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Use of Advanced Piston Ring Coatings on Agricultural Engines

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Abstract: The use of combustion engines on agricultural vehicles will persist much longer than on-road vehicles. Introducing new technologies in agricultural engines is crucial to mitigating emissions while accounting for customer cost-sensitivity, harsh operation conditions, and typically sub-optimal maintenance. This work describes the use of CrN and tetrahedral amorphous carbon (ta-C) DLC-coated rings in small agricultural diesel engines. Compared with the gas nitride rings, the CrN and the ta-C DLC coatings exhibited, respectively, 74% and 86% lower wear in rig tests. The DLC also presented a very low coefficient of friction and high resistance to scuffing. A similar wear trend was observed on durability engine tests, where the CrN top ring showed an 80% lower wear rate than the GNS used in a similar engine. Wear on the DLC oil ring was below the measurement capability. Liner radial wear was measured on the piston ring reversal points in four angular positions, and except for one position, was lower than 3 µm. At the end of the test, engine performance and emissions are nearly identical to those at the test's start, demonstrating that the use of advanced tribological solutions can significantly contribute to emissions mitigation in agricultural engines.

Keywords: DLC; PVD; friction; tribology; emissions

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1. Introduction

The agricultural sector accounts for a substantial amount of diesel consumption, and hence CO_2 emissions, reaching 118 Mtoe diesel in 2022 [1]. This figure is expected to rise, particularly in emerging and large-population countries [2]. China, as the world's largest emitter of CO_2, sees increasing emissions from its agricultural sector [3,4]. According to the China Mobile Source Environmental Management Annual Report 2021 [5] apud [6], non-road vehicles emitted 425,000 tons of hydrocarbon (HC), 4,782,000 tons of nitrogen oxides (NOx), and 237,000 tons of particle matter (PM) in 2020, accounting for 48%, 35%, and 39% of the total emissions, respectively.

Tractors are among the most fuel-consuming and polluting machines in agriculture [7]. They are used in various agricultural operations: plowing, soil tillage, pushing harvesting equipment, and others. Internal combustion engines will likely remain in use for a long time: however, maintenance and operation are often suboptimal, especially on small farms, where the engines are exposed to dust, fibers, etc. Robustness and low operation costs are essential for market acceptance and user satisfaction. While new engine technologies can reduce fuel consumption and emissions, they must be cost-effective. The introduction of new, improved, and efficient machinery can mitigate the environmental impact of

agricultural mechanization, particularly in developing countries [8,9]. In some cases, the purchase of modern machinery increases fuel consumption more than the increase in productivity [10] showing that reducing fuel consumption is necessary. On the other hand, studies show that CO_2 can be mitigated with the introduction of new technologies and that increasing energy efficiency is a more effective means to reduce CO_2 emissions than changes in the fuel mix [11].

Until recently, CrN applied by PVD (Physical Vapor Deposition) and DLC (Diamond-Like Carbon) low-friction rings were applied only to more advanced, larger HDD engines. More rigorous emission regulations for non-road vehicles, the increasing use of alternative fuels, and market competitiveness are promoting the use of more advanced technologies on agricultural engines [12].

Friction losses account for one-third of automotive fuel consumption [13–15]. Reducing these losses can enhance energy efficiency. The piston rings and piston account for around 50% of the engine friction losses [13,16,17] and, being a reciprocating system with variable loads and temperatures, they experience both boundary/mixed and hydrodynamic lubrication regimes [17–19]. The main research paths on vehicle powertrain to friction reduction include [20]:

- Use of materials/coatings with a low friction coefficient.
- Surface finish and/or texturing, especially via optimization using computer models and detailed topographic characterizations.
- Use of low-viscosity oils and improved friction modifier additives.

The increased operational demands on piston rings caused by biofuel use [21], along with low-viscosity oils, increase the need for better tribological solutions such as coatings and improved surface finishes. On diesel engines, it is still common to use Chromium coatings. For agricultural diesel and two-stroke gasoline engines, it is also common to use gas-nitrided rings (GNS) in combination with chromed-coated liners. More modern HDD piston rings have CrN- or DLC-coated rings [22–25].

There are several variants of DLCs, and their tribological performances depend on their structure, surface finish, and lubricant additives [26–28]. For piston ring coatings, variants range from relatively soft hydrogenated DLCs, used for break-in [23,29], to very hard ta-C (tetrahedral amorphous Carbon) [24,25]. Recent optimizations for DLC coating processes have allowed the mass production of ta-C coatings thicker than 20 µm [30–32]. Some studies indicate that H-free coated rings against cast iron cylinder iron may benefit from biofuels [28]. Figures 1 and 2 show the relative wear and friction of ring coatings in a reciprocating test.

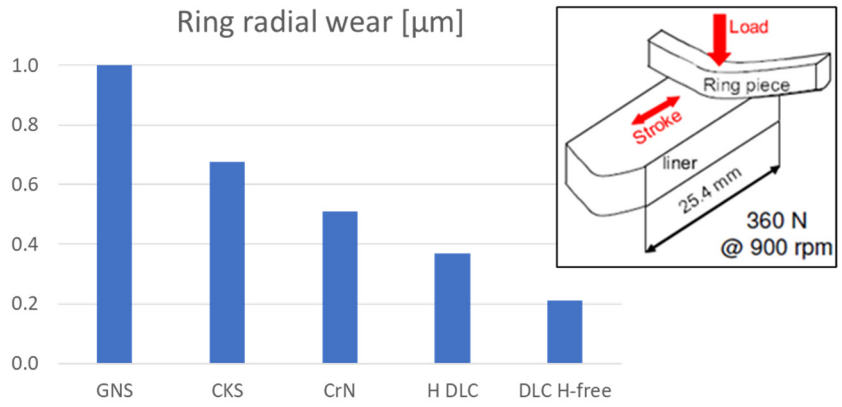


Figure 1. Relative ring coating wear. Adapted from [23,25,33].

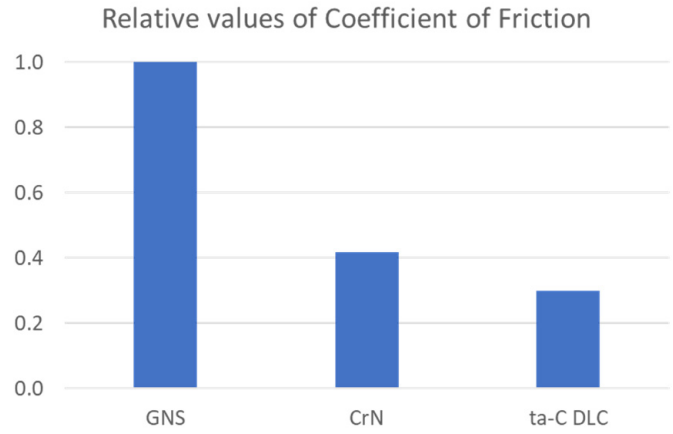


Figure 2. Relative coefficient of friction. Reciprocating tests, 450 N, 30 mm stroke, Ester oil, 190 °C. Adapted from [22].

The piston rings operate in a complex, transient tribological environment. Due to different transient gas pressures and temperatures, the rings face boundaries to hydrodynamic lubricant regimes. The top ring, closer to the combustion chamber, usually presents the highest wear rate. The use of lower-viscosity oils, one of the main paths to increase engine mechanical efficiency [17,18,20,34–39], tends to cause more boundary contact [18,36,37] and increase ring wear. Figure 3 shows the wear rate after 500 h tests. The use of a lower-viscosity oil (10W-30) caused a significant increase in wear; for example, 62% for the top ring. The use of ta-C DLC on the 10W-30 test returned the wear rate to a lower value.

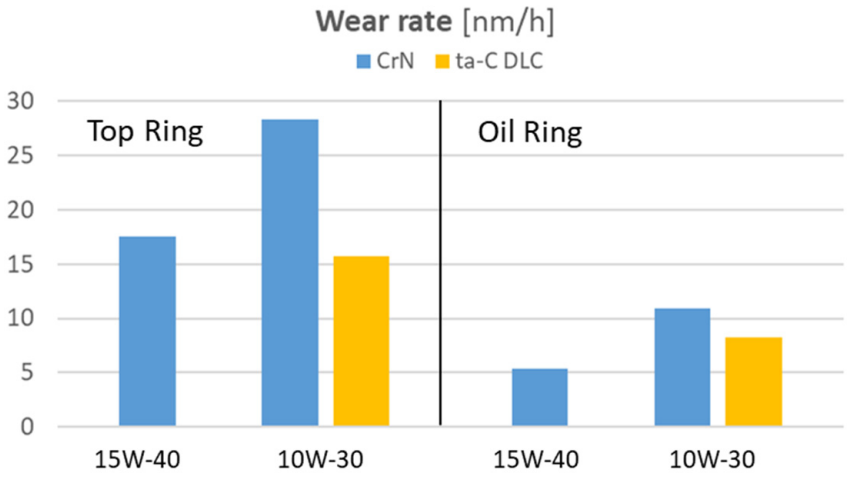


Figure 3. Ring wear rates after a 500 h test in HDD tests with two oil viscosities. Adapted from [36].

From the cylinder-liner perspective, improving the honing surface finish is the primary method for reducing friction and wear [20,39–45]. Cylinder honing is typically characterized by the Abbot curve, which defines the reduced peak height (Rpk), core height (Rk), and valley depth (Rvk). Figure 4 shows the typical values of the three most common cylinder honing approaches: standard (almost obsolete nowadays), plateau, and side honing. Slide honing, also called "glide honing", has lower peaks (Spk + Sk/2) to reduce boundary contact but also has shallower valleys to reduce oil consumption. Figure 5 shows the oil film thickness along the four strokes of an HDD at part load and the resultant contact area and oil volume for plateau and slide honing. The smoother slide honing has a much lower contact area, especially at the TDC (top dead center). The shallow valleys of slide honing also contain less oil, helping to reduce oil consumption and emissions.

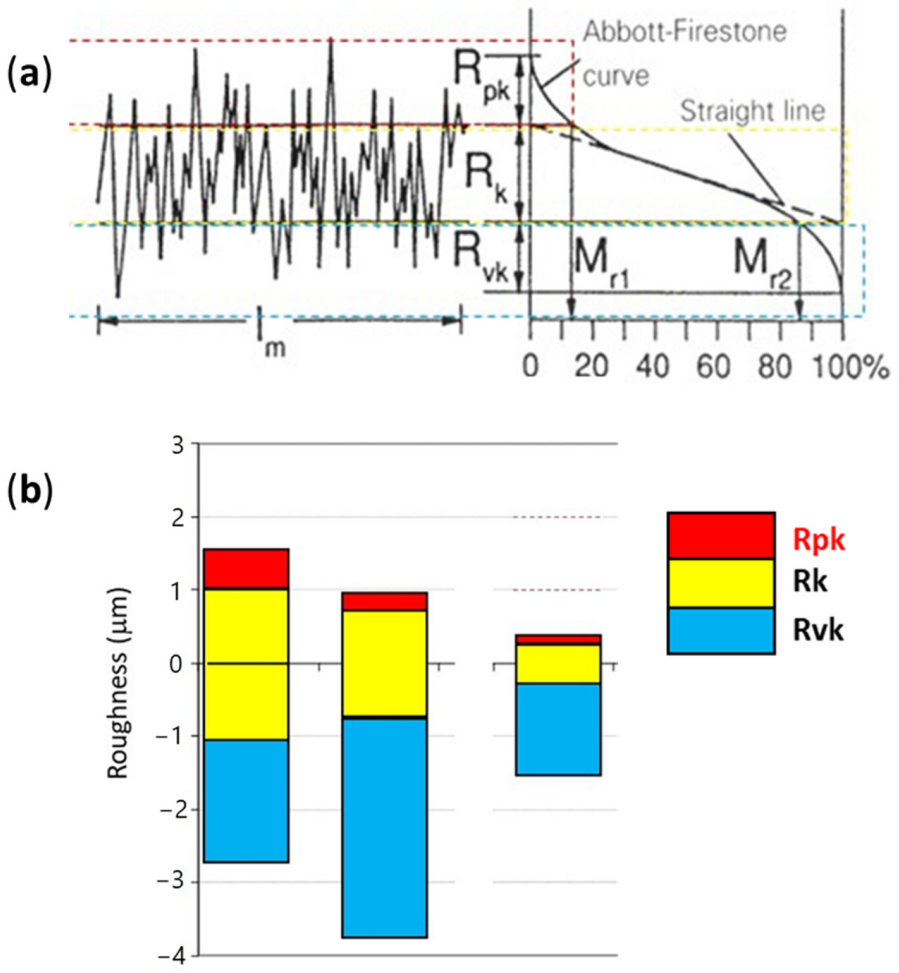


Figure 4. Scheme of the Abbott curve and the Rk roughness parameters. (**a**) Plateau and Slide honing topographies and their respective; (**b**) Typical honing values of cylinder liners.

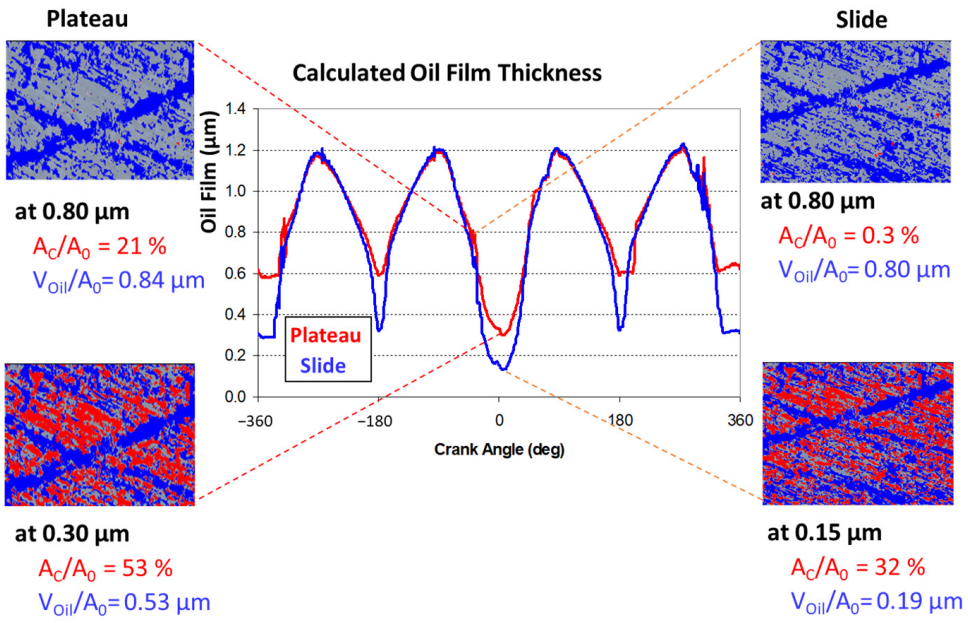


Figure 5. Calculated oil film thickness and area of contact, as well as oil volume along the engine's four strokes. Reproduced with permission from [46].

Soderfjall (2017) [40] studied the effects of different honing techniques, DLC-coated rings, and low-tangential-load OCRs on engine friction. Smoother plateau surface cylinder liner surfaces presented lower friction compared to the standard honed surface. The use of DLC-coated rings and TLOCR with a low tangential load (one of the combinations) showed an almost 50% OCR friction reduction while still indicating a small difference in oil supplied to the top compression rings. Tas [28] investigated the use of DLC rings against mirror-like cylinders and concluded that the low wear and high scuffing resistance were improved by the formation of tribofilms in the cast iron. Ferreira [47] and Liu [48] showed the importance of a good surface finish on DLC rings to reduce wear. However, despite the advances in material and coating characterization, as well as in wear simulation and durability prediction [17,19,34,35,49–56], actual engine tests are still needed to validate new technologies.

In this work, the use of the more advanced CrN and ta-C DLC ring coatings is investigated through tribological rig tests and engine durability tests on a small agricultural diesel engine. The ring and liner wear are compared with a previous engine version using GNS rings and chromed-coated liners. Some additional potential improvements, allowed by the very low wear, are discussed to reduce friction and fuel consumption.

2. Materials and Methods

2.1. Rig Tribological Tests

Friction, wear, and scuffing tests were performed in an in-house-built reciprocating test using piston ring specimens (Figure 6). CoF was defined as the cycle average. For scuffing, the liner was lubricated with a few oil drops, and the test duration was a minimum of 3 h or when CoF reached 0.3. Time to scuffing was defined as the minimum of three replications.

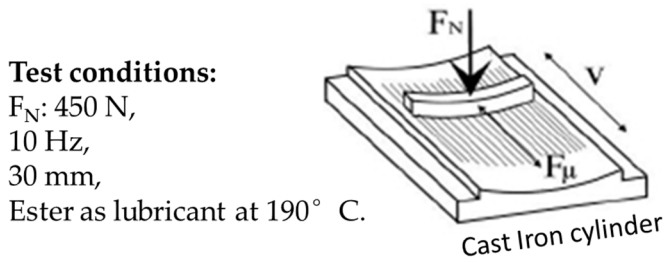


Figure 6. Scheme of the reciprocating rig test.

2.2. Engine Tests

Two agricultural diesel engines were used. Table 1 gives the main engine characteristics. Notice that the new engine, where the advanced piston ring coatings were tested, has 21% higher specific power. Both engines are marketed to small tractors and harvest machinery like the one shown in Figure 7. Similar small-power diesel engines are used in developing countries for irrigation, pumping, and other agricultural activities.

Table 1. Main engine characteristics.

	Production	**New**
Displacement volume [L]	3.5	3.6
Bore × stroke [mm]	98 × 115	98 × 120
Max. Power [kW]	95 @ 2600 rpm	118 @ 2400 rpm
Specific Power [kW/l]	27.1	32.8
Max. Torque [Nm]	450 @ 2000 rpm	550 @ 1700–1800 rpm
Cylinder	Chrome Coated	Cast Iron
Lubricant	20W-50	20W-50



Figure 7. Small agricultural tractors similar to the ones that will use the engine.

The main characteristics of the piston rings are described in Tables 2 and 3.

Table 2. Piston rings—engine in production.

	Top	**2nd**	**OCR**
Coating	Nitrided	Phosphate	Nitrided
material	Steel	Cast Iron	Nodular Cast Iron
Axial width [mm]	2.5	2.0	3.0
Radial [mm]	3.80	3.6	3.5
type	Keystone	taper-faced	2-piece
Tangential Force [N]	19.6	14.5	30.0

Table 3. Piston rings—engine under development.

	Top	**2nd**	**OCR**
Coating	CrN	Phosphate	ta-C, DLC
material	GNS	Cast iron	Nodular Cast Iron
Axial width [mm]	2	2	3
Radial [mm]	3.55	4.0	2.54
type	Keystone	taper-faced	2-piece, "LKZ" profile
Tangential Force [N]	15.1	15.9	41.8

Figures 8–11 and Table 4 show more details about the investigated ring coatings. The more wear-resistant CrN and DLC coatings were applied only to the running face over a nitriding face. The nitriding layer worked to protect the ring side faces and, in less demanding cases, acted as the wear-resistant surface treatment in the running face, as the engine in production used as a reference. An adhesion layer, usually chrome and around 1 µm thick, was used to promote good adhesion between the CrN and DLC coatings with the base material. Both the CrN and the ta-C DLC were deposited by Physical Vapor Deposition (PVD), also known as Ion Plating (IP). Process details are out of the scope of this paper, but for ta-C DLC, a filtered cathodic vacuum arc (FCVA) was used to ensure a good coating quality and a reduced number of pores and droplets. Details about FCVA can be found in [57,58].

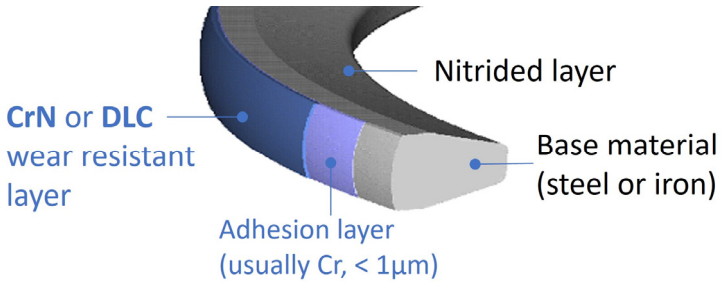


Figure 8. Ring cross-section scheme.

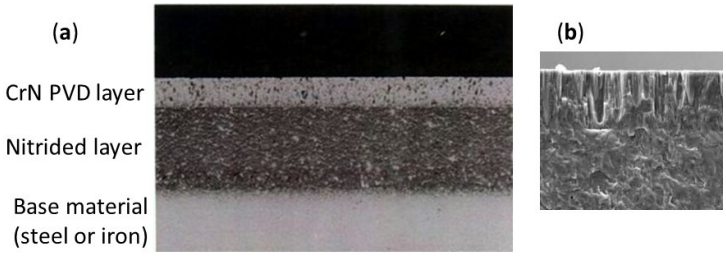


Figure 9. (**a**) PVD CrN ring cross-section. (**b**) SEM photo.

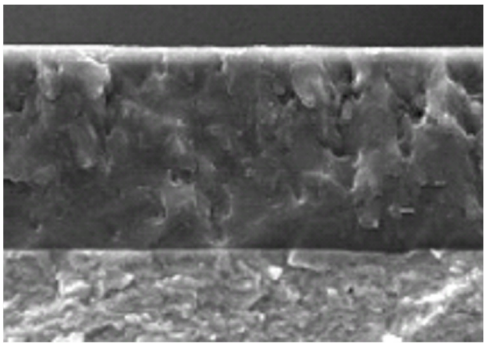


Figure 10. ta-C DLC coating, cross-section.

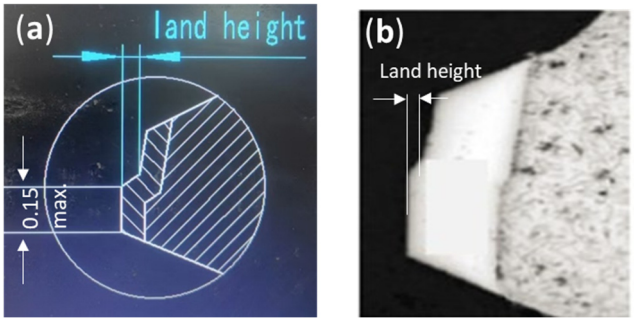


Figure 11. Oil control ring: (**a**) "LKZ®" profile; (**b**) cross-section showing the DLC coating.

Table 4. Piston ring coatings—main characteristics (as finished).

	GNS	CrN	ta-C
Deposition method	Gas Nitriding	PVD—Cathodic Arc	FCVA
Hardness [Hv]	900 min. at 10 µm	1100 min.	1700–3500
Thickness [µm], min.	100	100	20
Roughness [µm], max.	Rz 3.0	Rz 1.6	Rpk 0.2, Rk 0.6

Table 5 describes the cylinder liner's main roughness parameters. Figure 12 shows the topography measured by the Taylor-Hobson CCI-MP optical profilometer, and measure-

ments were carried out using a 20X lens. Roughness parameters were calculated by the equipment software, TalyMap Gold 6.2.6613.

Table 5. Cylinder liner material and roughness.

	Chromed	Cast Iron
Hardness, Hv	800 min.	400
Sa [µm]	0.28	0.62
Spk [µm]	0.21	0.19
Sk [µm]	0.66	0.28
Svk [µm]	0.77	2.62
Mr1 [%]	5.4	7.4
Mr2 [%]	81.3	72.6

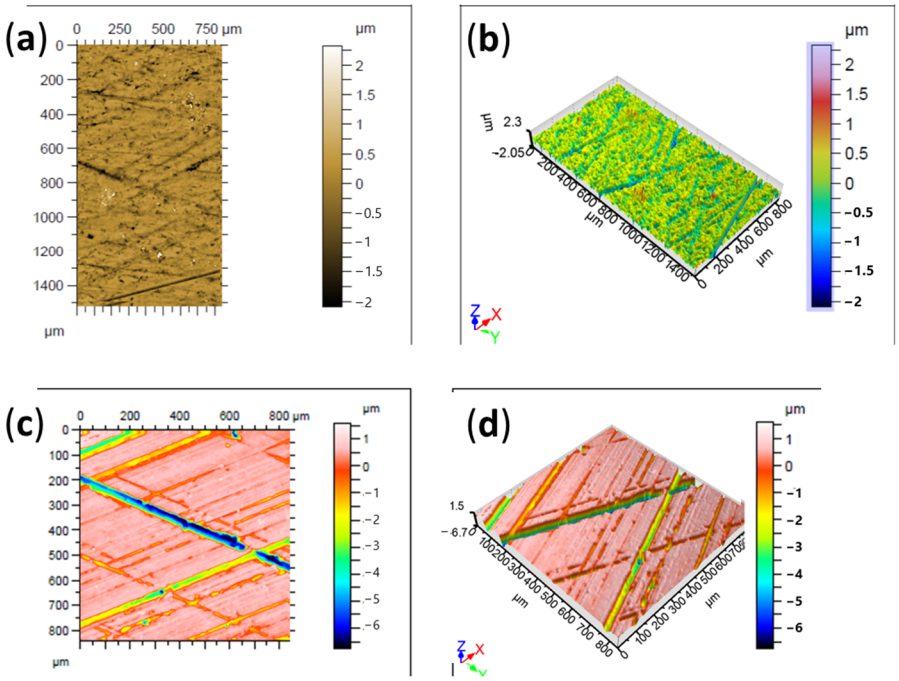


Figure 12. Topography of cylinder liner (**a**,**b**): production engine, chrome-coated. (**c**,**d**) Under-development engine, cast iron.

To simulate field operation conditions, the dynamometer test was conducted as follows:

(a) 0 to 300 h: full power.
(b) 300 to 800 h: full power.
(c) 800 to 1100 h: thermal shock, alternating every 6 min at full power with 95 °C cooling water and 4 min at idle with 30 °C cooling water.

The prototype fuel injector caused excessive piston carbon buildup. An improved fuel injector and new pistons, cylinder liners, and piston rings were assembled. Lubricant oil was changed every 300 h.

3. Results

3.1. Rig Tribological Tests

Figure 13 compares the friction and wear of the different ring coatings versus the cast-iron liner. The GNS ring has the same nitriding treatment but no CrN PVD overcoating (see Figure 8).

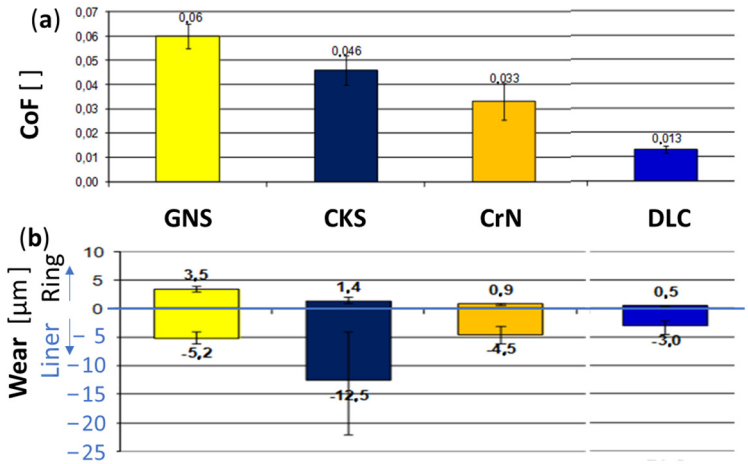


Figure 13. Tribological test results of ring coatings. (**a**) Friction. (**b**) Wear. GNS: gas-nitrided steel, CKS: chrome ceramic.

Figure 14 shows the scuffing resistance of chrome, CrN, and ta-DLC coatings with oils equivalent to SAE 40 (HTHS (high-temperature high-shear): 3.5 mPa.s) and SAE 30 (HTHS 2.9 mPa.s). Under the test conditions, the use of lower-viscosity oils decreased the scuffing resistance for both chrome and CrN coatings, while the DLC concluded the 250 min tests without scuffing. Similar trends were reported by [25].

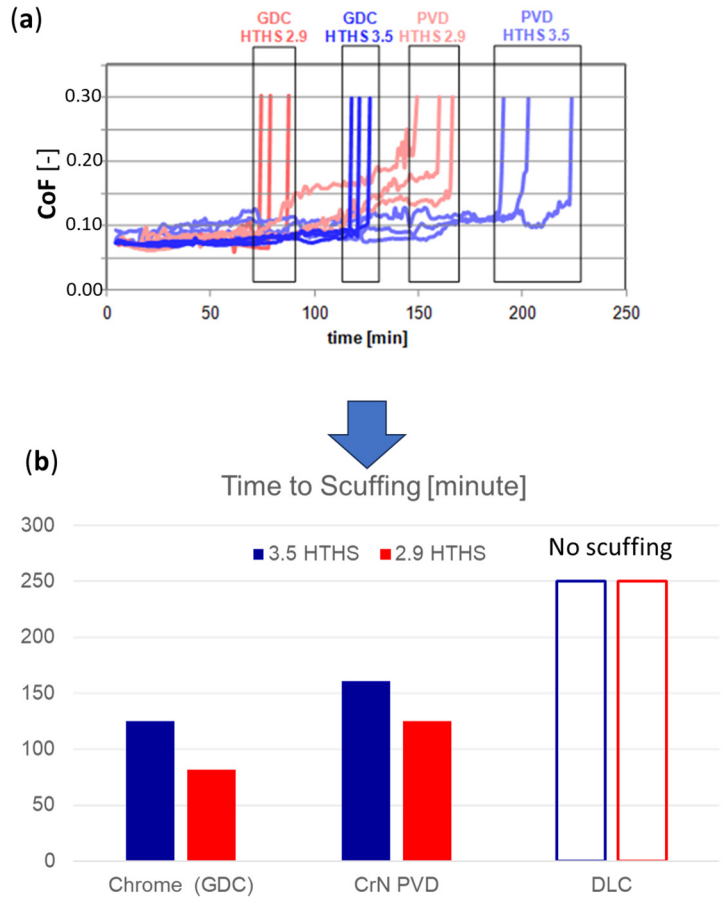


Figure 14. Time to scuffing in the rig test with oils of different viscosities. (**a**) CoF along the test. (**b**) Time to scuffing.

3.2. Engine Performance

Engine performance remained almost constant throughout the test (see Figures 15–17). Before the thermal shock, the engine had its calibration fine-tuned and underwent minor maintenance. The two values at 800 h show the values before and after the minor maintenance. Only maximum blow-by showed some increase along the abused thermal shock.

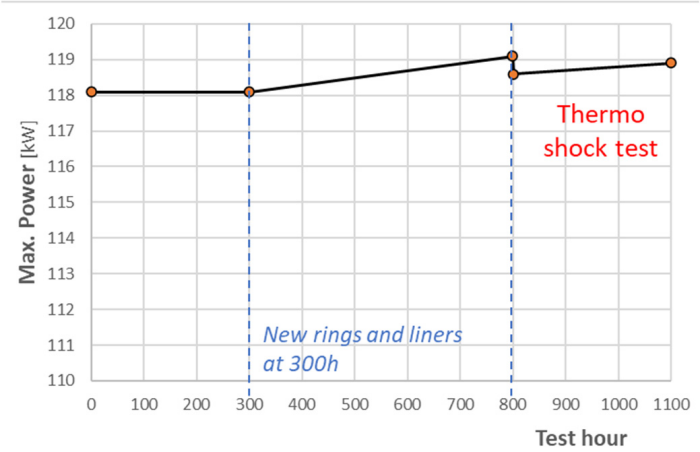


Figure 15. Maximum power during the test.

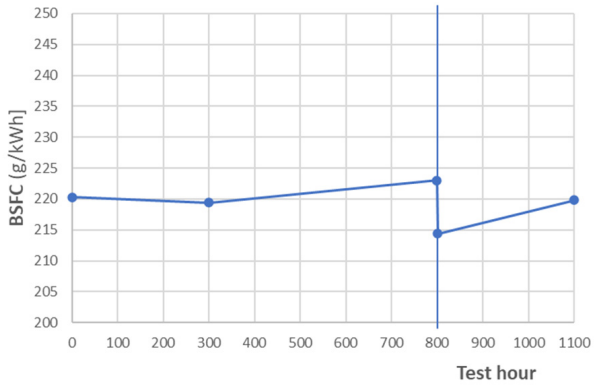


Figure 16. Brake-specific fuel consumption at full load during the test.

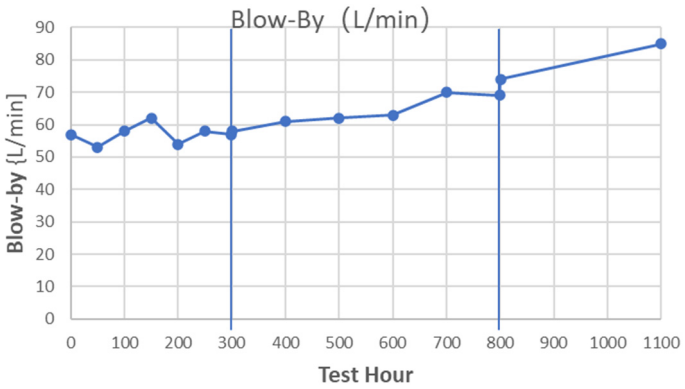


Figure 17. Maximum blow-by during the test.

Due to very low wear and engine degradation, emissions at the test end were similar to those at the test start (see Figures 18 and 19).

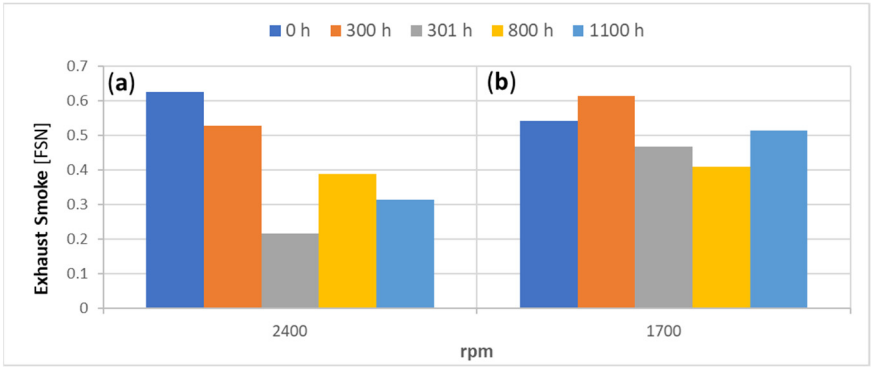


Figure 18. Exhaust smoke during the test: (**a**) at 2400 rpm, maximum power; (**b**) at 1700 rpm, maximum torque.

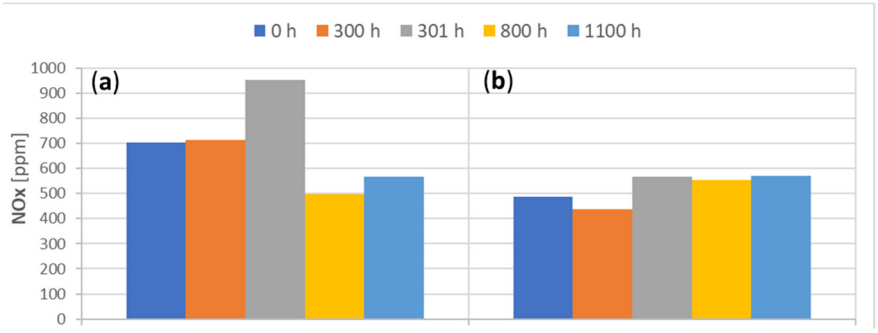


Figure 19. NOx during the test: (**a**) at 2400 rpm, maximum power; (**b**) at 1700 rpm, maximum torque.

3.3. Ring Wear

Ring radial wear was measured by superimposing the face profile before and after the test. On the GNS top ring, tested for 1000 h, the wear at ring tips was 6.5 µm. On the CrN, with an accumulated 800 h, wear was less than 2 µm (see Figure 20).

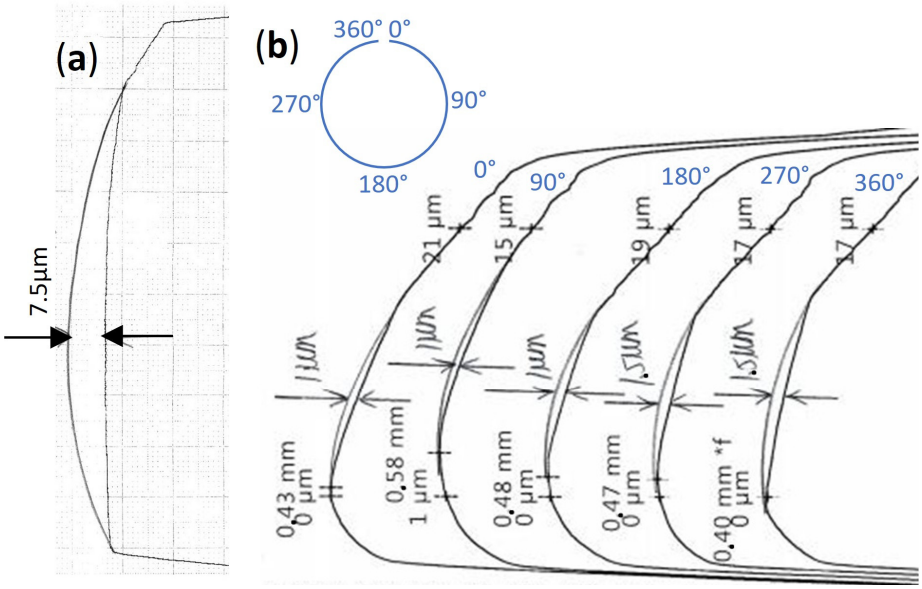


Figure 20. Top ring, running face profile after tests. (**a**) GNS ring tested in the production engine (**b**) CrN ring tested in the development engine.

The second ring, not directly exposed to the combustion pressure and temperature, is the lowest tribologically loaded. Being only phosphate-coated, the second ring presented

larger radial wear, between 8 and 10 µm (see Figure 21). Figure 22 shows the wear rate of the different rings. The wear rate of the second ring was very similar in both engines.

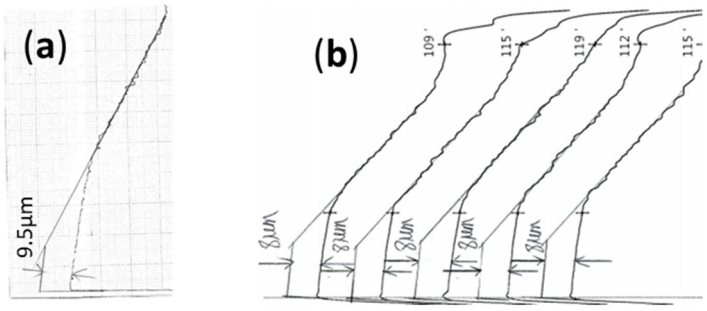


Figure 21. Second ring, only phosphate-coated, running face profile after test. (**a**) production engine (**b**) development engine.

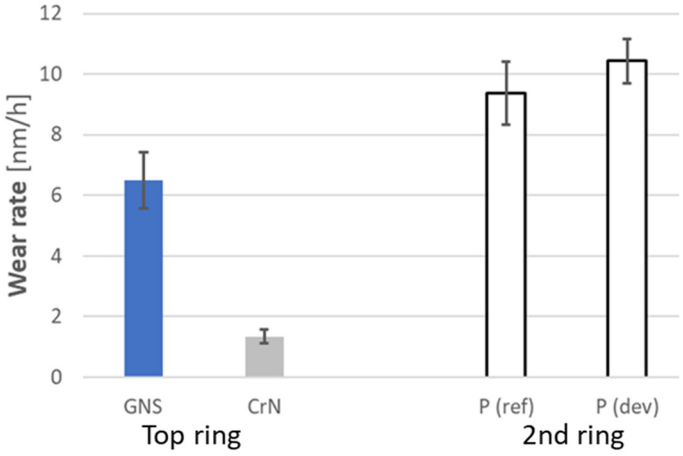


Figure 22. Ring radial wear rate.

Due to the almost flat running profile, the direct measurement of wear on the oil control rings was not possible. The DLC oil control rings were measured in five angular positions in the upper and lower lands (see Figure 23). Very low wear was evidenced by the fact that the minimum land height in all measured positions was 24 µm. The land height has dimensions similar to the DLC thickness (see Figure 11).

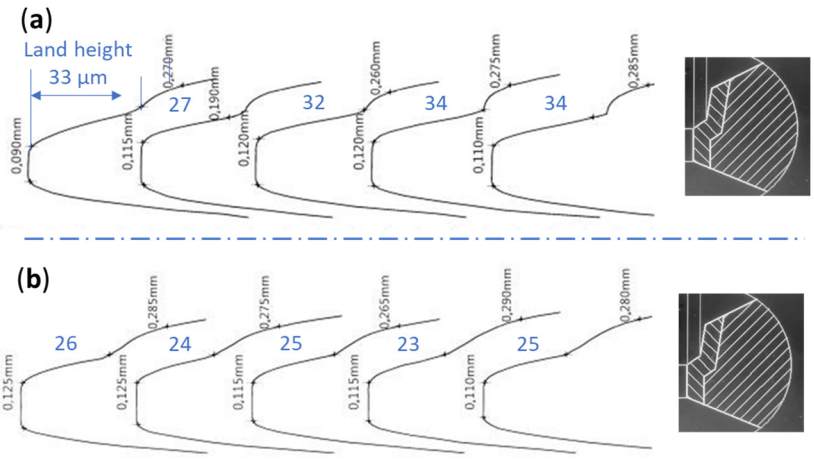


Figure 23. Oil Control, running face profile after test: (**a**) upper land; (**b**) lower land.

3.4. Cylinder Liner Wear

As shown in Figure 13, PVD and DLC ring coatings are highly wear-resistant and cause lower wear on the cylinder liner. While the engine production uses chrome-coated liners, the one in development uses uncoated liners. The use of smoother slide honing also contributes to low liner wear. Unfortunately, during the development of the new engine, liners of the 1000 h test in the production engine were not found to be measured. For the development engine, as mentioned for the rings, measurements were made at the end of the test, with rings and liners having accumulated 800 test hours. Liner honing was well preserved with no significant polishing or wear scratches. Honing grooves are visible even at the TDC (see Figure 24).



Figure 24. Typical visual appearance of the cast-iron liner after 800 h test, TDC, TS. Honing marks still visible. Honing marks were still visible even at TDC.

Liner radial wear was measured on the piston ring reversal points top dead center (TDC) and bottom dead center (BDC) in four angular positions (front, thrust side, back, and anti-thrust side) by a profilometer, see example in Figure 25 and except for one position, all values were below 4 µm (see Figures 26 and 27).

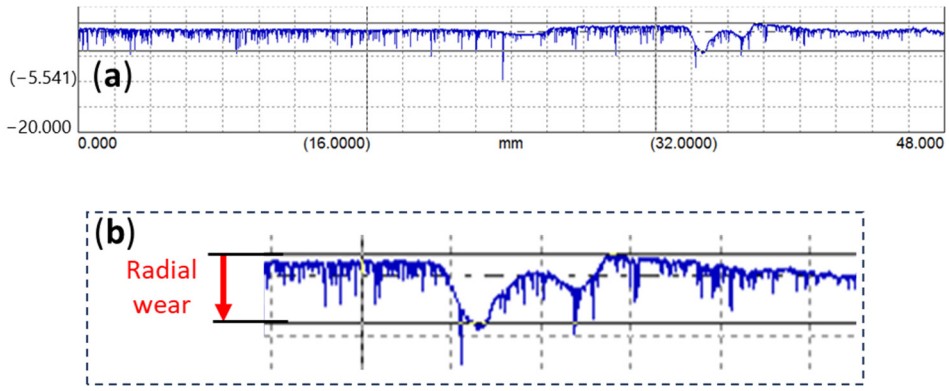


Figure 25. Example of liner measurement: (**a**) 48 mm measurement length; (**b**) details of the maximum found wear.

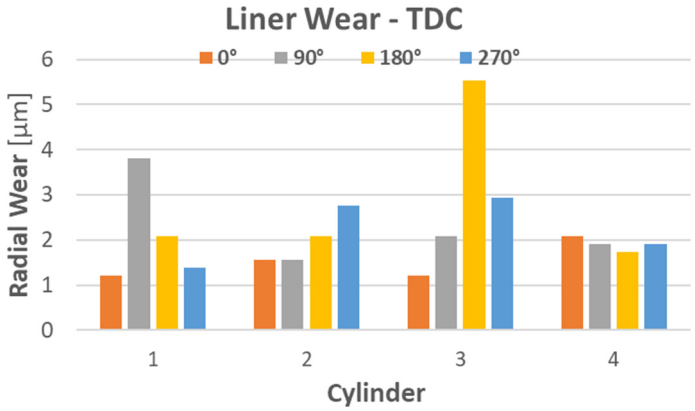


Figure 26. Liner wear at top dead center (TDC).

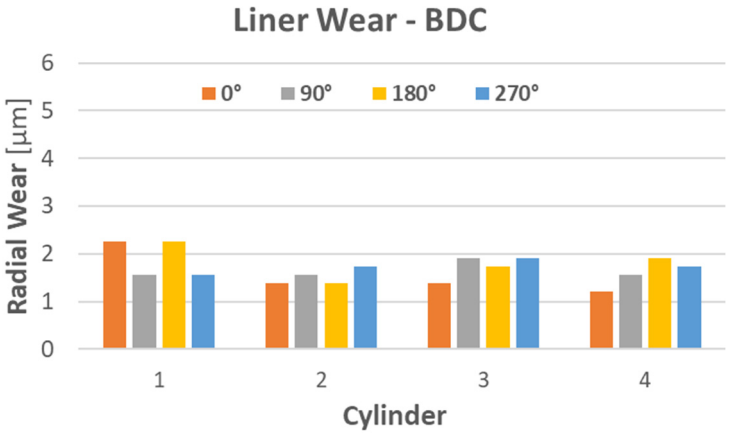


Figure 27. Liner wear at bottom dead center (BDC).

4. Discussion

This paper was offered to the Lubricants Special Issue "Tackling Emissions from the Internal Combustion Engine: Advances in Piston/Bore Tribology", for which one of the authors is co-editor. In the special edition, more detailed and rigorous investigations are described. The Special Edition articles covered themes from very detailed computer models [59–61], fuel consumption on emission tests, and the associated experimentation uncertainties [39,62] to long real-world vehicle tests using low-viscosity oils [63]. Stelllljess [64] showed a reduction in friction losses from 9% to 17.3% with the use of a profiled cylinder bore.

Technology advances need to be implemented in mass production products in order to generate the expected benefits to society. In the current work, we have tried to demonstrate the benefits of some advanced ring coatings on small agricultural diesel engines produced for emerging countries. Compared with the GNS rings tested in a similar engine already in production, the CrN top ring presented a wear rate five times lower. The ta-C oil ring presented wear below measurable capabilities. Despite a direct comparison not being possible since the engines and liners were different, the engine wear results correlated well with the rig tribological tests.

The very low wear found in the piston rings and liners creates opportunities for further improvements to reduce friction and fuel consumption:

1. The use of lower-viscosity oils: lower oil film thickness and higher boundary contact would be acceptable.
2. Smoother cylinder liners: honing grooves were preserved at the end of the test.

3. Reduced tangential load on oil control ring tangential: contact pressure was not reduced along the engine life due to ring face wear.

5. Conclusions

CrN PVD top rings and ta-C DLC oil control rings showed very low wear after the 800 h engine test. In combination with the ring coatings, the use of smoother slide honing on the cylinder also caused very low wear on the cylinder. Cylinder wear was measured by radial profiles at TDC and BDC, and it is in the order of 3 µm. No polishing or scratch marks were observed even in the ring reverse regions.

Except for the blow-by increase in the final hours of thermal shock, all engine parameters remain almost unchanged throughout the test. At test end, engine performance and emissions are almost identical to those at test start. This brings us to the conclusion that the integration of advanced piston ring coatings and optimized cylinder liner surfaces significantly reduces wear in agricultural diesel engines. The results from the reliability test indicate that these technological advancements not only maintain engine performance but also contribute to lower emissions, supporting sustainability in the agricultural sector.

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Data Availability Statement: Liner topography measurement reports and the respective measurement files are available under reasonable request. The influence of topography waviness, usually filtered on roughness measurements, will be investigated in a future paper.

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Conflicts of Interest: Xiaochao He Bang Liu, Eduardo Tomanik are employed Zhejiang Xinchai Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Venkatachalam, V. Oil and Gas in the Agriculture Sector. Research Canadian Energy Centre. 2024. Available online: https://www.canadianenergycentre.ca/energy-perspectives-oil-and-gas-in-the-agriculture-sector (accessed on 11 April 2025).
2. Ali, M. Impact assessment of energy utilization in agriculture for India and Pakistan. *Sci. Total Environ.* **2019**, *648*, 1520–1526. [CrossRef]
3. Xu, B.; Lin, B. Factors affecting CO_2 emissions in China's agriculture sector: Evidence from geographically weighted regression model. *Energy Policy* **2017**, *104*, 404–414. [CrossRef]
4. Lin, B.; Xu, B. Factors affecting CO_2 emissions in China's agriculture sector: A quantile regression. *Renew. Sustain. Energy Rev.* **2018**, *94*, 15–27. [CrossRef]
5. MEE. *China Mobile Source Environmental Management Annual Report 2021*; MEE: Beijing, China, 2021.
6. Hou, X.; Zhang, X.; Huang, S.; Xu, P.; Shen, J. Measurement of engine performance and maps-based emission prediction of agricultural tractors under actual operating conditions. *Measurement* **2023**, *222*, 113637. [CrossRef]
7. Janulevičius, A.; Juostas, A.; Pupinis, G. Engine performance during tractor operational period. *Energy Convers. Manag.* **2013**, *68*, 11–19. [CrossRef]
8. Special Agriculture 4.0. Centro de Ciências Agrárias—Universidade Federal do Ceará, Fortaleza, CE. Available online: www.ccarevista.ufc.br (accessed on 1 April 2025). [CrossRef]
9. Raza, M.Y.; Zhongpan, Q.; Pengju, W. Agriculture-related energy consumption, food policy, and CO_2 emission reduction: New insights from Pakistan. *Front. Environ. Sci.* **2023**, *10*, 1099813. [CrossRef]
10. Kubon, M.; Cupiał, M.; Szeląg-Sikora, A.; Kobuszewski, M. The Impact of Purchasing New Agricultural Machinery on Fuel Consumption on Farms. *Sustainability* **2024**, *16*, 52. [CrossRef]

11. Li, T.; Baležentis, T.; Makutėnienė, D.; Streimikiene, D.; Kriščiukaitienė, I. Energy-related CO_2 emission in European Union agriculture: Driving forces and possibilities for reduction. *Appl. Energy* **2016**, *180*, 682–694. [CrossRef]
12. Ji, Q.; Wang, Z.; Zhao, W.; Zhou, Y.; Wang, X.; Liu, J. Effects of ammonia energy fraction on combustion stability, carbon-based emissions and greenhouse effect of an agricultural ammonia-diesel dual-fuel engine. *Process Saf. Environ. Prot.* **2025**, *198*, 107107. [CrossRef]
13. Holmberg, K.; Andersson, P.; Erdemir, A. Global Energy Consumption Due to Friction in Passenger Cars. *Tribol. Int.* **2012**, *47*, 221–234. [CrossRef]
14. Holmberg, K.; Andersson, P.; Nylund, N.-O.; Mäkelä, K.; Erdemir, A. Global energy consumption due to friction in trucks and buses. *Tribol. Int.* **2014**, *78*, 94–114. [CrossRef]
15. Tung, S.C.; McMillan, M.L. Automotive tribology overview of current advances and challenges for the future. *Tribol. Int.* **2004**, *37*, 517–536. [CrossRef]
16. Schommers, J.; Scheib, H.; Hartweg, M.; Bosler, A. Minimising Friction in Combustion Engines. *MTZ Worldw.* **2013**, *74*, 28–35. [CrossRef]
17. Zhmud, B.; Tomanik, E.; Jiménez, A.J.; Profito, F.; Tormos, B. *Powertrain Friction Reduction by Synergistic Optimization of Cylinder Bore Surface and Lubricant—Part 2: Engine Tribology Simulations and Tests*; SAE Technical Paper; SAE International: Warrendale, PA, USA, 2021.
18. Taylor, R.; Morgan, N.; Mainwaring, R.; Davenport, T. How much mixed/boundary friction is there in an engine—And where is it? *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* **2020**, *234*, 1563–1579. [CrossRef]
19. Tomanik, E.; Profito, F.J.; Tormos, B.; Jiménez, A.J.; Zhmud, B. *Powertrain Friction Reduction by Synergistic Optimization of the Cylinder Bore Surface and Lubricant Part 1: Basic Modelling*; SAE Technical Paper; SAE International: Warrendale, PA, USA, 2021.
20. Wong, V.W.; Tung, S.C. Overview of automotive engine friction and reduction trends–Effects of surface, material, and lubricant-additive technologies. *Friction* **2016**, *4*, 1–28. [CrossRef]
21. Suthisripok, T.; Semsamran, P. The impact of biodiesel B100 on a small agricultural diesel engine. *Tribol. Int.* **2018**, *128*, 397–409. [CrossRef]
22. Araujo, J.A.; Banfield, R.R. *DLC as a Low-Friction Coating for Engine Components*; SAE Technical Paper; SAE International: Warrendale, PA, USA, 2021. [CrossRef]
23. Higuchi, T.; Mabuchi, Y.; Ichihara, H.; Murata, T.; Moronuki, M. Development of Hydrogen-Free Diamond-Like Carbon Coating for Piston Rings. *Tribol. Online Jpn. Soc. Tribol.* **2017**, *12*, 117–122. [CrossRef]
24. Bruno, R.; Rabello, R.; Silva, D.; Araujo, J. *DLC Coated Ring Pack for Heavy Duty Diesel Engines*; SIMEA 2017 Proceedings Ed.; Blucher: Vildbjerg, Denmark, 2017. [CrossRef]
25. Björling, M.; Isaksson, P.; Marklund, P.; Larsson, R. The Influence of DLC Coating on EHL Friction Coefficient. *Tribol. Lett.* **2012**, *47*, 285–294. [CrossRef]
26. Rübig, B.; Heim, D.; Forsich, C.; Dipolt, C.; Mueller, T.; Gebeshuber, A.; Kullmer, R.; Holecek, R.; Lugmair, C.; Krawinkler, M.; et al. Tribological behavior of thick DLC coatings under lubricated conditions. *Surf. Coat. Technol.* **2017**, *314*, 13–17. [CrossRef]
27. Tas, M.; Banerji, M.; Lukitsch, M.; Alpas, A. Roles of mirror-like surface finish and DLC coated piston rings on increasing scuffing resistance of cast iron cylinder liners. *Wear* **2017**, *376–377*, 1558–1569. [CrossRef]
28. Mobarak, H.; Masjuki, H.; Mohamad, E.N.; Rahman, S.A.; Al Mahmud, K.; Habibullah, M.; Salauddin, S. Effect of DLC coating on tribological behavior of cylinder liner piston ring material combination when lubricated with Jatropha oil. *Procedia Eng.* **2014**, *90*, 733–739. [CrossRef]
29. Mazuco, F.; Rezende, L.; Araujo, J.; Pereira, J.; Souza, R. Parameters study of carbon bombardment step for enhanced adhesion of thick DLC coating deposited by cathodic arc evaporation. *Surf. Coat. Technol.* **2023**, *457*, 129310. [CrossRef]
30. Mazuco, F.; Araujo, J.; Souza, R. Effect of long carbon bombardment step on the adhesion of thick amorphous carbon coating deposited by cathodic arc evaporation. *Diam. Relat. Mater.* **2021**, *116*, 108434. Available online: https://www.sciencedirect.com/science/article/pii/S0925963521001977 (accessed on 25 February 2025). [CrossRef]
31. Banerji, A.; Lukitsch, M.; Alpas, A. Friction reduction mechanisms in cast iron sliding against DLC: Effect of biofuel (E85) diluted engine oil. *Wear* **2016**, *368–369*, 196–209. [CrossRef]
32. Ferrarese, A.; Banfield, R.; Tomanik, E. *High Value PVD Top Ring for High Speed Diesel Engines*; SAE Technical Paper; SAE International: Warrendale, PA, USA, 2008.
33. Zavos, A. Effect of Coating and Low Viscosity Oils on Piston Ring Friction under Mixed Regime of Lubrication through Analytical Modelling. *Lubricants* **2021**, *9*, 124. [CrossRef]
34. Zavos, A.; Katsaros, K.P.; Nikolakopoulos, P.G. Optimum Selection of Coated Piston Rings and Thrust Bearings in Mixed Lubrication for Different Lubricants Using Machine Learning. *Coatings* **2022**, *12*, 704. [CrossRef]
35. Rejowski, E.; Tomanik, E.; Souza, J. Low viscosity oils impact on heavy duty diesel engine components. In *Anais do XXIV Simpósio Internacional de Engenharia Automotica—SIMEA 2016 [Blucher Engineering Proceedings]*; Blucher: São Paulo, Brazil, 2016; pp. 118–130. [CrossRef]

36. Tomanik, E.; Profito, F.; Sheets, B.; Souza, R. Combined lubricant–surface system approach for potential passenger car CO_2 reduction on piston-ring-cylinder bore assembly. *Tribol. Int.* **2020**, *149*, 105514. [CrossRef]
37. Tormos, B.; Jiménez, A.J.; Fang, T.; Mainwaring, R.; Lizarraga-Garcia, E. Numerical assessment of tribological performance of different low viscosity engine oils in a 4-stroke CI light-duty ICE. *SAE Int. J. Adv. Cur. Pract. Mob.* **2022**, *4*, 1524–1536. [CrossRef]
38. Rovai, F.F.; Sartori, E.; Crepaldi, J.; Rajala, S. Engine Lubricant Impact in Light-Vehicle Fuel Economy: A Combined Numerical Simulation and Experimental Validation. *Lubricants* **2025**, *13*, 137. [CrossRef]
39. Robota, A.; Zwein, F. Influence of cylinder bore topography on the oil consumption and particulate emissions of a DI TCI diesel engine. *MTZ* **1999**, *60*, 1999.
40. Soderfjall, M.; Herbst, H.; Larsson, R.; Almqvist, A. Influence on friction from piston ring design, cylinder liner roughness and lubricant Properties. *Tribol. Int.* **2017**, *116*, 272–284. [CrossRef]
41. Obert, P.; Müller, T.; Füßer, H.; Bartel, D. The influence of oil supply and cylinder liner temperature on friction, wear and scuffing behavior of piston ring cylinder liner contacts—A new model test. In *Tribology International—Amsterdam*; Elsevier Science: Amsterdam, The Netherlands, 2016; Volume 94, pp. 306–314.
42. Dimkovski, Z.; Cabanettes, F.; Löfgren, H.; Anderberg, C.; Ohlsson, R.; Rosén, B.G. Optimization of cylinder liner surface finish by slide honing. *Proc. Inst. Mech. Eng. Part B* **2012**, *226*, 575–584. [CrossRef]
43. Li, Y.; Chen, H.; Tian, T. *A Deterministic Model for Lubricant Transport Within Complex Geometry Under Sliding Contact and Its Application in the Interaction Between the Oil Control Ring and Rough Liner in Internal Combustion Engines*; SAE International: Warrendale, PA, USA, 2008.
44. Chen, H.; Li, Y.; Tian, T. *A Novel Approach to Model the Lubrication and Friction Between the Twin-Land Oil Control Ring and Liner with Consideration of Micro Structure of the Liner Surface Finish in Internal Combustion Engines*; SAE Technical Paper; SAE International: Warrendale, PA, USA, 2008.
45. Tomanik, E. Friction and wear bench tests of different engine liner surface finishes. *Tribol. Int.* **2008**, *41*, 1032–1038. [CrossRef]
46. Spencer, A.; Avan, E.Y.; Almqvist, A.; Dwyer-Joyce, R.S.; Larsson, R. An experimental and numerical investigation of frictional losses and film thickness for four cylinder liner variants for a heavy duty diesel engine. *Proc. Inst. Mec. Eng. Part J J. Eng. Tribol.* **2013**, *227*, 1319–1333. [CrossRef]
47. Ferreira, R.; Almeida, R.; Carvalho, O.; Sobral, L.; Carvalho, S.; Silva, F. Influence of a DLC coating topography in the piston ring/cylinder liner tribological performance. *J. Manuf. Process.* **2021**, *66*, 483–493. [CrossRef]
48. Liu, J.; Zhang, Y.; Liao, B. A review on preparation process and tribological performance of coatings for internal combustion engine piston ring. *Adv. Mech. Eng.* **2023**, *15*, 1–19. [CrossRef]
49. Tomanik, E.; Nigro, F. *Piston Ring Pack and Cylinder Wear Modelling*; SAE TRANS PAPER 2001; SAE International: Warrendale, PA, USA, 2001.
50. Corral, I.; Calvet, J.; Salcedo, M. Use of roughness probability parameters to quantify the material removed in plateau-honing. *Int. J. Mach. Tools Manuf.* **2010**, *50*, 621–629. [CrossRef]
51. Gu, C.; Wang, R.; Tian, T. Modeling the Fatigue Wear of the Cylinder Liner in Internal Combustion Engines during the Break-In Period and Its Impact on Piston Ring Lubrication. *Lubricants* **2019**, *7*, 89. [CrossRef]
52. Ma, Z.; Henein, N.A.; Bryzik, W. A model for wear and friction in cylinder liners and piston rings. *Tribol. Trans.* **2006**, *49*, 315–327. [CrossRef]
53. Giorgio, M.; Guida, M.; Pulcini, G. A state-dependent wear model with an application to marine engine cylinder liners. *Technometrics* **2010**, *52*, 172–187. [CrossRef]
54. Mezghani, S.; Demirci, I.; Yousfi, M.; El Mansori, M. Running-in wear modeling of honed surface for combustion engine cylinder liners. *Wear* **2013**, *302*, 1360–1369. [CrossRef]
55. Koszalka, G.; Niewczas, A.; Guzik, M. *Predicted and Actual Effect of Cylinder Liner Wear on the Blowby in a Truck Diesel Engine*; SAE Technical Paper; SAE International: Warrendale, PA, USA, 2008.
56. Lubrecht, T.; Biboulet, N.; Dufils, J.; Lubrecht, A.A. Piston Ring Mixed Lubrication Model Including Real Geometry Using Analytical Correction Coefficients: Theory and Experimental Validation. *Tribol. Lett.* **2023**, *71*, 73. [CrossRef]
57. Sheeja, D.; Tay, B.; Lau, S.; Shi, X.; Ding, X. Structural and tribological characterization of multilayer ta-C films prepared by filtered cathodic vacuum arc with substrate pulse biasing. *Surf. Coat. Technol.* **2000**, *132*, 228–232. [CrossRef]
58. Lee, W.-Y.; Jang, Y.-J.; Tokoroyama, T.; Murashima, M.; Umehara, N. Effect of defects on wear behavior in ta-C coating prepared by filtered cathodic vacuum arc deposition. *Diam. Relat. Mater.* **2020**, *105*, 107789. [CrossRef]
59. Dellis, P. Comparative Research in the Field of the Parametric Effect of Lubricant Cavitation Initiation and Development on Friction and Wear in Piston Ring and Cylinder Liner Assemblies. *Lubricants* **2024**, *12*, 460. [CrossRef]
60. Yang, T.-Y.; Li, M.; Tian, T. Modeling Inertia-Driven Oil Transport Inside the Three-Piece Oil Control Ring of Internal Combustion Engines. *Lubricants* **2024**, *12*, 394. [CrossRef]
61. Li, M.; Tian, T. Sources and Destinations of Oil Leakage through TPOCR Based on 2D-LIF Observation and Modeling Analysis. *Lubricants* **2023**, *11*, 522. [CrossRef]

62. Rovai, F.F.; Tomanik, E. Lubricant Viscosity Impact in Fuel Economy: Experimental Uncertainties Compensation. *Lubricants* **2025**, *13*, 49. [CrossRef]
63. Shao, H.; Hu, H.; Luo, Y.; Hua, L.; Pan, J.; Zhu, G.; Jiao, Y.; Yan, J.; Wei, G. Impact of Mid-to-Low-Ash, Low-Viscosity Lubricants on Aftertreatment Systems after 210,000-Kilometer Real-World Road Endurance Trials. *Lubricants* **2024**, *12*, 240. [CrossRef]
64. Stelljes, F.; Pohlmann-Tasche, F.; Dinkelacker, F. Experimental Investigation of a Free-Form Honed Cylinder Liner for Heavy-Duty Engines. *Lubricants* **2024**, *12*, 132. [CrossRef]

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