SURFACE CHARACTERIZATION OF A REAL-WORLD CYLINDER LINER SUBJECT TO DEPOSITION FROM COMBUSTION

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1 ABSTRACT

This paper investigates the effects of combustion product deposition using a cylinder liner taken from a C-segment passenger vehicle run for 105,000 miles. Using a novel methodology of Atomic Force Microscopy and X-ray Photoelectron Spectroscopy the pressure coefficient of boundary shear strength of asperities and the nature of the depositions along the liner is considered to predict the boundary friction of a piston ring pack. Results show that the combustion depositions create localized values of the pressure coefficient of boundary shear strength of asperities at top dead centre, mid-stroke and bottom dead centre, increasing ring pack friction by 50 N in the combustion stroke per engine cycle.

2 INTRODUCTION

The reduction of friction in the automotive industry is a key driver to achieve new emissions and fuel economy targets set by governments across the globe [1]. It is reported that frictional losses make up to 20% of the total losses in an Internal Combustion (IC) engine, of which the piston ring pack contributes 40-50% in both passenger and heavy-duty vehicles [2-4]. The accurate simulation of such systems is therefore essential when evaluating new designs and technologies. It is common that piston ring packs are subject to mixed or boundary regimes of lubrication due to the large in-cylinder pressures in the compression and combustion strokes of the engine cycle. The lack of film in the conjunction can lead to increased frictional losses due to direct contact of asperities resulting in wear of components [5, 6].

The necessity to model oil transport accurately within the ring pack is of particular importance due to the reduced lubricant availability during the combustion stroke, whereby the inlet is starved due to the high in-cylinder pressures. The model proposed by Tian et al [7] is commonly used as it considers the average flow model of Patir and Cheng [8, 9]. A one-dimensional model was developed for a compression ring and then further extended to three rings, whereby it is assumed that during the down-stroke the leading ring would always have sufficient lubricant available at the inlet. For the Reynolds exit boundary condition was replaced by a non-film separation condition, whereby the domination of squeeze effects is taken into consideration. It was also shown that the effects of surface roughness have a significant contribution to the mechanism of oil transport, highlighting the necessity of boundary friction models in ring pack simulation.

The surfaces of real IC engines, such as piston rings and cylinder liners, are rough and should be modelled accordingly as they contribute to boundary friction. The boundary friction model proposed by Greenwood and Tripp [10, 11] is often used in ring pack simulation [12-16], whereby the roughness heights follow a Gaussian distribution. In order to use the model, the boundary shear strength of asperities, ς, must be obtained experimentally for the softer of the two contacting surfaces. Atomic Force Microscopy (AFM) in Lateral Force Mode (LFM) is the approach used to obtain ς, and is documented in [17, 18]. These measurements are made at different locations on the surface to account for variation in surface characterisitcs. A more recent study has shown that there is even variation of ς depending on the location of the liner being measured [19] and it is further believed that the higher depositions are as a result of carbon deposits resulting in piston varnish.

This paper presents a system level (top compression and scraper ring) approach to the modelling of a ring pack analysis with a boundary friction model which uses experimental results from a real world cylinder liner run under operating conditions for 105,000 miles using a commercially available lubricant with a complete additive package. The model takes into account lubricant starvation at the inlet due to the physical lack of lubricant and also reverse flow. Analysis of the liner surface is also shown using X-Ray Photoelectron Spectroscopy (XPS) to identify the depositions on the surface and link their composition to the friction coefficients obtained using the AFM.

3 METHODOLOGY

3.1 Experimental Procedure

A Veeco Dimension 3100 AFM is used in LFM mode to obtain ς as described in [18-22]. Bruker DNP-10 probes with 4 tips were used for the experiments, the selected tip having a spring constant of 0.350 Nm^{-1} and a nominal tip radius of 20 nm. The AFM measurements were repeated 5 times for each region of the liner (Top Dead Centre (TDC), mid-stroke and Bottom Dead Centre (BDC)). To study the deposition on the surface, XPS analysis has been carried out. This technique is commonly used to identify the composition of a surface between 3-10 nm depth using an ion beam. Although it cannot be used to identify Hydrogen elements, it can be used to find chemical changes such as oxidation, corrosion and adhered films on surfaces such as a cylinder liner. Nine scans were carried out for each region of the liner to gain an understanding of what deposits are on the surface.

3.2 Numerical Simulation

To model the pressure distribution within the ring pack a solution of Reynolds equation is required taking into account the film shape and lubricant rheology. The model used in this analysis as well as validation can be found in [24]. This model was further developed to a system level whereby the effects of starvation were taken into account with a novel set of inlet boundary conditions to predict oil transport within the piston ring to liner conjunction through an engine cycle [25].

The system level model is now combined with a more accurate prediction for boundary friction using experimental results previously reported in [19]. The combination of these two models leads to a novel system level simulation procedure which has thus far not been reported in literature. Figure 1a shows a schematic of the oil flow through a ring pack and Figure 1b shows the different zones on the liner which were measured for this analysis.

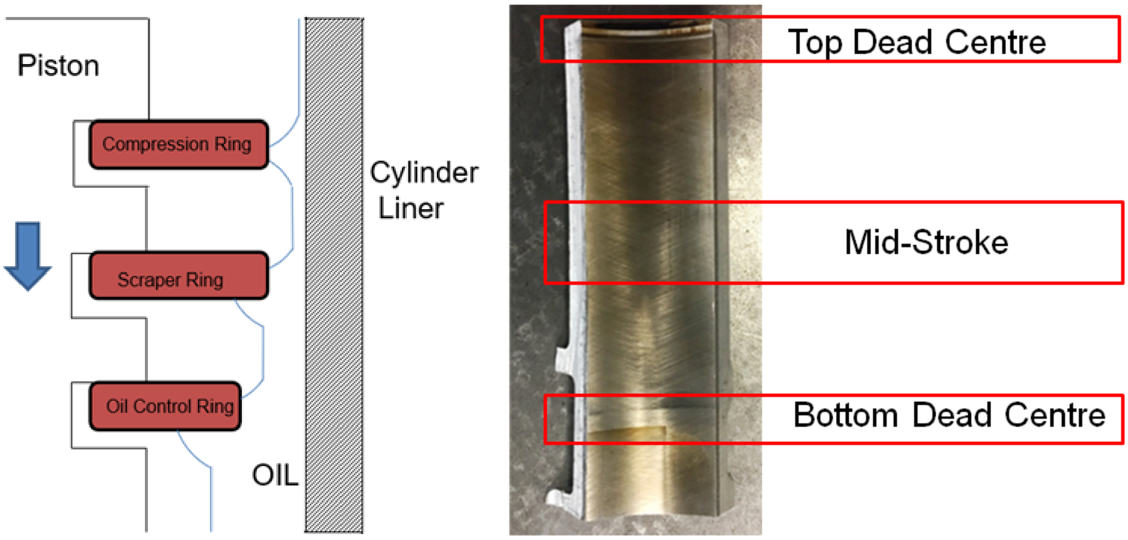

Figure 1: a) Schematic showing the flow of oil between the rings and liner for a down stroke (not to scale) and b) the liner zones measured for this analysis.

4 RESULTS AND DISCUSSION

For the experimental part of this work a cylinder liner was taken from a passenger vehicle engine which had completed 105,000 miles. The LFM measurements were conducted under wet conditions using Mobil Super 3000 5W-20, the same lubricant that was used throughout the fired engine testing. The gradients of the lines in Figure 2 represent the corresponding value of ς. The tests have been repeated 5 times for each zone and then averaged (Table 1). The results show that different ς values exist at TDC, mid-stroke and BDC. Further analysis using XPS was carried out and it was seen that the elements carbon and oxygen make up the main depositions on the liner (Table 2). It is likely that these are carbon black and carbon monoxide, with previous studies noting that a weight percentage of 60 Wt% carbon and 30 Wt% oxygen is indicative of piston varnish [26].

Zone	ς
TDC	0.253
mid-stroke	0.347
BDC	0.308

Table 1: Average ς values for the different measured zones

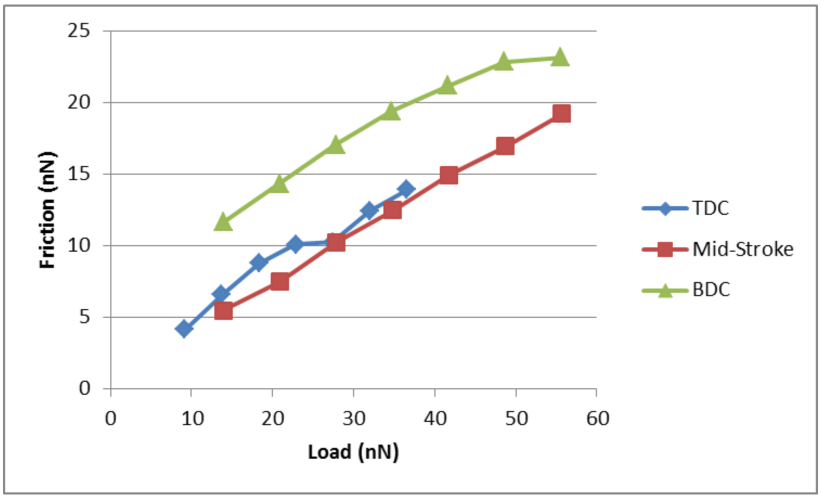

Figure 2: Measured wet contact LFM results

Element	C	Cl	Fe	K	N	Na	O	S	Si	Zn
Wt%	59.9	0.51	2.77	0.18	2.89	1.18	30.0	0.35	2.11	0.11

Table 2: XPS results for the liner at mid-stroke in Wt%

For the simulation procedure a 4-cylinder 4-stroke gasoline engine of a C-segment vehicle is used, the engine, lubricant and material data can be found in Tables 3, 4 and 5. The in cylinder combustion pressure and liner temperature for one engine cycle is presented in Figures 4 and 5. The engine speed is 1500 rpm which is the equivalent of 35 km/h on the New European Driving Cycle (NEDC) if the vehicle is in 3rd gear with an output torque of 52.03 Nm.

Parameter	Value
Torque [Nm]	52
No. of cylinders	4
Engine type	Gasoline SI
Crank-pin radius, *r* [mm]	39.75
Connecting rod length, *l* [mm]	138.1
Bore nominal radius, r_0 [mm]	44.52
Ring crown height, *c* [µm]	10
Ring axial face-width, *b* [mm]	1.15
Ring radial width, *d* [mm]	3.5
Ring free end-gap, *g* [mm]	10.5

Table 3: Engine data

Parameter	Value
Lubricant viscosity, η_0 [kg/ms]	0.05
Lubricant density, ρ_0 [kg/m^3]	833
Pressure-viscosity index α_0 [m^2/N]	1 x 10^{-8}
Eyring shear stress, τ_0 [MPa]	2.17

Table 4: Lubricant properties at atmospheric pressure and 40 ^{o}C

Parameter	Value
Liner Material	Grey cast iron
Modulus of elasticity of the liner material [GPa]	92.3
Poisson ration of the liner material	0.211
Density of the liner material [kg/m^3]	7200
Ring material	Steel SAE 9254
Modulus of elasticity of the ring material [GPa]	203
Poisson ration of the ring material	0.3

Table 5: Material properties

Simulation results of the minimum film thickness and cyclic total friction for the top compression and scraper ring are presented in Figures 6 and 7. It can be seen in Figure 6 that in the combustion stroke the film thickness drops from the mixed and into the boundary regime where $\lambda < 3$. In this stroke the localized value of ς plays a large role and the contribution due to the increased boundary friction results in a 20% higher peak friction during the cycle compared to when using an average ς value. This highlights the importance of taking into account such local effects, in particular those caused by deposition on the surface of a cylinder liner, when carrying out system level simulations.

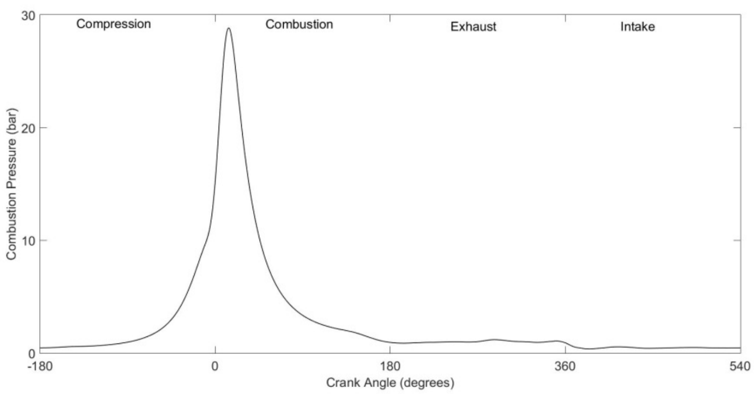

Figure 4: Combustion pressure

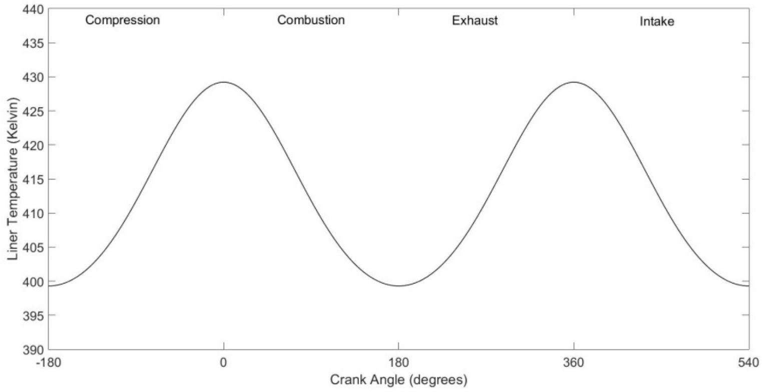

Figure 5: Liner temperature

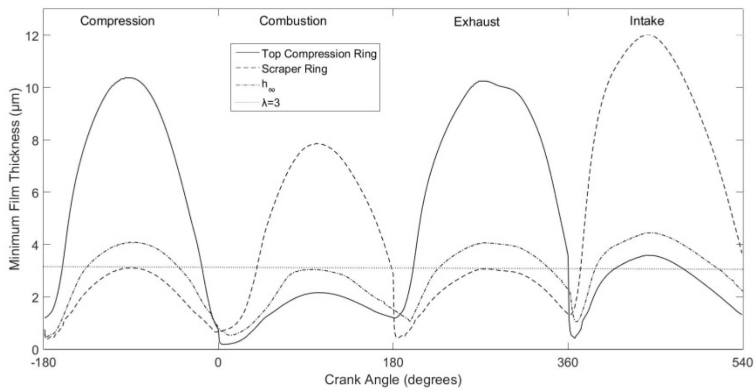

Figure 6: Minimum film thickness

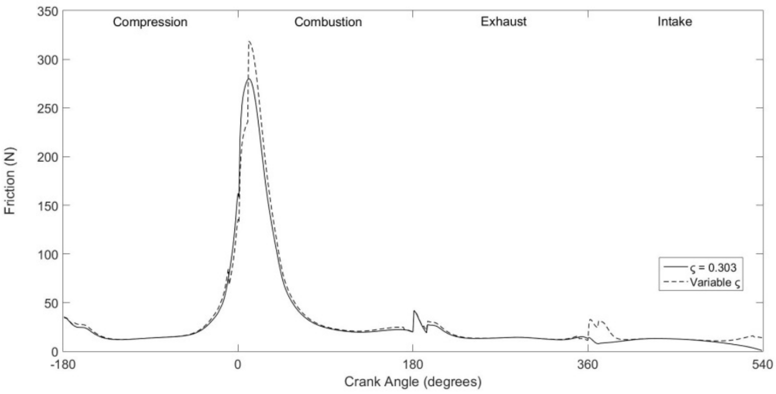

Figure 7: Total (viscous and boundary) friction for the ring pack

5 CONCLUSION

Experimental anlalysis shows that the effects of deposition such as piston varnish on a cylinder liner results in localized changes to the value of ς. This localized ς has a significant effect when boundary interactions occur. By using a system level model which takes into account starvation due to both the physical lack of lubricant at the inlet due to oil transport along the liner and lubricant recirculation, it can be seen that there are increased boundary interactions. By using a local ς values the resulting cyclic peak friction value is 20% higher than when using an average ς for the whole liner, thus showing the importance of such model enhancements for predicting boundary friction.

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