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Micromechanisms Controlling the Structural Evolution of Tribosystems

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1. Introduction

Development of scientific programs on the wear resistance is determined by economical significance of this issue for the development of productive potential of the world's countries. Deterioration is the main reason for removal of machinery and equipment from service; that is why controlling of the process of wear is the central core for such national scale issues as saving of non-renewable energy resources like hydrocarbon fuel and reducing the consumption of lubricants and structural materials. The condition of selective transfer in friction discovered by D.N. Garkunov and I.V. Kragelsky is the only effect theoretically admitting wearlessness (Garkunov, 2001). However, insufficiently developed physical and chemical basis for the theory of selective transfer hinders its wide deployment in engineering practices. The most controversial issue in the theory of selective transfer is considered to be the nature of products of chemical modification of friction surface. Traditional notions that are associated with the formation on a surface of either relatively simple inorganic compounds or tribopolymers are not sufficient to explain the unique tribotechnical characteristics in self-organizing friction systems. Considering the electronic structure of the rubbing metals, chemical properties of molecules of the active lubricant components, as well as the conditions of a frictional contact, one can expect that during friction of metals in the condition of selective transfer, in addition to normally expected products of the friction surface chemical modification, coordination compounds are generated. Those compounds, being more stable than tribopolymers and less stable than inorganic products of chemical modification can ensure a mass transfer process under the conditions of almost no-wear friction (Garkunov, 2001). Therefore, development of the fundamentals of the selective transfer theory and development of lubricants to put it into practice require considering the dynamics of physical and chemical processes and factors catalyzing the formation of complex compounds during friction, and their subsequent coordination on the surface. It is incontrovertible that with the help of additives it is possible to control almost all properties of lubricants. This being the case, oil acts as a carrier of the chemical reaction components, and a friction assembly act as a reactor, where processes are controlled not only by the composition of the lubricating medium and the nature of the rubbing surfaces, but also by the presence of external force action. In this connection, the analysis of the development trends for lubrication systems and existing advanced developments in chemmotology allows to highlight the following research directions in this research area:

a. decreasing the range of mineral lubricants replacing them with the highly compounded synthetic lubricants;
b. development of lubricants applied to the surface of a tribological conjunction once in the entire lifetime of a friction assembly;
c. development and creation of adaptive lubricating devices that represent an oil feeder controlled by a sensor responding to changes in key parameters of a friction pair;
d. application of centralized combined lubrication systems controlled by a microprocessor that will automatically change a lubrication mode either according to a preset program or depending on the operational performance of the friction assemblies controlled by sensors.

Active interference in electrochemical processes of a frictional contact is a very promising direction to prevent corrosion, to reduce oxidizing, mechanochemical and hydrogen wear, for instance, in metal-polymeric friction assemblies. It is known that the rate of electrochemical corrosion can be greatly reduced if a metal part is subjected to polarization. Polarization of a friction system pursues different objectives: to improve the wettability of the solid surface and adsorption of environment components. The friction system polarization method is that the potential of the system, with the help of an external source of polarization, is shifted to the area that is optimal for the friction process behavior, and then it is maintained at the required level during the work of a friction pair. The main difficulty in dealing with this kind of research is that the value of an electrode potential during friction may differ significantly from the electrode potential of the metal measured in static conditions (Goldade et al., 1993). In the first place, this is caused by mechanical cleaning of the surface from oxide films. In the second place, during friction secondary structures are generated shifting the potential to the positive or negative side. And, finally, the potential shift is affected by the plastic yield that leads to emergence of dislocated atoms in the crystal lattice of the metal. Being a fundamental characteristic of the electrical state of a "metal – electrolyte" interface, the electrode potential of the system can make a significant impact on the friction and wear of metals. The effect of polarization on the friction coefficient and surface damage of metals was discovered by Bowden and Young and further studied by other authors. Decreased friction factor and increased surface charge during polarization are associated with the increased wedge effect of the double electrical layer between the rubbing surfaces. Polymeric materials used in friction assemblies add some specific features to the electrochemical processes in the friction zone. During friction of metal-polymeric pairs, the polymeric components acquire the properties of surface-active substances, which substantially change the electrochemical activity of the metals (Pinchuk et al., 2004). The results of these studies are presented in details in the papers (Garkunov, 2001; Goldade et al., 1993; Kostetsky, 1980), where the influence of a friction system electrode potential on the adsorption, diffusion, oxidation, friction and wear of materials is noted. Unlike processes normally considered in electrochemistry, electrochemical processes during friction occur under the conditions of moving deformable discrete contacts of separate microroughnesses. This leads to generation of currents between the rubbing surfaces during friction (Ryzhikov & Dolgopolov, 2005). Roughnesses of two sliding bodies get elastic or plastic impacts; and consequently the equilibrium state corresponding to the minimal energy of the strained area is disturbed. Under the impacts, the microroughnesses oscillate with the frequency which is close to that of external action. Dynamic loads, causing a variable strain of the material in the mating parts contact, lead to emergence of an alternating magnetic flux in the strained layer. Changed magnetic flux induces an induction emf in the circuit generated by the mating parts. The electrical resistance between these parts conditioned by the properties of the oxide films and lubricant leads to a alternating potential difference in the contact area. If the body and counterbody are electrically isolated from each other with a dielectric layer (e.g., lubricant), the friction couple can be considered as a capacitor. When moving one body against the other, a point contact occurs due to existing surface roughness or other surface imperfections. When the point contacts diverge, the hydrodynamic effects occur like squeezing lubricant out of the friction area, generation of current-conducting seizure bridges from the products of erosion. Consequently, a kind of capacitor electric breakdown occurs, as a result of which a large amount of electrical energy accumulated by the friction surfaces is released. The lubricant and material of the surface layers are decomposed into the components of ionic, radical or ion-radical nature, transferring to the lubricating medium. In this specific short-circuited galvanic microelement, the potential probability is created of having on the friction surfaces the redox reactions of sedimentation of the lubricant medium's active components. Thus, during friction pair operation, an automatically functioning electrochemical mechanism of wear control appears. And this mechanism depends on such factors as the electromotive force of the galvanic cell, the shift of potentials during the circuit closing, the polarizability of the electrochemical circuit, and the rates of the electrode processes. Therefore, creation of alternative adaptive sources of polarization using design and technological features of a friction assembly itself, is of current importance. The main principle of operation of such adaptive lubricating device can be control of friction and wear processes via "external agents" - the force fields of different nature, which was named a "field effect" (Belyi, 1985; Shvedkov & Rovinsky, 1979). The "field effect" means a change of a friction coefficient and wear rate under the influence of electric, magnetic, thermal and radiation fields. Force fields are capable to change values of friction parameters by several times, and in some cases reduce them to zero ("the effect of abnormally low friction" (Shvedkov & Rovinsky, 1979)). Electromagnetic fields have a special place among the force fields (Garkunov, 2001; Goldade et al., 1993; Lubimov et al., 1992); the study of their influence on the performance of materials has occupied the minds of scientists since long ago. One of the problematic issues in reducing wear and friction of metals is the development of reliable and compact sources of electric polarization. The point is that the methods of polarization of a friction system by external sources have not found wide application in friction assemblies due to the bulky dimensions of the electrical sources, which significantly complicate the design of machines. However, today, in the century of rapidly developing microelectronics engineering, this problem can be perfectly solved. Based on the above said, we shall dwell on such aspect of the study of tribosystems as the capability to control their friction parameters directly in the conditions of dynamic interaction. This kind of work does not require interfering in the design features of a machine, which significantly reduces the cost and simplifies the potential possibility of its introduction into the production cycle of any engineering company.

2. Structural changes of tribounits

2.1 Third bodies of friction assemblies

According to present-day thinking, all triboeffects become evident on a macro scale, but the phenomena that cause and accompany them occur at a micro level. Friction is a combination of processes covering the thin surface layers of the contacting bodies. The work of the friction force equals to the energy of destruction of the interfacial bonds; about 99% of it turns into the heat that is spent for structural and thermal activation of the friction surfaces, and the remaining 1% of the energy is stored by a very small portion of surface and promotes activation of the surface bonds (Lubimov & Ryzhikov, 2001; Lubimov & Ryzhikov, 2006). Formation, growth and destruction of the interfacial bonds are determined by the nature of the contacting surfaces, the chemical processes occurring on them, and the stressed state of the surface layers caused by the loading conditions. I.V. Kragelsky coined the term "the third body" combining the interfacial bonds, the products of their destruction and the surface layers where the strains are localized. Later on, M. Godet developed the concept of the third body having expanded its meaning (Godet, 1984) that adds up to significant differences between the surface and bulk properties of the tribounit matter. The third bodies often have the form of film structures arising on the friction surfaces, which significantly affect the frictional characteristics of the friction assemblies. This phenomenon is especially evident when the effect of wearlessness or selective transfer takes place. In accordance with the model of Godet, the copper of the third body during selective transfer has a loose structure, different from a blocked one. It has a weak resistance to shear deformation and a low friction coefficient. These third bodies were named “servovite” films. Along with the servovite films, during a selective transfer the following structures that respectively belong to the third bodies are seen:

“Surfing” film - a molecular film structure consisting of associated coordination compounds;

Metal-cladding film – a protective film where a vacansion-dislocation deformation mechanism is partially realized;

“Dividal” film – a metal protective film formed as a result of discharge of metal ions in the contact area during friction;

“Nubial” film – a tribopolymer protective film consisting of tribopolymers chemisorbed on the active surface of the servovite film, which arise during destruction of lubricants (Polyakov, 1990).

Another type of third bodies appears on a friction surface during interaction of polymer or metal-polymer friction units. Such third bodies were named the friction transfer films; development of the theory of the friction transfer films is in many respects associated with the papers by V.A. Belyi and his school (Pogosyan & Oganesyan, 1986). In general case, during polymer-to-metal friction, as a rule, the transfer of the polymer onto the metal surface is observed. During the frictional transfer of the polymer, as a result of the molecular interaction, fine surface particles are separated and transferred to the active areas of the friction surfaces. During the transition to a steady friction state, in metal-polymer tribounits, actually the polymer rubs against polymer. When friction transfer films are generated, there are the following main types of adhesive interaction: adhesion of separate particles and a layer of particles, melt adhesion, wetting of the counterbody’s surface, and film adhesion. Generation of the friction transfer films has been especially well studied during frictional interaction between polytetrafluorethylene (PTFE) and a steel counterbody. As it has been established (Nikolsky et al., 1988), during the interaction of PTFE with a metal surface, the PTFE molecules are decomposed, and during this process the fluorine atoms are coming off and are being replaced by the hydrogen atoms. Furthermore, generation of a chemical bond between the fluorine and the metal is observed, which determines the adhesion of the PTFE to the metal counterbody (Buckley, D. (1986). The friction transfer films are formed not only during the friction of metal-polymer tribounits, but also during the interaction of metal with graphite. The emergence of third bodies in the frictional contact area in most cases leads to reduced friction forces and wear levels of the tribounit materials (Sysoev et al., 1990). The main reason for such an effect is that the atoms and molecules of a third body passivate the surfaces of friction, thus reducing the adhesive component of the friction force. Intensity of the formation of third bodies depends on a host of aspects related to the fact that a friction assembly is a single tribosystem, the evolution of which is described via the laws of synergetics and thermodynamics of open systems (Garkunov, 2001).

2.2 Higher energy states of a tribosystem matter

As stated above, the energy released during friction in the form of heat and stored by the surface layer of the material, leads to structural and thermal activation of the surface. The structural-thermal activation means the origination and emergence at the surface of dislocations and point defects. Therefore, energy in tribosystems is degraded, its mechanical form is continuously transformed into the thermal one, and the entropy is constantly reproduced. The discovery of the wearlessness effect has made it possible to single out the general principle of evolution inherent to all friction systems, which consists in their thermodynamic "openness", ability to exchange energy with the external environment, and possibility to reduce entropy. On this criterion, a friction assembly by the level of self-organization approaches to biological systems (Kadolich et al., 2001; Pinchuk et al., 2007). The decreased entropy growth in an open thermodynamic system is determined by the interaction of two energy flows. The thermodynamic forces emerging in them have an influence not only within their own energy flow but also on the adjacent flow. In tribology, such flows are the mass transfer (diffusion) and the heat transfer, and their interaction determines entropy change and the friction assembly structure. American tribologist Buckley has associated a mass transfer with the processes of self-regeneration of friction assembly materials, which prevents the destruction provoked by the heat flow. In the first approximation, the influence of the flows on the tribosystem entropy looks as follows: the diffusion decreases the entropy of the friction assembly; the heat transfer, on the contrary, increases it. Based on the above said, the conclusion can be made that the decrease of tribosystem's entropy relates to the system's structural complication - structural adaptability, and consequently, is identical to the optimization of tribosystem's properties which, in thermodynamic terms, are expressed in minimized entropy growth, and in tribotechnical terms - in reduced wear and friction forces. The structural adaptability is preceded by the changes that have been recently named "tribomutation" (Voinov, 2010). Tribomutation is recrystallization of the thinnest surface layers, decreasing of the free surface energy, elimination of the boundaries of surface and near-surface crystallites, and annihilations of dislocations as they emerge at the surface. The well-known Soviet physicist Zeldovich has demonstrated that in the near-surface layers, the defects with a minimum elastic energy occur; resulting in the loss of elastic properties by the solid bodies, their becoming plastic and fluid, and their transition to a "liquid-like" state. During friction, such physical constants of the material as Young modulus, Poisson ratio, dynamic strength, and acoustic stiffness lose physical meaning. The described structural changes are explained by the action of the processes accompanying the structural and thermal activation of the surfaces matter of a tribounit. Though the percentage of the frictional energy reserved by the surface is small in an absolute value, but, if we take into account that it is accumulated by thin surface layers with a thickness of fractions of micrometer and calculate the density of this energy, then the received numbers can reach critical values for this aggregate state of the material. The surface is supersaturated with dislocations and point defects; its behavior obeys the hydrodynamic laws, and in some extreme cases - the gas dynamics laws. In this extreme case, the movement of dislocations, according to Kuhlmann – Wilsdorf, is described by the equation (Cahn, 1968):

$$\frac{\partial^2 W_z}{\partial x'^2} - \frac{\partial^2 W_z}{\partial y^2} = 0 \tag{1}$$

$x' = \frac{(x - \upsilon t)}{\beta}$; $\beta = (1 - \frac{\upsilon^2}{c^2})^{\frac{1}{2}}$ – dimensionless parameter; c - velocity of elastic waves propagation in the matter; ϑ - velocity of dislocations propagation.
The energy of dislocation W ' moving with the velocity ϑ equals:

$$W' = \frac{W}{\beta} \tag{2}$$

W – energy of immobile dislocation.
When the dislocation velocity ϑ tends to "c", the parameter $\beta \rightarrow 0$ and, consequently, W' indefinably grows. Kuhlmann-Wilsdorf, by analogy with the theory of relativity, recorded the ratio for the W 'through the speed "c ":

$$W' = c^2 \times m' \tag{3}$$

$$m' = \frac{m}{\beta} \tag{4}$$

m – mass of the dislocation at rest, equal to $m = \rho \times b^2$; ρ - density of dislocation; b – Burgers vector.
Thus, the movement of dislocations is described by the equations identical to the equations of the special relativity theory (SRT). Therefore, in accordance with the postulates of the SRT, the specific effects predicted by this theory should occur in such systems: change of the space metric, increased mass and energy carried by the defects out to the surface, and the local time slowed down. The effect of these processes is determined by the relativistic parameter β. The value β depends on the speed "c", which, in the conditions of transition of the surface layers to the "liquid-like" state and then to the gaseous state, significantly decreases. Under the conditions of the frictional contact, the parameter β varies from 0.99 to 0.7, which makes the contribution of the relativistic correction to the equations of movement of dislocations very important. Consequently, a dislocation moving during friction can be regarded as a relativistic object, then according to the opinion of Nobel laureate L.D. Landau stated in the section "Relativistic Hydrodynamics" in the book “Gidrodinamika” (“Hydrodynamics") (Landau & Lifshitz, 2001): "The need for relativistic effects consideration ... may be associated not only with a high rate of macroscopic motion ... the equations (describing this motion (author's note)) also change significantly when this rate is not high, but high are the rates of the microscopic motions of the particles that constitute it". In other words, if a large "classical body" consists of small parts obeying in their movement the laws of the relativity theory, the entire body will be partly "relativistic". Hence, if the constituent

friction materials of a dislocation acquire relativistic properties due to structural and thermal activation, then the macro quantities of the tribounit matter start showing the special properties arising from the SRT equations. In this regard, it is very interesting to consider the time paradox that explains some anomalies in the physical and chemical processes of friction surfaces. The equations of the relativity theory do not make a distinction between the time directions; Einstein, as a matter of fact, stated that the past, the present and the future "are nothing but a human illusion devoid of physical sense..." At the same time, the equivalence of the future and the past leads to a number of paradoxes related to the violation of the causality principle, to obey which, the "time arrow" concept is introduced. The direction of the increasing entropy points which state in a couple of the adjacent events is the subsequent rather than the preceding. Many present-day physicists believe that the entropy is actually the arrow of time, which makes the time itself just a simple sequence of states. Time is a part of many physical laws, and it is quite possible that a change in the dimension of time can affect the behavior of various processes. In this connection, there are two interesting examples that illustrate the subsequent line of argument. The American theoretical physicist Feynman believed that an antielectron (positron) emerging in nuclear reactions is actually a normal electron moving backwards in time, and their positive and negative charges are nothing more than a direction indicator of time in which the particles make their way through the space-time at a given moment. The mathematical apparatus developed by Feynman has become a space-time interpretation of the quantum mechanics, for which he was awarded the Nobel Prize "for his fundamental contribution to the development of quantum electrodynamics, which had profound implications for particle physics" (Cholakov, 1986). Another leading theoretical physicist, the Englishman Hawking investigated changes in the entropy of a black hole system when a certain amount of substance gets to "beyond the event horizon". Since the latter is a measure of the entropy of a black hole, then, having become wider, it would increase its own entropy by exactly the same amount as was carried on itself by the substance falling into the black hole. But the substance has carried away into the black hole a part of the entropy which just equals to this increase, therefore the total entropy has not been changed, and its increment is zero. According to the "arrow of time" definition via entropy, Hawking has come to the conclusion about the stop of time in the black hole outskirts, relatively to an outside observer (Hawking & Penrose, 2007). This conclusion finds confirmation in astronomical observations of the movement of gas clouds in the areas of anticipated presence of black holes, where their speed is found to slow down. Based on this, we can assume that a tribosystem, in accordance with the definition given by Landau, can be classified as a relativistic object, representing an example of a relativistic solid state physics, which, according to Nobel laureate A. Heym, is "... a new scientific paradigm where quantum relativistic phenomena can be studied in normal laboratory conditions ..." (Morozov, 2008). And the decreased entropy increment and the related decrease of friction coefficients and wear rates are explained by slowing of the tribosystem's local time created by fast dislocations. An indirect example in favor of such an unusual interpretation of changes in anti-friction characteristics is the effect of anomalously low friction, opened by the Russian tribologist Silin (Svedkov & Rovinsky, 1979), where the friction factor was recorded to drop zero in the polyethylene-metal system when this friction pair was exposed to the radiation of α-particles flow and cooled down to the temperature of liquid nitrogen. Indeed, the exposure to low temperatures zeroes the entropy, and fast α-particles can be considered as "carriers of relativistic effects" into tribosystem. From a formal point of view, the zeroed entropy corresponds to the time stop within the tribosystem, which slows down the wear and decreases friction coefficients down to ultra low values. An extremely important factor influencing the change of tribosystems' surface states is the increased, due to relativistic effects, kinetic energy of dislocations which they pass to the matter as they emerge on the surface of the friction assembly. Given this adjustment to the energy reserved by the surface one can explain the transformations that happen with the aggregate state of the surface layer material. A discrete contact inherent to the rubbing surfaces leads to heavy stress fluctuations in the subsurface layers of the friction assembly at the initial moment of friction. Force and deformation processes in the spots of actual contact look like multiple short-time pulses the duration of which is limited by the time of the knock-on collision of the microroughness, ranging from 10^{-3} to 10^{-11}s. Under such loading conditions, the substance of the tribounit transforms to a high-energy state with significant concentrations of energy, nearing to the values leading to the phase transformations. A slightly increased energy flow associated with the relativistic increase of dislocation masses is capable to start the process of avalanche-like activation of the friction surfaces substance, the highest peak of which is the condition called triboplasma or magmaplasma (Garkunov, 2001; Heinicke, 1987). Triboplasma is an energetic bunch, into which the substance of the friction surface transfers. For a long time, triboplasma has been a hypothesis explaining many abnormal processes occurring during friction: mechanoemission by the friction surface of charged particles with energy of 5 eV; emission of electromagnetic radiation quantums, abnormal chemical activity, and many more. Since during friction the matter can not be fully ionized like it is observed to happen on stars or in a nuclear explosion, the triboplasma is classified as nonideal plasma.

In most studies, triboplasma is presented as a hypothetically postulated object, the properties of which are almost not described (Heinicke, 1987). In the works generalizing the previously published studies (Lubimov et al., 1998; Lubimov et al., 2007a; Lubimov et al., 2007b), reasonable assumptions are made about the properties of this aggregate state of substance. The listed papers are based on the study of the concentration profiles of the diffusion distribution of the matter in the surface layer of the friction materials, and the effect of the plasmatic states of the matter on this distribution. It was established that during friction the diffusion coefficients ($Д_э$) increase by tens compared with the diffusion coefficients typical for the solid state of matter. We have found the equation establishing the law of proportionality between the diffusion coefficient and the square root of the triboplasma temperature. This is typical for substances in a gaseous state, so it was assumed that triboplasma by its properties is close to gases (Lubimov et al., 2007b):

$$Д_э = \frac{2e}{h}\sqrt{\pi k} \times \frac{Q^*}{W}\sqrt{\frac{T}{n}} \tag{4}$$

T – temperature of triboplasma; n - average density of particles in the plasma, e - electron charge; Q * = kT + Q - value characterizing the kinetic energy of the thermal motion of the triboplasma particles; Q - heat released by friction; W – binding energy of the triboplasma components; h - Planck constant; k - Boltzmann constant.

Such a conclusion allows to simplify the discussion of the relaxation processes, applying the apparatus of the plasma kinetic theory and the wave physics. The value $\frac{Q^*}{W}$ is a characteristic for the degree of substance ionization as it shows by how many times the energy of the ionized plasma is greater than the energy of the same substance in a steady state. According to our evaluation, the ratio of $\frac{Q^*}{W}$ has an order of 10^{-7}. We have obtained the ratios allowing to evaluate the temperature, charge, mass and lifetime of triboplasma components (Lubimov et al., 2007a). Triboplasma lives for a very short time (less than 10^{-7} c) and has a very high local temperature (above 10^4 K) (Pinchuk, 2004; Lubimov et al., 1998). This is a higher excited state where the cohesive bonds in solids weaken considerably, and structural degradation processes occur associated with the emission of charged particles and photons of different wave lengths. In the gas plasma, in addition to the random thermal motion, particles are involved in the ordered processes of the so-called Langmuir waves having the plasma frequencies ω_p (Ginsburg, 1967). We have obtained the formula for the quantitative estimation of the ω_p value:

$$\omega_p = \frac{4\pi e^2}{h}\sqrt{\frac{k}{m}} \times \frac{Q^*}{W} \times \frac{\sqrt{T}}{Д_э} \quad (5)$$

m – electron mass.

The numerical solution of the equation (5) gives us the values of plasma frequencies in the gigahertz range of oscillations. Triboplasma as any high-energy metastable state is not stable and relaxes rapidly passing to the normal aggregate states of substance. This transition is a multistage process; in one of its intermediate stages, chemically very active postplasma states of substance are present, having a long lifetime. It is these long-lived postplasma states of the tribounit surface substance which cause the chemical processes to take place throughout the entire nominal contact area, not just in the spots of actual contact. Based on the plasma hypothesis, there exists a chemical model of "surfing" effect explaining the low values of the friction factor during a selective transfer. The latter process is associated with the time evolution of triboplasma's substance after it leaves the actual contact area and has step by step relaxation till the initial steady state. Complex compounds constituting the surfing film in the selective transfer mode and ensuring the minimal friction coefficient, are formed due to the tribochemical reactions associated with transformations occurring in triboplasma and postplasma phase (Garnovskyi, 1984). The modern day leading tribologists G. Heinicke, W. Ebeling, Belyi V.A., Garkunov D.N., Kostetsky, B.I., have pointed out the top-priority need to study tribochemical processes from the standpoint of plasma chemical substance transformations and the catalytic impact on them from physical fields.

2.3 Experimental study of triboplasma structural elements

Short lifetime of triboplasma and the fact that the friction contact can not be accessed with the analytical equipment make it difficult to study this aggregate state of the friction surface substance. For the purpose of this study, an experiment design was proposed aiming at separation of triboplasma in its "pure form". This plan was implemented using the experimental equipment representing a friction machine working in "shaft- bushing" contact mode with polytetrafluoroethylene - steel coupling. Shaft material is PTFE, bushing material is steel. The friction assembly is placed under a vacuum bell jar connected to a fore vacuum pump. The potential range from 0.5 to 200V can be applied to the friction assembly, and also a magnetic field is generated with an intensity of 10^4 A·m^{-1}. Electromagnetic oscillations of different frequencies within the range from 0 to 10 GHz are superimposed on the friction assembly, and the characteristic signals are read out. In the steel counterbody (bushing) there are plasmatic traps keeping the friction substance in an active state (Fig. 1). Signal from a plasmatic trap is sent to a spectrum analyzer that resolves it into the spectrum representing a set of harmonics with individual frequencies. The friction torque is recorded by a change of the current in the winding of the machine electrical motor (similar to the Timken friction machine (US)). Frictional parameters were controlled at a sliding velocity of 1 m/s and a load of 10N, test time is 5 hours.

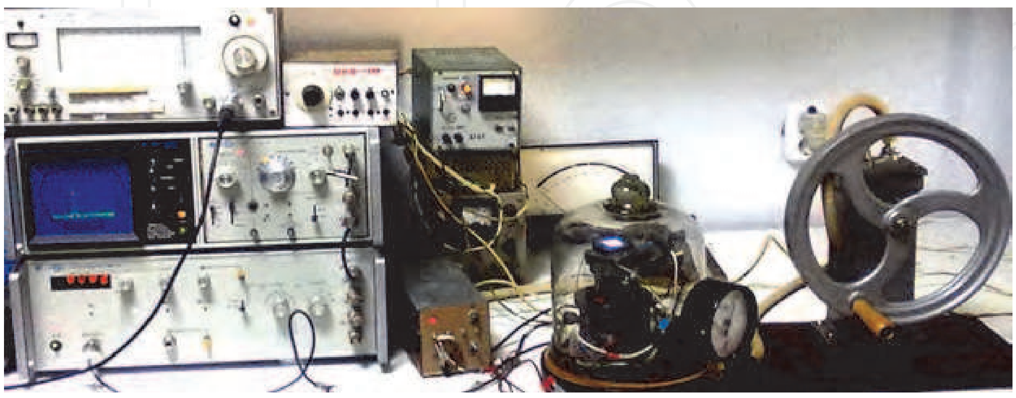


Fig. 1. Part of the laboratory system for the triboplasma study.

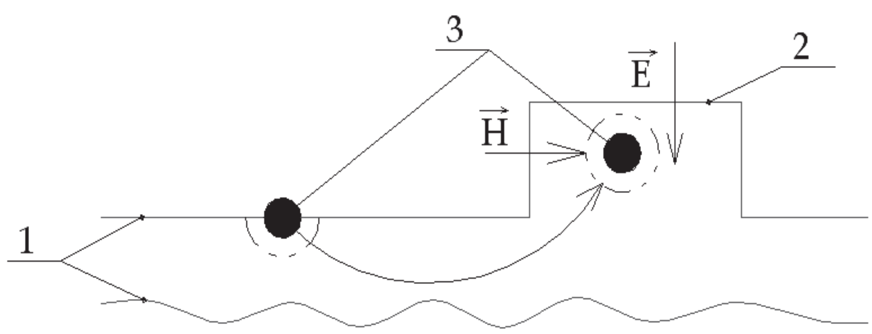


Fig. 2. Circuit diagram of a plasmatic trap: 1) friction surfaces; 2) plasmatic trap; 3) triboplasma particle. $\vec{H}$ and $\vec{E}$ are intensities of the magnetic and electric field.

We assumed that triboplasma is an electrically active state of substance, one of the fundamental properties of which is shielding the electrical potential applied to it. That is why its exposure to an outer electric or magnetic field discloses those oscillation spectrum harmonics which are directly connected with the triboplasma. Exposure to an outer force field discovers a response from the spectrum harmonics in the megahertz and gigahertz frequency range. Depending on alteration of the electromagnetic spectrum profiles recorded by the measuring equipment when the friction assembly is exposed to the electric and magnetic fields of different directions, we have established that the oscillators constituting the triboplasma are electrons and positively and negatively charged ions. The frequency values of the free oscillations of these oscillators split up into the two ranges: 10÷100 MHz and 1÷1.5 GHz. These match the theoretically found values of the plasmatic frequencies (5). We have discovered that in each of the mentioned range of frequencies (megahertz and gigahertz) there are two types of oscillators. For the gigahertz range, one of the oscillator types is electrons. While plotting the graph of the relation between the friction factor, the harmonic intensities of the electromagnetic spectrum (electrons and oppositely charged ions), and the test time, we have discovered that the positively charged ions of triboplasma decrease the friction factor, and the negatively charged particles (ions and electrons), on the contrary, facilitate its increase (Fig. 3). The decreased friction factor is seen to coincide with the increased harmonics corresponding to the positively charged particles.

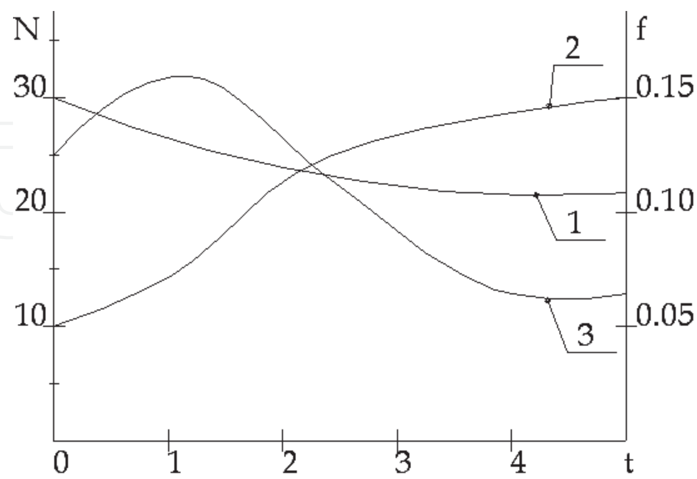


Fig. 3. Relation between the harmonic intensities N (in conditional units) of electromagnetic emission of tribloplasma components and the friction factor (f) of the "PTFE-steel" coupling, and the friction time (t, hours). 1) plot f(t); 2) plot N(t) for positively charged articles; 3) plot N(t) for negatively charged articles;

Based on the studies conducted, we can say that the exposure of the electrically active triboplasma components to an electromagnetic field of a certain direction and ripple frequency, leads to changes in the antifriction properties of a tribosystem. That is why, by changing the intensity of the electromagnetic field tuned to the resonance with the triboplasma components, it is possible to control the tribounit frictional parameters by intensifying the formation of lubricating structures on the contacting surfaces.

2.4 Impact of electromagnetic control of a frictional contact

It was shown that friction as a physical process generates electrically active responsive groups of triboplasma substance, which significantly influence the triboprocesses. Postplasmatic electrical states play a special role in that. They are complicated chemical structures carrying within them elements of free and bound charges, and also having extremely high chemical activity. They catalyze the formation of the "third bodies" driving a change in frictional characteristics of the friction assembly. In electrically conducting media, the influence of an electrical field upon the formation and growth of the thickness of the protective lubricating films on the friction surfaces, can be explained by the electrolytic transfer of the charges and substance. In dielectric media, which can be, for example, a lubricant or a friction transfer film of a metal-polymeric coupling, there are no free electrical charges in the form in which they are present in metals. Applying an electrical field of certain intensity to the frictional contact leads to redistribution of the charge densities in the constituting materials – a phenomenon of field polarization. The polarization is one of the fundamental properties of dielectrics, which consists in disequilibrium of charge distribution in the matter and appearance of a resultant moment $\vec{p}$ different from zero and proportional to the electric field intensity value $\vec{E}$:

$$\vec{p} = \alpha\vec{E} \tag{6}$$

α – substance polarizability, m^{-3}.

In the paper (Lubimov et al., 2009a) discussed the hydrocarbon lubricating media separating metal surfaces, it was proved that the interaction of an external electromagnetic field with a self electromagnetic field of the surface (induced by the frictional forces as a result of the dynamic contacting of the rubbing bodies), causes appearance of ponderomotive forces within the working layer of the friction assembly. These forces have a mechanical effect on the substance and cause to move the macrovolume of the friction substance. In the general case, the ponderomotive force value can be found from the ratio (7):

$$\vec{F} = \frac{m}{\mu}\alpha\omega\vec{S} \tag{7}$$

$\vec{F}$ – ponderomotive force; m – mass of the moving macrovolume; μ – molar mass of the moving substance; α – the substance polarizability; ω – frequency of the external, substance exciting factor; $\vec{S}$ – the Umov-Poynting vector.

Currents generated during friction, due to the contact discreteness, lead to appearance of electromagnetic fields in the gap between the rubbing bodies; that is why friction, as a physical process, per se generates forces of the electromagnetic nature. These forces, having orienting and structuring action on a very small amount of the lubricating medium near the surface of the solid body, facilitate emergence of ordered and stable states – multipoles, interfacing with the charged friction surface field. Under the electromagnetic field, the time limit of existence for the structurally activated substance of the gas triboplasma, increases due to non-dissipative electric drift of the plasma components in the electromagnetic field (Prokhorov, 1992). In other words, in the gas plasma, a weakly decaying electromagnetic wave is excited, which maintains the working layer substance in chemically active post-plasmatic state. Ponderomotive pressure exerted by the electromagnetic field upon the frictional substance depends on the properties of this substance (density, molecular mass, mass of polarizable volume), the field properties (field frequency and energy), and the contact geometry (gap size between the rubbing surfaces, dimensions of the metal surfaces). During the action of an electromagnetic field, favorable conditions are created for synthesis of the protective lubricating films covering the friction assembly surfaces. Our assumption is proved experimentally using the electromagnetic sanation method for the friction surface, during frictional interaction of the materials “epoxy-filled composite – zinc counterbody” (Lubimov et al., 2001). The amplitudes of the emergent high frequency harmonics of the electromagnetic oscillations spectrum depend upon the magnitude and direction of the electric field (Fig. 4). The recorded values of the harmonic amplitudes help to have a general idea of the quantity of the active particles that create oscillations in this frequency range, proved to be responsive to the external action.

From the plot one can see that with the applied potential (U, Volt) increased up to a certain value, the harmonic amplitudes increase correspondingly (ΔA). This is an evidence that more of the active centers (free charge states) response to the external action. The curve going parallel to the X-axis means that the mentioned charge states are present on the surface now not in the form of uncoordinated active centers, but in the form of multipoles constituting the “skeleton” of the protective lubricating structure – the “third body” – being formed on this surface. These multipoles passivate the solid body surface, and are electrically neutral formations; therefore, they do not react when exposed to an external field. Furthermore, the friction factor was recorded to drop during the transition from the negative to positive potential, which can serve as an indirect proof for the formation of the protective lubricating layer – the "third body".

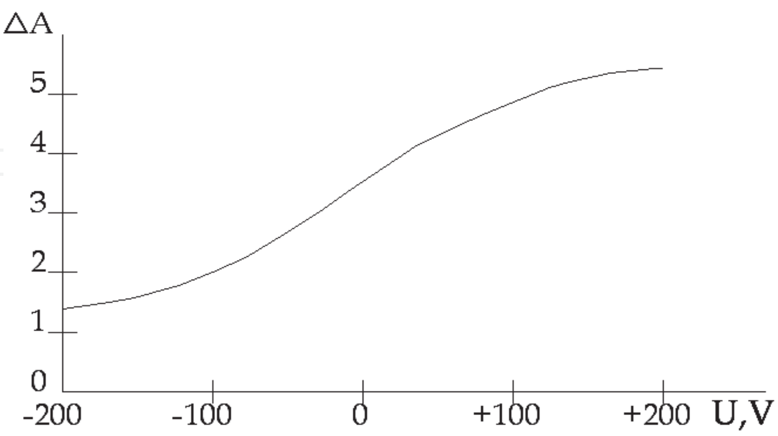
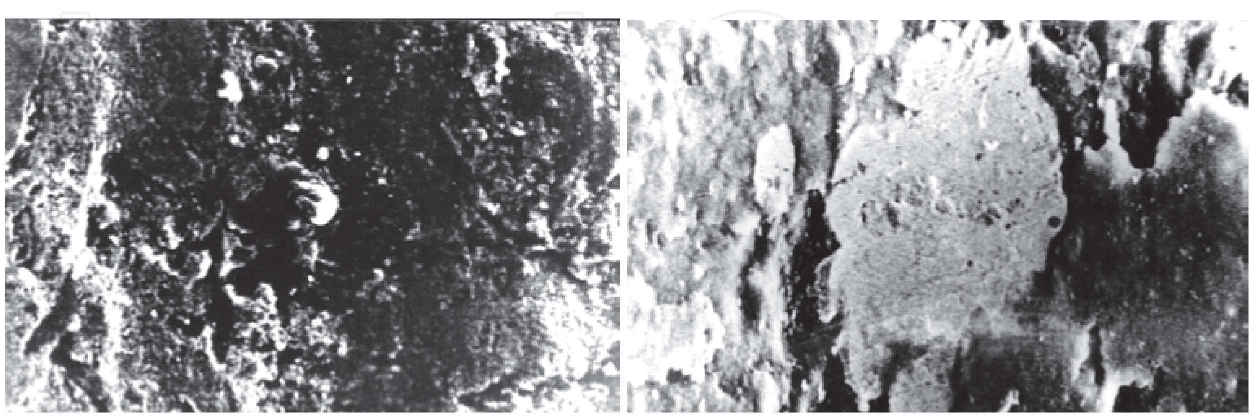


Fig. 4. Impact of the electric field magnitude and direction on the harmonic amplitudes change (ΔA) in a frequency range of 40 MGz for the friction pair "epoxy-filled composite – zinc counterbody".

Item No.	Potential applied to the metal counterbody, V	Friction Factor
1	-200	0,36
2	0	0,25
3	+200	0,12

Table 1. Change of frictional properties of the materials exposed to the electric field

The applied electric field influences not only the kinetics of the tribochemical reactions within the working layer, significantly increasing their speed, but also the orientation of components constituting the third body. At the same time, the frictional body polarized by the external electrical field, forms the lubricating film much more actively in comparison with the similar materials in the absence of the field (Fig. 5).



(a) (b)

Fig. 5. Photographs of friction paths in the coupling "PTFE – zinc counterbody" at the potentials applied to the metal counterbody: a) 0V; b) +100V.

As seen from the photos, when the field is present, the film structure is more homogeneous across the thickness, has no discontinuities and fully covers the zinc surface. On the right-hand photograph, the film has clearly seen new formations on the surface of the already existent layer. Besides that, the film, being developed under the action of the field, adheres to the metal surface more firmly. Such an intensive layer growth and visible increase of the third body volume filling the working layer, can be related to the better wetting of the metal surface by the polymer and higher adhesion of the polymer film. The electric potential in this example acts like the factor polarizing and maintaining the polarized state for the working volume matter. Molecule energy depends upon its position on the surface (Akhmatov, 1963). A polarized molecule (dipole and multipole) of a lubricating medium in the external force field of the surface, orients with regard to it so that its potential energy turns out to be minimal (8):

$$U(\alpha) = \frac{U_0\left(1 - \cos(n\alpha)\right)}{2} \tag{8}$$

$$p(\alpha)d\alpha = C \times \exp\left(-\frac{U(\alpha)}{kT}\right) \tag{9}$$

$U(\alpha)$ - dipole potential energy; U_0 – potential barrier; n – dipole order of symmetry; α – inclination angle of the dipole symmetry axis to the surface; $p(\alpha)$ – relative probability of the molecule orientation angle; C - constant.

In accordance with the above formulas (8) and (9), applying an external electric field results in the multipole molecules tending to take up a position perpendicular to the metal surface, orienting along the electric field force lines. Electrical action on a polarized molecule, ion, or radical fixed with their active center on the friction surface can lead to the molecule precession. This fact was recorded by S.Z. Zaitsev during the study of water molecule behavior with the help of a field ion microscope, and was discussed in the paper (Lubimov et al., 1994). As the observations showed, in an electric field, the water molecule, structurally being a dipole, starts to precess and nutate, i.e. make movements similar to the movement of a gyroscope with one fixed point. Schematic sketch of this process is shown in Fig. 6.

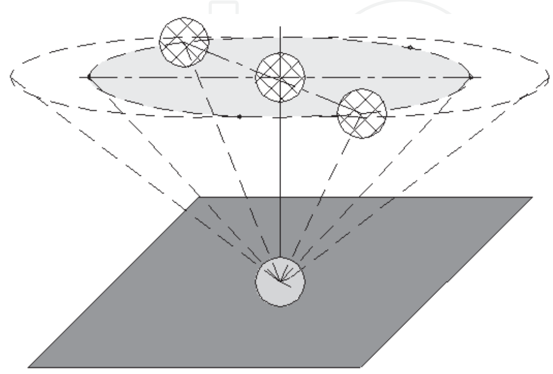
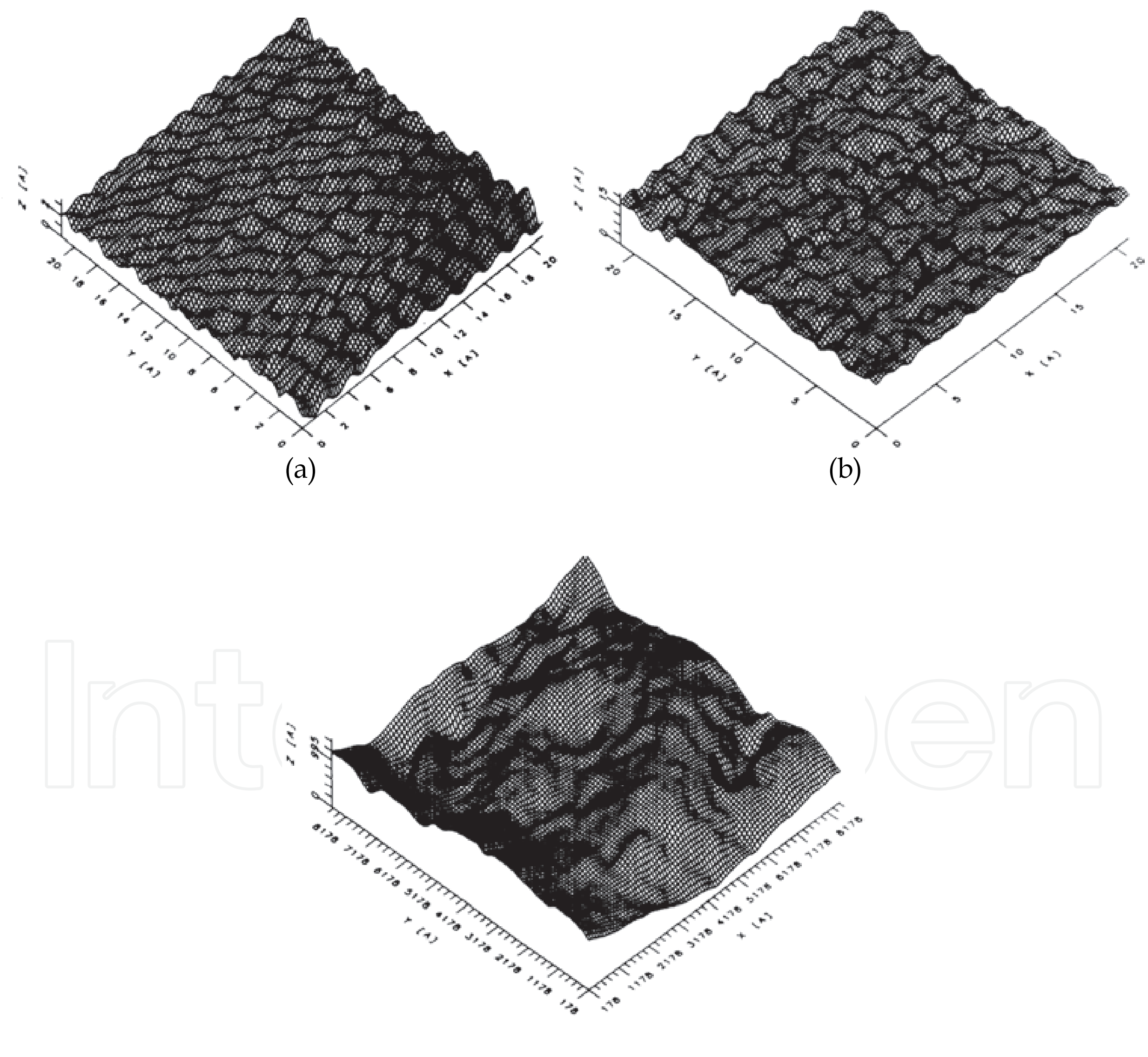


Fig. 6. Sketch of precession and nutation of a polarized molecule on the plane

There is none of the physically reasoned statement that would disprove the assumption that any other polar molecule, radical or ion ought to behave in an electric field in a similar way. For instance, during frictional interaction of polytetrafluoroethylene, the molecular chain is destructed with formation of its fragments that can be considered as radicals. Active ends of the molecular fragments make up a chemical bond with the frictional surfaces with energy of about 690 eV. Meanwhile, such a molecule tends to take up a perpendicular position, which is impeded by the frictional heat being emitted in the area of dynamic contact of the friction assembly, and by the intermolecular action (Nikolsky et al., 1988). Exposure to an external electric field changes the motion of a polytetrafluoroethylene molecule. As a result of precession and nutation processes, such a molecule becomes stable in its vertical position. The precession and nutation lead to the formation of an additional electron cloud, parallel to the friction surface plane. Presence of the Coulomb forces acting between the precessing molecules helps quite obviously to additionally organize their structural order, and resists to the disorganizing action from the temperature fields (Fig. 6). There being generated a structurally ordered molecular layer that is identical to a surfing film in terms of its action and structure.

3. Surfing films

The ultra low values of the friction coefficient recorded in the selective transfer mode are connected with appearance of surfing films on the friction paths. The “surfing” structures appear due to complex physical and chemical processes, and complexing processes become of a special significance among them (Polyakov, 1988). Complexing during friction occurs when the processes associated with triboplasma and postplasmatic transformation phase of the aggregate state of the tribounit surface layer matter, are directly involved. In the moment of closest approach of the rough edges of the conjugate bodies, the surface layer is cleaned from impurities, oxide films, and in the places of dislocation outcrops, resulting from the structural thermal activation, the surface atoms have additional bonds. As almost all metals are electron acceptors, and most additives or tribodestruction products of friction materials have electron donors within their structure, then the latter can act as ligands. This creates favorable conditions for the formation of complex compounds. In the wearlessness condition, it is typical that chemical bond occurs between lubricant ligands and metal surface atoms that have available bonds. In this case a particle on the surface can interact with several lattice atoms at once. Consequently, the total interaction will be very strong. The chemically active components of the lubricant – ligands – form metal-containing complexes with three-dimensional or two-dimensional structure at the dislocation outcrop areas or contact places. Formation of a coordination bond in a complex, leads to weakening or rupture of the metal atomic bonds in the complex with the metal atoms in the friction body lattice. The bond between the metal and complex becomes adsorptive. The complex is now capable to move across the surface and combine with other complexes in film islands (Lubimov & Ryzhikov, 2001). In further acts of contacting between the rough surfaces, the complexes may mechanically come off the surface transferring to the volume of the lubricant. This creates dynamic stability of the surfing structures, with which complex formation and decay processes run at the same speed. To minimize the frictional forces, the complex compound needs not only to develop on the friction surface but also to take a certain position. This positioning was named tribocoordination. Our studies conducted with a scanning tunnel microscope showed that the surfing films have quasi-crystalline structure, which is different from the surface structure where they appear. The important factor for the generation of a monomolecular and multimolecular highly oriented (coordinated) layer is the tribochemical interaction of the polar molecules with the solid body surface, which then provides easiest sliding of the lubricant on the boundary layer surface. This effect leads to the transition of the tribounit to the hydrodynamic friction condition with ultra low friction coefficient values inherent to it. A.S. Akhmatov has grounded the connection between the friction forces and structural organization of the lubricating layers' molecules. He has shown that ordered, pseudocrystalline structure of the lubricating layer adjacent to the solid surface is characterized by the friction modes transient to the hydrodynamic friction, and being accompanied with low values of the friction factor. For such a condition, it is typical to have oriented position of the filiform molecules. In this regard, specifically the surfing film's structure meets the friction moment minimization requirements most of all. Fig. 7 shows photographs of the friction surface conjugate with the epoxy-filled composite containing copper tetraethylthiuramdisulfide complex, which were made using a scanning tunnel microscope.



(a) (b)

(c)

Fig. 7. Surfing film area made of copper complexes

The film from Fig. 7 is fixed on steel at a voltage of 0.1V and 0.5 mA current; one can see that it represents the ordered atomic lattice with a distance between the atoms of 1.9Å. Increased vertical scanning up to 15Å (Fig. 7b), also gives us the ordered atomic grid with 1.9Å distance between the atoms, which resembles a crystal lattice. When larger areas are used (Fig. 7c), apparently the topography can be described as chaotic. Obtaining the friction surface images with the scanning tunnel microscope was possible thanks to the small thickness of the oxide layer. The thickness of metal oxide on the rubbing specimens' surface did not increase (in spite of their contact with atmospheric oxygen), because the oxide layer was covered with the surfing film layer. That is exactly why the topography of surfaces shown in Fig. 6 reflects mainly the morphology of the surfing film. Images of different surface areas in different scales given for each specimen, apparently for the first time allow establishing the relation between the large-scale structure of the surfing film surface, and the structure of the same film at the atomic level. Thus, comparing the images from Fig. 6, the conclusion can be made that the ordered position of the surfing film atoms, evident at the 22×22Å area, leads to the formation of long molecular chains oriented mainly in one direction. While obtaining an image in a larger scale, separate molecules and especially atoms become invisible. And the topography itself now starts reflecting the sliding pattern of tribounit surfaces.

It can be taken for granted that the substances structured as surfing films, regardless whether they are liquid or plastically viscous in mass, with the same temperature and load, in the boundary state on the friction surface take on elastic forms, turning into a different quasi-crystalline aggregate state. Such lubricating layer has a higher stability, and is not squeezed out of the frictional contact area under external forces. Exposure to an electric field facilitates the emergence of a lubricating film on the friction surface, structural orientation of which resembles the tribo-coordinated surfing film, consisting of highly oriented molecules that have chemical bond with the metal surface. The orientation of such films is additionally maintained due to Coulomb forces, which provides them with additional stability and decreases the friction factor and material wear by many times.

4. Control of frictional processes with an electric field

The impact of an electric field action on a frictional contact for various materials of contacting bodies was studied using a side friction machine with the "plane - three pins" testing scheme. Schematic diagram for the friction assembly of the testing machine is shown in Fig. 8. The frictional parameters to be recorded are the linear wear and mass wear of the specimens, friction factor, bulk temperature of the specimens and lubricant.

The cartridge clip with the fixed indenters is held down to the counterbody at the set pressure. The specimens are loaded with the help of the lever mechanism. The machine design provides for the capability to alter the rotational speed of the indenters from 0.5 m/s to 1.2 m/s. The friction factor is determined based on the measured friction torque, recorded by the strain gages fixed on the beam 6 using the half-bridge circuit. The beam is connected to the friction assembly via the rigid constraint that prevents specimen 1 located in the metal cup 5 from turning. The cup 5 is installed on the thrust bearing. The friction assembly is electrically insulated from the machine frame with the help of the textolite pad 7. The friction torque is recorded by the pointer indicator of the instrument TMM-48. The uncertainty of such measurement is 1 - 1.5% which ensures high accuracy of the obtained results. Mass wear of the specimens is determined on the laboratory balance with 0.5 mg measurement error.

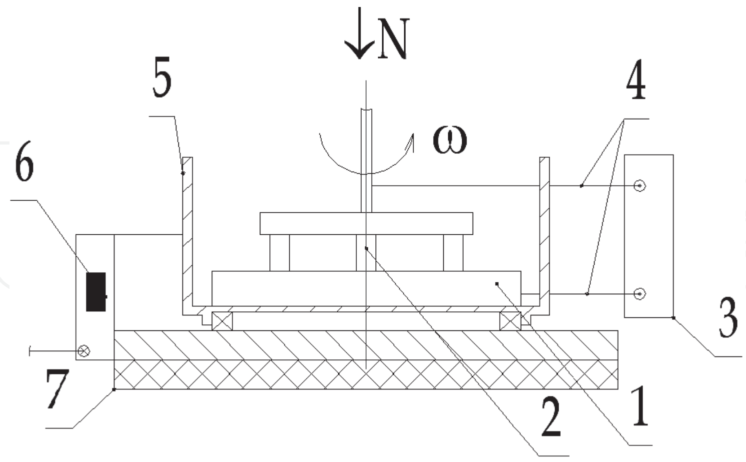


Fig. 8. Schematic diagram of the friction assembly to study the impact of an electric field upon the tribounit frictional parameters: 1) specimen; 2) counterbodies; 3) external source of electric energy; 4) electrodes providing the potential to the friction assembly; 5) testing cup for lubricants; 6) beam with resistance strain gages; 7) electrical insulating (dielectric) pad.

4.1 Application of an electric field to friction assemblies working in boundary lubrication conditions

Tests were carried out on the friction pair: "Bronze (БрО10Ц2, GOST 613-79) – Steel 45 (GOST 1050-88) in the lubricant medium - POLADYNE 10W-30 oil manufactured by Irvine, the US. Friction parameters: sliding velocity ϑ = 1 m/s, contact pressure P = 0.5 MPa. A series of tests was conducted without an electric field, as well as tests where a positive potential was created on the steel counterbody, and then on the rubbing bronze indenters. The friction coefficient was selected as a measurand. The measurement results are shown in Fig. 9.

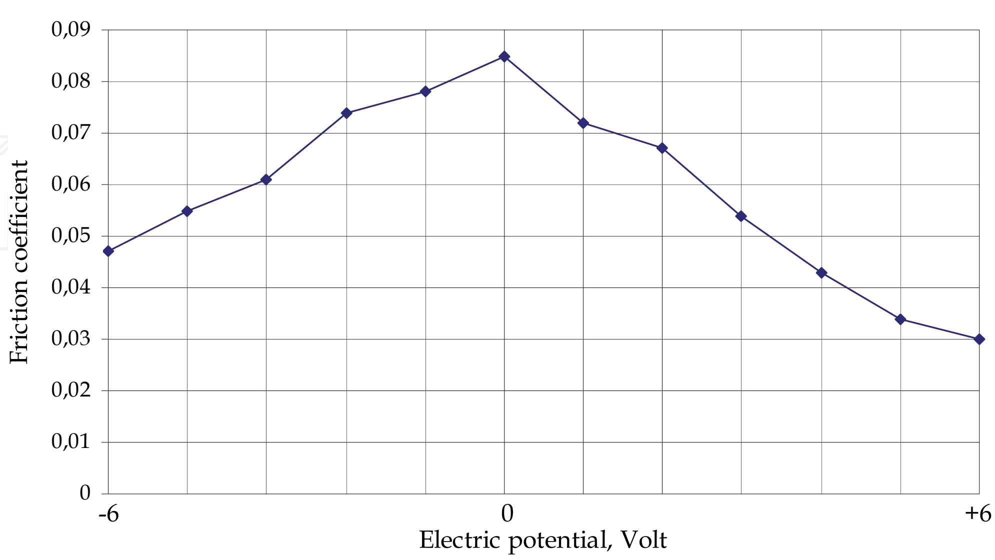


Fig. 9. Relation between the friction coefficient of the "bronze-steel" conjugation and the steel surface potential's value and sign

In our opinion, the significant decrease of the friction coefficient is driven by the intensifying effect of the electric field on the adhesive forces of the metal surface. The fact of the intensification of the adhesive forces under the action of the electric field was proved by experimental weighing (with an analytical balance) of the lubricant (adhesive), left on the steel counterbody surface after the friction. Relation of the adhesive mass and the magnitude and sign of the potential of the steel surface is shown in Figure 10. Along with insignificant amount of oil retained by the surface, it also has some amount of transferred bronze with the hardness that is smaller than that of steel.

Thus, the improved antifrictional characteristics observed in the tribounit are explained by the strengthened lubricant adhesion to the friction surfaces, which impedes its mechanical removal from the frictional contact area, and by the higher stability of the lubricating films. Also, higher chemical activity of the lubricant should be expected. Increased chemical activity of the present-day lubricants is one of the ways to achieve higher performance of friction assemblies. Oil's degree of activity can be visually monitored by the representative darkening after tests. Moreover, oil's reactivity can be evaluated by the decreased photo-emf and light flux, passing through the oil medium. The photo-emf measurement results for the tested oil samples, for each series, are shown in Fig. 11. It is evident that the oil taken after the tests where the positive potential had been applied to the steel surface is more chemically active. This can be explained by the fact that in this test, the recorded value of friction factor was minimal, as well as the frictional heating of the surfaces and the volume temperature of the lubricant. The oil has been depleted by the wear products and thermal decomposition products of its components. Visually it is lighter and therefore, weakens the light flux passing though it at a smaller extent.

Notable is total correlation of the dependencies shown in Fig. 9, 10, 11 which confirms the positive impact of the used electric field on the lubricant properties.

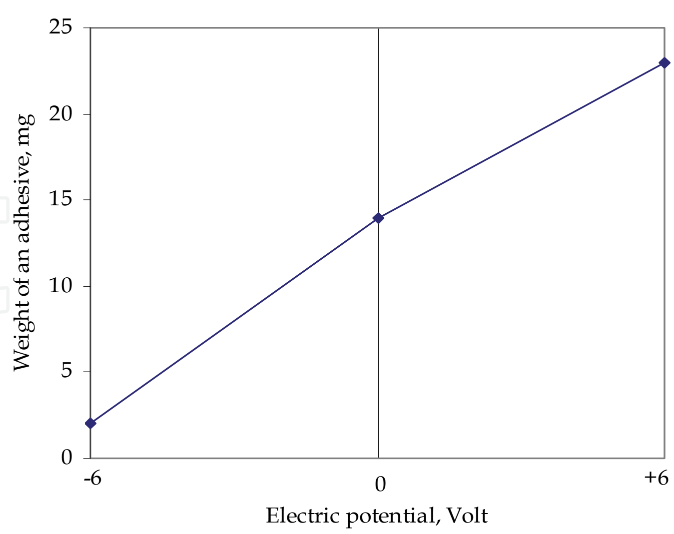


Fig. 10. Relation between the adhesive mass M (mg) and the magnitude and sign of the steel surface potential

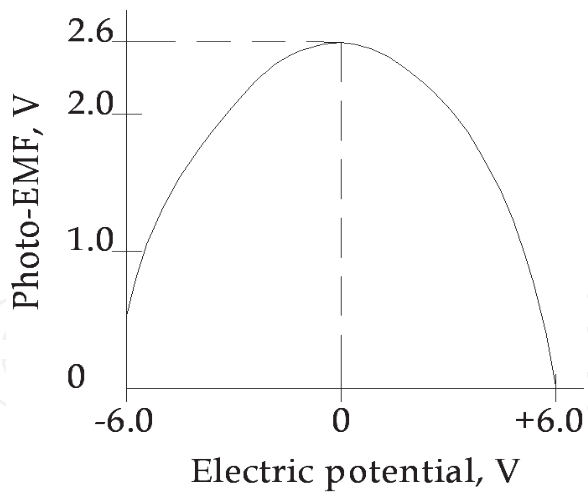


Fig. 11. Relation between the photo-emf and the magnitude and sign of the steel surface potential

4.2 Application of an electric field to metal-polymeric friction assemblies

Tests to evaluate the impact of an electric filed on metal-polymer conjugations with different combinations of polymer materials were carried out under the action of the load-and-speed factor ([pϑ]-factor) equal to 0.5 MPaxm/s, the test time was t = 2 hours. Intensity of wear of polymer materials is affected not only by the electrical field magnitude but by its direction, too (Fig. 12). This relates to the charge build-up on the metal surface in the metal-polymer friction pairs, and also to the fact that the metal surface has either cathodal or anodal polarization, depending on the rubbing polymer nature. Therefore, electric field application may lead to the surface depolarization, which in its turn will either increase or decrease the friction transfer of the polymer material.

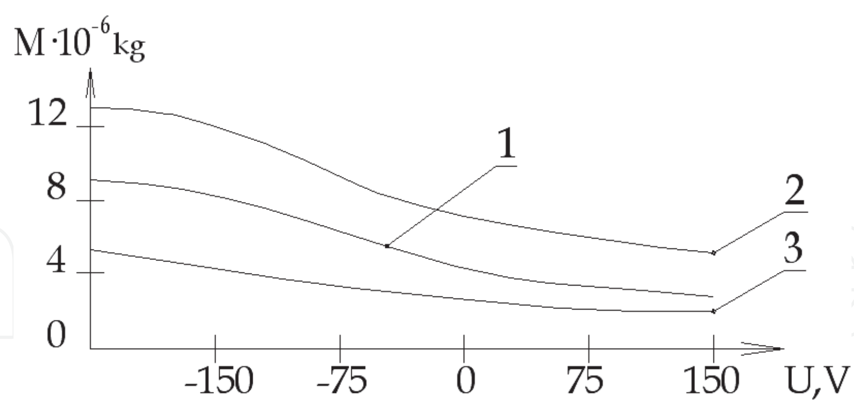


Fig. 12. Relation between the mass wear M and the magnitude and sign of the potential applied to the metal counterbody 1) polyethylene; 2) polypropylene; 3) polyamide 6.

More detailed research has determined that depending on the magnitude and direction of the external electric field, not only the extent of wear of the polymer material changes, but so do the wear conditions (Fig. 13), and the appearance of wear particles.

At the same time, it is evident that with the overall improvement of antifrictional properties of the metal-polymer tribounit, observed when a positive potential is applied to the metal counterbody, also the running-in time is observed to reduce. The plot of relation between the linear wear of the PTFE specimen and the test time for the friction pair "PTFE-steel" under an electric field, can serve as illustration to the previous statement (Fig. 14).

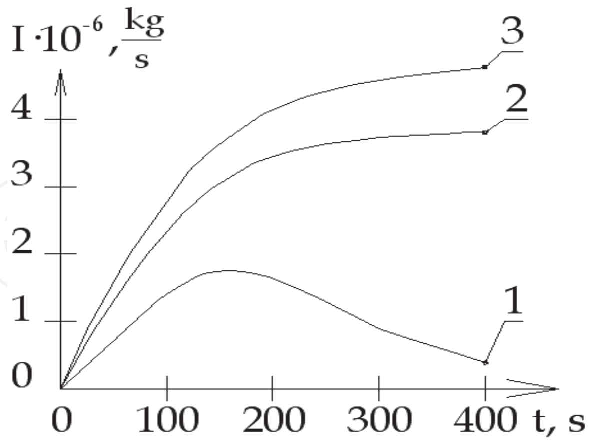
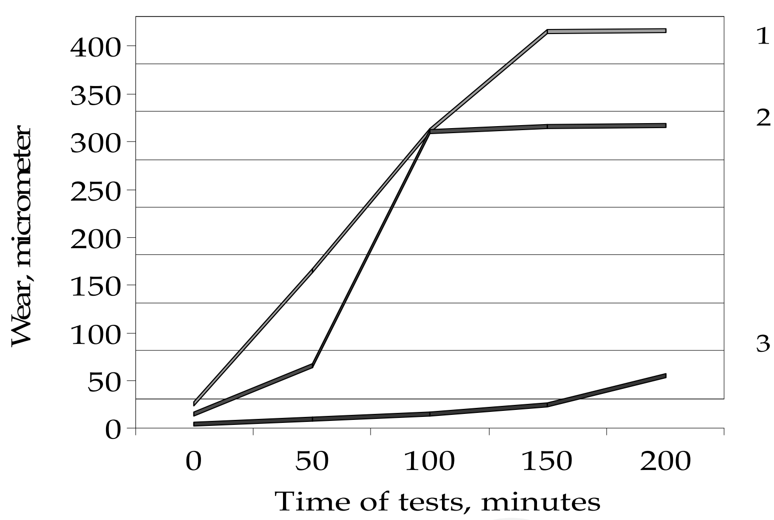


Fig. 13. Relation between the mass wear rate I and the friction time t for the friction pair "PTFE – copper": 1) +100V on metal; 2) 0V; 3) –100V on metal.



1) Heavy wear condition: -150V potential is applied to the steel counterbody; 2) Friction with no exposure to an electric field; 3) Minimal wear condition: +150V potential is applied to the steel counterbody.

Fig. 14. Relation between the running-in time for polymer material and the friction conditions.

It is evident that the superimposed electrical field is capable to not only decrease or increase the specimen wear by 6 times, but also to decrease the running-in time for the material. This is explained by the fact that, with a certain pattern of filed imposition on the metal countersurface, third bodies are increasingly generated which concurs with optimization of the frictional properties of the friction assembly and transfer to the steady state of wear. Therefore, the action of an electrical field leads to the improved tribotechnical parameters of friction assemblies. Characteristic feature of metal-polymer couplings is that it is possible, without fear of electrical breakdown, impose tens of volts on the friction assembly. As all negative issues associated with electroerosion damage of the surface taking place when an electrical breakdown occurs, depend not upon the magnitude of the applied voltage, but upon the breakdown current generated in the frictional contact. Having considered that, we developed and patented an electronic device for the dynamic control of friction and material wear processes, which was named “Electronic regulator of friction” (ERF).

4.3 Electronic regulator of friction

To control and regulate friction and wear processes of materials, it is necessary to provide a reference information channel which on the one hand, would transmit information about frictional processes, and on the other hand, would easily convert this information into a signal that controls the electrical field applied to the frictional contact area. The electronic friction regulator converts this reference signal into an electrical field with a certain voltage and direction. Frictional heating value of a friction pair can be selected as a reference signal. The heat Q emitted during friction is known to be a function of load N, friction coefficient f, sliding velocity ϑ, and friction time t:

$$Q = F(N; f; \vartheta; t) \quad (3)$$

In general terms, a change in tribological characteristics of a friction assembly reflects in the intensity of heating of the friction area. The less the contacting bodies are heated - the less apparent are the dilatation processes, the less is the bulk temperature of the lubricant, the better are the conditions to maintain the carrying capacity of the lubricating layer, stability of the lubricating protective films structure, and the less is the number of surface damages. Therefore, the increased heat release during friction may be identical to the deteriorated antifrictional parameters of a tribosystem. To prevent the wear of friction materials at high temperatures, surface active and chemically active additives are introduced into lubricants. Surface active additives ensure minimization of wear at relatively low temperatures – up to 300 ^{0}C, and chemically active additives decrease the wear and friction at higher temperatures – up to 800÷1200 ^{0}C. However, an additive added to a lubricant gradually deteriorates in the process of work, which entails its lower concentration in the friction area, and therefore the additive’s modifying properties lower, too. Besides this, additional introduction of different types of additives into a lubrication material may disturb the thermodynamic, kinetic or mechanical compatibility of the base oil components. The maximum possible fuel savings (%), depending on an engine type and conditions of their operation, determined by the efficiency of the used motor oils and their additives, are shown in Table 2 (Matveevskyi et al., 1989):

Engine Type	Short Runs		Middle Runs	Long Runs
	Cold Start	Town Conditions		
Gasoline	7,5	6,0	2,2	1,8
Diesel	5,8	4,8	2,5	3,0

Table 2. Fuel savings for vehicle engines

Advantage of adaptive electronic lubricating devices over additives to lubricants is that you enable the electronic module only one time and then its positive action upon mechanisms’ and machines’ friction assemblies is continuous and unflagging, while the intensity of an additive’s action decreases during operation process. The developed device in terms of its function may propose an alternative to quite a wide range of additives to lubricants, and has no restrictions related to the design and process features of friction assemblies. The device was developed for heavy loaded friction assemblies. The device was tested on the propulsion systems of passenger elevators, the electric drives of kettle mixers at lubricant factories, but the widest use this device has got in internal combustion engines. It was determined that this device connected to a power unit improves the power efficiency of engines for vehicles and drives of fixed machines. This happens due to the decreased friction forces in the mechanisms. Friction factors of the assemblies working in the boundary lubrication conditions decrease by 15%, and working with a lubricant – by up to 40%. Efficiency of the utilization of the Electronic Friction Regulator is determined by the load and speed performance of am operated friction assembly, as well as by the initial and maximal intensity of the electromagnetic field created by the device. The device itself has comparatively small dimensions (45 x 45 x 25 mm, its weight does not exceed 150 g). It is built as a stand-alone unit, and thanks to this it is adapted to the structures of machine's mechanisms without any design changes. At this stage of the accomplished work, the device is operable within the temperature range from minus 50 ^{0}C to plus 90 ^{0}C and has a service life no less than 15,000 hours. Application of an "ERF" in the friction assemblies of machines, at a certain intensity and direction of an electromagnetic field, will allow to:

- suppress the frictional electrification effect catalyzing development of corrosion and oxidation processes on the contacting surfaces, and metal anodic dissolution;
- improve lubricant adhesion to the surface being protected thus increasing the lubricant's protective functions;
- decrease a possibility for the hydrogen wear of the friction surface.

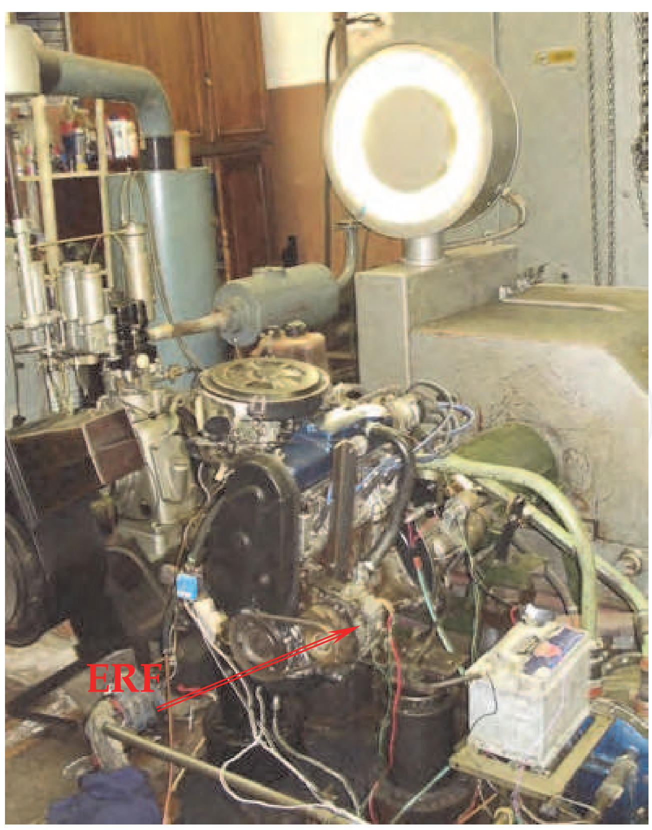


Fig. 15. General view of the test bed

Base Case												
Condition No.	Me, nm	Ne, kW	Gt, kg/hr	ge, kg/ kW-hr	ηe	ηm	Po, bar	Tdg, ^{0}C	CO,%	CH, ppm	NO, ppm	CO_2, %
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	20,16	4,22	1,99	0,471	0,174	0,543	2,8	383	0,102	93	1563	11,61
2	40,32	8,44	2,81	0,333	0,246	0,714	2,7	425	0,073	112	2687	11,43
3	60,48	12,67	3,71	0,293	0,279	0,797	2,6	480	0,067	110	3046	11,93
4	80,63	16,89	4,84	0,286	0,286	0,847	2,5	560	0,643	114	2420	12,28
5	83,15	17,42	6,15	0,353	0,232	0,852	2,5	540	6,441	177	596	9,58
Final condition, with the Electronic Regulator of Friction in 5 motor hours												
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	20,16	4,22	1,87	0,443	0,185	0,543	2,5	395	0,096	76	1710	11,96
2	40,32	8,44	2,67	0,317	0,258	0,713	2,5	421	0,070	97	2812	11,69
3	60,48	12,67	3,43	0,271	0,302	0,797	2,4	460	0,062	105	3675	11,73
4	80,63	16,89	4,62	0,273	0,299	0,845	2,4	555	0,585	95	2556	12,43
5	84,67	17,73	5,98	0,337	0,243	0,854	2,3	535	6,664	155	554	9,39

Table 3. Load characteristic at n = 2000 rpm

Base case												
Condition No.	Me, nm	Ne, kW	Gt, kg/hr	ge, kg/ kW-hr	ηe	ηm	Po, bar	Tdg, ^{0}C	CO,%	CH, ppm	NO, ppm	CO_2, %
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	20,33	6,39	2,96	0,463	0,177	0,503	2,8	502	0,213	82	2100	12,47
2	40,66	12,77	4,26	0,334	0,245	0,677	2,7	548	0,093	88	3487	12,56
3	60,98	19,16	5,38	0,281	0,291	0,765	2,6	596	0,089	97	3937	12,37
4	81,31	25,55	7,22	0,282	0,290	0,818	2,6	656	0,629	101	2981	13,12
5	97,58	30,65	9,81	0,320	0,256	0,848	2,8	610	7,171	189	602	9,95
Final condition, with the Electronic Regulator of Friction in 5 motor hours												
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	20,33	6,39	2,89	0,453	0,181	0,503	2,6	506	0,128	52	2211	12,51
2	40,66	12,77	4,10	0,321	0,255	0,677	2,6	537	0,097	73	3480	12,67
3	60,98	19,16	5,23	0,273	0,299	0,765	2,6	585	0,099	83	4013	12,61
4	81,31	25,55	6,90	0,270	0,303	0,818	2,6	650	0,785	90	2889	13,15
5	97,58	30,65	9,92	0,324	0,253	0,848	2,6	610	7,553	177	536	9,68

Table 4. Load characteristic at n = 3000 rpm

This entails the increased service lifetime of the machine mechanisms, as well as their better environmental performance. The device design and method of its connection to a car power plant are presented in the papers by (Lubimov et al., 2008; Lubimov et al. 2009b). There were conducted two series of tests of different designs of the device. Below are shown the device photograph and the results of its trials on the test bed simulating internal combustion engine’s operation.

As you can see from the picture, the dimensions of the Electronic Regulator of Friction (blue colored device indicated with the arrow) attached to the machine body are small in comparison to the machine overall sizes.

Rotation frequency, rpm	Initial condition		Outcome	
	Closed throttle	Open throttle	Closed throttle	Open throttle
300	26,0	23,0	24,0	22,0
500	17,5	17,0	17,0	16,5
800	16,5	12,5	16,0	13,0
1000	16,5	12,5	16,0	12,5
1500	18,0	13,5	17,5	13,0
2000	19,0	14,0	18,0	14,0
2500	21,0	16,0	20,0	16,0
3000	24,0	18,5	21,0	17,5

Table 5. Mechanical loss moment, Nm

Effective Power	Fuel Consumption	Effective Efficiency	CO	CH	NO_x
0,840	4,344	4,621	18,90	19,05	- 6,53

Table 6. Averaged effects, %, against the engine base case condition according to the results of the first series of tests, considering the changes for all the conditions

Symbols in the table: n – rotation frequency for the engine crankshaft; Me – net troque; Ne – effective power; Gt – fuel consumption per hour; ge – specific fuel consumption; ηe – effective efficiency; ηm – mechanical efficiency; Po – oil pressure; Tdg – temperature of discharge gases; CO – carbon oxide content in the engine discharge gases; CO2 – carbon dioxide content in the engine discharge gases; NO – nitrogen oxide content in the engine discharge gases; CH – residual hydrocarbons content the engine discharge gases.

From the given data, one can see that the enabled device decreases the fuel consumption and mechanical loss moment; increases the power and efficiency of the machine engine, decreases harmful contamination in the discharge gases, as well as their temperature. The observed effects were recorded after 5 motor hours of the experimental unit operation. After the device had been disconnected and the simulation machine had been restarted, the controlled variables again decreased down to the values corresponding to the base case condition of the engine. The next series of tests were aimed to study the impact of an electromagnetic field with 60 MHz frequency pulse action on the engine performance. For this purpose, the design of the Electronic Regulator of Friction was modified with some slight increase of its dimensions. The results of the development tests of this design version at n = 3000 rpm, as well as the averaged effects are shown in Table 7 and summary table 8.

At this moment, we can not provide the definite explanation for the increased content of nitrogen oxides in the discharge gases. One of the draft versions of reasoning is the ability of an electromagnetic field to inhibit generation of soot depositions on the friction surfaces of the piston-cylinder group of an internal combustion engine. Under the action of an electric field the working elements of the car engine are cleaned. Indirectly, this is proved by photographs of oil filters taken from the machines during operational tests of the device

(Fig. 16). In the presented figure, the upper image is a new filter of the VAZ 21099 car that has run 1500 km with ERF, the lower image is the condition of the oil filter after the scheduled oil replacement after 10,000 km. The upper filter is filled with particulate depositions of the soot nature. It seems that under the action of an electromagnetic filed, the above mentioned depositions were removed from the cylinders' wall surfaces and retained by the oil filter.

Fig. 16. Condition of the oil filters with the utilization of the ERF (above) and without it (below)

Base case												
Condition No.	Me, nm	Ne, kW	Gt, kg/hr	ge, kg/ kW-hr	ηe	ηm	Po, bar	Tdg, ^0C	CO,%	CH, ppm	NO, ppm	CO_2, %
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	20,33	6,39	2,90	0,455	0,180	0,503	2,7	494	0,135	55	2059	12,60
2	40,66	12,77	4,19	0,328	0,250	0,677	2,7	536	0,092	78	3421	12,67
3	60,98	19,16	5,28	0,276	0,297	0,765	2,6	585	0,099	95	4017	12,71
4	81,31	25,55	6,98	0,273	0,299	0,818	2,7	650	0,644	97	2987	13,32
5	98,59	30,97	9,98	0,322	0,254	0,849	2,8	612	7,356	174	574	9,96
Final condition, with the Electronic Regulator of Friction (60 MHz) in 5 motor hours												
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	20,33	6,39	2,79	0,436	0,187	0,503	2,7	506	0,132	55	2255	12,56
2	40,66	12,77	3,95	0,309	0,265	0,677	2,6	538	0,095	74	3562	12,64
3	60,98	19,16	4,99	0,261	0,314	0,765	2,6	582	0,100	86	4066	12,59
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
4	81,31	25,55	6,68	0,262	0,313	0,818	2,6	661	0,675	87	2988	13,21
5	98,59	31,23	9,38	0,303	0,270	0,849	2,7	608	8,024	163	488	9,48

Table 7. Load characteristic at n = 3000 rpm

Effective Power	Fuel Consumption	Effective Efficiency	CO	CH	NOx
1,392	5,036	5,233	21,14	24,78	-4,43

Table 8. Averaged effects, %, against the engine base case condition according to the results of the second series of tests, considering the changes for all the conditions

The important feature of the developed device is that it can be used both for the improvement of the lubrication conditions of friction assemblies and for controlled tightening of their frictional parameters. This feature allows to use the device for faster running-in time of new machines and mechanisms in the conditions minimizing the initial wear, and it can be helpful for machine engineering companies to reduce time and energy consumption when testing their fabricated products.

5. Conclusion

Today, research of the fine mechanisms of friction which are responsible for change of materials' antifriction parameters, and the impact of external force fields (electric, magnetic) on them, are underway. At this stage, a thesis has been defended which discusses the main principles of transformation of a matter aggregate state during friction, and impact of electromagnetic fields on lubricating action of oils and greases in metal couplings. The design of the Electronic Friction Regulator is being improved, and there being checked possible ways of its connection to vehicle engines with the purpose of finding the best option providing the maximal improvement of vehicle/machine power plant performance. Also, the research is underway to study possible negative consequences from utilization of this device. However, over the three years of monitoring of the technical condition of the machines operated with the electronic device, no negative aspects from its utilization were found.

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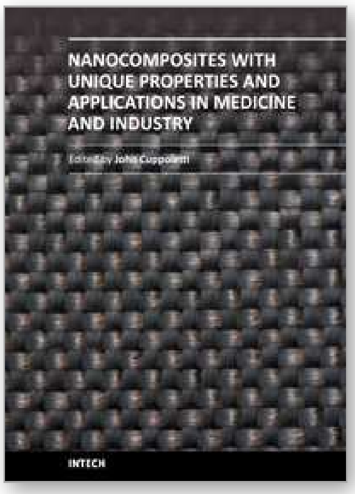

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This book contains chapters on nanocomposites for engineering hard materials for high performance aircraft, rocket and automobile use, using laser pulses to form metal coatings on glass and quartz, and also tungsten carbide-cobalt nanoparticles using high voltage discharges. A major section of this book is largely devoted to chapters outlining and applying analytic methods needed for studies of nanocomposites. As such, this book will serve as good resource for such analytic methods.