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EXPLORING A POSSIBILITY TO CONTROL THE STRESSED-STRAINED STATE OF CYLINDER LINERS IN DIESEL ENGINES BY THE TRIBOTECHNOLOGY OF ALIGNMENT

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Проведеними дослідженнями формування функціонального мідьвмісного поверхневого шару на деталях двигунів автомобілів триботехнологією припрацювання встановлено зниження зношування деталей підчас їх експлуатації. Виявлено, що сформоване покриття створює можливість еластичного шару який зменшує напруження в матеріалі деталей двигунів. Експериментальними дослідженнями коерцитивної сили робочих поверхонь деталей підтверджено зниження накопичення руйнуючих напружень в приповерхневих шарах матеріалу деталей. В свою чергу, порівняльний аналіз отриманих результатів коерцитиметричним методом підтверджує, що запропонована триботехнологя припрацювання приводить до зменшення напружено-деформованого стану та дає можливість підвищити зносостійкість і поліпшити технічний стан гільз циліндрів дизеля: величина коерцитивної сили знижується на 7,5 %, в той час коли напрацювання збільшується на 16 %. При цьому при більшому напрацюванні: 254,8 тис. км проти 220,5 тис. км за даними коерцитивної сили (14,2...9,1) А/см і (13,2...9,0) А/см знаходиться в практично однаковому технічному стані.

Функціональний поверхневий шар формується при впроваджені композиційної оливи в триботехнологію холодного припрацювання силового агрегату автомобіля. Запропоновано та реалізовано схему підключення електричного струму до деталей циліндропоршневої групи двигуна при дослідженні розробленої триботехнології припрацювання. Особливостями даної схеми є те, що постійний електричний струм подається наступною полярністю, плюсом, через щітково-колекторний вузол на колінчастий вал, а мінусом – через затискний контакт на блок картер.

Результати досліджень дають підстави стверджувати про можливість контролю внутрішніх напружень та подальшої величини зношування в матеріалі робочих важконавантажених деталей силових агрегатів автомобілів підчас певних їх сервісних дій. Запропонована триботехнологія припрацювання може представляти інтерес як для сервісних служб автотранспортних підприємств, так і для станцій технічного обслуговування автомобілів

Ключові слова: гільза, присадка, гліцерат міді, припрацювання, поверхневий шар, електроліт, коерцитивна сила, електрична схема, напруження, гільза циліндра

1. Introduction

At present, the reliability of systems and assemblies of cars is improved by selecting wear-resistant structural materials, by choosing oils for them, and by creating conditions for liquid lubrication of mating parts [1]. These issues are addressed by more intensive studies resulting in significant success at the design of tribomating parts. In turn, the progress of friction and wear processes during operation largely depends on the properties of a lubricating environment and the films of antifriction materials formed at the working surfaces.

In this case, the copper-containing materials are widely used for the surfaces of mating parts, operated under conditions of contact against high-temperature, abrasive-based substances. However, while possessing high electrical conductivity, as well as thermal conductivity, the parts' working surfaces have low wear-resistance [2]. In turn, high electrical conductivity of these materials leads to the rapid triboelectrication of surface layers, which induce an electric field that could affect the wear particles and additives. This effect is characterized positively during the period of working operation of additives, but at an increase in the number of wear particulate and the additives' wear a given effect manifests its negative side. Under such conditions, there occurs a faster drift of wear particles to the surface of a part, acting subsequently as abrasives, which reduce the wear resistance of working surfaces of mating parts.

One of the ways to eliminate this drawback is to create the anti-friction surface layers with high operational properties, based on steel or cast-iron, by applying the tribotechnology of alignment and restoration.

These technologies possess a significant advantage in the formation of the required set of operational characteristics and properties for the parts' surface layers. Their application makes it possible to ensure the equidistance of working surfaces of mating parts and to create conditions for the implementation of processes and states of the self-organization of materials both at friction in the initial period of work of mating parts and during the follow-up operation. The above provides for a minimum wear of mating parts, improving their durability and serviceability, which is certainly a relevant issue.

2. Literature review and problem statement

According to a general approach, all methods for improving the wear resistance of mating parts in the automobile diesel engines can be divided into three basic groups: structural, technological, and operational [1]. However, the focus should be on the relation between operational and technological groups from a tribotechnological point of view. Structural solutions aimed at increasing durability and reliability are implemented at the stage of designing the mating parts of powertrain in general. In this case, it is possible to reduce the loss of power on friction by 8...10 %, but the limitation is a complication of their assembly, an increase in fumes, the oxidation of oils, etc. [2]. In this case, it would be necessary to perform the task of selecting the technological and service operations for different assemblies during operation. The amount of wear of the working surface of mating parts is directly affected by the level of mechanical and thermal loads, the type and performance of structural tribomating parts [3]. However, the work failed to resolve the issue of control over mating parts by a tribotechnology of alignment.

Improvement of the operational properties of oils is achieved by introducing additives to them and by the formation of special films or coatings at the parts' friction surfaces [4]. However, there are no schemes to control the functional copper-containing coatings at the parts' working surfaces. By their effect on a friction surface, the following additives are categorized: surface-active; chemically-active; inactive; metal-plating and plastically-deforming additives [5], etc. However, there are no any complex of technological operations to prepare them and adjust to the tribotechnology of alignment. Under heavy operating conditions for mating parts, there may occur the self-organized tribo-alignment, allowing the adjustable wear processes and the regeneration of friction surfaces without maintenance [6]. The paper did not resolve the issue of self-organization, which would make it possible to reduce internal strains in the parts' materials. Despite the significant benefits, the additives are characterized by the following features: their action lasts at sufficient concentration; under some circumstances they may even increase the resistance to friction [7]. The optimal concentration of an additive positively affects the rheology of a lubricant material; because of the complexity of physical-chemical processes, transformations, additives do not demonstrate the versatility to materials and operating modes of tribomating parts [8]. The papers did not consider the possibility of making additives and the formation, with their help, of a copper-containing coating.

When studying the character and nature of the tribochemical processes of alignment [9], a method of electro-chemical-mechanical alignment showed a positive effect. The method implies that the region of friction is fed a special electrolyte as a lubricant, and the parts are given an electric current. As a result of mechanical and electrochemical interaction and the equidistance of surfaces of mating parts there occurs their rapid mutual alignment [10]. However, while resolving the issues on electro-chemical-mechanical alignment, the authors did not develop the scheme to connect parts with a reciprocating movement.

Application of oils with an additive during a technological run promotes the transition to the normal mechano-chemical wear of mating parts and the formation of juvenile surfaces capable to perceive operational loads [11]. However, it was necessary to solve the task on reducing internal stresses during operation. This stabilizes the technical condition, the composition, operational properties of the parts' friction surfaces and lubricating environments by their alignment [12]. The latter contributes to depositing metal ions at the worn-out surface of parts from a metallic insert isolated from the mating parts. This process predetermines the formation of new wear-resistant structures in the surface layers of tribomating parts and is a selective transfer. Accordingly, when a friction process occurs in the presence of copper glycerate one may observe a similar process of the formation of local regions with better physicochemical properties similar to the treatment with a concentrated energy flux [13]. The specified papers did not consider the mechanism of tribological activation of local regions, as well as improving their quality during operation as a technological operation.

For the tribotechnology of alignment and restoration, the most promising are the methods based on tribo-chemical reactions that proceed under conditions of mechanical activation in the system "metal composite oil" or "metal electrolyte" [14]. The main reason for the progress of such reactions is the transfer of a substance by electrically charged components. If one chooses the additives or electrolyte and activates the surface of a part exposed to an electrical field, it is possible to achieve the targeted delivery of wear-resistant components to it [15]. However, the papers did not document and consider the issues of control over reactions using a direct current and electrical diagrams of their implementation.

At present, reducing the level of wear and improving the reliability of mating parts in vehicle powertrains is achieved mainly by using the following methods:

– improving the accuracy of parts' machining for tribo-alignment [16];

– forming the roughness of surfaces, which ensures the oil-maintaining functions [17];

– forming the coatings at the working surface of tribomating parts, which reduce the friction coefficient [18];

– application of materials with high cyclic strength and damping capacity, etc. [19];

– development of surface layers with dissipating and rheologic properties [20].

The methods could be implemented when introducing the tribotechnologies of alignment and restoration of mating parts in a composite lubricant environment [21]. However, these tasks were resolved exclusively by using additives to oils without an electrical component.

For the optimal functioning of mating parts, it is necessary to create at their working surfaces a thin coating layer made from antifriction materials that would contribute to plasticizing and smoothing the micro-irregularities at friction surfaces [22]. The work did not consider the features of filling a surface layer made from copper-containing additives. This is achieved when using oils with metal-containing and metal-organic additives [23], that is, composite lubricant environments. The most commonly used among them are the metal-organic compounds of copper and molybdenum [24]. These additives demonstrate a low shear magnitude; it would be desirable to reveal the impact of these additives to the internal strains in components. A comprehensive research into the examined issue might imply investigating an analytical complex that splits the overall task into simpler research points [25]; general synthesis of data would make it possible to reveal the complete research pattern. Failure of cylinder-piston group of transport vehicles accounts for 5...25 % of the overall failure rate. An analysis of the main causes of failure shows that the main causes are: the excess load conditions; difficult conditions of operation; failure to comply with periodical technical maintenance of the system of lubrication and the use of oils defying the operating conditions [26]. However, the works did not consider the issue of change in the coercive force for a material of these mating parts and the influence of the stressed state on their performance. An important criterion for the implementation of tribotechnologies is their automation both in the production of systems and units for trucks and during their operation. One of the key fields at present is the hydro-elements that operate based on the principle of sticking a flow of the working environment. Using these elements make it possible to distribute the hydraulic flow, and redirect it to different technological operations, which is extremely important in the formation of composite motor oils [27]. However, for these elements, it would be desirable to resolve the issue on a dynamic displacement of mixtures and a possibility to control temperature.

The stressed-strained state can be also identified at friction by using various methods without disassembly, namely the methods of acoustic emission and coercive force on the working surfaces of parts [28]. The detection of such a state was performed in the regions of maximum wear, which did not make it possible to estimate the overall pattern of the examined state in a parts' material. Additional strains in mating parts are due to abrasive particles, which penetrate a tribological contact thereby forming local compression zones, which subsequently become the concentrators of stress [29]. However, the work failed to describe the modeling of these local zones. Forming these abrasive particles is possible due to clustering of wear particles and paint and varnish inclusions to a working oil, which in turn is not acceptable during operation of transportation vehicles. The formation of wear-resistant surface layers with favorable rheologic properties is carried out to reduce the internal stressed-strained state of machine parts. This is possible at a rational composition of a hydro-mixture or the composite lubricant environments [30]. First of all, one needs to discover the regularities of influence of additives from a composite oil on the working surface of components and the dissipative properties of the formed protective films. The latter, under certain conditions, can ensure a significantly lower temperature of welding in a tribological contact [31]. It would be desirable to describe the mathematical model of wear in the presence of additives to the oil.

Solving the task on improving the durability of machine parts requires a comprehensive approach and the consideration of each element in tribomating parts, which would positively affect the accuracy of defining the characteristics of parts' working surfaces. Modern power units, in order to improve their reliability, necessitate studying the formation of surface layers that contain copper at parts' working surfaces in the implementation of tribological alignment. There are almost no research into the dynamics of forming the coatings and the set of operational properties in the alignment process of different types of mating parts in composite lubricant environments.

3. The aim and objectives of the study

The aim of this study is to reduce the stressed state of parts in diesel engine vehicles during operation, based on a comprehensive study of the technology of tribological alignment of mating parts with the formation of functional copper-containing surface layers on cylinder liners.

To accomplish the aim, the following tasks have been set:

– to reveal the mechanism of formation of a copper-containing anti-friction coating based on the tribological processes and to theoretically substantiate a possibility of applying the tribological alignment of resource-defining mating parts in diesel cars;

– to identify the basic patterns in the process of the stressed state of the examined parts at tribotechnical alignment and to establish the analytical dependences of influence of its parameters on the resource of the examined mating parts;

– to theoretically and experimentally substantiate the effect of alignment parameters on the characteristics of working surfaces of parts in a cylinder-piston group and their stressed-strained state.

4. Materials and methods for the formation and studying the state of working oils and the surfaces of cylinder liners in truck engines

We modeled patterns in the stressed-strained state of junction between a cylinder liner and a piston ring and the cylinder liner's working surface using the method of finite elements. Applying a personal computer, we determined the most stressed local regions at the cylinders liners' friction surfaces, which are most exposed to wear, in order to further define the regions and control points of our study.

The field of stresses and strains was estimated by using the software suite COSMOSWorks integrated in the CAD-system SolidWorks 2011. In this case, at the first phase, we built a model of the cylinder liner, the piston ring, or their mating, in the CAD-system SolidWorks considering their geometric parameters. To analyze the constructed model, we enabled the module COSMOSWorks (Manager). B using a toolbar, we chose the window Study, in which we assigned the type of analysis, Static Type, and the type of finite elements, Mesh Type. We used the COSMOSWorks Manager to assign a material for a part or mating (menu Apply/Edit Material). Note that COSMOSWorks has a library of materials and their properties, which can be edited in the absence of information about the examined material by using the panel Material. Next, the COSMOSWorks Manager was used to assign boundary conditions – Restraints, we chose the surfaces of displacement, which, under conditions of tasks, were limited along the predefined directions. The loads that were distributed over the examined surfaces were similar to those observed during operation of CPG parts; we used the panel Pressure with relevant options.

After checking the settings on analysis, we used the method of finite elements to build a grid employing the panel Mesh, which assigns the necessary parameters and defines the size of the finite elements. Next, from a shortcut menu denoted by the icon Static Analysis – Pressure, we ran the calculation procedure by the command Run. In this case, the Manager displays folders Stress, Displacement, Strain, Deformation, Design Check, which show the results from calculations of relevant quantities and their visual representation. In the loaded parts, we highlighted characteristic regions with different magnitudes of strains. This is denoted by the color of regions. The amount of stress was estimated based on a predefined scale.

To implement the processes to improve the working surfaces of cylinder liners and piston rings by forming the antifriction copper-containing coatings for tribotechnical alignment, in this paper we used the oil composition containing the additive copper glycerate $Cu_3(C_3H_5O_3)_2$ in the amount of 3.5...4.0 % in the base oil M–10G$_2$. The choice of glycerin as the solvent to copper glycerate is due to the fact that it has high stability in lubricant compositions, and, during their storage, it enables obtaining stable and inexpensive composite oils for the implementation of a tribotechnology of alignment of mating parts in diesel engines. In addition, the choice of glycerin as the solvent is explained primarily by the fact that it has good lubricating properties and the capacity ability to reduce metals from their oxides.

Preparation of the lubricating composition implies the following. Dehydrated glycerin, heated to a temperature of 391...395 K, was supplemented with anhydrous copper acetate (II) in the amount of 7...8 % relative to the volume of glycerin; this process was accompanied by a moderate agitation. The specified temperature is the boiling point of acetic acid [31]. Duration of boiling is 2 hours. Preparation takes place in a thermoreactor. Cooling is carried out together with the reactor, within 1 hour, from 393 K to 293 K, in line with a linear law at a rate of 1.67 K/min, until the temperature decreases to room temperature. The obtained additive to the base oil M–10G$_2$ was kept in a glass or porcelain container at a temperature of 293 K.

Quality of the composite oil and its impact on the anti-wear and anti-chip properties of the working surfaces of mating parts in diesel engines based on the tests carried out at a specialized laboratory using the four-ball friction machine (FBM). The testing and determining the characteristics for oil mediums at FBM were carried out according to the identical standards GOST 9490-75, in Germany DIN 51350, in the United States ASTM D2783. To implement the methods of tribological alignment, during bench tests, we proposed a circuit to connect electric current to the parts in a cylinder-piston group of diesel engines at a single-cylinder installation (Fig. 1).

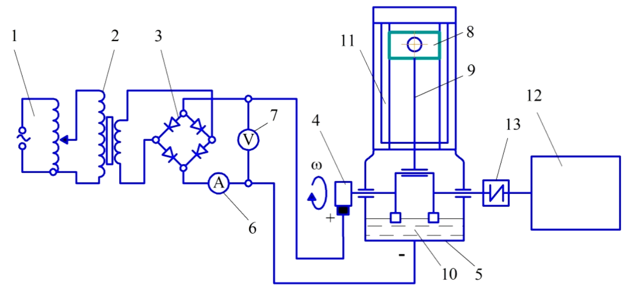


Fig. 1. Circuit to connect electric current to the parts in a cylinder-piston group of diesel engines at a single-cylinder installation: 1 — current source; 2 — resistance to control the magnitude of current; 3 — current rectifier; 4 — brush-collector node; 5 — carter for oil; 6 — ammeter; 7 — voltmeter; 8 — piston; 9 — connecting rod; 10 — lubricating environment; 11 — diesel cylinder liner; 12 — electric motor; 13 — clutch

We fed electric current of magnitude I=10 A and voltage U=1.2 V from the rectifier to the brush-collector node "plus", located at one end of the crankshaft, and "minus" – to the crankcase of a single cylinder installation. Rotation frequency of the installation's crankshaft was n=200 rpm.

We determined the degree of filling γ the surface of friction with a clad copper layer based on the results from a metallographic analysis of the surface using digital imaging techniques from the software Photoshop. To do this, we opened a file menu and selected the direction, which saved the recorded image of the friction surface in a monochrome format to reduce the error in determining the filling. Next, using the option "Magic tool", we highlighted the required fragments of the surface regions covered with copper. Next, we segmented brightness by using a quantization method of histograms' modes and chose the range of tones at the level 119...255. In accordance with the set task, we acquired a characteristic of the tone interval corresponding to the coating with copper, depicted in a monochrome mode.

The amount of wear of in diesel cylinder liners was determined by micrometry. The measurement procedure implied conducting measurements in planes at 45° and at not less than 8 points of measurements along the generatrix with a mandatory measurement in the middle position of the first piston ring. Measuring was performed at the position of the piston in the upper dead point and in the middle position of the last piston ring, the piston being at the bottom dead center.

We determined the stressed-strained state of a parts' material by a coercimetric method. We investigated the state of the friction surface of mating samples and components by experimentally determining the coercive force H_C in the local regions of their surfaces. Measurements were carried out in the region limited by a potentiometer's ferroprobe using the coercimeter KRM-C (Fig. 2).

The device's principle of operation implies magnetizing a local section at a part's surface followed by demagnetizing with an ascending field, registering the field's intensity that corresponds to the coercive force of a material, and measuring the amplitude of a signal from the ferroprobe. The device makes it possible to monitor the quality of the surface before and after the alignment, as well as a change in the physical-chemical and structural properties. If all the factors that define the state of a part's surface, except one, are fixed, then, within a single structure, the coercimeter makes it possible to detect anomalies associated with the state of mating parts.

Fig. 2. General view of coercimeter KRM-C (Russia)

The data from measurements of H_C are used to determine changes in the states of wear and the stressed-strained states of working surfaces of diesel cylinder liners. H_C was measured at selected local sections in accordance with GOST 30415-96:

– we applied the ferroprobes to the examined section;

– we supplied current from the control unit for inducing a local magnetic field in the material, compensated for by an ascending magnetic field of opposite direction;

– the registered value for the intensity of the compensated magnetic field (coercive force) was displayed by the device;

– we measured the surfaces of samples and parts in the selected directions at a certain step.

Using a PC, employing a database on experimental data, we built the distributions of values for H_C and their relation to basic load parameters: H_{C0} – starting (unloaded) state H_{Cp} – state that matches the physical limit of a material's yield σ_p; H_{Cs} – state that corresponds to the limit of its strength δ_s. Depending on requirements, we established the critical magnitude for coercive H_{Ccr}, which corresponds to the permissible magnitude for stress tension when calculating the strength σ_s of the surface layers of mating parts at tribo-alignment. Since H_C is defined by the vector sum of current stresses, the analysis of the stressed-strained state took into consideration not only its absolute magnitude but the direction relative to the location of magnetic force lines at measurement points.

Based on the measurements of H_C at the working surfaces of mating parts at tribo-alignment, and using the software MS Excel, we built the cartograms of coercive force distribution. In this case, the shades of coloring the regions of a cartogram correspond to different ranges of values for coercive force H_C, characteristic of the different states of a material according to the magnitude of residual stresses.

5. Results of research into the state of parts in a cylinder-piston group during the formation of surface layers by the tribotechnology of alignment in the environment of a composite oil

It is possible to describe the mechanism of emergence and formation of the stressed-strained on the basis of its simulation using the software suite COSMOSWorks integrated in the CAD-system SolidWorks 2011.

Results from simulation of strains in the mating parts "cylinder liner – piston ring" are shown in Fig. 3.

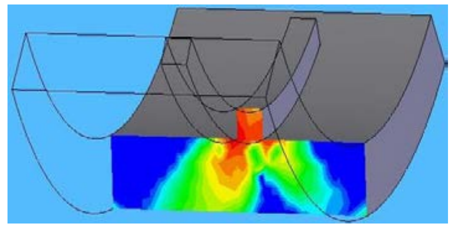


Fig. 3. Characteristic strain field distributions in the cross-section of mating samples "cylinder liner – piston ring": red color – maximum strains in the part; dark blue color denotes the minimum strains in the part

The strain distribution over the working surface of a cylinder liner (GCI-18) after the simulation is shown in Fig. 4.

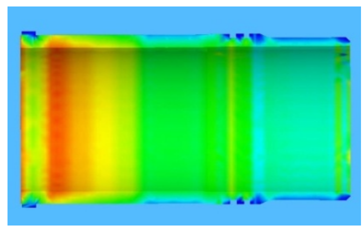


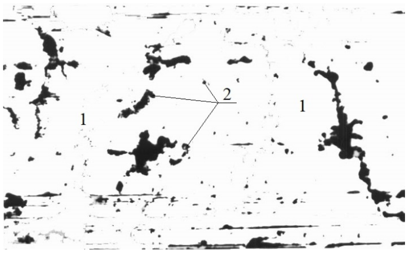
Fig. 4. Characteristic strain field distributions along t he working surfaces of a cylinder liner: red color – maximum strains in the part; dark blue denotes the minimum strains in the part

The results of the formation of a functional layer using a technology of tribological alignment of a cylinder liner. The degree of filling the copper-containing layer at the working surface of a cylinder liner by using a tribotechnology of alignment in the environment of a composite oil was determined using the processing of monochrome microphotographs of the examined surfaces in the software Photoshop (Fig. 5).

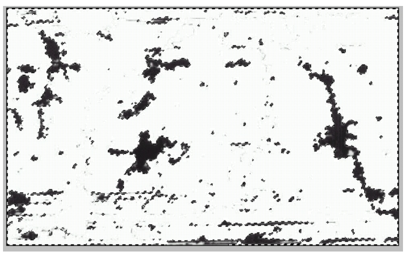
Results from studying the sample's' surface based on the segmentation for brightness using a mode quantization method are shown as histograms of tonal intervals (Fig. 6).

One can see that for a given case the degree of filling the friction surface with copper for the examined sample of a cylinder liner, Fig. 6, is γ_p=92.27 %, or 296,763 pixels; in Fig. 6, *b*, γ=7.70 %, or 24,756 pixels. Pixel analysis of microphotographs in the software Photoshop testifies to the formation of, and filling a large part of the friction surface with, a copper-containing film; the maximum possible degree of coverage equals 100 %, and the number of pixels is 312,618. For a better processing of visual data, in the form of microphotographs of the samples' surfaces, it was decided to initially reduce the number of colors; the images were taken under a monochrome mode. And, to reduce the overlapping of transition zones between the coating and the base, we applied for a monochrome image a more sophisticated technique of pixel analysis in the software Photoshop.

The visual representation of results in the change of the mean wear along the generatrix and the diameter of cylinder liners in the assembly KAMAZ-740 with and without the implementation of tribotechnology of alignment at different operating duration is shown in Fig. 7. The obtained patterns make it possible to perform a preliminary comparative assessment of matching the parts' wear against the emergence of the stressed-strained state in them.



a

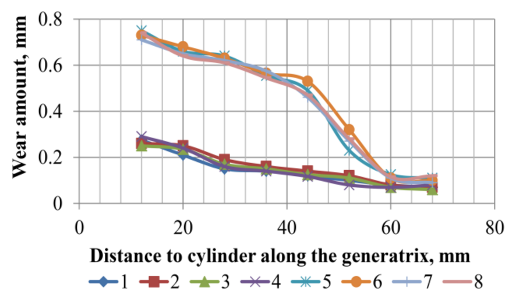


b

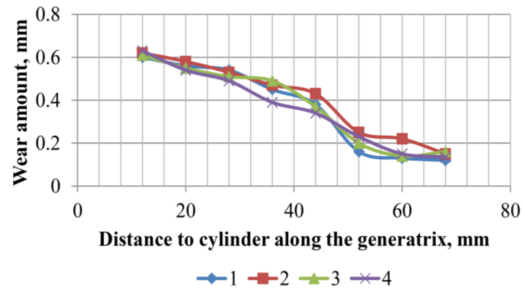
Fig. 5. Microphotograph of the friction surface friction plated with copper as a result of alignment of mating samples and parts in a composite lubricant environment exposed to a direct electric current (I=2.0 A, U=1.2 V, P=8 MPa, Δ=4 %, n=35 s^{-1}, t=45 min): *a* — monochrome photograph: 1 — region of copper coating; 2 — region of the base material of a part; *b* — highlighted regions of fragments over it in the software Photoshop (×500)

It is possible to estimate the actual stressed-strained state of a cylinder liner based on a change in coercive force at different height from the upper plane of a part. Change in the stressed-strained state varies depending on the execution of tribotechnology of parts' alignment. The results from constructing the histograms of state of cylinders liners at a different height from the upper plane, based on the magnitude for a coercive force, are shown in Fig. 8.

The above cartograms show a decrease in the coercive force on the cylinders liners that were exposed to tribological alignment, testifying to the positive effect of a given technology. By analyzing the cartograms, one can also argue that the use of tribotechnology of alignment makes it possible to reduce the stressed-strained state of the working surface of a cylinder liner and to prolong the operational duration of using this part.

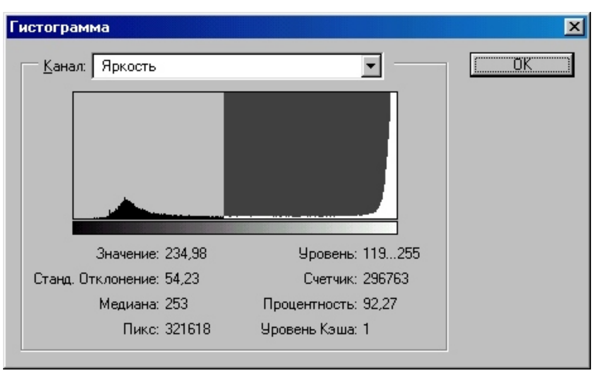


a

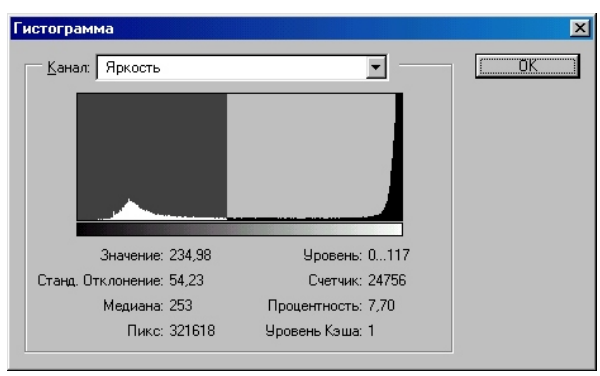


b

Fig. 7. Distribution of the mean wear along the generatrix and the diameter of cylinder liner in the assembly KAMAZ-740: *a* — operating duration: 112 thousand km (curves 1—4), 220.5 thousand km (curves 5—8), curves 1, 5 are in the plane parallel to the axis of the crankshaft (base plane), 0°; curves 2, 6, with a deviation from the base plane, clockwise, top view at 45°; curves 3, 7, with a deviation from the base plane, clockwise, top view at 90°; curves 4, 8, with a deviation from the base plane, clockwise, top view at 135°; *b* — operating duration: 254.8 thousand km (motor oil is added c_V=4 % of the copper glycerate additive): 1 — parallel to the axis of the crankshaft, 0°; 2 — with a deviation at 45°; 3 — with a deviation at 90°; 4 — with a deviation at 135°



a



b

Fig. 6. Part of the complete spectrum of a histogram's modes, which corresponds to the region of the friction surface, plated with copper at tribotechnology of alignment: *a* — in the environment of a composite oil with a 4 % content of copper glycerate; *b* — base oil without additives

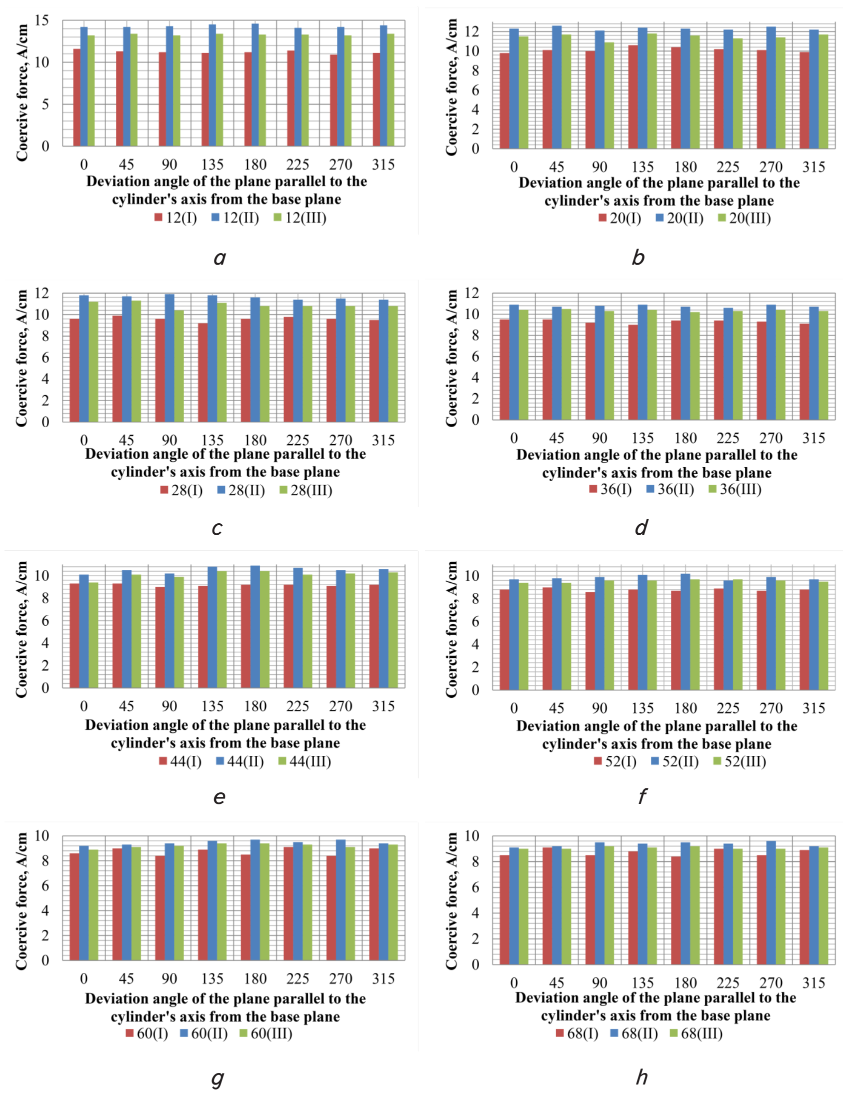


Fig. 8. Mean values for coercive force at the working surface of a cylinder liner in the diesel engine KAMAZ-740 along the generatrix at a distance from the upper plane: *a* – 12 mm; *b* – 20 mm; *c* – 28 mm; *d* – 36 mm; *e* – 44 mm; *f* – 52 mm; *g* – 60 mm; *h* – 68 mm; at operating duration: 112 thousand km (I); 220.5 thousand km (II); 254.8 thousand km (III) at the implementation of the proposed tribotechnology of alignment of working surfaces

acter of the local process of wear, the distribution of temperature field, and the moments of friction (Fig. 3, 4).

Patterns of distribution of the stressed state in cylinders loners (Fig. 4) demonstrate its uneven character: the most stressed is the region of the upper dead point, the region of the upper compression ring. This region wears out to the largest degree, which is why the stressed-strained state of a material is directly related to the wear of parts made from it.

The mechanism of forming an anti-friction protective coating on the materials for tribomating parts in the process of implementation of the proposed tribotechnology of alignment in a composite lubricant environment with a 4 % content of copper glycerate shall be considered from a tribophysical point of view. In this case, we consider the process of friction to be a totality of a large amount of mechanical interaction between the micro-irregularities of mated parts' surfaces. Under such conditions, the equilibrium state of surface layers is disrupted, which corresponds to the minimum potential energy at a deformed zone. The accumulation of energy of elastic deformations at the surface layers of components change their state, mechanical properties and thermal-physical characteristics of their materials. Given the insignificant volumes of surface layers, a value for the accumulated energy can prove to be critical with the surface layers of a parts' material entering a special, over-excited state. This state is unstable and rapidly relaxed, entering the original state. In this case, there is a stagewise formation of reactant compounds that have the radical, ionic-radical, or ionic structure.

6. Discussion of results of forming a functional copper-containing surface layer of cylinders liners at their tribological alignment

The results from modeling a field of strains at mating parts "cylinder liner – piston ring" indicate the necessity to form, on working surfaces, the functional coatings maximally filled with an anti-friction material lengthwise 12–68 mm along the generatrix of a cylinder liner.

The local character of wear in mating samples and parts of an engine is confirmed by studying the fields of strains in Fig. 4, modeling and analysis of which were carried out using the method of finite elements in the software suite COSMOSWorks, integrated in the CAD-system SolidWorks. Attention should be paid tos the distribution of stresses with a developed boundary effect, which, in proportion to the combined use of a tribotechnology of alignment in the composite oil, gradually fades. The above reflects the char-

The specified processes are accompanied by the emission of electrons from the surface friction into a composite oil. The electrons that hit the oil's molecules and the atoms from the additives' substances excite them. This leads to the ionic disintegration of structure of the additive's substances molecules, which triggers the mechanism that forms, on friction surfaces, the anti-friction coatings from the products of tribo-chemical reactions.

The intensity of the process of forming the antifriction coatings on the surface of friction depends on density of the uncompensated bonds in its local regions. The composition of the copper glycerate additive predetermines the process of finding active regions at the surfaces of parts and forming, on them, a protective copper-containing coating that is chemically stable, has high ion-exchange properties and is enough inert relative to chemically aggressive substances. The pores that are present in the created coating are the regions with an abnormally high activity of absorption and can effectively retain oil, thereby changing the modes of friction during operation. In addition, the presence of metals' ions in a composite oil promotes the binding of hydroxyl groups and oxygen, leading to the dissolution of the surface of a protective film and the implementation of gradient of its properties. Under a coating, there forms a surface layer oversaturated with dislocations, which leads to the formation of layers with a superlow resistance to the shear deformation. In turn, the specified layers in the collective interaction with the structure of an anti-friction film possess an abnormally high adsorbing capacity. These films create at the surface of friction favorable conditions for the development of extremely low levels of friction factor, the intensity of wear, and the implementation of certain processes and states of self-organization.

In terms of tribophysics, the mated parts can be considered to be electrical conductors insulated by a layer of dielectric from each other, that is, by a composite oil. At parts' tribo-alignment, the following electric phenomena occur:

– triboelectrication of surface layers of parts as a result of the contact interaction and an increase in the contact regions at friction;

– local accumulation of charges at surfaces due to their redistribution and the formation of double electric layers;

– the emergence of potentials' difference at motion of particles from an additive along narrow gaps of mated parts and their settling at a friction surface, etc.

These electrical processes are observed in the surface layers of a parts' material with the changes occurring in this case covering the volume of a layer of protective secondary structures. Electro-erosive destruction of the latter reinforces the exoelectron emission, and there is an additional influx of electrons from the surfaces of parts to the layer of a lubricating composition. This ensures the decomposition of its structure into ions (additional mass transfer) and creates favorable conditions for the formation of a new protective friction surface of parts. Mutual influence of the components from an additive predetermines, on the local regions of adhesion, the creation of galvanic pairs and a barrier to inhibit a hydrogen wear.

An analysis of the acquired data on the wear of a working surface of cylinders liners in diesel engines allows us to argue that the diameters of diesel cylinder liners operated over 112 thousand km (Fig. 7, *a*, curves 1–4) do not exceed the boundary or repair sizes, so the liners may execute their functions. The largest wear is observed in the region of a first compression ring. Further, along the generatrix, the wear of a liner exponentially decreases. Wear along the corner tiles around cylinder substantially no different. The wear of cylinders liners operated over 220.5 thousand km (Fig. 7, *a*, curves 5–8) is comparable to the maximally permissible magnitudes, so the liners need preventive and repair measures to bring their parameters back to the values for a workable condition. The intensity of wear of the cylinder liners at operating duration of 112 thousand km was $2.5\cdot10^{-6}$ mm/km, and at 220.5 thousand km – it increases by 1.36 times and amounts to $3.4\cdot10^{-6}$ mm/km. For the case illustrated in Fig. 7, *b*, curves 1–4, at operating duration of 254,800 km the intensity of wear is $2.4\cdot10^{-6}$ mm/km, there is a pattern of the distribution of wear along the generatrix, which testifies to an increase in the wear of cylinder lines at combined modification of the motor oil with a 4 % additive of copper glycerate and the implementation of the proposed tribotechnology of alignment and to an increase in the resource of cylinder lines by 16 %.

Consider from a theoretical point of view a change in the wear state of the tribo-alignment "cylinder liner – piston ring" when operated using the base and composite motor oil. At operating duration *L*, the wear of tribo-aligned parts is equal to:

$$u(L) = u_b(L) - u_k(L), \tag{1}$$

where $u_b(L)$, $u_k(L)$ is the wear of tribo-aligned parts for the base and composite oils.

Use the form of a function relating the wear of parts to operating duration:

$$u = K_p \cdot L^{\alpha_{I_u}}, \tag{2}$$

where K_p is a coefficient that depends on the mode of operation of the mated parts; α_{I_u} is the indicator of change in the intensity of its wear. In this case, the rate of wear is equal to:

$$du(L)/dL = \alpha_I \cdot K_p L^{\alpha_{I_u}-1} - K_p m(L), \tag{3}$$

where the first term describes the rate of wear of parts for the base motor oil, and the second – when adding the additive. In this case, a change in mass of the additive with oil at operating duration is:

$$m(L) = m_0 \exp((-I_u / V_M \rho_M) \cdot L), \tag{4}$$

where m_0 is the initial mass of the additive; V_M is the volume of a lubricant material; ρ_M is the density of an anti-friction material; I_u is the intensity of wear of parts. Considering (4) in equation (3), we obtain:

$$u(L) = \int_0^t \alpha_I K_p L^{\alpha_{I_u}-1} \mathrm{d}L - \int_0^t K_p m_0 \exp\left(-\frac{I_u}{V_M \rho_M} L\right) \mathrm{d}L =$$
$$= K_p L^{\alpha_{I_u}} - \frac{K_p m_0 \rho_M V_M}{I_u} \exp\left(-\frac{I_u}{V_M \rho_M} L\right). \tag{5}$$

The resulting expression is a mathematical model of wear of parts in diesel engines of trucking equipment when using active additives to motor oils. It indicates that the wear of parts increases due to changes in the characteristics and properties of motor oils and the periodic formation of a coating made from an anti-friction metal (copper) on their working surfaces.

Our micrometry of cylinder lines when determining wear has made it possible to assess the adequacy of results from using a coercimetric method in the determining of the stressed-strained state of parts in a cylinder-piston group. By analyzing the region for measuring a coercive force (Fig. 8), we revealed the evenly distributed values for H_c along the angular distribution; an increase in the distance from the upper plane of the liner leads to a decrease in coercive force. The represented histograms for the coercive force of working surfaces of cylinder liners make it possible to obtain an objective pattern of their stressed-strained state, and, therefore, the prerequisites for change in resource characteristics. The distribution of values for H_c along the generatrix testifies to their characteristic changes when measured in each sector and at different operating duration of the assembly, it is shown in Fig. 8.

The tendency in the distribution of coercive force (Fig. 8) is similar to the results from measurements of wear at certain points of a cylinder liner (Fig. 7). A significant convergence of the results (exceeding 90 % probability) from micrometry and a coercimetric method make it possible to reasonably predict the resource of cylinder liners and other components of diesel engines.

The results obtained suggest that even a larger operating duration: 254.8 thousand km vs. 220.5 thousand km based on the values for coercive force (14.2...9.1) A/cm and (13.2...9.0) A/cm, it is almost in the same technical condition. A comparative analysis of reported results allows us to argue that the implementation of the proposed tribotechnology of alignment in a composite oil of copper glycerate leads to the improvement in the technical condition of cylinder liners: the magnitude of coercive force reduces by 7.5 % while the operating duration increases by 16 %.

Based on the magnitude for coercive force H_C for cast iron GCI-18, we established the state of the local region for measuring a material of a cylinder liner compared to its initial state with the unloaded material $H_{C0}\approx(6.5...6.9)$ A/cm. It was determined that at $H_{Ci}\approx1.2...1.5H_{C0}$ one observes an elastic region; $H_{Ci}\approx1.5...1.6H_{C0}$ is the region of plastic deformations; $H_{Ci}\approx1.6...1.7H_{C0}$ is the elastic-plastic region; $H_{Ci}\approx1.7...1.9H_{C0}$ is the transition from a zone of plastic deformation to the zone of destruction. Of the greatest risk are the sections at the surface of a part at which H_{Ci} approached $H_{Cs}\approx(17.6...18.1)$ A/cm (coercive force for the limit of strength of a material) or $H_{Ci}>H_{Cp}\approx(15.3...15.7)$ A/cm (coercive force for the yield strength of a material). Under the specified condition, the surface layers of a material of a cylinder liner enter the plastic state, followed by strengthening, which could lead to corrosion-fatigue cracks.

In addition, it was established that a change in magnitude H_C due to load at points of maximum stresses makes it possible to define the modes under which diesel engines operated: reliable operation – $H_C\leq H_{Cp}\approx(7.6...15.1)$ A/cm; controlled operation – $H_{Cp}\leq H_C\approx(15.3...17.5)$ A/cm$<H_{Cs}$; critical mode of operation – $H_C=H_{Cs}\leq H_{CK}\approx(17.6...17.8)$ A/cm.

7. Conclusions

1. Using a finite element method, we have investigated the stressed-strained state of part in a diesel cylinder liner. It was established that the distribution of a stress field corresponds to the distribution of the mean wear along the generatrix and the diameter of cylinder liners in the powertrain KamAZ at different operating duration. It is shown that the coercimetric method makes it possible to obtain objective pattern of the stressed-strained state of cylinder liners by building a histogram of distributions of coercive force along their generatrix and the cross section. It was found that an important magnitude along the generatrix of the examined cylinder liners is within 12...68 mm along the generatrix from the upper plane.

2. It was established that the intensity of wear of cylinder liners at operating duration of 112 thousand km is $2.5\cdot10^{-6}$ mm/km; at 220.5 thousand km, it increases by 1.36 times and equals $3.4\cdot10^{-6}$ mm/km; following the implementation of tribotechnology of alignment, at operating duration of 254.8 thousand km the intensity of wear is $2.4\cdot10^{-6}$ mm/km. This shows the improved wear resistance of cylinder liners for the case of a combined modification of a motor oil with a 4 % copper glycerate additive and the implementation of the proposed tribotechnology of alignment, as well as the increased resource of cylinder liners by 16 %.

3. We have theoretically substantiated the dynamics of change in the wear resistance of the part consisting of a diesel cylinder liner when implementing the proposed tribotechnology of alignment, taking into consideration the character of additive wear. A refined mathematical model has been constructed for the wear of parts in the diesel engines when applying active additives to motor oils, which subsequently could be used for the theoretical estimation of their residual resource.

4. A comparative analysis of the results obtained from applying a coercimetric method confirms that the proposed tribotechnology of alignment leads to a decrease in the stressed-strained state. That enhances the wear resistance and improves the technical condition of diesel cylinder liners: the magnitude of coercive force reduces by 7.5 % while the operating duration increases by 16 %. In this case, at longer operating duration: 254.8 thousand km vs. 220.5 thousand km based on data on coercive force (14.2...9.1) A/cm (13.2...9.0) A/cm, it is in almost the same technical condition.

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