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COMPARISON OF ADDITIVE'S PROTECTIVE LAYER ON THE CYLINDER LINER SURFACE USING DIESEL ENGINE AND PIN ON PLATE TEST RIGS

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Abstract: *In this research, the layer formation of additives on the surface of cylinder liner (single cylinder Diesel engine liner operated 22 h) were examined by using binocular, optical, scanning electron microscope and energy dispersive x-ray spectra and were compared to the plates tested in reciprocating pin on plate tribotest machine. The additive materials such as Ca, Zn, P, and S displayed a significant presence in TDC (Top Dead Center), but relatively less so in MC (Middle Center) and no additive elements were found in the BDC (Bottom Dead Center). Six plates (A, B, C, D, E and F) were tested in tribotest machine and some of them showed surprisingly similar results on their rubbed surfaces as in cylinder liner of Diesel engine during microscopic examination. Additives were detected as islands in both Diesel engine cylinder liner and tested plates. Almost the same additives such as Ca, Zn, P and S detected in Plate A and B as well as in Diesel engine's TDC, MC. Plate C revealed also the presence of P and S elements. Most of the machining marks still remained on the surface of cylinder liner and plates.*

Keywords: *Engine Cylinder Liner, Plates, Additive's Layer, Microscopic Surface Examination.*

1. INTRODUCTION

To meet tough automotive competition and stringent government regulations, more efficient engine components and improved engine oils have been developed within the automotive industry. As part of the overall performance evaluation of these developments, the tribological performance of the piston ring-cylinder bore system must be determined [1]. In an internal combustion engine, piston rings and cylinder bore play very important roles in achieving desired engine performance and durability [2].

Ever since the invention of the internal combustion engine lubricant oils have been an essential component. Over the last century, an increasing range of additives have been incorporated into lubricating oils to confer improved performance [3]. Modern engine lubricants contain a wide range of additives which are blended with base oils to form a complete package capable of meeting demanding performance requirements.

The performance of additive mixtures results in detergency, wear protection, oxidation inhibition and corrosion inhibition in the bulk and on surfaces. Additives are used to reduce thermal and oxidative degradation, reduce deposits, change viscosity characteristics, minimize rust and corrosion, control frictional behavior, reduce wear, prevent destructive metal-metal contact, and control foaming. Additives may modify physical properties (viscosity, pour point, foaming) and chemical behavior (detergency, oxidation, corrosion, wear, extreme pressure resistance) of lubricating formulations [4].

Base oils are hydrocarbons and they tend to oxidize, thermally decompose, and polymerize [5]. The oxidation process is initiated by the formation of free radicals. The free radicals take part in a circular reaction pattern in which hydrocarbons are oxidized. The reaction slows down as the concentration of hydrocarbon is reduced, and free radicals react with each other to yield uncreative species. The reaction is thus halted. In short, the free radical mechanism can be described as follows:

creation of free radicals, radical chain reactions, chain branching, chain termination [6].

The accumulation (i.e. formation and removal) of deposits on the cylinder liners is a complex process. In the marine sector it is generally agreed that it is dependent on interactions among the fuel composition, lubricant formulation and engine design and loading [7]. There is general agreement amongst the sources that formation and accumulation of deposits appears dependent on the interaction between fuel composition, lubricant formulation, engine design and loading.[8]

Liner deposits are reported to consist of inorganic material that is derived from lubricant additives [6]. The inorganic material may constitute 80% of the deposit by weight, most of which reportedly are salts of Zn and Ca [9]. The deposits also typically consist of organic material that is believed to be polymerized hydrocarbon.

There is a great influence of the surface degradation and high temperature on the formation of the protective additive layers. The main mechanical conditions to obtain additive's layers on the surface are a small amount of oil, slight surface degradation and high temperature in boundary lubrication [10].

The purpose of this paper is to determine the additives on TDC, MC and BDC of 22 hour operated Diesel engine cylinder liner and to compare with the plates tested on reciprocating pin on plate test rig.

2. EXPERIMENTAL DETAILS

The both tests were run with commercial "Ribua TIR 6400" 15W40" mineral oil which belongs to Total-Turkey Ltd. Oil Company. Specifications of lubricating oil are listed in Table 1 where the additives content was given under their permission.

Table 1. Specifications of lubricating oil

Specification	Initial values (Method)
SAE Grade	SAE 15W 40
API service class	CH-4 / SJ (ACEA : E3)
TBN	9,7 mgKOH/g ASTM D 2896
Viscosity at 100 °C	14 cSt ASTM D 445
Viscosity index	130 ASTM D 2270
Flash point	>200°C ASTM D 92
Pour Point	-27 °C
Specific gravity at 15 °C	0,871 g/cm^3
Ca content (ppm)	Min 2580 Max 3036
Zn content (ppm)	Min 1363 Max 1610
Mg content (ppm)	Min 298 Max 336
P content (ppm)	Min 1250 Max 1474

2.1 Diesel engine test rig

The tests were carried out on a single cylinder, four stroke, air cooled type Diesel engine. Table 2 shows engine specifications and Figure 1 shows the image of test bench. It is located in the laboratory of Piri Reis University in Istanbul-Turkey.


(a) (b)

Figure 1. (a) Control panel and (b) engine test rig

Table 2. Technical specifications of test engine

Engine Manufacturer	Anadolu Motor Co. Turkey
Model	Diesel 4LD820
Type	4-stroke air-cooled Diesel
Aspiration	Naturally aspirated
Number of cylinders	1
Bore x Stroke (mm)	102x100
Cylinder Volume (cm^3)	817
Compression ratio	17:1
Crankcase oil capacity (l)	2.6
Speed range Max (rpm)	(2600)3000
Fuel injection pressure (bar)	134
Rated power and torque at 1600 rpm (kW-Nm)	13 - 48

The test engine was manufactured by Anadolu Motor (Antor Motor) Corporation and the model description is 4LD820. Performance test were performed via varying the load from control panel. During 22 hours of test, engine operated at 2270rpm corresponding to 100% of full load, this load point was determined by considering the stable operation of engine. Engine test conditions are shown in Table 3. At the beginning of the test, engine was installed with new oil filters and was flushed with new oil.

Table 3. Engine testing conditions

Specific Fuel Consumption (g/kWh) and Speed (rpm)	270 at 2270
Load %	100
Lubricating oil temperature (°C)	65
Ambient temperature (°C)	24
Duration (h)	22

At the end of the engine test, the cylinder liner was dismantled and cut accurately without damaging the rubbed surface, cleaned ultrasonically with hexane and then dried before and after the tests for microscopic examination. This gives the possibility to examine real protective additive's layers formed on the rubbed cylinder liner surfaces (see Figure 2).

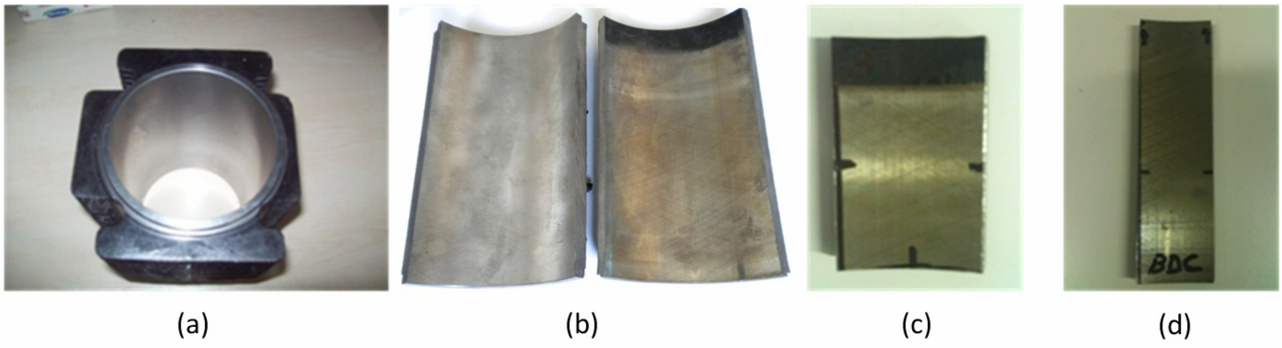

Figure 2. (a) Cylinder and liner before operation, (b) liner specimens cut from new cylinder (left) and cylinder of Diesel engine (right) operated 22h respectively, (c) liner specimen for TDC, (d) liner specimen for MDC (upper side) and BDC (down side)

2.2 Reciprocating pin on plate test rig

Reciprocating pin on plate test rig is used for the test of plates. Test rig is located in the laboratory of INSA in Lyon, France. A schematic diagram showing the main features of the test rig is given at Figure 3(a). In first step of the test procedure, three small drops of oil (approx. 1ml each of them) were dropped in the left, center and right of the wear track then unified those three points as a thin line with the extremity of the pipette before starting the tests. Then 100 N of load is applied on a single way of sliding direction.

Six plates (A, B, C, D, E and F) were tested in tribotest machine and three of them which are Plate A, Plate B and Plate C showed surprisingly similar results on their rubbed surfaces as in cylinder liner of Diesel engine during microscopic examination. The stroke and speed were controlled to produce a wear track length of 60 mm at constant load of 100 N, testing duration of 42 min, with a reciprocating velocity of 0,03 - 0,06 m/s and at the temperature of 95 °C. The only differences between plates were among the piston rings which changes the contact pressures. Plate A and B tested under Cr coated piston rings and Plate C tested under non-Cr coated piston ring. The contact pressure was 0,014 GPa for both Plate A and C, 0,0083 GPa for Plate B. For the test, fresh samples of piston rings and plates were assembled in the test machine and the bath was heated to the required temperatures and allowed to stabilize during test. The tests were run with the same sliding directions (see Figure 3(b)) for both types of piston rings.

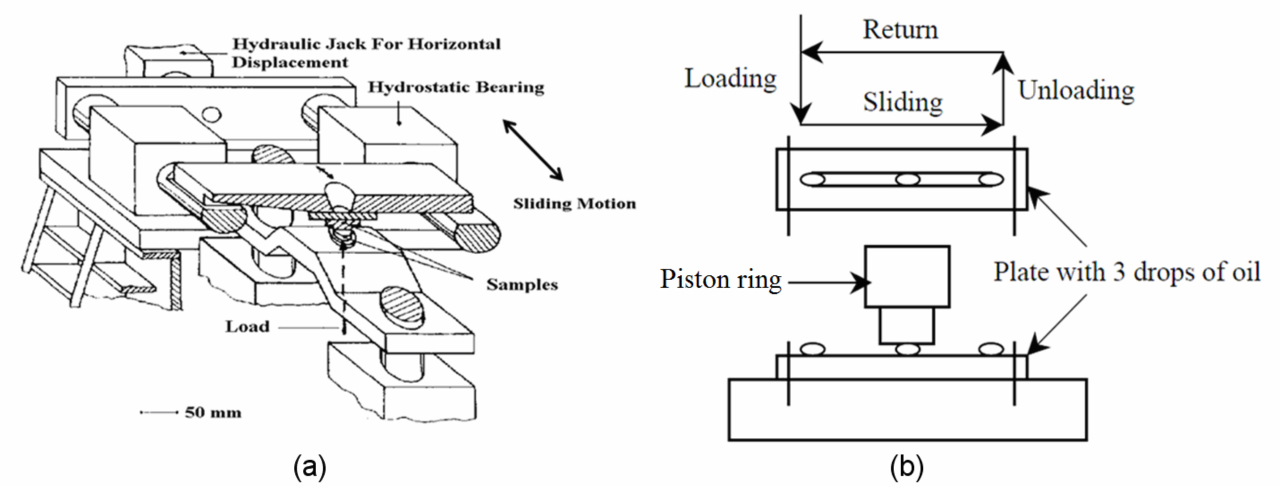

Figure 3. (a) Reciprocating pin on plate test rig, (b) Single way sliding direction of the pin (piston ring) configuration on the plate

Before the tests of the plates, the cylinder liner was cut accurately (for dimensions see Figure 4) without damaging the rubbed surface, cleaned ultrasonically with hexane and then dried before and after the tests for microscopic examination. This gives the possibility to examine the real protective additive's layers remained on the wear track.

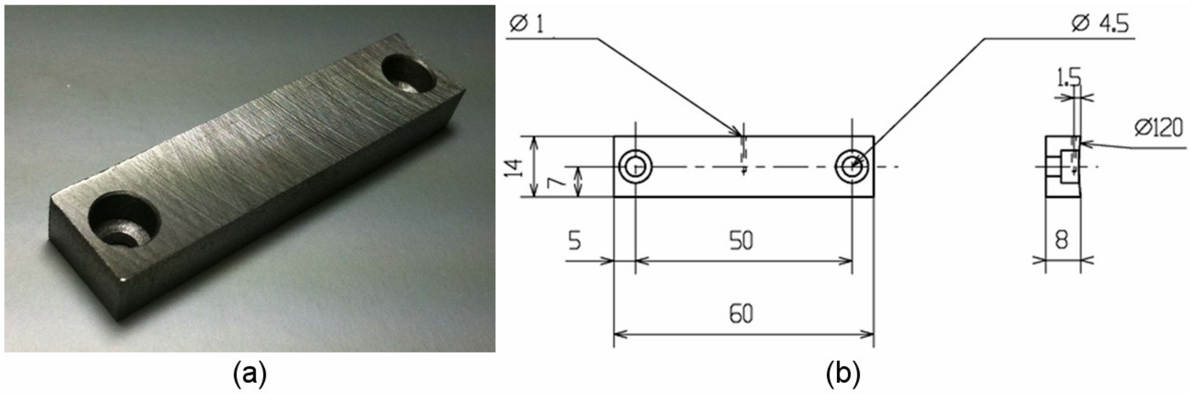

Figure 4. (a) Perspective view and (b) technical drawing of plates prepared for tests

3. COMPARISON OF THE 22H OPERATED ENGINE CYLINDER LINER (TDC, MC AND BDC) AND PLATES (A, B AND C) TESTED ON RECIPROCATING PIN ON PLATE TEST RIG

Optical, Scanning Electron Microscopy and X-Ray Spectra of the non-operated (new) cylinder liner surface is shown at Figure 5. The cylinder liner and plate material is cast iron that consists of Fe, C, Mn and Si and these are the main components which constitute the surface.

Figure 6 shows the TDC of the cylinder liner surface and Plate A tested on reciprocating pin on plate test rig in five different magnifications. For each magnification, six points are measured and examined. Black part at the top of the image identifies the line between the combustion chamber and TDC. Below 800 µm of that line is colorful and shows that the additives were covered the surface as islands.

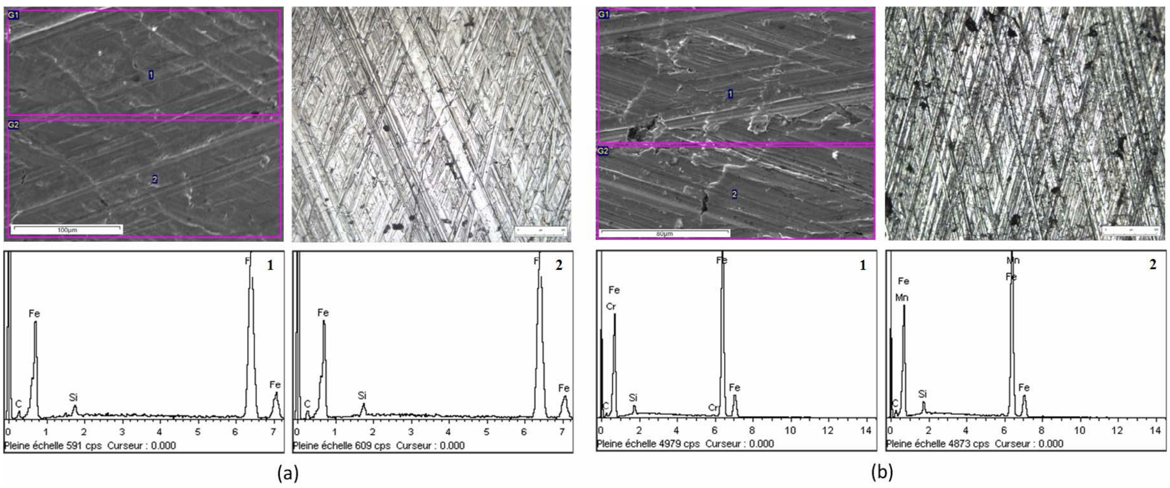

Figure 5. Optical, Scanning Electron Microscopy and X-Ray Spectra of the (a) New Cylinder Liner and (b) unused plate

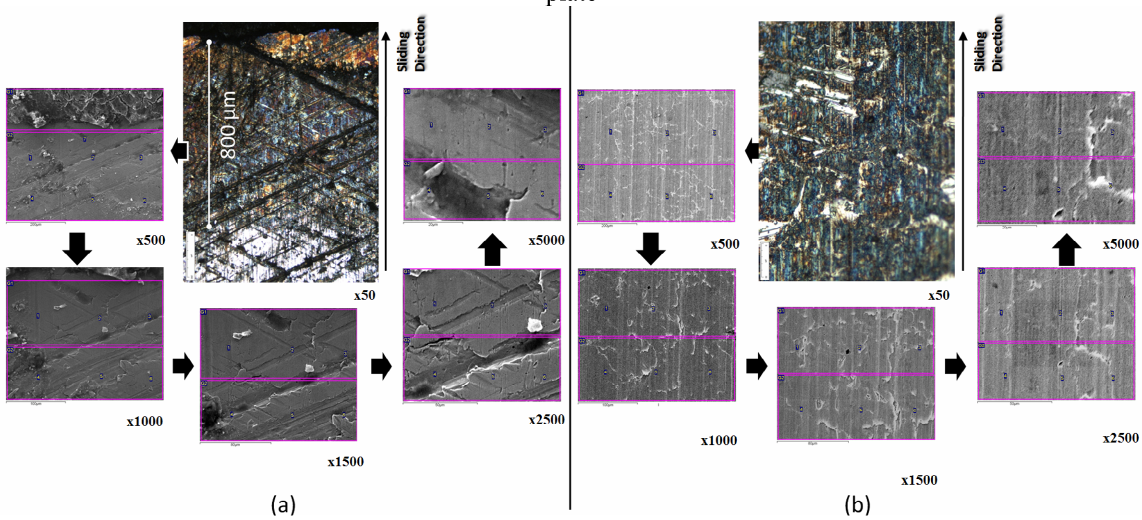

Figure 6. Optical and scanning electron microscopy of the TDC of the (a) engine cylinder liner operated 22h and (b) Plate A in five different magnifications such as x500, x1000, x1500, x2500 and x5000 respectively

Figure 7 is the identification of three points (3, 4 and 5) in x500 magnification of cylinder liner at TDC and two points (2 and 5) in x2500 magnification of Plate A. Ca, Zn, P and S are the main elements detected at the TDC and Plate A comparing to the new cylinder liner in Figure 5. All additives (Ca, Zn, P and S) are observed at the points 3, 4 and 5 and only element P is detected at the points 1, 2 and 6 of TDC. At Plate A points 2 and 5 contains all additive elements (Ca, Zn, P and S), point 1 contains P, point 3 contains Zn and P, point 4 and 6 contains P and S.

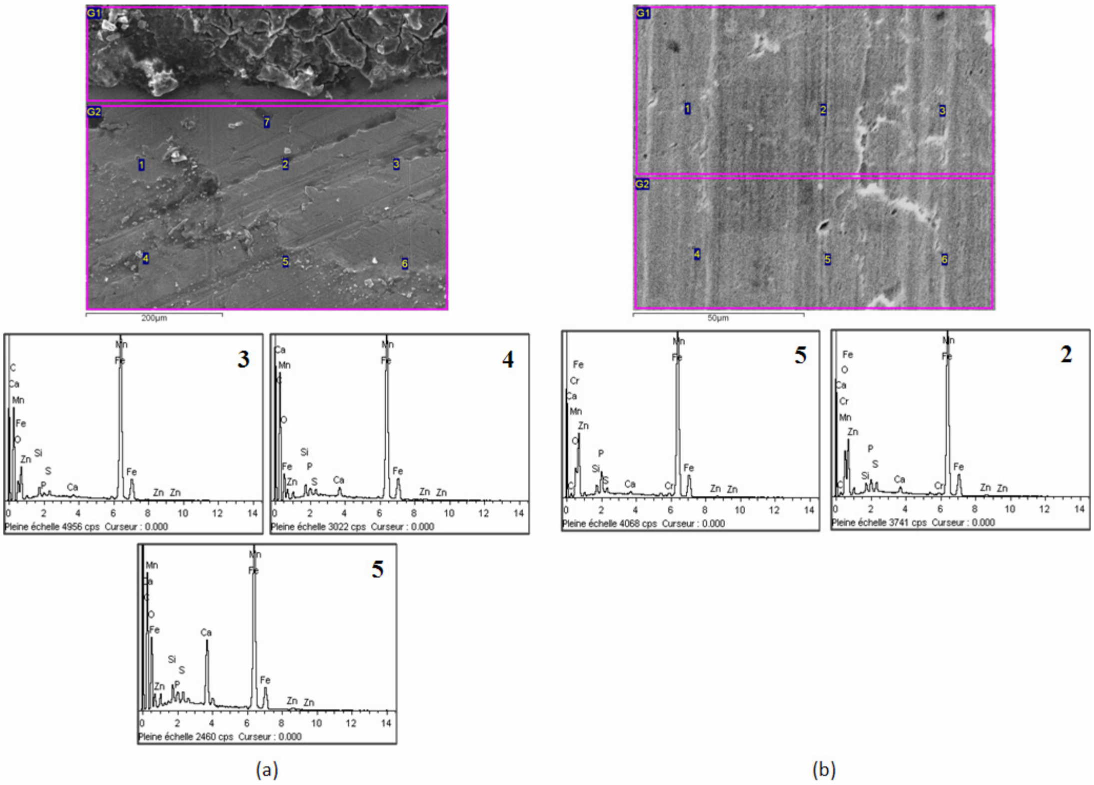

Figure 7. Scanning electron microscopy and X-ray spectra of the (a) cylinder liner TDC in x500 magnification of three points (3, 4 and 5) and (b) Plate A in x2500 magnification of two points (2 and 5)

Figure 8 shows the MC of the cylinder liner surface in five different magnifications and Plate B in three different magnifications tested on reciprocating pin on plate test rig. For each magnification, six points are measured and examined. For both cylinder liner MC surface and Plate B the honing machining marks can be observed. Optical images show that the color of the surface of MC and Plate B are less colorful than TDC and Plate A.

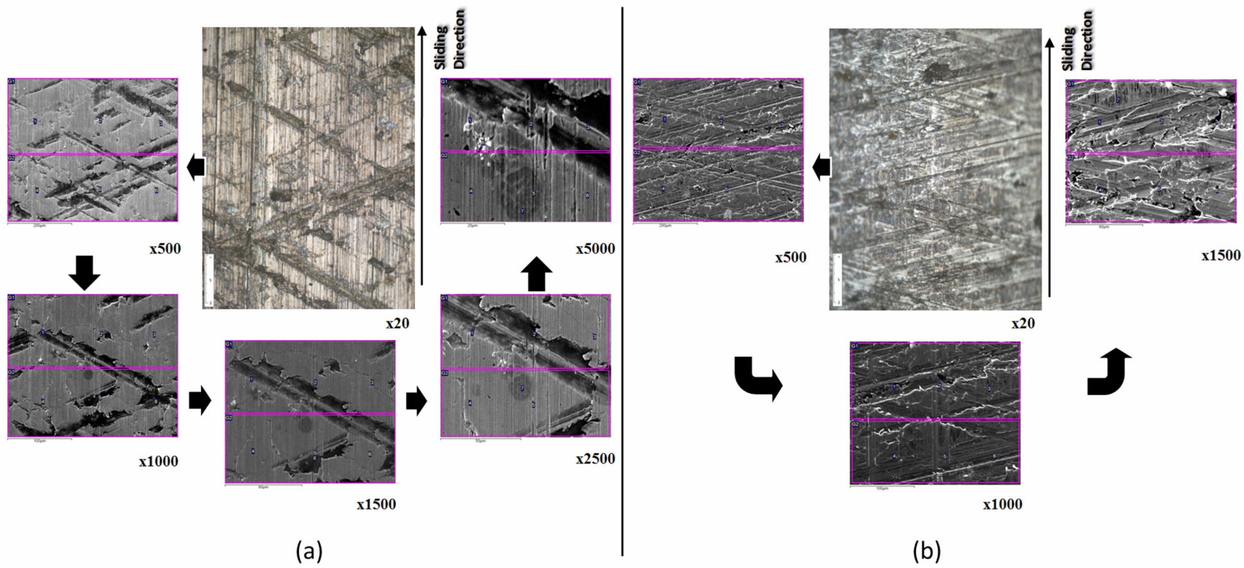

Figure 8. Optical and scanning electron microscopy of the MDC of the (a) engine cylinder liner operated 22h in five different magnifications such as x500, x1000, x1500, x2500 and x5000 respectively and (b) Plate B in three different magnifications such as x500, x1000 and x1500

Figure 9 presents the MC in magnification x1000 of the cylinder liner surface (points 1, 5 and 6) and Plate B in magnification x500 (point 1). Same additives such as Ca, Zn, P and S were detected at the MC and Plate B comparing to the new cylinder liner in Figure 5. All additives (Ca, Zn, P and S) are observed at points 1, 5 and 6 of MC and point 2 of Plate B. For both MC and Plate B, the points which all additives are observed are located in honing grooves as seen in Figure 9. Also, no additives found at points 2, 3 and 4 of MC and at points 1, 3, 4, 5 and 6 of Plate B. The points including additives which were detected in Figure 9 are less than in Figure 7.

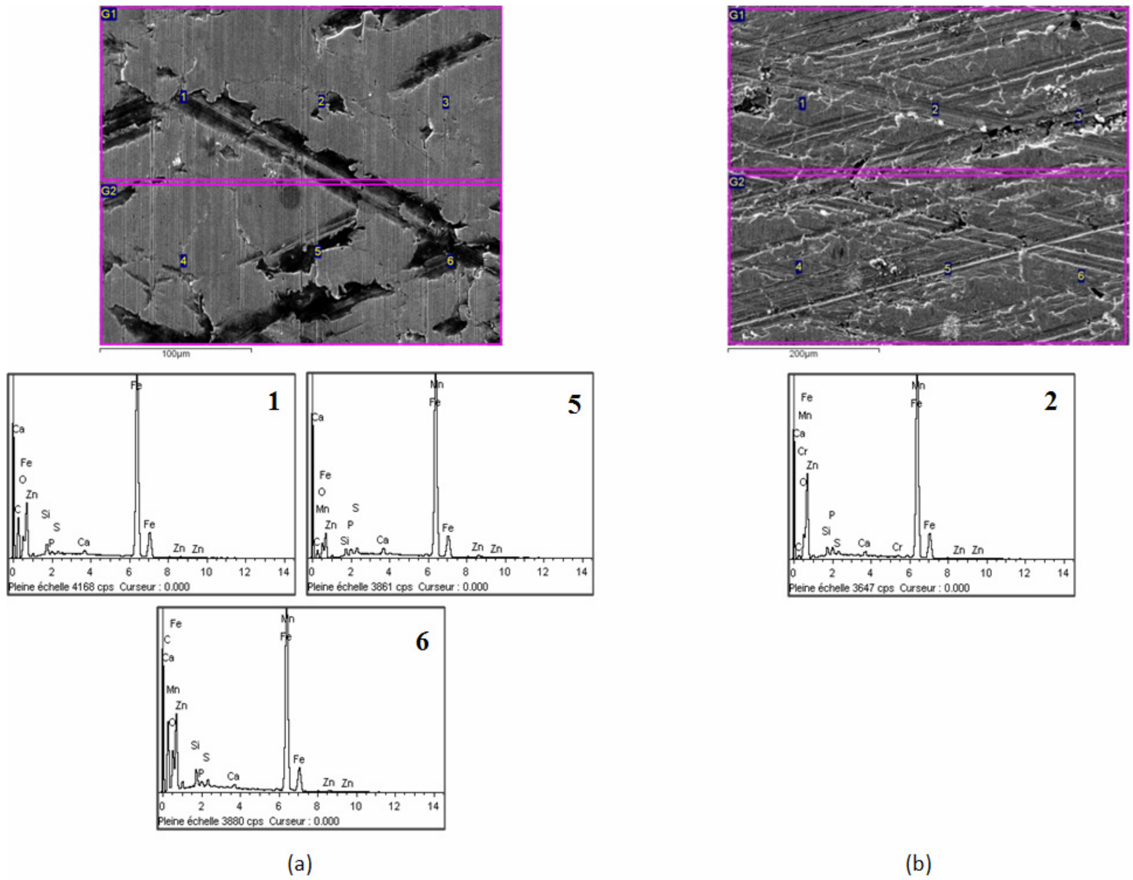

Figure 9. Scanning electron microscopy and X-ray spectra of the (a) cylinder liner MC in x1000 magnification of three points (1, 5 and 6) and (b) Plate B in x500 magnification of one point (2)

Figure 10 is the optical and SEM images of the BDC of the bore surface and Plate C. For each magnification, six points are measured and examined. The honing machining marks are remarkable on the rubbed area during sliding direction as shown in the optical images. BDC and Plate C were investigated in two different magnifications.

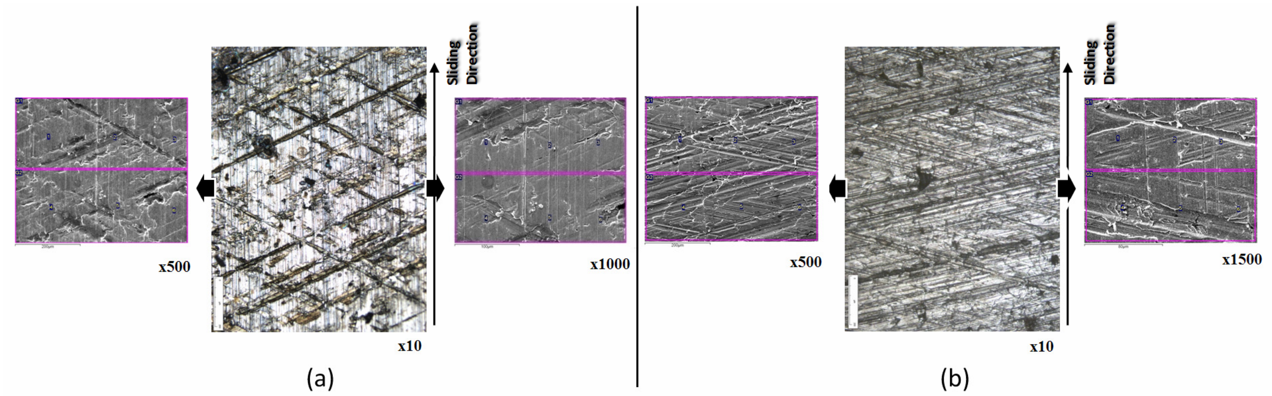

Figure 10. Optical and Scanning Electron Microscopy of the BDC of the (a) engine cylinder liner operated 22h and (b) Plate C in two different magnifications such as x500 and x1000; x500 and x1500 respectively

Figure 11 is the identification of one point in x500 magnification of cylinder liner at BDC (point 1) and used Plate C (point 3). The wear track BDC does not contain any additive's elements. Plate C contains P at points 3 and 6; S at point 3 and no additives found at other points. Point 3 and 6 of Plate C are located in honing grooves.

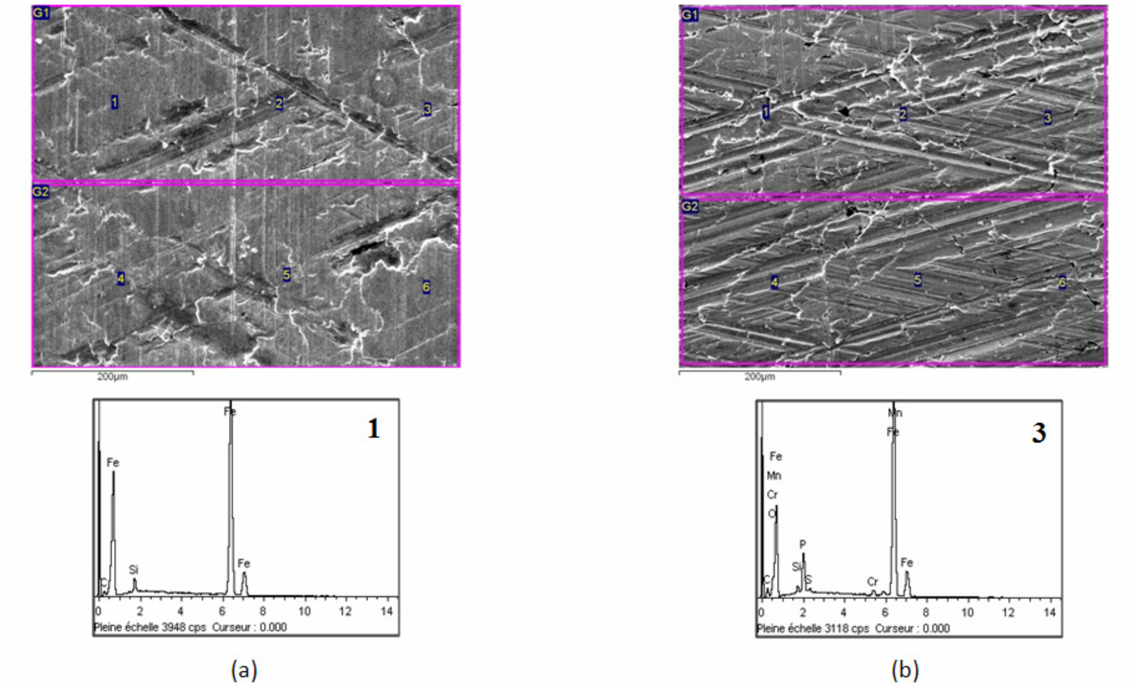

Figure 11. Scanning electron microscopy and X-ray spectra of the (a) cylinder liner BDC and (b) Plate C in x500 magnification of one point (1 and 3 respectively)

4. RESULTS AND DISCUSSION

The profile of the cylinder bore and the protective layer were observed at the same time of acquisition and acceleration of tension to clearly point out the differences between atomic percentage values of the additives in three areas (Top, Middle and Bottom Dead Center) and in plates (A, B, C) as an average of six points at five different magnifications such as x500, x1000, x1500, x2500 and x5000. Six considerable points were also emitted by X-Ray in each magnification and the average value of additives elements is calculated. It can also be seen from X-Ray spectra that the peaks of Ca, Zn, P and S are clearly detected in the protective layer area which is determined by the microscopic wear map. P and Zn are key elements of zinc-dialkyl-dithiophosphate (ZDDP) which is a typical anti-wear additive in engine oils. Ca is supplied by the oil detergent additive (calcium sulfonate). C, O and S are stemming from oil and fuel [7]. It is well known that ZDDP reacts with ferrous and chromium alloys to form a protective boundary film under thermo-mechanical stresses in tribotesting [11].

The comparison of the X-Ray spectra data (as an average of six points) taken from Top, Middle and Bottom Dead Centers of 22h operated cylinder liner [12] and Plate A, B and C in several different magnifications are shown in Table 4.

The graphs shown in Figure 12, 13, 14 and 15 are related to the values of Table 4.

Distribution of additive elements which were observed is shown in Figure 12. Additive elements mostly found at TDC, relatively less at MC and no additives found at BDC [12]. The deposits were distributed in the top regions of all the liners investigated pointing to the high temperature being the dominant factor for their accumulation [6,7]. It can be seen that Zn has the minimum value for each magnification group at TDC. Observed atomic percentages of P for all magnifications are approximately equal to each other for TDC. Measured atomic percentages of S are almost equal at magnifications x500, x1000 and x2500 for MC.

For both TDC and Plate A, the graph that illustrates the additive percentages of the surfaces is shown in Figure 13. Mostly same additive elements observed in each five different magnifications for both TDC and Plate A. Generally the amount of the additives of Plate A is higher than TDC of the wear track. As seen in Figure 13, Zn has the minimum value for each magnification on Plate A except x1500 which is similar to the TDC of 22h operated cylinder liner. P has the highest values comparing to the other additive elements for each magnification in Plate A.

Table 4. Values in atomic % of the wear track of cylinder liner from X-Ray at Top, Middle and Bottom Dead Centers in five different magnifications as x500, x1000, x1500, x2500 and x5000 respectively

		22H CYLINDER			PIN ON PLATE TRIBOTEST MACHINE		
		Values in Atomic % of the layer at TDC	Values in Atomic % of the layer at MC	Values in Atomic % of the layer at BDC	Values in Atomic % of the layer at PLATE A	Values in Atomic % of the layer at PLATE B	Values in Atomic % of the layer at PLATE C
X-Ray Spectra x500	Ca	1,00	0,13	0,00	0,53	0,75	0,00
	Zn	0,22	0,16	0,00	0,47	0,37	0,00
	P	0,41	0,09	0,00	0,95	0,61	1,41
	S	0,28	0,20	0,00	0,84	0,77	0,52
X-Ray Spectra x1000	Ca	0,30	0,22	0,00	0,00	0,59	-
	Zn	0,09	0,28	0,00	0,00	0,00	-
	P	0,41	0,36	0,00	4,57	0,79	-
	S	0,13	0,20	0,00	0,63	0,51	-
X-Ray Spectra x1500	Ca	0,65	0,00	0,00	0,00	0,86	0,00
	Zn	0,33	0,10	0,00	0,38	0,00	0,00
	P	0,41	0,00	0,00	0,95	1,35	1,22
	S	0,57	0,00	0,00	0,00	0,47	0,00
X-Ray Spectra x2500	Ca	0,31	0,24	0,00	0,72	-	-
	Zn	0,00	0,08	0,00	0,50	-	-
	P	0,44	0,42	0,00	3,57	-	-
	S	0,31	0,21	0,00	0,96	-	-
X-Ray Spectra x5000	Ca	0,44	0,11	0,00	0,59	-	-
	Zn	0,19	0,12	0,00	0,44	-	-
	P	0,43	0,00	0,00	3,14	-	-
	S	0,49	0,00	0,00	0,88	-	-

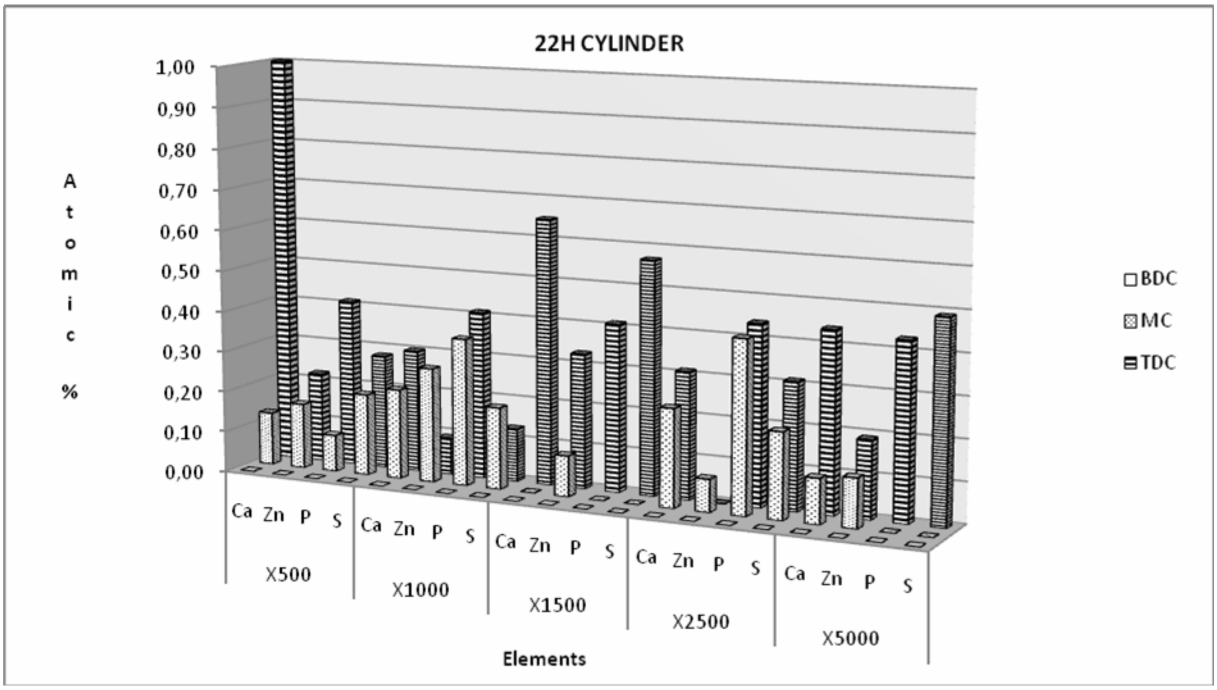

Figure 12. Elemental analysis in atomic % of additive's elements Ca, Zn, P and S in five different magnification x500, x1000, x1500, x2500 and x5000 from X-Ray Spectra of the cylinder liner from Top, Middle and Bottom Dead Centers

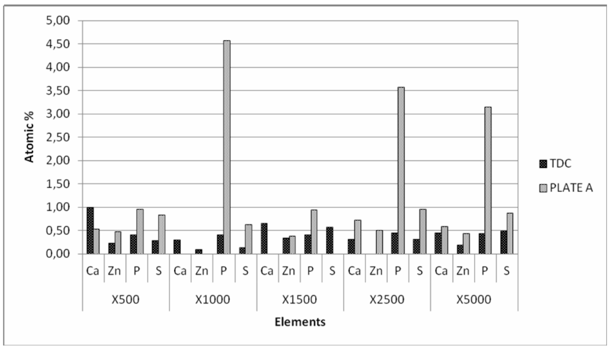

Figure 13. Elemental analysis in atomic % of additive's elements Ca, Zn, P and S in five different magnification x500, x1000, x1500, x2500 and x5000 from X-Ray Spectra of the cylinder liner from TDC and Plate A

The additive percentages of the MC and Plate B are shown in Figure 14. The graph indicates that the Plate B and MC have similar characteristics of additive distribution depending on atomic percentages. Generally amount of the Plate B's additives are higher than MC. It can be observed in Figure 14 that S has the highest atomic percentages comparing to the other additives for both MC and Plate B at the magnification x500. At the magnification x1000, P has measured more than other additive elements for both MC and Plate B. For all magnifications except x500 Zn atomic percentages are nil for Plate B.

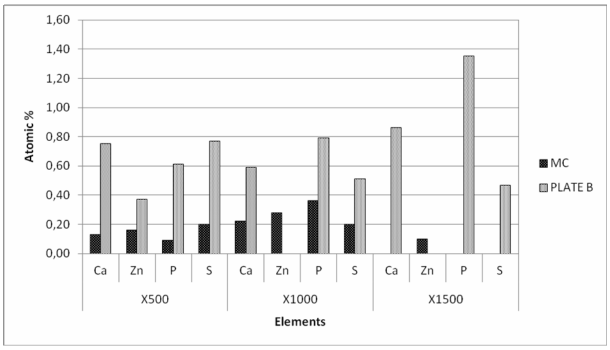

Figure 14. Elemental analysis in atomic % of additive's elements Ca, Zn, P and S in three different magnifications x500, x1000 and x1500 from X-Ray Spectra of the cylinder liner from TDC and Plate B

For both BDC and Plate C, the graph that illustrates the additive percentages of the surfaces is shown at Figure 15. At Plate C, as additive elements Ca and Zn values are nil for magnifications x500 and x1500. Also S value is nil for magnification x1500 at Plate C.

For both 22h Diesel engine cylinder liner and plates, additives are observed as islands. Also, Kaleli and Berthier observed that the steel stub 51115 provides high percentage of protective additive's layers and to cover uniformly the whole wear track in boundary lubricated conditions [13]. According to J. Keller et. al., the reason for additives to cover surface as islands is the microstructure of cast iron, as a result of experiments there was no film is formed on phosphorous eutectics, neither on carbides [14].

The average of all additive atomic percentage values for each 6 measurement points, in each magnification and for plates and cylinder liners (A, B, C and TDC, MC, BDC) are taken and illustrated at Figure 16. Mean additive values are decreasing from Plate A to C and cylinder liner TDC to BDC, which shows similar characteristics relatively.

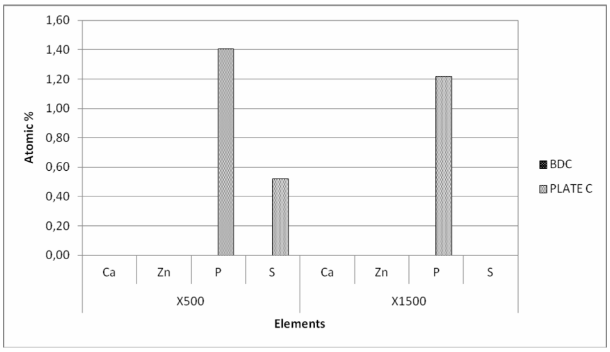

Figure 15. Elemental analysis in atomic % of additive's elements Ca, Zn, P and S in two different magnifications x500 and x1500 from X-Ray Spectra of the cylinder liner from BDC and Plate C

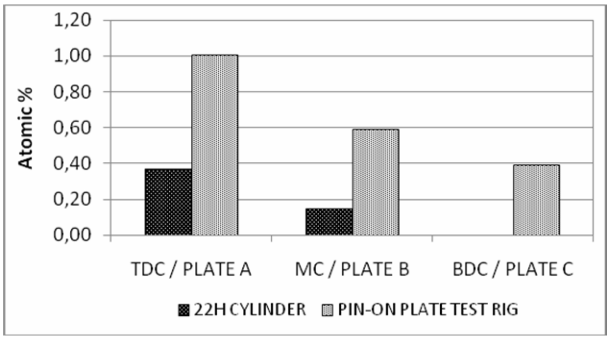

Figure 16. Additive characteristic comparison of plates (A, B and C) and cylinder liner (TDC, MC and BDC)

5. CONCLUSION

The following similarities found between plates (A, B and C) tested on reciprocating pin on plate test rig and 22h operated Diesel engine cylinder liner (TDC, MC, and BDC). Plate A and TDC, Plate B and MC, Plate C and BDC has similar surface characteristics surprisingly.

Most of the machining marks still remained on the surface of cylinder liner and plates.

Additive elements mostly found in the honing grooves of the cylinder liner and plates.

As surface characteristic similarity, it is also observed that the additives of Plate A and TDC, Plate B and MC, Plate C and BDC are similar surprisingly.

For both 22h operated Diesel engine cylinder liner and plates tested on reciprocating pin on plate tribotest machine, additives are covered the surface as islands.

Almost the same additives such as Ca, Zn, P and S detected in Plate A and Plate B as well as in Diesel engine's TDC, MC. There is no additive elements found in BDC. Plate C revealed also the presence of P and S elements.

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