Assessment of the influence of the surface modification process on the wear intensity in the operation of internal combustion engines loaded parts

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Abstract. The regularities of the influence of material surface layer parameters on the wear resistance of the rubbing surface of machines and equipment engine parts during operation are considered. The methods of wear intensity assessment for choosing the best constructive solutions of the aggregates and the optimal surface treatment of friction parts are proposed. The results of electromechanical treatment of friction surfaces of steel parts with the preliminary application of a thin antifriction layer of various solid lubricants on the surface of the workpiece, which improves the structure of the surface layer and increase performance, especially wear resistance and antifriction properties are shown.

In the process of operation in machines and equipment continuously processes occur, which not only reduce their performance but also lead to their failure. For internal combustion engines of multi-purpose tracked and wheeled vehicles the most common failure occurs due to wear of friction parts. The normal operation of the unit is characterized by the minimum wear intensity of the material [1, 2] and simultaneous formation of equilibrium geometric [3, 4] and physical and mechanical parameters of the machine parts surface layer [5-8].

The calculations of friction units for wear made at the design stage allow to choose the optimal unit design, to regulate operation modes, to predict the resource and technical condition [4, 5].

Existing calculation methods of wear intensity for machine parts differ. Some use wear intensity calculations on the specified parameters of the surface layer characteristics. In the other the wear intensity is determined for the specified processing modes, which do not always provide the equilibrium characteristics of the surface layer of machine parts required for normal unit operation. Therefore, the actual problem is the development of assessing methods for the wear intensity of friction parts, linking the technological conditions of machining, especially finishing operations and surface layer hardening technology, with the resulting equilibrium parameters of the characteristics of the surface layer of machine parts.

Along with the roughness in the burnishing process other characteristics of the friction surface: macro-deflection, waviness and physical and mechanical properties undergo changes. It is established that the equilibrium roughness arising in the friction contact zone at a constant mode of friction after completion of the burnishing process will depend on a number of factors: mechanical properties of surfaces, lubrication, the tribo-part operational conditions, configuration of conjugated surfaces, etc.
At the same time, the processes of changing the macro-slope, waviness, roughness and physical and mechanical properties of friction surfaces during the run-in period will be interrelated. The reduction of macro-inclination and waviness will lead to an increase in the nominal and contour contact areas, the number of contacting micro-irregularities and a gradual transition of contact plastic deformations to elastic ones, that is, to a change in the physical and mechanical properties of friction surfaces. Also, the value of the equilibrium roughness formed will depend on the other parameters of the friction surface, in particular on the macro-slope, waviness and physical and mechanical properties.

As a result of running-in of mating machine parts, the surface of the part comes to such a physical state and such a structure, in which the surface layer has a minimum potential energy, that is, it represents a stable system that allows minimal energy dissipation under these conditions. Thus formed geometric (roughness) and physical-mechanical (microhardness) quality parameters of the surface layer are characteristic of the equilibrium.

Interaction between friction surfaces of machine parts, during the burnishing period results in the formation of new surfaces, and the released energy of the $\gamma_{\text{af}}$ is [4, 9] equal to:

$$\gamma_{\text{af}} = f\left(F, R_z, HV\right),$$

where $F$ is the normal interaction force of the friction pair elements; $R_z$ is the height of the profile irregularities of the surface under study; $HV$ is the microhardness of the surface layer of the part under study by Vickers [4].

In accordance with the first law of thermodynamics, the work of the friction force $W_{TR}$ considering the specifics of the formation of the friction surfaces equilibrium state is [9]:

$$W_{mp.} = f\left(\mu, F, S_m, V_{sc}, R_{z_{\text{prav}}}, VH_{\text{prav}}, HV_0, \alpha_0, G\right),$$

where $\mu$ is the coefficient of friction; $F$ is the normal interaction force of the friction pair elements; $S_m$ – friction path; $V_{sc}$ – volume of worn material; $R_{z_{\text{prav}}}$ - the equilibrium roughness of the mating surfaces of the components; $HV_{\text{prav}}$ – equilibrium microhardness of the surface layer of the investigated part according to Vickers [4] at a certain depth; $HV_0$ – microhardness of the non-deformed material; $\alpha_0$ – parameter of the inter-dislocation interaction; $G$ – shear modulus of the studied material.

Due to continuously increasing quality requirements we face the need to ensure the reliability of machines. It is largely determined by the individual parts performance properties. The operational properties of machine parts depend significantly on the quality of the surface layer, determined by the geometric (macro-deviations, roughness) and physical and mechanical (microhardness, structure, residual stresses) characteristics. All these parameters depend on the technology of manufacturing parts. Often traditional methods of processing do not allow to obtain the necessary parameters of surface quality. Analysis of technological methods of surface treatment of machine parts showed [2, 4, 6-8, 10-17] that there are no universal methods. Each one has its own specific area of rational application, often quite narrow.

As it is known, the wear resistance of parts forming friction units depends primarily on the final (finishing [3, 5]) technological processing of the parts surfaces [10, 11]. There are extensive experimental studies on the effect of friction surface roughness on the parts wear intensity. It is established that the finishing affects not only the initial (running-in) wear and tear, but wear and the steady-state, i.e. the initial break-in period can affect the wear rate during long-term machinery operation.

In recent years, new technological methods of finishing allowing to reduce parts wearing and to improve the antifriction properties of the joint have been developed (to improve the lubrication of parts, reduce the coefficient of friction). This includes various vibration methods of processing, honing, diamond smoothing and others. For example, honing can provide the required surface roughness and a certain protrusions orientation which contributes to the lubricant retaining on the
work surface. However, the treated surface is more or less saturated with abrasive from the hone bars, which, despite the subsequent activities, remain on the working surface and in hard-to-reach places. During the subsequent operation, these particles fall into the lubricant, which leads to increased wear of the tribosystem parts. In this regard, there is a need for a method of final processing of parts, which excludes abrasive surface treatment.

Thus, to improve the anti-friction properties of surfaces in mechanical engineering and repair production, finishing antifriction-free treatment (FAAT) is widely used. The part friction surface is covered with a thin layer (1...2 μm) of copper or its alloys by using the phenomenon of metal transfer during friction [4]. FAAT gives high antifriction properties to steel or cast iron surfaces. This method improves the tribological performance through filling the cavities, the mouths of microcracks and cavities with asperities filler material. However, with this method of processing, the structure of the surface layer does not change and the wear resistance of the surface increases only partially.

Good results showed preliminary application of a thin antifriction layer of various solid lubricants on the surface of steel and cast iron parts followed by electromechanical treatment.

Electromechanical processing (EMP) [6–7, 9–17] is a special method of contact surface treatment by a highly concentrated source of electrical energy. It combines in a single technological scheme the power and thermal effect of the tool on the part which allows creating the unique properties of the surface layer of the parts. The main features of various types of EMP are the presence of several sources of heat (the main ones are electric current and friction), local heating of the processing zone, accompanied by the action of significant pressures, a short thermal processing cycle, a sufficiently high cooling rate, as well as the influence of other technological factors. Pre-application of a thin antifriction layer of various solid lubricants to the surface of the machined parts before the EMP allows you to change the structure of the surface layer, improve its wear resistance, performance and especially antifriction properties [2, 7, 8, 10]. This method of treatment can be called antifriction Electromechanical treatment (AFEMT).

Layered substance (such as graphite, dichalcogenides of refractory metals (molybdenum, tungsten, niobium), hexagonal boron nitride, etc.), anti-friction coatings formed on the working surfaces as a result of chemical reactions (sulfides, phosphates, high temperature thermal-chemical coatings based on molybdenum (demolay) and niobium), soft metals and their oxides (copper and its alloys, lead, babbitt, etc.), polymeric materials and others can be used as solid lubricants at AFEMT. In the case of antifriction coatings formed on the working surfaces as a result of the chemical reaction of polymeric materials and some other solid lubricants, it is necessary to ensure the temperature resistance of the applied material in the process of Electromechanical smoothing and eliminate the formation of secondary abrasive in the surface layer.

Solid lubricants can be applied to the surfaces to be treated in the following ways: by rubbing the surface, applying from the suspension in a mixture with a surface active substance (SAS), by gas-plasma spraying, gas-dynamic spraying, spraying with an ultrasonic tool, coating the surface with and without a binder, supplying a jet of liquid or gas, magnetic method, galvanic method, friction surfacing, vacuum deposition, thermal decomposition of vapors of organometallic compounds, rotaprin method, etc. [7]. At the same time, in order to ensure the quality of the solid lubricant pre-application to the part surface, one can be pre-treated to the required roughness or previously performed machining operations can take into account the subsequent application of anti-friction material by one of the above methods, providing the necessary roughness and hardness step-by-step (Figure 1).

On a surface with initial roughness (Figure 1, a), obtained in the previous stages of machining, which can be made dependent on the applied solid lubricant and its application technology, for example, forced friction on the surface of the part [10]. A surface consisting of the base material 1 and the antifriction layer 2, the particles of which are located in the of the initial profile depressions (Figure 1, b) is obtained. During the subsequent electromechanical treatment at the point of contact of the processing tool with the part, deformation and local heating of the surface above the phase transformation temperature occurs which leads to the crumpling of micro-irregularities with
simultaneous filling of cavities, mouths of microcracks and recesses with a solid lubricant antifriction material (Figure 1, d) and the formation of a "white" layer of high hardness 3 [6, 13]. In Figure 1, the step-by-step scheme of AFEMT with the application of an antifriction layer 4 of suspension in a mixture with SAS [7, 13] is presented, possibly on a pre-prepared surface 1, for example, with an Electromechanical tool with a small angle at the top. Pre-treatment allows to obtain a regular microrelief with certain characteristics that improve the quality and performance of the application process of antifriction material.

![Figure 1](image1.png)

**Figure 1.** Schemes of application of antifriction material on the surface of the base material with subsequent Electromechanical treatment: a – the initial surface; b – the surface after rubbing with an antifriction metal; c – the surface with a suspension of the antifriction mixture based on SAS; d – the surface (b) after EMT; g – the surface (c) after EMT; 1 – the main material; 2 – solid lubricant; 3 – a layer of high hardness material; 4 – antifriction layer.

The subsequent EMT forms a surface with the required, predetermined anti-friction characteristics, the cavities of which are filled with a solid lubricant anti-friction material 4 (**Figure 1, g**), the degradation products of which remain on the treated surface and contribute to the increase of anti-friction properties, besides, due to the thermo-deformation effect, a "white" layer 3 of high hardness is formed.

In the process of work in the friction units located in the cavities the suspension of solid lubricant due to heating and subsequent expansion fills the space between the friction parts, ensuring their lubrication. In the same cavity may fall and additional lubricant supplied to the friction parts, the action of which is similar.

The combined effect in the AFEMT process allows to obtain a surface consisting of a hardened layer with a hardness of up to 9 GPa (white layer 3 (Figure 1, d and 1, g)) and areas with a solid lubricant coating, which increases the anti-friction properties of the surface layer of the parts, as well as corrosion resistance.

To study the effectiveness of AFEMT samples of steel 45, 38HS, 40X, as the most common in the nodes of the chassis of multi-purpose tracked and wheeled vehicles are used. As a solid lubricant for application to the surface of the part by rubbing, copper M3, bronze BrOCC-3-5-5 and brass L-62 are
used. For the application of a suspension of solid lubricant material in mixture with a surfactant fine-dispersed powder of cryptocrystalline graphite (SKG), molybdenum disulfide (MoS$_2$), M3 copper, tin-lead bronze Br. OF4-0.25 and mixtures thereof in various proportions with a surface-active substance (surfactant) – glycerol are used. High-performance tool for AFEMT allows simultaneously to pre-create the necessary regular micrelief on the surface of the part by electromechnical treatment with a tool with a small angle at the top and to apply a solid lubricant by rubbing and conduct electromechanical smoothing with a carbide tool [9].

In the case of rubbing for the application of solid lubricant bronze showed the best results. When using copper, setting is observed, due to its high plasticity. The analysis of the dependence of the wear rate of samples treated with AFEMT by applying a suspension of a solid lubricant in a mixture with SAS has a characteristic character identical to all solid lubricants (Figure 2). Samples treated with AFEMT with cryptocrystalline graphite (SCG) and molybdenum disulfide (curves 1 and 2, respectively) showed the best results.

The wear rate of the samples, the surface of which is treated in the presence of copper (curve 3), about three times higher than that of the samples treated with SKG, in the case of bronze (curve 4) 3.5 times higher, the samples treated with quenching HDTV (curve 5), 5 times higher. In the course of the AFEMT the effect of technological processing modes (processing speed, the force of pressing the tool to the surface to be treated, the pressure of the antifriction material on the surface to be rubbed, in the case of rubbing, the magnitude of the electric current) on the transfer and adhesion to the surface of the part of the carbide material, resulting roughness and micro-hardness was studied.

![Figure 2](image.png)

**Figure 2.** Results of comparative wear tests, partial liner bronze br. AZH-9-4 and shaft steel 40H, processed AFEMT with the application of a suspension of various solid lubricants mixed with surfactants: 1 – graphite SKG; 2 – molybdenum disulfide; 3 – copper; 4 – bronze; 5 – hardening HDTV.

The best results are obtained in the following modes:

a) for the application of a solid lubricant in a mixture with SAS $I = 500...600$ A, $V = 8...10$ m/s, $P = 400...600$ N (pressing force of the tool);

b) for rubbing $I = 600...650$ A, $V = 1,4...2$ m/s, $P = 400...600$ N (force of pressing of the tool), $p = 10...20$ PA (pressure of antifriction material), giving of antifriction material $s = 0,05...1$ mm/about, at initial surface roughness $Ra2,5...6,3$.

To determine the anti-friction properties of the surface layers of machine parts treated with AFEMT, six batches of rollers were made of steel 40H. The first batch of samples was not subjected to additional hardening. The second batch was strengthened by volume quenching in water followed by low tempering. The third batch of samples was strengthened by hardening of HDTV, the fourth – by Electromechanical processing. The fifth batch was treated with rubbing AFEMT solid lubricant on the
treated surface, and the sixth batch of samples was treated with the application of AFEMT suspension of solid lubricant in a mixture with SAS.

After pre-weighing, the samples were subjected to tests for wear under the scheme-friction roller – partial liner with lubrication oil M-8BSAE 20W-20 machine MT-393 in accordance with the requirements of RD50-662-88. The partial liner was made of normalized steel 45. The test time was 90 minutes, the speed of the rollers – 500 min–1, the load on the pad – 650 N.

Analysis of the dynamics of changes in the friction torque on the results of the tests (Figure 3) showed that the rollers processed by AFEMT, working in tandem with the steel counterbody, show the lowest friction moment, and the samples treated with the application of AFEMT suspension of solid lubricant in a mixture with surfactant, have a minimum friction moment during the burnishing period in comparison with other pairs of materials. This is explained by the presence of solid lubricant degradation products on the friction surface, as well as surfactant residues after AFEMT, contributing to the reduction of friction torque in the coupling of friction parts [9, 16, 17].

![Figure 3](image)

Figure 3. The dependence of the friction moment on the burnishing time, the samples: 1 – without hardening; 2 – quenching with low tempering; 3 – quenching HDTV; 4 – EMT; 5 – AFEMT with rubbing of solid lubricant on the treated surface; 6 – AFEMT with the application of a suspension of solid lubricant in a mixture with SAS (SKG).

This indicates higher anti-friction properties of the surfaces obtained after AFEMT, which provides a lower wear rate of the samples compared to other methods of sample processing (Figure 4).

![Figure 4](image)

Figure 4. Results of comparative wear tests (samples – 40H steel paired with cast iron partial inserts): 1 – samples without surface hardening; 2 – samples after EMT; 3 – samples after AFEMT...
Testing of bushings made of 40H steel for wear was carried out in pair with cast-iron partial inserts, with a load on the liner at 800 N and a roller speed of 500 min⁻¹ (Figure 5).

Thus, a comparative analysis of the wear resistance of the surfaces of the samples after various methods of hardening showed:

– increasing the hardness of the sample volume quenching with tempering increases the wear resistance of the surface in 1.3...1.35 times in comparison with non-hardened samples, while the wear resistance of the partial liner increases in 2.1...2.3 times;

– Electromechanical hardening of the surface leads to an increase in wear resistance of 1.5...1.6 times, and inserts – 2.5...2.7 times;

– anti-friction Electromechanical treatment provides an increase in the wear resistance of samples in 1.7...1.9 times, inserts – about 2.8...3.0 times.

That is, the increase in the wear resistance of surfaces for samples after AFEMT in relation to samples processed by "classical" EMT technology was about 10...20%.

The greatest increase in wear resistance is manifested at the initial stage of work of rubbing parts, i.e. at the burnishing stage, which confirms a significant improvement in the anti-friction properties of parts and an increase in their durability in General when used as a reinforcing finish technology AFEMT.

The conducted researches allowed to reveal the dependence of wear resistance of machine parts after antifriction Electromechanical processing on the material of the mating liner. So, at friction of steel samples (steel 40H) after AFEMT with partial inserts from steel 45, gray cast iron SCH-21 and bronze BrOCC-3-5-5 it was found that the highest wear resistance is observed in the friction pair of the sample after AFEMT with a bronze liner, and the steel sample was processed by AFEMO with the application of a suspension of solid lubricant mixed with SAS (cryptocrystalline graphite (SCG) or molybdenum disulfide with surfactant) fed to the surface during processing. A pair of friction steel 40H after AFEMT – cast iron liner gives in comparison with other pairs of friction slightly higher wear of both the sample and the liner.

Theoretical and experimental studies have confirmed the adequacy of the proposed dependencies. The obtained generalized equation of the relationship between the wear intensity and geometric (roughness) and physical and mechanical (degree of hardening) parameters of the surface layer quality of machine parts under normal operation of the unit allows to calculate the wear intensity in the equilibrium state of the mating parts taking into account the technological conditions of mechanical and subsequent hardening finishing. The developed algorithm for determining the modes of mechanical and subsequent hardening finishing to ensure the wear resistance of the surface layer of machine parts allows the design stage of the process to determine the processing modes, which will
result in the formation of a surface layer with certain geometric and physico-mechanical properties, reducing the burnishing time of parts in friction units.

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