Low viscosity oils impact on Heavy Duty Diesel engine components

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Increasing fuel costs and stringent emissions standards in the world became the most important challenges for the transportation industry. The use of low viscosity oils is considered an effective way to reduce fuel consumption of Heavy Duty Diesel (HDD) engines. However, the impact of oil viscosity reduction and novel additive packages needs to be better understood in durability of engine components. This paper investigated the application of a low viscosity oil SAE 10W-30 (HTHS 2.9cP) with novel formulation prepared to withstand EURO VI and OEM demands, through a 500 hours durability dynamometer test with extended oil drainage interval. The main tribo system such as liner-rings-piston, rod bushing-pin-piston and rod-bearing-crankcase were evaluated in terms of wear impact by visual and dimensional analyzes. The results obtained with low viscosity oil test were compared with the same engine components which were tested with typical SAE15W-40 oil (HTHS 3.7cP min.) applied in EURO V/VI HDD engines. From the comparative analyses, it was possible to identify some engine components that do not require design updates or technologies changes. For others, it was possible to anticipate performance issues that will demand new design and or material upgrades. Oil analyses were done each 50h of test. The oil degradation due to the extended drainage time is discussed in this paper.

1. INTRODUCTION

Reducing viscosity of engine oil is considered one of the most interesting options for reducing friction losses; hence fuel consumption [1]. However, low viscosity oils may lead to higher wear rate, that if not solved can lead to increased maintenance costs and a reduced engine life, consequently increase on overall fleet operating costs. To counter the expected wear increase, work is being done to improve the lube additives [2; 3]. Studies about wear with different viscosities and additive chemistry on combustion engines using bench tests, virtual simulations and short running test in dyno were reported [4-8, 10].
Lower viscosity oils will increase their market share. A survey with heavy duty diesel engine fleet managers, suggested that the market share of 10W-30 oils will grow from about 6% to roughly 20% by 2022 [6].

The engine components experiment different lubrication regimes depending on the speed, pressure and temperature conditions. Such regimes are usually summarized in the "Stribeck" curve (see figure 1), where μ is the lubricant viscosity, v is the relative speed of the surfaces and p is the normalized load. Lower viscosity oils reduce the hydrodynamic friction but tend to lead to higher boundary contact. Anti-wear additives are thought to be active in the boundary and mixed lubrication regimes. In general this class of additives, with zinc-dithiophosphates (ZnDTP) as the most commonly used in combustion engine oils, deposits a solid anti-wear film onto the surface. In addition to anti-wear additives, detergents are also known to impact wear phenomena as additives from this class of components are surface active and form solid films on a metal surface [4, 8].

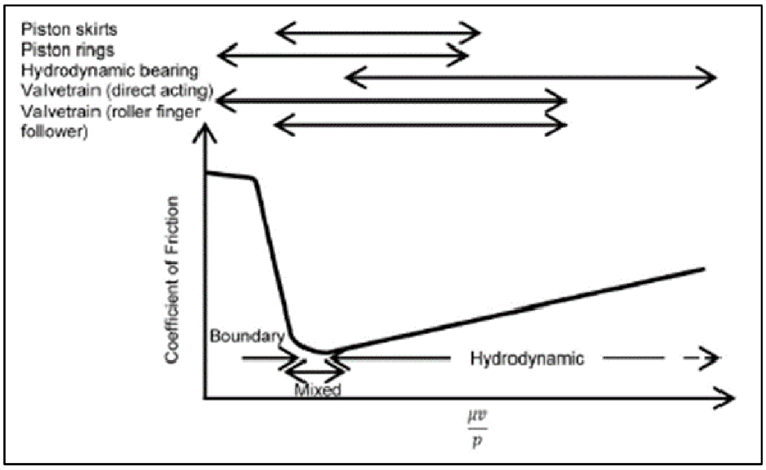

Figure 1 - Stylized "Stribeck Curve" [9]

Figure 2 summarizes wear on cylinder liner surface at Top Dead Center (TDC) region after short HDD engine tests (80h) with different candidates of anti-wear additives applied in two base oil variants: 15W-40 (HTHS 4.35cP) and 0W-40 (HTHS 3.81cP). While five out of the six evaluated 15W-40 formulations showed up to 20% reduction in liner wear, the difference that stands out the most is the increase in liner wear for the 0W-40 oils relative to the 15W-40 oils. It is also clear the impact of different additive packages even with same oil viscosity [4].

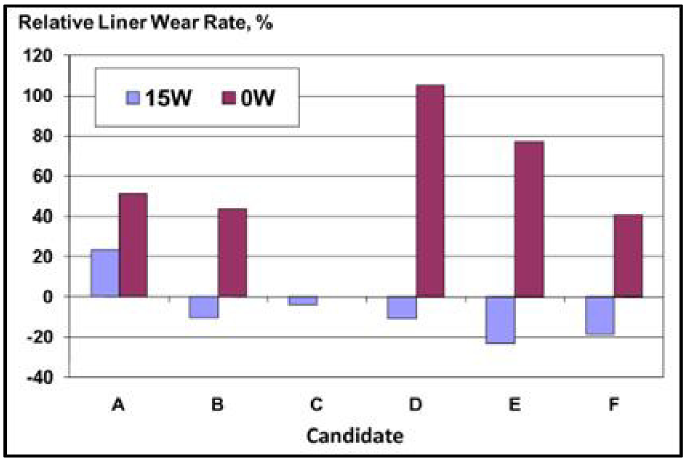

Figure 2 - Viscosity grade and anti-wear package impact on liner wear [4].

2. LOW VISCOSITY LUBE OILS FOR MODERN HDD ENGINES

Table 1 summarizes the SAE viscosity grades. In this work, a SAE15W-40 (HTHS 3.7cP) currently used in Brazil and a 10W-30 (HTHS 2.9cP) candidate for the European next generation engine were tested in the same engine, as described ahead. Additive package followed the lube generation, so not only the viscosity was changed from one oil to another.

Table 1 - SAE J300 engine oil viscosity grades (as Jan 2015) [8]

SAE Grade Viscosity	Low Temp. (°C) Cranking Viscosity, mPa.s, max.	Low Temp. (°C) Pumping Viscosity, mPa.s, Max, w/ no Yield Stress	Low Shear Rate Kinematic Viscosity (mm^2/s) at 100°C		High Temp. High Shear mPa.s at 150°C, min.
			Min	Max	
0W	6,200 at -35°C	60,000 at -40°C	3.8	-	-
5W	6,600 at -30°C	60,000 at -35°C	3.8	-	-
10W	7,000 at -25°C	60,000 at -30°C	4.1	-	-
15W	7,000 at -20°C	60,000 at -25°C	5.6	-	-
20W	9,500 at -15°C	60,000 at -20°C	5.6	-	-
25W	13,000 at -35°C	60,000 at -15°C	9.3	-	-
8	-	-	4.0	< 6.1	1.7
12	-	-	5.0	< 7.1	2.0
16	-	-	6.1	< 8.2	2.3
20	-	-	6.9	< 9.3	2.6
30	-	-	9.3	< 12.5	2.9
40	-	-	12.5	< 16.3	3.5 (a)
40	-	-	12.5	< 16.3	3.7 (b)
50	-	-	16.3	< 21.9	3.7
60	-	-	21.9	< 26.1	3.7
(a) Applied for 0W-40, 5W-40, 10W-40 Grades (b) Applied for 15W-40, 20W-40, 25W-40 Grades					

3. ENGINE TEST

A 13.0 liter, 6 cyl. HDD engine with 220 bar of Peak Combustion Pressure (PCP) was tested during 500h with each lube formulation. Oil drainage time followed the OEM recommended interval: 150h for the current oil[1] (15W-40) and 500h for the next generation low viscosity (10W-30) one. The engine test with current oil used current production engine components (typical technologies in series production for HDD EUR 5 engines) and the test with low viscosity had some cylinders with production parts and others with higher wear resistant products to allow both the comparison between oils and between component alternatives with the low viscosity oil.

Test procedure was 20h break-in followed by 500h in a durability cycle. Engine performance curve was done before and after the 500h durability test. Figure 3 shows the values at test start, no performance degradation was observed at test end. Fuel was the Brazilian Diesel S10 B5to7. Lube Oil consumption was measured by drain and weight every 50h, when also a small lube sample was removed for analysis. In case of SAE 10W-30 oil, small amount of fresh oil was added every 50h just to reach the engine oil volume requirement for dyno test.

[1] Due to leakage issues, the SAE 15W-40 had the oil exchanged at 150, 300 and 350h.

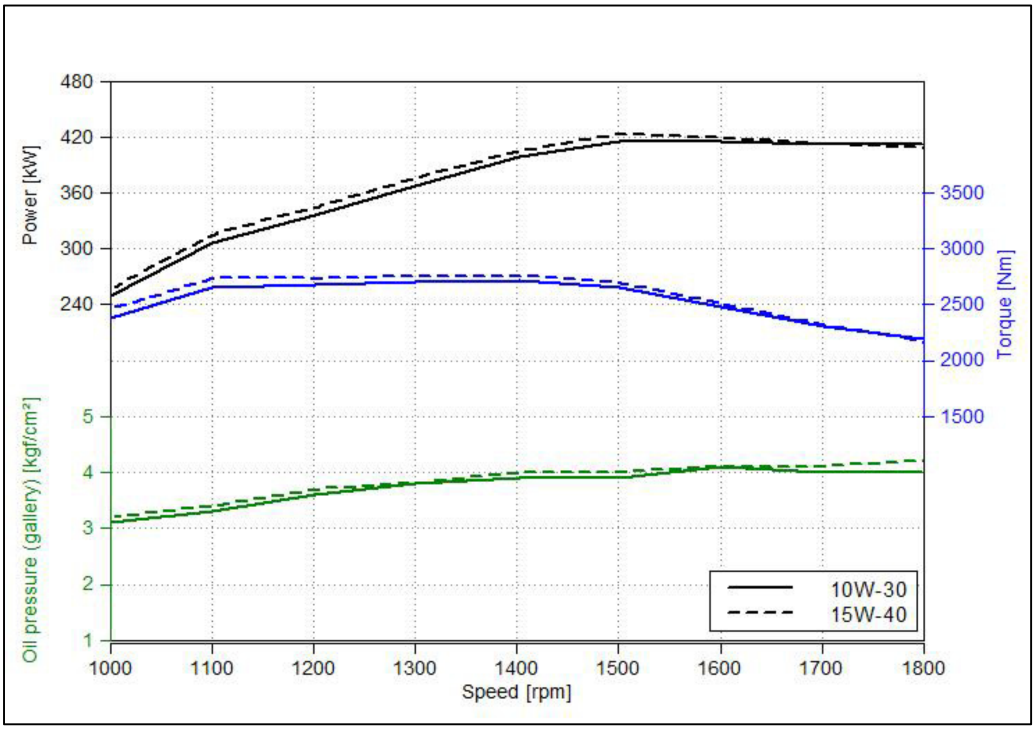

Figure 3- Performance curves at test start.

Eventual fuel saving with the lower viscosity oil would demand a more precise dynamometer than the used in this work and was not the scope of this investigation. Blow-by and Lube Oil Consumption (LOC) as well other engine parameters along the test were according the manufacturer limits. See table 2.

Table 2 – Blow and LOC data along the test

	SAE 15W-40 oil	SAE 10W-30 oil
Blow-by [l/min]	155 – 165	130 – 140
LOC [g/h]	18 – 31	12 – 21

3.1. LUBRICANT OIL ANALYSES

Lube oil was analyzed every 50h during engine test. Base number (BN – ASTM D2896), acid number (AN – ASTM D664), oil viscosity @ 100°C (ASTM D 445), metal presence and some additive components such as Mo, Zn and P (ASTM D4951) were monitored by ICP-OES (Inductively Coupled Plasma – Optical Emission Spectrometer).

BN and AN were in regular condition after 500 hours of test in both oil variants, see Figure 4. After 500h, with not oil change, the 10W-30 oil had almost BN and AN "crossed", i.e. reaching the same value, which is usually considered as limit to oil change. Nevertheless, BN decay of the 10W-30 was lower than with the 15W-40, the latter, without oil change, would have BN-AN crossing around 300h. Viscosity of both oils was within their respective SAE specification ("they stay in grade along the test") during 500h engine tests. See figure 5.

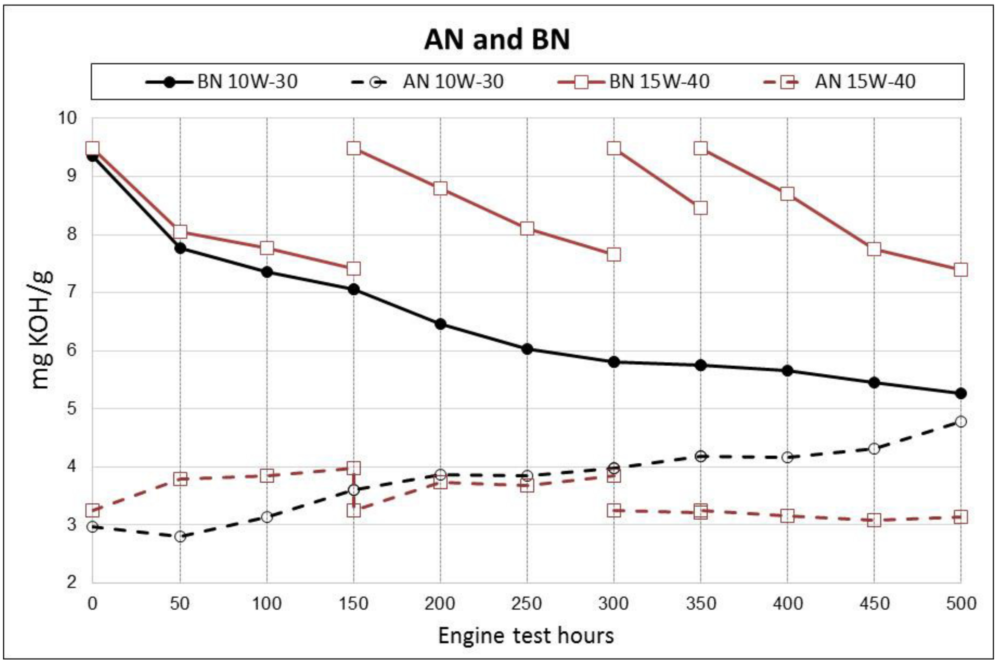

Figure 4 – AN and BN oil analyses during 500h engine tests.

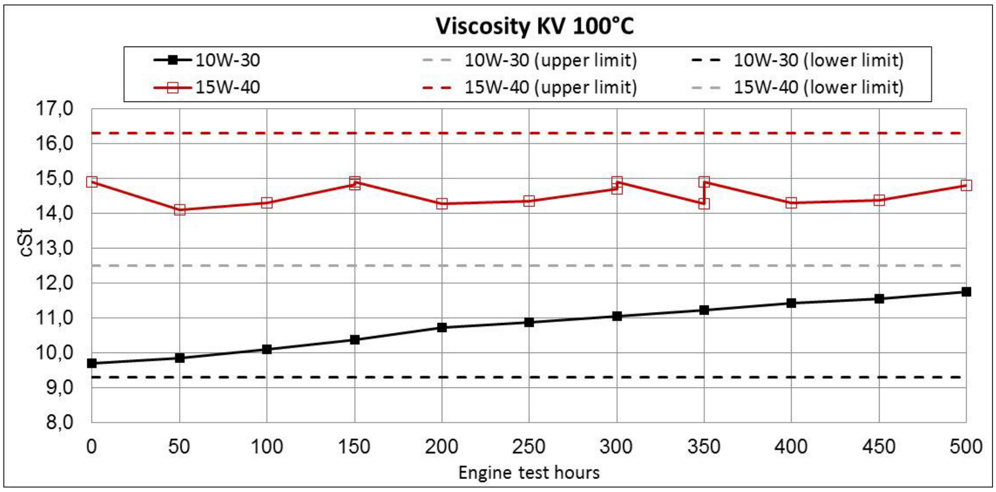

Figure 5 – Lube oil viscosity at 100°C during 500h engine tests.

Metal presence analysis showed a constant and significant increase of Fe content (up to 171 ppm) and peak of Cu content (200 ppm) at 200h engine test in the low viscosity oil test. Sources for both metals were not identified on the analyzed engine parts, see ahead. For better comparison, figure 6 shows the accumulated metal values for the SAE 15W-40, i.e. the values represent what would accumulate if oil was not changed along the test. Metal accumulated values were higher in the test with the low viscosity oil and longer drainage interval.

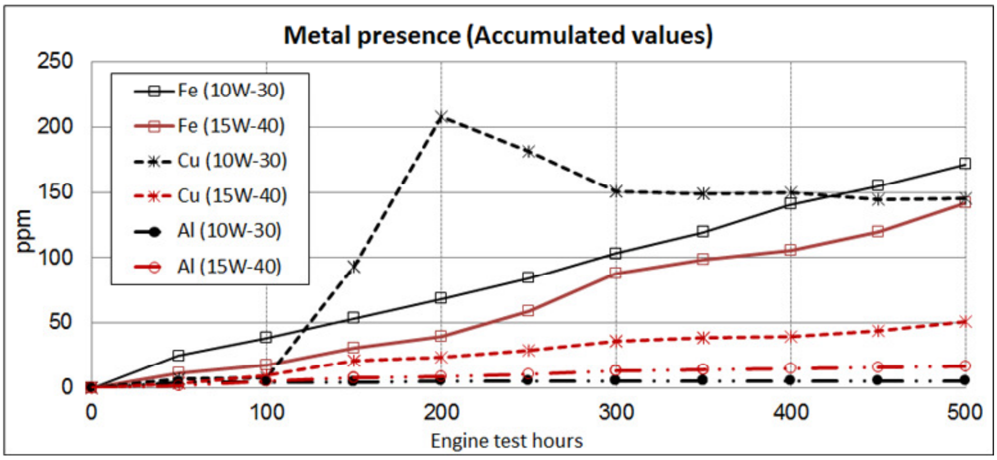

Figure 6 – Metal presence during 500h engine tests.

Zn and P analysis showed slight higher contents in the 15W-40. The 10W-30 oil goes in the trend of reducing SAPs. Zn and P variation along test was small for both oils. See Figure 7. Analyses indicate around 60 ppm of Mo in the 10W-30 and no Mo presence in the 15W-40 oil.

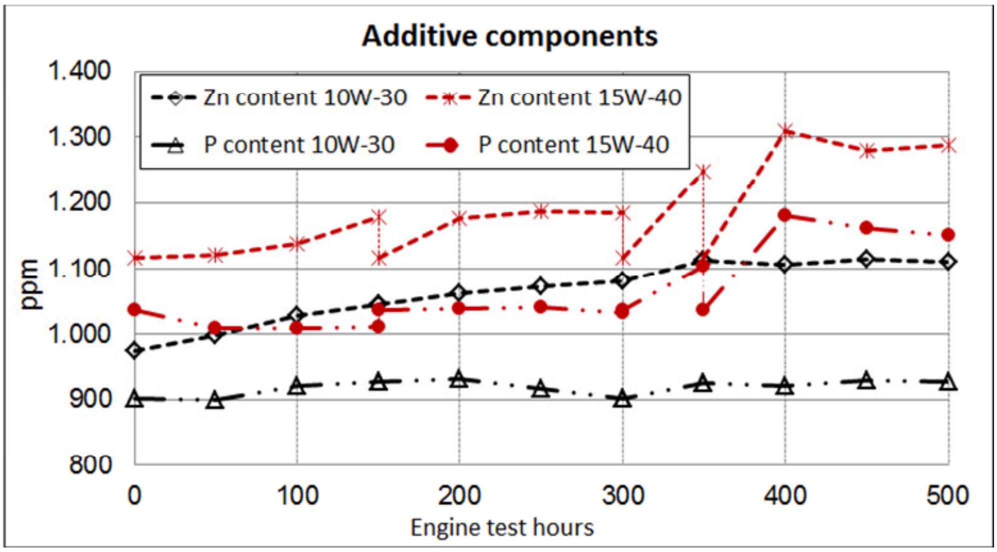

Figure 7 – Zn and P content along the tests.

3.2. PISTON

MAHLE Monotherm steel (38MnBVS6) pistons with graphite coating on the skirt surface were assembled in both engine tests. After 500h test, carbon deposits at top lands were small and similar with both oils and all rings were free to rotate, see figure 8. Piston groove, skirt and pin wear was too low in both tests to be measured by conventional methods.

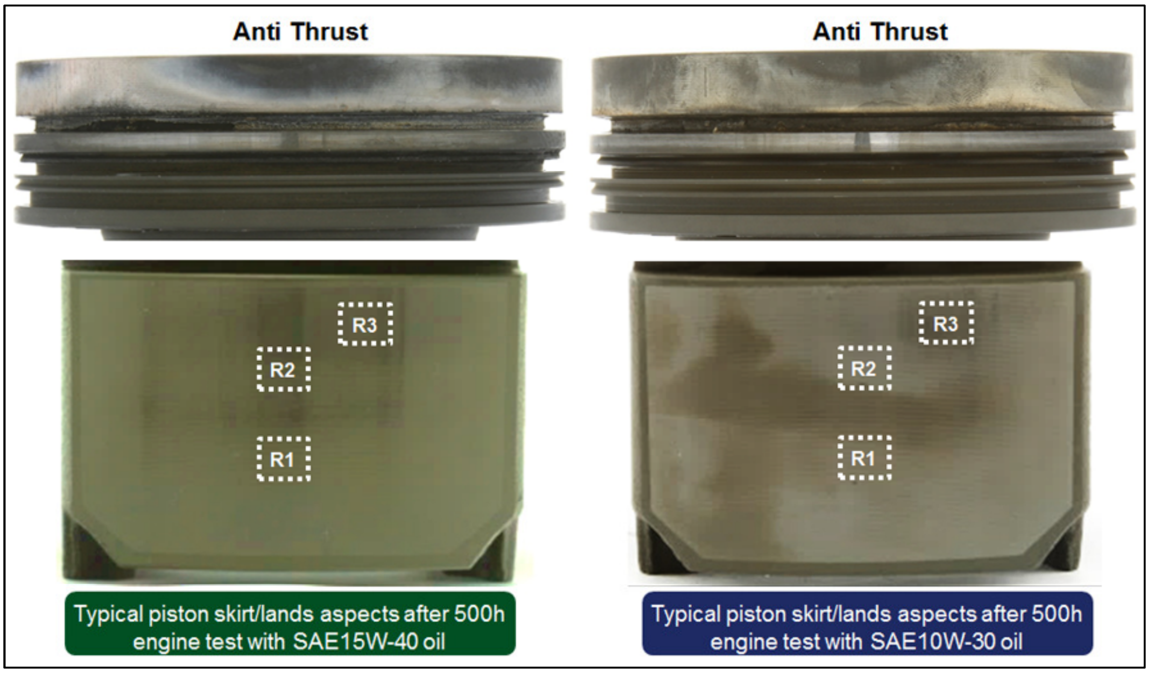

Figure 8 – Visual aspects of piston ATS after tests.

3.3. PISTON PINS

Current piston pin, made in 16MnCr5 steel, was assembled in both engine tests. Outside diameter and roughness were measured before and after engine tests. No signs for concerned were found. See Figure 9 and 10.

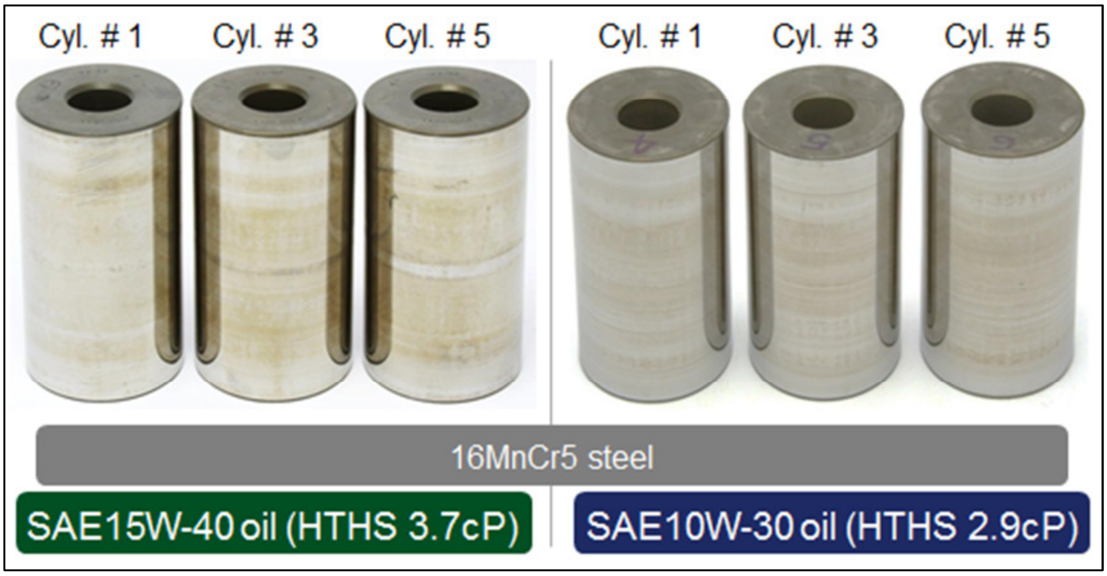

Figure 9 – Piston pins after 500h engine tests.

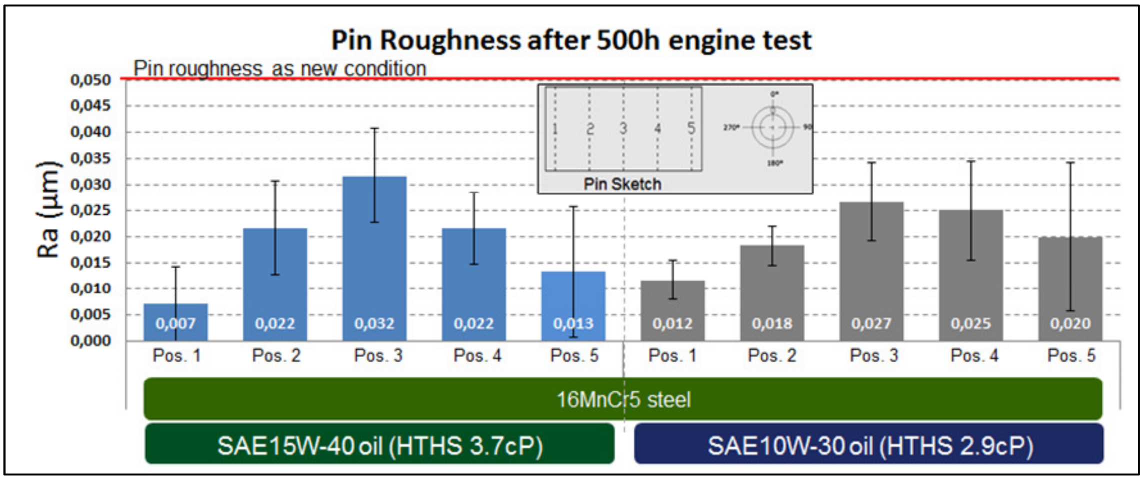

Figure 10 – Piston pin roughness measurements after 500h engine tests

3.4. PISTON RINGS

The current top ring with CrN PVD coating [11] in the running face over Gas nitrited steel (GNS) were tested with both oil variants. In the 10W-30 test, 3 cylinders (cyls) were assembled a high wear resistance DLC H-free coating over CrN PVD surface [13]. After test, both top ring variants presented good visual aspect without burning marks, cracks or coating spallation. In the 10W-30 test, the CrN PVD top ring presented 18% avg. wear increase in the contact face, while the DLC H-Free showed wear reduction of 44% compared to CrN. See figures 11 and 12. The DLC H-free with the low viscosity oil showed lower wear than the current ring with the 15W-40.

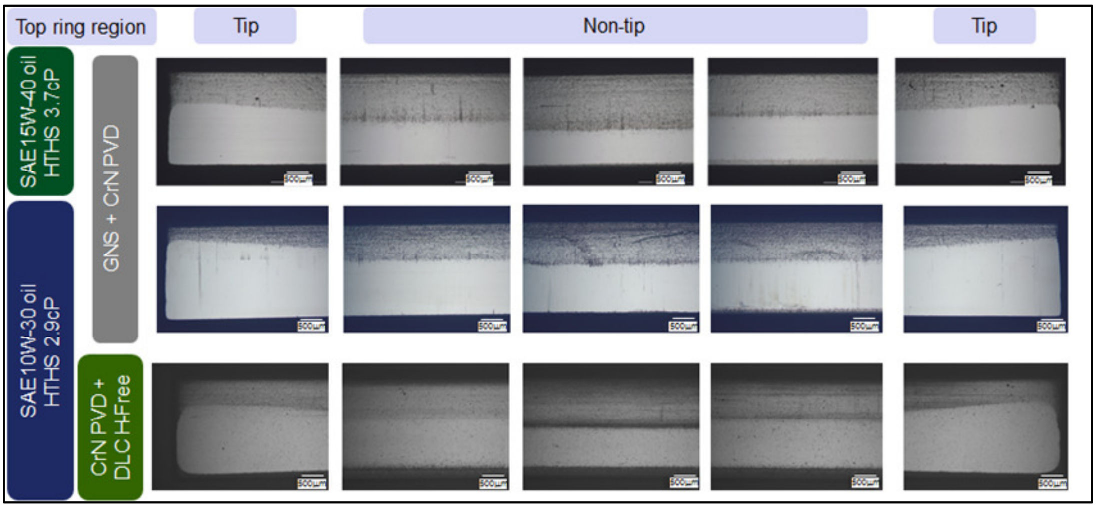

Figure 11 – Visual aspects of top ring sets after 500h HDD engine tests.

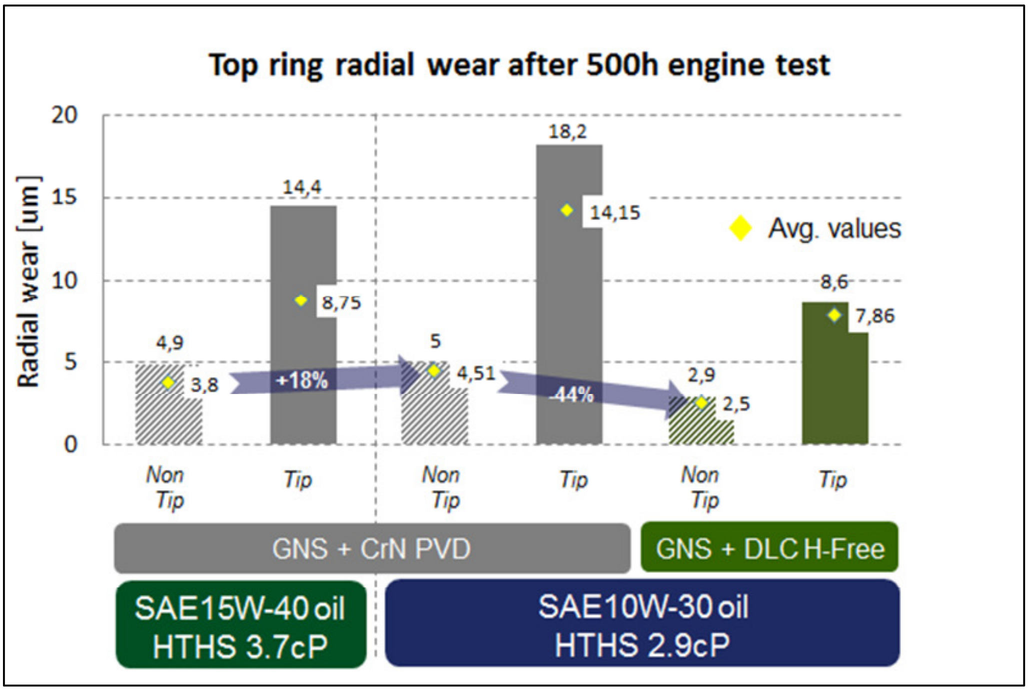

Figure 12 – Radial wear of top ring after 500h engine tests.

Similar evaluation was done for 2nd rings, where a more wear resistance CrN PVD coating over GNS ring was compared to the current GNS. Again, no issues were found, and the more resistant variant presented lower wear with the low viscosity oil than the current ring with the current oil. See figure 13.

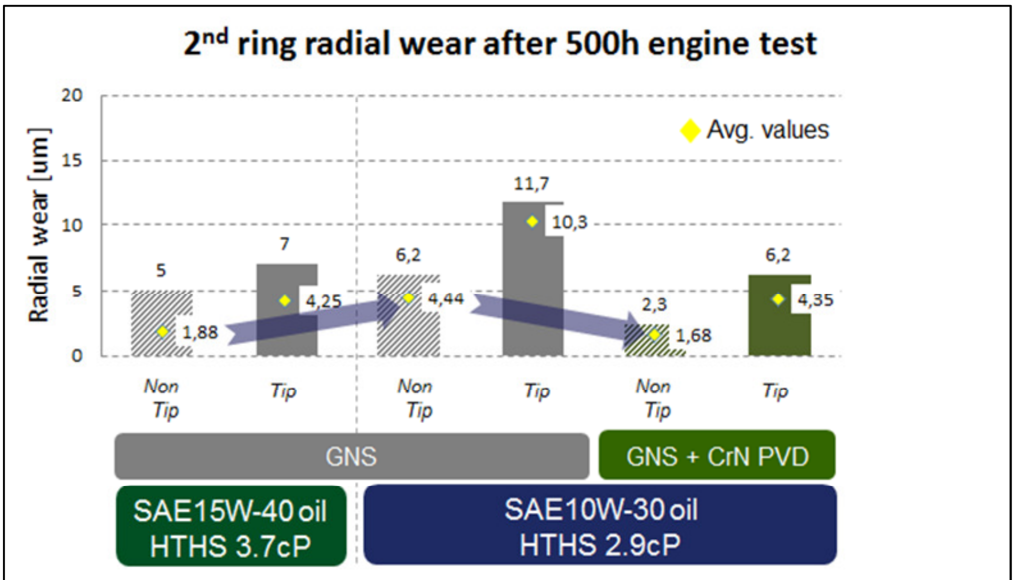

Figure 13 – Radial wear of 2nd ring sets after 500h engine tests.

Similar evaluation was done for the oil control ring, where the DLC H-free over the CrN PVD was compared with the current CrN only oil ring. No issues were found and again the more wear resistant DLC H-free showed lower wear with the low viscosity oil than the current ring with current oil. See figure 14.

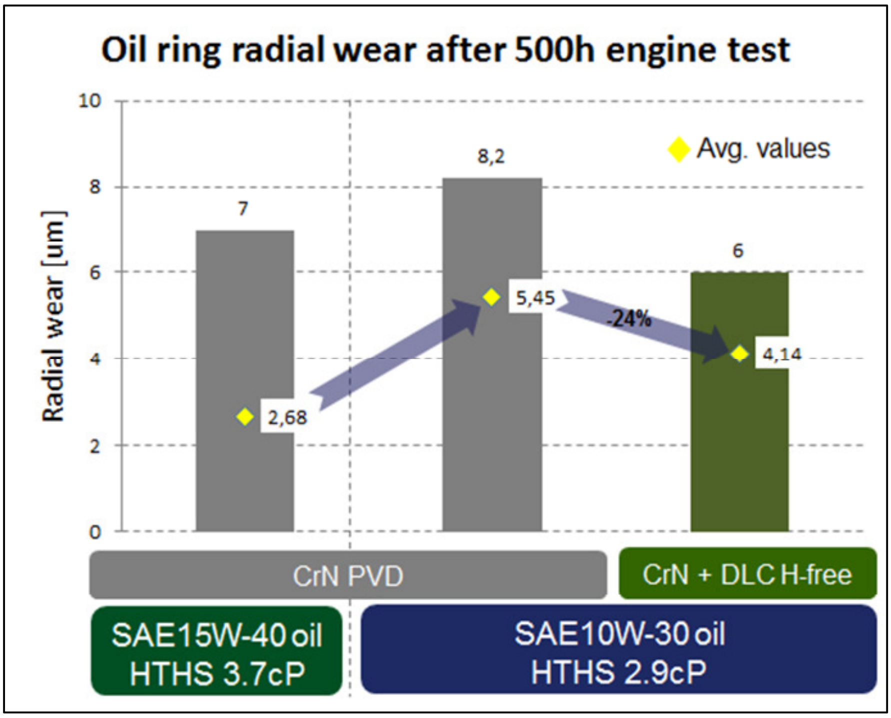

Figure 14 - Radial wear of OCR sets after 500h engine tests.

3.5. CYLINDER LINERS

Cylinder liners made in grey cast iron material (DIN GG25) with relative fine honing (a.k.a. "slide honing") honing were assembled in both engine tests. After tests, no severe contact or scuffing signs were found. Wear measurements by axial profile tracer at the critical TDC regions affected by fuel injection showed increased wear depth as expected in both tests. Nevertheless, the avg. wear showed similar results in both engine tests, with different oil viscosities and ring packs, see Figures 15 and 16.

Roughness parameters [ISO13565-2 / DIN 4776]	Average measured values
Rpk [µm]	0.26
Rpk [µm]	0.58
Rpk [µm]	1.93
Mr1 [%]	9.7
Mr2 [%]	80
Honing angle [°]	48

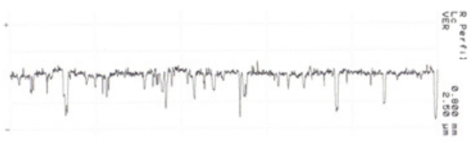

Figure 15 – Iron cast cylinder liner and typical honing roughness values as new.

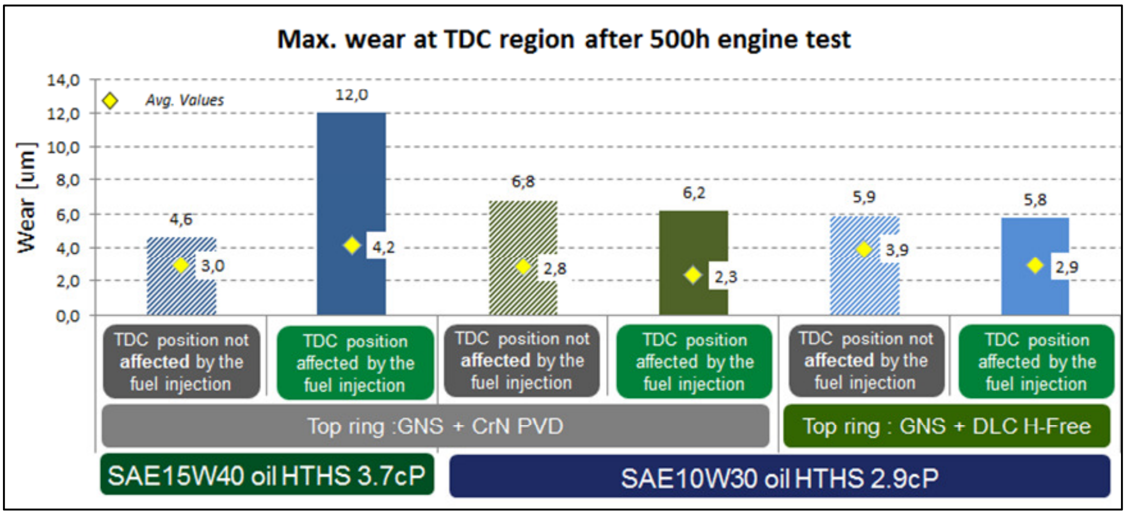

Figure 16 – Wear at liner TDC regions after 500h engine tests.

3.6. BEARINGS

The series leaded electroplated upper main bearings (UMB) were assembled in both engine tests. The parts presented good visual aspects and regular contact pattern after test. The lower main bearings (LMB) were assembled using the electroplated lead free technology and presented slightly higher contact pattern compared to UMB, as expected. No scuffing or bronze exposure was noticed on the tested parts. See figure 17. Wear was assessed by wall thickness and weight loss before and after engine tests. The wall thickness and weight loss were similar for the main bearings.

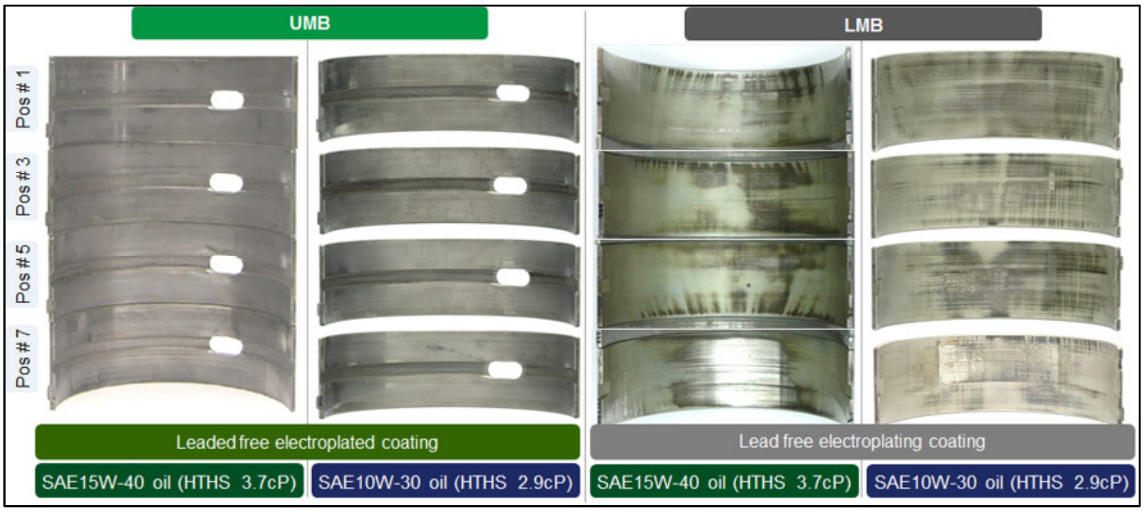

Figure 17 – Visual aspects of UMB and LMB after 500h engine tests.

The upper conrod bearings (URB) were assembled using two coating technologies in both tests. Three cylinders used lead free electroplated bearings and three others, bearings with a high wear resistant polymer coating [12]. For lower rod bearing (LRB) current production, bi-metal lining material was tested in both oil tests. After tests, both upper and lower conrod bearings presented good visual aspects. A wider bearing area was affected using the low viscosity oil. However the wear measurement did not indicate a worst condition. Some scratches were noticed, caused by foreign particles in all parts. No scuffing and no bronze exposure was noticed. See figure 18. Wear was assessed by wall thickness and weight loss before and after engine tests. The conrod bearings wall thickness and weight loss were similar for both oil conditions.

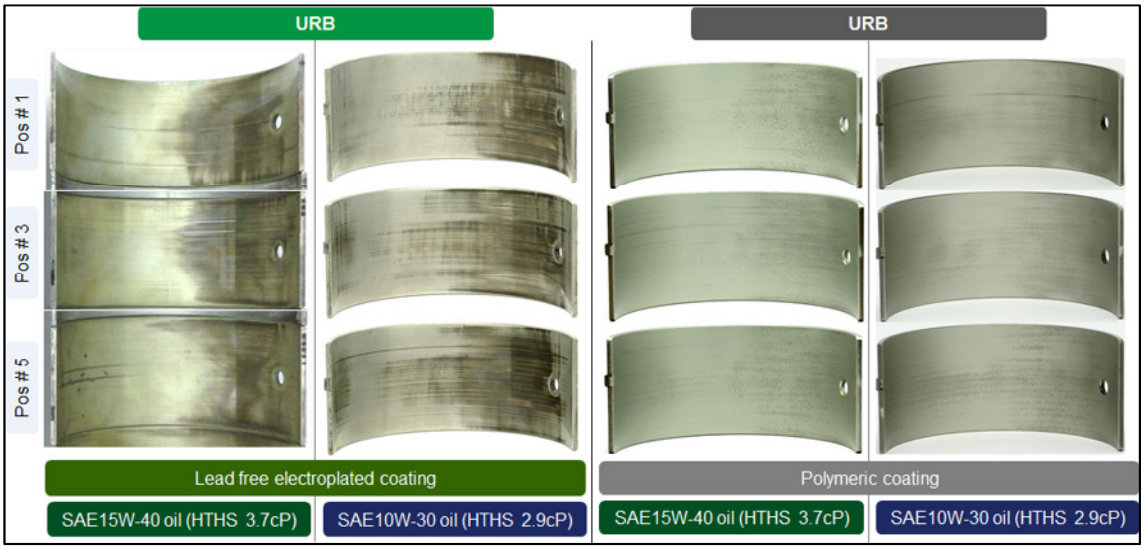

Figure 18 - Visual aspects of URB after 500h engine tests.

4. CONCLUSION

The 500h engine test with low viscosity oil 10W-30 and extended drainage time engine was successfully concluded without concerns. Some wear increase was observed on the piston rings but the more resistant alternatives, showed lower wear with the low viscosity oil than the current part with the higher viscosity oil.

Longer tests and analysis of other engine parts are recommended. On the tests components were the wear increase was higher, MAHLE has already alternatives showing lower wear with the low viscosity oil than the current one with the higher viscosity oil.

5. REFERENCES

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6. DEFINITIONS / ABREVIATIONS

API	American Petroleum Institute
AN	Acid number
BN	Base number
DLC H-free	Diamond-like carbon hydrogenated free coating
EMA	Engine Manufacturers Association
GNS	Gas nitrited steel
GHG	Greenhouse Gas
HDD	Heavy Duty Diesel
HTHS	High Temperature High Shear
ICP-OES	Inductively Coupled Plasma – Optical Emission Spectrometer
LMB	Lower main bearing
LRB	Lower rod bearing
LOC	Lube oil consumption
OEM	Original Equipment Market
TDC	Top dead center
UMB	Upper main bearing
URB	Upper rod bearing
ZnDtp	Zinc-dithiophosphates