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System analysis of friction and wear processes when using fullerene compositions in lubricants

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Abstract

The system-structural approach in researches of processes of friction and wear at application of fullerene compositions in lubricants is proved in the work. It is proposed to use a multilevel approach to study and model the processes of deformation of the surface layers of movable and fixed triboelements and the formation on energy-activated surfaces of wear-resistant structures containing fullerene molecules. The essence of the approach is to use multi-scale research methods to build mathematical models within a single research structure. Due to the fact that tribosystems differ in the integrity of the interconnected elements included in them, it is assumed that all processes occur at three hierarchical levels. At this level, they interact with each other and exchange energy and matter.

Input and output flows in studies of tribosystems are formulated. It is shown that the input streams include design parameters of the tribosystem, technological parameters, operating parameters. These parameters form the flow of matter, energy and information, which is the input effect on the tribosystem. The output flow from the tribosystem are the parameters: volumetric wear rate I, dimension m^3/hour; friction losses, which are estimated by the coefficient of friction f, dimensionless quantity. The output stream is the information flow of the tribosystem. When solving contact problems, this allows to take into account not only the level of stresses, but also the speed of deformation in the materials of the surface layers, as well as the depth of deformation, which in the models will take into account the volume of deformed material.

Depending on the tasks and requirements for their solution, the use of different methodological approaches for modeling is justified. It is shown that the application of mathematical models in the modeling of tribological processes depends on the correct choice of technical constraints that determine the range of optimal solutions.

Key words: fullerenes; fullerene solvent; fullerene compositions; tribosystem structure; dissipation speed; electrostatic field of the friction surface; deformation rate; volumetric wear rate; coefficient of friction.

Introduction

Processes of friction and wear in various designs of tribosystems belong to dynamic processes and develop according to the general laws of synergetics. A distinctive feature of such processes is the adaptation of the surface layer of tribosystems to the conditions of friction, which is called B.I. Kostecki structural adaptation of materials by friction, and then L.I. Bershadsky - adaptation, ability to learn and self-organization of tribosystems.

Self-organization is a fundamental phenomenon of nature, which is manifested in various areas of animate and inanimate nature. The essence of self-organization in tribosystems is that under the action of external perturbation the tribosystem adapts (learns, changes) so that its response to external perturbations maximally compensates for the cause of such perturbation, ie the ability of the tribosystem to return to stable conditions after cessation on the tribosystem of outrageous factors.

The use of fullerenes as antiwear, extreme pressure and antifriction additives to technical liquid lubricants gives an ambiguous answer about their effectiveness and limits of use. Such lubricants react to external influences on the tribosystem and are able to change the structure of surface layers, adapting to operating conditions. Controlling the process of formation of such structures will increase wear resistance and reduce friction losses of machines and mechanisms, which will help to save energy resources during operation.

One of the ways to solve this problem is the development of a systematic approach in studying the processes of friction and wear in the presence of fullerene compositions in lubricants and modeling of such processes in structures formed on the friction surface. The simulation results will allow to substantiate the composition and content of fullerene additives to lubricants for various purposes and groups of operation.

Literature review

In the last twenty years, a number of publications have appeared, where with the help of theoretical [1] and experimental research [2], as well as computer simulation [3] new knowledge about the processes of friction and wear of hard surfaces in the presence of an ultrathin film of liquid between them. In the given works it is established that in the course of functioning of a tribosystem the lubricating film becomes more and more thin, at first its physical properties change gradually, and then changes get sharply expressed character. Qualitative changes are expressed in the non-Newtonian shift mechanism and, according to the authors, in the replacement of ordinary melting - by glazing. However, the film continues to behave like a liquid.

In such films, phase transitions of the first kind to solid or liquid phases are possible, the existence of which has been proved in [4], whose properties cannot be described by such a term as viscosity. These films are characterized by a yield strength, which is a characteristic of fracture in solids and a large stress relaxation time.

In work [5] describes the dynamic properties of thin lubricating films by friction in the limit lubrication mode. Experiments performed on smooth friction surfaces in the presence of surfactants have shown that such phase transitions occur and are confirmed by other researchers [6]. Such processes cause stick-slip motion, which is characteristic of friction without lubricant and is characterized by periodic transitions between two or more dynamic states during the stationary process.

Since the intermittent motion is observed at a constant temperature of the friction surfaces, to explain it by the authors [6, 7] the concept of "shear melting" is offered. According to this concept, first the oil is solid (stick), then, when some critical stress value is exceeded, the oil abruptly turns into a liquid phase (slip) as a result of loss of strength. Upon further movement, under the action of the load, the oil again becomes solid (stick). According to the authors [8], such molecular rearrangement processes have a correlation in thin films at a short distance from the friction surfaces.

According to the work [9] the liquid state of thin films is characterized by an effective viscosity, which is many orders of magnitude higher than the viscosity for a bulk liquid and is non-Newtonian. This means that the effective viscosity decreases with increasing sliding speed, ie the thin film reduces the shear stress [10]. Under different conditions of sliding the authors of the work [11] it is established that the film changes the thickness and structure. In addition, liquids containing multicomponent additives undergo dynamic phase transitions, which is manifested in the appearance of intermittent modes of motion [12].

According to the experimental data presented in the work [13], oil on the friction surface is a very viscous fluid that behaves like an amorphous solid and is characterized by a yield strength. Therefore, based on rheological description of viscoelastic medium, which has a thermal conductivity in the [5] a system of kinetic equations is obtained, which agree and determine the behavior of shear stresses and strains, as well as the temperature in the thin film of oil on the friction surface [14]. The obtained rheological equations and the results of modeling using equations, allowed the authors to conclude that the value of the effective viscosity is very different from the value of the bulk viscosity and depends on the temperature. According to the authors [5] the specified feedback between the magnitude of stresses, temperature and deformation means that the transition of oil from solid to liquid state due to both heating and the effects of stresses created by solid friction surfaces. This is consistent with the consideration of the instability of the solid phase in the representation of shear dynamic melting in the absence of thermal fluctuations [15].

The results of the above analysis allow us to expand the existing understanding of the physics of processes occurring on the friction surfaces of tribosystems operating in the mode of extreme lubrication. This is especially true at the present stage of development of the science of tribology, when nanosized particles are used in lubricants and the classical law of Amonton-Coulon is not fulfilled. This is the opinion of the authors of the work [5]. The authors of this work argue that the melting of the ultrathin film of oil between the solid friction surfaces, is presented as a result of shear stresses and rapid heating of a small local volume. The critical temperature of the local volumes of the friction surface at which melting occurs increases with increasing characteristic value of shear viscosity and decreases with increasing modulus of shear of the oil according to the linear law. It is shown that the intermittent friction mode (stick-slip) is realized if the relaxation time of the temperature in the oil is much higher than the time value for shear stresses and strains.

The results of studies of boundary friction in the framework of a synergetic model based on the idea that the system is self-organizing are presented in work [16]. The paper describes the behavior of the limiting lubricant during the mutual movement of the friction surfaces, in particular, the studied hysteresis phenomena and fractal characteristics of time series of stresses. However, the author suggests that the properties of the oil layer are the same both inside the layer and near the contact surface. According to the results of the study of spatially inhomogeneous systems, the behavior of the lubricant in the process of friction is non-trivial. For example, at work [17] "vortex-like" movement of lubricant in the contact zone was detected. In addition, in [17] it is shown that during dry friction of rough surfaces, between them, as a result of mechanical action, a quasi-liquid layer is formed, as a result of which the coefficient of friction decreases with increasing shear rate. It is established that in the course of evolution the system strives for a homogeneous state in which shear stresses are realized in the whole region of contact, which have a constant value, which determines the relative speed of friction blocks.

In works [18, 19] attention is focused on the practical features of the use of lubricants with functional additives that provide a positive effect both in the manufacturing process and at the stage of operation of tribosystem parts. At the same time, the mechanisms of action of lubricating compositions on operational factors were not analyzed.

The analysis of the researches devoted to the thin-film object - the oil adsorbed on a friction surface allows to state that in the course of interaction of friction surfaces, the lubricating film has some phases: solid-like; rare and mixed. The phases, under the action of stress on the spots of actual contact and the rate of deformation of the material of the surface layers on the spots of contact, pass into each other. The classical term viscosity is not suitable for such phases, it is proposed to use the term - effective viscosity, the value of which is several orders of magnitude greater than the viscosity in the volume of lubricant. The magnitude of the roughness of the friction surface is a significant factor. The analysis also shows that the study of such thin-film objects is better done using the basic principles of the science of rheology, using the rheological equations of flow in such films. Based on the conclusions, we can put forward a working hypothesis that in the presence of nanoparticles in the lubricant, which are included in the form of aggregates (clusters, micelles), the effective viscosity in the volume of the thin-film object will act as a significant factor and determine wear resistance and friction losses. Determining the value of the effective viscosity and the dependences of its change on the magnitude of external influences, connected materials in the tribosystem, the design of the tribosystem and the tribological properties of the basic lubricant will control the processes of friction and wear.

Summing up the analysis of works on the formation of lubricating films on friction surfaces and the factors influencing this process, we can conclude that the aim of this study is to develop a system-structural approach in the study of friction and wear in the application of fullerene compositions in lubricants and theoretical studies of the formation of the lubricating film in the presence of such compositions. This task requires the development of a mathematical model of the interaction of electrically active heterogeneous fine systems at the interface friction surface - lubricating medium and modeling of such processes. The model should take into account the generation of friction surfaces of the connected materials of the electrostatic field and the influence of this force field on the electrically active units in the lubricating medium. As a result of such interaction, a lubricating film of a certain thickness and structure is formed on the friction surfaces.

Purpose

The purpose of this work is to develop a systematic approach to studying the processes of friction and wear in the presence of fullerene compositions in lubricants and to simulate such processes in structures formed on the friction surface. The simulation results will allow to substantiate the composition and content of fullerene additives to lubricants for various purposes and groups of operation.

Methods

The technical term tribosystem will mean a complex of at least four elements E and existing links between them R, which form a single set and operate within a more complex system of which it is part, ie $S = (E, R)$. Each tribosystem can be divided into subsystems, while maintaining the existing connections within the system, which allows you to consider the resulting subsystems separately. This division was first performed by G. Chikhos, where the subsystems are called friction planes. A characteristic feature of systems analysis is that when studying part of the population it is necessary to take into account the whole set of elements and connections.

Under the input streams we will understand: design parameters of the tribosystem; technological parameters; operating parameters.

The output flow from the tribosystem are the parameters: volumetric wear rate I, dimension m^3/hour; friction losses, which are estimated by the coefficient of friction f, dimensionless quantity. The output stream is the information flow of the tribosystem.

The task of this work is to study the processes of formation of surface structures of triboelements in the presence of fullerene compositions in the lubricant and the mechanisms of influence of such structures on the volumetric wear rate and friction coefficient. According to the formulated task is subject to change:

- concentration of fullerenes in the basic lubricant, dimension g/kg;

- concentration of fullerene compositions containing fullerene powder and vegetable oil as solvent of fullerene powder, dimension g/kg;

- tribological properties of the basic lubricant to which fullerenes or fullerene compositions are added, dimension J/m^3;
- coefficient of shape of the tribosystem, dimension m^{-1};
- structure of connected materials in the tribosystem, which is taken into account by a complex parameter - the internal friction of triboelement materials;
- load-speed range of operation or operation of the tribosystem, which is taken into account by the product of load and sliding speed, dimension J/s.

Flows of materials and energy are integral components of the processes of formation on the friction surface of wear-resistant structures, and the flow of materials reflects the object of influence, and the flow of energy - a means of influence.

In the framework of this work it is proposed to use a multilevel approach to study and model the processes of deformation of the surface layers of movable and fixed triboelements and the formation on energy-activated surfaces of wear-resistant structures containing fullerene molecules. The essence of the approach is to use multi-scale research methods and approaches to building mathematical models within a single research structure.

Due to the fact that the tribosystem differs in the integrity of the interconnected elements included in it, we assume that all processes occur at three hierarchical levels, fig. 1. At this level, they interact with each other and exchange energy and matter.

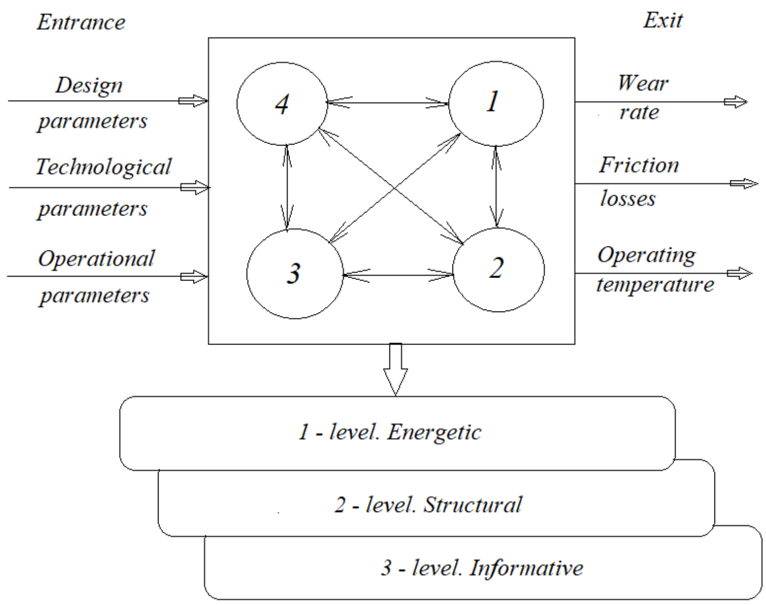

Fig. 1. Hierarchy of levels of the tribosystem:
1 – movable triboelement;
2 – fixed triboelement;
3 – lubricating or working medium;
4 – environment

Results

The first level in the hierarchy of the tribosystem is the energetic level. In the study of processes of this level, the input parameters are design, technological and operational factors, as shown in fig. 2.

The initial parameters are the speed of dissipation in the tribosystem – W_{TS}, dimension J/s. The rate of dissipation in the tribosystem is the part of the energy that goes to change the structure of the surface layers of materials of movable and fixed triboelements.

The energy (power) that is supplied to the tribosystem can be determined by expression:

$$W = N \cdot v_{sl}; \left[N \cdot \frac{m}{s} = \frac{J}{s} = W \right], \tag{1}$$

where N – is the load on the tribosystem, N;

v_{sl} – is the sliding speed, m/s.

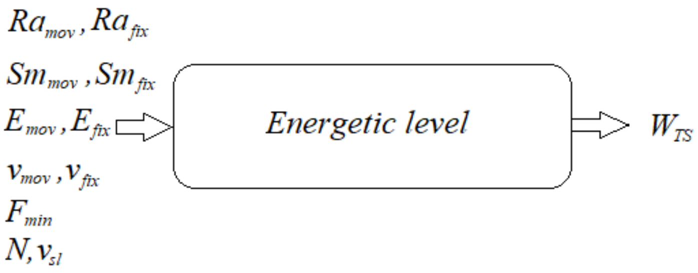

Fig. 2. Block diagram of the energy level of the tribosystem

The input parameters that affect the rate of dissipation in the tribosystem are:

1. Technological parameters - parameters of roughness of contacting friction surfaces:

- Ra_{mov}, Ra_{fix} – arithmetic mean deviation of points of profile of movable and fixed triboelements, m;
- Sm_{mov}, Sm_{fix} – average step of inequalities along the middle line of the profile of movable and fixed triboelements, m.

Parameters Ra and Sm are determined in accordance with GOST 2789-73.

2. Physico-mechanical properties of contact materials in the tribosystem:

- E_{mov}, E_{fix} – modulus of elasticity of materials of movable and fixed triboelements, Pa;
- υ_{mov}, υ_{fix} – Poisson's ratio of materials of movable and immovable triboelements.

3. Design parameters of the tribosystem:

- $F_{\min}$ – smaller area of friction of one of the triboelements, m^2.
- $\sigma_n = N/F_{\min}$ – rated voltage at contact of triboelements, Pa.

The rate of dissipation in the tribosystem, according to the work [20] is determined by the expression:

$$W_{TS} = W_{TS,mov} + W_{TS,fix}, \tag{2}$$

where $W_{TS,mov}$ and $W_{TS,fix}$ – is the speed of dissipation in movable and fixed triboelements, dimension J/s.

The speed of dissipation in movable and fixed triboelements, according to the work [20] is determined by the expression:

$$W_{TS,mov} = \sigma_{acs} \cdot \dot{\varepsilon}_{mov} \cdot V_{dmov} \cdot n \text{, J/s,} \tag{3}$$

$$W_{TS,fix} = \sigma_{acs} \cdot \dot{\varepsilon}_{fix} \cdot V_{dfix} \cdot n \text{, J/s,} \tag{4}$$

Voltage at the actual contact spots (ACS) – σ_{acs}, dimension Pa, and the number of contact spots n depends on the load on the tribosystem N, N, modulus of elasticity and roughness of contact materials of triboelements and is calculated by the formulas given in work [20].

The deformation rate of the material of the movable triboelement per unit ACS is calculated by expression [20]:

$$\dot{\varepsilon}_{mov} = 75(1+\upsilon_{mov})(0{,}86-1{,}05\upsilon_{mov})\frac{\sigma_{acs}\cdot\upsilon_{sl}}{E_{mov}\cdot d_{acs}} \text{, 1/s,} \tag{5}$$

for the material of the fixed triboelement:

$$\dot{\varepsilon}_{fix} = 75(1+\upsilon_{fix})(0{,}86-1{,}05\upsilon_{fix})\frac{\sigma_{acs}\cdot\upsilon_{sl}}{E_{fix}\cdot d_{acs}} \text{, 1/s.} \tag{6}$$

The diameter of the actual contact spot d_{acs}, m, calculated according to the formulas given in the work [20].

The volume of movable material V_{dmov} and fixed V_{dfix} triboelements, m^3, which participates in deformation in the process of friction, is calculated by the formulas given in the work [20]:

$$V_{dmov} = F_{\max} \cdot h_{dmov}, m^3, \tag{7}$$

$$V_{dfix} = F_{\min} \cdot h_{dfix}, m^3, \quad (8)$$

where $F_{\max}$ –is the large area of friction of one of the triboelements, m^2.

Depth of deformation of the surface layers of the movable material h_{dmov} and fixed h_{dfix} triboelements is calculated by the formulas given in the work [20]:

$$h_{dmov} = 0{,}5 d_{acs}\left(1 - e^{-D_{mov}}\right), \text{ m}, \quad (9)$$

$$h_{dfix} = 0{,}5 d_{acs}\left(1 - e^{-D_{fix}}\right), \text{ m}, \quad (10)$$

where D_{mov} and D_{fix} – is the coefficients that take into account the ability of the material to deform under the action of surfactants, for movable and fixed triboelements, respectively, dimensionless values. Calculated on the basis of work [20]:

$$D_{mov} = \frac{6{,}5 \cdot 10^8 \sigma_{acs}^2}{E_{mov} \cdot E_u}, \quad (11)$$

$$D_{fix} = \frac{6{,}5 \cdot 10^8 \sigma_{acs}^2}{E_{fix} \cdot E_u}, \quad (12)$$

where E_u – is the tribological properties of the lubricating medium, J/m^3, are determined on a four-ball friction machine, take into account the anti-wear and anti-emergency properties of lubricants, are calculated by the formula given in the work [21].

The processes that take place at the energy level are as follows. Under the action of load, sliding speed and temperature gradient, the formation of equilibrium roughness on the friction surfaces. The diameter of the actual contact spot changes d_{acs} in the direction of increase, which leads to a decrease in stress σ_{acs} on the spot of actual contact. It should be noted that during the running-in of the tribosystem, the diameter of the actual contact spot increases slightly, not more than twice. However, the number of contact spots n increases by an order of magnitude. After completion of the running-in process, the number of contact spots and their diameter are stabilized near equilibrium [22].

Due to the decrease in stresses on the spots of actual contact and the simultaneous increase in the diameter of the spots, the rate of deformation of the materials of the surface layers decreases, this follows from the formulas (5) and (6). At the same time, the depth of deformation in the surface layers decreases, this follows from the formulas (7) - (12).

As a result, after completion of running-in, the surface layers of the movable and fixed triboelements form a certain structure of the material, which corresponds to the input effect on the tribosystem. When you change the magnitude of the input action, all of the above processes will change, so the structure of the surface layers will change.

The criterion that is a measure of such changes is the rate of dissipation in the tribosystem – W_{TS}, dimension J/s. This criterion is a way out of the energy level of the tribosystem, fig. 2 and at the same time is the entrance to the second level - the structural level of the tribosystem.

The block diagram of the second - structural level of the tribosystem is presented in fig. 3.

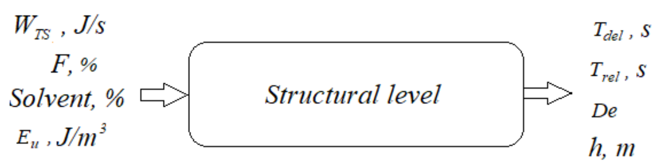

Fig. 3. Block diagram of the structural level of the tribosystem

Under the action of energy, the value of which is estimated by the speed of dissipation, the surface layers of movable and fixed triboelements act as a "generator of electrostatic force field". The force field of the friction surfaces will affect the formation of a lubricating film on the friction surfaces in the presence of solutions of fullerenes in the lubricant.

Adding electrically active heterogeneous fine systems of different concentrations to the basic lubricating medium will create an electrostatic field in the volume of lubricant (liquid). The increase in the force field in the volume of the liquid is associated with a high value of the dipole moment of the fullerene molecule, which is equal to $3{,}34\cdot10^{-30}$ C·m. Fullerene molecules, in the field of electrostatic forces of friction surfaces, will form clusters that actively interact with the "electrostatic field generator". The result of this interaction is the formation of wear-resistant structures on the friction surfaces.

Based on the analysis of work on the use of fullerenes, it is concluded that fullerenes are insoluble in technical oils of petroleum, semi-synthetic or synthetic origin. Such systems are characterized by sedimentation processes. In this paper, a working hypothesis is formulated that the use of "solvents" of fullerenes significantly increases the electrostatic field strength of the liquid. As solvents for fullerenes, you can use high-oleic vegetable oils, such as rapeseed, which are well soluble in all types of technical oils. During the solution of fullerene molecules in vegetable oil, micelles are actively formed, where the nucleus of the micelle is a fullerene molecule, or several fullerene molecules. The application of such a technological approach as the preliminary dissolution of fullerene molecules in vegetable oil, and then the addition of such a composition to base oils, will significantly increase the strength of the electrostatic field of the liquid. This is due to the fact that the dipole moment of the micelles based on fullerenes, which is equal to $p_m=9{,}04\cdot10^{-26}$ C·m, an order of magnitude greater than the dipole moment of fullerene-based clusters, which is equal to $p_k=3{,}31\cdot10^{-27}$ C·m. This will create more effective wear-resistant structures on the friction surfaces in comparison with technological approaches, where there is no pre-dissolution of fullerenes.

In the process of functioning of the tribosystem due to the influence of temperature, as well as load and sliding speed, the process of cluster and micelle formation, as well as their destruction, can occur simultaneously, therefore, the total electrostatic field of the lubricating medium E_{fl} defined as the sum:

$$E_{fl} = E_k + E_m,\ \text{V/m},$$

where E_k and E_m – is the voltage of the electrostatic field of the liquid due to the formation of clusters and micelles, dimension V/m;

Working hypothesis on the formation of wear-resistant surface structures based on fullerene compositions (vegetable oil + fullerenes), has rational limits of effective use. It is necessary to confirm theoretically and experimentally that for tribosystems having a certain design and load-speed range of operation, there are optimal modes of operation, when the friction surface generates the maximum value of electrostatic field strength, which is the driving force for electrostatic field formation in the lubricating film volume.

The lubricating film formed on the friction surface can act as two structures, as an elastic solid, or as a viscous non-Newtonian fluid. In such structures, the process of stress relaxation at the spots of actual contact will take place in different ways, which requires the development of a mathematical model. The mathematical model should consist of a macro-rheological and micro-rheological model of stress relaxation on the actual contact spots in the presence of fullerene compositions in lubricants. The macroreological model can be represented in the form of second-order differential equations and their solutions, the microreological model in the form of expressions for determining the parameters included in the differential equations and their solutions. Solutions of differential equations will allow modeling the process of stress relaxation on actual contact spots in the tribosystem, which allows to determine the friction losses.

When planning research at the second - structural level, the following working hypothesis is formulated. The formation of a lubricating film on the friction surface of tribosystems containing fullerene compositions, in contrast to the known, must take into account the structural viscosity and structure of the formed film under the action of the electrostatic field of the friction surface. The working hypothesis of formation of such structures is offered, where films in the field of action of electrostatic forces acquire structure of gel, and out of action of electrostatic forces - structure of sol. According to the hypothesis, a framework of "crosslinked" molecules of fullerenes and oleic acid is formed on the friction surface, which absorbs stress. In the process of sliding, under the action of stresses, the framework can collapse, and fullerene molecules make rotational movements between the friction surfaces, which leads to a decrease in viscosity (the liquid acquires non-Newtonian properties). After coming out of contact, the structure of the frame is restored under the action of electrostatic forces of the surface. It is assumed that the structural viscosity of the lubricating film is influenced by the magnitude of the electrostatic field of the friction surface, the orientation of the flocks to the friction surface and the concentration of fullerenes in the lubricating film in the field of electrostatic forces.

The dependences of the change of the parameters of the rheological model of the stress relaxation process on the actual contact spots, which confirm the working hypothesis, can be performed theoretically, based on the developed rheological model. The dependences of the change in the stress relaxation time in the structure of the lubricating film on the friction surface, as well as the magnitude of the delay time in the stress relaxation and the Deborah number [23], will confirm the working hypothesis that the lubricating film acquires the properties of an elastic solid.

When planning research, it is suggested that such physical quantities as the relaxation time of stresses in the structure of the lubricating film and the Deborah number are a measure of the transition of the viscous properties of the lubricating film into elastic and vice versa - elastic into viscous.

Physical quantity - time of delay in distribution of stresses, characterizes inertia of structure of a lubricating film and possibility of residual deformations in this structure after stress removal. The large value of the delay time characterizes the presence of delays and the presence of residual deformations in the film structure after stress relief. Factors influencing the value of the structural viscosity of the lubricating film formed on the friction surface are to be established.

These processes of the second structural level are intended to formulate criteria for evaluating the elastic or viscous properties of wear-resistant structures on friction surfaces. Such criteria may be the relaxation time of the stresses at the spots of actual contact – T_{rel}, delay time in stress relaxation – T_{del}, Debory's number - De and the thickness of the lubricating film h. These are the initial parameters from the second structural level of the study, fig. 3. These initial values have a functional relationship with the values of the concentration of fullerenes, the concentration of the solvent - vegetable oil and the tribological properties of the basic lubricant, to which are added fullerene compositions. These are the input values of the second structural level of the study of this work.

The block diagram of the third - information level of the tribosystem is given on fig. 4.

The input factors of the third information level are: stress relaxation time on the spots of actual contact – T_{rel}, delay time in stress relaxation – T_{del}, Debory's number - De and the thickness of the lubricating film h. The initial parameters are the volumetric wear rate I, m^3/hour and coefficient of friction.

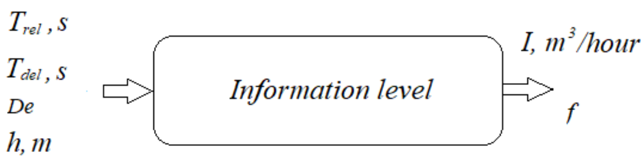

Fig. 4. Block diagram of the third information level of the tribosystem

The third level of information aims to calculate, using mathematical modeling, to determine the volumetric wear rate and friction coefficient. When performing the simulation of the initial parameters, the following assumption was made. Structures formed on friction surfaces, which have the properties of an elastic body or a viscous fluid, have a certain thickness h. The thickness of this structure depends on the magnitude of the voltage of the generated electrostatic field, which is affected by the magnitude of the rate of dissipation in the tribosystem – W_{TS}. The structures formed on the friction surfaces change the roughness of the friction surfaces. Such structures "align" the friction surface by reducing the magnitude Ra and increasing the magnitude Sm in movable and fixed triboelements. This will reduce the rate of dissipation in the tribosystem, which is determined by the formulas (2) - (12). Based on these values, a new value of the dissipation rate in the tribosystem is determined – $W_{TS(F)}$, which corresponds to the use of different concentrations of fullerene compositions in lubricants with different tribological properties, and calculates the value of the volumetric wear rate by expression [24]:

$$I = 6 \cdot 10^{-10} \exp\left(0{,}795 \cdot 10^{16} \cdot \frac{1}{E_u} \sqrt{\frac{\pi}{\left(\delta_{mov} \cdot \delta_{fix}\right)}} \cdot W_{TS(F)} \right), \text{ m}^3\text{/hour}, \tag{13}$$

where δ_{mov} and δ_{fix} – is the internal friction of the structure of materials of movable and fixed triboelements, is calculated by the expressions given in the work [25].

The coefficient of friction, which determines the friction losses in the tribosystem, is calculated by [24]:

$$f = \frac{W_{TS(F)}}{W} = \frac{W_{TS(F),mov} + W_{TS(F),fix}}{N \cdot \upsilon_{sl}}. \tag{14}$$

The third - the information level of processes in the tribosystem allows to theoretically obtain information about the effectiveness of fullerenes or fullerene compositions in lubricants. Based on the results of the research and mathematical modeling, the following practical questions can be answered:

- determine the design of tribosystems, where there is an optimal range of operation in terms of sliding speed and load, which will provide a minimum of friction losses, and the maximum percentage of their reduction compared to basic lubricants without fullerenes;

- determine the rational range of tribological properties of lubricants, the addition of which to fullerene compositions will give the maximum effect of reducing the volumetric wear rate and friction coefficient;

- to determine the influence of material compatibility in the tribosystem, which is determined by the amount of internal friction of the structure of materials of triboelements, which increases the effect of reducing the coefficient of friction from the use of fullerenes in basic lubricants.

The presented research structure demonstrates a multilevel approach within the scientific problem - the formation of surface wear-resistant structures on the friction surfaces of various structures of tribosystems in the presence of lubricants fullerene additives or fullerene compositions. This approach allows a more detailed and comprehensive study of the dynamics of processes occurring on the surface of the contact spots during friction. In particular, when solving contact problems, this allows to take into account not only the level of stresses, but also the speed of deformation in the materials of the surface layers, as well as the depth of deformation, which in the models will take into account the volume of deformed material.

In addition, the use of a multilevel approach allows you to develop models and model processes on the friction surfaces that occur, dividing them into levels within a single scientific problem, which is fundamentally important for the correct solution of dynamic problems of friction. It is shown that the application of mathematical models in the modeling of tribological processes depends on the correct choice of technical constraints that determine the range of optimal solutions. The search for optimal conditions for the use of fullerenes or fullerene compositions as additives to lubricants should be carried out under the condition of selected technical constraints arising from the operating conditions of tribosystems.

Conclusions

The system-structural approach in researches of processes of friction and wear at application of fullerene compositions in lubricants is proved. It is proposed to use a multilevel approach to study and model the processes of deformation of the surface layers of movable and immovable triboelements and the formation on energy-activated surfaces of wear-resistant structures containing fullerene molecules. The essence of the approach is to use multi-scale research methods to build mathematical models within a single research structure. Due to the fact that the tribosystem differs in the integrity of the interconnected elements that are part of it, it is assumed that all processes occur at three hierarchical levels. At this level, they interact with each other and exchange energy and matter.

Input and output flows in studies of tribosystems are formulated. It is shown that the input streams include design parameters of the tribosystem, technological parameters, operating parameters. These parameters form the flow of matter, energy and information, which is the input effect on the tribosystem. The output flow from the tribosystem are the parameters: volumetric wear rate I, dimension m^3/hour; friction losses, which are estimated by the coefficient of friction f, dimensionless quantity. The output stream is the information flow of the tribosystem. It is shown that this approach allows to study in more detail and comprehensively the dynamics of processes occurring on the surface of contact spots during friction. In particular, when solving contact problems, this allows to take into account not only the level of stresses, but also the speed of deformation in the materials of the surface layers, as well as the depth of deformation, which in the models will take into account the volume of deformed material.

Depending on the tasks and requirements for their solution, the use of different methodological approaches for modeling is justified. It is shown that the application of mathematical models in the modeling of tribological processes depends on the correct choice of technical constraints that determine the range of optimal solutions. The search for optimal conditions for the use of fullerenes or fullerene compositions as additives to lubricants should be carried out under the condition of selected technical constraints arising from the operating conditions of tribosystems.

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Кравцов А.Г. Системний аналіз процесів тертя та зношування при застосуванні фулеренових композицій в мастильних матеріалах**.**

В роботі обґрунтовано системно-структурний підхід в дослідженнях процесів тертя та зношування при застосуванні фулеренових композицій в мастильних матеріалах. Запропоновано використовувати багаторівневий підхід для дослідження і моделювання процесів деформації поверхневих шарів рухомого і нерухомого трибоелементів і формування на енергетично активованих поверхнях зносостійких структур, які містять молекули фулеренів. Суть підходу полягає в використанні різномасштабних методик дослідження до побудови математичних моделей в рамках єдиної структури досліджень. У зв'язку з тим, що трибосистеми відрізняються цілісністю взаємопов'язаних елементів, що входять до них, прийнято припущення, що всі процеси відбуваються на трьох ієрархічних рівнях. При цьому рівні взаємодіють між собою і обмінюються енергією і речовиною.

Сформульовано вхідні та вихідні потоки при дослідженнях трибосистем. Показано, що до вхідних потоків відносяться конструктивні параметри трибосистеми, технологічні параметри, експлуатаційні параметри. Перераховані параметри формують потік матерії, енергії та інформації, який є вхідним впливом на трибосистему. Вихідним потоком з трибосистеми є параметри: об'ємна швидкість зношування I, розмірність м^3/год; втрати на тертя, які оцінюються коефіцієнтом тертя f, безрозмірна величина. Вихідний потік є інформаційним потоком трибосистеми. При вирішенні контактних задач це дозволяє враховувати не тільки рівень напружень, а й швидкість поширення деформації в матеріалах поверхневих шарів, а також глибину поширення деформацій, що в моделях буде враховуватися об'ємом деформованого матеріалу.

В залежності від поставлених завдань і вимог до їх вирішення обґрунтовано застосування різних методичних підходів для моделювання. Показано, що застосування математичних моделей при моделюванні трибологічних процесів залежить від правильного вибору технічних обмежень, які визначають область існування оптимальних рішень.

Ключові слова: фулерени; розчинник фулеренів; фулеренові композиції; структура трибосистеми; швидкість роботи дисипації; електростатичне поле поверхні тертя; швидкість деформації; об'ємна швидкість зношування; коефіцієнт тертя