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# Theoretical and Practical Study of Possibility to Decrease Thermal Stress in Pistons of Internal Combustion Diesel Engine by Using Galvanic Plasma Modification

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## Abstract:

The article discusses a method for solving the problem of restoring parts of a cylinder-piston group with a simultaneous increase in the wear resistance of surfaces, as well as obtaining heat-shielding coatings on parts made of aluminum alloys by the method of galvanic-plasma surface modification. The article establishes the relationship between the modes of oxidation with the properties obtained by the method of microarc oxidation of coatings on the bottom of the piston of an internal combustion engine (ICE). The dependence of the thickness of the oxidized layer on the voltage applied to the electrodes and the current density is investigated.

***Keywords :*** *oxidized layer, voltage, current density, electrolyte, Piston.*

## Introduction

The piston is the most important and complex part of the engines of internal combustion, as it is subjected to mechanical and thermal loads together, which may sometimes lead to failure. Studies should result in its design, analysis and study. This research represents a new method in terms of drawing and analysis without neglecting any part of the piston parts. At the point when the fuel-air mixture burns in the cylinder of the internal combustion engine (ICE) a lot of heat is released. A Part of it leaves with the exhausted gases, the other part is transferred to the headwalls of the cylinder, and also the piston. If the piston design did not allow the heat to be discharged from the bottom into the skirt of the piston, the piston would quickly overheat, lost efficiency and burned out The burnout is usually called destruction surface layer of the bottom of the piston, which occurs as a result of the hard work of the engine with a high gradient of pressure buildup in the working chamber and high temperature. The appearance of this defect begins on the surface of the bottom of the piston there are traces of thermal effects in the form of thermal cracks, including further. Development goes into disintegration and deep erosion, covering sometimes the whole surface of the bottom. A piston burn can also cause damage to the cylinder wall, as it contributes to the formation of scoring and the rolling of material the piston on the sleeve.The issue of controlling cylinder burnout is the most applicable for diesel engines. It's associated within pressure and temperature of the gases upon combustion in the diesel engine is higher than that of a gasoline engine, resulting in an increase in the amount of heat transferred to the walls of the combustion chamber through the piston. For example, the piston of a gasoline engine it gives about 3% of the heat released in the cylinder, and the piston of the diesel engine - 5-8% of the heat [8]. However, concerning fuel engines, the phenomenon of burnout is not uncommon. The main modern trends in engine building are associated with an increase in engine power with a simultaneous desire to reduce the mass, which leads to an even greater increase the thermal tension of the pistons and, as a consequence, the formation of burnout and the formation of thermal cracks. It is obvious that the reduction in the probability of occurrence of burn-troughs on the pistons is actually the problem of modern engine building.

Research goal

- Thermal analysis of piston.
- investigate potential for reducing thermal stress in ICE pistons by using galvanic plasma modulation (GPM) as further development of micro arc oxidation

At the moment, various technologies (anodizing, spraying, metallization) are used to increase the wear resistance of the piston surface; however, the possibilities of obtaining a multifunctional coating with control of the final part size are conveniently combined in the technology of galvanic-plasma surface modification. This allows you to restore the size of the part while improving its technological parameters (increase the service life of the repair part relative to the new uncoated, increase engine efficiency). The essence of the method is the formation of a high-strength wear-resistant and Heat-resistant coating consisting principally of high-temperature oxides. Under the conditions of operation of a diesel engine, it is necessary to ensure the following coating parameters: For thermal protection functions (piston bottom and flame belt) high durability of the coating and the absence of defects; the value of the volume porosity of not less than 10-15%; the proportion of α-phase of aluminum oxide in the coating composition at the level of 25 ... 30%. For the purpose of improving wear resistance and restoring sizes (piston skirt) the predominance of the γ-phase of aluminum oxide in the layer (not less than 70%); the minimum volumetric porosity is 2-5%; pore size less than 3-4 microns; maximum values of hardness and uniformity of the coating (microhardness at the level of 18 ... 22 GPa) . The application of this method of restoring parts with the modification of their surfaces for the repair of cylinder-piston groups of diesel engines Cummins KTA-38 and KTA-50 used on mining dump trucks by the coal-mining company SUEK was carried out on the basis of the laboratory oftechnological systems of Belgorod State University. Pistons made of aluminum cast alloy, similar to AK12MMrH (AL30), participated in the research.

## Theoretical researches

The difference in heating of a typical piston and an oxidized-bottom piston can essentially be reduced to determining the value of the average specific flow through the wall (q). This value will depend on the average resultant gas temperature per cycle ($t_g$), the time-average and surface heat transfer coefficient from gases to the wall ($\alpha_g$), and on the wall temperature$T_{spg}$, or from the temperature drop in the wall, defined as the temperature difference between the temperature $T_{spg}$ and the bottom temperature piston $T_{spc}$ from the side of the crankcase, the coefficient of thermal conductivity of the material λ and the wall thickness δ. Using the known expression for the heat flux, it is possible to determine the average value of the wall temperature on the hot side, if we agree on the choice of the quantities $\alpha_g$, $t_g$ ,$t_{spg}$

$$q = \alpha_g . \left( t_g - T_{spg} \right) = \frac{\lambda}{\delta_p} . \left( T_{spg} - T_{spc} \right)$$

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Where $T_{spg}$ is piston surface temperature on the side of gases, K; $T_{spc}$ is piston surface temperature on the side of thecrankcase, K; $\delta_p$ is thickness of the piston wall, m; $\lambda$ is the thermal conductivity coefficient of the piston material,W/m·K; $\alpha_g$ is heat transfer coefficient from gases to the piston head.

To determine the heating difference, in typical piston and piston with oxidized, the heat transfer process must be considered as transfer of heat through a three-layer wall. The first layer is an oxidized layer, the second is the base material of the piston, and the third is the layer of cooling engine oil

The specific heat flux passing through the oxidized piston rings will be described by the equations:

$$q_1^{'} = \frac{(T_{spg1} - T_{spc1})}{\frac{\delta_p}{\lambda_p} + \frac{\delta_o}{\lambda_o}}$$

$$q_2^{'} = \frac{(T_{spg2} - T_{spc2})}{\frac{\delta_p}{\lambda_p} + \frac{\delta_o}{\lambda_o}}$$

$$q_3^{'} = \frac{(T_{spg3} - T_{spc3})}{\frac{\delta_p}{\lambda_p} + \frac{\delta_o}{\lambda_o}}$$

where $q_1^{'}$ , $q_2^{'}$, $q_3^{'}$ are heat flux passing through the groove of the first, second and oil piston rings respectively, W/m2.

## Experimental and Results of study

The obtained using a Quanta 200 scanning electron microscope (SEM) showedfig (1) that pistons are made of alloy AK12MMGH. Heat-resistant alloys of the type AK12MMGH system form of The A1 – Si – Fe –Cu.

| element | Burning 1 | Burning 2 | Burning 3 | Burning 4 | Burning 5 |
|---|---|---|---|---|---|
| Al | 82.6 | 83.2 | 83.4 | 83.1 | 81.9 |
| Si | 12.9 | 12.9 | 12.7 | 13.1 | 14.0 |
| Fe | 0.625 | 0.514 | 0.509 | 0.494 | 0.525 |
| Cu | 1.27 | 1.07 | 1.12 | 1.07 | 1.17 |
| Mn | 0.0197 | 0.0138 | 0.0137 | 0.0148 | 0.0176 |
| Mg | 1.09 | 0.946 | 0.898 | 0.948 | 1.00 |

Fig (1) Quantitative result of the analysis of a piston aluminum alloy

Galvanic Plasma Modification of the pistons produced on a set oflaboratories and experimental - industrial equipment for microarc oxidation of titanium alloys Equipment for the study and application of methods for modifying the surface of metals by plasma - electrolytic oxidation.

The process of micro-plasma oxidation is the creation of a coating on the surface of parts placed in an electrolyte medium. The composition of the electrolyte consists of a Potassium Hydroxide (KOH) with the addition of water glass as well as additional elements for doping or creating coatings with certain optical properties. The effect of current on the quality of the formed coating for aluminum alloys has been studied quite well. The choice of the working value of the current and the range of its change was made as follows. The value of current density below 2-3 A/dm$^2$does not provide coating. Values of current density above 20 A/dm$^2$lead to electric arcs in the coating, which degrade the properties of the coating and destroy it. Acceptable properties of coatings are achieved in the range of current density changes of 8-14 A/dm$^2$ .The capacitance of the GPM installation, C, was 900 μF The processing time significantly affects the total thickness of the coating and its layers (working and technological), the phase and component composition of the coating. However, the upper limit of processing time is limited by the time after which the process slows down significantly or stops completely, and the lower limit is determined by the need to obtain a given coating thickness. Accepted indirect method of controlling the thickness of the formed coating in the process of formation is to control the maximum value of the amplitude of the cathode voltage.

In order to search for the reference modes of the formation of coatings with the desired properties, a number of preliminary treatments of control samples (which were made of a defective piston) were made with the following parameters:

- Potassium Hydroxide (KOH) concentration: 4, 7, 10, 20 g / l;
- Concentration of liquid glass: 4, 9, 10, 20, 30 g / l;
- Specific capacity in the soft symmetric condenser processing mode: 235, 460, 590 μF/dm$^2$;this concentration is optimal for the studied piston aluminum alloys). This setting allows you to adjust the total ion current density I and the quantitative ratio of the cathode and anode currents IK / IA over a wide range. Installations for microplasma oxidation are a bath with electrolyte, ventilation, cooling and electrolyte circulation systems.Processing time from 30 minutes to 2.5 hours. In the event of the termination of the coating formation process (microarc discharges), as well as the occurrence of arc discharges on the surface of parts, the process was terminated.

Data on the studied modes and the values of the coating thickness are presented in Table 1 and in the graph (Figure 2).

| | | | A | B | K | C | F | D | E |
|---|---|---|---|---|---|---|---|---|---|
| | | KOH, g/l | 4 | 4 | 7 | 10 | 10 | 10 | 20 |
| | | Na2SiO3, g/l | 9 | 30 | 20 | 4 | 10 | 30 | 10 |
| **1** | Specific capacity 235 μF/dm$^2$ | 30 min | | 0,079 | | 0,0035 | | 0,058 | |
| | | 60 min | | 0,139 | | 0,027 | | 0,071 | |
| | | 90 min | | 0,124 | | 0,027 | | 0,091 | |
| | | 120 min | | 0,144 | | 0,0365 | | 0,111 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **2** | Specific capacity 460 µF/dm$^2$ | 30 min | 0,165 | 0,145 | 0,11 | 0,0095 | 0,067 | 0,093 | 0,024 |
| | | 60 min | 0,174 | | 0,150 | 0,023 | 0,087 | 0,138 | 0,049 |
| | | 90 min | | | | 0,041 | 0,114 | 0,19 | 0,129 |
| | | 120 min | | | | 0,07 | | | 0,155 |
| **3** | Specific capacity 590 µF/dm$^2$ | 30 min | | | | 0,0365 | 0,057 | | 0,076 |
| | | 60 min | | | | 0,106 | 0,099 | | 0,188 |
| | | 90 min | | | | | | | |
| | | 120 min | | | | | | | |

Table 1. The value of the thickness formed coating under different processing conditions.

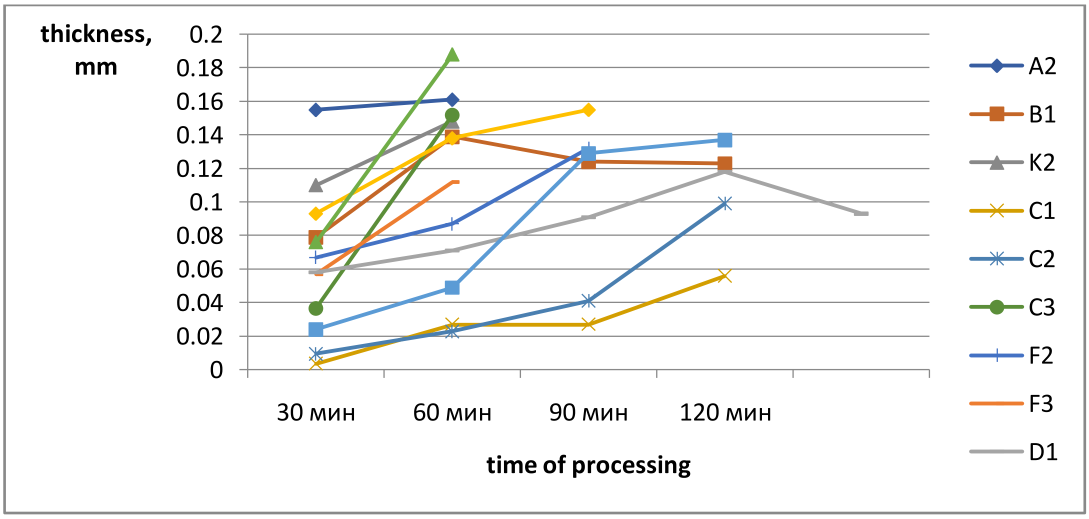

Figure 2. The dependence of the thickness of the formed coating in different modes

Performing a full experiment with 4 influencing parameters (Potassium Hydroxide (KOH), Concentration of liquid glass, specific process capacity and process time) requires a large number of samples and time to conduct research, therefore, the search for reference modes was performed in a number of reference points. For example, in samples B1, C1 and D1 with a capacity of 235 µF / dm2, the coating growth rate is much lower than in other conditions, the D2 mode is preferable to A2, B2, E2 and E3 mode, although A2 and B2 cover growth is faster and the volume porosity is higher, but the coating is loose. The C3 mode is preferable to the C2 and C1 modes - since the growth of coverage is faster. In modes F2 and F3, the coating thickness is limited to values of the order of 100 µm, which is insufficient for the reconstruction technology.

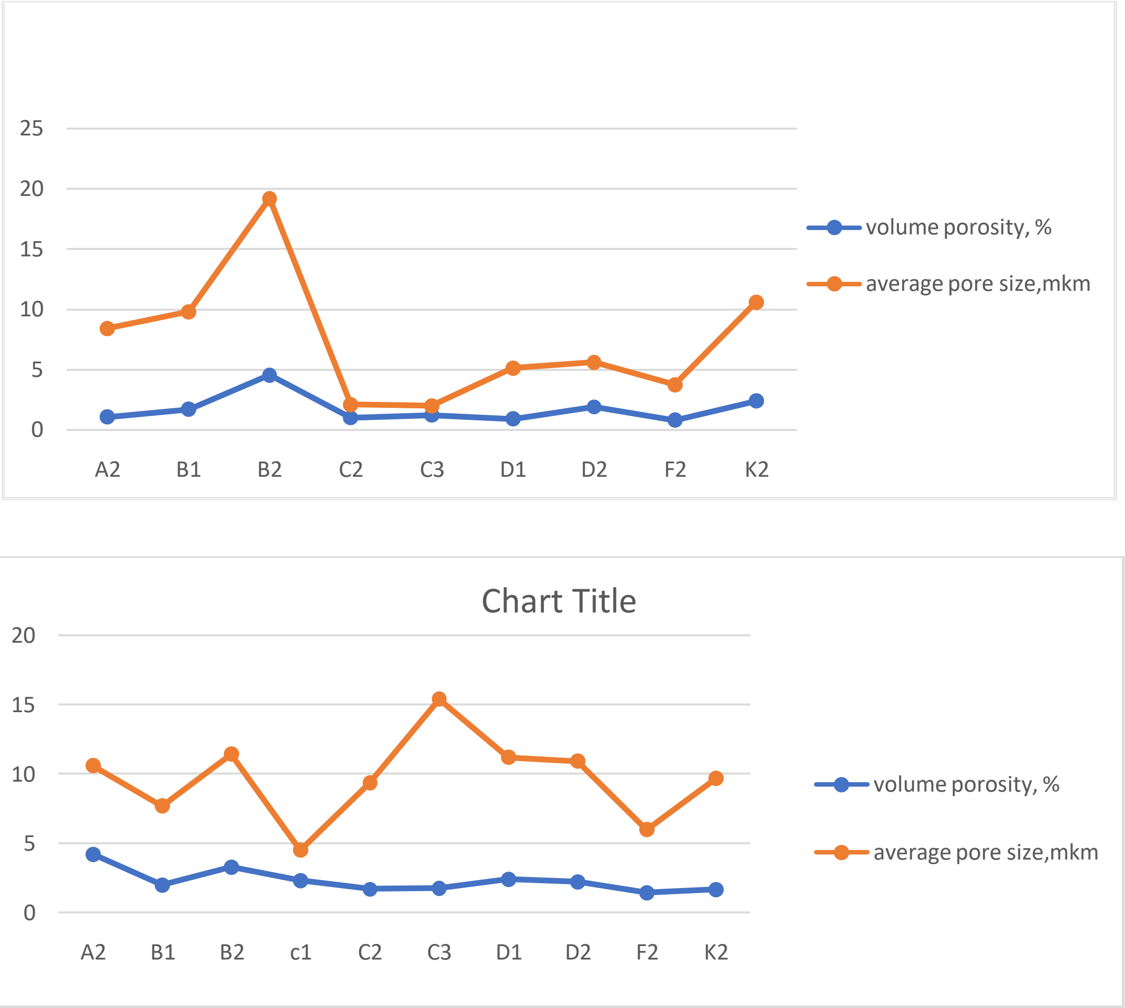

Figure 3. The porosity of the coating for different processing modes (a - porosity on the transverse section - internal, b - surface porosity)

Measurement of the average proportion of porosity was carried out by the ratio of the coverage areas and pores, respectively, in the pictures of different areas of the coating according to

$$P(100\%) = \frac{\sum_i^n \frac{s_{p_i}}{s_{c_i}}}{n} \cdot 100\%$$

Where $sp = \sum_i^m p_i$ - total area of pores in the area, P - pore area in coating; Sc - is the total area of the coating area; n is the number porosity measurement sites

From the point of view of minimum porosity of the coating (~ 1.99%) and small average pore size (~ 1.21%), the C3 mode stands out (Figure 3), it is worth noting that the growth rate of the coating and the achievable values of the coating thickness meet the specified requirements. For thermal protection purposes, you need a strong coating with a higher porosity of the coating and surface. For this indicator, suitable coatings obtained in modes K2 and D2. Coatings obtained in modes B1 and B2 have visible cracks and defects (Figure 4) and therefore cannot be recommended for use. More modes that are suitable is mode K2 (Figure 5). The K2 mode is selected between the B2 and D2 modes, the growth of the coating in it is faster, and the bulk porosity is greater than in the D2 mode, which is better for heat-shielding properties.

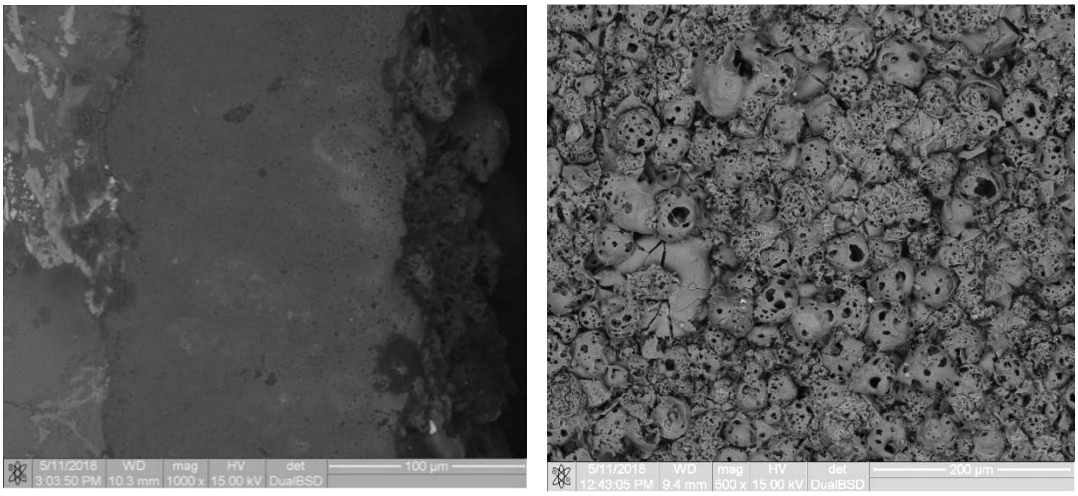

Figure 4. The appearance of the coating (a) and the transverse grinding of the coating for mode C3

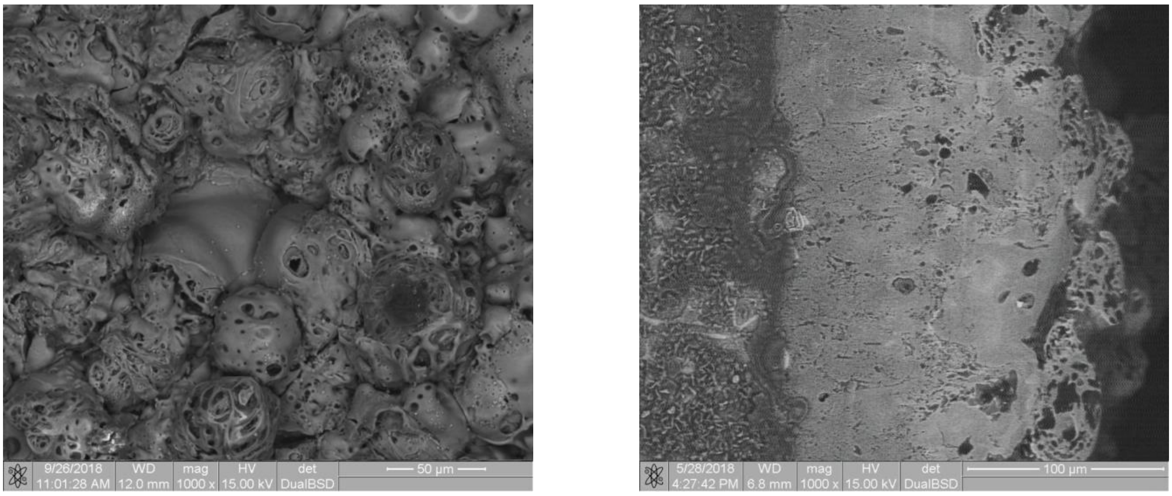

Figure 5. Appearance of the coating (a), transverse grinding of the coating (b) for the K2 mode (60 minutes)

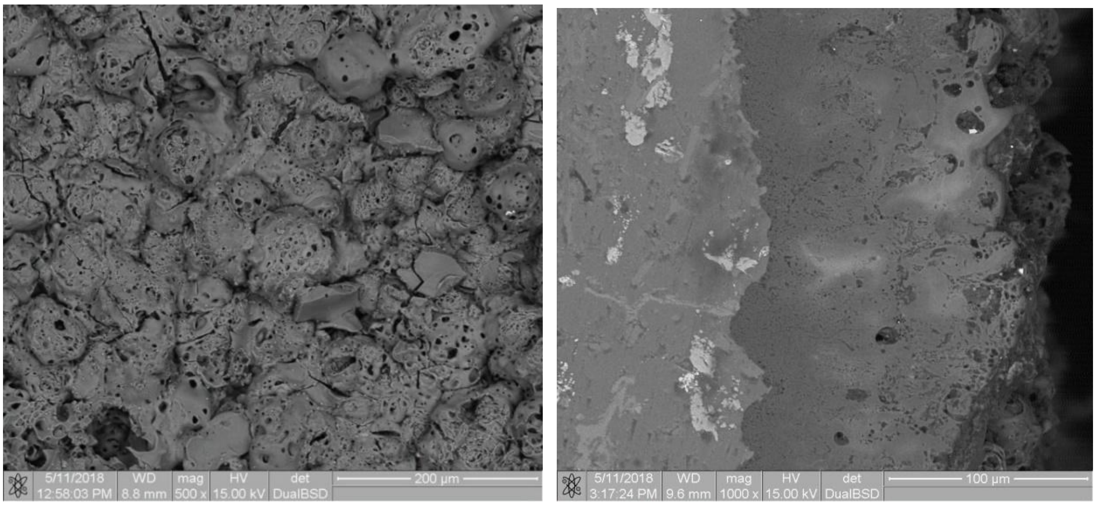

Figure 6. Appearance of the coating (a), transverse grinding of the coating (b) for the D2 mode (90 minutes)

According to the data, the combination of the most suitable indicators of the quality of the coating and the minimum processing time is obtained where a heat-shielding coating in the K2 mode and wear-resistant coating in C3 mode.

In the D2 processing mode, show clearly that the walls between the pores consist of a dark inner layer and a lighter outer one. This contrast is explained by thedifference in the chemical composition of the layers, the outer layer of oxide is contaminated with extraneous ions, while the inner layer is a dense layer of pure aluminum oxide. Depending on the processing mode, but the low porosity of

The working layer adversely affects its heat-shielding properties; however, this mode is applicable to the formation of a wear-resistant coating.

For mode C3 and D2, microhardness measurements were performed. The microhardness of the sample coating C3 after treatment is 827.7 HV, sample D2 is 783 HV at a microhardness value of the initial alloy 113 HV. The chemical composition of the coatings of modes C3, D2 and K2 is shown in Figure 6. Corundum predominates in the C3 coating composition, which ensures high wear resistance of the surface coating. Also present is silicon oxide in the amorphous phase, which reduces the crack resistance of the coating. In the coating formed in the K2 model, the proportion of silicon oxide is higher, which is due to the higher concentration of liquid glass in the electrolyte in order to achieve an increased thickness of the heat-shielding layer. In this case, a monotonic decrease in the concentration of silicon from the surface into the formed layer is observed (see Figure 7).

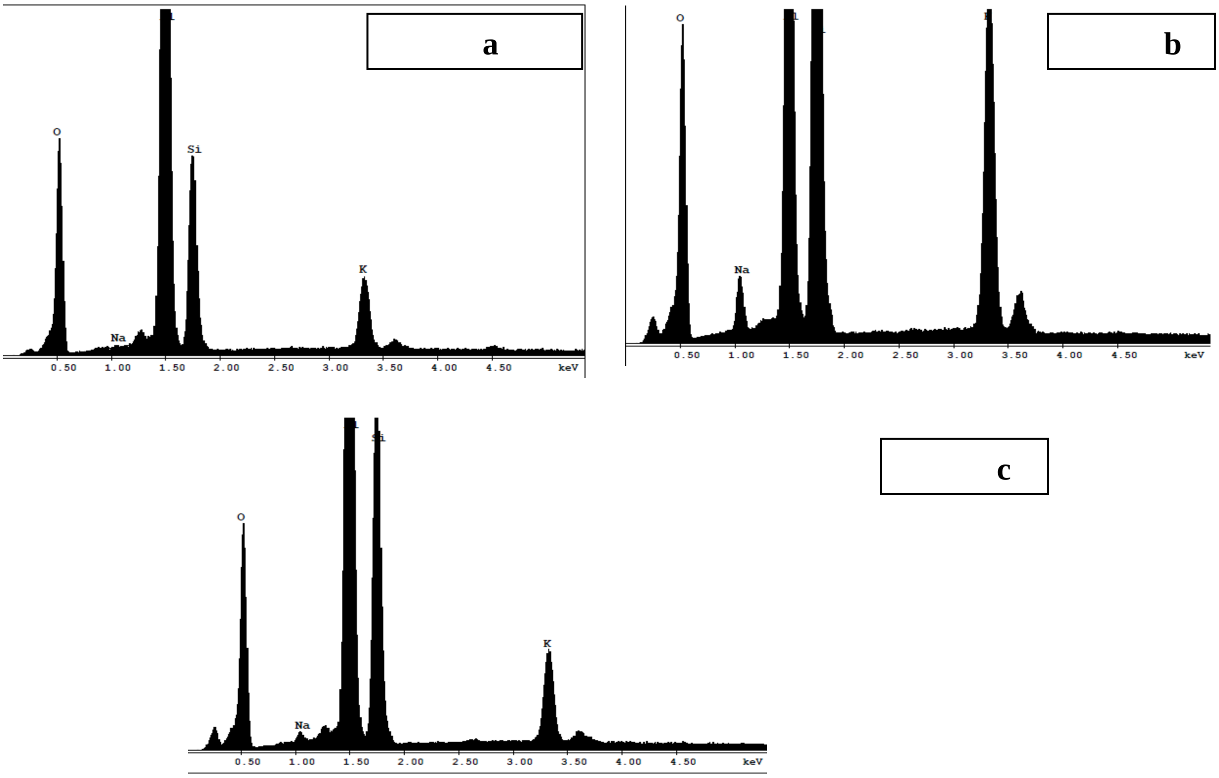

Figure 7. Data on the chemical composition of the coating for mode C3 (a), D2 (b) and K2 (c)

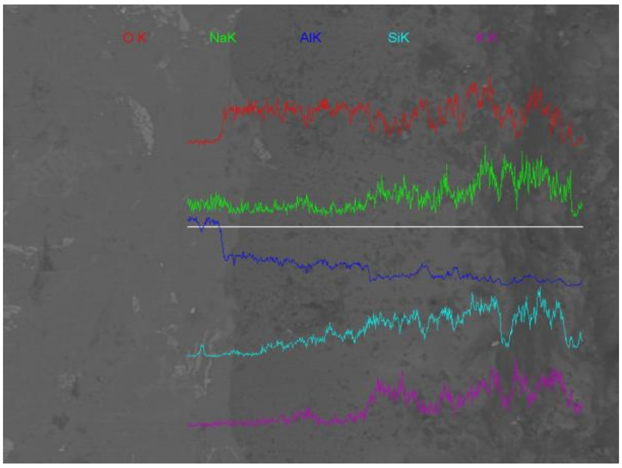

Figure 8. Distribution of elements over the coating thickness

The heat shield should have a low thermal conductivity, of the order of 0.6 W / m * K, which is possible only with a volume porosity of at least 10–15%. The thermal barrier created by such a heat shield must be at least 70 ... 100 ° C in order to ensure tangible influence on the thermodynamic cycle of the internal combustion engine. At the same time its thickness should be from 0.12 to 0.2 mm. The increase in thickness leads to a sharp decrease in cyclic resistance due to an increase in temperature gradients during engine operation.

Thus, 3 treatment modes were selected, which provide the necessary quality indicators for coatings for 2 different areas of use. It should be noted that although the C3 mode allows you to get the best thickness and composition of the coating, a technological problem arises when processing the piston skirt, therefore, the D2 mode was chosen (with a lower concentration of liquid glass (in the process of piston restoration - 25 g / l) Modes D2 and K2 are then used to form coatings with desired properties and the required thickness. In the case that the treatment mode is selected (composition and concentration of the electrolyte, a capacitance of capacitors), the effect on the coating thickness is only the processing time is required. The principle of repairing cylinder-piston groups is to restore the size of the piston skirt to the calculated size in order to further form individual “piston-sleeve” pairs to ensure the required working clearance. The dimensions of the sleeves are determined after the technological treatment consisting in finishing polishing and applying hong.

The formation of coating layer thickness occurs by setting a specific processing time. To determine in each case the required processing time, providing the desired increment of the part size, it is necessary to determine the experimental or analytical dependence of the change in the coating thickness on the processing time. Experimental dependencies for the processing modes K2 and D2 are presented in the graph (see Figure 1). The process of forming coatings of the required thickness was provided by processing in 2 stages. Using data on the growth rate of the coating in the D2 and K2 modes on the test samples, the predicted processing time is determined to obtain a given thickness. This time, reduced by 5-10%, is used for the first stage of coating formation, at which about 80% of the thickness is formed. After which the process stops, measurements of the actual size of the piston $D_1$ are carried out. Based on the measurement results, the required additional time for carrying out the T2 process is calculated to achieve a given coating thickness $D_2$.

$$T_2 = k \cdot (D_2 - D_1),$$

Where k: is the proportionality coefficient equal to the specific growth rate of the coating in the considered mode. This method provides the necessary accuracy in the formation of a coating of a given thickness. The parts to be processed fall within the required tolerances with little or no additional processing. However, carrying out such a two-stage treatment process with an intermediate measurement and stopping the coating formation process significantly complicates the recovery process, makes it more dependent on measurement accuracy and increases its cost. The calculation of the required time of the process of forming a coating in one stage, or the automatic decision to stop the process of processing can significantly reduce its complexity and cost. In order to improve the prediction accuracy and improve the manufacturability of the recovery method, the possibility of predicting the required mode time using the neural network tools or regression analysis is considered.

Fully the process of restoring worn parts CPG consists of the following steps:

1. Parts of CPG are cleaned from carbon and deposits by washing and sandblasting the bottom of the pistons with a soft abrasive;
2. After cleaning, the value of the maximum wear of the sleeves is determined (measurements are carried out in 2 diametrically opposite planes at 4 different heights of the sleeve);
3. The liner is being repaired by honing until cylindricity is restored with the formation of the required surface texture of the cylinder surface;
4. The piston dimensions are monitored (measurements are carried out in 2 perpendicular planes on the piston bottom, as well as in 2 perpendicular planes at 2 heights on the piston skirt), piston-sleeve pairs are formed with a maximum difference of 260 microns. For each pair, the required thickness of the coating is determined to obtain the allowable thermal gap, taking into account the allowance for finishing;
5. According to the developed methodology, the required thickness of the coating on the piston skirt is formed;
6. Formed heat-shielding coating on the bottom of the piston and the heat zone;
7. Finishing is performed, removal of the technological coating layer, which ends when the specified repair size is reached.

The resulting data on fuel efficiency, presented in Figures 8 and 9, were obtained during bench tests of KTA38S engines at AO Chernogorsky Mechanical Repair Plant, part of SUEK, and confirmed by test reports.

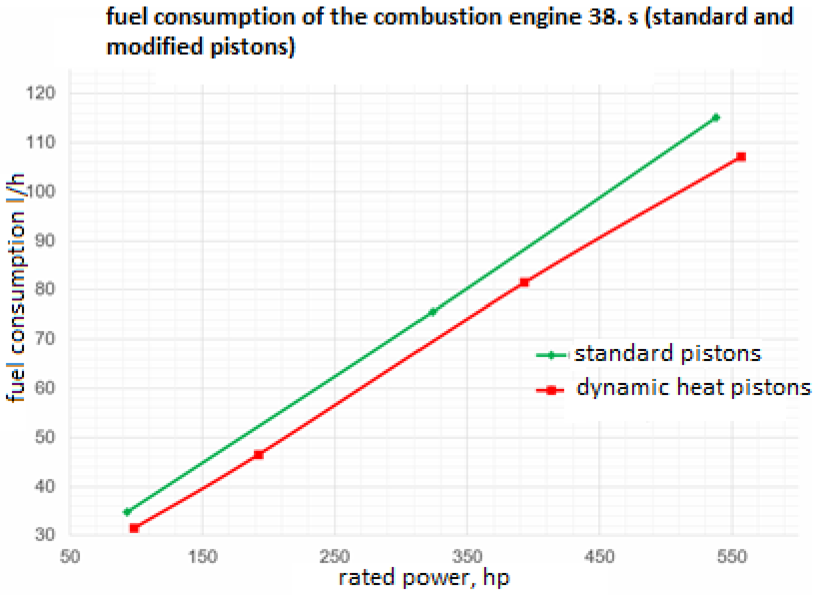

Fig. 9. Test results of ICE KTA-38 with pistons equipped with dynamic thermal protection and standard pistons

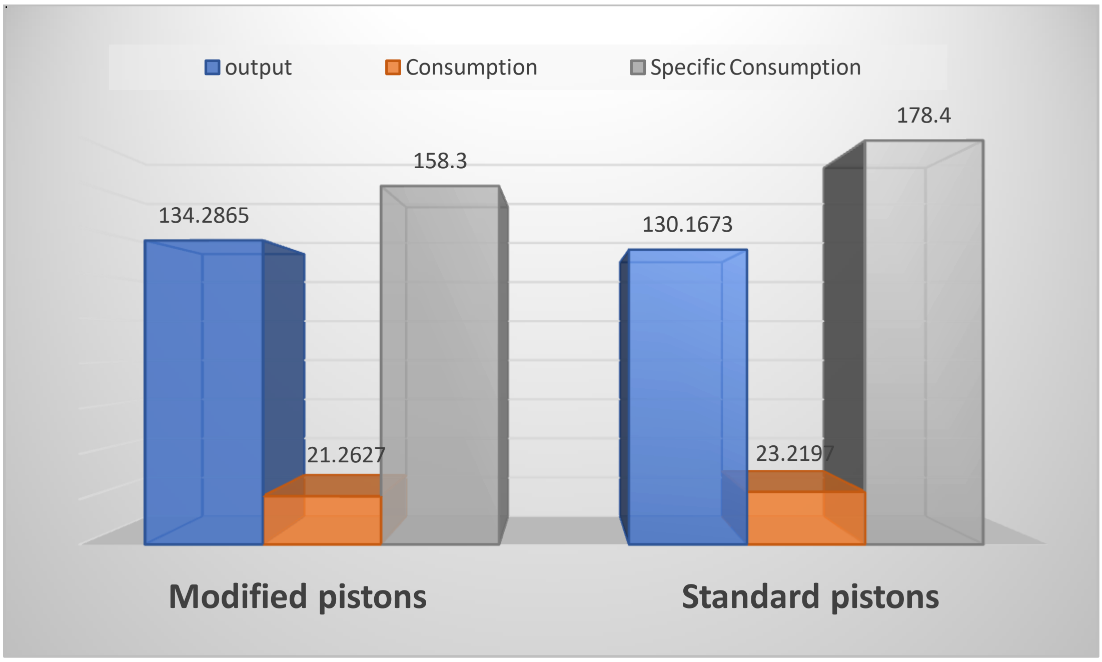

Fig. 10. Results of field tests of ICE KTA-38 with pistons equipped with dynamic thermal protection and standard pistons

According to the data obtained at the Montenegrin section of LLC SUEK-Khakassia (Minutes No. 1 of the technical meeting at Chernogorsky RMZ JSC from 09/27/2017), for the period from 1.08.2017 to 18.09.2017, the fuel efficiency of the proposed technology under identical engine operating conditions was 11%. There are no remarks to the operation of the KTA38-C engine No. 33180593.

The method for restoring parts of the PBC, proposed and tested by the authors of the article, provides several key advantages as compared with the installation of new parts, namely:

- as a result of bench and field tests conducted on 4 Terex dump trucks, an increase in the engine's fuel efficiency by 5 ... 7% was established due to the dynamic thermal protection of the piston head, leading to a decrease in heat losses and an increase in the thermal efficiency of the engine;

- found experimental confirmation of the CPG repair technology with the formation of a reducing corundum layer on the piston skirt, providing a resource of at least 18,000 hours, which corresponds to the overhaul life of Cummins KTA series internal combustion engines, which costs no more than 20% of the cost of the new set of CPGs.

The results of technology testing in real-life conditions allow us to consider this method of repairing the CPG and increasing the fuel efficiency of diesel internal combustion engines as one of the most promising for use in industrial production.

## CONCLUSIONS

1.Theoretically justified reduction of wear parts of the “piston groove - piston ring” interface by increasing the microhardness of the working surfaces of the piston grooves (with other constant parameters), forming an oxidized layer on the working surfaces of the piston head.

2.For the formation of an oxidized layer 150 µm thick and microhardness 827 HV microhardness on the working surfaces of the pistons, the technological mode of MAO was theoretically and experimentally justified: the concentration of orthophosphoric acid in an aqueous solution is 180 g / l, the current density is 42.8 A / dm2, the voltage applied to the bottom of the piston is 550 V, the electrolyte temperature is 25 ° C, the oxidation time is 120 minutes. Using this process mode, a set of pistons for the ICE KTA-38engine. The results of laboratory studies of a fragment of an oxidized piston layer show that the oxidized layer has good adhesion with the main material of the aluminum alloy, a clear relief and heterogeneous in composition, , cracks and fractures in the area of contact “the main material - the oxidized layer” is not The intercalation of the oxidized layer into the base of the material is clearly observed, According to the results of elemental composition in atomic concentrations, normalized to 100%, it was found that the oxygen saturation in the oxidized layer on the piston head increased by 25.9%, on the side surface of the piston head by 5.3%, on the top and side surfaces of the piston groove under the first compression ring, respectively, by 13% and 2.7%, compared with a typical piston.

3. The use of pistons with oxidized working surfaces of the heads in the ICE KTA-38 engine reduces wear on the first piston grooves by 1.67 times, increases effective power by 5.3%, maximum torque by 6.5%, reduces hourly and specific fuel consumption, respectively by 5.7% and 9.4%, the content in the exhaust gases of carbon monoxide by 13% and hydrocarbons by 9.3%, compared with typical pistons.

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