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Experimental Study of the Micro-Arc Oxide Coating Effect on Thermal Properties of an Aluminium Alloy Piston Head

N.Yu. Dudareva*, O.P. Dombrovskiy, R.V. Kalschikov and I.A. Butusov

Ufa State Aviation Technical University, Ufa, Russia – 450008

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Abstract

The purpose of the present study is to investigate the influence of differently sized microarc oxidation coatings, applied to the bottom of pistons made with an Al-12Si-Mg-Cu-Ni alloy, on its thermal properties by simulating the operation of a real engine. This study is based on the premise that the alumina coating thickness affects the heat transfer and temperature distribution in the piston. The analysis of thermal properties of pistons and suggestions for the optimal thermal barrier coating thickness are presented.

Keywords micro-arc oxidation, alumina coating, piston, thermal barrier coating.

1. Introduction

The trend in modern engine-building development is to continuously improve the operating performance of internal combustion engines (ICE), and particularly to increase the mean effective pressure in a combustion chamber; increasing as the result the mechanical and thermal loads on the cylinder-piston unit. The piston is the most heat loaded engine component as it is exposed to high cyclical temperatures, which lead to damage and burnout of the piston bottom.

In such conditions the piston material must meet the following requirements:

- to have low density to reduce inertial forces;
- to have high thermal conductivity to provide engine cooling;
- to have high strength properties at high temperatures;
- to have high wear resistance;
- the difference between the piston material's coefficient of thermal expansion and that of the cylinder barrel material must be kept to a minimum.

Aluminum alloys meet these requirements to a maximum, but in order to ensure high strength and good tribological properties of the alloys under heavy thermal cyclic load conditions, special protective coatings need to exist; among them, the development of new surface hardening technologies and surface layers that are well-bonded with the base material and have improved physical and mechanical properties is what is required.

The research and development of thermal barrier coatings (TBC) to be applied to the bottom of an engine piston , as well as to improve the operating characteristics of modern and future engines, are very important scientific and technological issues.

There are currently few methods of TBC known, among them: cladding the piston bottom with laminated plates, using special top plates, and forming ceramic coatings [1,2]. The most commonly used materials for such coatings are aluminum oxide and zirconium dioxide [3]. However, all types of such coatings present cracking problems and layer separation due to high-frequency thermal loads. At the moment, the development of TBC for combustion engine pistons using the micro-arc oxidation (MAO) process arouses considerable interest worldwide [4-5].

The principle of MAO lies in forming a high-impact ceramic layer (MAO layer) on the part surface with micro-arc discharge, which consists mainly of α-Al2O3 (corundum) and other aluminum oxides. The method produces coatings with a thickness of up to 400 μm and high microhardness of 5–24 GPa [6]. In this case, MAO layers show good adhesion with the base material even in heavy thermal cyclic loads conditions [7]. The surface layers formed by MAO are ceramics and have low thermal conductivity, which makes using MAO layers as thermal barrier coatings very effective [8].

However, the engine building theory and practice do not have a well-developed scientific and technological basis for the reduction of the thermal factor of aluminum alloy pistons by coating a piston bottom with thermal barrier oxide layers produced with MAO. There are published papers [9-10] in which research of the influence of an MAO layer on the piston thermal condition and engine operating characteristics has been performed. The results [11] obtained used special equipment and show that MAO layers with a thickness of 25–30 μm formed on the bottom and in grooves allow the reductionthe temperature of piston underside area by 23.9%. The calculated data provided in [12] shows that a layer 8 μm thick can reduce the piston temperature by 25%. Unfortunately, all this research was conducted with special equipment which differ real engine operation conditions, and calculations significantly depend on the initial conditions; moreover, there are no recommendations on how to choose the optimal thickness of a thermal barrier layer. As a result,

* E-mail address: natalia_jd@mail.ru
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the information on the effectiveness of thermal protection of internal combustion engine (ICE) pistons with MAO , as presented in scientific literature, is insufficient and contradictory.

The purpose of this work is the experimental study of the effect of various size MAO coatings, applied to the bottoms of ICE pistons, on piston thermal behaviour by simulating real engine conditions.

2. Materials and Methods

The work was conducted on a motorless bench of special design for studies of thermal conditions of a two-stroke engine piston. The motorless bench included a housing with a cylinder barrel installed in it, the piston to be studied, and a directed flame source which was a gas burner with a container containing gas fuel , which was a mixture of propane, butane and isobutane. The bench can have other heat sources, for example, a heating lamp. The housing had a water cooling jacket. The water circulation was provided by a pump connected through a pipe with the housing cooling jacket to simulate a water cooling system of an engine.

With the help of the gas burner, a temperature of (635±10)ºC was achieved in the area above the piston (see Fig. 1). This temperature was calculated from actual engine operating characteristics. The initial water temperature of the cooling system was set to (47±1)ºC and during testing it rise up to (54.5±1.5)ºC, which corresponds to a real engine operating mode.

The studies were conducted on an engineering sample of a standard two-stroke engine piston fabricated from AK12D (Al-12Si-Mg-Cu-Ni) aluminum alloy (see Fig. 2a), as well as on a similar piston having a thermal barrier coating formed on the piston bottom with MAO (see Fig. 2b). For testing purposes, pistons were fabricated with MAO layer thicknesses of 60 µm, 100 µm, 120 µm and 160 µm .

The MAO coating was performed in an alkaline electrolyte prepared with distilled water, KOH (2.5 g/l), and Na2SiO3 (2.5 g/l). The coating thickness was measured using a TT-220 eddy current gauge. After building the MAO layer, the piston was washed with stream , and 15–20 µm of mullite were mechanically removed from the surface.

At the beginning a piston without MAO coating was tested. It was installed in the motorless bench barrel and exposed to heating. During 30 minutes of testing the distribution of thermal fields at the piston bottom in the above piston area was recorded at 3-minute intervals (see Fig. 1). Temperature was monitored using a FLIRP 660 thermal imager, which allows measuring temperatures from 200ºC to +1200ºC and has a resolution of up to 0.1ºC at a recording speed of 15–25 frames per second. The water temperature was measured with a CENTER 350 infrared thermometer. The flame temperature was recorded with a TPM-200 measuring device and a K-type thermocouple (chromel–alumel) connected to it and securely fixed in the above piston area at a 10 mm distance away from the piston surface, above the bottom center (see Fig. 3). Testing of the piston with a MAO coating was conducted in a similar fashion.

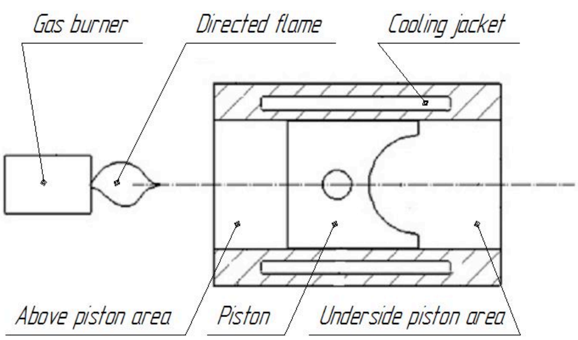
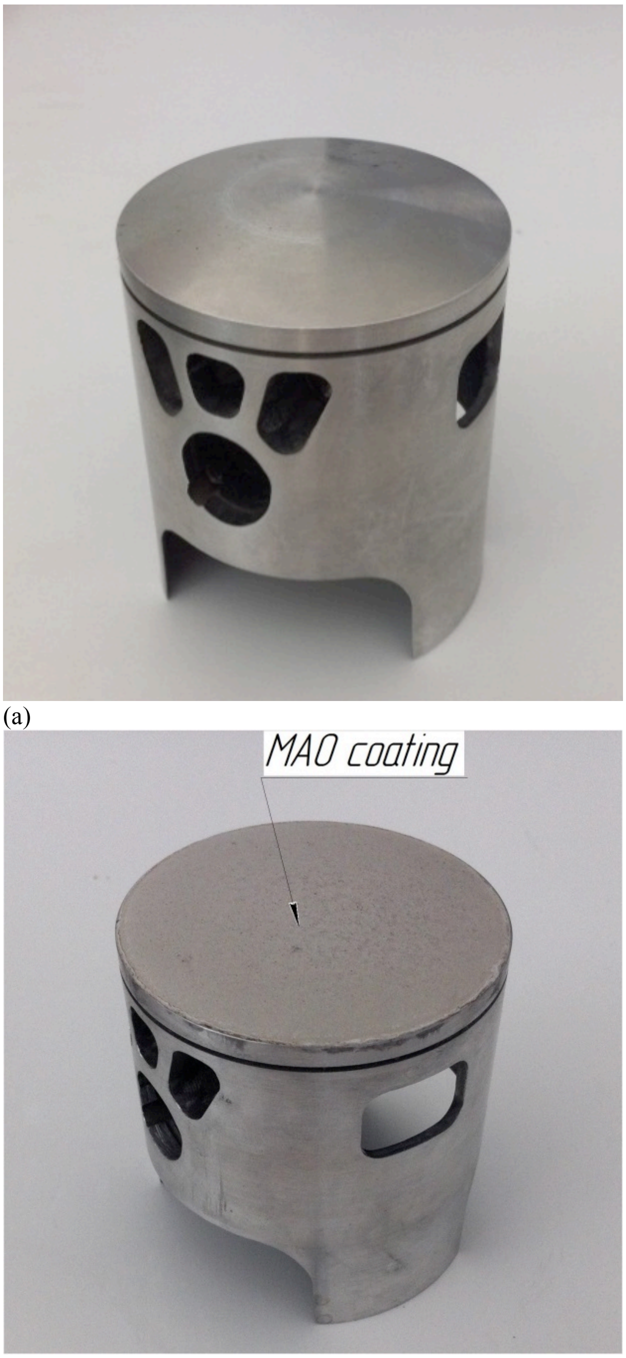


Fig. 1. Set up for piston heating in the motorless bench



(a)

(b)

Fig. 2. Two-stroke engine piston: a – without thermal barrier coating; b – with MAO coating.

Fig. 3. Area on top of the piston

3. Results and Discussion

Fig. 4 shows the change of the maximum piston surface temperature recorded by the thermal imager during testing. Tab. 1 shows the piston temperature reduction due to the MAO coatings with different thickness used

From the experiments it was found that the main temperature spike of the piston bottoms occurred 9 minutes after the test start. The results showed that the 100-µm MAO-layer piston had the lowest bottom temperature (144ºC), while the standard piston temperature achieved was 171ºC during testing. Over the length of time of the experiment, the 100-µm MAO-layer piston showed the best results. The effect of the piston temperature reduction due to the MAO thermal barrier layer could be seen in the high-temperature range, which is very important for high power engines.

Monitoring the cooling liquid temperature showed that it increased less when the 100-µm MAO-layer was present which is an indirect evidence that using MAO coating lowers heat transfer to the piston.

The maximum temperature of the piston bottom was measured at an exhaust port (see Fig. 5), due to the burning gases passing through it.

Further experiments will focus at the careful simulation of real engine thermal conditions in which temperature cycling in a combustion chamber will be considered. Moreover, it is reasonable to perform tests using another heat source – a heat lamp which does not simulate oxidation processes but provides a more uniform and steady heat flow affecting the piston bottom. The results of such a study can be useful for numerical modeling of ICE operations.

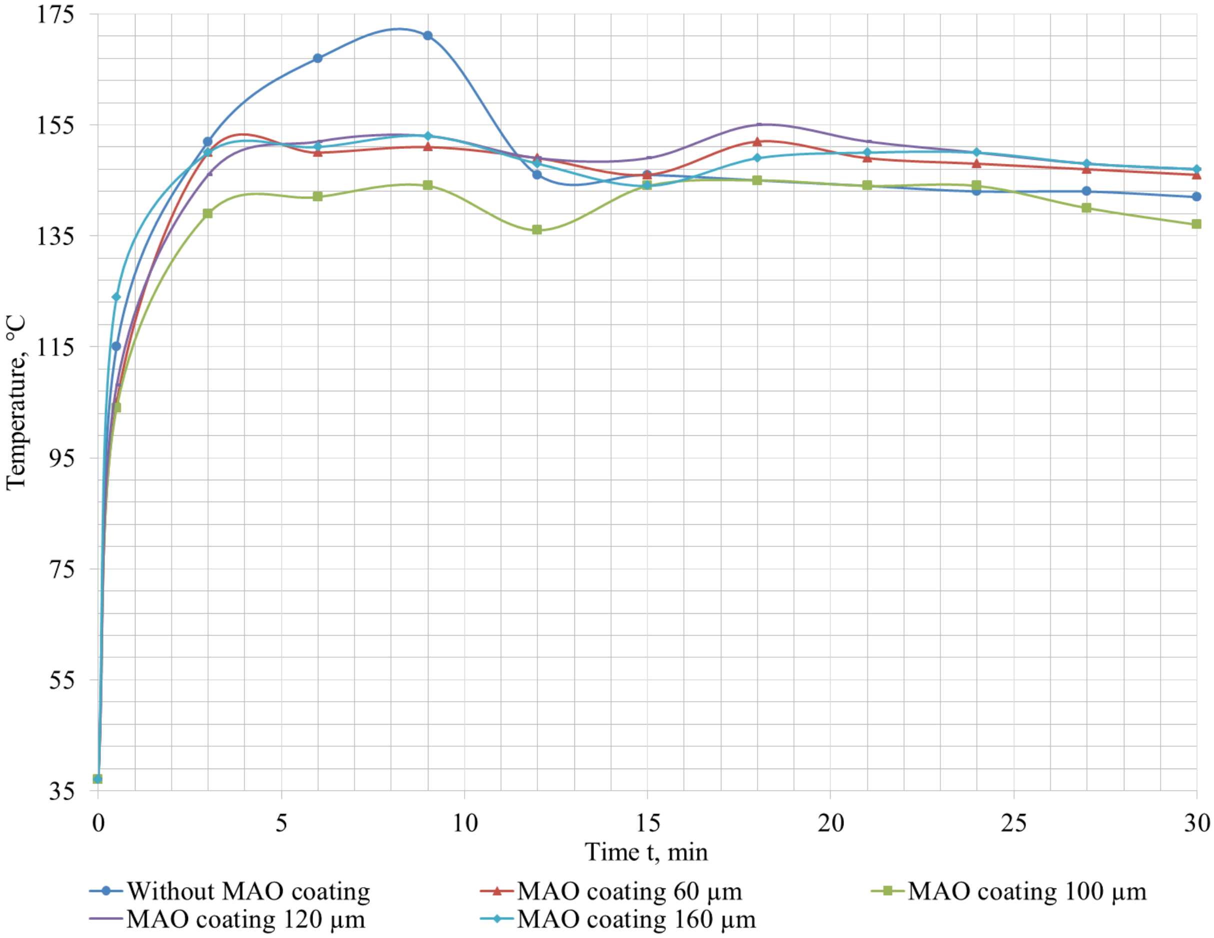


Fig. 4. Maximum piston temperature in the piston underside area.

Table 1. Piston temperature change due to different MAO coatings .

MAO coating thickness, *h*, µm	**Maximum piston temperature in the piston underside area, $t_{p.max}$, °C**	**Piston temperature reduction by comparison with uncoated piston, Δt, °C**
0	171	-
60	151	20
100	144	27
120	153	18
160	153	18

4. Conclusion

This work shows that the correct choice of the thickness of the MAO thermal barrier layer applied to the piston bottom can lower its thermal factor effectively, particularly in conditions of increased thermal loads in the engine. The experiments show that the heat-protective effect of a MAO-layer is 8 % on the average. It has been found that the most effective MAO-layer thickness is 100 µm to provide the best piston thermal protection.

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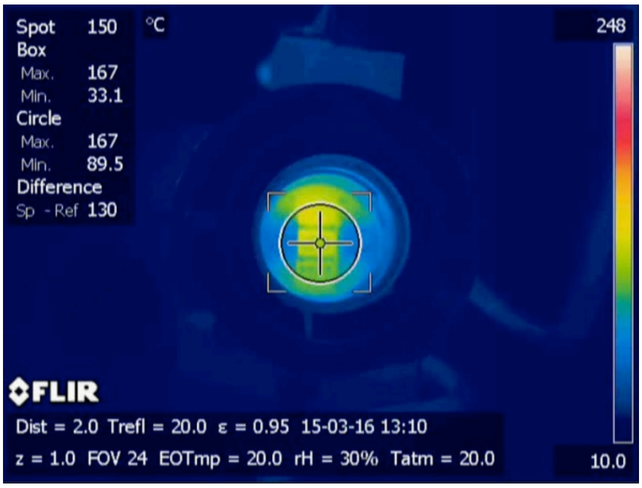

Fig. 5. Temperature pattern for a piston bottom without coating. Infrared image.

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