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Superior reliability piston rings made of alloy steel with PVD coating

Tribology

Minoru Kawanishi, RIKEN Corporation

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ABSTRACT

Cast iron has long been used as the base material for piston rings for medium-speed engines, and the sliding surfaces of piston rings have been coated with hard chromium plating or chromium ceramic coating. On the other hand, alloy steel has been applied as the base material for piston rings in small-bore engines for more than 50 years, and PVD coatings are now very popular or standardized. It is well known that alloy steels have better bending and fatigue strength compared with cast iron, and PVD coatings have better wear and scuffing resistance compared with hard chromium plating or chromium ceramic coating.

In 2013, RIKEN launched a special project to apply the small-bore piston ring technology described above to large-bore piston rings in order to significantly improve the high and long-term reliability of future high-output engines.

Rig tests have shown that alloy steel has approximately 60% improvement in fatigue strength compared with ductile iron, and PVD coating improves wear on their own approximately 70% compared with chromium ceramic coating while at the same time the liner material has also been improved by approximately 65%.

The most noteworthy point was that the PVD coating applied to the top ring sliding surface provides excellent wear resistance even under extremely harsh lubrication conditions with lubricating oil consumption of approximately 0.1g/kWh due to the optimal design of the oil control ring.

The excellent wear resistance of the PVD coating allows the barrel shape of the top ring to be maintained for a long period of time, and allows the formation of an optimal lubricant film between the top ring sliding surface and the liner wall. This effect further reduces the risk of scuffing, in addition to the high scuffing resistance of the PVD coating itself.

Furthermore, abnormal combustion and knocking are not welcome situations for all engines, but the top ring made of alloy steel never collapsed even under the above conditions.

Through various rig tests and firing tests, the superior reliability of piston rings made of alloy steel with PVD coating was proven.

1 INTRODUCTION

Piston rings are one of the most important components in all types of internal combustion engines, providing gas sealing, heat transfer, and lubricant oil distribution. Cast iron has long been used as the base material for piston rings in medium-speed engines, and the sliding surfaces of piston rings have been coated with hard chromium plating or chromium ceramic coating. On the other hand, alloy steel has been applied as the base material for piston rings in small-bore engines for more than 40 years, and PVD coatings are now very popular or standardized. It is well known that alloy steels have better bending and fatigue strength compared to cast iron, and PVD coatings have better wear and scuffing resistance compared to hard chromium plating or chromium ceramic coating. On the other hand, in order to improve the efficiency of medium-speed engines, the maximum combustion pressure is increasing year by year, and it looks that the maximum combustion pressure of medium-speed engines is currently very close to 300 bar. In 2013, RIKEN launched a special project to apply the small-bore piston ring technology described above to large-bore piston rings in order to significantly improve the high and long-term reliability of future high-output engines. This means applying steel alloy materials and PVD coatings to piston rings with diameters over 200mm for medium speed engines. These piston rings have been shown in calculations and firing tests to have both less blow-by and less oil consumption compared to current standard piston rings.

2 BASE MATERIALS FOR PISTON RINGS

Figure 1 shows the base materials for piston rings.

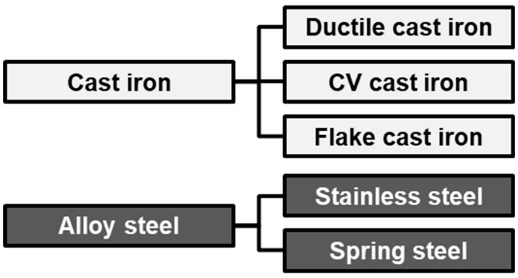

Figure 1. Base materials for piston rings

Ductile cast iron and flake cast iron are commonly used as base materials for piston rings for medium speed engines, and CV cast iron is used for piston rings for low speed engines mainly. There are two kind alloy steel materials for piston rings, both stainless steel and spring steel are applied for piston rings of some heavy duty engines whose diameter is below approximately 200mm. In the case of piston rings, stainless steel is generally nitrided to improve its sliding performance. And, spring steel is used for piston rings in medium duty engines or passenger vehicle engines mainly. If piston rings collapse, the engine will suffer major damage, leading to a serious accident. Therefore, one of the most important mechanical properties required for the base material of piston rings is fatigue strength. Figure 2 shows the fatigue limit diagram of the hard chrome plated ductile cast iron specimen and nitrided and PVD coated stainless steel specimen. The results showed that the nitrided and PVD coated stainless steel specimen performed approximately 60% better than the hard chrome plated ductile cast iron specimen. This effect reduces the risk of piston rings collapse when abnormal combustion such as knocking occurs during combustion tests and the combustion pressure becomes extremely high.

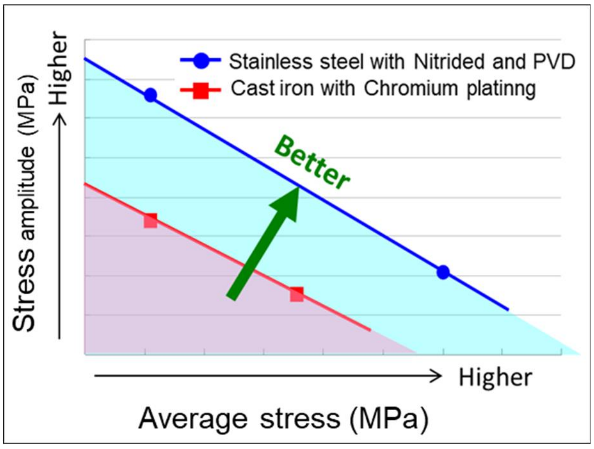

Figure 2. Fatigue limit diagram

3 SURFACE TREATMENTS FOR PISTON RINGS

Several kinds of surface treatments exist for the sliding surfaces of piston rings, but the most common treatment is hard chromium plating, and hard chromium plating can be applied to both cast iron and alloy steel. Chromium ceramic coating which has better wear resistance and scuffing resistance compared to hard chromium plating, is also a very common surface treatment derived from chromium plating. Plasma spraying is one of the common surface treatments applied to the sliding surfaces of piston rings, and currently it is mainly applied to piston rings for low-speed engines. PVD coating is the most common surface treatment mainly for small diameter piston rings up to 200mm in diameter combined with nitrided stainless steel or spring steel as base materials, but PVD coating has not been applied to piston rings over 200mm in diameter. Nitriding treatment is a little bit unique compared to other treatments like hard chromium plating, chromium ceramic coating, plasma spray and PVD. Nitriding treatment is a method of hardening steel by heating it in an atmosphere containing nitrogen to form nitrides on the steel surface. Surface treatments other than nitriding form a film on the outside of the base metal, but nitriding forms a hardened layer on the surface of the steel. Surface treatments generally require better wear and scuffing resistance for maintain functionality of piston rings, and these matters are extremely important. Figure 3 shows wear resistance and Figure 4 shows scuffing resistance of each surface treatment. Figure 3 shows that PVD coating has been successful in reducing approximately 50% both its own wear and liner wear compared to the chromium ceramic coating, which is one of the greatest advantages of PVD coating.

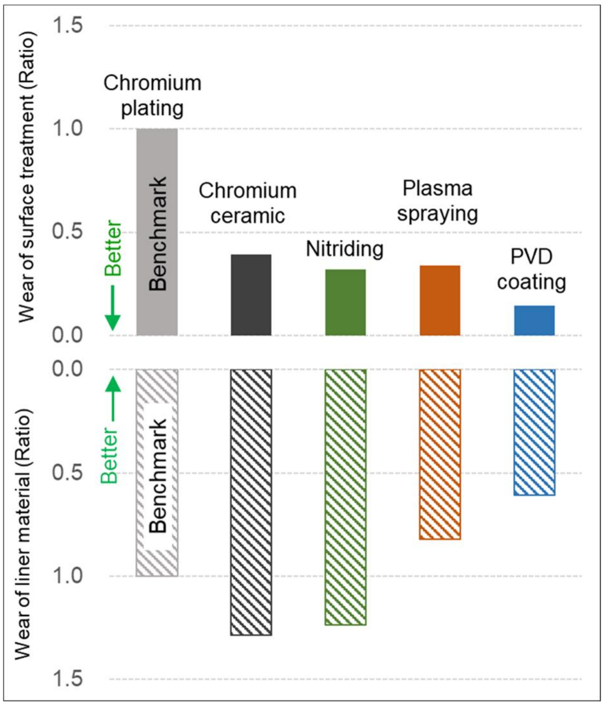

Figure 3. Wear resistance of surface treatments and liner material

Figure 4 shows that PVD coating has been successful in improving approximately 20% scuffing resistance compared to chromium ceramic coating.

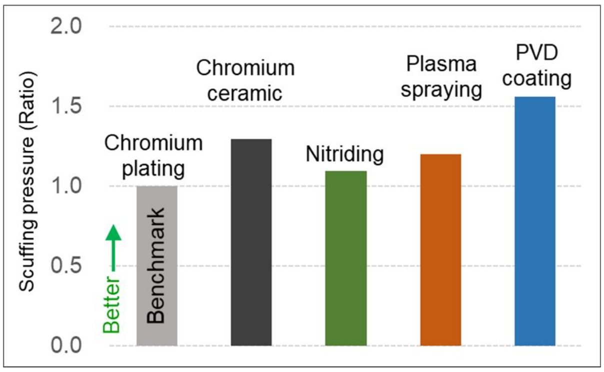

Figure 4. Scuffing resistance of surface treatments

Furthermore, in addition to better wear resistance and scuffing resistance, the adhesion of the surface treatment is also an important matter for improving the reliability of piston rings. The adhesion of surface treatments are affected by the roughness and cleanliness of the substrate before treatment, therefore these factors must be properly controlled and managed in the production process for any surface treatment. On the other hand, surface treatment itself is affected by the internal residual stress of surface treatment, and the bonding method between surface treatment and base material. Generally tensile residual stress is negative impact and compressive residual stress is positive impact regarding adhesion. Figure 5 shows that PVD coating has compressive residual stress, hard chromium plating, chromium ceramic coating and plasma spray have tensile residual stress.

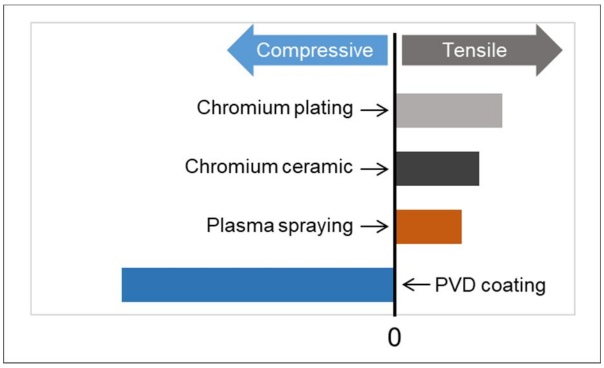

Figure 5. Residual stress

Bonding methods include "ionic bonding," "metallic bonding," and "mechanical bonding" for surface treatment of piston rings in descending order of bond strength. Base material of piston ring and PVD coating are bonded by ionic bonding, hard chromium plating and chromium ceramic coating are bonded by metal bonding, and plasma spraying is bonded by mechanical bonding. From these results, it can be concluded that at present, PVD coating is a far superior surface treatment for medium-speed engine piston rings due to their superior wear resistance, scuffing resistance and adhesion compared to current common surface treatments such as chromium plating and chromium ceramic coating.

4 PVD COATED PISTON RINGS MADE OF STAINLESS STEEL

4.1 Details of “New concept” rings

Piston systems generally consist of 3 or 4 rings combined with compression rings and an OIL control ring(s). Figure 6 shows the very common 3 rings configuration. Right side of Figure 6 shows the "New concept" rings configuration applying stainless steel for the TOP ring and OIL control ring. And nitriding and PVD coating are applied. Left side of Figure 6 shows "Conventional" rings configuration applying cast iron and chromium plating or chromium ceramic coating.

		Conventional	New concept
TOP ring	Cross section	Rectangle & Asym.BF	Rectangle & Asym.BF
	Axial height (h1)	5.0mm	4.0mm
	Base material	Cast iron	Stainless steel
	Sliding surface	Chromium ceramic	Nitrided+PVD
	Both flanks	Chromium plating	Nitrided
2ND ring	Cross section	Taper faced	Taper faced
	Axial height (h1)	5.0mm	4.0mm
	Base material	Cast iron	Cast iron
	Sliding surface	Chromium plating	Chromium plating
	Both flanks	Phosphate	Phosphate
OIL control ring	Cross section	Two-pieces	Two-pieces
	Axial height (h1)	8.0mm (Rail:0.7mm)	6.0mm (Rail:0.3mm)
	Base material	Cast iron	Stainless steel
	Sliding surface	Chromium plating	Nitrided+PVD
	Both flanks	Phosphate	Nitrided

Figure 6. 3 rings configuration

Figure 7 shows the cross-sectional view of the “New concept” TOP ring, and Figure 8 shows the cross-sectional view of the “New concept” OIL control ring.

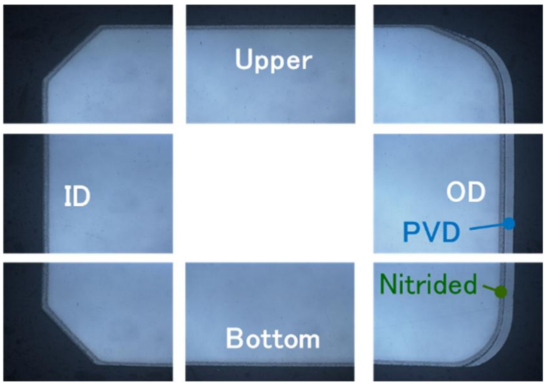

Figure 7. Cross section of “New concept” TOP ring

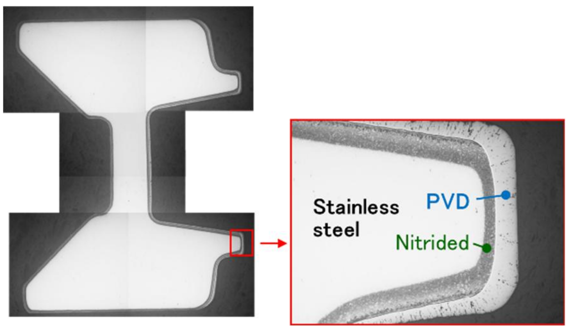

Figure 8. Cross section of “New concept” OCR

Both piston rings are designed with the target of "Excellent durability" .Stainless steel was applied as base material for both piston rings in order to form a nitrided layer that prevents wear on both flanks of piston rings. In addition, PVD coating was applied on the sliding surface of both piston rings. In other words, it has a two-layer structure with a nitride layer and PVD coating, designed for long-term use due to the higher durability. Piston rings are succeeded in downsizing by applying stainless steel, this has created the following new benefits. Downsized TOP ring allows for more stable axial behavior within the groove during engine operation, improving the gas seal at the bottom flank and reducing blow-by. Narrow rail width of Oil control ring allows for thinner oil film between rail of Oil control ring and cylinder liner wall, and this effect means that the oil consumption is reduced. Downsized rings also allows for greater flexibility in piston design and is expected to reduce piston temperature by optimizing cooling channels.

4.2 Calculation results

Riken calculated axial behavior of piston rings in the grooves, amount of blow-by and oil consumption by using an in-house made original calculation program focused on piston rings. The axial height of the TOP ring and OIL control ring in the “New concept” shown in Figure 6 is thinner than that of “Conventional” piston rings, and the rail contact width of the OIL control ring is also narrower. The closed gap (s1) and contact pressure are the same in each ring between “Conventional” and “New concept” to make sure the effects are correct. The material's density, expansion coefficient, elastic modulus, piston and liner temperature data, combustion pressure data, etc. are required for calculation. Figure 9 shows the comparison of the calculated axial behavior of each piston ring. The blue group of lines means the “New concept” and the red group of lines means the “Conventional” one. The “New concept” TOP ring is positioned at the bottom of the groove for a longer time compared to the “Conventional” TOP ring, which improves the bottom side seal of the TOP ring and therefore reduces the volume of blow-by.

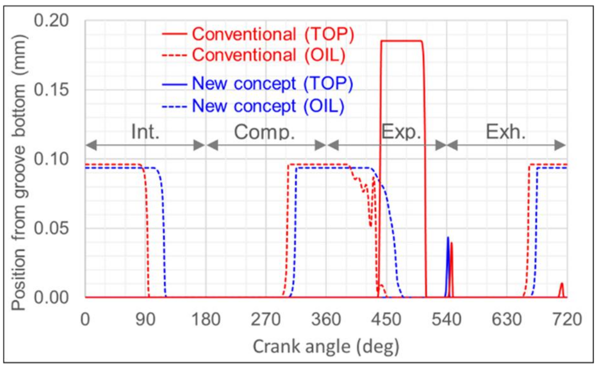

Figure 9. Axial behavior of each ring

On the other hand, the “Conventional” TOP ring float up and are positioned at the top of the groove in the expansion stroke, which worsens the bottom side seal and increases both the volume of blow-by gas and blow-up gas. Both 2nd rings stayed at the bottom of the groove in all strokes, in this calculation.The amount of gas leakage from the “New concept” TOP ring can be reduced by approximately 36% compared to the “Conventional” TOP ring on calculation, resulting in lower second land pressure, resulting in 20% less as total blow-by gas and extremely less blow-up gas in Figure 10. Less blow-up gas can reduce the oil consumption, therefore it can be said, that the stable TOP ring axial behavior can reduce both blow-by gas and oil consumption.

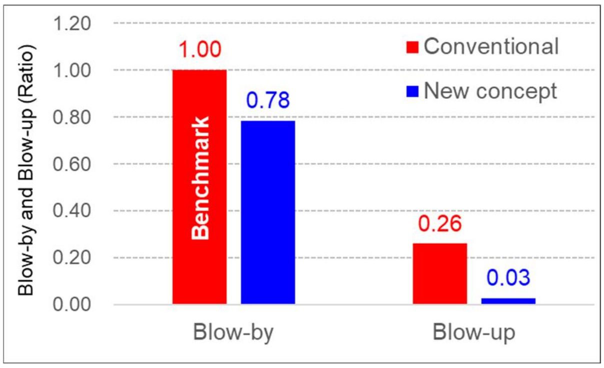

Figure 10. Blow-by gas and Blow-up gas

Generally, the tangential load of the OIL control ring is increased to reduce oil consumption. However, a “New concept” oil control ring took a new method which means applying a narrow contact width of the rails of the OIL control ring under the same contact pressure compared to the “Conventional” one. Figure 11 shows when one of two surfaces moves parallel to the other, the longer the length of the moving side, the greater the oil pressure generated between two surfaces and the thicker the oil film between two surfaces. Thicker oil film thickness means increased oil consumption on this calculation.

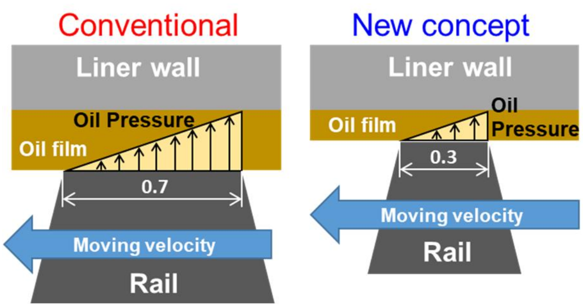

Figure 11. Relationship between rail width and oil

Figure 12 shows the oil film thickness of each TOP ring and OIL control ring. Oil film thickness of the “New concept” oil control ring is extremely thinner compared to the “Conventional” one. In addition, the “New concept” TOP ring oil film thickness is also thinner compared to the “Conventional” due to the effect of OIL control ring oil film thickness.

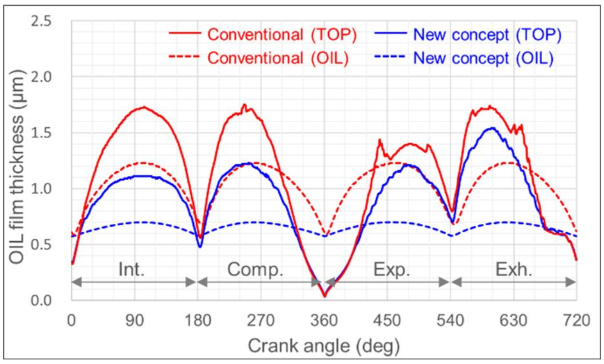

Figure 12. Oil film thickness

Consumption of oil occurs due to four factors mainly, "oil mist by blow-up gas", "evaporation", "scattering" and "passing through the closed gap". However, volume of oil evaporation is dependent on the engine side temperature management, therefore calculated total oil consumption is considered "oil mist by blow-up gas", "scattering" and "passing through the closed gap" this time for deeper understanding of the effects of the “New concept” ring pack. Figure 13 shows that calculations have shown that the oil consumption of the “New concept” ring pack can be reduced by approximately 50% compared to the “Conventional” ring pack. Through this calculation, the “New concept” ring pack demonstrates the feasibility of improving blow-by gas and improving oil consumption.

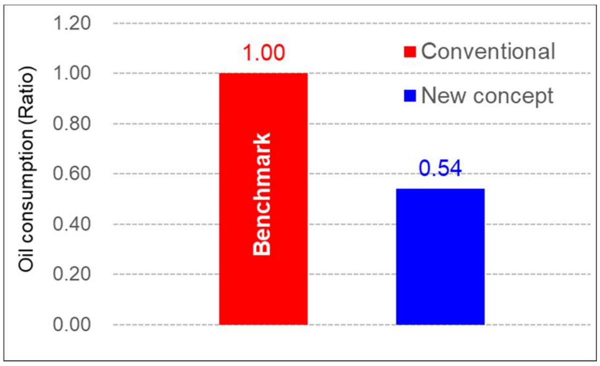

Figure 13. Calculated oil consumption

4.3 Firing test results

Firing tests were conducted several times with the “New concept” ring pack installed in an actual medium-speed dual fuel engine with approximately 300 mm bore. In this engine test, blow-by gas volume was measured with the engine speed fixed at constant at several engine loads, from low to high, and figure 14 shows the results. The "New concept" ring pack successfully reduced blow-by gas at all engine load ranges, achieving a reduction of more than 25%. By reducing blow-by gas, it is expected improvements in engine efficiency and prevent oil deterioration.

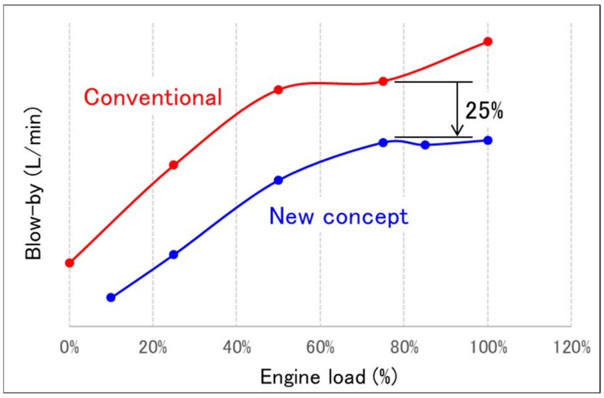

Figure 14. Blow-by gas measurement results

In order to measure oil consumption more accurately, the oil sump level reduction method was applied and measured the oil consumption at 100% engine load, and the results are shown in Figure 15. 0.12g/kWh oil consumption was measured in the firing test, which is an extremely low oil consumption never before seen. Generally, a standard oil consumption for medium-speed engines is approximately 0.2 to 0.3g/kWh, so it can be said that "New concept" ring pack can reduce oil consumption by about 50%.

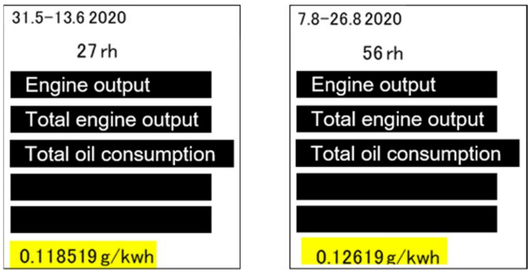

Figure 15. Oil consumption measurement results

Less oil consumption means thinner oil film thickness on each ring sliding surface. Therefore, one concern is that as the wear on each ring surface increases, it is necessary to check the wear on each surface after the durability test is completed. Figure 16 shows the wear on sliding surfaces of each ring after approximately 400 hours of running, with the amount of wear on the TOP ring being extremely small at just 1.5µm, and it looks like just after running-in was completed with no scuffing. This is due to the excellent wear resistance and scuffing resistance of the PVD coating shown in Figure 3 and Figure 4. Based on the results of this firing test, the estimated service life of the "New concept" ring pack is at least more than 35,000 hours.

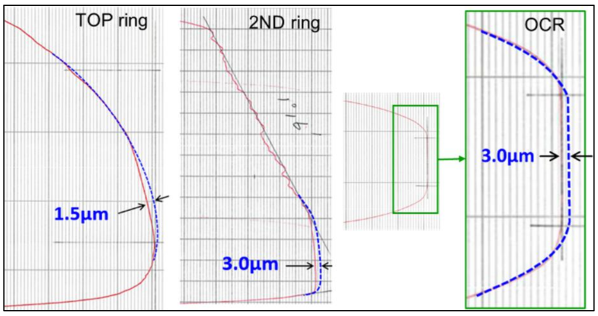

Figure 16. Wear of each sliding surfaces

Under less volume of oil condition, there was concern that bottom flank wear of TOP ring would increase, bottom flank wear of TOP ring was measured and the results are shown in Figure 17. Almost no wear was observed, and this result indicates that the nitrided layer is suitable for preventing the bottom flank wear of the piston ring.

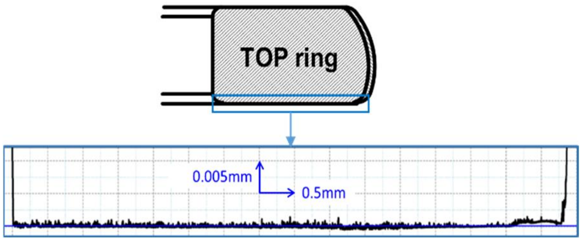

Figure 17. Bottom flank wear

In the early development stage, during another durability test under extremely severe condition to verify engine performance, abnormal knocking occurred with a maximum pressure exceeding 350 bar, and PVD coating on the gap area of the TOP ring caused melting loss, as shown in figure 18. However, there was no collapse to the TOP ring due to the steel material, and no scuffing occurred other than gap area due to the better scuffing resistance of the PVD coating.

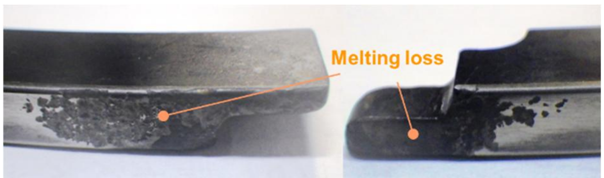

Figure 18. Melting loss of PVD by heavy knocking

5 CONCLUSIONS

1. The "New concept" ring pack designs a steel alloy as the base material and is PVD coated on the sliding surface of the piston rings. Compared to the "Conventional" ring pack, the "New concept" ring pack is designed to achieve superior reliability, such as "excellent wear resistance," "excellent scuffing resistance," and "excellent collapse resistance" of the piston rings.

2. Regarding seal performance of "New concept" ring pack has expected less blow-by gas and less oil consumption in the actual firing tests, and these series of calculation results show that the stable axial behavior of the TOP ring can reduce both blow-by gas and oil consumption.

3. Generally, the most common way to reduce oil consumption is to increase the tangential load of the OIL control ring, however this time a new idea that thinning the contact width of the OIL control ring rail without changing the contact pressure is applied. According to the calculation results, narrowing the contact width of the rail of the OIL control ring, the oil pressure generated between the rail surface and the liner wall is reduced, resulting in a thinner oil film thickness. This thinner oil film thickness means oil consumption can be reduced.

4. It can be concluded that the "New concept" ring pack performed very well during the combustion test. This is because the "New concept" ring pack produced more than 25% less blow-by gas and reduced oil consumption by approximately 50% compared to the “Conventional” one. In addition, after a 400 hours durability test, there was very little wear on each sliding surface of piston rings, and almost no wear was observed on the bottom flank of the TOP ring. Therefore, this "New concept" ring pack can be expected to have a longer service life with less blow-by gas and less oil consumption both.

5. Riken's unique calculation system helps to deeply understand the theoretical mechanism of reducing blow-by gas and oil consumption, and the calculation results are in good agreement with the combustion test results. Therefore, this unique calculation system can be said to be a very useful tool for engineering.

6. ACKNOWLEDGMENT

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7. REFERENCES AND BIBLIOGRAPHY

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