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NEW COATINGS AND FINISHING METHODS FOR TOP PISTON RINGS OF DIESEL ENGINES TO REDUCE FRICTIONAL LOSS AND TO ENSURE ADEQUATE BEHAVIOUR UNDER MOST DIFFICULT REGIMES OF OPERATION

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Abstract: As a part of a most comprehensive research work, the present paper is enhancing the role of a rightly chosen and realised coating and finishing for the top piston ring sliding surface to diminish friction and wear, to ensure adequate resistance to its ever harder operating conditions, and to prolong its life in the couple cylinder-piston ring.

Composition, hardness, crystalline structure and orientation, resistance to scuffing, wear, and, most of all, to peeling-off tendency, are important characteristics to be analysed and solved with the coating of the top piston ring.

New finishing methods are also required for the piston ring active surface to generate extra oil micro-reservoirs to ensure a minimum oil film under the worst operating regimes (to avoid in any case, metal-to-metal contact that is characterized by importantly increased frictional loss and worsened functioning).

Keywords: piston ring, ion-plating chromium nitride coating, diamond-like carbon coating, composite coating, laser surface micro modeling.

1. BACKGROUND

Market requirements for high quality and efficiency at minimum costs, dictate that fuel and oil economy of the modern day internal combustion engines (ICE) should be maximised. ICE world-wide builders have to cope as well with the more and more complex and urgent to be solved problem of the exhaust polluting emissions due to ICE.

It is well known among specialists, that the assembly cylinder-piston-piston rings is the main contributor to the engine frictional losses, and that the performance of the piston rings importantly affects power, fuel and oil consumption, level of harmful emissions, blow-by, wear, noise and cooling of the engine. In consequence, the optimisation of the tribological working parameters in the piston ring-cylinder couple constitutes one of the most important ways to achieve highly efficient diesel engines.

The cylinder-piston ring contact is subject of the most adverse operating conditions: piston rings must seal effectively against the cylinder wall and maintain the seal during millions of working cycles, while deposits, piston motions, inertial forces, cylinder distortions, in-cylinder pressure and its gradients, hydrodynamic forces, elevated temperatures and wear, all combine to make the piston rings life difficult.

In the tribological couple, the piston ring detains the main function of gas sealing to assure that the combustion chamber of the ICE is gas tight. The piston ring also controls the thickness of the lubricating oil film formed on the cylinder liner inner surface, and ensures the heat conducting from the piston, which is heated by fuel combustion, to a cylinder liner in order to cool the piston. To realize such functions, a piston ring must be always subject to tension stress that will cause it to bulge and tightly contact with a cylinder liner. As a result, a piston ring will then seal high-pressure combustion gas generated in the combustion process of an engine. The sliding surface of a top ring is, therefore, inevitably subjected to high pressure and exposed to conditions under which wear and scuffing are liable to occur.

In recent years, the operating conditions of the piston rings, in particular of the top piston ring, have tended to become increasingly severe because of the following factors. To meet with tightened exhaust gas regulations, combustion temperature and surface pressure load are enhanced. Low-viscosity lubricating oil is employed. Meanwhile, high-pressure fuel injection is also often employed in medium-to-high loaded diesel engines. Thus, improvement in wear resistance and scuffing resistance of a piston ring will have to be required.

To achieve these goals, the modern usual solutions involve the coating of the sliding surface of the piston ring with hard layers, wear resistant, such as Cr, CrC or CrN, TiC or TiN. The main disadvantage with the piston ring coating classical methods is the relatively low adherence of the coating layer to the basic piston ring surface. In this paper is analyzed the performance of more coatings and a choice is made for a composite coating of the top piston ring outer surface to best ensure the required hardness, wear and scuffing resistance, together with best adherent properties.

As experimental tests shown, the worsened top piston ring operating conditions especially near Top Dead Center (TDC) generates boundary lubrication, and even metal-to-metal contact [1]. The piston ring surface higher self-lubricating quality may be achieved applying adequate coating and by its laser micro modeling.

2. NEW COATINGS FOR PISTON RINGS

2.1 Chromium-nitride ion-plating coating:

As mentioned hereinabove, higher and higher levels of wear and scuffing resistance are required in recent years particularly in diesel engines. The development of the ion-plating chromium nitride coatings having improved wear and scuffing resistances and having improved resistance against defective peeling off is keenly desired.

A coating with a fracture toughness value of approximately $3 \text{ MPa}\cdot(\text{m})^{1/2}$ or more, a hardness of Hv 1600 or more (that would be free of defective peeling off and would have improved wear resistance), free of porosity (hence exhibiting no hardness reduction and high fracture toughness value) would be useful for the outer peripheral surface of a top ring mounted on the present high load diesel engine.

To achieve the above-mentioned goals, it is required a chromium nitride coating with a CrN crystal structure mainly composed of chromium, nitrogen, and carbon and characterized by [2]:

- A columnar crystal morphology having oxygen content in solid solution in the range of approximately 0.5 to 2.5 percent in weight;
- A morphology having the content of dispersed micro-pores in the coating inferior to 10% in volume;
- A concentration of carbon relative to the total concentration of the main components from 4 to 8% by weight, chromium at 70 to 80 percent by weight and nitrogen at 20 to 30 percent by weight;
- Crystalline orientation defined by the intensity ratio of dense crystal planes (111) to crystal planes (200) parallel to the coated surface between 0.80 to 1.20 and the texture of CrN (111) plane orientation is from 0.4 to 2.0 in terms of the CrN (111) structural coefficient: the crystal planes (111) have closer atomic nature, i.e., a structure with less space among atoms, together with a higher fracture tenacity, and consequently, a higher resistance to the initiation of cracks originated by external stress applied;
- A range of Vickers Hardness from 1,500 to 2,500 HV;
- A thickness of the coating film within the range of 5 to 80 microns.

Crack propagation in a direction parallel to the coating can be suppressed without decreasing a coating hardness, when the chromium ion-plating coating is so dense and free of pores and the fracture surface of the coating has a columnar morphology extending toward the surface of the respective coating.

Desirably, the columnar crystals oriented toward the coating surface of a chromium nitride ion-plating coating have a diameter of 0.2 to 5 μm . When the diameter is 0.2 μm or less, the columnar crystals are not effective for suppressing crack propagation. On the other hand, when the diameter is 5 μm or more, pores are so large that coating hardness diminishes, and hence wear resistance is reduced (Figure 1, [2]).

To enhance the coating hardness and avoid crack propagation in a direction parallel to the coating, thinning and shortening the columnar structure of chromium nitride is required. This is attained by the incorporation of carbon that provides a new starting origin of columnar crystal growth.

The chromium nitride ion-plating coating preferably has a main structure of CrN-type chromium nitride rather than Cr₂N-type chromium nitride structure that tends to have a fracture toughness value lower than that of the CrN-type chromium nitride structure.

Such coating is resistive to defective peeling off and does not cause abnormal wear, the piston ring doted with it having improved durability even when used in a high load diesel engine that operates under most severe wear circumstances.



Figure 1: Coating columnar structure

The chromium nitride ion-plating coating is formed by an arc ion-plating method in low-pressure gas atmosphere consisting of nitrogen gas, hydrocarbon gas, and argon gas, at -30V to 0V of bias voltage. Argon gas should be added in an ion-plating apparatus to supplement the decomposition and ionization.

Due to ion impact, when the bias voltage is lower than -30V, the diameter of columnar crystals is too large and the fracture toughness value of the coating is less than the minimum intended of $3\text{MPa}\cdot(\text{m})^{1/2}$.

2.2 Diamond-like carbon (DLC) coating for piston ring:

A metastable state amorphous carbon DLC coating is deposited on the external surface of the piston ring substrate or on the surface treatment surface or on the nitrifying layer to ensure better wearability.

The carbon atoms in the DLC coating are combined with one another mainly by sp^3 and sp^2 hybrid bonds and the performance of the piston ring surface approaches to the one of the diamond [3].

The hardness of DLC coating is two to three times higher than the one of chrome plated or nitrified piston ring surface, and the friction coefficient is extremely low, less than 0.1, so that the attack of the ring on the cylinder sleeve is reduced.

In consequence, the piston ring scraping and abrasion resistance is improved, the service life of the ring and cylinder liner are prolonged greatly.

2.3 Diamond-like composite coating:

A diamond-like **composite coating** with high hardness and good abrasion proof as well as with self-lubricating properties is deposited on the surface of a piston ring. A nitriding layer with high bonding strength, high hardness and good abrasion resistance is formed on the surface of the piston ring by the low-temperature plasma nitriding treatment; a non-hydrogen diamond-like surface layer with solid lubricating property is deposited by the combination of magnetic filtration cathode arc and magnetic control sputtering [4]. The resulting final piston ring surface nitriding/diamond-like composite coating is dense and smooth and possesses excellent abrasion proof and self-lubricating properties. Compared with the durionising piston ring or CrN plating piston ring, the diamond-like composite coating of the piston ring has higher comprehensive performance.

3. LASER MICRO MODELING TECHNIQUES FOR THE PISTON RING SURFACE

3.1 Piston ring upper and lower end-surfaces laser micro modeling:

The metallographic organization consists of a micro-geometrical structure obtained after the upper and the lower end-surfaces of the piston ring are processed by a laser micro modeling.

The geometric parameters of the micro-geometrical structure are the radius of the pit, **rp** equal to 20 to $50\mu\text{m}$, the depth of the pit, **hp** equal to 2 to $8\mu\text{m}$, the area occupancy of the pit, **Sp** equal to 5% to 15%, and the distance of the pit, **L** equal to 90 to $230\mu\text{m}$ (**Figure 2**, [5]).

The advantages are that after the upper and the lower end-surfaces of the piston ring are processed by the laser micro modeling, the metallographic organization is changing, the hardness is improved and the wearing resistance is enhanced; the micro-pits store lubricant and wearing particles improve the lubrication and reduce the wearing. The extrusion effect of the lubricating oil film of the pit reduces the break of the piston ring.

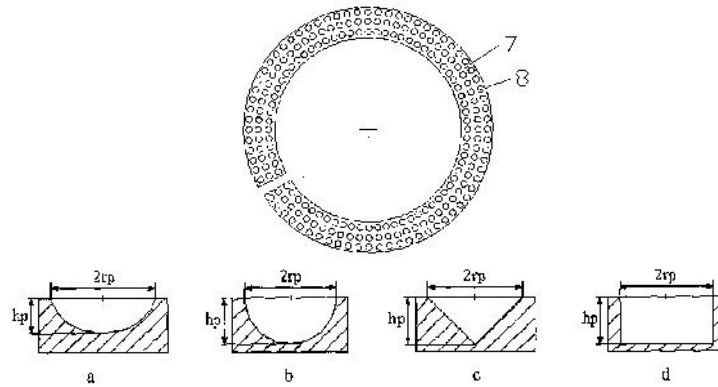


Figure 2: Laser micro modeling on the upper end surface and the lower end surface of the piston ring
7 – interspaces; 8 – protrusions.

3.2 Piston ring sliding surface laser texturing:

Surface texturing as means for enhancing tribological properties of mechanical components is well known since many years. Perhaps the most familiar and earliest commercial application of surface texturing in engines is that of cylinder liner honing.

Surface texturing in general and **laser surface texturing (LST)** in particular has emerged in recent years as a potential new technology to reduce friction in mechanical components [7].

A significantly lower friction was obtained with optimum partial LST cylindrical face Cr-coated piston rings, where only a portion of the ring face width was textured. The partial LST is based on a “collective” effect of the dimples [8] that provides an equivalent converging clearance between nominally parallel mating surfaces similar to the “inlet roughness” concept in [9].

Experiments showed that a **friction reduction of up to about 25%** could be obtained with partial LST cylindrical face rings [10].

The partial LST-treated piston rings exhibited up to **4% lower fuel consumption** under mid-load conditions. This level of fuel economy was obtained at the maximum torque of the engine. It was found that the effect of the LST is lower for particularly high and particularly low engine loads (**Figure 3**, [6]).

From the data collected during experiments with and without LST [6], there was no noticeable difference in the engine oil temperature or the crankcase pressure, thus indicating no negative effect of the LST on a possible leakage between the in-cylinder and crankcase compartments. The laser texturing did not produce a significant change in the exhaust gas composition.

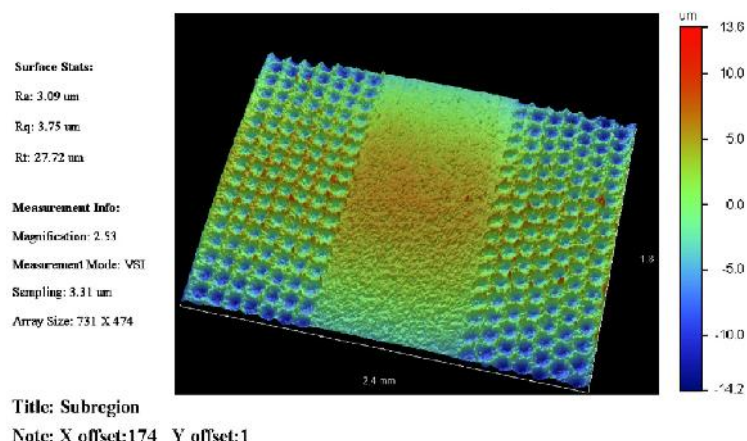


Figure 3: 3-Dimensional interactive display of the textured piston ring sample

4. CONCLUSIONS AND FURTHER DEVELOPMENT OF THE RESEARCH WORK

Applied together, the above-described coating and texturing methods could bring important benefits to the piston rings performance in terms of friction, wear loss, oil, fuel and particulate emission reduction, hydrodynamic

lubrication extension to significantly prolong piston rings service life and raise the internal combustion engine efficiency (**Figure 4**).

Considering especially the top compression piston ring, that normally operates under most severe conditions, its tribological parameters in its sliding contact with the cylinder liner, its resistance and efficiency will be further improved after deeply studying the ideal geometry of the sliding surface and the ring shape.

One solution for the ring shape is represented in **Figure 4** where it is shown a ring with inclined upper and lower sides in an adequately shaped groove, to avoid adherent wear [11].

As to the ring sliding surface geometry, the double-barreled ring face ([1], [12]) will be further developed to avoid limited lubrication when piston is near top dead center.

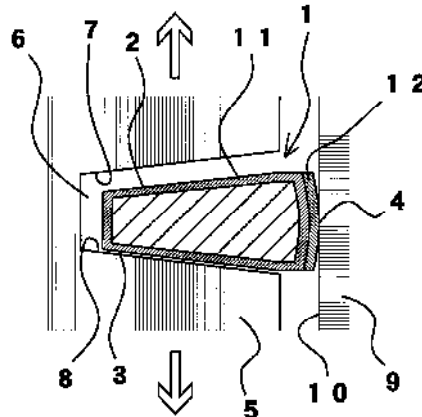


Figure 4: Schematic section through the tribological ensemble cylinder-piston-piston ring:

1 – piston ring; 2 – the upper end surface of the piston ring; 3 – the lower end surface of the piston ring; 4 – the cylinder-piston ring sliding contact; 5 – piston; 6 – the groove for the piston ring in piston; 7 – the upper side of the piston ring groove; 8 – the lower side of the piston ring groove; 9 – cylinder; 10 – in-cylinder honed surface of contact; 11 – ion-plated nitrified layer of the piston ring; 12 – diamond-like carbon coating on the sliding piston ring surface.

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