



Optimizing the Piston/Bore Tribology: The Role of Surface Specifications, Ring Pack, and Lubricant

Boris Zhmud Applied Nano Surfaces

Eduardo Tomanik LFS - USP

Wieslaw Grabon Rzeszow University of Technology

Dietmar Schorr Steinbeis Transfer Centre Tribology

Boris Brodmann OptoSurf GmbH

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Abstract

The present study looks into different possibilities for tribological optimization of the piston/bore system in heavy duty diesel engines. Both component rig tests and numerical simulations are used to understand the roles of surface specifications, ring pack, and lubricant in the piston/bore tribology. Run-in dynamics, friction, wear and combustion chamber sealing are considered. The performance of cylinder liners produced using a conventional plateau honing technology and a novel mechanochemical surface finishing process - ANS Triboconditioning® - is compared and the importance of in-design "pairing" of low-viscosity

motor oils with the ring pack and the cylinder bore characteristics in order to achieve maximum improvement in fuel economy without sacrificing the endurance highlighted. A special emphasis is made on studying morphological changes in the cylinder bore surface during the honing, run-in and Triboconditioning® processes. It is demonstrated that the Triboconditioning® treatment, while in certain aspects resembling the run-in process, provides a greater effect depth and results in a beneficial tribological performance profile. In particular, the Triboconditioning® treatment of cylinder liners allows significant reduction in top ring wear when low viscosity motor oil is used for improved energy efficiency.

Introduction

The continuing pursuit for better fuel efficiency stands behind many recent advancements in engine technology. Advanced surface finishing methods, such as self-lubricated hard coatings, mirror-like thermally sprayed bores, mechanochemical surface finishing, helical slide honing etc. as well as availability of high-sensitivity testing rigs and "digital twin" simulation tools create new opportunities for engine tribology optimization [1, 2, 3, 4, 5, 6, 7]. On the lubricant side, there is an increasing use of synthetics due to their superior performance. The move towards lower viscosity crankcase lubricants helps further reduce on-road greenhouse gas (GHG) emissions [3].

However, a narrow-sighted one-component-at-a-time optimization approach still prevailing at many OEMs is often a limiting factor for the development. There are many examples proving that the one-component optimization is often nothing less than misleading, necessitating the need for a complete system approach [4]. For instance, there is no point in optimizing the friction of the top ring without taking into account the oil control ring, as all rings in the ring pack work together. Also, what is optimal for a high-speed short-stroke engine is

not necessarily optimal for a low-speed long-stroke engine. In heavy-duty diesel engines, the power cylinder unit (PCU) accounts for approx. 50% of overall frictional losses in the engine. Motored tear down tests show that more than two third of the PCU friction losses come from oil control ring (OCR). However, at high load and low speed, the compression ring (CR) contribution becomes more important. Hence, the primary strategies for reducing piston ring assembly/cylinder bore friction are (i) to reduce OCR tension and (ii) to reduce CR width [5,6]. Unfortunately, unless counteracted by the bore finish tuning, these strategies may potentially lead to increased oil consumption and/or blowby. Increased oil consumption leads to more soot, while increased blowby compromises engine efficiency.

Furthermore, it should be realized that the ring pack is designed to work with a specific viscosity grade of motor oil. In the heavy-duty sector, it is usually SAE 15W-40 motor oil. However, following the introduction of API FA-4 category, a variety of low viscosity HDEO grades, such as SAE 10W-30, 5W-30 and 5W-20, started to come to market. While justified by improved fuel economy, a move towards low viscosity oils is not as straightforward as it appears, as it requires re-defining

“optimal properties” for nearly every engine component: PCU, bearings, oil pump, etc. This is to say that a complete system approach is a must: you cannot design a low-friction ring pack without knowing what are the peak cylinder pressure, piston speed, oil viscosity, etc. Neither can you design an “energy saving” motor oil without knowing in which engine it’s going to be used [4].

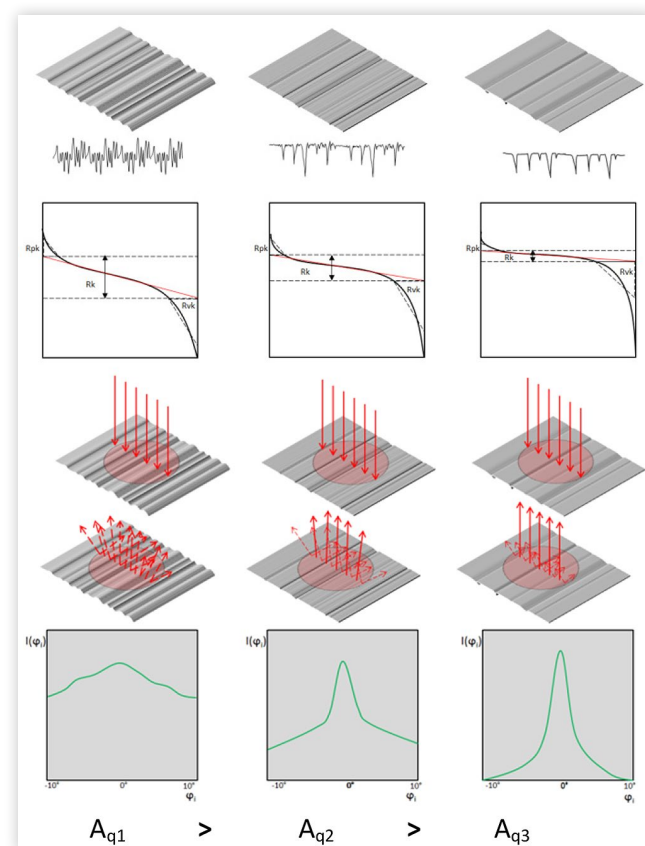
Experimental Section

Surface Analysis

Surface roughness characterization of cylinder liner bores was carried out using common ISO 4287 and ISO 25172 compliant surface metrology tools: M1 perthometer (Mahr), WYKO NT 1100 white light profilometer (Veeco Instruments), and Talyscan 150 3D scanning system (Taylor Hobson).

To characterize gradient roughness, angle-resolved scattered light (ARS) measurements were carried out using an OptoSurf system (OptoSurf GmbH). ARS is a VDA 2009 certified surface analysis method that allows the determination and surface mapping of the variance of angular distribution of scattered light (A_q -value) [8,9]. Various surface roughness

FIGURE 1 Principle of angle resolved light scattering measurements. Decrease in gradient surface roughness results in lower A_q values.



profiles produce different A_q values (from 1.6 to 100): plateaued surfaces producing lower A_q 's, while saw-like surfaces with sharp asperities producing higher A_q 's [10]

In order to look into morphological changes occurring in the topmost material layer during various surface finishing operations or the running-in process, photothermal surface analysis was used. The photothermal analysis is a non-destructive surface-sensitive method which uses a simple physical principle: a diode laser beam creates a hot spot at the surface of a sample in study. The resulting thermal expansion of the material generates an acoustic wave in the sample. The effective penetration depth depends on laser modulation frequency and material properties; the characteristic range for steel being from 10 to 2000 μm . Reflected IR radiation is then focused by a thermal lens onto an IR detector. The signal from the latter is digitally processed and the difference in amplitude and phase between modulated laser and detected radiation is determined. The phase shift and amplitude damping depend on the thermal conductivity and specific heat capacity of the sample material. Thus, any differences in the structural density of the material - including those originating from impurities, dislocations, cracks, or density fluctuations due to compression or stretching - can be detected [11].

Triboconditioning® Treatment of Cylinder Liner Bores

EURO 6 plateau-honed grey cast iron (GCI) cylinder liners for a heavy-duty diesel engine were additionally treated using the proprietary Triboconditioning® process [12].

Fuel Consumption Engine Tests

Fuel consumption engine tests were carried out using a 13L heavy duty diesel engine. Heavy duty motor oils of SAE 15W-40 API CK-4, SAE 10W-30 API FA-4 and a prototype SAE 5W-20 high performance fuel saving oil provided by BIZOL Germany GmbH were used in tests.

FIGURE 2 Principle of photothermal analysis. The difference in amplitude and phase between the modulated laser beam and the emitted infrared radiation is determined and linked to morphological changes in the topmost material layer.

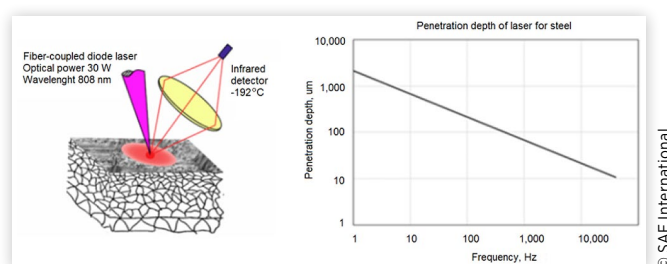
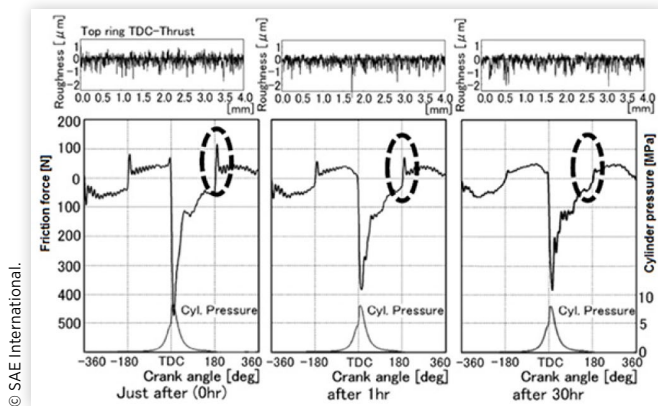


FIGURE 3 Reduction top ring friction due to the run-in [14]

Piston/Bore Tribology Simulations

AVL EXCITE™ simulation software was used to run EHD simulations of the ring pack/cylinder bore tribology for different cylinder bore roughness profiles, including “new”, “run-in”, and “post-Triboconditioning®”.

Results and Discussion

Run-In

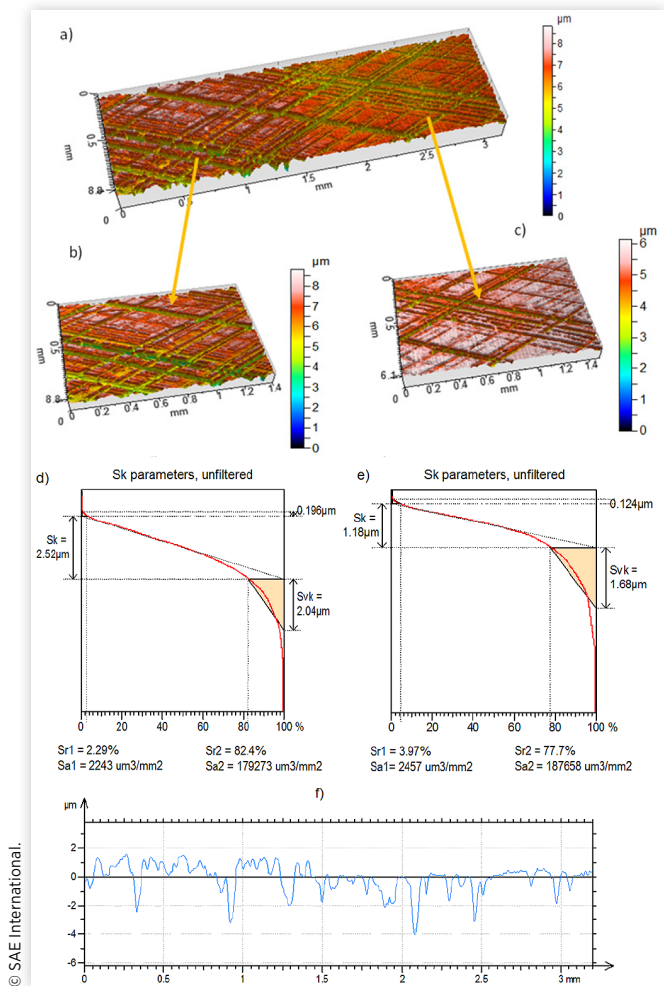
Run-in, or break-in, is an essential element of the engine tribology. During the run-in, rubbing parts achieve conformal alignment required for maintaining a stable lubricant film during the subsequent operation. In the full-film lubrication regime, wear is minimal and frictional losses are dominated by the lubricant viscosity.

Run-in modifies the surface roughness profile of load-bearing surfaces by breaking away any loose particles left after machining and wiping out sharp peaks protruding from the surface [13,14]. This results in reduced engine friction and increased power output [14].

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In the present study, we have simulated the run-in behavior of cylinder bore and piston skirt surfaces in a heavy duty diesel engine. Plateau honed GCI liners and turned pistons were used in a custom-built friction and wear tester. The test conditions (load, speed) were chosen to mimic the system tribology near the top-dead center where the most severe bore polishing would normally occur. For the piston skirt, the area most affected by piston slap was examined. Mild running-in was carried out to minimize risk of scuffing.

After the test, one can clearly see the boundary between the run-in and intact surface, see Fig. 4. Surface roughness parameters as per ISO 25172 (Talyscan 150) are also presented there. Even the visual comparison of the run-in and intact parts of the surface allows one to conclude that the run-in has caused material removal leading to smoother plateau areas. On the basis of the value of the parameter S_v (the maximum pit height) the same conclusion can also be inferred: S_v has dropped from 6.31 μm for the intact surface to 4.94 μm for

FIGURE 4 Changes in the surface roughness profile of the cylinder bore during the running-in. (a) The 3D surface profile of the liner segment in study after the running-in has been completed: the left half (b) is the intact surface, and the right half (c) is the run-in surface; (d) and (e) are the corresponding bearing area curves; and (f) is the 2D profile scan from the left to the right: 0 to 1.5 mm range being the intact surface; and 1.5 to 3.0 mm range being the run-in surface.

the run-in one. A decreasing S_v indicates material removal, while a constant S_v would indicate plastic deformation [15,16].

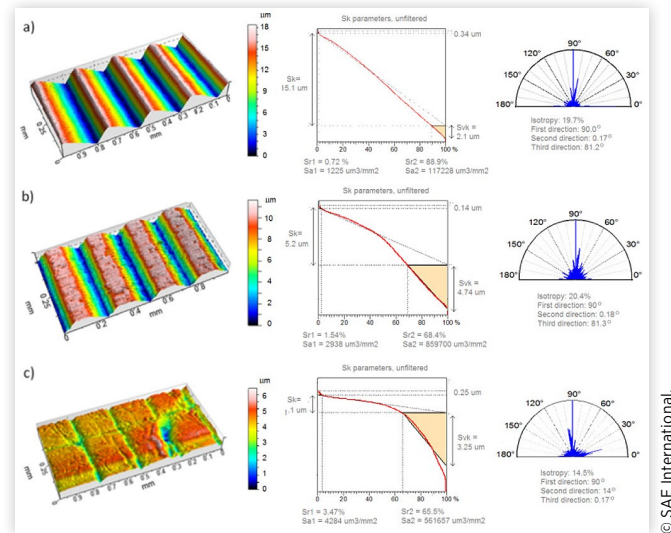
One can further notice that almost all amplitude parameters are lower for the run-in surface. For instance, the core roughness, S_k , and peaks height, S_{pk} , are reduced by nearly half. At the same time, the reduced valley depth, S_{vk} , is less affected.

Furthermore, surface skewness, S_{sk} , is getting increasingly negative during the running-in, indicative of an increasingly plateaued surface roughness profile [17, 18, 19].

Performance Enhancement Due to Triboconditioning®

The ANS Triboconditioning® process modifies the surface roughness profile the same way as the run-in process does:

FIGURE 5 Changes in the surface roughness profile of the piston skirt during the run-in. Turning direction is perpendicular to the stroke direction. (a), (b), and (c) refer to different stages of the run-in process: (a) being the original turned surface, (c) being the run-in surface.



the surface is rendered more plateau-like (negatively skewed) with a significant reduction in peak height, see Fig. 6.

The treatment results in a significant drop of the gradient roughness, as manifested in a reduced A_q value, see Fig. 7. As has been reported earlier [10,20], this type of surface modification leads to lower friction under mixed lubrication conditions. Therefore, one can expect a reduction in friction mean effective pressure (FMEP) near the reversal points, similar to that shown in Fig. 3.

Similar to the run-in process, the Triboconditioning® treatment leads to a decrease in the R_{pk} , see Table 1. Hence, the Triboconditioning® treatment can be viewed as an in-manufacture run-in process.

The major difference is that the conventional run-in process will normally take 200-300 hours to complete. The Triboconditioning® process allows in-manufacture running-in of cylinder bores in less than a minute with a superior result.

Apart from the surface roughness profile modification, Triboconditioning generates a low friction tribofilm on the cylinder bore surface and produces compressive stresses in the topmost surface layer, to a depth of ca 10 μm [10,21]. In

FIGURE 6 Changes in the surface roughness profile of the cylinder bore due to the Triboconditioning® treatment.

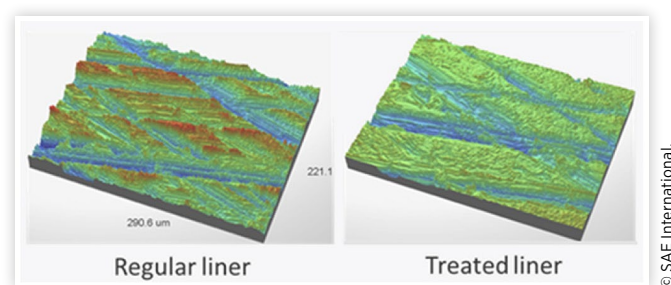
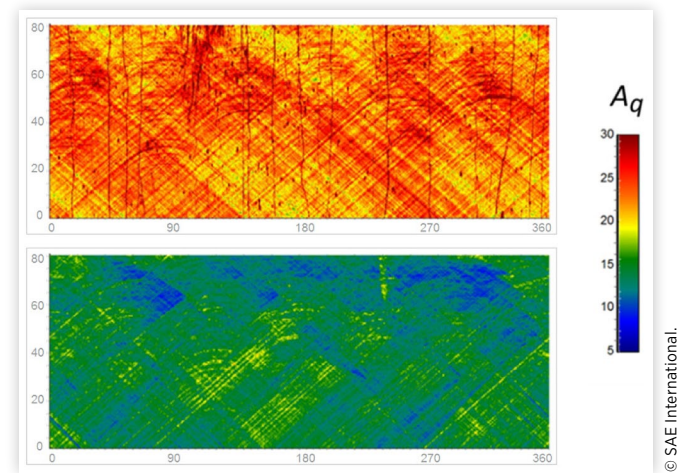


FIGURE 7 A_q value maps for the intact plateau-honed cylinder liner and the same liner after the Triboconditioning® treatment.



this regard, the Triboconditioning process is different from both the conventional run-in and the advanced honing methods, such as plateau honing and helical slide honing, that are often used in the industry. Thus, the Triboconditioning® produces morphological changes through a deeper material layer than the conventional run-in process. This is clear from phase shifts recorded during the photothermal probing of the intact honed liner surface, a run-in surface, and a surface after the Triboconditioning® treatment, see Fig. 8. To allow some quantitative associations, a steel pin with five straps treated using different process intensity was used.

AVL EXCITE simulation software was used to evaluate the effect of the Triboconditioning® treatment on the piston/bore tribology. Input parameters for 12L heavy duty diesel truck engine MAN D2866 were used: bore diameter 128 mm, stroke 155 mm, peak cylinder pressure (PCP) 190 bar. The ring pack configuration used in the simulations is depicted in Fig. 9.

Piston ring pack/bore tribology was simulated at full load at 800, 1200, 1500 and 1800 rpm. To facilitate comparison and trend analysis, all regimes were assumed to have same temperatures, combustion pressure, etc. Typical properties of SAE 15W-40, 10W-30 and 5W-20 motor oils from the AVL EXCITE database were used.

Fig. 10 summarizes FMEP data for the entire ring pack for different engine speeds and oil viscosities. Contrary to the popular belief that low viscosity oil always gives a reduction in FMEP, at low engine speed, one can see instead a small increase in FMEP for the new production liner when moving

TABLE 1 Surface roughness parameters of GCI liners in study

Roughness Parameter, μm	Cylinder Bore Surface Condition		
	Production New	Production Run-in	ANS New
R_q	0.74	0.64	0.49
R_a	0.47	0.43	0.38
R_{pk}	0.25	0.19	0.11
R_k	0.66	0.62	0.76
R_{vk}	1.87	1.77	0.90

FIGURE 8 Photothermal phase shift data for the new liner, run-in liner and a liner after the Triboconditioning® treatment. A steel pin with five surface straps corresponding to different intensities of the Triboconditioning® treatment was used as a reference.

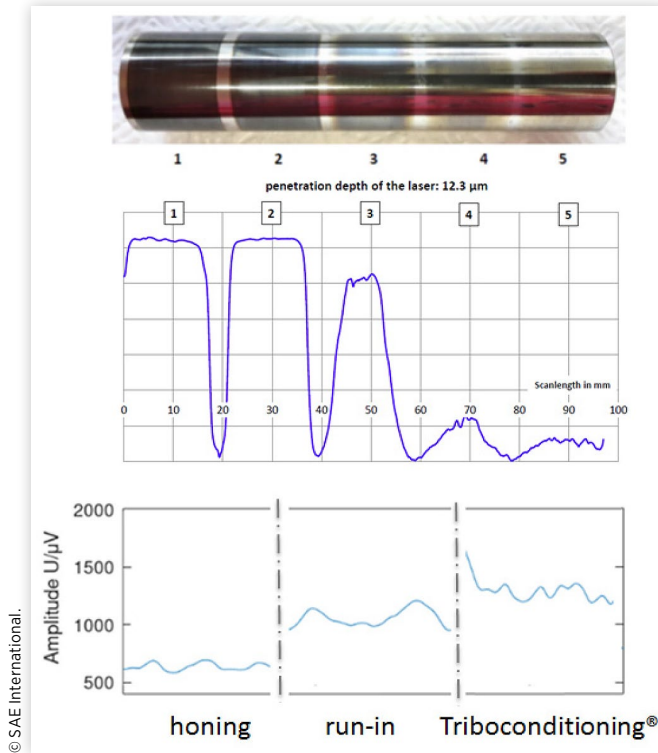
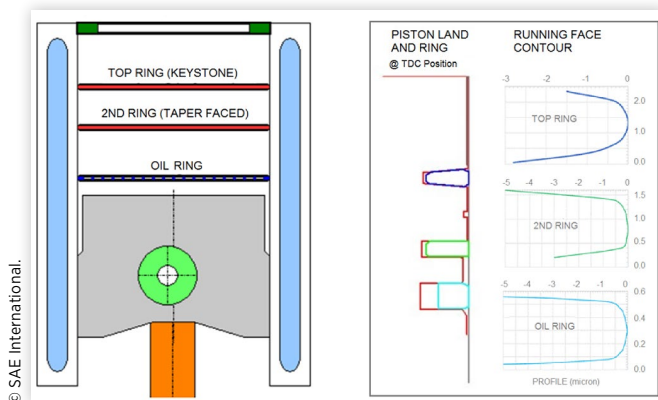


FIGURE 9 Ring pack parameters used in the AVL EXCITE simulations.



from the SAE 15W-40 to SAE 5W-20 viscosity grade. This observation goes in line with what has been previously reported for passenger car engines [22, 23, 24, 25]. A plausible explanation of this behavior is that low viscosity oil fails to build a sufficiently thick film to effectively separate sliding surfaces, and the resulting increase in asperity friction overweighs the decrease in hydrodynamic friction (cf. Fig. 11, 12). The complete engine may still demonstrate some decrease in FMEP due to contributions from bearings and other components, but this is achieved at a price of higher wear.

FIGURE 10 Ring pack friction mean effective pressure (FMEP) for different cylinder bore finishes and oil viscosity grades.

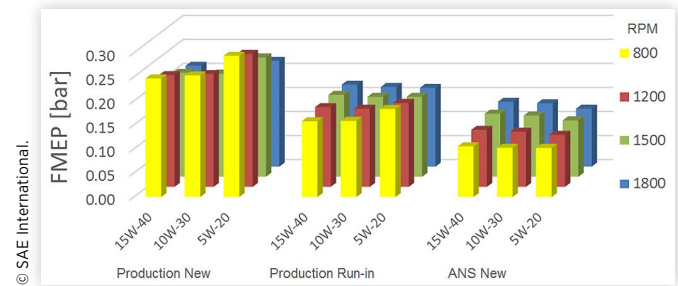


FIGURE 11 Asperity friction contribution to the ring pack FMEP for different cylinder bore finishes and oil viscosity grades.

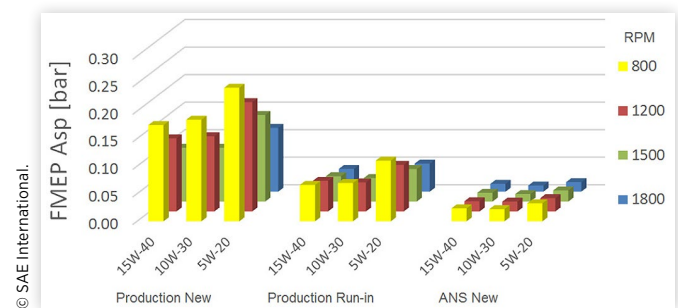
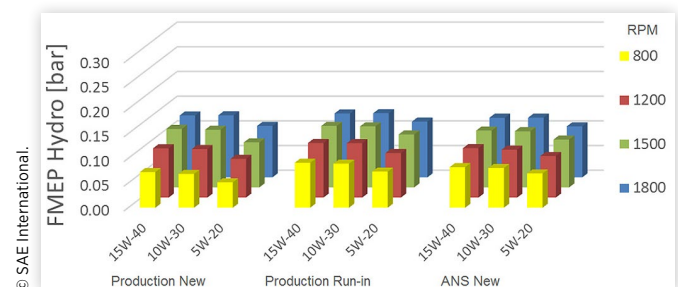
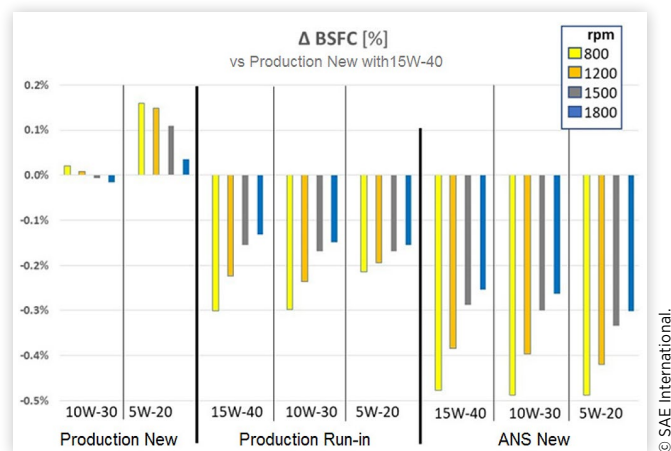


FIGURE 12 Hydrodynamic contribution to the ring pack FMEP for different cylinder bore finishes and oil viscosity grades.



Both the run-in and Triboconditioning® processes wipe out the surface peaks, and hence the asperity friction goes down. So does the ring pack FMEP. The fact that FMEP increases with engine speed indicates full film lubrication. It is interesting that, for 5W-20 oil, the hydrodynamic friction for new liner is lower than for the run-in and post-Triboconditioning® variants. This observation highlights the importance of a system approach to the piston/bore tribology optimization: smooth surface finishes may shine in simple reciprocating rig tests prioritizing the mixed lubrication conditions but drawing any far-fetching conclusions from such an experiment would be a mistake. For instance, older honing processes have been optimized for lubrication with 15W-40 viscosity grade. One common issue on switching to lower viscosities is the liner scuffing. Hence, in order to safely switch to a lower viscosity grades, a different surface texture having specific functional properties (smoother plateaus, deeper valleys) is

FIGURE 13 Changes in the BSFC compared to the classical “new liner/15W-40 HDEO” combination.



required. No single surface configuration can be universally good for every use.

To get an idea about the fuel economy effect compared to “the new liner/15W-40 HDEO” combination, Δ FMEP/IMEP ratios can be used [2], the latter being proportional the brake specific fuel consumption (BSFC), Fig. 13. This shows that, by blindly switching from 15W-40 to 5W-20 while keeping the “classical” honing structure, one will not improve but rather degrade the fuel economy before the run-in is complete. At the same time, post-Triboconditioning® liner performs well from the beginning.

The obtained results conform to the experimental data regarding the effect of oil viscosity on fuel economy for Volvo D12D engine [26,27], see Fig. 14. From these, one can derive how different bore finishes will fire in a given driving cycle. Thus, Fig. 15 compares fuel efficiencies of the standard plateau-honed liner and a liner treated using the Triboconditioning® process. While the fuel economy benefits may appear rather unimpressive, the effect on ring wear is significant, see Fig. 16.

FIGURE 14 Effect of oil viscosity grade on fuel economy [26].

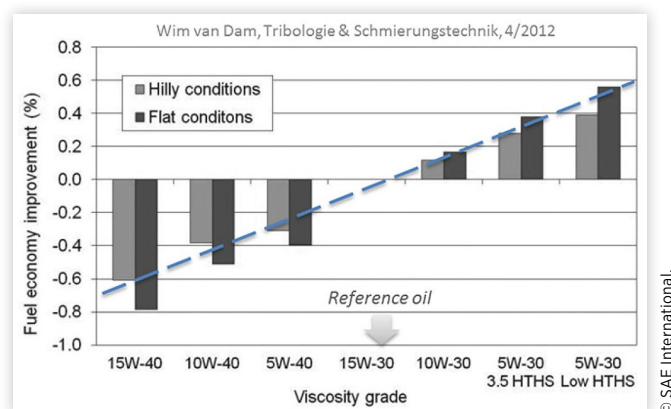


FIGURE 15 Fuel economy improvement achieved by changing from a legacy SAE 15W-40 HDEO to a novel SAE 5W-20 HDEO under different speed/load conditions under the European Stationary Cycle (ESC).

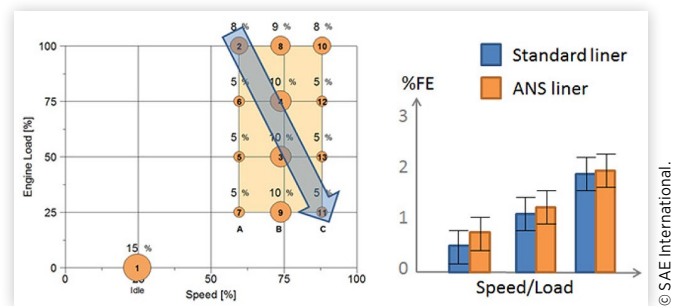
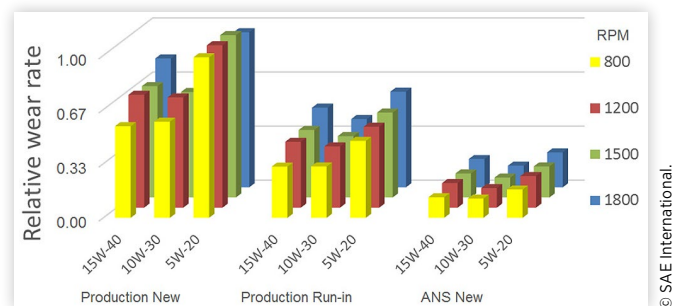


FIGURE 16 Relative comparison of the mean ring pack wear rate (arbitrary units). Maximum wear rate for the new production liner with SAE 5W-20 motor oil is used as reference.



Conclusions

A complete system approach is a must when optimization of the “piston/bore” tribology is concerned. The characteristics of the piston ring pack, cylinder bore surface finish and engine oil are all important for the performance. A move toward lower viscosity engine oil requires a revision of the bore finish, and eventually, ring pack properties. Triboconditioning® technology for cylinder bores enables smooth migration to lower viscosity oil for maxing up fuel efficiency without compromising longevity.

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Contact Information

Boris Zhmud, Ph.D., Assoc. Prof.

Phone: +46 70 9371310

boris.zhmud@appliednanosurfaces.com

Definitions, Acronyms, Abbreviations

ARS - Angle resolved scattered light

API - American Petroleum Institute

AVL - AVL List GmbH, the world's largest independent company for the development, simulation and testing of powertrain systems

BSFC - Brake Specific Fuel Consumption

CR - Compression Ring

FE - Fuel Economy

FMEP - Frictional Mean Effective Pressure

EHD - Elasto-Hydro-Dynamic

ESC - European Stationary Cycle

GCI - Grey Cast Iron

GHG - Greenhouse Gas

HDEO - Heavy Duty Engine Oil

HTHS - High Temperature High Shear

IR - Infra Red

OCR - Oil Control Ring

OEM - Original Equipment Manufacturer

PCP - Peak Cylinder Pressure

PCU - Power Cylinder Unit

RPM - Revolutions per Minute

SAE - Society of Automotive Engineers

VDI - The Association of German Engineers (Verein Deutscher Ingenieure)