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NANOSCALE TRIBOLOGICAL INFLUENCE OF NBA ADDED IN ENGINE OIL FOR FRICTION AND WEAR BEHAVIOUR IN DIESEL ENGINE CYLINDER LINER SURFACE RUBBED UNDER 1ST AND 2ND PISTON RINGS

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RESEARCH ARTICLE

ABSTRACT: Nanoparticles are particles between 1 and 100 nanometres (nm) in size with a surrounding interfacial layer. One of these famous nanoparticles is nanoboric acid (nBA) additive added in engine oil that drastically lowered friction and wear. This scientifical and experimental work presents the developped new suspended nanoboric acid (nBA) additive added in engine oil and lowered friction and wear in Diesel engine specimens tested in reciprocating tribometer.

Proving nBA particles that were in colloidal form in engine oil with Turbiscan Tower Stability Analyzer, the engine oil is tested between piston ring and cylinder liner system in order to investigate their effect on friction and wear under boundary lubricated conditions. Simulation and measurement of friction and wear were conducted using a reciprocating tribometer. Surface analysis was performed using 3D digital optical microscope, Field Emission Scanning Electron Microscope (FESEM)/X-Ray, X-ray photoelectron spectroscopy (XPS) and Atomic Force Microscopy (AFM) from macro to nanoscale. Boron (B) from BA is well detected and mixed with other elements of additives protecting the surface under boundary lubrication conditions. It has found that the friction coefficient is reduced with nBA suspended engine oil and protected the surface mostly on cylinder liner mixing with other additives.

KEY WORDS: *Nano boric acid, Diesel Engine, Friction, Wear, Surface Analysis*

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TRIBOLOŠKI UTICAJ DODATOG NBA U MOTORNO ULJE NA PONAŠANJE TRENJA I HABANJA NA POVRŠINI KOŠULJICE CILINDRA DIZEL MOTORA KOJA SE TRLJA ISPOD PRVOG I DRUGOG KLIPNOG PRSTENA U NANO RAZMERI

REZIME: Nanočestice su čestice veličine između 1 i 100 nanometara (nm) sa okolnim međupovršinskim slojem. Jedna od ovih poznatih nanočestica je aditiv nanoborne kiseline (nBA) dodat u motorno ulje koji drastično smanjuje trenje i habanje. Ovaj naučni i eksperimentalni rad predstavlja razvijeni novi suspendovani aditiv nanoborne kiseline (nBA) dodat u motorno ulje i smanjuje trenje i habanje u uzorcima dizel motora testiranim u klipnom tribometru.

Ispitivan je uticaj čestica nBA, u koloidnom obliku u motornom ulju, na trenje i habanje u uslovima graničnog podmazivanja između sistema klipnog prstena i obloge cilindra, pomoću Turbiscan Tower Stability Analyzer-a. Simulacija i merenje trenja i habanja sprovedeni su pomoću klipnog tribometra. Analiza površine je izvršena pomoću 3D digitalnog optičkog mikroskopa, skenirajućeg elektronskog mikroskopa sa emisijom polja (FESEM)/X-zraka, rendgenske fotoelektronske spektroskopije (XPS) i atomske sile mikroskopije (AFM) od makro do nano razmere. Bor (B) iz BA je dobro detektovan i pomešan sa drugim elementima aditiva koji štite površinu pod uslovima graničnog podmazivanja. Utvrđeno je da se koeficijent trenja smanjuje sa suspendovanim nBA u motornom uljeu i štiti površinu uglavnom na košuljici cilindra mešanjem sa drugim aditivima.

KLJUČNE REČI: *Nano borna kiselina, dizel motor, trenje, habanje, analiza površine*

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INTRODUCTION

More effective or enhanced lubrication is needed to meet the increasingly more stringent operational conditions of future engine systems and drivetrain components. The fuel economy, durability, and environmental soundness of all engines are closely related to the effectiveness of the lubricants being used. Poor or inefficient lubrication may result in high friction and wear losses, which can in turn adversely affect the fuel economy and durability of these engines [1, 2, 3, 4].

Automotive engine oils demand superior tribological properties to prolong the lifespan of mechanical components. Engine lubrication is critical for saving energy, reducing material losses, and enhancing both engine durability and fuel economy in automobiles. From an energy-saving standpoint, the transportation sector alone consumes almost 30% of the total energy produced today. Unfortunately, approximately one-third of this energy is still wasted due to friction and wear in various moving components of cars, trucks, and buses, which are integral to our mobility (Lubrication mechanism analysis). Only 21% of the fuel used in automobiles is actually used for driving; the remaining 79% is lost to energy loss. Frictional losses cause an estimated 11.5% reduction in the engine's overall power output. Consequently, enhancing the tribological properties of mechanical components and reducing engine friction losses becomes imperative in order to raise brake engine power and enhance engine durability. Therefore, the exploration of engine oil additives has become a central area of research and development in the automotive industry, with the goal of enhancing the efficiency, durability, and reliability of engine oils, as well as fuel economy [5, 6].

One of the major losses occurring in the engine of an automobile is due to friction between its moving parts. This loss is significant and approximately 15% of the total loss of energy and has a direct impact on the efficiency and durability of the engine. Different mechanical systems require a variety of functional lubricants to reduce the friction and wear of contacting surfaces as well as a significant reduction in the total energy consumed by mechanical systems [7].

Engine oil is an efficient means of minimizing friction, dissipation of frictional heat, and controlling wear by creating a lubricating layer with low-shear strength between rubbing surfaces that rub against each other in mechanical systems [8, 9].

Recent research papers have reported that the addition of nanoparticles to lubricant is effective for the reduction of wear and friction in mechanical systems. Because of the remarkable tribological properties of nanoparticles, nanotechnology is regarded as the most revolutionary technology of this century [10].

Numerous nanoparticles have recently been investigated for use as oil additives. Nano-powders of some metals and their compounds exert an especially effective influence on the characteristics of lubricants. The use of nanoparticles that include Cu, CuO, Fe, Ni, TiO2 and other metallic nanoparticle additives in lubricating oils provides good friction reduction and anti-wear behavior. Among these additives, nano boric acid (BA) nanoparticles have received significant attention because they deposit on the friction surface, improve the tribological properties of the base oil and display good anti-friction and wear reduction characteristics [11].

Boric acid owes its self-lubricating nature to a lamellar crystalline structure. When present between sliding surfaces, it can shear easily to provide low friction. Boron Carbide (B4C) on which the boric acid film was formed is a well-developed and adapted hard coating for sliding engine and bearing applications mainly because of its excellent resistance to wear and scuffing [1, 12].

Research specifically aimed at the use of boric acid in engineering systems has also been undertaken in 2000s [13, 12]. These studies have indicated that boric acid's unique layered inter-crystalline structure (see figure 1) makes it a very promising solid lubricant material because of its relatively high load carrying capacity and low steady-state friction coefficient [14].

Boric acid has been identified as a potential solid lubricant due to its lamellar molecular structure. Further, it is abundant and environmentally benign, with no known health risks to humans. These experiments clearly indicate that powder delivery of boric acid is a viable technique for providing in situ lubrication for concentrated metal contacts [15]. In the early 1990s, the lubricity of boric acid, an overlooked but extremely available and environmentally benign lamellar solid, was demonstrated by Erdemir, et al. [12, 16, 17].

1 EXPERIMENTAL DETAILS

In this study, the tribological performance of nano boric acid suspended in 5W-40 fully synthetic commercial engine oil was characterized by turbidimetry method and investigated under pin (piston ring)-on-plate (cylinder liner) line contact set-up using a custom-made reciprocating tribological test rig.

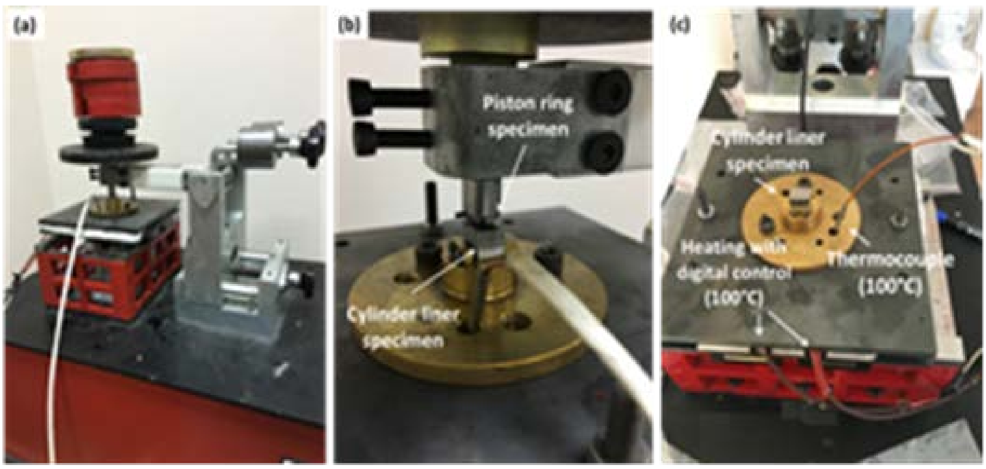


Figure 1 Reciprocating tribotest rig General view of the test rig, (b) Specimens mounted in the test rig, (c) Heating control and temperature measurements.

Table 1 Experimental parameters in tribometer

Load (N)	60.5
Frequency (Hz)	2
Stroke (mm)	8
Oil Temperature °C	99
Test Duration (min)	21

The work consists of tribometer experiments. Friction tests were conducted through a reciprocating tribotest machine (see Fig. 1). The parameters of tribological test are summarized in Table 1. Tests were conducted with a one drop of suspended 5W-40 oil and 5W-40+BA oil on the wear track of cylinder liner.

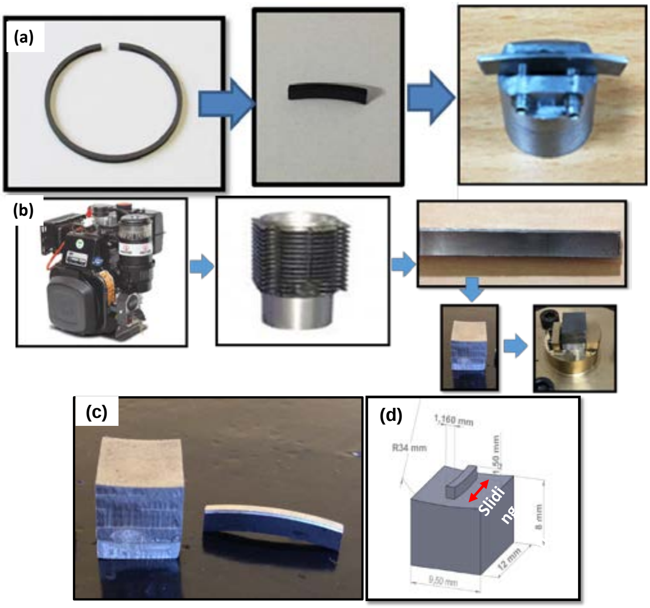


Figure 2 Preparation of piston ring and cylinder specimens (a) Piston ring, (b) liner cut from a new Antor Diesel engine,(c) and (d) specimens with contact position and sliding direction

Figure 2 shows the preparation of piston ring and cylinder specimens; (a) and (b) are piston ring and liner cut precisely from a new Anadolu Motor Antor 6 LD 400 Diesel engine for Tribometer tests. (c) and (d) present the ready specimens with contact position in reciprocating sliding direction. At the end of the tribometer tests, optical, scanning electron microscopy (SEM) with EDS and atomic force microscopy (AFM) have been applied to determine the surface morphology and chemical structure of the piston rings and cylinder liners tested in tribometer. For time/line 1.5 s, for points/line 256 have been used at AFM . Setpoint has been chosen as 20 nN during the AFM tests.

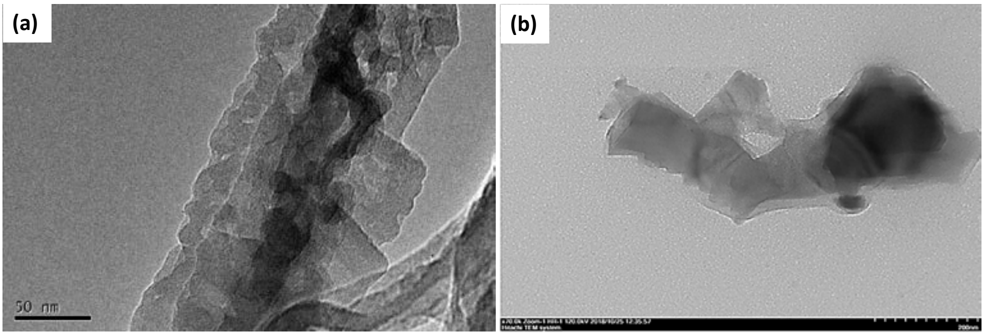


Figure 3 TEM of nBA prepared with Hexane

Figure 3 presents TEM of BA (black patches). The size of BA which varies between 50nm to the 200nm. This size is well acceptable and appropriate passing nanoparticles from engine oil filter. It is added 0.2 % in the oil.

2 DISCUSSIONS AND RESULTS

The primary function of a lubricant is to keep two metal surfaces apart thus reducing friction and preventing wear. Modern machinery with its constantly increasing speed and size has put demands upon lubricants which cannot be met by unfortified petroleum products [18].

Frictional losses in a typical automobile accounts significantly for the reduction of useful power otherwise available for the motion. Almost 15 % of the total energy loss comes from the friction generated between the sliding parts. Lubricants are supplied to reduce such frictional losses. Frictional losses arise mainly at the piston rings, bearings and transmission parts which undergo boundary lubrication or starved lubrication at certain periods during operation. Additives in lubricants come into effect under such conditions. Nano particulate suspended additives in the base oil are of some interest to address the boundary lubrication issues [19].

Hwang et al. (2011) investigated the effect of size and morphology of nanoparticles suspended in lubricating oils on the lubrication performance. The effect of the size of dispersed particles on the lubrication performance was examined by varying the primary size of the spherical-like graphite particles: 55 nm, 450 nm and 5μm. The lubrication performance clearly improved with decreasing size of the particles suspended in the mineral oil. This suggests that nano-sized particles effectively play the role of ball bearings and reduce contact between frictional surfaces [20].

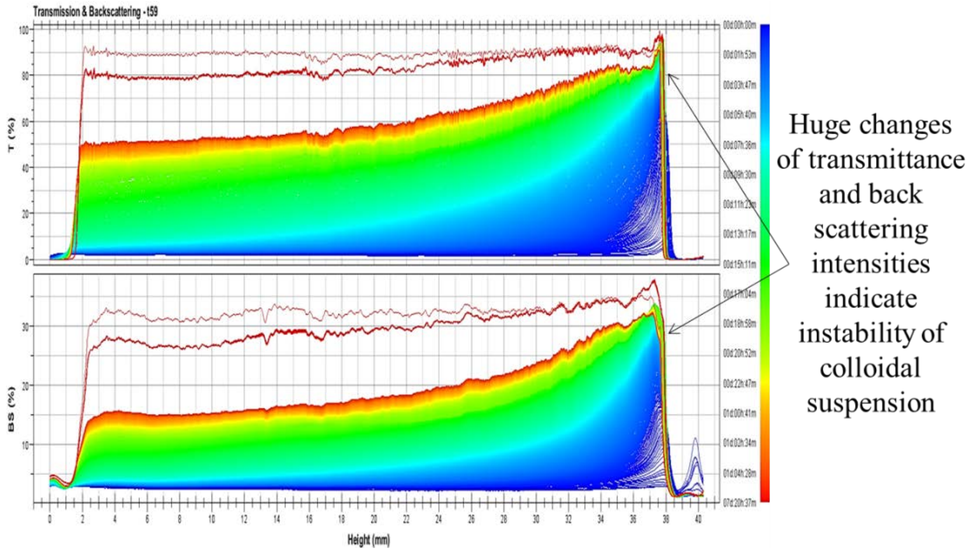


Figure 4 Transmitance and back scattering profiles of non-marketed (non-commercialized) additive showing the (sediment) in 5W-40 engine oil

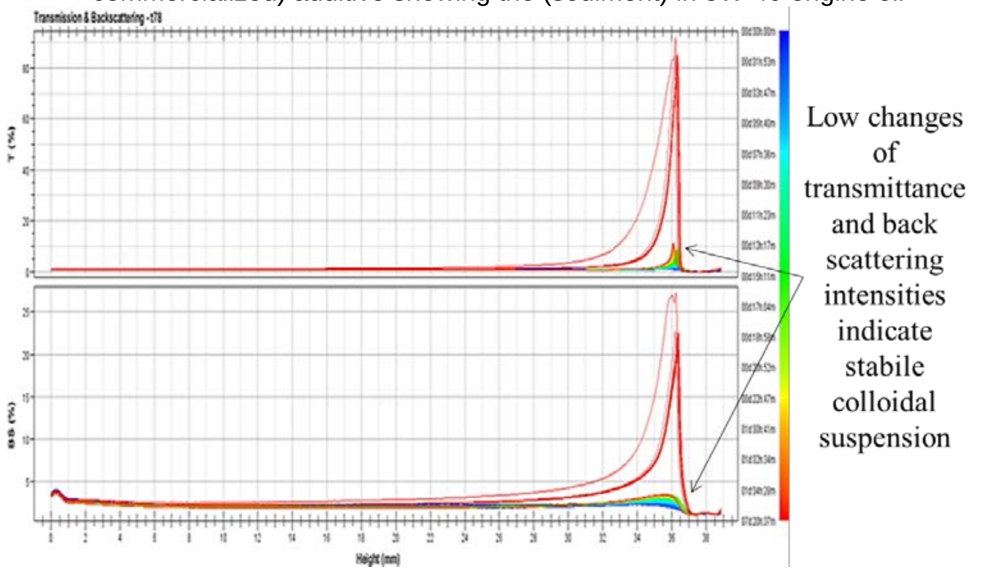


Figure 5 Transmitance and back scattering profiles of BA showing stable suspension in 5W-40 engine oil

Turbidimetry of the samples were observed by turbiscan tower, both the back scattering and transmittance curves changes were analyzed. Backscattering and transmittance signals recorded through 24 h at 20°C. Figure 4 presents transmittance and back scattering profiles of non-marketed (non-commercialized) additive showing the (sediment) in 5W-40 engine oil. Change of transmittance and back scattering intensity is very high in case of non-commercialized additive as seen in Fig.4 that indicate instability of colloidal suspension. The new invention of stable colloidal suspension of nano boric acid (BA) additive added into 5W-40 fully synthetic commercial lubricating oil is well demonstrated in Fig. 5. This invention is supplied by Tribor ARGE Co. in Teknopark of YILDIZ Technical University in Istanbul-TURKEY. They invented new method of synthesis of nano boric acid.

In this study, real 1st and 2nd piston rings-cylinder liner specimens of Anadolu Motor Antor 6 LD 400 Diesel engine were tested and compared with reciprocating tribometer under boundary lubrication conditions, 100°C, 60.5N using fully formulated engine oil and BA particles suspended in engine oil to investigate their wear and friction behavior. Test were repeated twice.

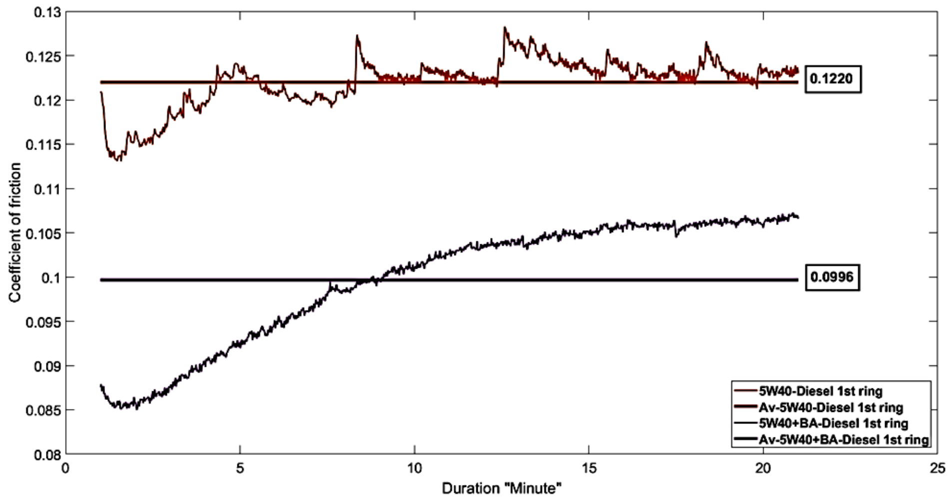


Figure 6 Friction coefficient of 5W-40 engine oil with suspended BA additive via 5W-40 engine oil for the 1st ring test

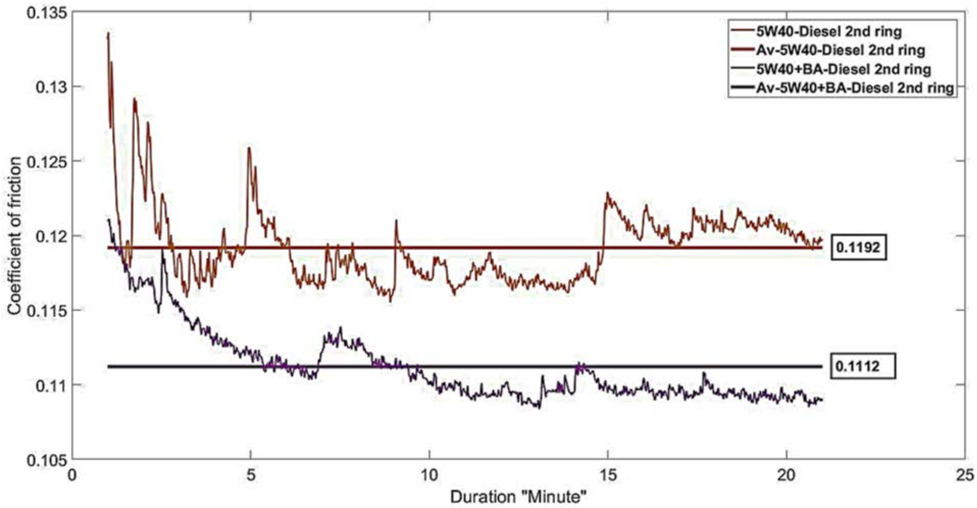
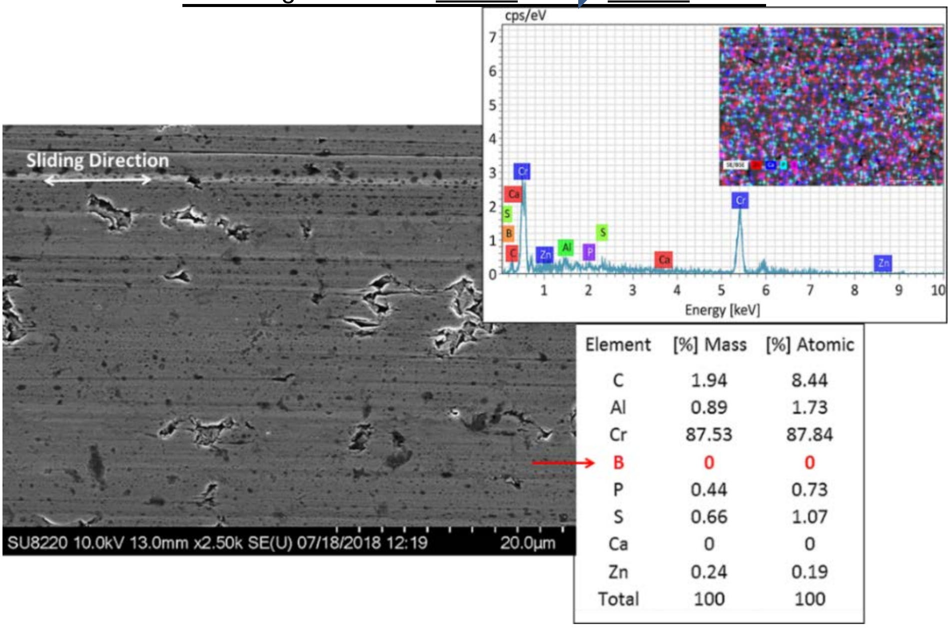


Figure 7 Friction coefficient of 5W-40 engine oil with suspended BA additive via 5W-40 engine oil for the 2nd ring test

According to the results, it has been found that engine oil with BA showed almost similar friction results with the tests of 1st piston ring (0.0996 with BA-0.1220 non BA) (See Fig.6) and obtained less friction, better lubrication and protective performance then oil without containing BA with the tests of 2nd ring (0.1112 with BA-0.1192 non BA) (See Fig 7) against cylinder liner.

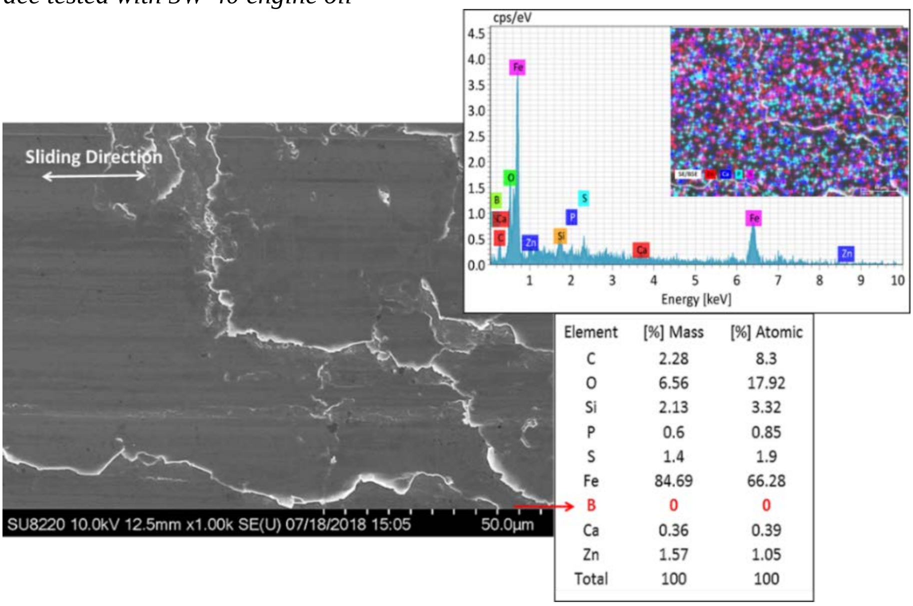
Table 1 Comparison of COF results

Test No	5W40	5W40+BA
1st ring	0.1220 →	0.0996
2nd ring	0.1192 →	0.1112



Element	[%] Mass	[%] Atomic
C	1.94	8.44
Al	0.89	1.73
Cr	87.53	87.84
B	0	0
P	0.44	0.73
S	0.66	1.07
Ca	0	0
Zn	0.24	0.19
Total	100	100

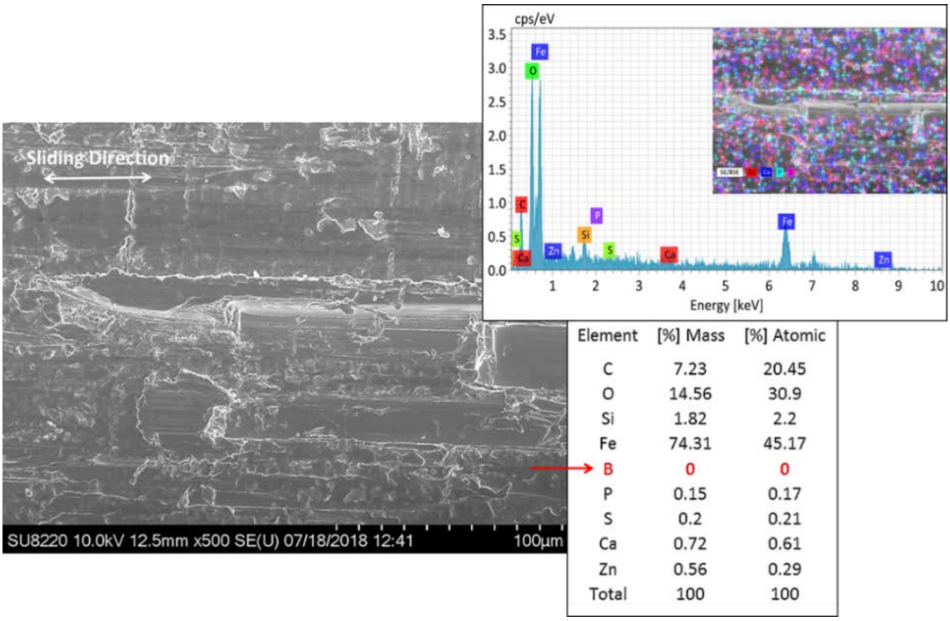
Figure 8 FESEM, X-Ray, mapping and elemental analysis of the rubbed 1st piston ring surface tested with 5W-40 engine oil



Element	[%] Mass	[%] Atomic
C	2.28	8.3
O	6.56	17.92
Si	2.13	3.32
P	0.6	0.85
S	1.4	1.9
Fe	84.69	66.28
B	0	0
Ca	0.36	0.39
Zn	1.57	1.05
Total	100	100

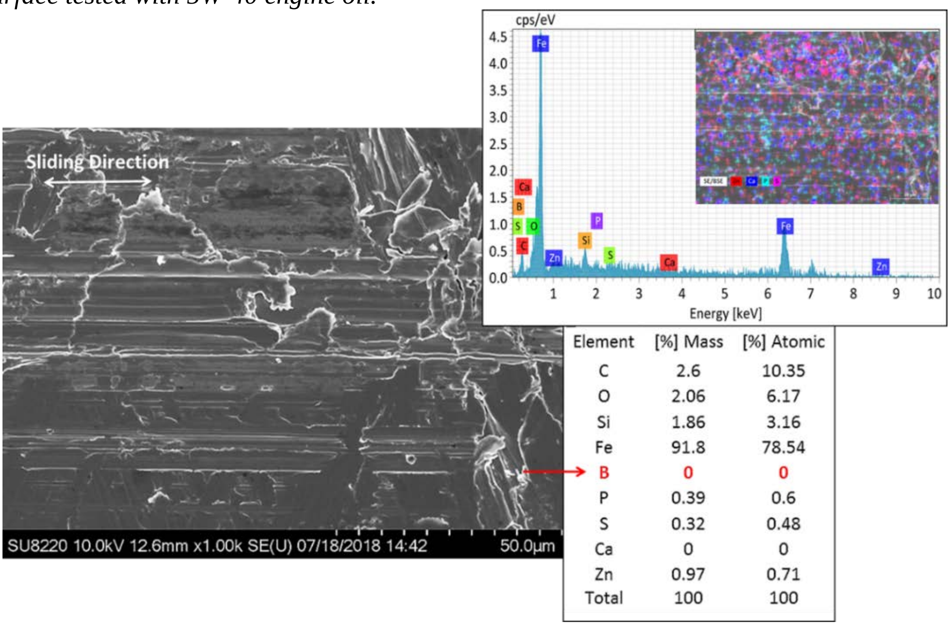
Figure 9 FESEM, X-Ray, mapping and elemental analysis of the rubbed cylinder liner surface under 1st piston ring tested with 5W-40 engine oil.

Figures 8 and 9 are FESEM, X-Ray, mapping and elemental analysis of the rubbed 1st piston ring and cylinder liner tested with 5W-40 engine oil. Any B is detected on the rubbed surface. Elements such as Zn, Ca, P and S were formed layer on the surface, as usual. 5W-40 engine oil does not contain BA.



Element	[%] Mass	[%] Atomic
C	7.23	20.45
O	14.56	30.9
Si	1.82	2.2
Fe	74.31	45.17
B	0	0
P	0.15	0.17
S	0.2	0.21
Ca	0.72	0.61
Zn	0.56	0.29
Total	100	100

Figure 10 FESEM, X-Ray, mapping and elemental analysis of the rubbed 2nd piston ring surface tested with 5W-40 engine oil.



Element	[%] Mass	[%] Atomic
C	2.6	10.35
O	2.06	6.17
Si	1.86	3.16
Fe	91.8	78.54
B	0	0
P	0.39	0.6
S	0.32	0.48
Ca	0	0
Zn	0.97	0.71
Total	100	100

Figure 11 FESEM, X-Ray, mapping and elemental analysis of the rubbed cylinder liner surface under 2nd piston ring tested with 5W-40 engine oil

Figures 10 and 11 are FESEM, X-Ray, mapping and elemental analysis of the rubbed 2nd piston ring and cylinder liner tested with 5W-40 engine oil. Any B is detected on the rubbed surface. Elements such as Zn, Ca, P and S were formed layer on the surface, as usual. 5W-40 engine oil does not contain BA.

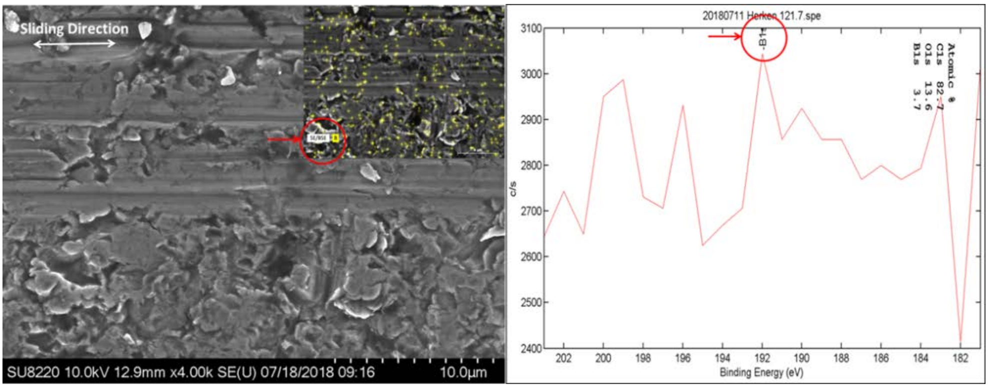
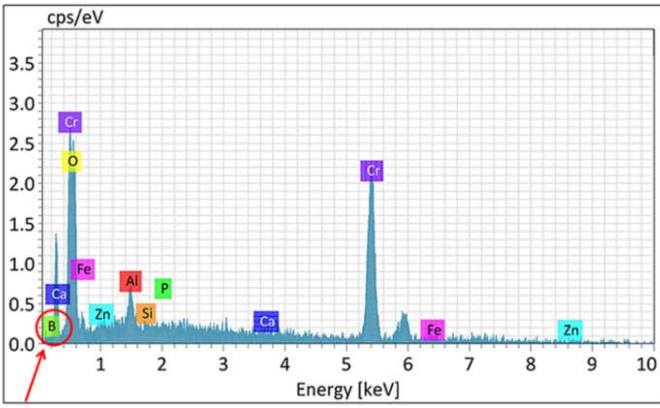


Figure 12 FESEM of the 1st piston ring surface rubbed with 5W-40 engine oil+B where B is detected with X-Ray mapping and XPS



Element	[%] Mass	[%] Atomic
Al	1.78	1.69
Si	0.15	0.14
P	0.13	0.12
Ca	0	0
Zn	0.17	0.16
Fe	4.02	3.81
B	0.9	0.85
O	3.23	3.06
Cr	95.24	90.17
Total	100	100

Figure 13 X-Ray and elemental analysis of the 1st piston ring surface tested with 5W-40 engine oil+B where B is detected from the Fig. 12.

Figures 12 and 13 are FESEM, mapping, XPS, X-Ray and elemental analysis of the 1st piston ring surface rubbed with 5W-40 engine oil+B against cylinder liner where B is well detected showing with red circles. B from NBA (nano boric acid) is mixed with other additives such as Zn, Ca, P and S that formed protective layer on the wear track.

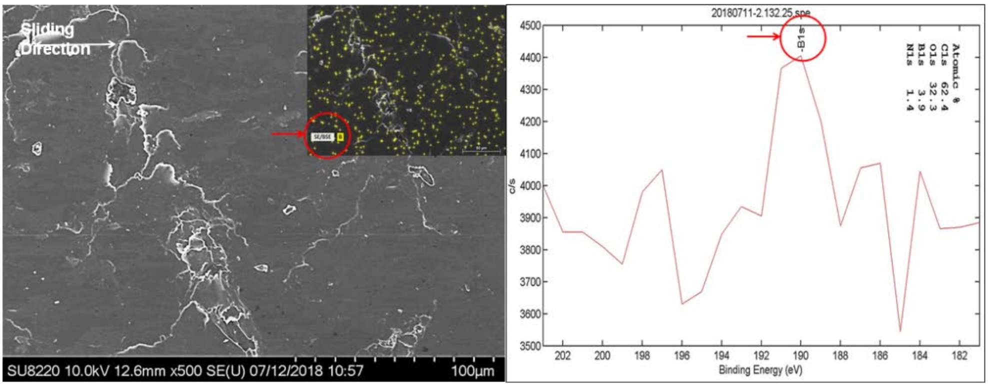
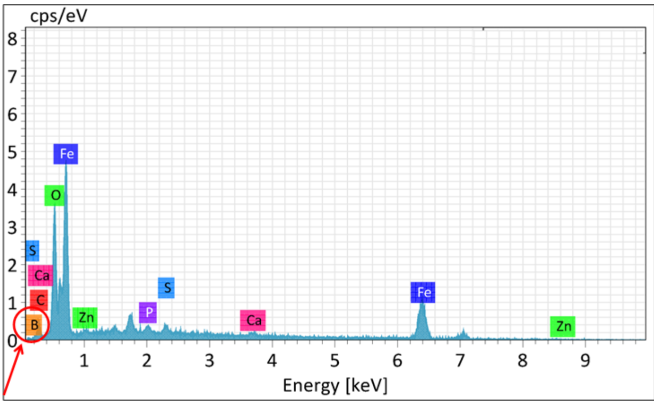


Figure 14 FESEM of the rubbed cylinder liner under 1st piston ring tested with 5W-40 engine oil+B where B is detected with X-Ray mapping and XPS.



Element	[%] Mass	[%] Atomic
C	2.68	7.82
O	12.46	27.35
Si	1.76	2.2
Fe	88.29	55.51
B	1.69	5.49
P	0.36	0.41
Zn	1.13	0.61
Ca	0.35	0.3
S	0.29	0.31
Total	100	100

Figure 15 X-Ray and elemental analysis of the rubbed cylinder liner under 1st piston ring tested with 5W-40 engine oil+B where B is detected from the Fig. 14.

Figures 14 and 15 are FESEM, mapping, XPS, X-Ray and elemental analysis of the cylinder liner rubbed under 1st piston ring tested with 5W-40 engine oil+B where B is well detected showing with red circles. B from NBA (nano boric acid) is well mixed with other additives such as Zn, Ca, P and S, so that formed protective layer on the wear track and it is higher as mass and atomic percent on the surface of cylinder liner rather than piston ring.

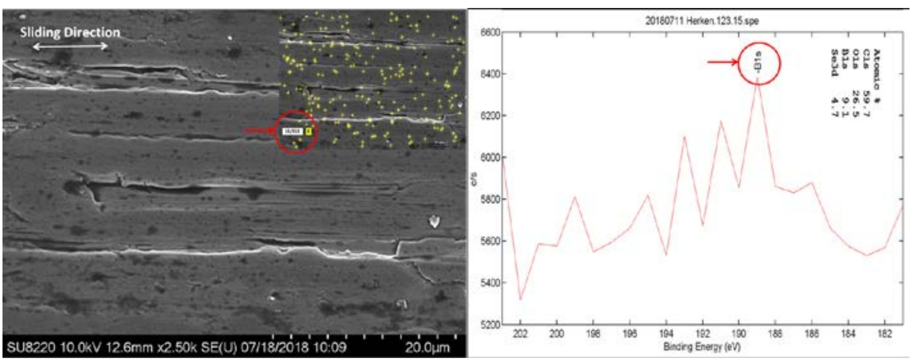
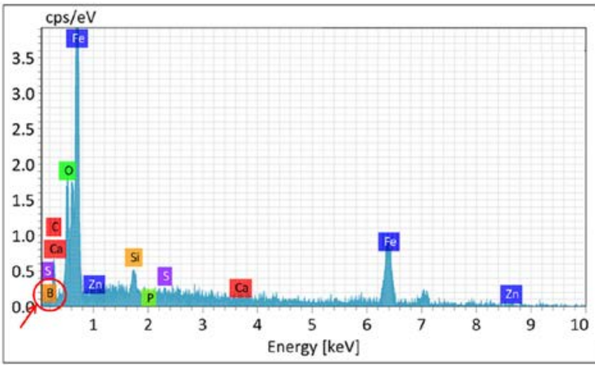


Figure 16 FESEM of the 2nd piston ring surface rubbed with 5W-40 engine oil+B where B is detected with X-Ray mapping and XPS



Element	[%] Mass	[%] Atomic
O	6.19	16.68
Si	1.42	2.19
Fe	81.6	63.02
B	1.36	5.41
S	0.19	0.25
P	0	0
Ca	0.05	0.06
Zn	0.21	0.14
C	3.42	12.27
Total	100	100

Figure 17 X-Ray and elemental analysis of the 2nd piston ring surface tested with 5W-40 engine oil+B where B is detected from the Fig. 16

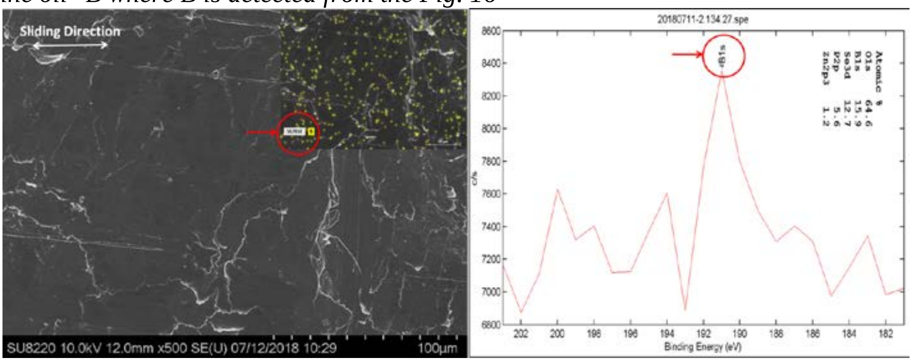
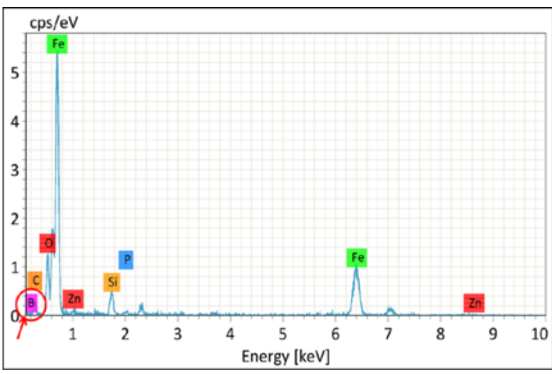


Figure 18 FESEM of the rubbed cylinder liner under 2nd piston ring tested with 5W-40 engine oil+B where B is detected with X-Ray mapping and XPS.



Element	[%] Mass	[%] Atomic
O	4.61	12.81
Si	2.21	3.5
Fe	83.75	66.68
B	1.83	7.52
Zn	1.19	0.81
C	2.23	8.27
P	0.29	0.41
Total	100	100

Figure 19 X-Ray and elemental analysis of the rubbed cylinder liner under 2nd piston ring tested with 5W-40 engine oil+B where B is detected from the Fig. 18

Figures 16 and 17 are FESEM, mapping, XPS, X-Ray and elemental analysis of the 2nd piston ring surface rubbed with 5W-40 engine oil+B against cylinder liner where B is well detected showing with red circles. B from NBA (nano boric acid) is mixed with other additives such as Zn, Ca, P and S that formed protective layer on the wear track. Figures 18 and 19 are FESEM, mapping, XPS, X-Ray and elemental analysis of the cylinder liner rubbed under 2nd piston ring tested with 5W-40 engine oil+B where B is well detected showing with red circles. B from NBA (nano boric acid) is well mixed with other additives such as Zn, Ca, P and S, so that formed protective layer on the wear track and it is higher as mass and atomic percent on the surface of cylinder liner rather than piston ring.

Table 2 2D-Ra and-3D Sa AFM roughness value.

AFM Roughness measurements	Sa (nm)	Ra (nm)
(b) Tested 1st piston ring with 5W40	101,019	92.013
(c) Tested 1st piston ring with nBA	178,37	198.06
(e) Tested liner under 1st piston ring with 5W40	251,39	260,84
(f) Tested liner under 1st piston ring with nBA	68,238	52,496
(b) Tested 2nd piston ring with 5W40	228,08	237.61
(c) Tested 2nd piston ring with nBA	65,119	51.713
(e) Tested liner under 2nd piston ring with 5W40	602,55	363,19
(f) Tested liner under 2nd piston ring with nBA	503,57	342,12

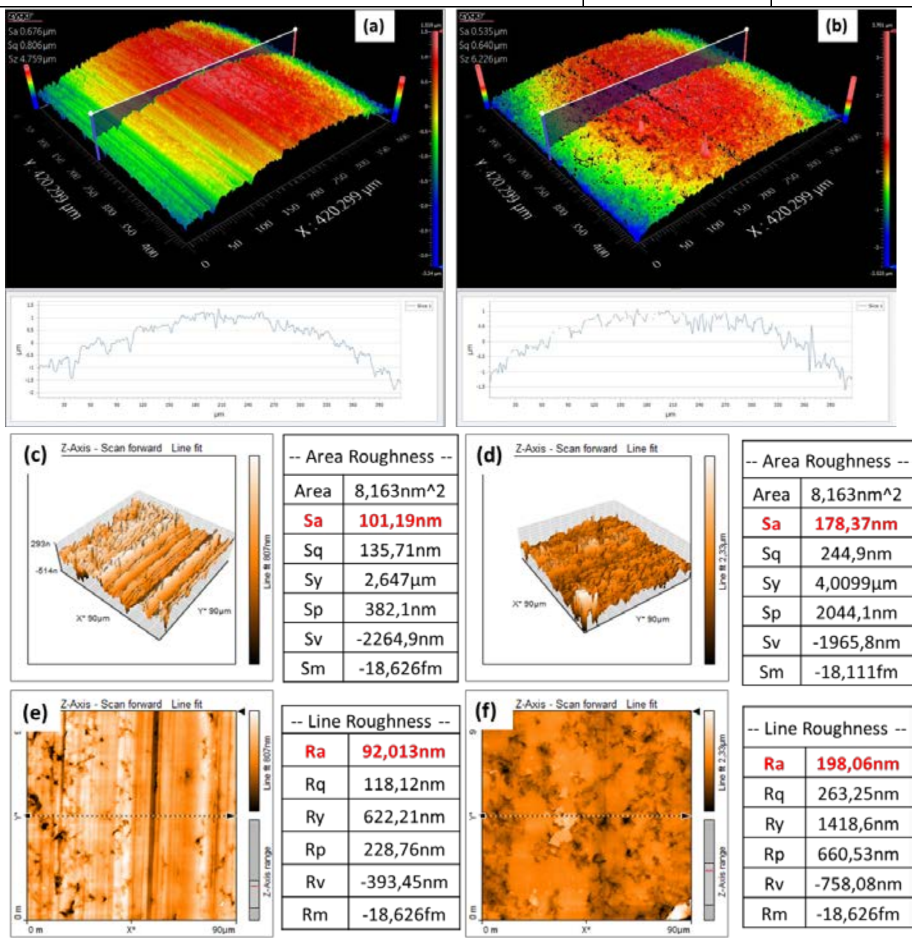


Figure 20 Optical 3D, 3D and Sa of AFM, 2D and Ra of AFM of the 1st piston ring surface tested with 5W-40 engine oil (a, c, e) and 5W-40 engine oil+B (b, d, f)

Figure 20 shows 3D digital optical microscopy, 3D and (surface average) Sa of AFM, 2D and (roughness average) Ra of AFM of the 1st piston ring surface tested with 5W-40 engine oil (a, c, e), and 1st piston ring surface tested with 5W-40 engine oil+B (b, d, f), respectively. Sa (178.37nm) and Ra (198.06nm) of the surface tested with 5W-40 engine oil+B were found higher than the test Sa (101.19nm) and Ra (92.013nm) with 5W-40 engine oil as presented in Table 2.

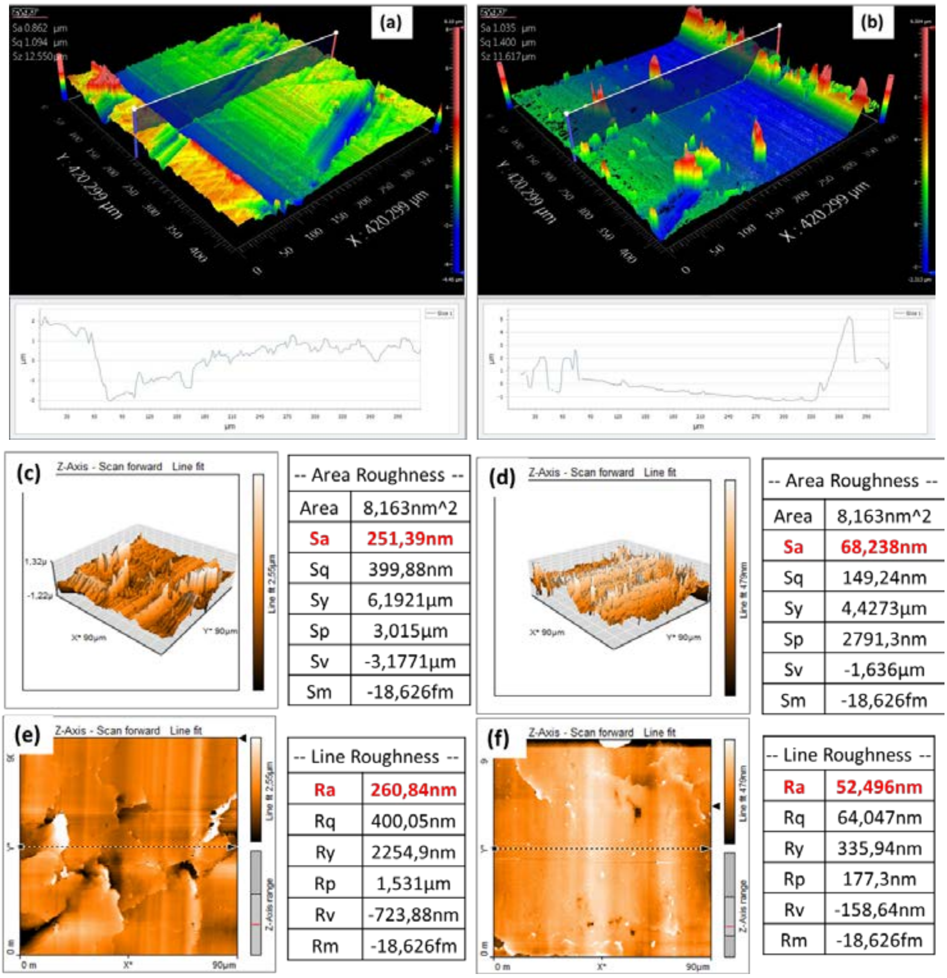


Figure 21 Optical 3D, 3D and Sa of AFM, 2D and Ra of AFM of the cylinder liner surface rubbed under 1st piston ring with 5W-40 engine oil (a, c, e) and 5W-40 engine oil+B (b, d, f).

Figure 21 shows 3D digital optical microscopy, 3D and (surface average) Sa of AFM, 2D and (roughness average) Ra of AFM of the cylinder liner surface rubbed under 1st piston ring with 5W-40 engine oil (a, c, e), and 1st piston ring surface tested with 5W-40 engine oil+B (b, d, f), respectively. Sa (68.238nm) and Ra (52.196nm) of the surface tested with 5W-40 engine oil+B were found lower than the test Sa (251.39nm) and Ra (260.84nm) with 5W-40 engine oil as presented in Table 2.

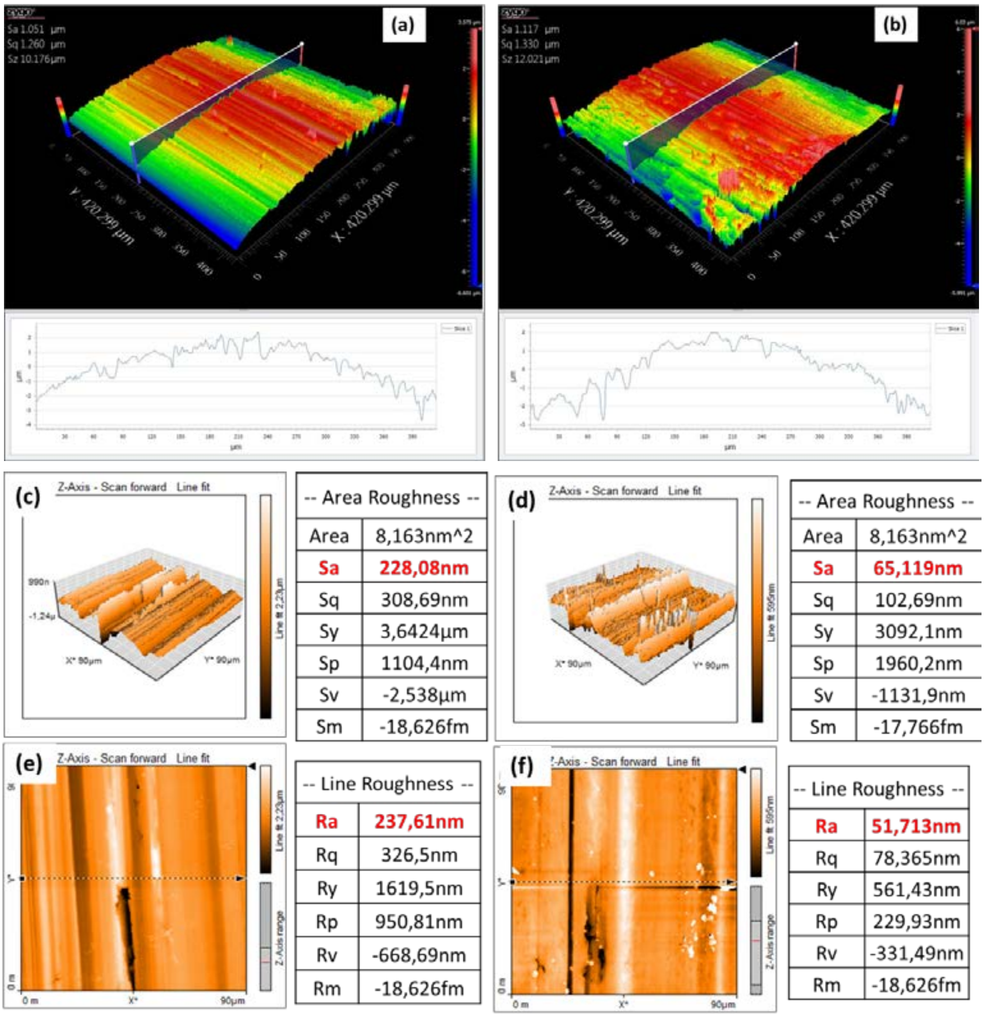


Figure 22 Optical 3D, 3D and Sa of AFM, 2D and Ra of AFM of the 2nd piston ring surface tested with 5W-40 engine oil (a, c, e) and 5W-40 engine oil+B (b, d, f).

Figure 22 shows 3D digital optical microscopy, 3D and (surface average) Sa of AFM, 2D and (roughness average) Ra of AFM of the 2nd piston ring surface tested with 5W-40 engine oil (a, c, e), and 1st piston ring surface tested with 5W-40 engine oil+B (b, d, f), respectively. Sa (65.119nm) and Ra (51.713nm) of the surface tested with 5W-40 engine oil+B were found lower than the test Sa (228.08nm) and Ra (237.61nm) with 5W-40 engine oil as presented in Table 2.

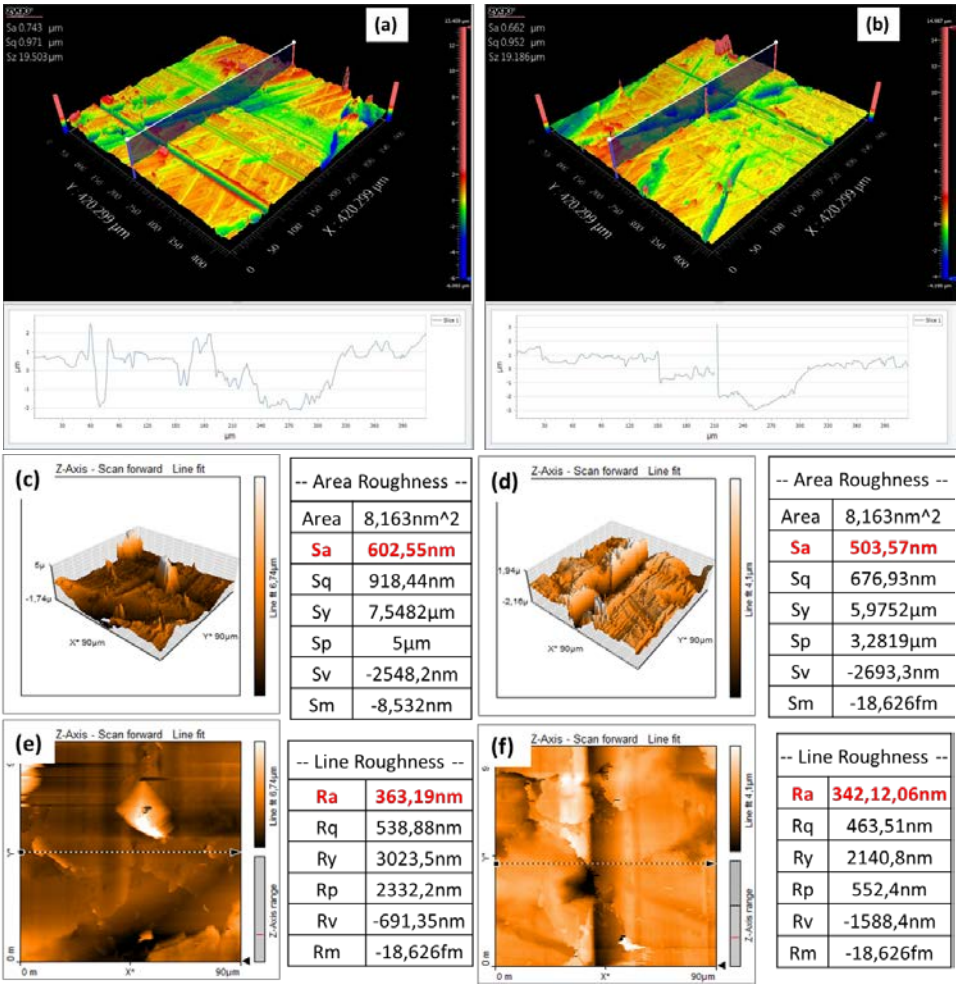


Figure 23 Optical 3D, 3D and Sa of AFM, 2D and Ra of AFM of the cylinder liner surface rubbed under 2nd piston ring with 5W-40 engine oil (a, c, e) and 5W-40 engine oil+B (b, d, f).

Figure 23 shows 3D digital optical microscopy, 3D and (surface average) Sa of AFM, 2D and (roughness average) Ra of AFM of the cylinder liner surface rubbed under 2nd piston ring with 5W-40 engine oil (a, c, e), and 1st piston ring surface tested with 5W-40 engine oil+B (b, d, f), respectively. Sa (503.57nm) and Ra (342.12nm) of the surface tested with 5W-40 engine oil+B were found lower than the test Sa (602.55nm) and Ra (363.19nm) with 5W-40 engine oil as presented in Table 2.

These results determine that BA was more effective to protect the surface on cylinder liner than piston ring. Thus, the amount of B has been found higher in elemental analysis of the rubbed cylinder liner according to the piston ring. The main reason is the degree of the surface degradation. Not only chemical mechanism, but also mechanical mechanism is also the main factor which play an important role in the activation of NBA and additives to form the protective layers on the wear track. In micro experiments, the formal tests conditions were determined and they concluded that the surface degradation is a mechanical action and favours chemical reaction; so that satisfactory degradation or sufficiently smoothed surface where the additives act with respect to the intensity of degradation (so that having perfect activated surface) allow higher amount of additive layer protection on the wear track.

To prove this results; Friction force and COF of **cylinder liner surface** rubbed under ***1st and 2nd piston ring*** with 5W-40 and 5W-40 engine oil+B engine oil were measured also in Nanoscale. Friction Force is obtained in V. It is calibrated and obtained in nN. Then COF is calculated in Nanoscale form. Figures 24, 25, 26, 27 show ***COF of friction force in Nanoscale of cylinder liner surface rubbed under 1st piston ring with 5W-40 engine oil.***

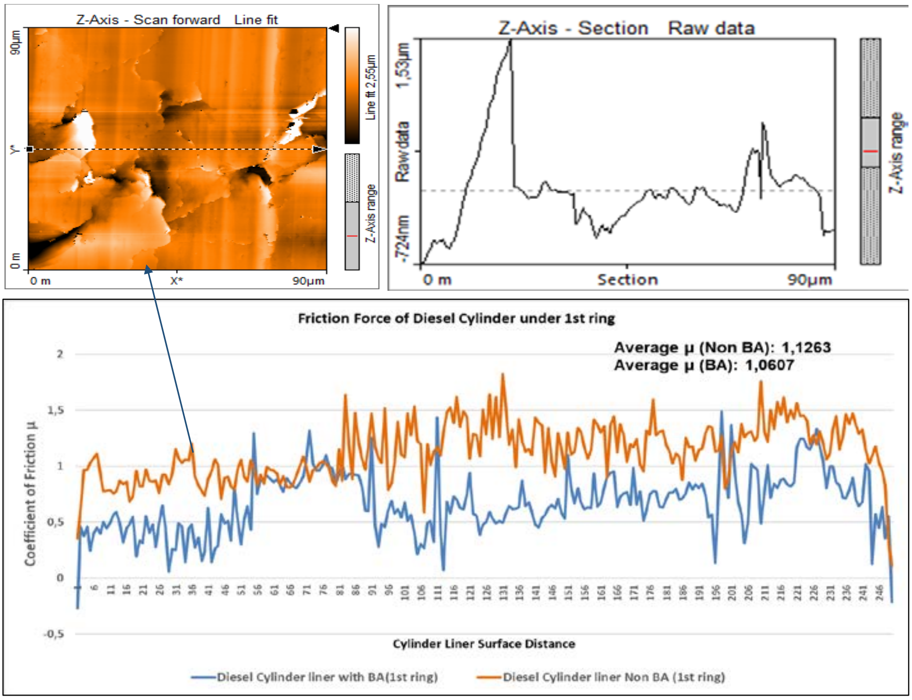


Figure 24. COF in Nanoscale of cylinder liner surface rubbed under 1st piston ring with 5W-40 engine oil

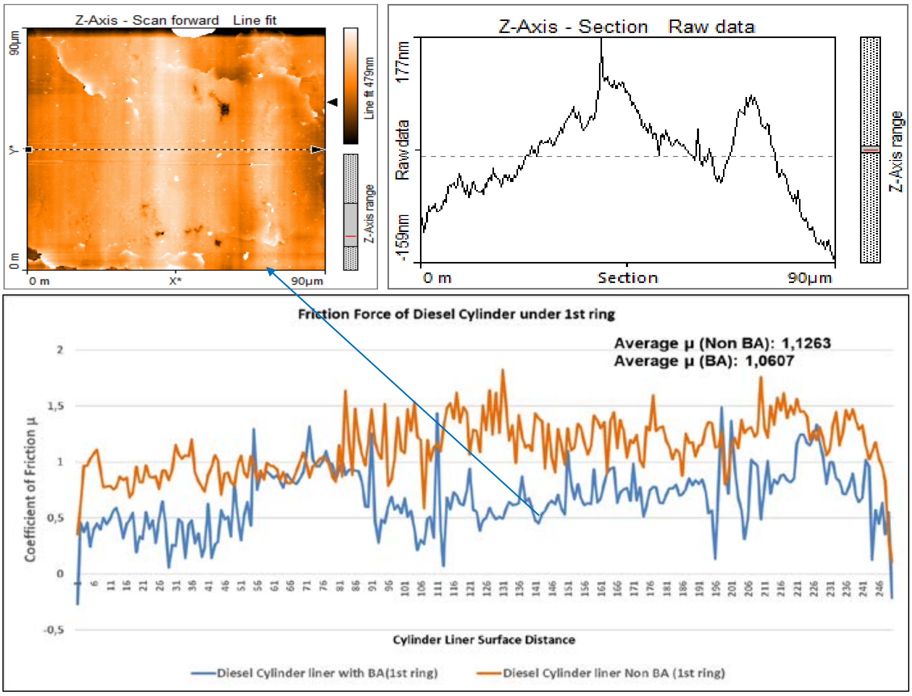


Figure 25. COF in Nanoscale of cylinder liner surface rubbed under 1st piston ring with 5W-40 engine oil+B

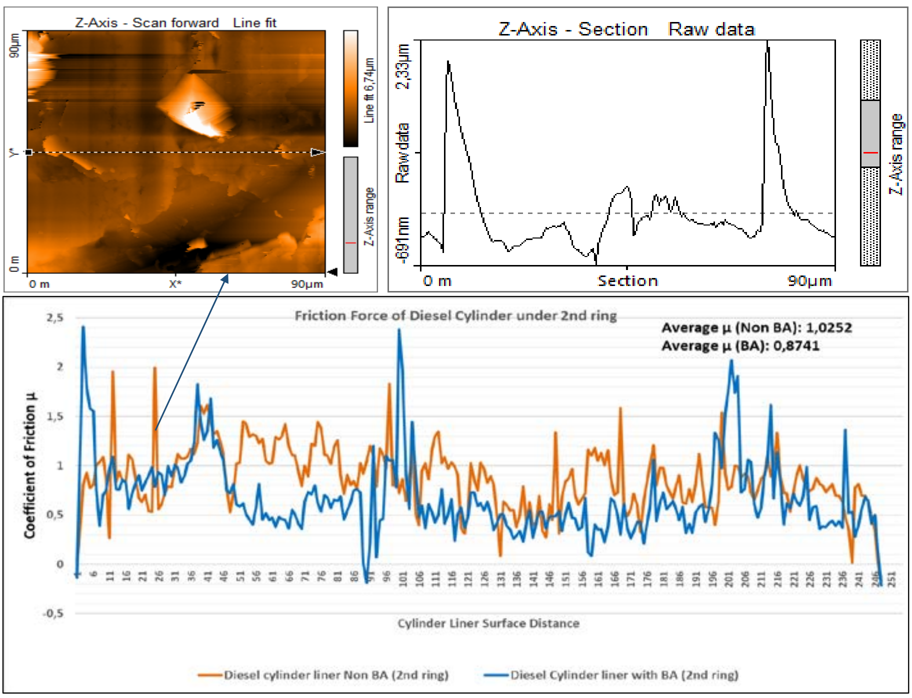


Figure 26. COF in Nanoscale of cylinder liner surface rubbed under 2nd piston ring with 5W-40 engine oil

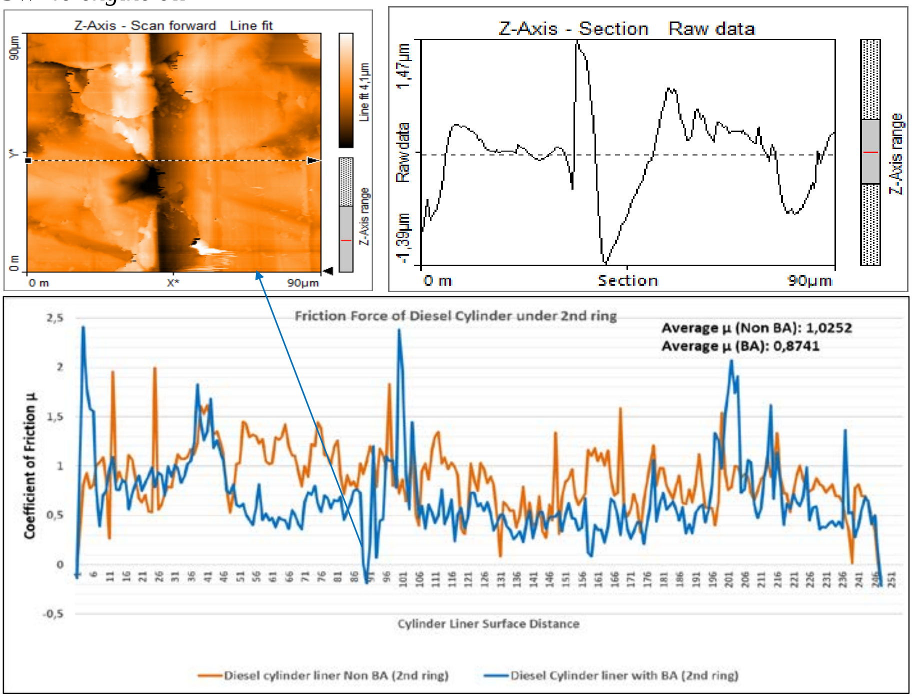


Figure 27. COF in Nanoscale of cylinder liner surface rubbed under 2nd piston ring with 5W-40 engine oil 5W-40 engine oil+B

3 CONCLUSIONS

New invention came out with the successful suspension of nano boric acid (BA) additive added into 5W-40 fully synthetic commercial lubricating oil. This invention is well proved with Turbiscan analyze.

Lubricant with BA additive showed almost similar friction results with the tests of 1st piston ring against cylinder liner and obtained less friction, better lubrication and protective performance then oil without containing BA with the tests of 2nd ring against cylinder liner.

COF of friction force in Nanoscale of cylinder liner surface rubbed under 1st and 2nd piston ring presented less friction, better lubrication and protective performance then oil without containing BA.

Protective layer of suspended nano boric acid is well determined with B element on the surface examination with TEM, Turbiscan, FESEM, X-Ray, mapping, AFM for the 1st and 2nd piston rings and cylinder liners, respectively. 3D surface and roughness average (Sa) and (Ra) showed lower values with 5W-40 engine oil containing BA then 5W-40 engine oil on the wear track of cylinder liners. It should be emphasized that 5W-40 engine oil is well known fully formulated oil marketed in the world.

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