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Usage of the Cast Iron Cylindrical Liner in an Automobile Engine Block

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Abstract

This study addresses the issues related to the quality of the connection between cast iron liners and inserts in a pressure die-cast automotive engine block, along with the macro and micro wear of the cylinder bearing surface. it was found that the commonly used HPDC high-pressure casting technology of Al-Si alloy engine blocks with cast iron liners, in which the cylinder liner is then recreated, does not ensure their metallic connection. The micro-gap created there becomes thicker as the engine is used, which worsens the conditions for heat dissipation from the sleeve to the block. Locally, on the surface of the cylinder bearing surface, reductions in honing effects and longitudinal cracks were observed. The presented literature mechanism of micro wear of the cylinder bearing surface, dependent on the morphology of graphite segregations, was confirmed. The mechanism of creating micro-breaks in the area of phosphoric eutectic and graphite precipitation occurrence was presented, initiated by the formation of microcracks in the eutectic and delaminations at the eutectic-matrix boundary.

Keywords: Cylinder liner, Phosphoric eutectic, Graphite, Macro and micro wear

1. Introduction

During engine operation, the piston-cylinder assembly is subjected to high pressures within the cylinder, during the combustion process and the associated cyclic thermal loads, as well as lateral forces from the crankshaft system. The large, variable rotational speeds of the crankshaft, transmitted to the piston, significantly affect the working conditions of the piston rings with the cylinder bearing surface, influencing its abrasive wear. The tribological characteristics of cylinder liners and piston rings are crucial in the generation of energy losses in internal combustion engines [1].

Therefore, ongoing efforts have been made to improve the materials of cylinder liners and rings, as well as their geometric surface structure, to enhance working conditions and reduce friction and wear. To lower research costs, these efforts are conducted based on laboratory tests. Few studies on this issue are conducted on components from engines with sufficiently high mileage.

In commonly used passenger cars, the cylinder bearing surface is reproduced in cast iron liners and inserts poured in the pressure die-casting process of engine blocks. It should be assumed that such a connection may result in the formation of microgaps, complicating heat flow [2]. A tight metallic connection can be achieved by shaping an alfinated layer from an aluminum-silicon alloy between the surface of the cast iron liner-insert and the cylinder block [3,4,5]. However, this solution is associated with higher production costs.

According to the authors of [6], this type of connection of cast iron liners-inserts with a block made of an aluminum-silicon alloy was applied in the Mercedes Benz V6 CDI engine and the Mercedes Benz V8 CDI engine.

To achieve a continuous metallic connection of cast iron liners-inserts with a block made of an aluminum-silicon alloy, the technique of thermally spraying the external surface of the cast iron liner-insert with Al-Si alloy powders is also used [7,8].

According to the authors of work [9], thermally sprayed insert sleeves for the production of cylinder block castings from the Al-Si alloy using high pressure die casting was applied by Mitsubishi in the NNC engine, Volvo in the N2P2S engine, and Mercedes in the M266 engine.

High performance properties and long service life are required from cylinder blocks with cast iron sleeves with inserts manufactured using high pressure casting.

The material and technology for preparing cylinder bearing surfaces should ensure a low coefficient of friction, high resistance to abrasive and corrosive wear, low susceptibility to seizure, high vibration damping capability, and associated resistance to cavitation wear, good thermal conductivity, and the ability to transmit mechanical and thermal loads [9,10].

According to car manufacturers' data, the basic construction material used for cylinder liners is gray cast iron with flake graphite in a pearlitic matrix [9], as it meets the performance requirements for liners and, importantly, has good casting properties and machinability [11].

The low cost of manufacturing is also a factor in favour of using this casting material. The favourable frictional characteristic of iron is explained by the self-lubrication of graphite [12] and the presence of phosphoric eutectic [13], whose microparticles accumulate in the tribological layer, along with the broad possibilities of modelling the geometric surface structure [10,14,15].

Significant influence on the durability of cylinder liners is exerted by mixed friction occurring at the reversal points of piston positions ZZ, ZW, where a substantial reduction or loss of the lubricating wedge occurs. Under these conditions, as well as during engine start-up, the thickness of the oil film may be so small that metallic contact occurs between rubbing elements. Another cause of excessive wear of the cylinder bearing surface is the presence of hard particles from contaminants entering the friction zone from air, fuel, or oil, as well as those dislodged from the surfaces of piston rings or the cylinder bearing surface.

Due to the high costs of work on new material and structural solutions that can be used for internal combustion engine liners, studies on abrasive wear in the liner-ring sliding assembly are conducted on simplified setups such as pin on disc [16], high-temperature tribometers [17], or reciprocating motion test rigs [18-20]. Based on the results obtained, decisions can be made about the application of a new material and structural variant for use in the test engine. The costs of long-term engine testing are very high. Therefore, the test results regarding the wear of a car engine operated in various conditions should be of interest to manufacturers.

The aim of this study was to determine the structural and material solution for the engine cylinder liners of a renowned automotive company, where one of them experienced seizure, and to understand the mechanism of wear in the cylinder bearing surface.

2. Experimental procedure

2.1. Material

The material for the study was obtained from an equipped block of an automotive engine from a well-known Japanese company. This engine had covered a distance of 250,000 km. A view of a representative engine section is presented in Figure 1.

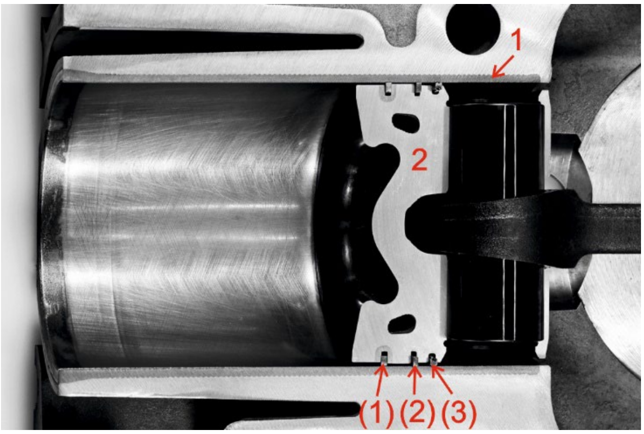

Fig. 1. Engine section view. 1 – cylinder liner-insert of the engine block, 2 – piston with piston rings: looking from the right (1) sealing, (2) sealing-scraping, (3) segmented scraping ring

Chemical composition analysis revealed that the cylinder liner-insert was made of iron (3.2%C, 2.75%Si, 0.42%P, 0.43%Cr, 0.70%Mn, 0.27%Cu, rest Fe), and the cylinder block was made of an aluminum-silicon alloy (11.64%Si, 2.73%Cu, 0.81%Fe, 0.55%Zn, 0.19%Mn, 0.14%Cr, 0.12%V, 0.02%Mg, Al – rest).

2.2. Construction of the cylinder liner

The cylinder liner contained a cast iron insert, in the pressure die-casting of the block. To ensure good anchoring in the block, its external surface was developed to obtain a grooved liner. The distance between its peaks was 1,300 µm. The peaks had a height of 300 µm. The thickness of the prepared insert, measured from the bearing surface to the peaks of the elevations, was 240-243 µm.

The beneficial effect of using a cast iron insert was the clear fragmentation of the material microstructure of the block in the region adjacent to it (Fig. 2).

The fragmentation of the microstructure of the aluminium alloy influences the increase in its mechanical properties and fatigue strength, which should be advantageous for anchoring the liner-insert in the cast block. On the other hand, microstructure studies showed that the cast iron insert did not undergo alfin treatment. This resulted in the lack of its metallic connection with the block. Samples cut perpendicular to the bearing surface spontaneously detached from the Al-Si alloy casting. Therefore, observations of the connection state between the liner-insert and the casting were made directly on the section from Figure 1.

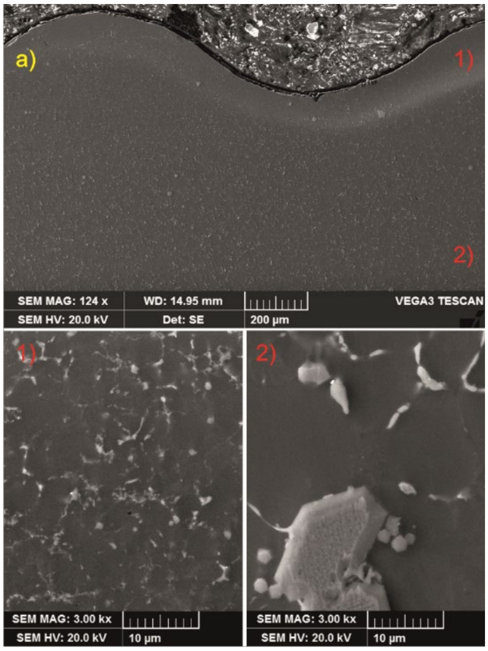

Fig. 2. Section of the block surface profile reproduced by the external surface of the cast iron liner-insert - a). Differentiation of the microstructure of the block material in the zone of interaction with the heat exchanger in the form of the liner-insert – 1) and in the zone without the influence of the heat exchanger – 2))

This is illustrated in Figure 3. For clarity, the connection view is presented for three areas along the length of the insert.

The particularly low quality of the connection from the cylinder head side is noteworthy. It is presumed that the appearance of microcracks, especially clearly visible in the regions of the liner-insert-block connection (from the cylinder head side – Fig. 3a), is a result of cyclically variable high values of pressure and temperature, as well as the influence of different coefficients of linear thermal expansion between the liner-insert material and the block material.

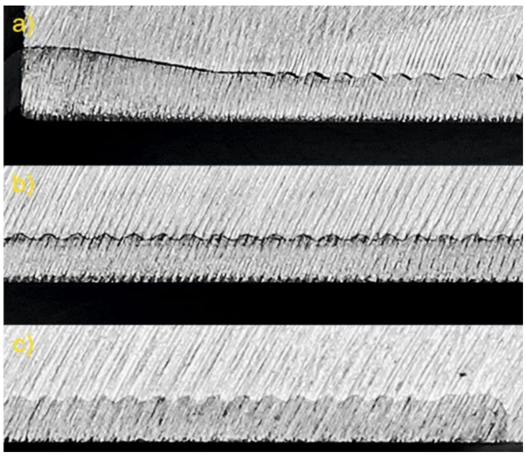

Fig. 3. View of the connection state between the liner-insert and the block in the area from the cylinder head side - a) at half the height of the liner - b), and from the crankshaft side - c)

The movement of piston rings across the cylinder bearing surface induces cyclic elastic deformations in the near-surface layer of the liner-insert. Their level is high enough to cause cracking of the phosphorous eutectic skeleton, even at a depth of about 55 µm (Fig. 4).

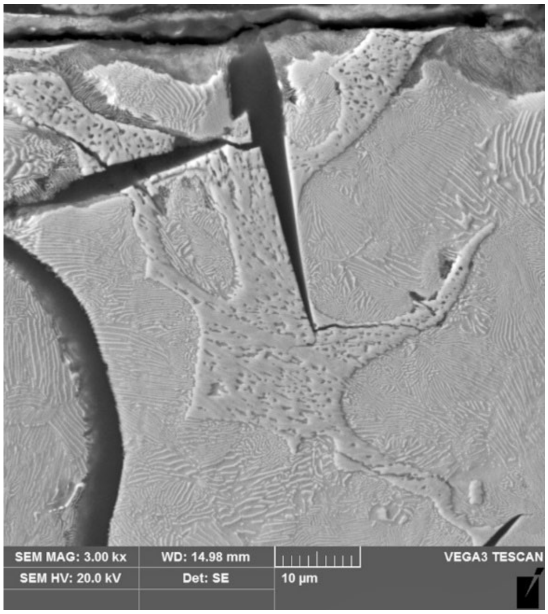

Fig. 4 View of microcracks in the phosphorous eutectic below the surface of the cast iron liner-insert

It is known that raising the surface temperature of the liner material reduces the heat transfer coefficient. This fact, combined with the presence of a gap at the boundary between the liner-insert and the cylinder block, adversely affects the heat dissipation process. On the other hand, it is known that good heat exchange enables an increase in the performance of engines [6].

2.3. Macro-wear of the cylinder bearing surface

To determine the macro-wear of the bearing surface, its surface was examined in the area where the piston rings did not move and in the areas between the reversal points (Fig. 5).

The results obtained indicate non-uniformity of the honed surface due to width of the honing grooves (Fig. 5b), and different depths. This resulted in a significant loss of honing effects, especially in the reversal point areas. The consequence was a deterioration of lubrication conditions, an increase in the tendency to seizure, and thus an increase in bearing surface wear.

Numerous crack marks along the length of the liner were revealed on the working surface, indicating low air filtration care, introducing hard particles into the combustion chamber. This suggests that the car was operated in conditions of significant environmental dust.

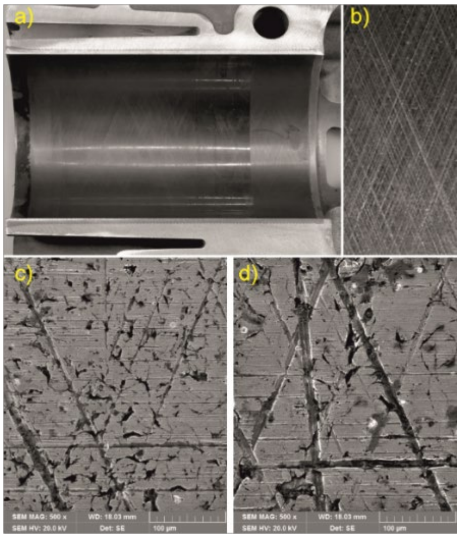

Fig. 5. View of the cylinder bearing surface reproduced in the cast iron liner-insert -a), honed surface where the piston rings did not move -b), surface from the reversal point ZZ area -c), and the area halfway along the liner -d)

2.4. Micro-wear of the cylinder bearing surface

Studies of the microstructure of the liner material showed that the requirements of the BN-78/1372-01 standard [21] are met regarding the shape, size, and distribution of graphite precipitates, as well as the matrix and phosphorous eutectic precipitates.

However, it is known that the morphology of graphite precipitates determines the mechanism of micro-wear of the liner surface [22].

The studies were conducted on metallographic sections of samples cut perpendicular to the bearing surface.

It was found that the morphology of graphite precipitates has the same influence on the micro-wear mechanism of the liner-insert as schematically presented in the study [23] (Fig. 6).

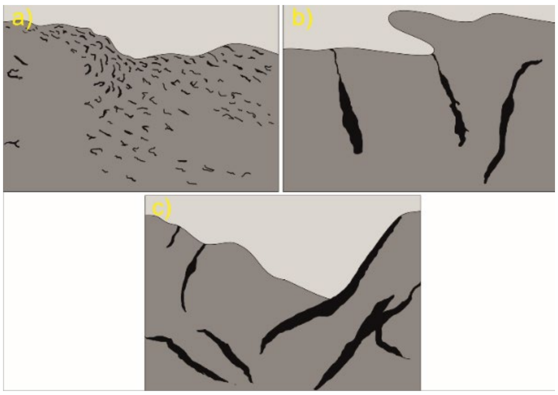

Fig. 6. Schematic illustration of frictional-wear mechanism: a) cast iron with graphite precipitates of flake length up to 15 µm; b) cast iron with graphite precipitates of flake length of approximately 45 µm; c) cast iron with graphite precipitates of flake length 90–180 µm [6]

The results of the study on the influence of phosphorous eutectic precipitates on the micro-wear mechanism of the cylinder bearing surface are illustrated in Figures 4 and 7. The creation of cracks at an angle or parallel to the rubbing surface is particularly prone in the near-surface layer up to a depth of about 35 µm.

In creating tears, cracks in the eutectic and delaminations at the eutectic-matrix boundary, as well as graphite precipitates, interact with each other. Graphite precipitates arranged diagonally (Fig. 7b) or parallel to the rubbing surface (Fig. 7c) are particularly detrimental. Many tears were limited from below by cracks in the eutectic and cracks running along the surface of the eutectic-phosphorous matrix or along the surface of the matrix-graphite separation, as illustrated in Figures 7c and 7d.

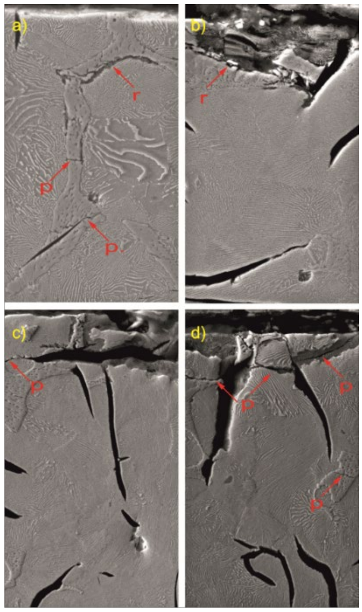

Fig. 7. View of phosphorous eutectic cracks and delaminations at its boundary with the matrix and material tears near the bearing surface. Magnification: 3000x

The significant depth at which cracks were observed in long, perpendicular to the rubbing surface, eutectic precipitates (Fig. 4) can be explained by the high level of cyclically variable stresses originating from thermal loads and piston rings. The cause of such damage should also be sought in the low susceptibility to elastic and plastic deformation of the phosphorous eutectic compared to the matrix. It is much harder and thus more brittle than the matrix. The microhardness measured by the Oliver and Pharr method was 1020 HVIT and 425 HVIT, respectively. It can be assumed that crushed, hard particles of the eutectic, but also particles of the matrix, participated in the creation of cracks on the bearing surface. On the other hand, it is known that graphite and eutectic micro-particles build a tribological layer [12, 13] on the bearing surface, which is advantageous for reducing friction work.

3. Conclusions

The obtained research results allow for the formulation of the following statements:

- The technology of pressure die casting of engine blocks with cast iron liners-inserts does not provide them with metallic bonding. This fact, in conjunction with particularly high, cyclically variable thermal loads and gas pressure in the combustion chamber, as well as significantly different coefficients of linear thermal expansion of iron and Al-Si alloy, promotes the development of microcracks. The microgap hinders heat flow, negatively affecting engine power [6].
- The non-uniformity of the honed surface was identified, characterized by varying widths and depths of honing marks, especially in the areas of reversal points.
- A significant number of scratches along the length of the liner were revealed, differing in width. It is likely that they were formed by dust particles introduced into the combustion chamber with air, torn from the liner surface particles of phosphorous eutectic and matrix, as well as particles torn from the sliding surface of the piston rings coated with chromium.
- It was confirmed that the micro-wear of the liner surface due to the action of graphite precipitates is consistent with the scheme presented in the study [23].
- It was found that micro-wear of the liner in the area of phosphorous eutectic precipitates is initiated by its microcracks and delaminations at the eutectic-matrix boundary, which are oriented parallel to the sliding surface. In the presence of graphite precipitates nearby, these cracks propagate through the graphite-matrix interface or through graphite to the liner surface. The microcracks thus formed surround the micro-area of the material from below, which then undergoes tearing.

References

[1] Kim, J.-K., Xavier, F.-A. & Kim, D.-E. (2015). Tribological properties of twin wire arc spray coated aluminum cylinder liner. *Materials & Design.* 84, 231-237. DOI: 10.1016/j.matdes.2015.06.122.

[2] Longa, W. (1978). *Theory of foundry processes*. AGH, Wydział Odlewnictwa, Instytut Odlewnictwa. (in Polish).

[3] Pietrowski, S. & Szymczak, T. (2004). Construction of the connection between alfined coating and silumin. *Archives of Foundry.* 4(14), 393-404. (in Polish).

[4] Pietrowski, S. (2004). Construction of the alfined layer on gray cast iron. *Archives of Foundry.* 4(11), 95-104. (in Polish).

[5] Pietrowski, S. & Szymczak, T. (2006). The influence of selected technological factors on the structure of the alfined layer on iron alloys. *Archives of Foundry.* 6(19), 251-266. (in Polish).

[6] Pawlus, P., Michalski, J. & Ochwat, S. (2012). Surface characteristics of cylinder liners intended for pouring using the Alfin method. *Pomiary Automatyka Robotyka*. 4, 61-65. (in Polish).

[7] Mahle Diesel Symposium, Stuttgart 2005.

[8] Volvo, DAF, MAN, PSA-BMW technical information from Mahle project meetings. Unpublished materials. Krotoszyn 2005-2010. (in Polish).

[9] Gruszka, J. (2011). Global trends in cylinder liners technology. *Polskie Towarzystwo Naukowe Silników Spalinowych.* 50(3), 1-7.

[10] Kozaczewski, W. (2004). *Construction of the piston-cylinder group of combustion engines*. Wydawnictwa Komunikacji i Łączności WKŁ. (in Polish).

[11] Podrzucki, Cz. (1991). *Cast iron: structure, properties, application*. Kraków: Wydaw. ZG STOP.

[12] Çakır, M. & Akcay, İ.H. (2014). Frictional behavior between piston ring and cylinder liner in engine condition with application of reciprocating test. *International Journal of Materials Engineering and Technology*. 11(1), 57-71.

[13] Shirokov, V.V., Arendar, L.A., Slyn'ko, H.I. & Volchok, I.P. (2003). Influence of phosphide eutectics on the wear resistance of high-strength cast irons. *Materials Science.* 39(2), 295-298. DOI: 10.1023/B:MASC.0000010284.56057.72.

[14] Uetz, H. (1969). Einfluß der honbearbeitung von zylinderlaufbuchsen auf die innere grenz-schicht und den einlaufverschleiß. Forschungsvereinigung Verbrennungskraftmaschinen. *MTZ,* 3.

[15] Ronen, A., Etsion, I. & Kligerman, Y. (2001). Friction-reducing surface-texturing in reciprocating automotive components. *Tribology Transaction.* 44(3), 359-366. DOI: 10.1080/10402000108982468.

[16] Picas, J.A., Forn, A. & Matthäus, G. (2006). HVOF coatings as an alternative to hard chrome for pistons and valves. *Wear.* 261(5-6), 477-484. DOI: 10.1016/j.wear.2005.12.005.

[17] Skopp, A., Kelling, N., Woydt, M. & Bergrer, L.-M. (2007). Thermally sprayed titanium suboxide coatings for piston ring/cylinder liners under mixed lubrication and dry-running conditions. *Wear.* 262(9-10), 1061-1070. DOI: 10.1016/j.wear.2006.11.012.

[18] Grabon, W., Pawlus, P., Woś, S., Koszela, W. & Wieczorowski, M. (2016). Effects of honed cylinder liner surface texture on tribological properties of piston ring-liner assembly in short time tests. *Tribology International.* 113, 137-148. DOI: 10.1016/j.triboint.2016.11.025.

[19] Johansson, S., Nilsson, P.H., Ohlsson, R. & Rosén, B.-G. (2011). Experimental friction evaluation of cylinder liner/piston ring contact. *Wear.* 271(3-4), 625-633. DOI: 10.1016/j.wear.2010.08.028.

[20] Igartua, A., Nevshupa, R., Fernandez, X., Conte, M., Zabala, R., Bernaola, J., Zabala, P., Luther, R. & Rausch, J. (2011). Alternative eco-friendly lubes for clean two-stroke engines. *Tribology International.* 44(6), 727-736. DOI: 10.1016/j.triboint.2010.01.019.

[21] BN-78/1372-01. Piston combustion engines. Cylinder liners made of alloy cast iron. General requirements and tests. (in Polish).

[22] Orłowicz, A.W., Mróz, M., Tupaj, M., Trytek, A. (2015). Shaping the microstructure of cast iron automobile cylinder liners aimed at providing high service properties. *Archives of Foundry Engineering.* 15(2), 79-84. DOI: 10.1515/afe-2015-0043.

[23] Orłowicz, A.W. & Trytek, A. (2003). Effect of rapid solidification on sliding wear of iron castings. *Wear.* 254(1-2), 154-163. DOI: 10.1016/S0043-1648(02)00301-0.