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Nano-scale Investigation of frictional characteristics of tribo-films in sliding contacts of representative in-cylinder conditions

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1. Introduction

Improving fuel efficiency of automotive engines and reducing emissions are key development targets. In a typical light duty automotive engine, there is 50-60% thermodynamic heat loss from the cooling system and exhaust gasses [1]. The frictional losses accounts for almost 15-20% of all engine losses [2]. This can increase up to 20-30% in urban driving cycle [3], of which 45% is due to the frictional loss of the piston assembly [1]. The piston-ring-liner interface in a typical internal combustion engine results in 7-8% of energy loss [4,5]. Therefore, this provides an opportunity for efficiency enhancement. It is essential to design systems to minimise frictional losses in piston-cylinder system [6].

The piston compression ring-cylinder liner conjunction is primarily responsible for sealing of the combustion chamber [7]. There are outward radial force due to ring tension and gas pressure loading, forcing the ring against the liner surface, thus resulting in frictional losses [7, 8]. In addition, the reciprocating kinematic behaviour of the piston ring causes a cessation of lubricant entrainment at and in the immediate vicinity of dead centre reversals. Consequently, there is a diminution of lubricant film thickness, promoting direct interaction of the contiguous surfaces. During this mixed regime of lubrication, the role of surface active lubricant additives becomes critical in reducing frictional losses and incidence of wear through formation of a tribo-film of rather complex chemistry [9]. The complex interaction of lubricant additives with contacting surfaces is as the result of competitive action of additive species in the process of bonding/adsorbing to the surface topography [10,11].

The effect of viscosity and additives on the reduction of friction in internal combustion engines has been widely reported in literature [12–14]. There has been significant progress in developing surfaces to minimise friction at the ring-cylinder liner interface, either by coating with specified material or having a textured pattern to create the micro-hydrodynamic lift, retaining reservoirs of lubricant [6,15,16]. The integerated study of lubricant and surface provides futher oportunity for improvement of the tribological contact [17].

In this paper a sliding tribometer is used with a lubricant and surface combination to activate lubricant additves to bond/adsorb to the surface of specimen. Surface chemical analysis of the test specimens is conducted before and after the application of the lubricant and activation through tribometry. The spectra of the form tribo-films show the presence of a Zinc Dithiophosphate (ZDDP) layer. Complementary data from lateral force mode using atomic force microscopy indicates an increase in nanoscale friction due to the presence of a ZDDP tribo-film, used as an anti-wear agent. Such an increase has been widely reported in open literature with micro-scale tribometry [18,19] which is confirmed by the current paper at the lower meso and nano-scales. This approach has not hitherto been reported in literature.

2. Experimental Method

The investigation is conducted through precision experimentation incorporating the use of a sliding strip tribometer, atomic force microscopy (AFM) in lateral force mode (LFM) and spectrometry of surface adsorbed/bonded chemistry using X-ray photoelectron spectroscopy (XPS). The experimental analysis is divided into three categories; pre-lubricated (dry) surface, lubricated (wet) and post-lubricated (dry, after removal of bulk lubricant) analysis as shown in Figure 1. First a pre-lubricated (dry) analysis is carried out as a base line. The pre-lubricated (dry) is to benchmark the surface sample for topography, elemental composition and frictional characteristics. The lubricated (wet) tribometry is carried out in the presence of a fully formulated lubricant on the surface. Applied contact pressure and sliding shear as well as generated flash contact temperature activate the boundary active elements within the lubricant, which then bond or adsorb to the surface of the specimen. For a post-lubricated (dry) analysis, the oil is removed from the surface of the specimen with standard procedure, only leaving any formed tribo-film on the surface. The lubricated (wet) phase produces the necessary tribo-film for given operating conditions; sliding speed, contact temperature and pressure. The post-lubricated (dry) analysis of surface provides the effect of any formed tribo-film in comparison with the initial bench-marked dry sample.

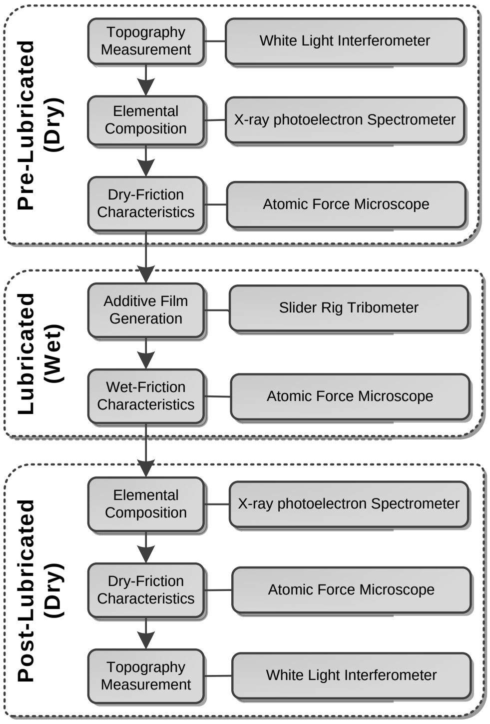

Figure 1: Experimental procedure

A reciprocating sliding tribometer (Figure 2) is employed to activate the surface-active constituents in the lubricant additive package. The speeds and loads used are representative of the piston compression ring-cylinder liner conjunction at the top dead centre reversal in transition from the compression to power stroke [20]. Friction is measured using a floating plate, mounted upon low friction bearings, representing the liner surface. The floating plate is dragged by the generated contact friction which is measured directly by high precision piezoelectric load cell and total friction [20]. The surfaces are then analysed to ascertain changes to their surface topography, as well as the chemistry of activated surface tribo-film.

Surface topography is monitored using white light interferometry, as well as in more detail using atomic force microscopy. AFM is also used in LFM mode [20, 21] to determine small scale adhesive friction. XPS is used to measure the changes in the surface chemistry.

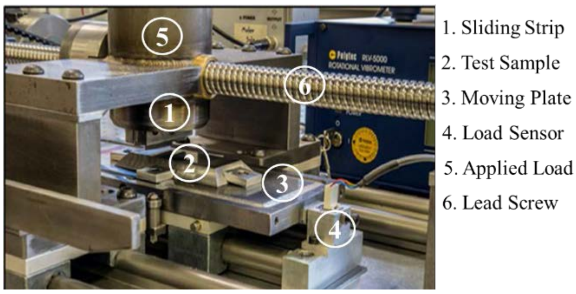

Figure 2: The sliding strip tribometer [22]

3. Results

An AISI 4140 steel substrate (plate) sample is used with the sliding strip of the same contact face geometry as a compression ring, made of AISI 440C steel ring material. Fully formulated 5W30 oil at room temperature is employed. Friction is measured at an applied contact forces per unit length of 413 N/m [6]. The resulting static and kinetic coefficients of friction along with the standard error bars are shown in Figure 3.

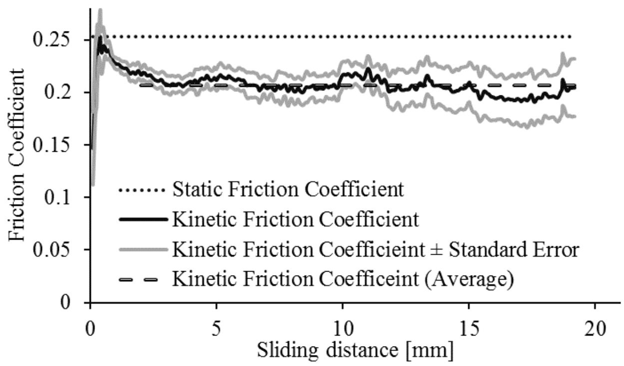

Figure 3:Measured static and kinetic coefficient of friction using the sliding strip tribometer

An elemental composition of the steel sample surface is conducted by Thermo-Scientific K-Alpha X-ray Photoelectron Spectrometer (XPS). The sample was scanned in XPS before application of lubricant to benchmark its surface elemental composition as given. The XPS scan of sample after the tribometry and removal of the hydrocarbon residue confirms the activation and formation of a ZDDP additive tribo-film on the sample. The XPS scan was conducted at nine different locations on the surface as the ZDDP makes patches of tribo-film on the surface. The results for the pre-lubricated (dry) and post-lubricated (dry) are shown in Figure 4.

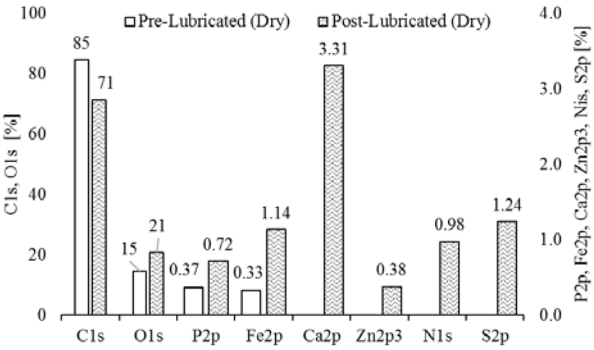

Figure 4: XPS scan of flat steel plate samples for Pre-lubricated (Dry) and post-Lubricated (Dry)

Similarly, the nano-scale friction, obtained by AFM in LFM mode for the steel sample in pre-lubricated conditions and post-lubricated dry with the effect of ZDDP tribo-film were obtained. The measurements were carried out, using a DNP-10 Si_3N_4 tip with a cantilever spring constant of 0.12 N/m. Friction with the ZDDP tribo-film is noted to increase in the patches on the surface. Friction at various loads for pre-lubricated and post-lubricated at five different locations on the sample are shown in Figure 5.

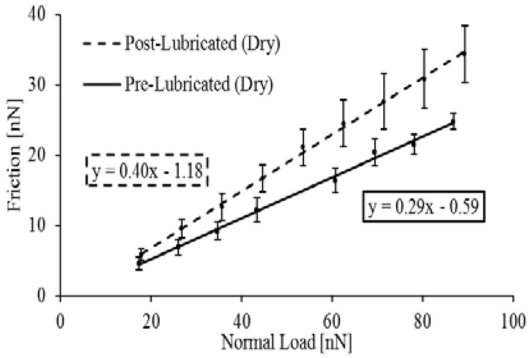

Figure 5: Friction at various normal loads in Pre-lubricated (solid line) and Post-lubricated (dashed line) measurements

4. Conclusion

The detailed experimental procedure for the pre-lubricated (dry), lubricated (wet) and post-lubricated (dry) provides an opportunity to critically examine the contribution of tribo-films formed on the contacting real rough surface. The designed procedure ensures the generation of a tribo-film on the surface and the evaluation of its effect at micro and nano-scales.

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