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Mechanical and Microstructural Characterisation of Cylinder Liners

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Abstract. The automotive industry is seriously concerned with emission level control, vehicle weight reduction and recycling. These are the purposes of introducing the all aluminium cylinder blocks for the combustion engine. The spray forming process led to the fabrication of cylinder liners made of high aluminium silicon alloys. The aim of the present work was to evaluate and compare the microstructures and mechanical properties of three cylinder liners: grey cast iron; and two aluminium silicon alloys. Their surface roughness and topology also have been investigated.

Introduction

Some aluminium-silicon alloys have characteristics such as good wear resistance combined with low coefficient of thermal expansion. These alloys also have a high strength to weight ratio. Due to these properties, such alloys have been used for several applications in the automotive, aerospace and electric industries [1-4]. Recent engineering efforts towards improving the physical and mechanical properties have focused on chemical composition modifications with the objective of improving mechanical strength, wear resistance, ductility and toughness properties of such alloys. This led to hypereutectic compositions that present low coefficient of thermal expansion and excellent wear resistance. The outstanding wear resistance is due to the high volumetric fraction of fine primary silicon phase and intermetallics. Applications of the Al-Si alloys in the automotive industry, include engine blocks and parts of engines, particularly, cylinder liners. The main advantages of the use of these alloys are weight reductions, less emission of gases and low fuel consumption [1,2].

The use of engine blocks made of hypereutectic aluminium alloys has been considered by many world manufacturers. Blocks of the Al17Si4CuMg alloy are very difficult to cast and have been produced by expensive processes, such as chill mould casting at low pressure. This process was necessary to obtain refined silicon particles used in the contact area between the cylinder and the piston rings. The conventional die cast Al9Si3Cu alloy has been preferred due to economic reasons. However, the tribological properties of the late alloy do not favour its use in the combustion chamber area. The accepted solution is to use cylinder liners made of cast irons; cast or spray formed high silicon aluminium alloys, composites or coatings in this area [2].

Hypereutectic alloys can be produced by ingot metallurgy [1,2] or by rapid solidification processes, such as: melt spinning [4], atomisation [4,5] and spray forming [4-8]. The use of ingot metallurgy for the production of these alloys is limited by the range chemical compositions possible. That can be attributed to the formation of eutectic phases and coarse primary silicon phase, due to the low cooling rates associated to the ingot metallurgy. The distribution of coarse silicon particles in the alloy leads to low ductility and limited workability of the hypereutectic Al-Si alloys produced by ingot metallurgy.

Many of the problems associated with ingot metallurgy processing can be overcome by rapid solidification techniques. The main advantage of the use of the rapid solidification process is the significant modification of size, morphology and distribution of the primary silicon phase in the matrix, comparatively to the conventional process. This has been achieved by spray forming hypereutectic Al-Si alloys or co-depositing Si particles.

The technology for producing cylinder liners by casting iron and spray forming aluminium alloys is well established. The use of aluminium alloys for such application was made possible by the admixture of large amounts of alloying elements that precipitate as hard second phase particles. The use of such alloys with hard particles is viable if these particles are finely dispersed, allowing further mechanical working. The aim of this study is to evaluate and compare the microstructures and mechanical properties of three cylinder liners alloys: grey cast iron; and two-aluminium silicon alloys either cast or spray formed.

Experimental

Samples taken from three different types of cylinder liners were analysed: a centrifugal grey cast iron; a spray formed and a cast Al-Si alloys here named Al-Si-1 and Al-Si-2, respectively. The grey cast iron cylinder liner was examined as brand-new and the Al-Si cylinder liners after running in combustion engine. The conditions under which the engines were run are unknown. The materials were characterised chemical analysis, microstructural characterisation and mechanical testing.

The chemical analysis was carried out by atomic absorption spectrophotometry and silicon was analysed by the gravimetric technique. Microstructural characterisation was carried out by means of optical microscopy - OM and scanning electron microscopy - SEM. The surface finishing of the cylinder liners was observed by SEM.

The mechanical property was evaluated in terms of Vickers microhardness. The load used throughout was 100 g. For each sample, at least ten measurements were made and the mean value and standard deviation calculated. The roughness of the samples surface was evaluated in a roughness meter and the measurements were expressed in Ra (arithmetic mean roughness), Rz (mean peak-to-valley height) and Rmax (maximum individual peak-to-valley height). The roughness testing was carried out in two regions, one as worn by the piston or piston rings out and another region not reached by them.

Results And Discussion

Chemical analysis

Table 1 shows the chemical compositions of the cylinder liners materials and published values [10]. The aluminium alloys showed high amounts of silicon. However, the spray formed Al-Si-1 alloy has a significant higher amount of this element. Conversely, the cooper content of Al-Si-2 is almost twice that of Al-Si-1 alloy.

Table 1. Selected chemical compositions of cylinder liners (wt. %).

Material	C	Al	Si	Mg	Ni	Cu	Fe
Grey cast iron	3.50	...	...	0.04	0.12	0.51	balance
Al-Si-1	...	balance	23.16	1.00	0.96	2.70	0.19
Al-Si-2	...	balance	16.13	0.64	0.04	5.00	0.49
Al-Si ref. [10]	...	balance	23.0-28.0	0.8-2.0	1.0-5.0	3.0-4.5	1.0-1.4

... Nihil.

Microstructural analysis

The surface of the grey cast iron cylinder liner consisted of the standard honing topology. Hence, it is not shown here. Figs. 1 and 2 present the surfaces of the two Al-Si cylinder liners studied. These SEM micrographs were taken from the region not reached by the piston rings. They clearly show that two different procedures were used to manufacture the cylinder liner final surface. Fig. 1 shows that the surface was polished by honing, producing groves for lubricant oil retention. Fig. 2 shows that the cylinder liner Al-Si-2 surface was electrochemically etched, leaving secondary phase, such as very fine silicon particles and intermetallics protruding.

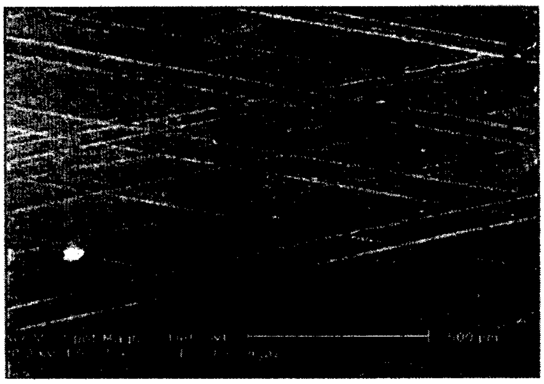

Fig. 1. Secondary electron micrograph of a cylinder liner, alloy Al-Si-1, showing clearly the honing groves in the surface.

Fig. 2. Secondary electron micrograph of a cylinder liner, alloy Al-Si-2, showing that the surface of the material was electrochemically etched.

Figs. 3 to 5 show the polished surfaces of the three cylinder liners. The grey cast iron material showed graphite flakes of type I, homogeneously dispersed, see Fig. 3. The SEM micrograph of Al-Si-1 alloy, Fig. 4, shows a very fine distribution of silicon particles measuring 0.5 μm to 5 μm and many intermetallic particles. Fig. 5 shows an optical micrograph of the cast Al-Si-2 alloy, showing primary silicon particles (dark phase) and eutectic microstructure. In Al-Si-2 alloy the silicon particles are much coarser (35 μm mean size) than those present in Al-Si-1 alloy.

Fig. 3. Secondary electrons micrograph of the grey cast iron cylinder liner, showing graphite type I (homogeneous lamella homogeneously dispersed).

Fig. 4. Secondary and backscattered mixed electron micrograph of spray formed Al-Si-1 alloy, showing protruding fine intermetallic particles (white phase) and primary silicon (light grey) particles, in an aluminium matrix, homogeneously distributed throughout the material.

Fig. 5. Optical micrograph of Al-Si-2 alloy showing primary silicon particles (dark phase) and the eutectic microstructure.

Microhardness

Vickers microhardness results are presented in Table 2. This table show that the grey cast iron has a much higher hardness value than the Al-Si alloys. It is worth remembering that the outstanding tribological properties of the Al-Si alloys reside in the fine distribution of hard silicon particles. The higher hardness value of the Al-Si-2 alloy might be explained by the presence of the Al-Si eutectic microstructure, as showed in Fig. 5.

Table 2. Vickers hardness measurements of grey cast iron and Al-Si alloys used as cylinder liners.

Material	Grey cast iron [9]	Al-Si-1 [9]	Al-Si-2
HV 0.1	283 ± 43	99 ± 6	119 ± 10

Roughness testing

Tables 3 and 4 present the roughness values for the cylinder liners evaluated. Since the grey cast iron cylinder liner was received as brand new, it was only measured the surface roughness as fabricated. For the spray formed and cast Al-Si alloys, both regions were evaluated.

Table 3. Roughness values for the cylinder liners in the region not reached by the piston rings. For comparison, data from a patent is also showed [10].

Material	Ra µm	Rz µm	Rmax µm
Grey cast iron	1.20	10.90	...
Al-Si-1	0.61	5.40	...
Al-Si-2	0.38	4.66	5.53
Al-Si [10]	...	2-5	5

... Not available.

Table 4. Roughness values obtained for the cylinder liners in the area worn by the piston or piston rings.

Material	Ra µm	Rz µm	Rmax µm
Al-Si-1	0.32	3.2	...
Al-Si-2	0.25	2.18	4.10

... Not available.

The surface finish of the grey cast iron cylinder liner was coarser than that of the Al-Si alloys. This was demonstrated by the Ra and Rz values, see table 3. It should be pointed out that the surface finish of the grey cast iron and Al-Si-1 alloy cylinder liners were attained by honing, whereas for alloy Al-Si-2 by electrochemical etch. Besides, Al-Si-2 alloy has lower Ra values than Al-Si-1, the (Rz) peak-to-valley height is almost similar, which is important for oil retention and lubrication. Table 4 indicates that the cylinder liner surface of the spray formed Al-Si-1 alloy has been smoothed by the piston or piston rings movement, but its peak-to-valley heights are still under the specifications, i.e. between (Rz) 2-5 μm [10].

Conclusions

The fabrication of Al-Si cylinder liners, of chemical compositions showed in this study, is viable when rapid solidification techniques are used, e.g., spray forming. Otherwise, coarse second phase particles are formed and the obtainment of mechanically worked cylinder liners is not easily achieved.

Appropriate cylinder liner surface finish for the spray formed aluminium-silicon alloy may be attained the honing method. Whereas, a cast alluvium-silicon alloy can be conveniently electrochemically etched.

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