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Effects of ethanol content on cast iron cylinder wear in a flex-fuel internal combustion engine–A case study

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ABSTRACT

The localized wear within a four-cylinder automotive spark-ignition internal combustion engine was investigated using a dynamometer durability test. The test engine was equipped with flexible fuel technology, popularly known as "Flex-Fuel", capable of operating under any mixture of gasoline and ethanol in the fuel. A 2-D profilometer analysis was conducted on engine block specimens from the Top-Dead-Center (TDC) and Bottom-Dead-Center (BDC) positions in order to identify localized wear characteristics. The profiles have shown localized wear dependence in regions of the cylinder bore, as did comparative results between two test conditions: (i) an engine fueled with local gasoline (E25) and (ii) an engine fueled with ethanol (E100). Selected localized wear regions have been characterized using scanning electronic microscopy. Complementary piston ring wear analysis was carried out to assess the remaining coating thickness at the end-of-test. The test with ethanol resulted in the highest localized wear, which occurred at the Bottom-Dead-Center position. A condensed literature review was conducted. An attempt was made to correlate the observed wear features with possible mechanistic theories found in the wear literature. Characterization results indicated that three-body abrasion by carbon residues and piston ring particles is one of the important mechanisms contributing to the cylinder bore wear.

1. Introduction and literature review

Considerable efforts have been devoted to producing increasingly efficient vehicles and machines, not only for economic reasons, but also to reduce anthropogenic greenhouse gas emissions [1]. The internal combustion engine (ICE) is used worldwide in very large numbers, be it in self-propelled vehicles or stationary applications [2]. The engine and its components, e.g., the cylinder block, are designed to offer the highest performance and durability, in association to minimum levels of air pollution [3].

Indeed, cylinder bore wear may influence both the chamber sealing and friction losses, therefore affecting fuel consumption and gas emissions [4]. Accordingly, it has been an important area of research, involving industries, universities and technological institutes, over the past decades [4–28] and currently [29–36].

Despite the level of advances achieved, the survey of the literature [4–36] has revealed limited information on the wear found in the lower portion of the cylinder, which is known as the Bottom-Dead-Center (BDC) [6,10,35]. Although a great deal is known about the wear on ICE cylinders running with diesel [8,11,22,32,35] as well as with gasoline [10,20,27,33] fuels, little has been published about the effects of ethanol fuel on the wear [36–38].

The use of ethanol usually brings drawbacks that may affect the wear of cylinder bores. Due to its lower heat content, the peak combustion pressure needs to be adjusted to levels about 20–30% higher than with gasoline [38], therefore intensifying the tribological severity at the piston ring-cylinder bore interface [36,37]. In spite of the numerous studies, the wear mechanisms acting on ICE cylinders seem to be a still wide-open field for research.

Previous studies have been conducted to investigate wear-related aspects of ICE cylinders after being subjected to dynamometer durability tests [10,20,27,33]. Here, the cylinder bore material was either cast iron [10,20] or aluminum alloy [27,33].

Studying cast iron liner wear using a dynamometer test, Sreenath and Raman [7] inferred that metal to metal contact takes place at certain cylinder dead center locations, and the rapid wear at these positions helps to achieve quick conformance between rings and the liner during running-in. At locations where there is considerable relative velocity between ring and liner surfaces, the combined sealing effect of the surfaces and the hydrodynamic oil film reduces blowby considerably, whereas at dead center locations, sealing is mainly due to the conformity of contacting surfaces. The authors believed that, in the initial breaking-in period, the surfaces could be smoothed due to material removal from the asperities summits. However,

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with regard to Sreenath and Raman results, Barber and Ludema [10] discuss that the action of piston rings could develop new asperities well below the level of the hone marks. The hypothesis proposed by Barber and Ludema was based on the fact that the asperities were originally of a 0.48 µm centerline average height whereas an average of 2.1 µm of material was worn away before the flat tops were seen.

Barber and Ludema [10] examined cylinder walls and piston rings of gasoline-fueled engines, which ran both on the road and in dynamometer tests. The cylinders were made of pearlitic gray cast iron. In the TDC region, the wear process is described as a progression of events involving sliding and abrasive wear, where the moving piston ring breaks off material from honing grooves ridges, and uses it to scratch vertical grooves in the cylinder wall. With further wearing, all of the ploughed material is removed and the slower wear processes then operate to remove most of the grooves from the surface.

Vatavuk and Demarchi [13] studied the localized wear mechanisms acting on cast iron cylinders of a diesel engine subjected to a dynamometer test. They found that the lubricant and fuel properties are important to the localized wear in the TDC, as they affect the film thickness at high temperatures near the combustion chamber and, therefore, the probability of metallic contact at the top ring reversion point. In addition to metallic contact under sliding condition, Vatavuk and Demarchi reports that a corrosive environment increases the detachment of hard particles, constituting a wear mechanism due to corrosion. The detached material will further act as abrasive particles.

Another possible wear mechanism in cast iron cylinders was described by means of cracks and the formation of large debris associated to the graphite flake morphology [8,39,40]. Riahi and Alpas [39] investigated the sliding wear of a gray cast iron after being tested against bearing steel, under an extensive range of loading and sliding speed conditions. In the mild wear regime, the graphite flakes morphology acted as weak points where the material near the contact surface would fail preferably. The large-size debris formation was described by the authors as a mechanism called “failed necks”. In this mechanism, the metallic particles did not oxidize quickly. The behavior was attributed to their large size. The particles would remain in the tribo-system as loose debris or would be entrapped in the interface. At high loading conditions, the temperature and pressure on the particles appeared to be sufficiently high to cause post welding events [39].

Schneider and Blossfeld [20], in 2004, reported dynamometer durability tests results of an automotive spark-ignition (SI) engine fueled with gasoline. The cylinder bore wear rate was measured using a radiotracer method. An average wear rate of 4 nm/h was reported, which occurred in the TDC, in the piston top ring position.

Gangopadhyay [17] performed wear measurements in automotive engine cylinders, from 3.0 L and 4.6 L displacement SI engines which had accumulated usage running in USA cab vehicles. The localized maximum wear valleys observed in several vehicles were measured and reported, after engine disassembly. For example, a case of an engine cylinder was reported; its localized wear valley achieved 10 µm wear, extracted from a vehicle that ran 110 thousand km.

Of the few available studies quantifying the wear occurred in the BDC, an attempt to correlate in-service wear profiles with theoretical calculations were performed by Ting and Mayer [5,6]. In order to demonstrate and to confirm the formulated theory, an 8-cylinder diesel engine cylinder bore was analyzed, after 75,690 km vehicle mileage, by wear profile measurements. The load pressure acting on the cylinder wall is composed of the gas pressure behind the ring and its natural spring tension. There is a decrease of wear at the mid-stroke due to the hydrodynamic regime granted by the higher piston speed, while the wear at the motion reversal points is increased due to the loss of oil film hydrodynamic action. The authors argue that the degree of wear at the bottom of stroke should be comparatively less than at the top of the stroke, since the gas pressures behind the rings are smaller. Indeed, most of the actual wear profiles measured by Ting and Mayer presented the maximum localized wear in the TDC. Conversely, in some cases, the localized wear in the BDC resulted in equal or higher magnitude than in the TDC [6].

Dimkovski, Baath, et al. [32] characterized wear particles embedded in the deposits inside the cylinder bore honing grooves. Among other chemical elements, the authors found iron and silicon. The iron origin was attributed to the cast iron matrix or wear debris embedded in the deposits, while the silicon would derive either from the liner material or from the charge air. Here, metallic particles were embedded into the deposits as a result of the simultaneous processes of wear and deposit accumulation. In another study, Dimkovsky, Anderberg, et al. [28] discuss a potential event occurring due to the imperfection of the manufacturing process of cast iron bores, where the honing grooves, especially the deep ones, are smeared and interrupted by folds. According to Dimkovski et al., a portion of the folds would eventually detach during the running process and act as abrasive particles increasing the wear in the cylinder. Additionally, the characterization of worn cylinder liner surfaces by segmentation of honing and wear scratches demonstrated abrasive wear predominating in the TDC, whereas few scratches were found in the BDC [35].

Using the TEM technique, Meng-Burany, Perry et al. [33] showed details of the oil residue layer and ultrafine grains on which an oil residue layer was formed after the wear tests. The layers incorporated debris described as nanocrystalline fragments of silicon and aluminum. The study was based on a V8 gasoline engine with monolithic Al-Si engine block.

Khorshid and Nawwar [12] reviewed the effect of sand dust and filtration on automobile engine wear, highlighting the external sources of abrasive particles. In addition, Michalski and Woś [34] performed dynamometer tests on free aspired air-cooled aircraft engines, during 10 h of fired running-in period, 21 h operation of intensified abrasive wear in the piston–cylinder assembly. The wear was forced by dosing road dust into the inlet manifold. It was reported that, in this condition, the abrasive particles caused the equivalent wear rate as during 1500 h of durability test in real conditions.

Furthermore, the fuel type affects the carbonaceous deposits formation during engine combustion [41]. According to Kalghatgi [42], the nature of the carbonaceous residues varies from soft and oily to sticky varnish to hard and coke-like. In gasoline engines, one of the possible mechanisms described would comprise evaporation of lighter hydrocarbons, resulting in a thin film rich in heavier hydrocarbons. The film oxidizes to form a sticky varnish that can bake into a hard deposit given sufficient time. This deposit can bind particulates such as airborne dirt and solids that get into the intake manifold [42].

Regarding the biofuel ethanol, DeSilva, Priest et al. [36] investigated the friction at the piston ring and cylinder bore interface with a formulated engine lubricant contaminated with ethanol and water, using a reciprocating tribometer test. The lubricant mixture was separated into two phases, an oil phase and a water and ethanol-based ‘white sludge’ phase. The authors concluded different dependences of friction on the oil/fuel mixture. When the system was lubricated with the separated oil phase, temperature was shown to be the dominant contributor to the frictional response. When lubricated with the separated sludge phase, ethanol independently contributed to the frictional response. The interactions between ethanol and temperature, water and temperature and water and speed were also important to the results.

The most common flexible fuel engine type is the one capable of working with both gasoline/ethanol fuels, in any mixture proportion. It is colloquially termed as “Flex-Fuel” engine. In the case study presented herein, we report and discuss results of the wear aspects at the top, middle and bottom ring reversal points, with regard to Flex-Fuel engines. An engine fueled with local gasoline (E25)[1] and another one

[1] Currently, there are no vehicles in Brazil running on pure gasoline. The government made it mandatory to blend anhydrous ethanol with gasoline. The gasoline blend with 25% (and permissible variation margin) of anhydrous ethanol is known as “E25 gasoline”, or simply “gasoline” in the present research context. The term “E100 ethanol”, or simply “ethanol” in the present research context, refers to hydrous ethanol (E100). The fuels are regulated by the Brazilian National Agency of Petroleum, Natural Gas and Biofuels.