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High Value PVD Top Ring for High Speed Diesel Engines

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ABSTRACT

Due to several market demands of higher wear and scuffing resistance, Duplex PVD (Physical Vapor Deposition) CrN top ring has been used in Heavy Duty Diesel (HDD) engines. The ring comprises a nitrided high chromium stainless steel with a PVD ceramic CrN coating. For High Speed Diesel (HSD) vehicles with lower demands, MAHLE has developed an alternative PVD coated ring, which balances the cost and performance ratio. This alternative, named High Value PVD (HV-PVD), consists of applying the best resistant coating for wear and scuffing, PVD, onto a less costly ring material, Ductile Cast Iron.

The HV-PVD top ring has been tested in HSD engines and shown excellent performance. Additional advantages of the HV-PVD are its lower friction coefficient and better tribological compatibility with the cylinder bore materials when compared to the traditional galvanic chrome based coatings. Such features lead to reduced engine friction and lower cylinder wear. Besides the superb product performance, the demands for environment friendly processes are complied by the vacuum technology of PVD process.

This paper presents bench tests evaluation for wear, friction and scuffing resistance. Engine tests for different European passenger car applications are also presented.

INTRODUCTION

Emission restrictions imposed by the more demanding environmental legislation, as well as customer expectations have lead to significant reductions of the lube oil consumption and increase of specific power. For the engine components, more specifically for the piston rings, the consequence is the need for higher resistance to wear and scuffing.

For HDD engines, some of the actions applied to meet the emissions targets were:

- Increase Exhaust Gas Recirculation (EGR)
- Increase Peak Cylinder Pressure (PCP)
- Reduce Lube Oil Consumption (LOC)

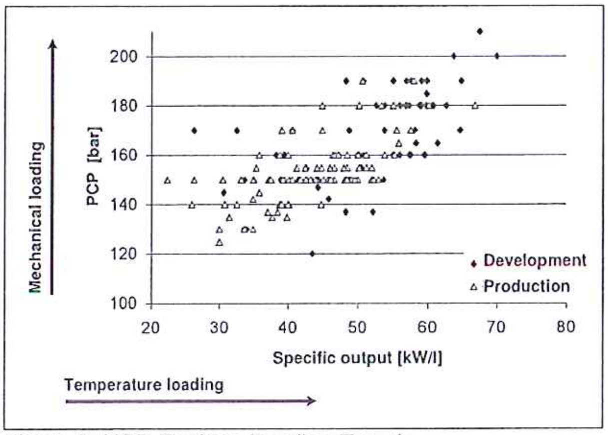

Figure 1: HSD Engines Loading Trends.

A similar trend is occurring in diesel engines for passenger cars. Fig.1 summarizes the Peak Combustion Pressure, PCP, and the specific output of production and in development engines of passenger cars. The PCP levels are reaching 200+ bar, same level of in development HDD engines. Such level has shown to be the borderline to galvanic Chromium based top ring coatings, suggesting that adoption of a higher scuffing resistance will be mandatory in the near future also for HSD engines.

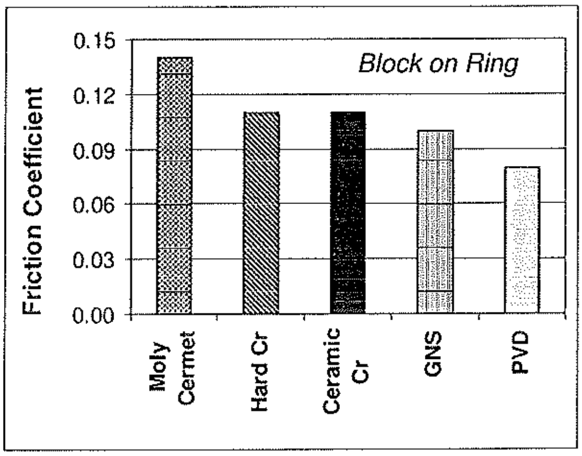

Figure 8: Block on ring friction evaluation.

Due to its very low friction coefficient, PVD top rings are attracting attention and some use even for gasoline engines. Figure 9 compares the measured friction, in a firing floating liner device, of a PVD top ring against a Gas Nitrided Steel in a gasoline engine [3]. The pack using a PVD coated ring showed 10% less friction.

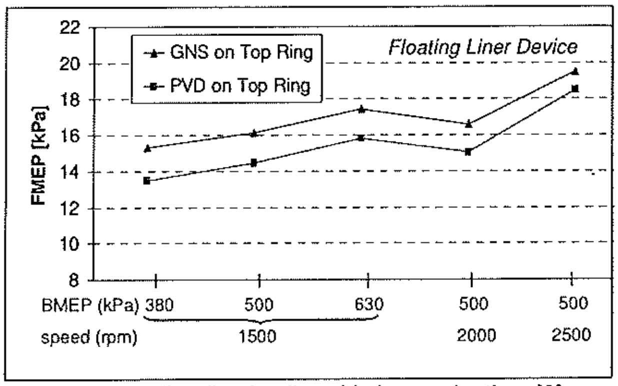

Figure 9: Gasoline floating liner friction evaluation. [3]

HIGH VALUE PVD

Compared to commercial vehicles, for passenger cars engines less demanding conditions prevail such as reduced durability requirements, which may permit the use of ring coatings with reduced thickness. Also, the use of a base material with higher conformability would be an advantage since HSD engines usually have less stiff engine blocks, with expected higher deformations. For such applications MAHLE has developed a "higher added value" design where a thinner PVD coating is applied directly on Ductile Cast Iron substrate material. This solution is called High Value PVD, see Fig. 10. Table 1 compares the HV-PVD with the premium PVD used in HDD engines.

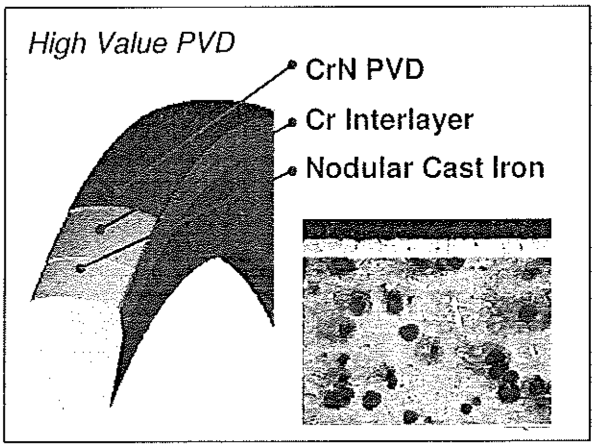

Figure 10: High Value PVD concept.

Table 1: Premium and High Value PVD comparison.

	Substrate material	Typical PVD thickness (µm)	Coating Hardness (HV0.1)
Premium PVD	Nitrided Stainless Steel	30 - 50 µm	1,200-1,600
HV-PVD	Ductile Cast Iron	20 - 30 µm	1,200-1,600

The HV-PVD concept for HSD only presents thinner coating than Premium PVD for HDD, because of the higher demands of HDD applications. If compared to Premium PVD for HSD applications (10 µm), it is significantly thicker. It was designed to have no substrate exposure after durability homologation, see test results.

TEST RESULTS

Based on bench test evaluation and the successful application in HDD where the usually applied ceramic chrome wore twice than the PVD (Figure 4), accelerated dynometer tests were performed in several HSD engines, as described ahead.

Case 1 – 2.0L, 4 cylinders inline, 110 kW @ 4200 rpm, 160 bar of PCP, see Figure 11.

This engine was tested using Ceramic Cr as baseline, even with the short duration of the test, it is possible to verify the wear advantages of HV-PVD.

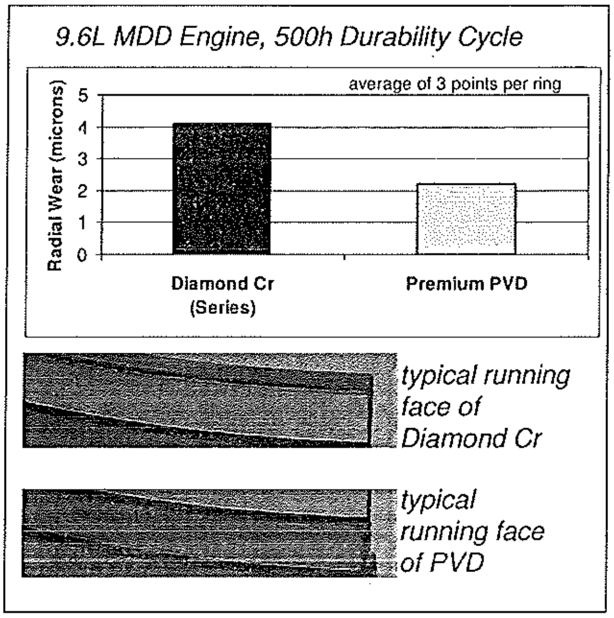

Figure 5: MDD 500 h dyno test.

Fig. 6 presents the engine test results of a comparison between two generations of the same engine. One without EGR, PCP of 185 bar and a relatively high cylinder roughness. The other, more recent, with 20% of EGR, higher PCP and lower cylinder roughness. Even with the higher PCP and EGR rate, the smoother liner presented lower wear than before and the ring wear was almost unchanged. Such good tribological compatibility of the PVD with smoother cylinder finish is believed to be due to the combined PVD properties of low friction, very low roughness and absence of hard particles.

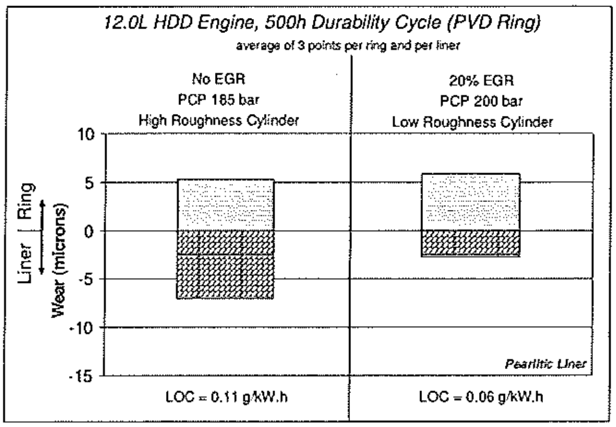

Figure 6: PVD compatibility with liner.

SCUFFING RESISTANCE

For scuffing analysis, MAHLE has developed an abusive HSD engine test. The test characteristics are summarized below:

- Reduced piston top land height
- Increased piston top land clearance
- Gallery oil temperature: 150 °C
- Charge air temperature: 90 °C
- Coolant is substituted by an anti-freeze, to support temperatures up to 120 °C.

The engine is run at full power for 10 h. If the ring survives, the test is repeated at successively increased coolant temperatures. After each stage, the engine is disassembled and the top rings are inspected. The ring region with strong marks on the running face is photographed and compared with a visual standard.

Fig. 7 shows a comparative evaluation of the running face of three different coatings at an abused running condition. The PVD ring showed no scuffing marks, differently from the galvanic ceramic and diamond chrome based coatings.

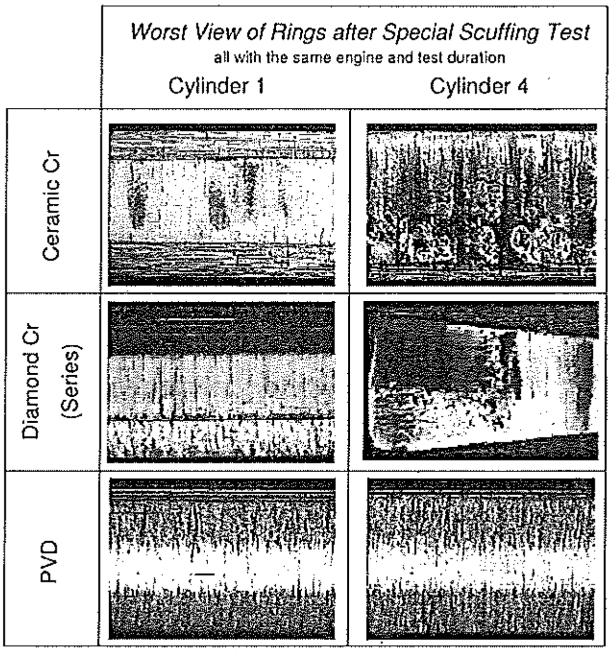

Figure 7: Special scuffing test.

FRICTION

PVD has the lowest friction coefficient among the wear resistant ring coatings. Figure 8 shows the measured friction coefficient in a block on ring test.

MAHLE has been using the Premium PVD for HDD engines [2], see Fig. 2.

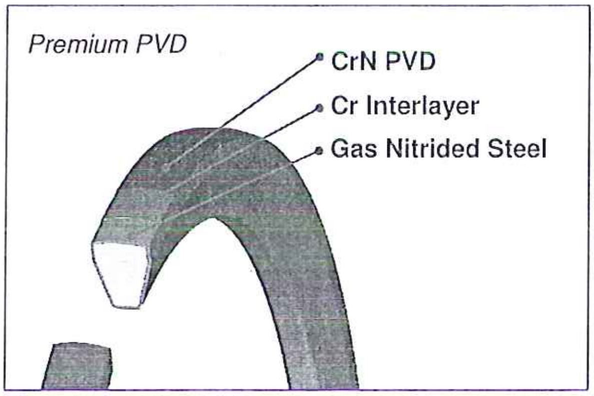

Figure 2: Premium PVD top ring.

The steel nitrided layer works as an emergency layer in the eventual situation that the PVD coating is completely worn in a specific ring region. In such situations, the bore/ring contact has had accommodated, and the tribological resistance of the GNS (Gas Nitrided Steel) is sufficient.

PVD COATED RING

WEAR RESISTANCE

Relative ring coating wear was evaluated in a reciprocating bench test. Normal load is applied using a closed-loop servo mechanism, and normal load and friction forces are measured with strain-gages. The experimental setup is shown in Fig. 3. The test consists of a four hour test with an applied ring nominal pressure of 12 MPa (120 bar) and a rotational speed of 900 rpm. To accelerate ring wear, the oil is doped with hard particles. The wear test procedure was developed empirically and found to increase ring wear, even for PVD coatings, while causing a reasonable liner wear. Ring and liner wear is measured by comparing the respective profiles, before and after test, see Fig. 3.

In the reciprocating test, PVD presented the lowest ring and bore wear.

As an example of the use of PVD top rings on HDD market, Fig. 4 presents the results of a 12.0L HDD engine, 6 cylinders inline, 343 kW @ 1900 rpm, 200 bar of PCP. In this evaluation, Ceramic Cr was used as the baseline. The results of wear present a significant advantage for PVD.

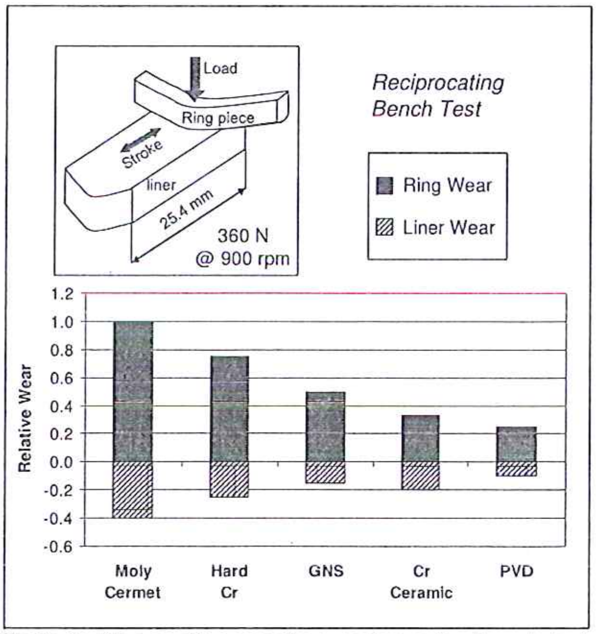

Figure 3: Ring coating wear in a reciprocating bench test.

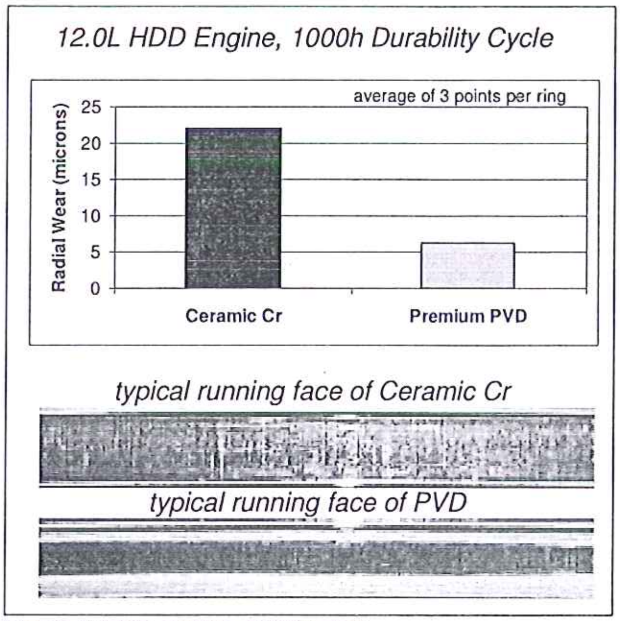

Figure 4: HDD engine, 1000 h test.

After the Heavy Duty Diesel market, Medium Duty Diesel (MDD), engines are also starting to use PVD top rings. Figure 5 presents the comparison of Premium PVD against Diamond Cr in a 500 h dyno test. The tested engine has 9.6L, 6 cylinders inline, 326 kW @ 2300 rpm, 195 bar of PCP. In this test also, PVD presented a significant wear advantage, see Fig. 5.

Lower friction coefficient is also another important characteristic of PVD compared with other coatings available for rings.

High Value PVD was tested in different engine platforms against chromium based alternatives. It confirmed the supreme performance in HSD engines as observed in HDD engines.

ACKNOWLEDGMENTS

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REFERENCES

1. Tomanik, E. and Nigro, F.; "Piston Ring Pack and Cylinder Wear Modelling", SAE2001-01-0572, Detroit, EUA, 2001.
2. Warkentin, T., Banfield, R., Nocera, E.; "New Ring Pack for HDD Engines", SAE2007-01-2846, Sao Paulo, Brazil, 2007.
3. Tomanik, E. and Ferrarese, A.; "Low Friction Ring Pack for Gasoline Engines", ASME ICEF2006-1566, Sacramento, USA, 2006.

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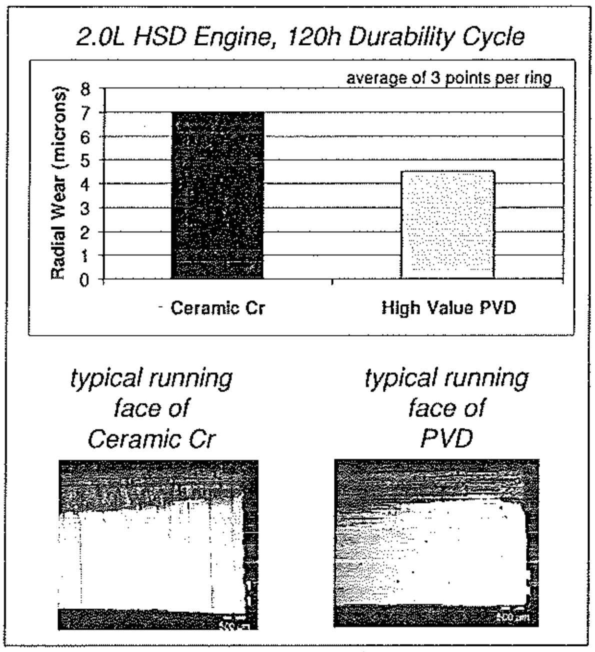

Figure 11: 2.0 L HSD engine, 120 h test.

Case 2 – 1.6L, 4 cylinders inline, 80 kW @ 4000 rpm, 160 bar of PCP, see Figure 12.

The engine was tested for 250h at rated power. Radial wear of the HV-PVD top ring was about 4 µm.

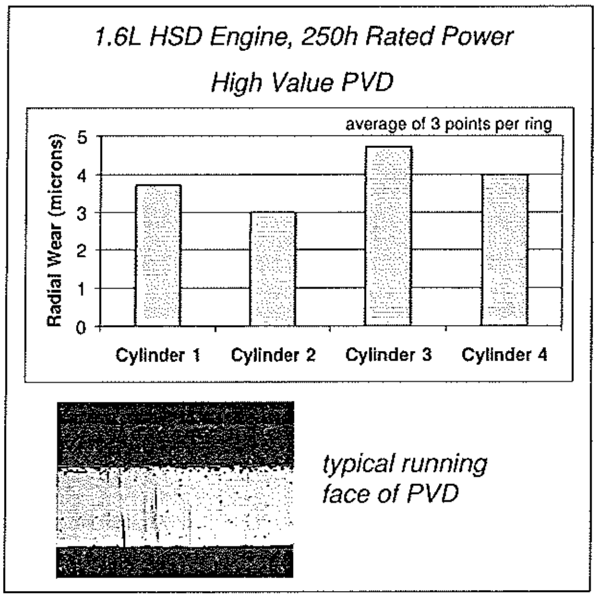

Figure 12: 1.6L HSD engine, 250 h test.

Case 3 – 2.0L, 4 cylinders inline, 95 kW @ 3800 rpm, 160 bar of PCP, see Figure 13.

A 500 h engine split test was carried out, 2 cylinders were assembled with the Series galvanic Ceramic Chrome top rings, the 2 others were assembled with the HV-PVD. Figs.13 presents wear resistance comparison of HV-PVD against Ceramic Cr. The results consolidate the significant PVD advantage on face wear on HSD engines as observed on HDD engines. Once the coating is 20 µm minimum, the engine tested in Fig. 13 points out to no substrate exposure before 1000h. Such estimation is given considering constant wear rate, which is known to be a conservative safety factor, since after break-in, ring wear rate usually reduces.

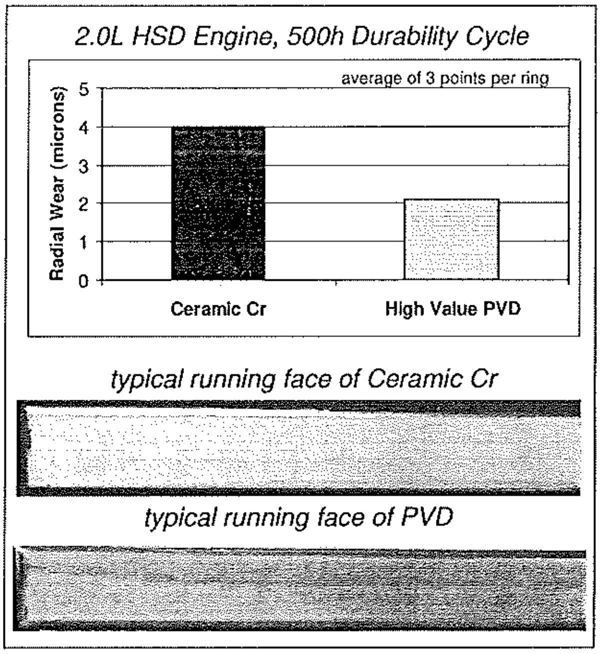

Figure 13: 2.0 L HSD engine, 500 h test.

CONCLUSION

Premium PVD top rings are already established in the HDD market due to its excellent tribological properties under very demanding conditions. As passenger car engines are pointing out similar operating trends, but cost is a stronger concern, MAHLE has developed a High Value variant, applying the PVD on a less costly base material, ductile cast iron.

PVD showed to be the best coating for rings in terms of wear for bench and engine tests. Such wear resistance is in this case combined with excellent liner compatibility.

Scuffing abusive tests showed that PVD is also more resistant than galvanic chromium based coatings.