Application of MAO coatings in a two-stroke internal combustion engine for thermal protection against burning-through of the piston

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Abstract. Nowadays, a significant problem of high powered two-stroke engines is burning-through of the piston. This problem can be solved by the thermal barrier coatings. It is formed by the method of microarc oxidation (MAO). In this work it was proved that MAO coating of the piston bottom increases the burning-through resistance of two-stroke internal combustion engines. The influence of MAO-layer on the two-stroke engine characteristics (torque, brake specific fuel consumption, temperature under the spark plug and emissions) are investigated. As result, in case of MAO coating of the piston bottom 2.4 times reducing of the burning-through likelihood is take place. Negative impacts on the engine parameters (brake characteristics or emissions) are not detected.

1. Introduction

Two-stroke spark-ignition engines are indispensable when weight, power density and simplicity are critical. Therefore, these types of engines are widely spread in snowmobiles, two-wheeled vehicles, small boats and off-road motorcycles. [1].

But exploitation of high performance two-stroke engines can be a number of problems. One of this is an air-fuel mixture leaning. As result, the combustion chamber temperature and, accordingly, the piston head temperature are increases. For this reason, pistons are quite often out of order [2]. In addition, the surface of the piston is in constant contact with fuel and oils, which have a corrosive effect [3]. The most dangerous destruction is the piston burning-through. Burning-through is a surface destruction of the piston bottom in the result of the high gradient pressure and temperature increases in the engine combustion chamber [4-6]. Thus, the engineering of high performance protective piston bottom coatings is an actual problem of engine technology.

Today, there are various methods of the piston aluminum alloys coating, such as plasma spraying [7], magnetron sputtering [8], and electron-beam vapor deposition [9]. However, coatings, formed by these methods, do not provide sufficient layer thickness and adhesion to the piston material. As result, the thermal protection of these coatings is not effective. A possible solution of this complex scientific and technical challenge may be in the piston bottom nanostructured ceramic coatings by micro-arc oxidation (MAO).

MAO coating is formed in the electrolyte. As a result of complex electrochemical processes, at the surface take place the microdischarges, which is formed modified surface layer. MAO coating consist of aluminum and silicon oxides with a thickness up to 400 µm [10-12]. Such surface layers

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significantly increase the piston burning-through resistance at high temperatures that occur when the mixture is leaning [13-15]. However, the number of studies on the effects of MAO coating on the piston burning-through resistance is very little.

Therefore, the aim of this work is to study the impact of MAO coating on the piston burning-through resistance of two-stroke engine.

2. The method
All studies were carried out on the engine RMZ-550, which is mounted on snowmobiles. Specifications of this engine are presented in table 1.

| Table 1. Specifications of the engine RMZ-550. |
|-----------------------------------------------|
| Model | RMZ-550 |
| Displacement, cm³ / Cylinders | 553 / 2 |
| Power, HP | 50 |
| Type | 2-stroke |
| The cylinder diameter × piston stroke, mm | 76x61 |
| Fuel system | 1-carburetor |
| Carburetor/ type | Mikuni /float |
| Cooling | Air |
| Exhaust system | Muffler with resonator |
| System intake | Reed valve |
| Lubrication | Joint |

The test bed for the engine RMZ-550 based on the load device AVL-DP 80. This device allows the measurement of the engine torque to a value of 200 N•m and the rotational speed up to 10,000 min⁻¹ [16]. In addition, the test bed was fitted with a device, permitting remote control of the throttle valve of the engine, which provided a convenient change of operating modes. The load device connected to the engine PTO shaft (Figure 1). Fuel consumption was recorded by the AVL fuel balance system that is used as a fuel tank. This system has special AVL software, which was installed on a personal computer [17]. The measurement results were transferred to computer and recorded in real time. For the analysis of exhaust gases was used a gas analyzer "Infrakar 5M2" [18]. This device allows controlling the main toxic components (CO, CH, NOₓ) and other components of the exhaust gas (CO₂, O₂). The probe of gas analyzer was mounted in the exhaust pipe at a distance of 300 mm from its edge. To measure the temperature under the spark plug on both cylinders of the engine were installed temperature sensors connected to the device TRM-200 [19]. The study was carried on the maximum engine power mode (full throttle opening and engine speed 6500 min⁻¹).

The engine was tested with two types of pistons sets: 1) regular pistons without MAO coating (Figure 2A); 2) modified pistons with the MAO coating on the bottom (Figure 2B). Regular pistons (made in Austria) made of aluminum alloy M244 with content of Si 26 % [4]. Modified pistons were made on the base of the regular pistons by means of MAO coating technology in a silicate-alkaline electrolyte. This technology was developed in USATU. The thickness of the MAO-layer was measured eddy-current thickness gauge TT-210 and was 130±10 µm.
Figure 1. The test bed for the engine RMZ-550: 1 – the temperature sensor under the spark plug TRM-200; 2 – exhaust pipe; 3 – the throttle valve of the engine.

Figure 2. Pistons of the engine RMZ-550: a – regular; b – modified with MAO-layer.

Primarily, it is needed to determine a measure of the piston burning-through resistance. As this measure one special the engine operating mode was selected. This mode inevitably leads to the regular pistons burning-through because of air-fuel mixture leaning. It achieved by installation the nozzle with a smaller orifice into the carburetor, which leads to an increase of temperature in the combustion chamber and temperature of the walls. In addition, using nozzles with a smaller orifice increases the knock probability. The workflow becomes "harder", the pressure and temperature are increased [20]. For comparison, the engine was also tested with the serial settings of fuel equipment. These settings provide the long-term engine operation with optimum performance. Thus, testing for each set of pistons (coated and regular) was carried out in two stages:
1. The engine testing with regular settings of the fuel equipment (Mode 1). Main fuel orifice (MFO) had a sectional area of 370 mm² (MFO-370). The engine key features are recorded in this mode (engine power – Ne, brake specific fuel consumption – Ge, temperature under the spark plug - TS, and emissions). The scheduled duration of engine operation was 60 minutes.

2. The engine testing with increases the piston burning-through likelihood (Mode 2). This mode is characterized by a lean fuel mixture. This is achieved by using MFO with a smaller cross-sectional area equal to 320 mm² (MFO-320). In this mode are also recorded the engine key features. The piston burning-through resistance was characterized by engine operation duration before the occurrence of burning-through. The fact of the piston burning-through was determined by spontaneous engine stop and was confirmed by visual inspection.

3. Result and discussion

During engine testing on Mode 1 it was recorded that the engine with regular pistons and the engine with mao coated pistons showed no burning-through signs after 60 minutes of work. During engine testing on Mode 2 burning-through of the regular pistons occurred after 25 minutes of work. mao coated pistons still showed no burning-through signs after 60 minutes of work on Mode 2, despite a significant air-fuel mixture leaning. The engine with MAO coated pistons there was a slight increase in temperature under the spark plug of right cylinder, and small reduction of brake specific fuel consumption of 7.1% when working on Mode 2. The test results are shown in table 2.

Table 2. The test results.

| Mode | Operation time (min) | Ne (h.p.) | Ge (g/h.p. h) | T_s (°C) |  
|      |                     |          |              | The right cylinder | The left cylinder |
|------|---------------------|----------|--------------|-------------------|------------------|
| 1    | 60                  | 42,5±2,1 | 337±17       | 150               | 162              |
| 2    | 25                  | 42,0±2,1 | 330±17       | 178               | 175              |

| Mode | Operation time (min) | Ne (h.p.) | Ge (g/h.p. h) | T_s (°C) |  
|------|---------------------|----------|--------------|-------------------|------------------|
| 1    | 60                  | 39,8±2,0 | 350±17       | 170               | 156              |
| 2    | 60                  | 40,7±2,0 | 313±17       | 180               | 175              |

Figure 3 shows the regular piston (Figure 3a) and the MAO coated piston (Figure 3b), after work on mode 2. On the surface of the regular piston bottom is clearly visible burning-through in the form of irregular shape hole (Figure 3a). On the surface of the MAO coated piston burning-through not observed (Figure 3b).

Figure 3. Pistons of the engine RMZ-550: a – regular piston after testing (burning-through); b – MAO coated piston after the testing (without burning-through)
Figure 4 shows emissions of the experimental engine. Figure 4a shows the emissions of CO and CO$_2$ on regular and MAO coated pistons. Figure 4b shows the emission of NO$_x$ on regular and MAO coated pistons.

4. Conclusions
1. The experiments are shown what the regular piston was burned-through after 25 minutes of working on Mode 2, while the MAO coated piston has been worked 60 minutes and the damage on its surface was not marked. This fact shows the ability of MAO coating to increase the piston burning-through resistance. It is explained by formation of MAO-layer on the piston bottom surface with a low coefficient of thermal conductivity.
2. Visual analysis of MAO coated piston surfaces showed that the coating has high adhesive strength in conditions of ICE combustion chamber, since the chipped and peeling on the surface are absent (Figure 3b).
3. The presence of MAO-layer does not effect on the engine operation, as the main engine characteristics (power and fuel consumption) when working on all the test modes do not change significantly. The presence of the minor deviations associated with changing of environmental conditions during the experiments (table 2).
4. The measurement of engine emissions (Figure 4) shows that the presence of MAO-layer has no negative impact on the CO and CO$_2$ emissions. It is noted a slight decrease in NO$_x$ emissions (approximately 13%), which can be explained by the thermal state deviations when using MAO coated piston, or catalytic action, which is possible MAO-layer has on the combustion process.

Research have shown that the MAO coating of the piston bottom possible to reduce the burning-through probability at least 2.4 times (in operation time) when working on a lean air-fuel mixture. The negative influences of the MAO coating on the engine workflow has not been revealed.

In the future it is planned to explore:
- the lean limits of the combustible mixture before the onset of burning-through on the MAO coated pistons.
- reasons for the NO$_x$ emissions decrease when using the MAO coated pistons. This effect is important for improving ecological characteristics of 2-stroke engines.

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References

[1] Martins J, Pereira C and Brito F 2016 A New Rotary Valve for 2-Stroke Engines Enabling Over-Expansion SAE Technical Paper 2016-01-1054, doi:10.4271/2016-01-1054

[2] Singh O P, Umbarkar Y, Sreenivasulu T, Vetrivendan E, Kannan M and Babu Y R 2013 Piston seizure investigation: Experiments, modeling and future challenges Engineering Failure Analysis 28 pp 302–310

[3] Kaiser M S and Swagata Dutta 2014 Comparison of corrosion behaviour of commercial aluminium engine block and piston in 3.5% NaCl solution MSEJ Vol. 1, No. 1

[4] MAHLE GmbH 2012 Pistons and engine testing

[5] Tomasz A and Piotr L 2015 Selected failures of internal combustion engine pistons Logistyka 3 pp 48-55

[6] Ayatollahi M R, Mohammadi F and Chamani H R 2011 Thermo-Mechanical Fatigue Life Assessment of a Diesel Engine Piston International Journal of Automotive Engineering 4 pp 256-266

[7] Bai Y, Zhao L, Wang Y, Chen D, Li B Q and Han Z H 2015 Fragmentation of in-flight particles and its influence on the microstructure and mechanical property of YSZ coating deposited by supersonic atmospheric plasma spraying Journal of Alloys and Compounds 632 pp 794–799

[8] Wei Li, Ping Liu, Yongsheng Zhao, Fengcang Maa, Xinkuan Liu, Xiaohong Chen and Daihua He 2013 Structure, mechanical properties and thermal stability of CrAlN/ZrO2 nanomultilayers deposited by magnetron sputtering Journal of Alloys and Compounds 562 pp 5–10

[9] Limin He, Xin Zhou, Bintao Zhong, Zhenhua Xu, Rende Mua, Guanghong Huang and Xueqiang Cao 2015 Phase evolution, interdiffusion and failure of La2(Zr0.7Ce0.3)2O7/YSZ thermal barrier coatings prepared by electron beam–physical vapor deposition Journal of Alloys and Compounds 624 pp137–147

[10] Ernst P and Distler B 2012 Optimizing the Cylinder Running Surface SAE International 9

[11] Yerokhin A and Khan R H U 2010 Anodising of Light Alloys Surface Engineering of Light Alloys: Aluminum, Magnesium and Titanium Alloys ed Cambridge pp 83-109

[12] Yerokhin A L, Nie X, Leyland A, Matthews A and Dowey S J 1999 Plasma electrolysis for surface engineering Surface and Coatings Technology 122, pp 73-93

[13] Dudareva N Yu, Butusov I A, Kalschikov R V, Grin R R, Alexandrov I V and Musin F F 2014 The Investigation of the Effect of Micro-Arc Oxidation Modes on the Adhesion Strength of Coatings Journal of Engineering Science and Technology Review 7 pp 5-8

[14] Dudareva N Yu, Enikeev R D and Ivanov V Yu 2017 Thermal Protection of Internal Combustion Engines Pistons Procedia Engineering 206 pp 1382–87

[15] Rozhdestvensky Y, Lazarev E and Doikin A 2016 Effect of the Heat Insulating Coating of the Piston Crown on Characteristics of the "Piston-Cylinder Liner" Pair Procedia Engineering 150 pp. 541-546

[16] AVL DynoPerform Load system with eddy current dynamometers https://www.avl.com/load-unit-for-engine-testing/asset_publisher/gYjUpY19vEA8/content/avl-dynoperform

[17] AVL fuel balance fuel consumption measurement https://wwwavl.com/documents/10138/2699442/Product+Description+Fuel+Balance

[18] Automobile 5-component gas analyzer Infrakar 5M-2.01 http://www.infracar.ru/products/group24/product24.htm

[19] TRM200 two-channel meter with universal input and RS-485 https://www.owen.ru/product/trm200

[20] Heywood J 1988 Internal combustion engine fundamentals McGraw- Hill