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RESEARCH

Tribological Investigation of The Effect of Aluminum Alloy in Accordance with Cast Iron Liner on Engine Wear

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A B S T R A C T

The tendency to use aluminum alloys to replace conventional gray cast irons (GCI) materials in engine blocks of passenger cars is gaining more and more importance driven by reduction of engine weight to achieve expectation for lowering fuel consumption and CO_2 emissions. In this work the tribological effect of new produced aluminum engine cylinder liner is compared with the conventional cast iron the cylinder bore for friction, lubrication and wear-resistance. Their tribological performance was evaluated through a reciprocating tribometer, using steel ball (100 CR6) on an aluminum and cast iron Diesel engine cylinder liners with 5W-40 engine oil to investigate their wear and friction behavior in boundary lubrication regime. There is a great effect of the roughness of machining marks (honing) on the surface of the liner. Although the same honing type was applied on both liner sleeves, aluminum liner presented less wear track, less roughness smoother surface related to cast iron liner. Repeated friction tests presented almost similar coefficient of friction data. Friction and wear comparison is well determined and the rubbed surfaces as well as all additives were analyzed through 2D-3D roughness digital optical microscopy, SEM-EDX analysis.

1. INTRODUCTION

To meet more demanding fuel economy and emission standards, new challenges in engine design include reduced weight, reduced friction, and higher engine operating temperatures. General Motors has been working internally and with partners to develop and evaluate environmentally sound and cost effective coating materials and processes for aluminum pistons to run in aluminum bore engines [1].

The common types of aluminum engine blocks are based on open-deck and closed-deck designs. The choice depends mostly on cylinder liners, bores, complexibility of the design and method of manufacturing process. The use of an aluminum material as a running surface for cylinder bores has been interesting to automotive design engineers for many years because of the lower mass and improved heat transfer in comparison to the widely used gray iron [2].

Excellent thermal conductivity and lower density make Al–Si alloys a suitable alternative for cast iron in the fabrication of engine components. The increase in the maximum operation temperature and pressure of engines necessitates improving the thermomechanical fatigue performance of Al–Si alloys [3].

This paper has the major part focussing on the use of Al–Si based alloys in cylinder liner of engine blocks. This study aims to compare new produced aluminum engine cylinder liner with the conventional cast iron the cylinder bore for friction, lubrication and wear-resistance.

2. EXPERIMENTAL DETAILS

Anadolu Motor Antor LD400 Diesel engine has been choosen for this work. Its technical specifications are presented in Figure 1. It is air cooled and single cylinder engine.

Engine	Specification
Model diesel	6 LD 400
Cylinder volüme	395 cm³
Cylinder diameter	86 mm
Compression ratio	18.1
Max. speed	3600 rpm
Max. power	8.5 HP
Max. torque	2 kgm @2200 d/dk
Fuel capacity	4.5 lt
Fuel consumption	220 gr/HP/hour
Oil consumption	13 gr/ hour
Oil capacity	1.2 lt
Dry weight	45 kg

Fig. 1. Anadolu motor Antor 6 LD 400 diesel engine and its technical specifications.

The new (dry cylinder liner of the Antor LD 400 engine, is purchased as a spare part (See Fig 2). The bore diameter is 86 mm and the honing height is 77 mm.

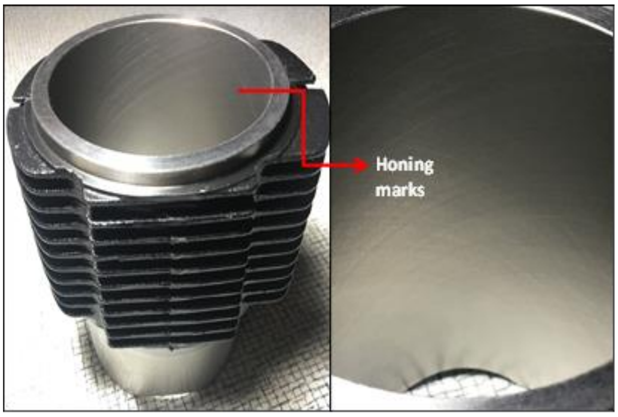


Fig. 2. Dry cylinder liner of Anadolu motor Antor 6 LD 400 diesel engine with honing marks.

Aluminun material standart is EN AW-7075/ ISO (Al Zn5,5MgCu) as the chemical composition is presented in Table 1. Figure 3 shows the aluminum block drilled and honed as the same of Anadolu Motor Antor 6 LD 400 Diesel engine.

Table 1. Chemical composition of EN AW-7075 in mass %.

Fe	Si	Cu	Mn	Mg
0.5	0.4	1.2-2.0	0.3	2.1-2.9
Zn	Cr	Zi-Ti	Remark	Al
5.1-6.1	0.18-0.28	0,25	0.15	88.47

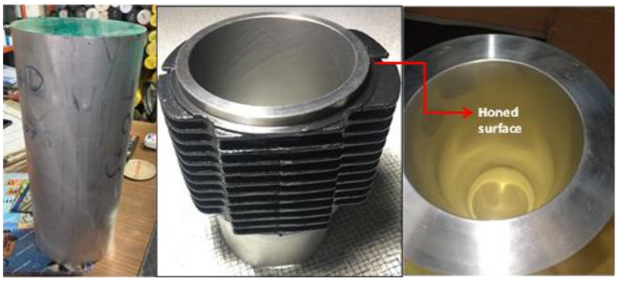


Fig. 3. Aluminum block drilled and honed as the same of Anadolu motor Antor 6 LD 400 diesel engine.

Figure 4 and Figure 5 present the preparation of cylinder liner specimens in cast iron and aluminum for tribotest. Both cast iron and aluminum cylinder barrel test specimens were cut accurately by dry cutting method. The cutting process is performed accurately in Dünya Kalıp limited using CNC milling process technology in Istanbul TURKEY without damaging the honed surfaces. It has considered the substrate temperature and controlled the temperature during the cutting process due to possible material property changes at cylinder liner substrates induced by heat. During the cutting process, surface temperature was controlled by infrared digital thermometer and measurements showed that surface temperature had not exceeded 49°C. They are cut for (10X10X13 mm) dimension to fit in Tribometer.

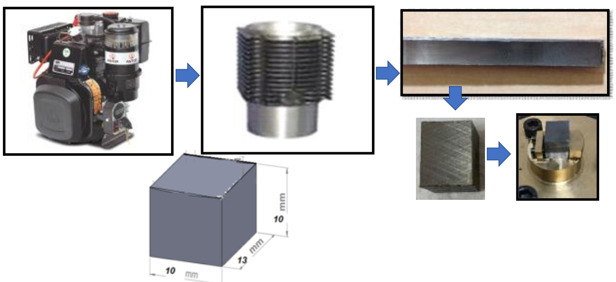


Fig. 4. Preparation of cylinder liner specimens in cast iron for tribotest.

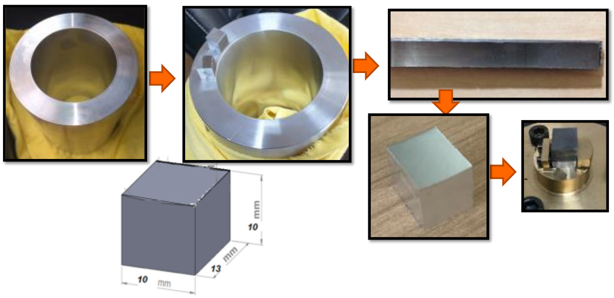


Fig. 5. Preparation of cylinder liner specimens in aluminum for tribotest.

Tribological performance of the cast iron and aluminum liners was performed with 5W-40 synthetic engine oil according to formal, well-established test parameters as some properties are listed in Table 2, utilizing a customized reciprocating tribometer setup, as showed in Figure 6.

Table 2. The properties of 5W-40 synthetic engine oil.

Some Properties of 5W-40 synthetic engine oil	
Total Base Number (TBN)	11.28 mg KOH/g
Flash point	217 °C
Viscosity @100 °C	13.59 cSt
Viscosity @40 °C	84.27 cSt

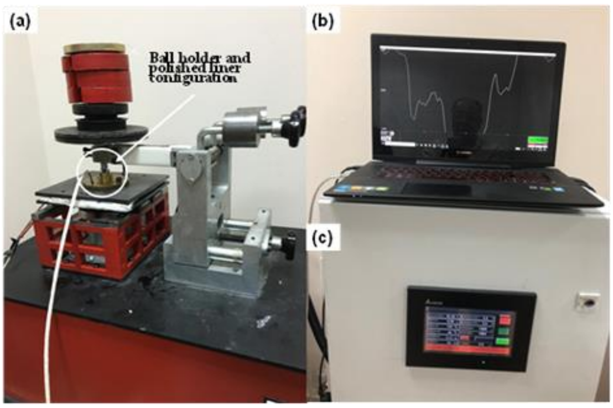


Fig. 6. Reciprocating tribotest setup: (a) general view, (b) recording of accurate friction force data measurement, (c) heating and temperature control and monitoring.

The tribometer is driven by a servomotor, and 800 data (values) per second were collected from the load cell, using a data logger, directly connected to a monitor. Each stroke lasted 0.8 s (640 data per second) and in this way the average CoF of the wear track during the measurement was estimated. All tests were carried out under boundary lubrication conditions at 100 °C. Normal load during the tribological measurements was set to be 60.5 N. Sliding speed or reciprocating velocity and stroke were 0.055 m/s and 8 mm, respectively. The temperature of the block was set up to 100 °C, using an advanced heater, equipped with a digital controller mounted on the setup. To run a 21 min tribotest measurement, three drops from engine oil were dropped on the surface of the liner specimens. Then, the 100CrMn6 steel ball rubbed on it under boundary lubrication conditions, as displayed in Figure 7. Data acquisition was done by a specific software, developed using MATLAB, which was used in order to filter any vibrational noise and to calculate the average CoF, by plotting the final CoF curve, as a function of time. In this set-up, the liner is sliding against a stationary ball.

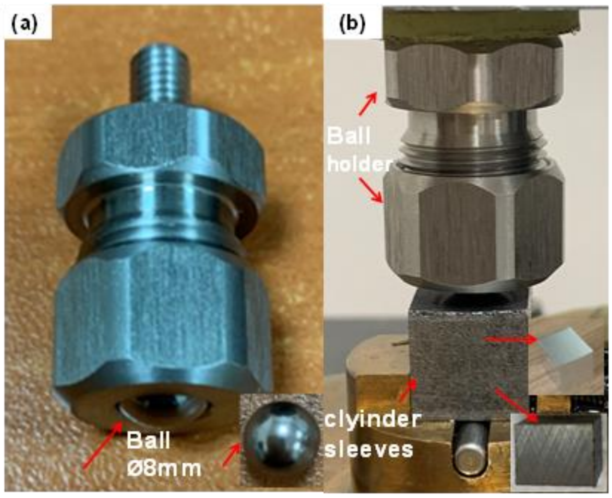


Fig. 7. Ball and liner specimen configuration: (a) Ball placed in the holder, (b) Ball holder and liner integrated configuration.

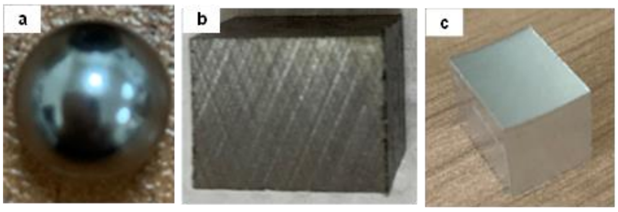


Fig. 8. Photos of the ball (a), cast iron (b) and aluminum (c) liners before test

Figure 8 shows the photos of the ball (a), cast iron (b) and aluminum (c) liners before test

3. RESULTS AND DISCUSSIONS

Figure 9 presents the optical digital images of the wear scar diameter (horizontally and vertically) of the balls tested on the (a) cast iron and (b) aluminum liner with 5W40 engine oil. As seen in table 3, surprisingly wear scar diameter of the ball presented lowest value horizontally and vertically on aluminum liner related to the cast iron liner.

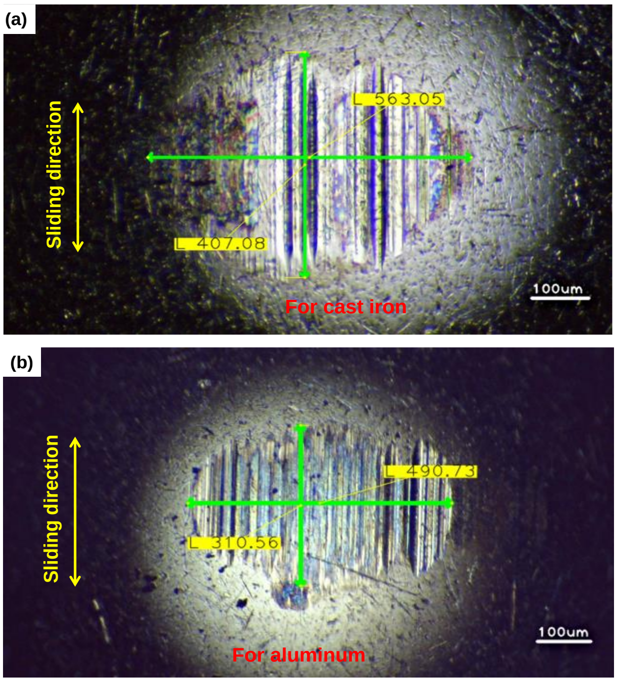


Fig. 9. Optical digital images of the wear scar diameter (horizontally and vertically) of the balls tested on the (a) cast iron and (b) aluminum liner with 5W40 engine oil.

Table 3. The data of the of wear scar of balls tested on the cast iron and aluminum liners.

Tested material ball on	Wear scar diameter (horizontal) (µm)	Wear scar diameter (vertical) (µm)
Cast iron liner	563.05	407.08
Aluminum liner	490.73	310.56

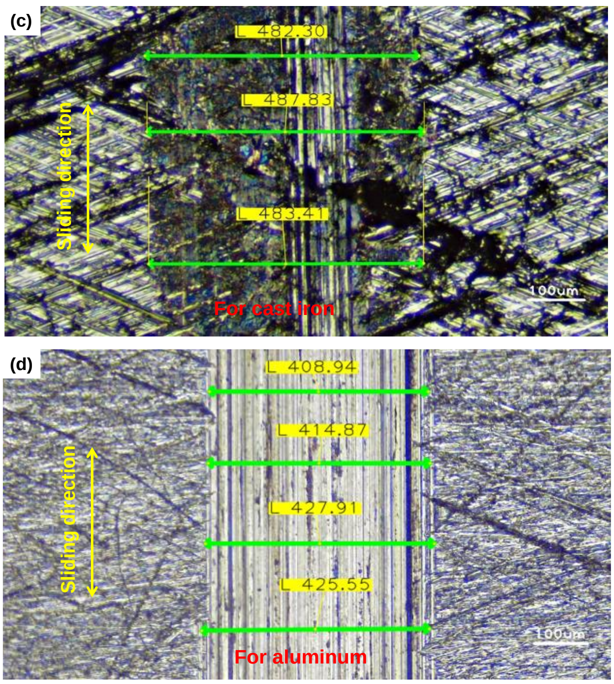


Fig. 10. Optical digital images of the wear scar distance of the (a) cast iron and (b) aluminum liners tested with 5W40 engine oil.

Figure 10 presents the optical digital images of of the wear scar distance of the (a) cast iron and (b) aluminum liners tested with 5W40 engine oil. As seen in table 4, maximum an minimum wear scar width of the liner presented lowest value on aluminum liner related to the cast iron liner.

Table 4 The data of the of wear scar width of the cast iron and aluminum liners

Tested material liner	Max. wear scar width (µm)	Min. wear scar width (µm)
Cast iron	487.83	482.30
Aluminum	427.91	408.94

Surface analysis of the ball and liner sliding pairs has been carried out through a fully digital optical microscope, as well, in order to compare the degree of deformation occurred upon testing the liner samples, while 2D/3D roughness parameters were measured by a 3D high resolution optical profilometer, before and after tests. All roughness measurements were carried out with X10 Olympus objective choosing high quality removing background section in software. Ra and Sa values were taken into account for comparison. 2D/3D roughness parameters can be seen clearly in figures as they are less than 1 µm (item no 336 polishing for Ra from 0.0125 to 0.26 um and Rz from 0.25 to 1.6 in Microsurf series of comparators) which conforms well with UKAS (National Accreditation Body for the United Kingdom) as mentioned in The Microsurf Series Of Comparators - Rubert & Co Ltd [4].

Figures 11 and 12 show 2D-3D roughness digital optical microscopy of the tested ball on aluminum and cast iron cylinder liners. Roughness parameters such as Sa and Ra values were found smaller in aluminum liner related to the cast iron liner as presented in table 5. Abrasion lines are visible on the rubbed wear scar.

Table 5. Comparison of 2D-3D profiles of the balls tested on the cast iron and aluminum engine liners.

Tested material	Sa (µm)	Ra (µm)
Ball (non tested)	0.765	0.056
Ball tested on cast iron liner	0.615	0.071
Ball tested on aluminum liner	0.586	0.010

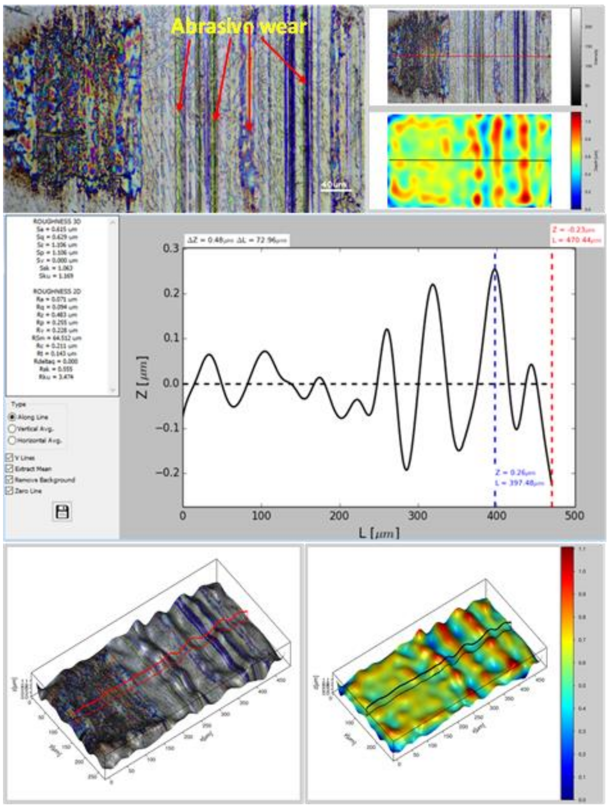


Fig. 11. 2D-3D roughness digital optical microscopy of the tested ball on cast iron cylinder liner.

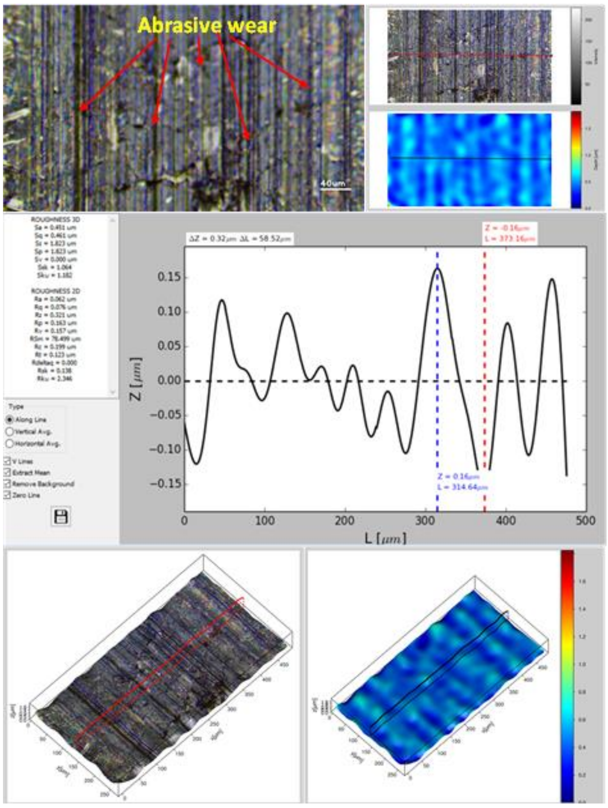


Fig. 13. 2D-3D roughness digital optical microscopy of the tested cast iron liner.

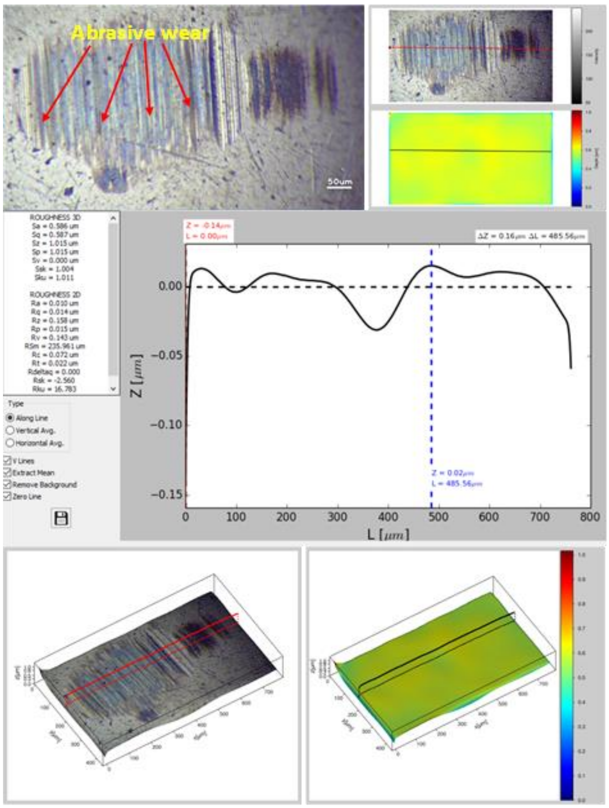


Fig. 12. 2D-3D roughness digital optical microscopy of the tested ball on aluminum cylinder liner.

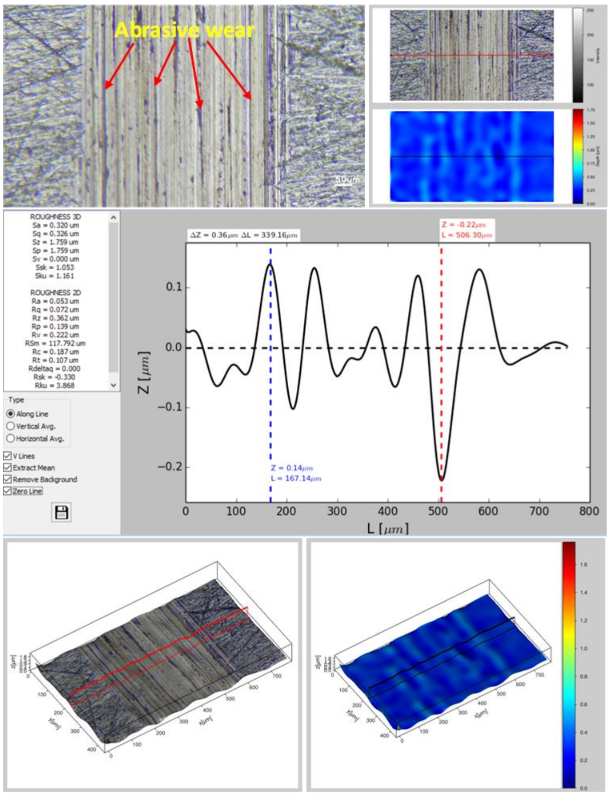


Fig. 14. Figure shows 2D-3D roughness digital optical microscopy of the tested aluminum liner.

Figures 13 and 14 show 2D-3D roughness digital optical microscopy of the aluminum and cast iron cylinder liners rubbed under steel ball. Roughness parameters such as Sa and Ra values were found smaller in aluminum liner related to the cast iron liner as presented in table 6. Abrasion lines are visible on the rubbed wear scar.

Table 6. Comparison of 2D-3D profiles of the cast iron and aluminum engine liners tested steel ball.

Tested material	Sa (μm)	Ra (μm)
Cast iron liner (non tested)	0.604	0.078
Cast iron liner (tested)	0.451	0.062
Aluminum liner(non tested)	0.608	0.010
Aluminum liner (tested)	0.312	0.063

Over the past decade, Al–Si casting alloys have increasingly been used in the automotive industry as a suitable alternative for cast iron in fabrication of engine components. The major advantage of Al–Si alloys, besides their high strength to weight ratio, is their excellent thermal conductivity, which allows the combustionheat to be extracted more rapidly compared to cast iron. On the other hand, the automotive industry been ever facing the challenge of improving efficiency and overall performance of engines. To increase the efficiency, the maximum operation temperature and pressure of theengine must be raised. The increase of operation temperature, which leads to softening of hypoeutectic Al–Si alloys, necessitates high-temperature strengthening of the Al–Si alloys [3].

3.1 Coefficient of fricion results

Friction tests were repeated 3 times.

Average of COF of three tests of Figures 15,16,17 is increased as 1.449% in aluminum liner as showed in Figure 18.

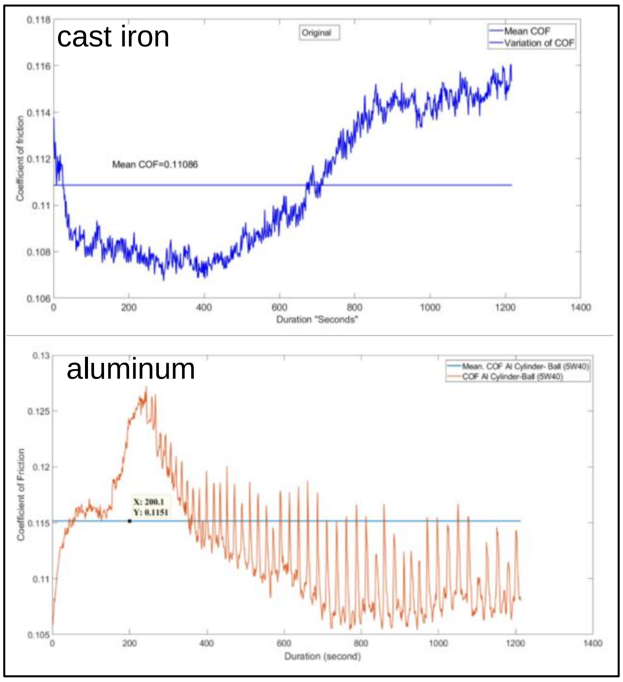


Fig. 15. Plotting and average CoF values obtained after experimental reciprocating tribotest of the first test with cast iron and aluminum cylinder liner using engine oil (5w40).

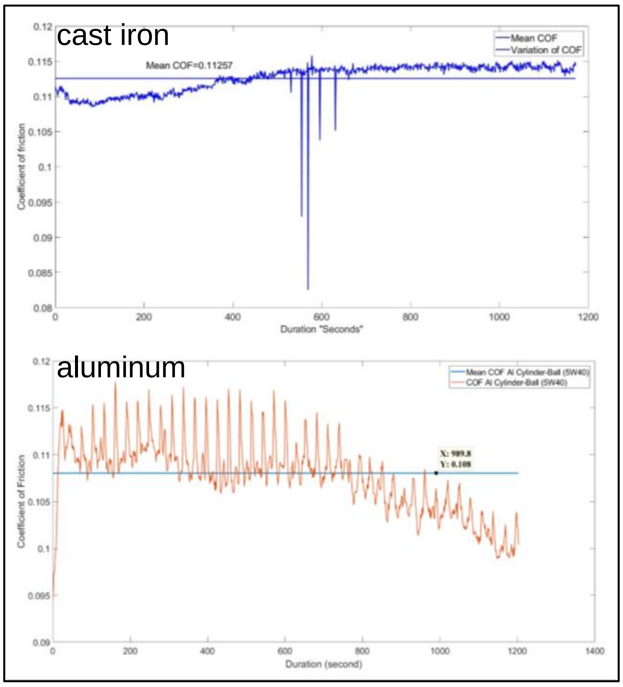


Fig. 16. Plotting and average CoF values obtained after experimental reciprocating tribotest of the second test with cast iron and aluminum cylinder liner using engine oil (5w40).

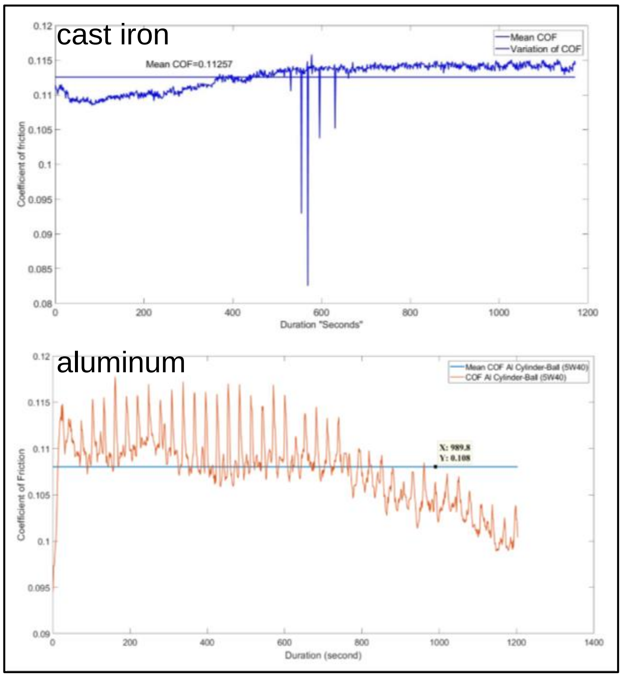


Fig. 17. Plotting and average CoF values obtained after experimental reciprocating tribotest of the third test with cast iron and aluminum cylinder liner using engine oil (5w40).

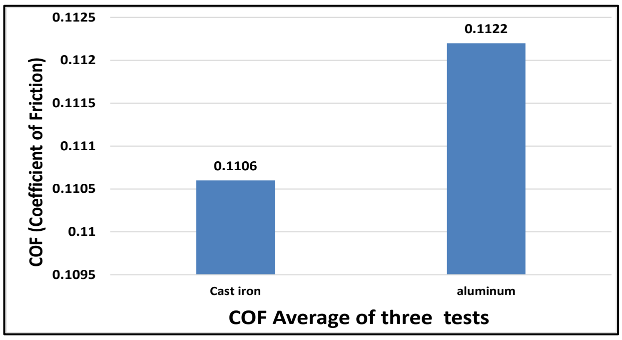


Fig. 18. COF average of three tests.

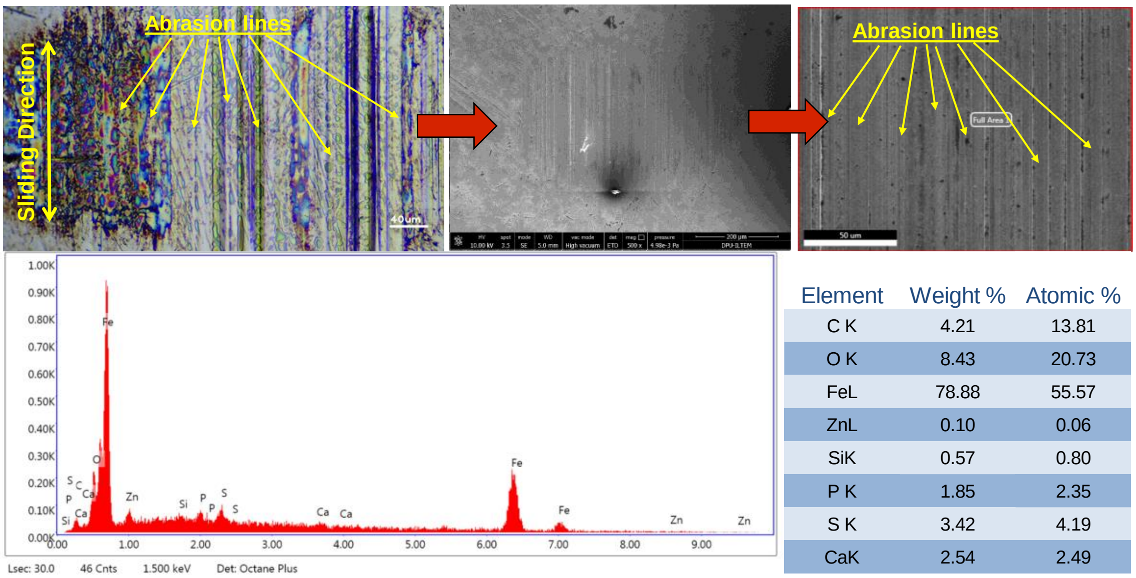
3.2 Surface characterization

It is evident that additional protection to rubbing surfaces from wear was provided, due to the formation of a protective layer, represented by colorful regions, as displayed in the first optical microscopy images of teh Figures 19, 20, 21, 22 [5].

We know well that the wear resistance and tribo-properties of aluminum are the problem [6]. For this purpose we applied the same material in Diesel engine as a liner sleeve and tested in engine dynamometer. Engine worked properly without having any problem. Our research is still keeping on going.

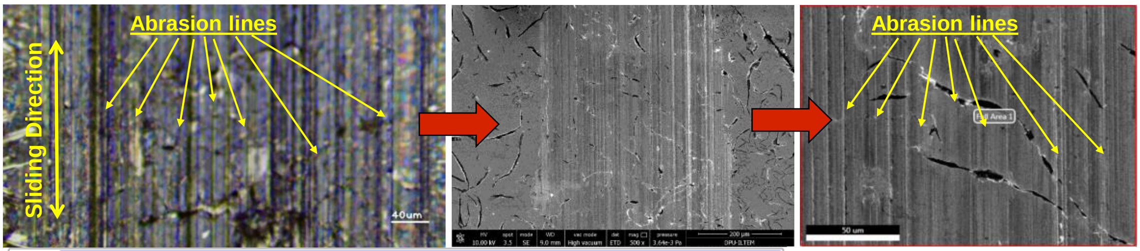
The engine block alone accounts for 3-4% of the total weight of the average vehicle. Thus it played a key role in all weight-reduction considerations. Aluminium casting alloys as a substitute for the traditional cast iron can mean a reduction in engine block weight of between 40 and 55%, even if the lower strength of aluminium compared to grey cast iron is considered [7].

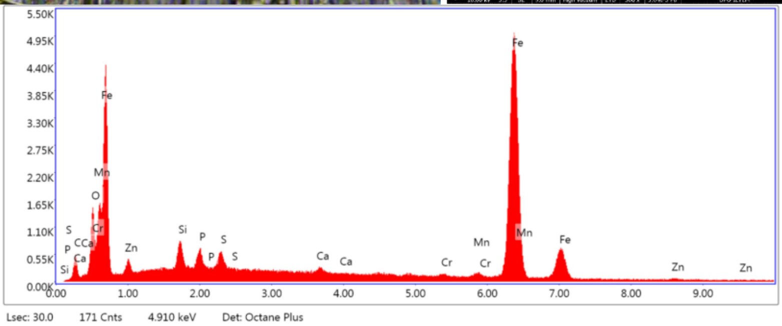
Aluminum continues to gain in importance as a material for lightweight machine design. One of the applications is replacing of material for engine blocks, which has been traditionally produced of gray cast iron. Application of aluminum contributes also to reducing fuel consumption that has a direct impact on reducing exhaust emissions [8].



Element	Weight %	Atomic %
C K	4.21	13.81
O K	8.43	20.73
FeL	78.88	55.57
ZnL	0.10	0.06
SiK	0.57	0.80
P K	1.85	2.35
S K	3.42	4.19
CaK	2.54	2.49

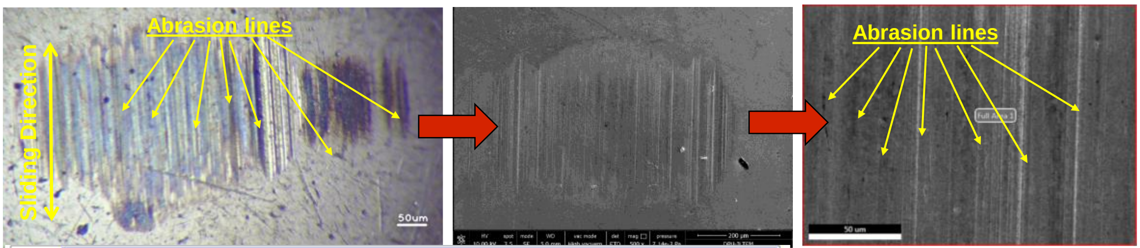
Fig. 19. SEM image with elemental analysis of the rubbed surface of the ball rubbed on the cast iron liner tested with 5W40.

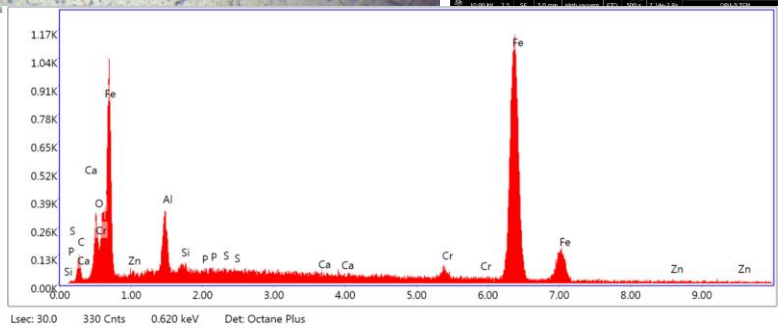




Element	Weight %	Atomic %
C K	7.30	22.48
O K	6.68	15.43
FeL	57.74	38.22
ZnL	0.00	0.00
SiK	2.85	3.75
P K	2.21	2.64
S K	2.41	2.78
CaK	2.08	1.91
CrK	4.62	3.28
MnK	14.12	9.50

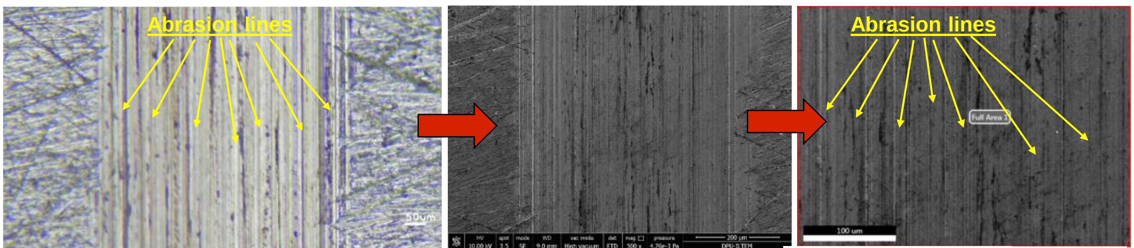
Fig. 20. SEM image with elemental analysis of the of the tested cast iron liner under steel ball.

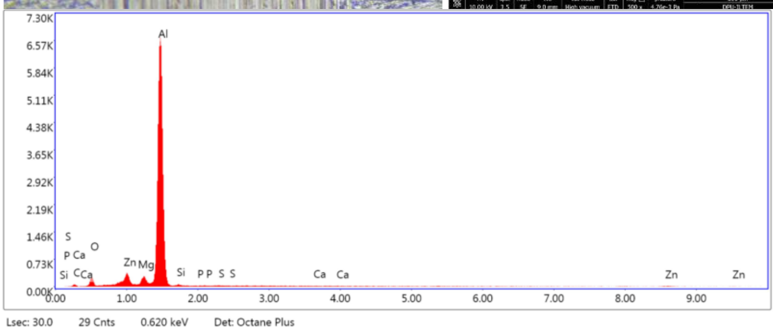




Element	Weight %	Atomic %
C K	5.85	18.85
O K	4.98	12.04
FeL	56.22	38.95
ZnL	0.00	0.00
AlK	7.14	10.23
SiK	0.09	0.13
P K	0.00	0.00
S K	0.23	0.28
CaK	2.45	2.36
CrK	23.04	17.15

Fig. 21. SEM image with elemental analysis of the rubbed surface of the ball rubbed on the aluminum liner tested with 5W40.





Element	Weight %	Atomic %
C K	2.98	6.53
O K	2.75	4.52
ZnL	5.23	2.10
MgK	2.64	2.86
AlK	85.51	83.30
SiK	0.29	0.27
P K	0.02	0.02
S K	0.14	0.11
CaK	0.43	0.28

Fig. 22. SEM image with elemental analysis of the of the tested aluminum liner under steel ball.

4 CONCLUSIONS

1. The effect of aluminum cylinder barrel of Diesel engine on friction, wear is well compared and investigated with related to cast iron liner using reciprocating tribometer,
2. It has been demonstrated that under the boundary lubrication conditions, the wear scar diameter as well as wear scar width presented lowest values on the ball and liner tested with aluminum cylinder liner related to the rubbing surfaces of cast iron liner using 5W40 oil measuring with digital optical microscopic examination. The wear mechanisms of all specimens were dominantly abrasive wear mechanism,
3. We can say that friction coefficient is is almost the same and it is increased only 1.449% for aluminum liner. This is usual as aluminum is lighter than cast iron,
4. It has also been measured that the roughness parameters such as Sa and Ra values were found smaller on the balls as well as liner tested with aluminum related to the cast iron liner in 2D and 3D roughness measurements.
5. The main reason is the homogeneous plastic deformation which makes the surface smooth and reactive providing better surface degradation, this allows quick surface reaction between the lubricants and sliding pairs for the test of aluminum liner because additives such as Zn, Ca, P content mixed with it and formed protective layers.

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