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Investigation of the effect of engine running time on the material characteristics of a piston

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Regardless of the class of passenger car, manufacturer, or type of internal combustion engine, vehicle owners strive to ensure the longest possible period of reliable engine operation. The reliability and performance of an internal combustion engine are key indicators of its quality and prestige. Numerous research and development studies have focused on optimizing piston design and identifying the causes of piston failure. However, to better understand degradation mechanisms and trends in modern piston design, it is necessary to investigate the phenomena affecting the piston during typical engine service life. Thermomechanical stresses, friction, elevated and fluctuating temperatures, and contaminants all contribute to piston wear and reduce its service life. In this study, a new aluminum piston was compared with a piston extracted from an engine after approximately 200,000 kilometers of operation. The influence of engine operating time on piston surface condition, hardness, microstructure, and surface quality was analyzed. These parameters provide insight into the impact of friction and thermal loads on piston wear. Based on the investigations, the influence of piston operating time on surface degradation and changes in the mechanical properties of the piston material was determined. Furthermore, areas most susceptible to long-term loads and exhibiting the highest wear were identified. The results enable identification of piston regions requiring reinforcement or design optimization to minimize the risk of damage from prolonged engine operation.

Key words: *pistons, microstructure, wear, tribological analysis*

1. Introduction

In internal combustion engines and compressors, the piston's movement with sealing rings in the cylinder liner plays a key role in energy consumption, primarily due to elevated friction and component wear. The effect of friction is not limited to energy losses; it also poses a risk of component failure and engine power reduction [2, 14]. The wear intensity of the piston assembly depends on numerous factors, including operating pressure and temperature, engine rotational speed, surface roughness, engine load, material quality, the performance of the cooling system, the type of lubricating oil used, and potential manufacturing defects [4, 7, 14, 25–27].

A significant mismatch in thermal expansion between the aluminum piston and the cast iron cylinder liner can reduce the working clearance and impair the formation of the lubricating oil film. Inadequate lubrication of the piston–liner contact surfaces increases friction-generated heat, further intensifying thermal expansion and potentially leading to seizure of the interacting components [26]. Several strategies exist to mitigate these risks, such as surface roughness optimization, application of protective coatings, chemical composition modifications, and the use of composite materials [3, 6]. Equally important is the proper selection of engine oil and ensuring effective delivery to all critical contact zones [23]. The highest frictional forces in the piston assembly occur during cold start-up. According to the literature, the system initially operates under boundary or mixed lubrication conditions and gradually transitions to hydrodynamic lubrication. Poor oil selection or improper maintenance may initiate accelerated wear processes or even lead to piston failure [15].

During its operating cycle, the piston undergoes deformation due to gas pressure and contact forces acting along its working plane. The lateral and angular movement of the piston causes impacts between the piston skirt and the cylinder liner, leading to dynamic fluctuations in hydrodynamic forces. The maximum impact force occurs in diesel engines during the compression stroke and is concentrated at the upper ends of the piston skirt. An increase in clearance between the piston skirt and the cylinder liner results in greater lateral displacement and a larger tilt angle, which, in turn, increases the piston's lateral acceleration and intensifies impact forces [9]. An example of engine block damage caused by this phenomenon is shown in Fig. 1.

Fig. 1. Photograph of a four-cylinder passenger car engine block [16]

The wide variety of piston damage types and their underlying causes compels engine designers to consider the effects of design changes on piston durability from the earliest development stages. Therefore, numerous studies are conducted to analyze piston wear mechanisms, such as the one presented in this article, as well as attempts to develop algorithms capable of predicting the influence of design modifications on service life – e.g., through thermal exchange modeling [8, 12].

2. Literature review

Accurate identification of piston damage requires knowledge not only of metallurgy and piston design but also of the operational principles of internal combustion engines. The diagnostic process is challenging, as the root cause is often not immediately visible [20]. When analyzing piston failures, they can be classified according to the location of the damage [21]:

- damage to the piston crown
- damage to the piston pin boss or skirt
- damage to the piston rings
- damage to the cylinder liner.

However, a more functional and diagnostically useful classification is based on the underlying cause of the failure. One of the most common and severe types is piston seizure due to overheating, as illustrated in Fig. 2. There are four primary causes of such failures: delayed combustion-induced overheating, incorrect piston installation (wrong piston type), blocked oil injection, and cooling system malfunction [21].

Fig. 2. Photograph of a piston damaged by seizure [21]

Another common type of piston failure in internal combustion engines is damage to the piston crown. This type of failure may have multiple causes, including: incorrect valve recess depth, excessive piston protrusion above the cylinder deck, carbon deposits on the piston crown, excessive machining of the cylinder head sealing surfaces, improper cylinder head sealing, insufficient valve clearance, and incorrect valve timing [21]. An example of piston crown damage is shown in Fig. 3.

Fig. 3. Photograph of a piston with a damaged crown [21]

A more dramatic form of piston failure in internal combustion engines is piston material melting. An example of a piston exhibiting material melting is shown in Fig. 4. According to the literature, there are six primary causes of piston melting:

- incorrect fuel injection quantity
- improper injection timing
- faulty or damaged injector nozzles
- delayed ignition
- insufficient compression
- oscillations in the fuel injection lines.

Fig. 4. Photograph of a piston damaged by crown melting [21]

Another common type of piston failure is cracking of the piston crown and combustion chamber area [19, 21]. This type of damage is particularly frequent in older-generation diesel engines. An example of such failure is shown in Fig. 5. The most common causes include:

- incorrect fuel injection timing
- damaged or unsuitable injector nozzle
- improper fuel injection quantity
- lack of piston cooling
- chip tuning (increasing engine power without accounting for thermal limits)

- installation of pistons with improper combustion bowl geometry
- insufficient compression.

Fig. 5. Photograph of a piston damaged by cracking in the combustion chamber [21]

Axial wear caused by contamination is shown in Figure 6. Dirt and other impurities that enter the engine oil form an abrasive mixture that acts like sandpaper, leading to wear of the piston skirt. Infrequent oil and filter changes can significantly accelerate piston degradation and may ultimately result in critical engine failure.

Fig. 6. Photograph of a piston damaged by dirt intrusion [21]

Numerous scientific publications have investigated the causes of piston damage and methods for its prevention. One particularly noteworthy study is [19] by Siadkowska, which provides a detailed analysis of steel and aluminum piston designs. A comprehensive source of technical knowledge is also provided by Kolbenschmidt [20] and Motorservice [21], which offer in-depth classifications of piston damage types, supported by extensive illustrations. The mechanisms of friction-related piston failure in internal combustion engines are thoroughly discussed in publications [17–19, 22]. One of the more interesting articles discussing the proper preparation of piston surfaces and coatings that extend piston service life is by Wróblewski and Nakashima, whose studies have a significant impact on current knowledge of the relationship between the surface condition of an internal combustion engine piston and its durability [28].

2. Analysis of the effect of piston operating time on its mechanical properties

2.1. Comparative visual analysis of pistons

To investigate the influence of engine operating time on the mechanical and tribological properties of a piston, a comparative analysis was conducted between a new diesel engine piston and a piston from an engine with approximately 200,000 kilometers of mileage. The analyzed pistons are shown in Fig. 7. Both pistons share an identical design and components. The diameters of both pistons are identical, and they are manufactured from the same material. The operating conditions of the engines from which the examined pistons were taken are comparable. The only structural difference is the presence of valves in one piston. However, it should be emphasized that the present analysis focuses on the influence of engine operation on the properties and microstructure of the piston material, rather than on design differences. The first piston ring groove contains a reinforcing cast iron insert, designed to increase the mechanical strength of the piston. This insert is made of spheroidal graphite iron, subjected to alfin treatment, and subsequently cast with molten aluminum to form a durable metallurgical bond. Additionally, both pistons are equipped with an internal cooling channel to protect the piston crown and combustion chamber from overheating caused by the high thermal loads generated during combustion.

The piston pin bores are fitted with cold-pressed brass bushings to extend the piston's service life.

Fig. 7. Analyzed pistons from diesel engines

Figure 8 presents a comparison of the piston crown and combustion chamber area between a new and a used internal combustion engine piston. On the surface of the used piston crown, residual soot is visible in the form of a black deposit. Minor scratches were also observed, likely caused during disassembly or handling. No cracks, melting, or material loss were identified. The crown edges remain smooth, with no visible deformation. The piston crown and combustion chamber surfaces show no wear beyond what would be expected from the normal combustion process of the air-fuel mixture during engine operation.

a) b)

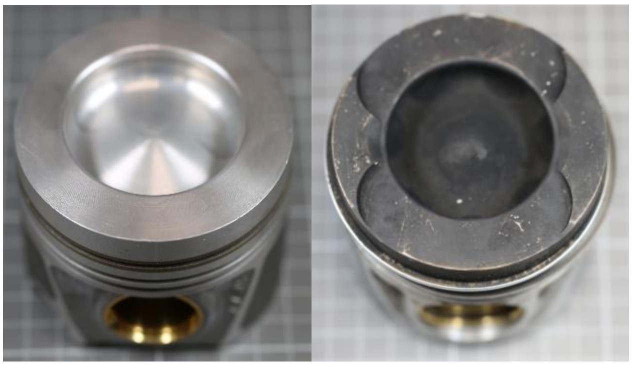


Fig. 8. Piston crown with combustion chamber: a) new diesel engine piston, b) piston after approximately 200,000 kilometers of operation

Figure 9 presents a comparison of the skirt and ring land areas of a new piston and a used piston from an internal combustion engine with approximately 200,000 kilometers of service. The comparison reveals noticeable wear on the piston's lateral surface. The graphite-based coating on the load-bearing surface has worn off, with no longitudinal scratches observed. The wear pattern corresponds to the contact zone between the piston and the cylinder wall. A significant accumulation of carbon deposits is visible on the fire land, forming a thick layer. Discoloration is also apparent on the ring land surfaces.

a) b)

Fig. 9. View of the piston skirts from internal combustion engines: a) unused piston, b) used piston

The final area showing visible changes compared to the new piston is the underside of the piston crown in the combustion chamber region, as shown in Fig. 10. Despite the presence of an internal cooling channel, this surface was exposed to significant thermal stress. No surface damage or cracking was observed on the inner side of the piston. However, the area exhibits signs of overheating, likely due to localized exceedance of thermal limits.

The presence of significant thermal influence, visible wear, and surface scratches prompted the authors of this study to perform a hardness analysis across the piston cross-section, examine its microstructure, and observe the lateral surfaces under magnification. The results of these investigations are presented in the following sections of the article.

Fig. 10. View of the overheated internal area of a used internal combustion engine piston

2.2. Chemical composition analysis of piston material

The most commonly used material in the production of internal combustion engine pistons is silumin – an Al-Si-based alloy valued for its unique technological and physicochemical properties [1, 5, 6, 10, 11, 13, 24]. The most frequently used silumins are hypoeutectic alloys containing approximately 11–13% silicon and hypereutectic alloys with 17–24% silicon. A significant drawback of these alloys is the rapid decrease in tensile strength and hardness with increasing temperature. For hypoeutectic silumins, tensile strength decreases by approximately 40–50% at 250°C, and by up to 65% at 300°C. In the case of hypereutectic silumins, the decrease is about 5% lower [4].

Piston-grade silumins are among the most chemically complex aluminum alloys. Their composition typically includes elements from the Al–Si–Cu–Mg system, with additions of Ni, Mn, Fe, Zn, and occasionally Mo, Cr, V, Co, and W. They are also modified with elements such as K, Na, and Sr (silicon eutectic modifiers), Ti, Sc, V, Zr, B (grain refiners), as well as P and S (modifiers of primary silicon crystals) [4].

To determine the chemical composition, the analyzed pistons were sectioned along their axis, perpendicular to the piston pin bore. The measurements were carried out using a spectrometer. Measurement points are marked in Fig. 11 for the new piston and in Fig. 12 for the used piston. Three measurements were taken on the new piston and four on the used piston.

The results of the chemical composition measurements are presented in Table 1. The analysis indicates that the examined pistons are made of silumin containing approximately 12.3% silicon and around 4% copper. The main alloying elements include magnesium (Mg), nickel (Ni), iron (Fe), manganese (Mn), zinc (Zn), and titanium (Ti). Both materials exhibit nearly identical chemical compositions, and the minor differences observed may be attributed to variations between production batches at the piston manufacturing facility.

Fig. 11. Chemical composition measurement points on a new internal combustion engine piston

Fig. 12. Chemical composition measurement points on a used internal combustion engine piston

Table 1. Chemical composition analysis of used and new pistons

Element [%]	Used piston	New piston
Si	12,35	12,34
Cu	3,91	3,98
Mg	0,708	0,6
Ni	2,97	2,85
Fe	0,479	0,389
Mn	0,0724	0,113
Zn	0,083	0,062
Ti	0,029	0,033
Pb	0,004	0,003
Zr	0,05	0,05
V	0,037	0,044
Sn	0,0025	0,0023
P ppm	30,16	29,72
Cr	0,0099	0,016
Na	<0,3	<0,3
Ca ppm	1,07	2,2
Sb ppm	12,1	16,77
Li ppm	<0,05	<0,05
Sr ppm	<0,1	<0,1

The piston-grade silumin used in the analyzed pistons exhibits the following physical-mechanical properties:

– thermal conductivity at 200°C: approximately 128 W/(m·K)
– coefficient of linear thermal expansion: 21×10^{-6} 1/K
– tensile strength (Rm): approximately 240 MPa
– hardness: ranging between 110 and 150 HB.

2.2. Hardness profile analysis

The operating cycle of a piston in an internal combustion engine involves repeated heating and cooling. The temperature dependence of material strength presents a significant limitation for both increasing engine efficiency and extending service life. To evaluate the effect of the engine's thermal cycles on mechanical properties, both a new piston and a used piston (with approximately 200,000 kilometers of service) were sectioned longitudinally along the axis, in a plane perpendicular to the piston pin bore. Hardness measurements were performed using the Brinell hardness scale (HB). The measurement points for the new piston are shown in Fig. 13. The hardness values ranged from 118 to 131 HB, with an average value of 124.6 HB and a measurement spread of 13 HB.

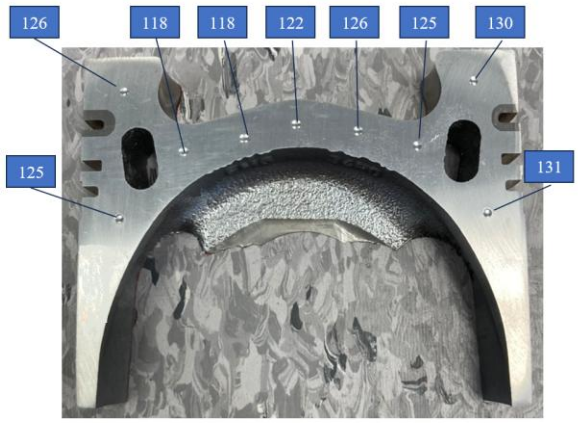


Fig. 13. Unused diesel engine piston with marked hardness measurement points and HB values

The hardness measurement points for the used piston are shown in Fig. 14. Measurements were taken at seven locations. The highest recorded hardness was 94 HB, while the lowest was 84 HB. The average hardness of the used piston was 90 HB, with a spread of 11 HB. The lowest hardness values were observed near the piston crown, whereas the highest values occurred near the oil gallery on the combustion chamber side.

Figure 15 compares the hardness profiles of a new diesel engine piston and a piston with 200,000 kilometers of service. The new piston exhibits consistently higher hardness across the entire cross-section, on average approximately 28% greater than that of the used piston. The most significant reduction in hardness was observed near the piston crown, amounting to approximately 34%.

To verify the significant hardness reduction observed near the piston crown, additional hardness measurements were performed directly on the crown surface. Four measurements were taken for both the new and the used piston: two along the axis of the piston pin bore and two in a plane perpendicular to that axis. The locations of the measurement points are shown in Fig. 16.

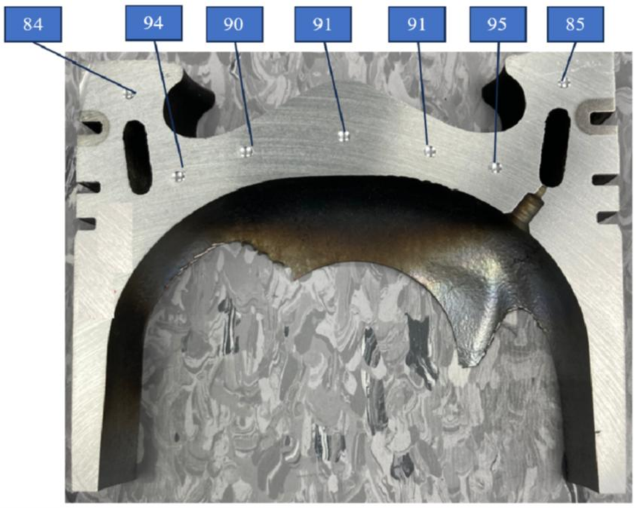


Fig. 14. Used diesel engine piston with marked hardness measurement points and HB values

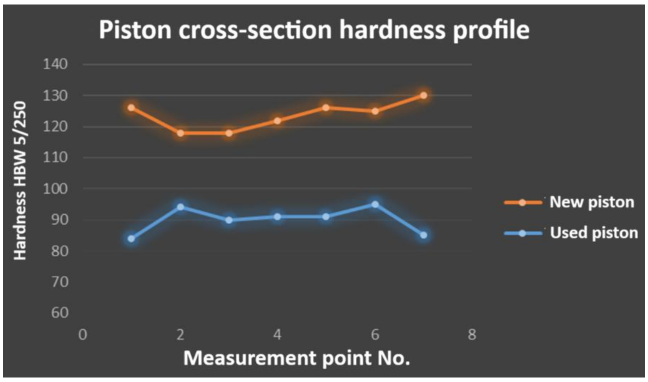


Fig. 15. Comparison of hardness profiles of new and used pistons in cross-section

The measured hardness values on the crown of the new piston were: 124, 127, 117, and 127 HBW. For the used piston, the corresponding values were: 80, 79, 82, and 79 HBW. The hardness reduction along the piston pin bore axis was approximately 33%, while along the skirt axis it was about 38%. This significant decrease in hardness on the piston crown is likely due to prolonged exposure to elevated temperatures during engine operation. Such a substantial loss of hardness adversely affects the fatigue strength and overall durability of the piston, increasing the risk of premature wear or mechanical failure.

a) b)

Fig. 16. Hardness measurement of the piston crown: a) new piston, b) used piston

According to the literature, the local temperature on the piston surface in the combustion chamber region may reach approximately 250–350°C. For the AlSi12Cu4Ni2Mg alloy used in the analyzed pistons, the temperature range of 250–300°C corresponds to the onset of the material's slow softening process. Prolonged exposure to such elevated temperatures during engine operation can lead to a gradual reduction in hardness. This provides clear evidence that further research and development on new piston alloys or technologies to enhance the durability of aluminum pistons is fully justified.

2.3. Microstructural analysis

High temperatures, along with cyclic heating and cooling, affect the material's hardness and mechanical properties. To determine whether these factors influenced the surface condition and microstructure, metallographic cross-sections were prepared for both the new and used pistons, as shown in Fig. 17a and 17b, respectively.

a) b)

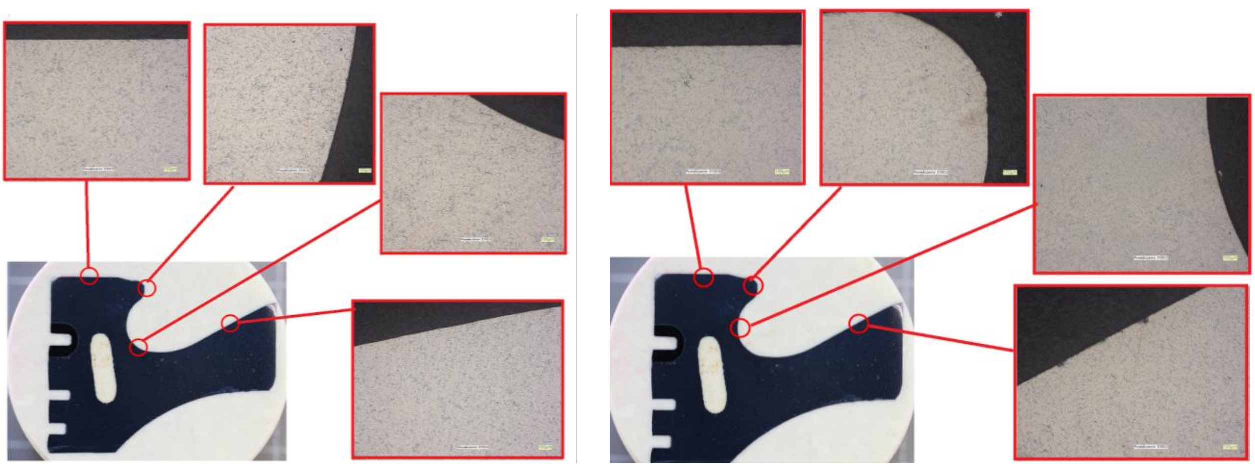
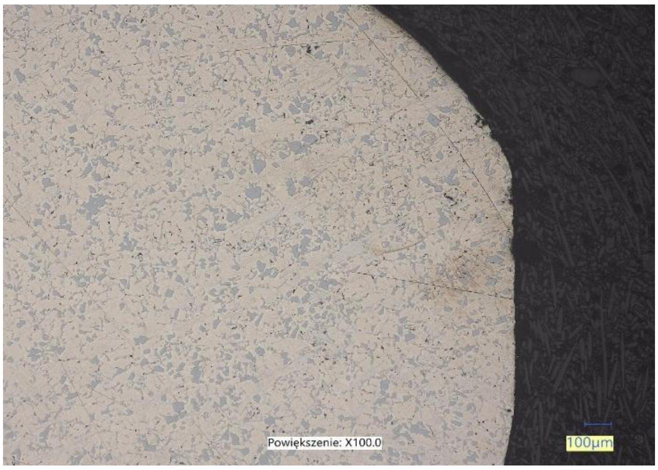


Fig. 17. Microstructure analysis locations: a) new piston, b) used piston

The metallographic specimen included the ring land area, piston crown, and combustion chamber region. Figure 17a shows the new piston with the selected areas marked for analysis. Four zones were examined: the piston crown, the combustion chamber edge, and two locations within the combustion chamber. All examined edges in the new diesel engine piston were continuous, uniform, and free of any irregularities. The microstructure in these areas was fine-grained and consistent across all analyzed zones. Figure 18a shows the edge of the combustion chamber in the new piston, while Fig. 18b presents the same area in the used piston. In the used piston, burn marks and localized edge degradation up to 0.04 mm deep were observed. These thermal erosions are numerous and distributed across the entire surface of the combustion chamber.

a)



b)

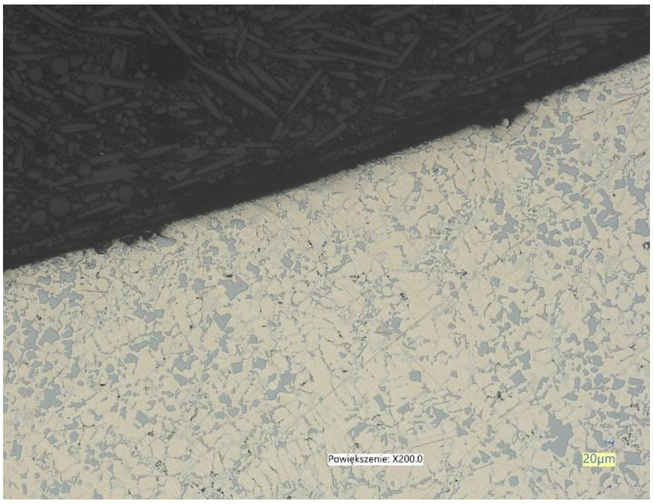
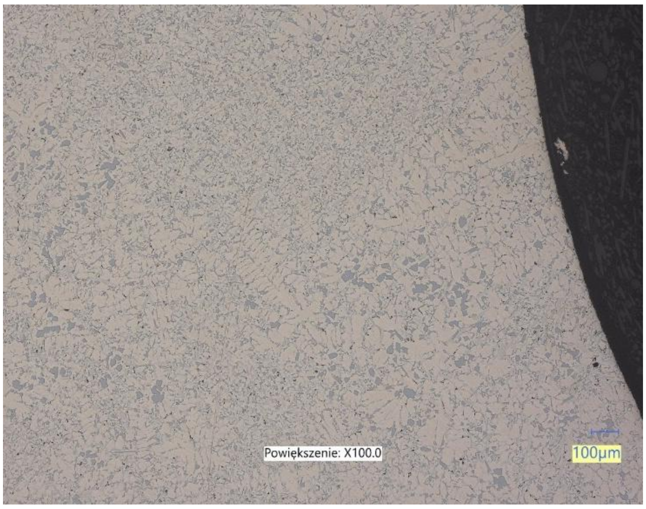


Fig. 18. View of typical burn marks on the surface of a used piston: a) combustion chamber edge, b) combustion chamber

Analysis of the microstructure of the used internal combustion engine piston in various regions revealed grain refinement in the combustion chamber area adjacent to the piston's internal cooling channel, as shown in Fig. 19a. When compared to the microstructure near the piston crown (Fig. 19b), the difference in grain size is clearly noticeable. This effect was not observed in the new piston. The analyzed region is subjected to both high temperatures and pressures generated during combustion, as well as thermal gradients caused by the cooling channel extracting heat from the combustion chamber. The presence of the cooling channel may have contributed to the observed local microstructural refinement in this area.

a)



b)

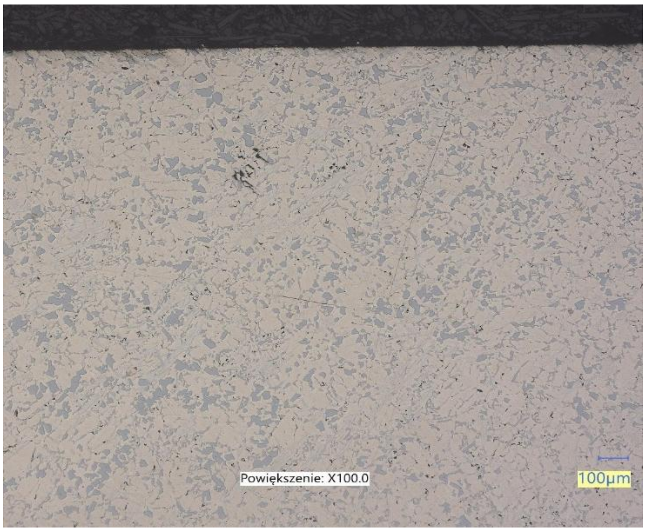


Fig. 19. Metallographic cross-section of the upper part of the piston pin bore in the used piston

For comparison, Fig. 20 presents the microstructure of the new piston in the combustion chamber region. The structure is homogeneous, with clearly visible solidification lines typical of the silumin casting process. A distinct difference can be observed between the microstructures of the new and used pistons. The edge in this area is smooth, uniform, and free of any discontinuities.

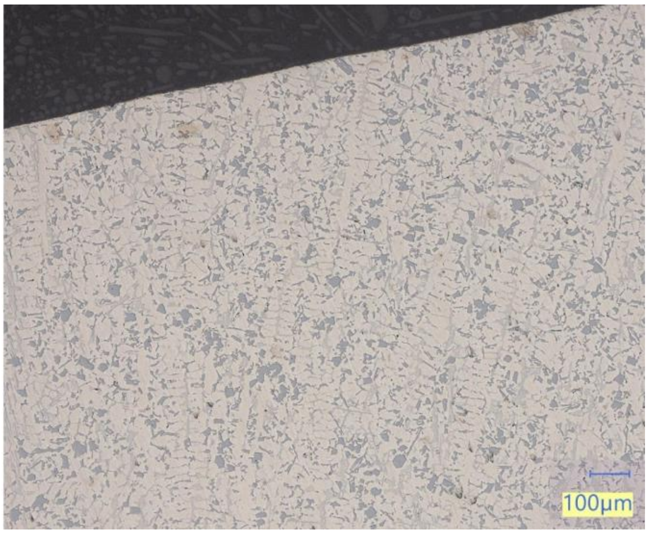


Fig. 20. Metallographic cross-section of the combustion chamber of a new internal combustion engine piston

3. Conclusions

Pistons in internal combustion engines undergo gradual wear throughout their service life due to friction, elevated temperatures, and the high pressures generated during engine operation. Understanding these degradation mechanisms enables the design of more durable and reliable pistons, which directly impacts both vehicle performance and operational costs.

The analysis clearly demonstrated that, during engine operation, significant alterations occur on the piston surface, particularly in the combustion chamber area and on the piston crown; both the material hardness and its microstructure undergo measurable changes. Based on the comparative analysis of a new piston and a piston extracted after approximately 200,000 kilometers of engine operation, the following conclusions can be drawn:

- Traces of graphite layer wear were observed on the skirt surface of the used piston
- Signs of thermal degradation were visible on the inner, central region of the piston
- The average hardness across the cross-section of the used piston was 34 HB lower than that of the new piston
- The piston crown of the used piston exhibited a hardness reduction of 44 HB compared to the new one
- At 100× magnification, thermal damage and crater formation were observed on the surface of the combustion chamber area
- In the region near the cooling channel, microstructural grain refinement was evident in the used piston.

These findings suggest that destructive processes may already have initiated in the analyzed piston, potentially leading to failure if continued operation is pursued.

If the manufacturer aims to extend the service life of pistons in this engine type, the following improvements are recommended:

- Reinforcement of the combustion chamber, e.g., by applying Durablow® technology or protective coatings on the piston crown
- Enhancement of heat dissipation efficiency through optimization of the cooling channel geometry
- Reduction of frictional wear on the piston skirt by applying advanced graphite-based coatings.

Although many approaches exist to improve piston durability, lifecycle analyses, such as the one presented in this study, provide valuable insights into the specific areas of piston design that require refinement.

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