DOI: https://doi.org/10.17816/0321-4443-586629

Original Study Article

The efficiency of thermal protection of ICE pistons with the micro-arc oxidation

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ABSTRACT

BACKGROUND: In order to protect pistons of internal combustion engines (ICE) from burnout and increase their durability, it is reasonable to use ceramic coatings formed on the piston head with micro-arc oxidation (MAO). Many scientific papers have been devoted to the study of the efficiency of these coatings. However, most of these studies were carried out at laboratory facilities simulating the engine operation, generally, not taking into account the real thermophysical parameters of the MAO coating. Therefore, the thermal protection efficiency of these coatings is difficult to assess.

AIM: Study of efficiency of the thermal protection of pistons using a ceramic coating formed by micro-arc oxidation on the piston head with numerical simulation.

METHODS: The study was conducted in the SolidWorks Simulation software. Two piston aluminum alloys were used as the piston material: AK12d (with a silicon content of 12%) and AK4-1 (with a silicon content of 0.35%). Temperature loads corresponding to the operation of a real engine were applied to the surfaces of the model piston. At the first stage of the study, the thermal state of pistons made of different uncoated alloys was simulated. At the second and third stages of the study, the effect of the coating thickness on the piston thermal state was simulated. The piston material of the second study stage was the AK4-1 alloy. The piston material of the third study stage was the AK12d alloy. Ceramics, which properties correspond to the coatings properties formed with the micro-arc oxidation method on these alloys, were used as the coating material. The coating thickness varied in the range from 50 to 350 μm in increments of 100 μm. The probing method was used to determine the temperature in various areas of the piston, such as at the piston head surface at the MAO coating and under it, in the area of piston grooves, at a piston skirt and the piston head from the side of a crankcase.

RESULTS: With the simulation, it was found that:

1. The micro-arc coating of the piston head reduces the thermal tension of the piston regardless of the aluminum alloy chemical composition.
2. The efficiency of the piston's thermal protection increases with an increase in the ceramic coating thickness and a decrease in its thermal conductivity coefficient.
3. The greatest heat-protecting effect is achieved by the piston made of the AK12d eutectic alloy.

CONCLUSIONS: It is found that the MAO coating at the piston head is an effective way to reduce the thermal tension of the ICE pistons. Increasing the ceramic coating thickness and a decrease in its thermal conductivity coefficient increases the efficiency of the pistons thermal protection. Reducing the thermal conductivity of the MAO coating and increasing the MAO coating thickness increases the temperature on the coating surface.

Keywords: Internal combustion engines; thermal protection; ceramic coating; piston; micro-arc oxidation.

To cite this article:
Dudareva NYu, Kolomeichenko AV, Kisel YuE. The efficiency of thermal protection of ICE pistons with the micro-arc oxidation. *Tractors and Agricultural Machinery.* 2024;91(1):101–112. DOI: https://doi.org/10.17816/0321-4443-586629

Received: 21.09.2023 **Accepted:** 20.01.2024 **Published online:** 15.03.2024

DOI: https://doi.org/10.17816/0321-4443-586629

Оригинальное исследование

Эффективность тепловой защиты поршней ДВС покрытием, сформированным микродуговым оксидированием

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АННОТАЦИЯ

Обоснование. Для защиты поршней двигателей внутреннего сгорания (ДВС) от прогара и повышения их долговечности целесообразно использовать керамические покрытия, формируемые на днище поршня микродуговым оксидированием (МДО). Исследованию эффективности такого покрытия посвящено много работ. Однако, большинство подобных исследований проведены на лабораторных установках, имитирующих работу двигателя, и обычно не учитывают реальные теплофизические параметры МДО-покрытия. Поэтому оценить эффективность тепловой защиты такого покрытия довольно сложно.

Цель работы — исследование методом численного моделирования эффективности тепловой защиты поршней посредством керамического покрытия, формируемого методом микродугового оксидирования на поверхности днища поршня.

Методы. Исследование проводилось в программе SolidWorks Simulation. В качестве материала поршня использовались два поршневых алюминиевых сплава: АК12д (с содержанием кремния 12%) и АК4-1 (с содержанием кремния 0,35%). К поверхностям образцового поршня прикладывались температурные нагрузки, соответствующие работе реального двигателя. На первом этапе моделировалось тепловое состояние поршней из разных сплавов без МДО-покрытия. На втором и третьем этапах исследовалось влияние толщины керамического покрытия, сформированного на днище поршня, на его тепловое состояние. На втором этапе материалом поршня являлся сплав АК4-1, а на третьем этапе — сплав АК12д. В качестве материала покрытия использовалась керамика, свойства которой соответствовали свойствам покрытий, формируемых методом микродугового оксидирования на рассматриваемых сплавах. Толщина покрытия изменялась с шагом 100 мкм в диапазоне от 50 до 350 мкм. Температура определялась методом зондирования в различных областях поршня: на поверхности днища на МДО-покрытии и под ним, в области поршневых канавок, на юбке поршня и на поверхности днища поршня со стороны картера.

Результаты. Моделированием установлено:

1. Покрытие днища поршня микродуговым оксидированием снижает тепловую напряженность поршня не зависимо от химического состава алюминиевого сплава.
2. Эффективность теплозащиты поршня повышается при увеличении толщины керамического покрытия и при уменьшении его коэффициента теплопроводности.
3. Наибольший теплозащитный эффект достигается у поршня из эвтектического сплава АД12д.

Заключение. Установлено, что МДО-покрытие на днище поршня является эффективным способом снижения тепловой напряжённости поршней ДВС. Повышение толщины керамического покрытия и снижение его коэффициента теплопроводности ведет к увеличению эффективности тепловой защиты поршней. Снижение коэффициента теплопроводности МДО-покрытия и увеличение его толщины также приводит к росту температуры на поверхности керамического покрытия, нанесенного на днище поршня.

Ключевые слова: двигатель внутреннего сгорания; тепловая защита; керамическое покрытие (МДО-покрытие); поршень; микродуговое оксидирование.

Как цитировать:
Дударева Н.Ю., Коломейченко А.В., Кисель Ю.Е. Эффективность тепловой защиты поршней ДВС покрытием, сформированным микродуговым оксидированием // Тракторы и сельхозмашины. 2024. Т. 91, № 1. С. 101–112. DOI: https://doi.org/10.17816/0321-4443-586629

Рукопись получена: 21.09.2023 **Рукопись одобрена:** 20.01.2024 **Опубликована онлайн:** 15.03.2024

BACKGROUND

Pistons are heavily loaded parts of internal combustion engines (ICE). During engine operation, the piston heads perceive high pressure (up to 8 MPa), come into contact with gases formed during fuel combustion, whose temperature reaches approximately 2500°C, and heat at temperatures of up to 350°C–450°C [1, 2]. These cyclic temperature and mechanical loads, which lead to burnout of the bottom parts of the pistons, result in the destruction of the pistons and ICE failure [3, 4]. For this reason, the choice of piston material is a key factor in ensuring reliable and durable operation of not only this part but the entire engine. Aluminum alloys are typically used in the production of pistons; however, because they do not have high heat resistance, use of this material can increase the probability of burnout [5].

To prevent burnout, various methods are used, namely, 1) the rejection of aluminum alloys and production of pistons from steel, cast iron, or composite materials; 3) the use of special heat-insulating linings and inserts for the bottom part; 2) the application of special heat-insulating coatings on the surface of the pistons, consisting mainly of oxides, such as ZrO_2, Al_2O_3, MgO, BeO, or complex-component coatings, such as NiCrAl [6–8]. However, such solutions are not always optimal due to various reasons [9].

At present, the most promising and actively developing technology that allows the formation of heat-protective ceramic coatings on parts made of aluminum alloys is microarc oxidation (MAO) [10, 11]. Their many advantages include the following: thicknesses of up to 300–400 microns, consist predominantly of aluminum oxides, characterized by high adhesion to the base material even under conditions of significant thermal cyclic loads, and good corrosion resistance, high microhardness (up to 22 GPa) [12], and low thermal conductivity coefficient of approximately 0.5–5 W/(m·K) [13, 14]. Another distinctive feature of MAO coatings is that their thermal conductivity coefficient depends on the substrate material. For example, the thermal conductivity coefficient of the MAO coating on aluminum alloys with a small amount of silicon in the chemical composition (AK4-1 type) is approximately 4.5–5.0 W/(m·K) [15], while the thermal conductivity coefficient is 1.0–1.5 W/(m·K) on alloys with a high silicon content (12% and more) [16].

Currently, MAO coatings are already used for the thermal protection of pistons. A study [17] demonstrated a temperature decrease of 33°C (23.9%) on the surface of the piston crown on the crankcase side when a coating with a thickness of only 25–30 microns is applied to the piston crown and piston grooves. Other studies note that 25–30 µm MAO coating reduces the thermal effect on the piston by only 15% [18]. Furthermore, studies conducted on diesel ICEs have shown that MAO coatings with a thickness of 120–160 microns reduce piston temperature by 6.5°C [19].

Despite the abovementioned findings, available scientific and technical information is unsystematized and insufficient in terms of depth and volume. While the information presented enables researchers to conclude that MAO coatings can be used for the piston thermal protection, it does not allow for evaluations of the effectiveness of these coatings. This gap can be attributed to several reasons. First, past research did not consider the fact that the thermophysical properties of MAO coatings (specific heat capacity and thermal conductivity coefficient) largely depend on the aluminum alloy chemical composition from which the piston is made [14–16]. Such studies typically use a reference value for the thermal conductivity coefficient of aluminum ceramics, which differs significantly from those of MAO coatings [13, 20]. Second, the technical and methodological complexities of organizing thermophysical measurements on the piston of a running engine contribute to the fact that many of the experimental data were obtained on nonmotorized stands or in laboratory installations, whose operating conditions differ from the operation of real ICEs. Third, many of the experimental data indicated in the works were obtained on pistons with different MAO coating thicknesses, whereas the thickness of the ceramic coating, like any heat-protective layer, has a significant impact on the effectiveness of the thermal protection of the part.

One modern approach that can be used to examine the influence of the MAO coating on the thermal state of the piston, while considering its complex geometric shape, material properties, and the thickness and thermophysical properties of the MAO coating, is numerical modeling using modern application programs [21, 22]. The main aim of the current work is formulated based on this approach.

STUDY AIM

The work aim is to study, using numerical modeling, the effectiveness of pistons thermal protection due to the ceramic coating formed by MAO on the piston crown.

STUDY METHODS AND DESIGN

The study was performed on a three-dimensional (3D) model of the piston using numerical modeling in the SolidWorks 2018 program in the SolidWorks Simulation application. These programs are used for thermal calculations of parts taking into account temperature loads of various types [21, 22].

The research was performed in three stages. At Stage 1, the thermal state of pistons without ceramic coating was simulated. This experiment enabled us to determine the influence of the piston material properties on its thermal state. In accordance with GOST 4784-2019, the materials were set as two deformable aluminum alloys with different amounts of silicon in the chemical composition, namely, hypoeutectic aluminum alloy AK4-1 and eutectic alloy AK12d with silicon contents of 0.35% and 11%–13% Si (by weight), respectively.

At Stage 2, an experiment was performed to determine the influence of the thickness of the MAO coating formed on the piston crown on its thermal state. Here, AK4-1 alloy was chosen as the piston material. Four calculations were performed, with different MAO ceramic coating thicknesses.

Stage 3 was similar to Stage 2, in which we chose AK12d alloy as the piston material. At this stage, four calculations were performed for different thicknesses of the ceramic coating. The temperature loads applied to the piston surfaces were specified by boundary conditions, namely, temperature and convective heat transfer coefficient of the gases.

The boundary conditions were the same for all stages of modeling.

ELIGIBILITY CRITERIA

In the research, we used a 3D piston model made in the SolidWorks program (Fig. 1a). The piston has a diameter of 76 mm. The piston crown was spherical and convex, with a radius of curvature of 322 mm. This piston was chosen as a model due to the fact that, previously, in the ALBEA simulation system, a complex web of temperature loads acting on the surface of this piston was determined and the convective heat transfer coefficients were calculated [23, 24]. Diagrams of the application of the main loads on the base surfaces of the piston and on the surface of the piston grooves are presented in Fig. 2a and 2b, respectively. The values of the boundary conditions are presented in Table 1.

The choice of materials for modeling was determined by the following facts. First, the bulk of modern pistons are made of eutectic aluminum alloys, such as AL30, AK12, and AK12d. All these alloys contain 11%–13% silicon, and because it is the main alloying element, this determines the physical and mechanical properties of the alloy. The AK12d alloy, a eutectic wrought alloy,

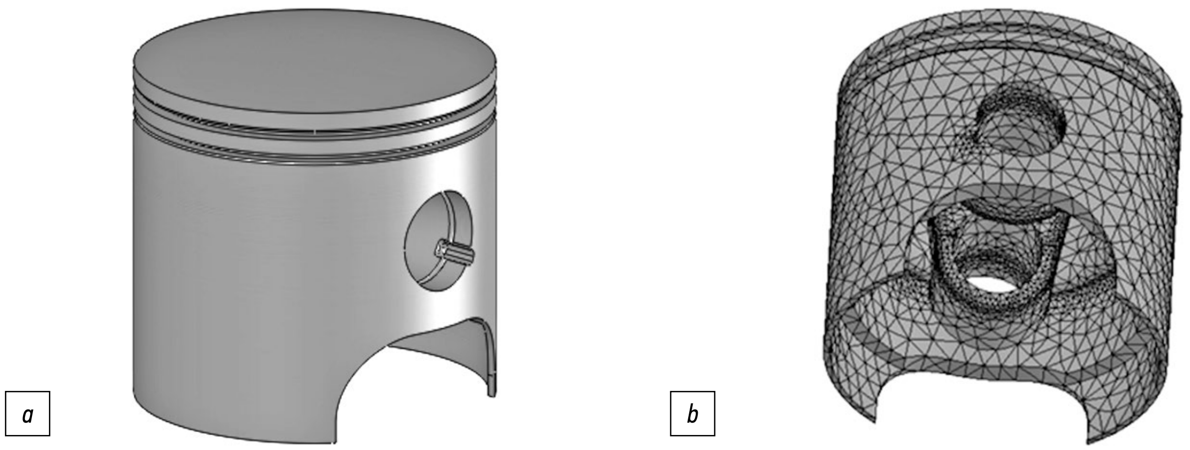

Fig. 1. The engine piston assembly model: *a* — the SolidWorks 3D-model; *b* — the meshed model.
Рис. 1. Модель поршня двигателя: *a* — 3D-модель в SolidWorks; *b* — модель с сеткой.

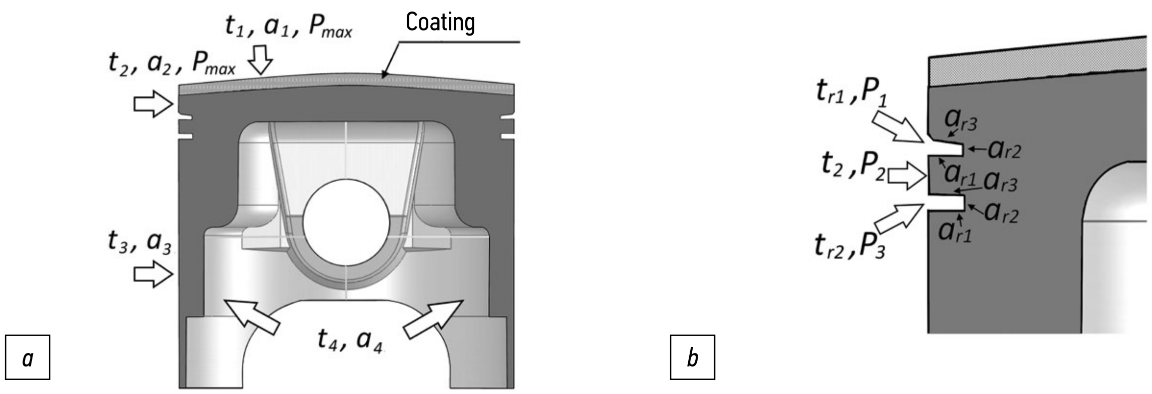

Fig. 2. Diagram of temperature and mechanical loads: *a* — at the main piston surfaces; *b* — at the piston grooves surface.
Рис. 2. Схема температурных и механических нагрузок: *a* — на основных поверхностях поршня; *b* — на поверхностях поршневых канавок.

Table 1. Boundary conditions
Таблица 1. Граничные условия

Convective heat transfer coefficient, W/(m²·K)		Temperature, K	
Designation	**Value**	**Designation**	**Value**
a_1	592	t_1	1413
a_2	148	t_2	1413
a_3	1485	t_3	473
a_4	174	t_4	363
ar_1	11609	tr_2	423
ar_2	97	tr_1	573
ar_3	1818		

was chosen as the study material. AK4-1 aluminum alloy is also a piston wrought aluminum alloy, which is close to duralumin in terms of composition and is widely used throughout the world due to its high heat resistance [25]. Second, for MAO coatings obtained on these alloys, the thermophysical properties (thermal conductivity coefficient and specific heat capacity) were previously determined [15, 16], allowing us to conduct research using the current values of thermophysical properties not only for aluminum alloys but also for MAO coatings.

The calculations for Stage 1 were performed on a 3D model of the piston, whereas the calculations for Stages 2 and 3 were performed on multilayer structures representing a 3D assembly of the piston and ceramic coating. The ceramic coating model was a thin film that replicated the surface of the piston crown in terms of shape and size. Calculations were performed for MAO coatings of different thicknesses: 50, 150, 250, and 350 μm. The choice was justified by the technological capabilities of MAO, as this technology does not allow the formation of ceramic coatings with a thickness of more than 350–400 μm [12, 13].

CONDITIONS

The application of temperature loads considered the fact that the temperature field of the piston during the ICE operating cycle changes insignificantly and can be considered stationary. Therefore, local values of gas temperatures and convective heat transfer coefficients were replaced by average constant values of temperatures and convective heat transfer coefficients. This approach is often used in the thermal modeling of ICE parts [24, 26, 27].

STUDY PROCEDURES

The materials of the piston and MAO coatings were specified prior to the simulation. Due to the fact that the SolidWorks library does not contain all materials, it is possible to create new materials and change their properties. Thus, a user-defined material was selected for the piston based on an aluminum alloy, the properties of which were adjusted in accordance with the alloys used in the study, namely, AK4-1 or AK12d. The material chosen for the MAO coating was ceramics, whose basic properties were also adjusted in accordance with the reference data [28]. The thermophysical parameters of MAO coatings were preliminarily calculated using the equations presented in [15, 16] while also considering the piston alloy. The characteristics of aluminum alloys and MAO coatings formed on these alloys and used in subsequent modeling are presented in Table 2. When modeling, we used the characteristics of MAO coatings and aluminum alloys corresponding to a piston heated to a temperature of 350°C.

Due to the fact that calculations of a piston with MAO coating were performed in assemblies consisting of “piston” and “coating” models, we ensured that the nodes of the finite element meshed on the coinciding mating models, thereby allowing us to obtain the most accurate results [29]. For this purpose, when creating the assembly, two mates were specified between the “piston” and the “coating,” namely, “coincidence” and “concentricity” for the spherical faces and the cylindrical edges of the piston and the coating, respectively. Next, temperature loads were applied to the 3D model of the piston (Fig. 2, Table 1).

A finite element mesh was constructed after specifying the materials on the models. The mesh quality was set to “high,” and this was constructed by considering the mixed curvature of the surfaces (Fig. 1*b*). With such a mesh, the finite elements had a minimum size of 1.01 mm, a maximum element size of 5.08 mm, and minimum element thickness corresponding to the thickness of the MAO coating. The number of finite elements in the models was 38406, while that in the nodes was 62112.

The thermal state of the piston was calculated after creating the finite element mesh.. Next, the piston temperature was determined at specific points. Their location is presented in Fig. 3.

Table 2. Properties of piston materials (the AK4-1 and AK12d aluminum alloys) and MAO coatings [15, 16, 28]
Таблица 2. Свойства материалов поршня (алюминиевых сплавов АК4-1 и АК12д) и МДО- покрытий [15, 16, 28]

Characteristics	Values			
	AK4-1		AK12d	
	Aluminum alloy	MAO coating	Aluminum alloy	MAO coating
Density, ρ, kg/m^3	2800	3128	2680	2720
Yield strength $\sigma_т$, MPa				
– at 20 °C	310–330	–	190–230	–
– at 350 °C	30–50	–	20–30	–
Tensile strength, σ_u, MPa				
– at 20 °C	380–400	172	200–250	172
– at 350 °C	30–50	172	35–55	172
Elasticity modulus, E, GPa	72	220	80	220
Poisson's ratio, μ	0,33	0,22	0,33	0,22
Shear modulus, G, GPa	27	90	27	90
Thermal expansion, α, 10^{-6} 1/K				
– at 20 °C	20,6	4,7	20,6	4,7
– at 350 °C	23,4	5,2	23,4	5,2
Thermal conductivity, λ, W/(m·K)				
– at 20 °C	144	5,1	162	1,5
– at 350 °C	175	4,4	165	1,6
Heat capacity, C_p, J/(kg·K)				
– at 20 °C	863	803	818	851
– at 350 °C	1053	1232	970	1032

MAIN RESEARCH OUTCOME

As a result of modeling at Stages 2 and 3, temperature values on the surface of the piston coating (T_1–T_3) were obtained. Temperatures were determined at points on the surface of the piston crown (T_4–T_6), which, for Stages 2 and 3 of modeling, were under the MAO coating. The temperature at the center of the piston crown on the surface located on the crankcase side (point T_7) was also determined.

ADDITIONAL RESEARCH OUTCOMES

Due to the fact that burnout is sometimes noted in the area of the piston grooves, the effect of the MAO coating on the temperature in the area of the grooves (T_8–T_{10}) was determined as additional modeling results. As an additional parameter, the temperature on the piston skirt at point T_{11}, located in the middle of its height, was determined.

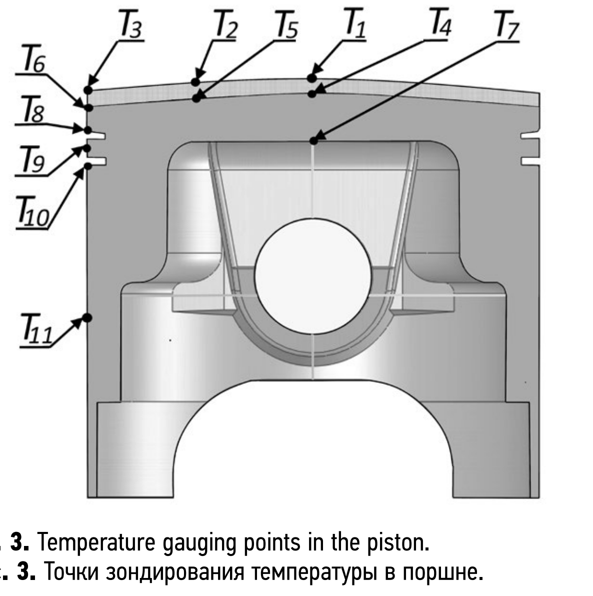

Fig. 3. Temperature gauging points in the piston.
Рис. 3. Точки зондирования температуры в поршне.

ANALYSIS IN SUBGROUPS

To analyze the temperature distribution in the piston, all the results obtained were divided into subgroups. Group 1 included temperatures that facilitated the evaluation of the heating of the piston crown with MAO coating (T_1, T_2 и T_3). Group 2 included temperatures characterizing the state of the metal surface of the piston crown under the coating T_4, T_5, T_6. The temperature state in the piston grooves area was estimated by temperatures T_8, T_9 and T_{10}, which were included in Group 3.Temperatures T_7 and T_{11} were independent measurements.

METHODS OF OUTCOME REGISTRATION

A SolidWorks Simulation tool called a probe was used to record temperatures at specific points on the piston. By using such a tool, the temperature can be determined in a specific finite element of the object under study.

STATISTICAL ANALYSIS

Principles for calculating sample size

Dividing the simulation data into groups facilitated the estimation of the temperature in individual areas of the piston. In the formed subgroups, the average temperature value was calculated as the arithmetic mean. The average temperature on the coating in Subgroup 1 (T_{av1}) was calculated as the arithmetic mean of the values T_1, T_2, and T_3. The average temperature value in Subgroup 2 (T_{av2}) and in Subgroup 3 (T_{av3}) was calculated in a similar manner.

Methods of statistical data analysis

Statistical analysis of the data was not performed because the research results were obtained using the finite element method and did not contain random and instrumental errors.

RESULTS

Objects (participants) of the study

As a result of the simulation, an array of data on temperatures at individual points of the piston was obtained.

Main research results

All data on temperatures at the probing points of the piston with MAO coating on the bottom are presented in Table 3.

Additional research results

The results of data processing for Subgroups 1–3 are presented in Figs. 4–6, respectively.

DISCUSSION

Summary of main research results

Analysis of the data obtained revealed that, regardless of the chemical composition of the aluminum alloy, the presence of MAO coating on the piston crown reduces its thermal stress. Furthermore, the efficiency of thermal protection increases with increasing thickness of the MAO coating and decreasing thermal conductivity coefficient. The greatest heat-protective effect is registered for a piston made of eutectic alloy AK12d.

Table 3. Temperatures of the piston with various thickness of the MAO-coating

Таблица 3. Температуры поршня с разной толщиной МДО-покрытия

MAO coating thickness, μm	Temperature at probing points, K										
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}
for AK4-1 alloy piston											
0	–	–	–	619	603	582	608	575	527	512	498
50	625	609	585	618	601	581	605	573	526	512	495
150	626	613	594	617	600	580	604	572	525	511	496
250	627	617	605	616	599	579	604	572	525	510	496
350	630	621	616	620	602	581	607	573	524	510	495
for AK12d alloy piston											
0	–	–	–	624	612	585	611	577	527	511	499
50	644	622	593	620	603	581	605	574	526	512	498
150	645	635	618	618	601	580	605	572	524	509	495
250	645	646	644	615	598	577	603	570	523	508	494
350	645	657	668	613	603	574	600	568	522	507	494

DOI: https://doi.org/10.17816/0321-4443-586629

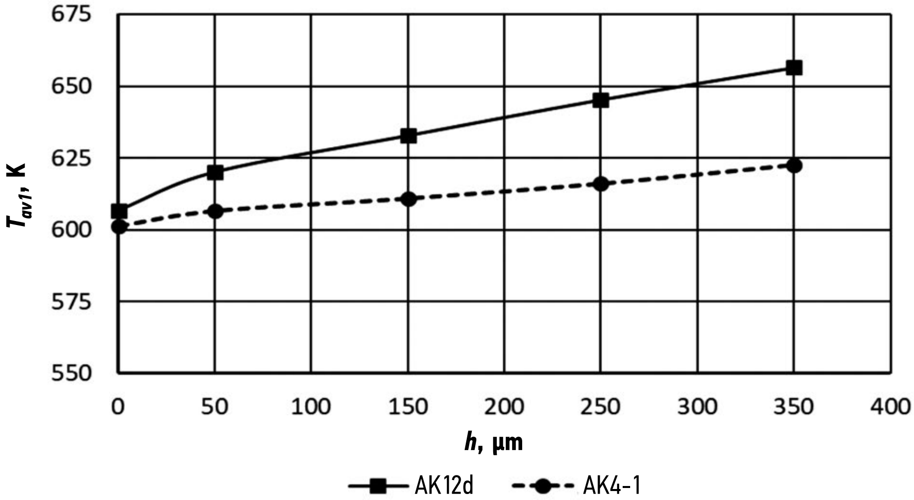

Fig. 4. Average temperature at the piston head surface.
Рис. 4. Средняя температура на поверхности днища поршня.

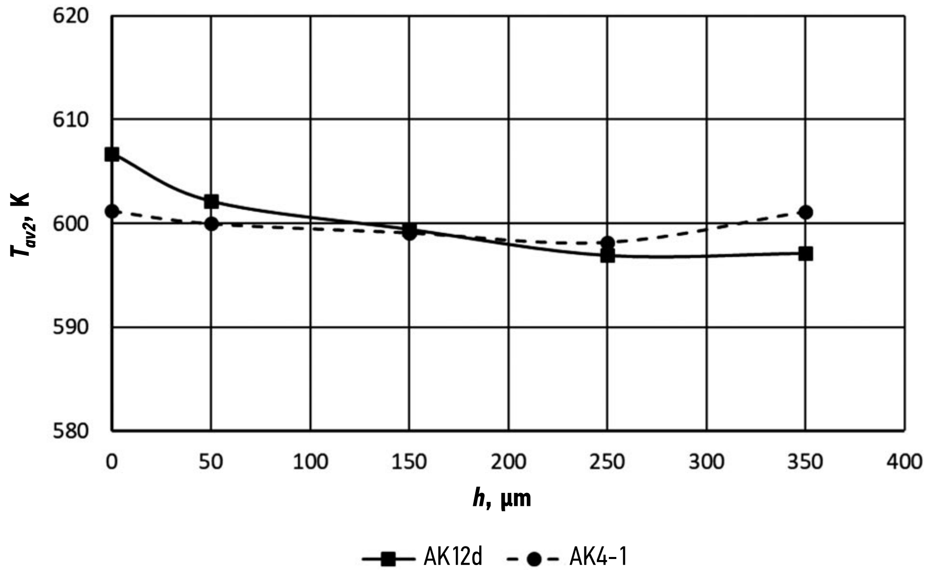

Fig. 5. Average temperature at the piston head surface under the coating.
Рис. 5. Средняя температура на поверхности днища поршня под МДО-покрытием.

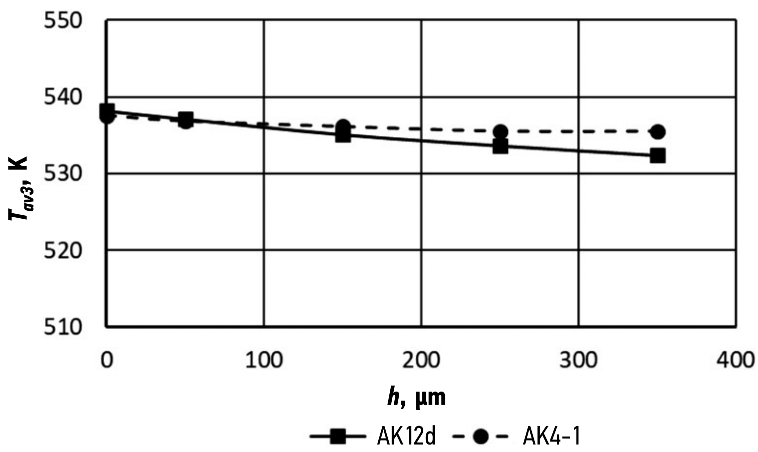

Fig. 6. Average temperature in the area of piston grooves.
Рис. 6. Средняя температура в области поршневых канавок.

Discussion of the main research result

The results also showed that in the absence of a ceramic coating, the properties of the aluminum alloy have little effect on the thermal state of the pistons. The temperatures in the area of the piston grooves and on the piston skirt (at points T_8, T_9, T_{10} and T_{11}) for both the piston made of AK4-1 alloy and the piston made of AK12d alloy are practically the same, although they differ by no more than 2 K. In addition, the temperature of the bottom part of the piston from AK4-1 is lower on average by 5 K, given that this alloy has a higher thermal conductivity coefficient. As a result, heat removal from the bottom improves and its temperature decreases (Table 3).

The MAO coating on the bottom reduces the temperature of the piston metal. The greatest effect for a piston made of AK4-1 is recorded with a coating thickness of 250 μm; the temperature at the center of the bottom under the MAO coating decreased by 3 K compared with an uncoated piston. However, increasing the coating thickness to 350 μm leads to an increase in the temperature on the surface of the coating itself, which increases the temperature under the coating. As a result, the heat-protective effect of the thick coating (350 μm) on the AK4-1 alloy piston almost disappears. Furthermore, we established that the temperature at the center of the piston crown (point T_4) made of AK12d alloy decreases by 11 K with a coating thickness of 350 μm (Fig. 5), which can be attributed to the low thermal conductivity coefficient of the MAO coating. The dependence of the average temperature under the coating on a piston made of AK12d alloy is expressed in the following equation:

$$T_{av2(\text{АК12д})} = 604,6 - 0,026h, \qquad (1)$$

where T_{av2} is the average temperature of the piston under the ceramic coating, K, and h is the ceramic coating thickness, μm.

For a piston made of AK4-1 alloy, this equation has the following form:

$$T_{av2(\text{АК4-1})} = 600,2 - 0,002h, \qquad (2)$$

The temperature reduction in the area of the piston grooves also depends on the MAO coating thickness on the bottom and has an average value of 2.3 K with thicknesses of 350 microns and 6 K for AK4-1 and AK12d pistons, respectively. The effect of the ceramic coating on the temperature in the area of the piston grooves can be described by the following linear relationships (Fig. 6):

$$T_{av3(\text{АК12д})} = 538 - 0,017h, \qquad (3)$$

$$T_{av3(\text{АК4-1})} = 537,3 - 0,006h, \qquad (4)$$

where T_{av3} is the average piston temperature in the area of the piston grooves, K.

The temperature at point T_7, located on the piston crown on the crankcase side, is reduced because of the ceramic coating on the AK4-1 piston by 4 K at 250 μm and on the AK12d piston by 11 K at 350 μm (Table 3). Similarly, the temperature on the piston skirt at point T_{11} is also reduced due to the ceramic coating, so that with a thickness of 350 μm, the reduction is 5 K on a AK12d piston and 3 K on a AK4-1 piston (Table 3).

The MAO coating helps to increase the temperature on its surface, such that the lower the thermal conductivity coefficient of the ceramic coating, the higher this temperature becomes (Fig. 4). The MAO coatings on the AK12d and AK4-1 alloys have thermal conductivity coefficients of 1.6 and 4.5 W/(m·K), respectively. As a result, with a ceramic coating thickness of 350 μm, a temperature increase of 50 K is registered on the surface of the AK12d alloy piston; under the same conditions, the temperature increase on the AK4-1 piston crown is recorded at 21 K (Fig. 4). The dependence of the average temperature on the coating surface T_{av1} for pistons made of different alloys can be represented by the following equations:

$$T_{av1(\text{АК12д})} = 610,4 - 0,137h \text{ and}$$

$$T_{av1(\text{АК4-1})} = 602,2 - 0,058h.$$

Study limitations

Despite the fact that the temperature distributions in the piston determined in this work were obtained for a specific two-stroke engine, this effect can also be attributed to the pistons of other ICEs. If the chemical composition of the piston material and the temperatures of the piston without coating are known, then the temperatures can be predicted in different zones of the piston with an MAO coating on its piston crown in accordance with Eqs. (1)–(4).

CONCLUSION

As a result of the research, we established that the MAO coating on the ICE piston crown is an effective way of reducing the thermal stress of pistons made of aluminum alloys. Our findings reveal that the piston temperature decreases under the ceramic coating, under the piston crown on the crankcase side, in the area of the piston grooves, and on the piston skirt. Increasing the MAO coating thickness increases the efficiency of the pistons' thermal protection. A decrease in the thermal conductivity of a MAO coating leads to an increase in the temperature on its surface and an increase in the heat-shielding effect. The greatest heat-shielding effect is registered on a piston made of eutectic alloy.

DOI: https://doi.org/10.17816/0321-4443-586629

ADDITIONAL INFORMATION

Authors' contribution. N.Y. Dudareva — literature review, collection and analysis of literary sources, performing simulations, preparation and writing of the text of the article, interpretation of the results; A.V. Kolomeichenko — collection and analysis of literary sources, editing of the article; Yu.E. Kisel — collection and analysis of literary sources, editing of the article.
All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

Competing interests. The authors declare that they have no competing interests.

Funding source. The research was supported by the Ministry of Science and Higher Education of the Russian Federation within the framework of the State Assignment No. FEUE-2023-0007 (UUST).

ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад авторов. Н.Ю. Дударева — обзор литературы, сбор и анализ литературных источников, проведение моделирования, подготовка и написание текста статьи, интерпретация результатов; А.В. Коломейченко — сбор и анализ литературных источников, редактирование статьи; Ю.Е. Кисель — сбор и анализ литературных источников, редактирование статьи. Авторы подтверждают соответствие своего авторства международным критериям *ICMJE* (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией).

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с проведённым исследованием и публикацией настоящей статьи.

Источник финансирования. Исследование выполнено при поддержке Министерства науки и высшего образования РФ в рамках Государственного задания № FEUE-2023-0007 (УУНиТ).

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