Promising methods for strengthening piston aluminum alloys of heat engines

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Abstract. Due to the increase in the specific power of heat engines, one of the most pressing problems of modern engineering is the increase in the contact strength and heat resistance of piston aluminum alloys. The article considers the main promising methods of strengthening piston aluminum alloys in the aspect of modern technologies. Long-term operation of heat engines in operating conditions close to critical conditions contributes to melting of the grain boundaries of piston alloys, which negatively affects the reliability of internal combustion engines. In General, the task of increasing the heat resistance of piston aluminum alloys is one of the main tasks of modern engineering.

1. Introduction
Improving the performance of automotive diesels in the face of increasing demand in the automotive industry is one of the most urgent tasks. This task is solved both by improving the engine workflow and by optimizing the main components and parts.

The possibility of improving the working process of a piston engine by increasing gas pressures and thermal loads on parts is largely related to the design of the piston, the technologies and materials used in its production. This is especially true when using alternative fuels, in particular natural gas, when the temperature in the combustion chamber increases significantly [1-3].

When the engine is running, especially under high temperatures and pressures, special attention is paid to the design of the piston, which determines the main performance of the engine [4-6].

The piston must have sufficient strength characteristics that provide the necessary reliability and durability in conditions of high dynamic, mechanical and thermal loads. At the same time, it must have a low mass, high wear resistance of the contact surfaces, low friction losses with minimal mounting gaps in the cylinder, optimal thermal conductivity and a low coefficient of thermal expansion.

A special place is given to working out the design of the piston using the latest computational optimization methods, which will allow you to choose the best material, type of hardening and geometric configuration for a particular type of engine, ensuring compliance with environmental standards and high fuel efficiency.

2. Main methods of strengthening piston aluminum alloys
Currently, various methods of hardening aluminum alloy parts are used. The use of these methods is associated with known difficulties typical for surfacing aluminum alloys.
The most common technology for hardening aluminum alloy parts is argon-arc surfacing. Alloying elements can be introduced into the molten metal in the form of filler wire or powder. Solid cross-section, powder, and composite wires are used for hardening.

Among the first to be developed was a method for restoring aluminum pistons by means of mechanized argon-arc surfacing with a melting electrode along a helical line [7-9]. The filler wire used was SV-AK5 and SV-Amgb wire with a diameter of 1.8 and 2.0 mm. The standard welding wire used in this case does not allow sufficient alloying of the surfacing metal, which leads to obtaining a weld metal with an insufficiently high hardness. And, in addition, during the surfacing process, due to the extended surfacing cycle (17 passes), there is a significant softening of the base metal associated with increased heat stress.

A method of hardening is used with the use of steel wire of the SV-08G2S brand [7, 8]. During the remelting process, the additive material interacts with the matrix aluminum alloy. The use of steel wire for hardening does not allow to obtain a uniform structure. During crystallization, large macro-inclusions of intermetallides up to 3 mm in size are formed, which cannot be crushed even by repeated remelting.

In the metal deposited on the AL 25 alloy using the SV-08G2S wire as an additive, its insoluble particles remain, which are painted during mechanical processing [9-11].

The technology of plasma hardening of aluminum alloy parts is widely known. There is a sufficient choice of surfacing materials to obtain the deposited metal of the required hardness and wear resistance. A method for strengthening tractor pistons by plasma arc surfacing with a direct current of reverse polarity according to the scheme of using a straight arc with the use of aluminum filler wire has been developed. The surfacing process lasts 15 ... 17 minutes, the height of the weld reinforcement is 10 ... 12 mm [11, 12].

The technology of plasma surfacing of wear-resistant metal with simultaneous use of aluminum welding wire and powders of wear-resistant materials is well known [13]. In this case, a shell is formed, the material of which is an aluminum matrix with chromium particles distributed in it. The main drawback of the developed technological process is the production of a deposited composite alloy with a fairly large uneven distribution of the introduced powders and their high dispersion. Despite the fact that the plasma hardening process allows you to widely adjust the composition of the deposited metal, in real conditions this is not achieved due to the use of standard welding wires with a limited number of alloying components and modifying additives.

There is also a method for strengthening aluminum parts using electron-beam surfacing [14]. Using a concentrated source of energy, it is possible to achieve a sufficiently large depth of penetration. Despite the fact that various powders of wear-resistant materials, wires, foils and a number of other materials can be used as alloying additives for electron-beam surfacing, the use of this method is difficult due to low productivity and complexity of the equipment.

Recently, much attention has been paid to research in the field of applying wear-resistant coatings with gas-thermal spraying.

The use of self-fluxing materials for this purpose is impossible due to the high heating of aluminum parts during the melting of coatings, and the widespread use of aluminum-Nickel compositions obtained by chemical deposition of Nickel on aluminum powder is complicated by high cost and scarcity. In addition, thermal deposition of wear-resistant materials on the grooves of aluminum alloy pistons does not provide sufficient adhesive strength when working with a piston ring-groove pair under shock-cyclic wear conditions at temperatures up to 573 K.

Recently developed method of pulsed arc welding with consumable electrode in shielding gases having a number of advantages compared with known methods of welding aluminum alloys [8, 15].

The introduction of high-performance plasma-arc processes for surfacing aluminum pistons was hindered by the lack of an electrode material that would provide the required content of alloying elements (Si, Fe, Si, V, Ni.) in the deposited metal and the corresponding characteristics of mechanical properties. Attempts to use high-alloy electrode wire of continuous cross-section were restrained due to the non-technological nature of its drawing due to the fragility of such alloys.
The use of cored wires and tapes as a melting electrode has significant prospects, which allow changing the chemical composition within a wide range and creating a composite deposited metal with high performance characteristics [9, 16]. The use of an aluminum shell and a powder core makes it possible to obtain surfaced aluminum alloys of almost unlimited chemical composition with a uniform distribution of alloying elements over the surfacing volume [9, 17]. The use of a pulse-arc process allows you to control the transfer process of the electrode metal and ensure high stability of the surfacing process.

A method is known when the piston material is melted by an electron beam in a vacuum on the hardened zone of the annular groove of the piston blank with the simultaneous addition of an additive material to the molten piston material. As an additive material, copper is used in an amount of 1.5...2.0% of the volume of the molten material of the piston needed to perform an annular groove in the hardened zone, or nichrome in an amount of 3.5...4.0% of the specified volume. The piston is made of a non-eutectic silumin. Increasing the hardness of the material in the zones of the ring groove walls as a result of electron-beam surfacing with the proposed filler material allows increasing the engine life and operational reliability of the pistons.

One of the most common ways to harden the surfaces of parts is the technology of electrodeposition of composite electrochemical coatings. Its essence is that together with the metal from the galvanic bath, various non-metallic particles are deposited on the hardened surface of the part: carbides, oxides, sulfides, borides, polymer powders, etc. The presence of these materials in the coating changes its properties, including increasing their wear resistance. Significant disadvantages of electrochemical coatings include low productivity and high energy consumption of the process of obtaining them, as well as toxicity.

3. Ways to solve the problem

Micro-arc oxidation (MDO) is a relatively new type of surface treatment and hardening of metal materials, originating from traditional anodizing, and therefore refers to electrochemical processes. Micro-arc oxidation makes it possible to obtain multifunctional coatings with a unique set of properties, including wear-resistant, corrosion-resistant, heat-resistant, electrical insulation and decorative coatings [11, 18].

A distinctive feature of MDO is the participation in the process of coating formation of surface micro-discharges, which have a very significant and specific effect on the formed coating, as a result of which the composition and structure of the resulting oxide layers differ significantly, and the properties are significantly increased compared to conventional anode films [12, 19]. Other positive features of the MDO process are its environmental friendliness, as well as the absence of the need for careful pre-surface preparation at the beginning of the process chain and the use of refrigeration equipment to obtain relatively thick coatings.

MDO oxidation of the surfaces of products made of metals of the valve group (aluminum, titanium, etc.) makes it possible to form a strong oxide coating on them with a hardness close to corundum, good adhesion, low porosity and high anti-corrosion properties. This is especially true for parts of limited mass, such as internal combustion engine pistons, turbine blades, various sealing assemblies, and so on. It is also used for parts that work under severe conditions of high temperatures, aggressive media and high mechanical loads. MDO contributes to the formation of high temperature modifications of Al₂O₃ with high microhardness.

MDO technology is quite well developed mainly for aluminum alloys. MDO coatings are increasingly being used in a wide variety of areas - from the production of household goods and medicine to instrumentation and the aerospace industry, including in the engine industry.

The bottom is the most thermally loaded part of the piston. As the piston diameter increases, the bottom temperature increases, as the path of heat removal to the cylinder walls increases, as well as the ratio of the bottom surface that receives heat to the surface through which it is withdrawn to the cylinder walls.
For example, thick coatings on aluminum obtained in a silicate-alkaline electrolyte consist of three layers (figure 1): 1 - a thin transition layer; 2 - the main working layer, with maximum hardness and minimum porosity, consisting mainly of corundum (Al$_2$O$_3$) and 3 - an external process layer enriched with aluminosilicates.

Figure 1. Structure of MDO coatings on the piston: 1 - thin transition layer; 2 - main working layer; 3 - outer process layer.

The essence of the MDO is that the part located in the electrolytic bath is supplied with a current through a special power source, which leads to the formation of microplasma discharges on the surface of the part, under the influence of which the surface layer is processed into aluminum oxide. As a result, a strong oxidized layer is formed on the surface of the part [11, 20-22].

Thus, it can be stated that the main difference between the MDO process is the use of energy of electric discharges migrating along the treated surface immersed in the electrolyte, which have a specific thermal, plasma-chemical and hydrodynamic effect on the base metal, the coating itself and the electrolyte, resulting in the formation of ceramic-like coatings with a wide range of adjustable element and phase composition, structure and properties. Obtaining such an oxide thermal barrier layer will protect the piston from the effects of high temperature heat flux coming from the combustion chamber, which will reduce the thickness and weight of the piston, the effective specific fuel consumption, increase the effective power and effective efficiency of engine, reduce exhaust gas toxicity.

Currently, four main groups of electrolytes are used. In the first group of electrolytes, the coating is formed mainly due to the oxidation of aluminum. In the electrolytes of the second and third groups, not only the oxidation of aluminum occurs, but also the inclusion of a substance from the electrolyte in the coating. In the fourth group of electrolytes, the coating is formed mainly from the material present in them as a suspension. Due to the fact that the process is carried out under conditions of spark discharge on the surface of the oxidized part at local temperatures in the reaction zone of 700...250ºC, additives of the necessary metals that are in the electrolyte in the form of powders are fused with other coating components, forming a strong layer. The use of these electrolytes makes it possible to form coatings using aluminum oxide, titanium oxide, and other materials introduced into the electrolyte, which significantly expands the possibility of obtaining coatings with different functional properties.

One of the simplest and most recognized electrolytes of this group was a solution containing KOH, with a concentration of 2...8 g/l, which makes it possible to obtain high-quality ceramic coatings on aluminum alloys [23, 24]. For the same purpose, solutions of certain acids (sulfuric, phosphoric, oxalic, citric, etc.) can be used, among which sulfuric acid is the most common. It should be noted that sulfuric acid, like others, is only suitable in concentrated form, since dilute acid is not able to passivate aluminum, which is a decisive factor in the conduct of MDO.
When using electrolytes of the fourth group, the geometric dimensions of the processed parts do not change. The reinforced layer is formed on the inner side, that is, at the metal-film interface. In this case, the coating is deepened into the metal, and the outer actual size of the part does not change.

4. Conclusion
In terms of technological advantages, the micro-arc oxidation technology allows you to obtain a coating with a wide range of applications and apply the coating both to new products and to restore coatings after wear, reduces the coating time, allows you to use less equipment, less production space, and saves water consumption.

The method of micro-arc oxidation allows to form coatings that have various functional properties, such as corrosion-resistant, wear-resistant, heat-resistant, electrical insulation, protective and protective-decorative. This versatility of coatings allows them to be used in a wide variety of industries.

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