velocity defines velocity of particle movement in the quasi-liquid layer. Chaotic particle movement produces an additional component of normal pressure related with particle kinetic energy. This component has the same physical nature as pressure of ideal gas. It is known that such pressure is of the same order of magnitude as kinetic energy of gas. The pressure can be estimated using the following expression:

\[
P \equiv \rho' \nu^2. \tag{10}
\]

At high sliding velocity, by \( \nu \) is meant the piston movement velocity; at low sliding velocity — the characteristic velocity \( \nu_0 \) (7). In the second case “gas-dynamic” component of pressure can be written as

\[
P \equiv \frac{\rho' \sigma_0^2}{\rho \ 2\mu} (\nu \leq \nu_0). \tag{11}
\]

Let us introduce characteristic pressure \( P_0 \) in accordance with the following definition:
cannot be produced under other conditions \[8\]. Deformation under applied pressure such alloys arise which reactions do not preclude repeat “welding” because in shear alloying. Even oxidation processes and other chemical processes is similar to processes that occur during mechanical to one of the surfaces at the same nanosecond scale. This remain in the closed friction zone and are “welded” again after friction beginning. However, spalled particles of 10–100 nm fracture takes place within the first nanosecond and pitting of surface layers of contact bodies. The simulation results show that it is not nearly so. At the scale level of characteristic velocity and pressure are confirmed by the numerical simulation results.

7. Wear model

Wear is often understood as a synonym of microfracture and pitting of surface layers of contact bodies. The simulation results show that it is not nearly so. At the scale level of 10–100 nm fracture takes place within the first nanoseconds after friction beginning. However, spalled particles remain in the closed friction zone and are “welded” again to one of the surfaces at the same nanosecond scale. This process is similar to processes that occur during mechanical alloying. Even oxidation processes and other chemical reactions do not preclude repeat “welding” because in shear deformation under applied pressure such alloys arise which cannot be produced under other conditions \[8\].

The conclusion can be done that the popular notions of wear have to be essentially corrected. A frequently used wear criterion, where surface pitting is identified with wear, appear to be unusable in many real cases. In particular, plastically deformed layers wear out mostly due to slow stochastic mass transfer from the friction zone. From the macroscopic viewpoint this process can be considered as “extrusion” of the surface layer under the action of normal pressure.

Several approaches to “extrusion” rate calculation are possible. First suppose that the quasi-liquid layer is extruded similarly to a liquid layer with the same thickness and viscosity (Fig. 12). A thinning rate of the liquid layer is determined by the equation \[9\]:

\[
\nu^* = \frac{P(h^2)}{\eta(L)} h,
\]

where \(P\) is normal pressure; \(\eta\) is viscosity; \(h\) is thickness of the quasi-liquid layer, and \(L\) is diameter of the friction zone. By the extrusion rate \(\nu^*\) is meant a thinning rate of the liquid layer due to mass transfer from the friction zone. Substitution of \(\eta\) from Eq. (3) into Eq. (14) gives a wear rate (extrusion rate) in the form

\[
\nu^* = \frac{P}{\eta} \left( \frac{h^2}{L} \right).
\]

Notice that this relationship contains only measured quantities and can be easily verified by comparison with experimental data.

Expression (15) can be obtained by another way. Assume that we have experimental data about formation of thin surface layer wherein processes of plastic deformation are localized (due to described above dynamic processes or by other reason). Denote a yield stress of the layer by \(\sigma_0\). Assume that counterface in the friction zone entrains the upper part of the layer with the velocity \(v\). For simplicity we shall use the model of a perfect plastic layer. On reaching the yield stress, deformation of the layer continues under invariable stress \(\sigma_0\). It is easy to see that the layer can be formally characterized by certain effective (depending on velocity) viscosity:

\[
\eta = \frac{\sigma_0 h}{v}.
\]

Actually, the following relationship takes place for dissipative stress in viscous liquid:

\[
\sigma = \eta \frac{\partial v}{\partial x}.
\]

Substitution of \(\sigma_0\) instead of \(\sigma\) and \(v/h\) instead of \(\partial v/\partial x\) gives Eq. (16).

It can be shown that the perfect plastic layer uniformly deformed in the horizontal direction with the velocity \(v\) responds to small actions in the direction normal to motion as linear Newtonian liquid with viscosity (16). Since ex-
pression (16) coincides with Eq. (3), we are led to the same expression (15) for the rate of extrusion of the plastic layer. Of special note is the superposition principle is applicable to linear liquid. The essence of the principle is that an average result of many actions is equal to the result of average action. In our case it is meant that time and space average value of normal pressure should be used as pressure in equation (15).

Notice that equation (15) is similar to classical equations of abrasive and adhesive wear [10]. In particular, wear rate is proportional to average normal pressure and sliding velocity and is inversely proportional to hardness of solid. The significant difference of equation (15) from the classical one consists in dependence of wear rate on linear dimensions of the friction zone.

Estimation of assumption of uniformity of plastic layer deformation is carried out in [11]. The numerical solution of a corresponding problem shows that adjusting factor 0.38 has to be introduced in (15):

$$v^* = 0.38 \frac{P}{\sigma_0} \frac{h}{L}.$$

(18)

Proportionality of wear rate to square of thickness of the tribomutated layer (here it is identified with the layer wherein severe plastic deformation takes place) is confirmed by experiments on production engines and standard tribometers [1].

8. Numerical estimations and their correlation with experimental results

A reliable estimate of an average pressure value on a wall of combustion engine cylinder has been a problem. So, to simulate real situations in combustion engine, additional “rod-on-disk” tests were carried out using the homemade tribometer. One of the tests was done using a rod with diameter 3 mm. It is moved with the velocity $v = 8$ m/s. Average pressure over a rod cross-section was held at constant value $P_0 = 90$ MPa. Therefore, average pressure $P$ over a friction zone area is 0.56 MPa. Measured thickness of a formed tribomutated layer reaches 15 nm. Substitution of $\sigma_0 = 10$ MPa (yield stress of graphite) into Eq. (16) gives the following estimation of wear rate: $v^* = 4.2 \cdot 10^{-1}$ nm/s = 15 nm/h. This result is in a good agreement with experimentally measured value $v^* = 14.5$ nm/h.

9. Conclusions

It is shown that nearby the friction surface the layer is formed during friction of solids at moderate normal pressure and velocities of the order of 10 m/s (typical value for combustion engines). Severe plastic deformation and mass mixing take place in this layer. Thickness of the layer is determined by viscosity and strength parameters of the solid. Mechanical mass mixing leads to change of layer chemical composition due to enrichment by elements from fuel, oil lubricant and air (carbon, oxygen and other elements).

Wear rates measured in engines and tribometric experiments can be properly estimated based on the concept wherein wear is considered as a slow mass transfer from the friction zone.

Parameters of the quasi-liquid layer depend not only on material properties but also on sliding velocity and normal pressure. The latter dependence represents a response of nanolayer properties to surface relief characteristics. Investigation of influence of processes in nanolayers on surface relief formation, as well as investigation of influence of relief on features of dynamic nanolayers, is the line of further investigations in the field of the physics of friction processes in combustion engines.

References


