

Analysis of scooter engine piston damage

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Abstract. The causes of operational damage to the piston of a single-cylinder two-stroke internal combustion engine (ICE) of a scooter, made of a piston aluminum-silicon alloy by mold casting, were investigated. It was found that the AK21M2.5H2.5 type alloy has a dispersed eutectic structure ($\alpha+\beta$ -Si) with a small number of primary silicon crystals of a compact shape, the size of which does not exceed 10 μm . The porosity of the cast alloy of the piston is less than the lowest 1st porosity point, as well as the quality structure, could not be the cause of its damage.

The average value of the microhardness measured on the surface of the piston head (70 HV_{0.98}) is slightly less than the standardized hardness (90 HB \div 100 HB) of ingots after mold casting and artificial aging without preliminary hardening, which indirectly indicates overheating of the piston during operation. The detected damage to the outer surface of the piston in the form of deep scratches and worn stripes is not caused by metallurgical or technological factors, but by violations of operating conditions: overheating and lack of lubricant in the contact zone of the piston and cylinder.

1 Introduction

The vast majority of power units in the world are driven by piston internal combustion engines (ICEs) due to their versatility and reliability. However, they have a significant drawback, namely, relatively low thermal and mechanical efficiency [1]. It is quite natural that significant energy losses stimulate persistent continuous search by engineers and researchers for ways to increase the efficiency of ICEs by increasing specific loads, temperatures, and speeds of movement for the main friction components of the engine, first of all, parts of the piston group. Pistons are the most loaded and critical components of ICEs [2]. Taking on the energy of the fuel explosion in the cylinder, they work under conditions of dynamic, cyclic alternate loads and high temperatures, as well as in aggressive environments. In such harsh conditions, the price of error in the selection of piston material, and deviation from optimal technological modes and operating conditions increases. Improperly selected material and violation of technological or operational modes lead to premature failure of not only the piston but also other engine components that work together with it [3].

For the proper functioning of the piston, its material should possess [4]:

- high specific strength and heat resistance to withstand gas pressure, high temperature, and inertial forces;
- minimum mass to minimize inertial forces;
- good resistance to thermal fatigue;
- good thermal conductivity to remove heat from the head to the rings and cylinder walls;
- high wear resistance at operating temperatures;

- good anti-friction properties to ensure minimal friction work, high-speed reciprocating movement without noise;
- low coefficient of thermal expansion;
- to be corrosion-resistant in aggressive environments.

For the manufacture of pistons, the standard regulates materials that meet these requirements; in particular, these are alloys of the Al–Si system [5]. The task of design engineers and process engineers is to manufacture pistons that meet the requirements established by regulatory and technical documentation, in particular the standard DSTU 2839-94 [6], regarding the presence of technological defects, mechanical properties, etc. However, even in the case of high-quality production of pistons due to violation of optimal operating modes, premature failure, damage, or fracture may occur. Mechanisms of piston degradation have different origins and are primarily related to wear, mechanical or thermal fatigue, and the effects of high temperature and corrosive environment [2]. Therefore, the study of the causes of piston failure is the basis for recommendations on increasing the reliability and lifetime of ICEs.

In this work, a comprehensive analysis was performed to find out the possible causes of degradation of the ICE scooter piston cast from aluminum alloy.

Research methodology. The determination of the elemental composition of the aluminum alloy of the ICE scooter piston was carried out by the method of X-ray fluorescence analysis using the energy spectrometer of X-ray radiation CEP-01 “Elvax Light” [7].

Documentation of the macrostructure was performed with a Casio Exilim 8.1 camera and using a MBC-9 microscope. The microstructure of the aluminum alloy was studied using an MMT-14II optical microscope with

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an LCMOS14000KPA eyepiece camera at magnifications from $\times 100$ to $\times 500$. Different reagents were used for the chemical contrast of aluminum alloys to identify different components of the structure (Table 1) [8]. The best result in terms of identifying the structure, shape, and distribution of structural components on surfaces of polished samples was provided by chemical contrast with a reagent of 4% aqueous NaOH solution, close in chemical composition to Weck's reagent (Table 1, No. 3).

Vickers microhardness was determined on a NOVOTEST TC-MKD1 microhardness tester by DSTU ISO 6506 – 1:2007 [9]. The measurements were carried out at room temperature (20 ± 2) °C, under the indentation load of 0.9807 N (100 g) and a holding time of 8 s.

The estimation of gas porosity of ingots was performed by the standardized method according to DSTU 2839 - 94 [6] on the areas of the bottom of the piston where there is no shrinkage looseness and central porosity.

Research results. The object of the study was a piston of a single-cylinder two-stroke ICE for a scooter (Fig. 1).



Fig. 1. General view of the piston

The working volume of the ICE was 49 cm³. This piston was damaged as a result of the operation. The overall dimensions of the mold-cast piston were as follows: the diameter was 50 mm and the height was 60 mm. On the outer guide surface of the piston, so-called “the skirt”, there are traces of intense wear in the form of deep scratches and grooves

2 Examinations and discussion

2.1 Elemental composition and modification of piston alloy

To determine the elemental composition of the piston alloy, X-ray fluorescence analysis was performed on the cleaned and polished surface of the piston head. Based on the analysis of the spectrogram and decoding of the results of the elemental composition by the software of the spectrometer, it was found that the alloy belongs to the aluminum alloys of the Al–Si system (Table 1).

By comparing the results of the elemental composition of the studied scooter piston alloy (Table 2)

with the composition of standardized brands of piston aluminum alloys (Table 3), it was revealed that the studied material corresponds to the AK21M2.5H2.5 alloy according to DSTU 2839-94 [6].

Table 1. Reagents and modes of etching of aluminum alloys

Reagent No.	The composition of the etching reagent	Etching mode	The action of the reagent on the surface
1	distilled water – 92 ml, HNO ₃ – 6 ml, HF – 2 ml (Kroll's reagent)	The etching time is 30–60 s at room temperature	Detects eutectics, Si crystals, grain boundaries are poorly detected
2	H ₂ SO ₄ – 10 ml, water – 100 ml	The etching time is 5–30 s, rinse in cold water	Detects FeAl ₃ and grain boundaries of pure Al
3	H ₂ O – 100 ml NaOH – 1 g KMnO ₄ – 4 g (Weck's reagent)	The etching time is 5–10 s at room temperature	Detects non-metallic inclusions, grain boundaries of Al–Si alloys
4	H ₂ O – 95 ml, HNO ₃ – 2.5 ml, HCl – 1,5 ml, HF – 1 ml (Keller's reagent)	The etching time is 10–30 s at room temperature	Detects grain boundaries of Al–Si alloys

Table 2. Elemental composition of the investigated piston alloy

Atomic number	Element	Series	Intensity	Concentration
13	Al	K	471364	75.0007 ± 0.1062%
14	Si	K	166829	19.5660 ± 0.0973%
29	Cu	K	322986	2.6780 ± 0.0122%
28	Ni	K	185819	2.0667 ± 0.0110%
22	Ti	K	1646	0.2716 ± 0.0222%
26	Fe	K	10593	0.2371 ± 0.0060%
15	P	K	4721	0.1154 ± 0.0086%
30	Zn	K	5704	0.0355 ± 0.0037%
31	Ga	K	2396	0.0133 ± 0.0020%
23	V	K	125	0.0113 ± 0.0110%
40	Zr	K	2621	0.0045 ± 0.0011%

The mechanical properties of AK21M2.5H2.5 alloy in ingots are presented in Table 4.

Table 3. Comparison of the elemental composition of the studied piston alloy with the compositions of standardized piston aluminum alloys

Element	Studied alloy	Alloy brand according to the standard	
		KC741 DSTU 3752-98	AK21M2.5H2.5 DSTU 2839-94
Fraction of basic elements, wt.%			
Si	19.5660 ± 0.0973	19 – 22	20 – 22
Cu	2.6780 ± 0.0122	1.8 – 2.4	2.2 – 3.0
Ni	2.0667 ± 0.0110	1.1 – 1.7	2.2 – 2.8
Ti	0.2716 ± 0.0222	–	0.1 – 0.3
Fe	0.2371 ± 0.0060	up to 0.5	up to 0.9
P	0.1154 ± 0.0086	–	–
Zn	0.0355 ± 0.0037	–	up to 0.2
V	0.0113 ± 0.0110	–	–
Zr	0.0045 ± 0.0011	–	–
Cr	–	–	0.2 – 0.4
Mn	–	0.6 – 1,1	0.2 – 0.4
Mg	–	0.7 – 1.2	0.2 – 0.5
Al	75.0007 ± 0.1062	balance	74.9 – 69.5

Table 4. Mechanical properties of the AK21M2.5H2.5 cast alloy according to DSTU 2839-94

Casting method	Thermal treatment	Ultimate tensile strength σ_b , MPa	Hardness, HB
Mold casting	T2 Annealing	157	90
	T1 Artificial aging without hardening	186	100

Al–Si hypereutectic alloys, which contain more than 13 wt.% Si, are considered promising in engine manufacturing due to high wear resistance, strength, corrosion resistance, low coefficient of thermal expansion, and excellent casting properties (high fluidity and relatively low shrinkage) [10]. Increasing the copper content in alloys of this type to 3% in the presence of nickel to 2.5% increases the heat resistance due to the formation of intermetallic particles Al_6Cu_3Ni blocking the growth of α -phase grains, and causes reduction of the coefficient of thermal expansion of the piston alloy [11].

Even though the increased content of silicon in the hypereutectic alloys improves casting and mechanical properties and reduces the coefficient of thermal expansion compared to eutectic alloys, it increases the danger of the formation of a large number of coarse and brittle primary silicon crystals in the structure, which embrittle the alloys. They create a concentration of stresses, easily crack, and peel off from the matrix, initiating the cracks and fracture under dynamic loads

[12]. Therefore, alloys with a coarse morphology of primary silicon crystals do not meet the requirements for piston alloys, primarily in terms of endurance, impact toughness, or fracture toughness.

To improve the mechanical properties of piston alloys by refining the structure, its modification with various modifiers (sodium, strontium, rare earth elements, phosphorus) is used as the most common and simplest technological method [13, 14].

Sodium-based modifiers are widely used due to the availability of sodium salts and the good modifying effect of sodium as a modifier of the Al–Si eutectic. However, the scope of application of such modifiers is limited to alloys with eutectics as the main structural component. In addition, a significant disadvantage of modifying alloys with sodium is the increased tendency to the formation of gas porosity [13].

Spectral analysis of the alloy of the studied piston showed that the alloy contains 0.15% P, which was most likely introduced into the melt before casting as a modifier. Since copper (2.67%) is present in the alloy, phosphorus was introduced as part of a copper-containing ligature, namely, Cu–P or Cu–P–Al.

The mechanism of the modifying effect of phosphorus is described in [15]. After adding the ligature alloy, phosphorus atoms dissolve in the melt at operating temperature and form an AlP_3 compound with aluminum. The particles of this compound become the centers of heterogeneous nucleation of compact primary silicon crystals. Silicon and aluminum phosphide are related in their crystallographic structure, so they have a low energy of interphase boundaries, which is a sufficient condition for epitaxy and heterogeneous nucleation of silicon crystals on phosphide surfaces. Silicon crystals inherit their compact shape and size from AlP_3 particles, as they are formed by accretion controlled by the diffusion of silicon atoms [16]. Therefore, dark inclusions of AlP_3 can be observed in the centers of the primary gray silicon crystals in the images of the microstructure of hypereutectic alloys. Thus, the effect of refining primary silicon crystals is determined by the dispersity of the aluminum phosphide particles themselves, which depends on the amount of phosphorus and the temperature mode of modification.

2.2 Microstructural analysis

The microstructural analysis carried out in the work (Fig. 2) confirms the conclusion about phosphorus modification of the studied alloy. The structure of the cast alloy (AK21M2.5H2.5 type) consists of a small number of fine primary crystals of the silicon β -Si phase of gray color in the shape of rectangles, with the size of the sides up to 10 μm (Fig. 2d, f). In the center of some primary silicon crystals, dark inclusions of dispersed nucleators, namely, AlP_3 particles can be observed (Fig. 2f).

The main structural component of the alloy is eutectic, namely, a mechanical mixture of $\alpha + \beta - Si$. Eutectic is characterized by a different arrangement: areas of dendritic structure alternate with areas of rosette structure and areas of disordered arrangement of silicon phase

crystals. Eutectic silicon crystals are mostly elongated rod-shaped, and less often they are of a rounded or irregular shape. The length of the rods is $5\div 10\ \mu\text{m}$ and their thickness is up to several micrometers. Crystals of a rounded shape are about $1\ \mu\text{m}$ thick, whereas crystals of an irregular shape are somewhat coarser, up to $5\ \mu\text{m}$. In dendritic areas, silicon crystals are located at the boundaries of cells, which are grains of α -phase.

Summarizing the results of the microstructural analysis, it should be noted that the studied piston hypereutectic alloy has a dispersed structure of primary and eutectic crystals of the silicon phase, which was ensured by high-quality modification, most likely by a phosphorus-containing ligature. Therefore, the microstructure of the piston alloy could not be the cause of its damage.

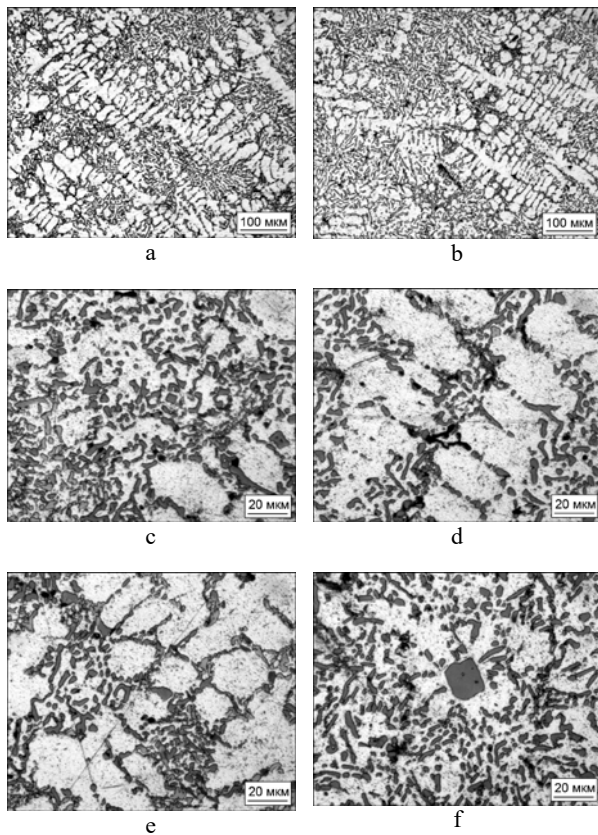


Fig. 2 Microstructure of AK21M2.5H2.5 piston alloy after modification and mold casting

2.3 Estimation of gas porosity of the piston

One of the common casting defects of aluminum alloy ingots is gas porosity. This defect of ingots in the form of small scattered pores reduces mechanical and operational properties, in particular strength, which is important for ingots of pistons that operate under conditions of alternate loads [14].

Gas porosity is formed due to the release of gases during the crystallization of the melt. Aluminum-silicon melt actively absorbs gases from the environment. As the temperature decreases at the moment of transition to the solid state, the solubility of gases decreases. At the interface between the solid and liquid phases, gas nuclei are formed,

which are held by capillary forces and increase in volume due to the diffusion of gases to them. When the force of detachment of a gas bubble becomes greater than the force of adhesion, it breaks away from the solid surface and rises up. Gas bubbles that did not have time to rise during crystallization to the surface of the melt, remaining in it, contribute to the formation of gas porosity.

After a microscopic examination of the polished unetched samples, a slight porosity of the scooter engine piston ingot, which was cast in a metal reusable mold, was revealed (Fig. 3.5a, b). Separate coarse pores of mostly rounded or oval shapes with a size of $5\div 10\ \mu\text{m}$ are concentrated mainly in the areas of the α -phase (Fig. 3c, f). Instead, small pores are scattered in the structure of the alloy (Fig. 3c-f) and are localized at the interphase boundaries of β -phase crystals (Si) with α -phase grains. They have a globular or elongated (vermicular) shape. The size of the globular pores does not exceed $2\div 3\ \mu\text{m}$ (Fig. 3d, f). Instead, vermicular pores with a thickness of $2\div 4\ \mu\text{m}$ are bent along the interphase boundaries, reaching $5\ \mu\text{m}$, and some even $10\ \mu\text{m}$ in length (Fig. 3c, d).

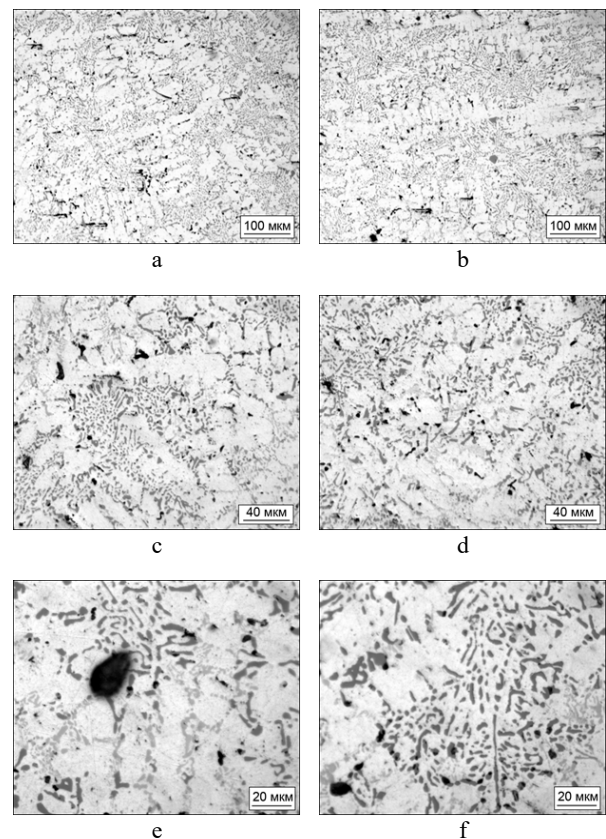


Fig. 3 Microstructure of polished piston alloy samples (detected porosity)

To evaluate the porosity of the alloy of the investigated piston, the standardized method of determining the porosity of aluminum alloys by DSTU 2839 – 94 [6] was used. It was found that contrast with a reagent (10% NaOH aqueous solution, $70\ ^\circ\text{C}$) clearly outlines the existing and reveals smaller pores that were not visible during the macroscopic examination of the studied samples before contrast. Using the method of

comparison with reference scales, it was found that the average porosity of the ingot is less than the lowest 1st porosity point, which corresponds to a pore diameter of up to 0.1 mm and an allowable number of pores up to 5 pieces on a surface area of 1 cm². Therefore, such low porosity cannot threaten to reduce the tightness and mechanical strength of the scooter engine piston.

2.4 Hardness

Hardness is the most common mechanical characteristic of structural materials, easy to determine, and does not require complex equipment and special requirements for samples. It characterizes the ability of the material to resist plastic deformation and allows predicting other mechanical properties, in particular the ultimate tensile strength of the material.

Due to the small thickness of the head (2 mm) of the investigated piston, the Vickers microhardness method was chosen to estimate the hardness of the piston alloy [9]. An additional advantage of this method was the accuracy of the hardness measurement, which made it possible to select the appropriate areas on the polished and slightly etched surface of the piston head. Since the structure of the alloy is quite dispersed and consists mainly of fine silicon crystals scattered in the eutectic and small grains of the α -phase, it was impossible to distinguish them by hardness. Therefore, according to the results of the measurements, the average value of the microhardness of the mechanical mixture of these phases varied in a narrow range from 68 HV_{0.98} to 72 HV_{0.98}, which is slightly lower than the standard values for the AK21M2.5H2.5 alloy (Table 2).

2.5 Operational damage

Inspection of the defective piston (Fig. 1) with the naked eye revealed damage on the guided part of the piston in the form of scratches and burrs parallel to the piston axis. Burrs occupy almost the entire area, starting from the oil removal ring and ending with the lower end of the skirt. Since the piston has no damage on the surfaces above the placement of the oil removal ring, there is a high probability that the scratches were caused by insufficient lubrication in the operating area. This, in turn, caused increased friction between the piston skirt and the cylinder surface [17]. During a detailed inspection of the surface using an MBC-9 microscope, significant damage was recorded on the outer surface (Fig. 4a) and especially in the area of the holes for the supply of antifriction fluid (Fig. 4b, c), which confirms the already existing assumption about incorrect engine operation (lack of lubrication).

In addition to the above-mentioned defects, the macroanalysis revealed a casting defect “inflow” in the hole for the connecting rod finger (Fig. 4d). Given the place of formation, this type of defect could not be formed during injection molding, since this technology ensures the highest accuracy of the ingot surface. In addition, the use of expensive equipment for the production of such relatively small parts as a piston will

have a negative impact on the cost of the product and its subsequent sale on the market. A more likely cause of the formation of the inflow, taking into account the location of this defect, the complex shape of the ingot, and the serial production, is damage to the rod during mold casting. Mold casting is much cheaper and more efficient for this ingot [18], but the complex structure requires the installation of a rod to form a hole for the connecting rod finger.



Fig. 4 Photos of piston surface defects obtained during detailed macroanalysis

The use of a metal rod, despite greater accuracy, requires adaptation of the mold shape, namely the creation of its detachable version, which will be assembled before pouring. This technical solution requires additional investments and increases the labor intensity of the preparatory stage of production. In addition, as a result of mold wear, there is a risk of the formation of more serious defects in the geometry of the ingot.

The use of a rod made of sand-clay mixtures allows for avoiding the complex structure of the mold and facilitates its dismantling. However, this can cause inflows in the piston. The gain in cost is compensated by the lower strength of the rod, which increases the risk of its partial or complete destruction during the production process. Installation of such a damaged rod in the mold will lead to incorrect reproduction of the corresponding surfaces with which it is in contact because liquid metal will fill the destroyed place of the rod. It is possible that this defect could have caused the formation of scratches on the surface of the skirt because the inflow could contribute to increasing the gap between the connecting rod finger and the corresponding hole in the piston. This, in turn, would cause foreign solid particles to enter the cylinder.

Therefore, one of the above-mentioned factors or their simultaneous action contributed to the degradation of the ICE scooter piston. If a defect is observed after production, measures should be taken to prevent it, namely, strengthen defect control of ingots, use analogs of production materials with better properties, and optimize casting parameters.

3 Conclusions

The piston of a single-cylinder two-stroke internal combustion engine (ICE) with a volume of 49 cm³ was made of a piston aluminum-silicon alloy alloyed with copper and nickel, AK21M2.5H2.5 type (DSTU 2839 – 94), using mold casting. The basis of the structure of the hypereutectic alloy after casting is dispersed eutectic ($\alpha+\beta$ -Si) with a small number of primary silicon crystals of a compact shape, the size of which does not exceed 10 μ m. The dispersed structure of the primary and eutectic crystals of the silicon phase was most likely provided by modification with a phosphorus-containing ligature. Such a quality structure, as well as porosity less than the lowest 1st porosity point, of the cast alloy of the piston, could not be the cause of its damage.

The average value of the microhardness measured on the surface of the piston head (70 HV_{0,98}) is slightly less than the standardized hardness (90 HB ÷ 100 HB) of ingots made of the AK21M2.5H2.5 alloy after mold casting and artificial aging without preliminary hardening (DSTU 2839 – 94), which may indirectly indicate overheating of the piston during operation. The detected damage to the outer surface of the piston in the form of deep scratches and worn stripes is not caused by metallurgical or technological factors, but by violations of operating conditions: overheating and lack of lubricant in the contact zone of the piston and cylinder.

However, the insignificant thickness of the head of the piston under study, which is 2 mm, makes it impossible to determine the hardness according to Brinell, since this method requires the measurement under significant indentation loads.

Therefore, the Vickers microhardness method [14] was chosen to estimate the hardness of the piston alloy. An additional advantage of this method was the accuracy of the hardness measurement, which made it possible to select the appropriate areas on the polished and slightly etched surface of the piston head.

Since the structure of the alloy is quite dispersed and consists mainly of fine silicon crystals scattered in the eutectic and small grains of the α -phase, it was impossible to distinguish them by hardness.

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