

Piston Ring Tribological Challenges on the Next Generation of Flex-fuel Engines

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ABSTRACT

With the current use of bio-renewable fuel, the application of Ethanol in Flex-Fuel vehicles presents a very low CO₂ emission alternative when the complete cycle, from plantation, fuel production, till vehicle use, is considered. In Brazil more than 80% of the car production is composed of Flex-Fuel vehicles. Due to the lower heating content of the Ethanol, more aggressive combustion calibrations are used to obtain the same engine power than when burning gasoline. Such Ethanol demands, associated with the continuous increase of engine specific power has lead to thermo-mechanical loads which challenges the tribology of piston rings.

The ethanol use brings also some specific tribological differences not very well understood like fuel dilution in the lube oil, especially on cold start, corrosive environment etc. Under specific driving conditions, incipient failures like spalling on nitrided steel top rings have been observed. When running with Ethanol, Flex-Fuel engines present higher PCP and this peak occurs in a crank angle closer to the Top Dead Center. Such condition increases ring wear, scuffing risk and tribological conditions that may lead to cracks on the nitrided case and later spalling.

This paper covers the top ring performance on flex-fuel engines on the tribology perspective. It is discussed how the ethanol use on Flex-fueled engines affects the top ring in terms of wear, scuffing, spalling and friction. For the evaluation of wear and spalling resistance, dyno engine tests are presented. On scuffing, block on ring tests were performed and a rank of ring coatings is presented. Top ring friction behavior and its impact on fuel consumption are also

discussed. Test results on engine floating liner are presented. Finally, ring technical solutions to overcome these challenges are discussed. Among them, steel piston ring with an improved nitriding treatment for increased toughness and a PVD coating to improve wear resistance and friction.

It is presented several rig and engine tests to support the discussed technical solutions. Engine tests are based on an abusive procedure to evidence/anticipate the effects on performance caused by the unique characteristics of flex-fueled engines running with Ethanol.

INTRODUCTION

Use of bio-fuels has gained attention in the last years due to the reduced CO₂ emissions if the fuel complete cycle, from fuel production till vehicle use, is considered [1]. Among the bio-fuel alternatives, use of ethanol in SI engines is the one with major use. In Brazil, consumption of ethanol has surpassed the gasoline consumption, especially after the introduction of the so called Flex-fuel engines. Flex-fuel engines can burn everything from pure ethanol (E100) to pure gasoline (E0). The engine fuel flexibility allows the user choice of which fuel is more economically interesting since the ratio price between gasoline and ethanol changes seasonally and also per region.

Considering the complete fuel cycle, the average Brazilian vehicle CO₂ emission is estimated in less than 75 g/km, about 35 g/km if only the ethanol running fleet is considered. However, the use of ethanol also brings some drawbacks: due to its lower heat content, fuel consumption with ethanol is about 30% higher than with gasoline. In order to achieve same engine performance and making use of the higher octane value of ethanol, engines are usually calibrated to have

Peak Combustion pressure 20-30% higher with ethanol. Figure 1 shows the Combustion Cylinder Pressure of a Flex-Fuel engine. Running with Ethanol, the Peak Combustion Pressure, PCP, is not only higher but occurs closer to the top dead center (crank angle equal zero in Fig.1). Such combination increases the tribological severity, especially for the piston ring, since the maximum load occurs in an angle with lower sliding speed. With ethanol, about 30% more fuel mass is injected in each cycle, increasing the chance of fuel dilution in the lube oil, further increasing the tribological severity.

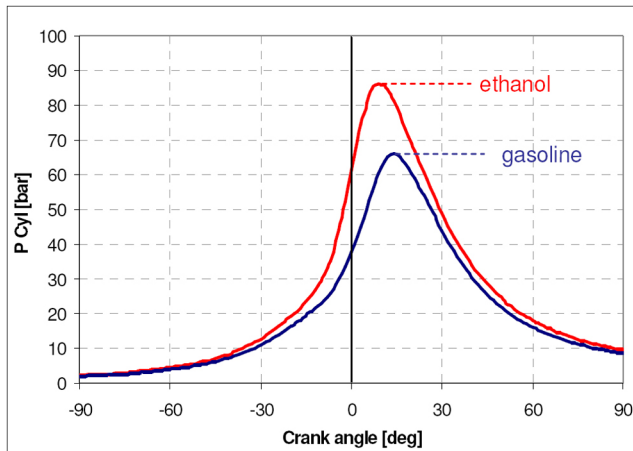


Figure 1. Combustion pressures of a 1.6 Flex-Fuel SI engine at rated power.

TOP RING TECHNOLOGY

Top rings for SI engines are mainly made in ductile cast iron or more commonly in steel, with different running face coatings. The most popular configuration is the gas nitrided stainless steel, GNS. In comparison with the coatings, the gas nitriding surface treatment allows sharper corners and other design features that promote better sealing [2]. For more demanding engines, PVD coated rings are being introduced. PVD coatings combine excellent wear, scuffing resistance combined with very low friction coefficient [3], [4] as well as lower wear on the cylinder bore [5] but its cost is still higher than conventional rings.

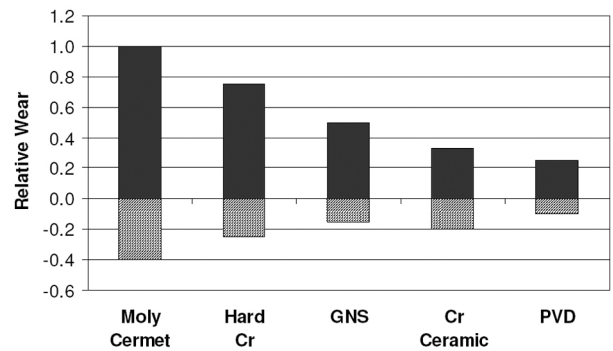


Figure 2. Relative ring and bore wear [5].

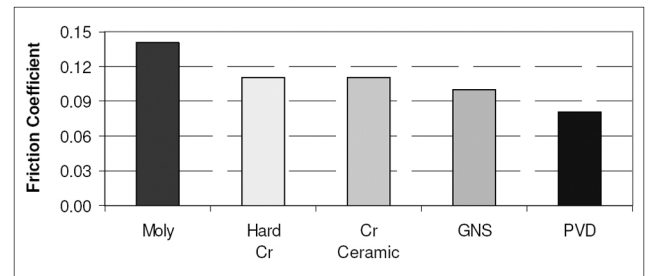


Figure 3. Friction Coefficient of the different ring coatings. [4].

As mentioned, stainless steel gas nitrided is the most common SI top ring type. That is true especially in Brazil, where more than 90% of the Flex-Fuel engines use it. However, due to the higher tribological severity of the Ethanol use, in some incipient cases the GNS may fail: some spalling occurs. Figure 4 shows one example of such occurrence.

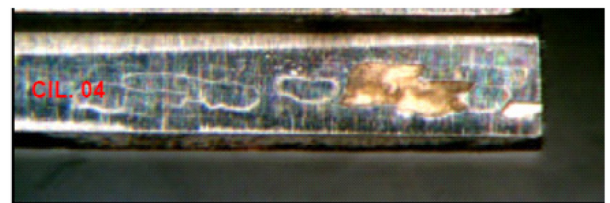


Figure 4. Spalling in a GNS top ring. [6].

The use of flex fuel engines is also common on USA, most of the new engines able to burn up to 85% of Ethanol in the fuel (E85). In such applications, besides the higher levels of PCP near to the top dead center, there is a significant concern about cold start due fuel dilution. Once such tests usually occurs in a temperature level of about -20 or -30 °C, the bore washing by excessive ethanol is a critical condition that can lead top ring to scuffing. Figure 5 shows the rank of current top ring technologies to scuffing resistance.

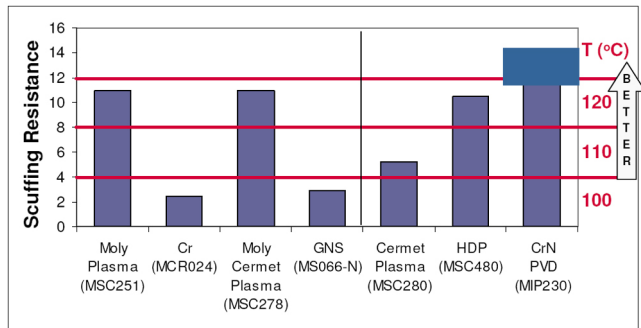


Figure 5. Scuffing rank of ring coatings.

Due to the mentioned facts, there is a need for development of the current coating portfolio for Flex-Fuel engines:

- Nitriding: mostly used in Europe and Brazil. It has excellent resistance to wear which fits to the increased PCP of FFE. However it presents lower toughness which may lead to spalling.
- Thermal spray: mostly used in USA. Some increase on the wear resistance is necessary due to the trend of increased PCPs. Eventual surface failure is characterized by thermal degradation, usually called “heat checking”.
- PVD: it is the premium solution to reduce friction and has the highest wear resistance. In very specific cases may present spalling occurrences, so improvement on the coating toughness would be beneficial.

NEW TOP RING COATINGS AND SURFACE TREATMENTS

To meet the current and future demands on SI engines, especially for Flex-Fuel use, MAHLE has developed or improved its top ring portfolio. Ahead are described the new ring technologies that best fit on Flex Fuel Engines. Novel nitriding, moly plasma and PVD ring technologies are presented and briefly discussed.

GNS-FLEX - INNOVATIVE NITRIDING TREATMENT

To counter the spalling problems described before, without jeopardizing the wear resistance of the nitrided layer, it was developed a novel nitriding case with improved toughness, patent required.

Gas nitrided stainless steel, GNS on top ring for SI engines has surface hardness around 1200HV_{0.1} [7]. It is believed that the hardness provided by the nitrided layer is directly linked with wear resistance for piston rings. Nitriding process temperature for all steels is between 495 and 565 °C [8].

In order to increase the surface toughness, without jeopardizing the wear resistance, a novel nitriding process was

developed for piston rings. The rings were nitrided according a novel recipe. An unique combination of nitriding parameters produced a case where although the surface hardness was maximum 800HV, well below 1200HV as the typical GNS, even though the wear resistance was not affected. The lower hardness and a different microstructure resulted in a case with higher spalling resistance, as described ahead.

The typical nitrided ring for SI applications has surface hardness of about 1200HV and presents one nitriding diffusion layer with relative abrupt hardness gradient. See [Figure 6](#). The developed new recipe produces a surface hardness of around 750HV, with a smoother hardness gradient. The total nitriding layer thickness is about 60 μm, well suited for SI applications. The new product was aimed at reduction of crack nucleation formation and propagation, maintaining the good characteristics on wear resistance.

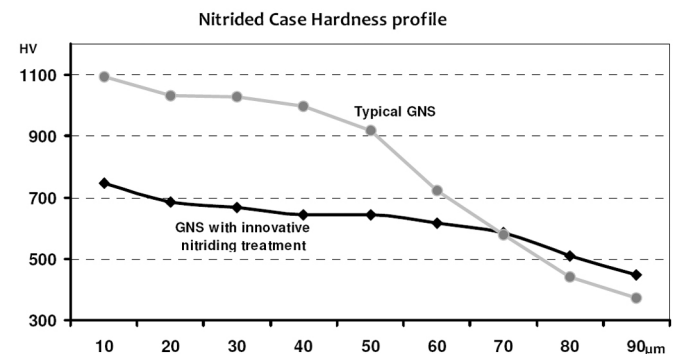


Figure 6. Hardness profile of nitriding treatment, typical and innovative recipes.

The novel nitriding case presents a different nitriding network pattern than the current GNS, the latter shows precipitation of fine carbides at grain boundaries, parallel to the surface, typical of such treatment. See [figure 7](#). These carbides, although fine, under high cyclic working loads, can create conditions to crack propagation through the grain boundaries (where the carbides are precipitated), possibly originating cracks with consequent GNS surface detachment (spalling).