Friction and Wear of Tribo-Elements in Power Producing Units for IC Engines- A Review

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***Abstract*— Piston rings are vital components in the internal combustion (IC) engines having reciprocative motion. The oil film thichness plays important roll and finally affects the performance of engine. Surface roughness of tribo pair material at the junction produce friction and it varies throughout the stroke length of piston. Loss of power in lubrication has the shear force due to boundary conditions. The tribological performance in IC engine can be understood when friction and wear are considered. It is also necessary to study the factors influencing reliability and performance along with wear . From the view point of tribo element it is very important to know the specific load, speeds and temperatures for the major components of engine like piston assembly, valve train, the journal bearing and lower viscocity engine oil for lubrication. This paper explains the studies made on Cylinder liner and Piston rings interface. Published data on friction and wear have been collected from various researchers concluded from their experiments and experiences.**

***Keywords*— Piston Rings, Friction, Cylinder liner, IC Engines, Wear**

I. Introduction

Piston rings are important elements in the internal combustion (IC) engine. Their prime function is to facilitate smoth running of reciprocating part and dynamically seal the distance between the moving piston and the cylinder liner interface to prevent the escape of the combustion gases from the combustion chamber into the crankcase and at the same time the leakage of the lubricating oil from the crankcase into the combustion chamber. During the running of an IC engine, the hydrodynamic oil film at the interface between the different rings and liner is encouraged preferred. Thin lubricating film reduces both engine wear and friction. The performance, durability and exhaust emissions are greatly affected by the phenomena of lubrication at the junction rings and liner. The frictional force at the rings is determined by the load on the ring, the material surface properties and the lubrication conditions as determined by the velocity gradient viscosity and availability of the oil. The load on the ring comprises the ring pre-tension and the gas forces acting on the back-side of the ring. The total tension of the piston rings in the ring pack determines the friction losses at power producing unit. Wear of the cylinder liner is caused to a great extent by the action of the piston rings. Practical observations and theoretical analyses correlate well in terms of the strongest wear of the cylinder liners taking place in the vicinity of the top reversal point of the top piston ring, where the thermal, chemical, erosive, adhesive and abrasive conditions are the severest. A high sulphur content of the fuel can increase the proportion of tribochemical wear of the cylinder liner dramatically, particular at low cylinder surface temperatures. High wear of the cylinder liner is furthermore associated with the top reversal point of the next to top piston ring, and to a less extent with the bottom reversal points of the piston rings. Carbon deposits above the ring pack on the piston may significantly increase the cylinder liner wear near the TDC region. This paper explains the studies made on Cylinder liner and Piston rings interface. Published data on friction and wear have been collected from various researchers concluded from their experiments and experiences.

II. Literature Review

Researchers continuously involve in study of the lubrication charecteristics and different zones of lubrication at the motion of piston ring with respect to cylinder liner. Many researchers had considered that the entire surface of the ring was enveloped in an oil film, but much experimental research has discovered that not all the entire surface was soaked. Dong-Chul Han and Jae-Seon Lee, [7] analysed the piston ring lubrication with a new boundary condition. They considered a partially lubricated ring, with the following conditions; oil starvation was applied to the inlet region and the open-end assumption to the outlet region. The algorithm confirmed flow continuity and the pressure was allowed to go down to the saturation pressure. Using these new boundary conditions, the actual effective width participating in ring lubrication was determined and the minimum film thickness and flow rate for the ring pack were calculated. The effective width was expected to be about 20 to 30 percent of the whole width of the ring, and the minimum film thickness was less than the result obtained by using the Reynolds cavitation boundary condition. Ming-Tang Ma et al., [18] developed a model for piston-ring lubrication in IC engines with circular and non-circular cylinder bores considering the influences of many factors, such as level of bore distortion, ring conformability, axial motion of the ring, and circumferential variation of the ring face profile. An improved method for determining oil availability in a ring pack was also developed by considering the effect of relative locations of rings on the piston and oil accumulation in front of the ring. The performance of piston rings in the fully flooded lubrication condition was simulated through solving the Reynolds equation, whereas a flow-continuity approach was developed and used to predict the behaviour of piston-rings in the more realistic lubrication conditions which are usually encountered in conventional engines. The computerized model offered engine designers a useful tool and was used to investigate the effects of the following variables on the tribological performance: E.P. Becker and K.C Ludema, [8] formulated qualitative empirical model of cylinder bore wear. In their investigation, they used a laboratory simulator to identify the important variables influencing cylinder bore wear.

1. bore distortion/ring conformability,
2. composite surface roughness,
3. relative ring (groove) positions,
4. constant ring eccentricity,
5. constant ring twist,
6. axial motion of ring,
7. circumferential variation in ring face profile,
8. circumferential ring gap position.

The same characteristics of wear were observed in the simulator as in running engines, even though the simulator did not attempt to duplicate all the conditions found within an engine. Data were collected showing the influence of several parameters. In particular, a strong effect from ring material was observed. A new picture of wear in cylinders was presented, consistent with the data and previous work on boundary lubrication. This qualitative model took care of the evolution of the cylinder running surface in terms of composition and texture changes. The model also used to determine the relative importance of the many variables that can influence wear behavior, including contributions from lubricant chemistry, material properties, and mechanical loading. M. Priest et al., [16] studied the predictive wear modelling of lubricated piston rings in a diesel engine, Their works review the nature of the surfaces encountered in the piston assembly, valve train and journal bearings of the internal combustion engine and how mathematical models of engine tribology are endeavouring to cope with the extreme complexities the incorporation of surface topography potentially brings. Key areas for future research and the implications for design are highlighted.

Simon C. Tung and Hong Gaob [24] investigated the friction and wear performance of coatings on nitrided stainless steel (NSS) piston rings and chrome plated stainless steel rings sliding against cast iron cylinder liner segments in fully-formulated engine oils by using a high frequency reciprocating tribometer. The ring coatings include thermal-sprayed CrN and physical vapor deposited (PVD) diamond-like-carbon (DLC). The tribological characteristics of piston ring coatings were determined by applying several advanced piston ring coatings and energy-conserving lubricants containing friction modifiers. The impacts of E85 ethanol fuel (a fuel blend of 85% ethanol and 15% unleaded gasoline) on scuffing of the chrome-coated piston ring and cast iron cylinder liner segment were studied with different fuels varying in their degree of acidity. The tribological characteristics due to surface interactions between piston ring coatings and energy-conserving engine oils containing molybdenum dithiocarbamate (MoDTC) or an organic friction modifier were compared and analyzed. The test results showed that the DLC coating produces the lowest wear on the cylinder liner segment and has a similar ring wear to nitrided and CrN coated piston rings.With MoDTC present in the engine oil, friction and wear were effectively reduced. The acidic fuel promoted the occurrence of scuffing. Zenon Krzyzak and Pawel Pawlus [27] performed an analysis of the surfaces of a large number of piston skirts after engine operation. Changes of piston skirts surfaces under the “zero-wear” condition were analysed. The amplitude of worn piston skirt surfaces decreased, the ordinate distribution became asymmetric, summit density increased and lay direction changed from circumferential to axial during wear. The relationship between microgeometry parameters was studied using correlation and regression analysis. It followed from the study that one can fairly precisely describe a piston skirt surface topography using the following parameters: Sq, SSk (or Sp/St), Str and Sdq. The parameters $St \pm 3\sigma$, Sku, Sds, SSc and P_ax/P_ay are recommended for detailed description. It was decided to determine the local wear of piston skirts based on the changes in amplitude parameters. An increase in the initial surface height caused and increase in piston skirt wear. The local linear wear of piston skirts was bigger on the thrust side than on the anti-thrust side of the cylinder.

M. Hahna et al., [15] investigated a cylinder that was run in a road test motor. The relevant piston ring positions that fully describe the tribosystem defined at the combustion chamber (CC), top dead centre (TDC), stroke and bottom dead centre (BDC). Transmission electron microscopy (TEM) and energy-filtered transmission electron microscopy (EFTEM) were used to analyse these contact zones in terms of microstructure and chemistry. Nanocrystalline surface layers up to a thickness of 100 nm occurred in all areas of contact whereas subsurface zones revealed differing microstructural changes. Thus the influence of thermal impact and different mechanical load conditions in a motor cylinder were evident. EFTEM elemental mappings verified the incorporation of elements that stem from lubrication or combustion residues. L. Garaa et al., [13] performed cylinder liner surface roughness and wear measurements through an experimental study of a single cylinder diesel engine operating at a steady state. A replication method was used to evaluate wear and surface roughness on a cylinder liner, where measurements were made at different locations on the cylinder liner before and after each test. Replicated surface profiles were measured by a WYKONT 1100 optical surface profilometer. It was found that surface roughness decreased with time and the rate of decrease was higher during the run-in period. A unique wear volume calculation method that includes bearing ratio parameters was proposed, and reasonable results for wear volume were obtained. Cylinder bore wear rates measured by this replication method were consistent with long-term wear observed in different tests of diesel engines.

B.E. Slattery et al., [3] investigated of wear induced surface and subsurface deformation in a linerless Al–Si engine. The wear mechanisms of a linerless eutectic Al–Si engine subjected to extensive dynamometer testing have been thoroughly investigated using scanning and transmission electron microscopy, focused ion beam milling, optical surface profilometry, X-ray photoemission spectroscopy, and nano-indentation techniques. The as-prepared chemically etched cylinder, which consisted of silicon particles initially exposed 1.1µm from the aluminum matrix, exhibited sufficient wear resistance to operate under ultra mild wear conditions. Silicon particles were found to decrease to an equilibrium height of nearly 0.6–0.7µm. Under these particles, plastically deformed regions of aluminum and ultra-fine grain formations were observed, suggesting that the silicon particles support a significant portion of the load and that the aluminum matrix deforms to accommodate the exerted pressures. Oil deposits were abundant on the worn surface and were shown to fill/protect uneven areas on the aluminum matrix. These amorphous structures were found to consist of combustion byproducts, elements from the oil, and nano-sized aluminum and silicon debris. Staffan Johanssona et al., [25] considered new materials, coatings and high-tech machining processes that previously were too expensive and therefore only used in complex applications. The reciprocating tribometer at Volvo Technology was updated to better evaluate the frictional difference between material combinations/ surfaces; it was possible to evaluate a number of operational parameters in each experiment. The components that were studied were a piston ring running against a cylinder liner. Friction, wear and change in surface morphology were studied in the experiments and design of experiments were introduced based tribometer test the interaction of dynamic viscosity, velocity and contact pressure can be studied within one experiment. The results show differences in friction which could be explained as the surface creating beneficial contact conditions for oil film build-up. It is also apparent that surface roughness is important regardless of material properties. To better understand the correlations between friction and surface roughness a future study should include a study of similar materials with different roughness values.

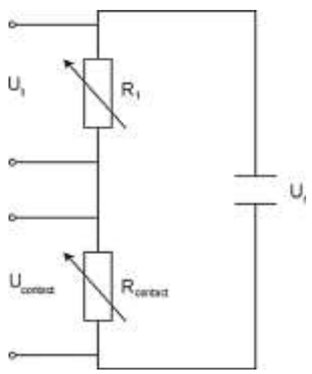


Fig 1: Circuit diagram of electrical resistance measurement between piston ring and cylinder liner.[25]

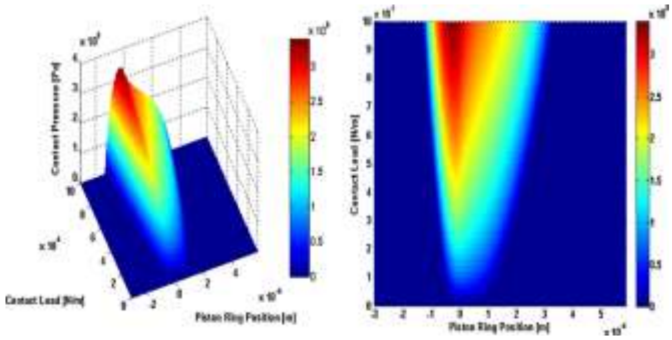
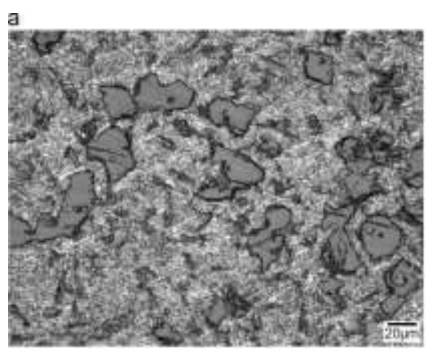


Fig 2: The contact pressure as a function of piston ring position and contact load.[25]

J.C. Walker et al., [12] explained the influence of start–stop transient velocity on the friction and wear behavior of a hyper-eutectic Al–Si automotive alloy. In order to determine the effect of a start–stop velocity cycles on the lubricated friction and wear behavior of a hyper-eutectic Al–Si liner, an Interrupted reciprocating laboratory tribometer test programme was developed based upon the European Urban Cycle standard. Refined cast iron piston ring segments were slid at 23Hz frequency, 4MPa Nominal contact pressure and 25 mm stroke length against a conformal honed Alusil cylinder liner segment. Regular velocity interruptions at 60s intervals did not significantly inhibit the dynamic friction behaviour between the liner and the cast-iron piston ring segment, indicating that lubricant additive function was not significantly inhibited. However contact potential and FIB–SIMS depth profiles indicated that anti-wear tribo-film thickness was reduced as a result of start–stop cycling. Mass loss from the piston ring was also notably higher as a result of the interruption of elasto-hydrodynamic lubrication causing boundary conditions at re-start and subsequent 2-body abrasion by harder protruding Si particles. Specific wear rates for the Al–Si liner as a result of start–stop velocities were surprisingly lower compared to uninterrupted tests and was believed to be due to faster running-in of the piston ring surface. These results were discussed in terms of the viability of Al–Si as engine materials running start–stop technology.



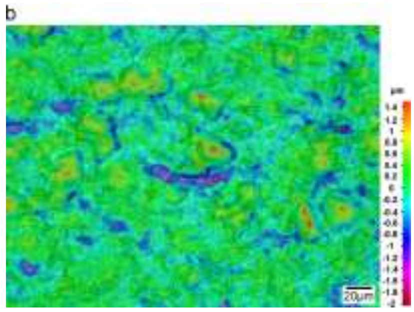


Fig 3: (a) Optical micrograph of the Alusil liner and (b) corresponding Colour depth map from the same area.[12]

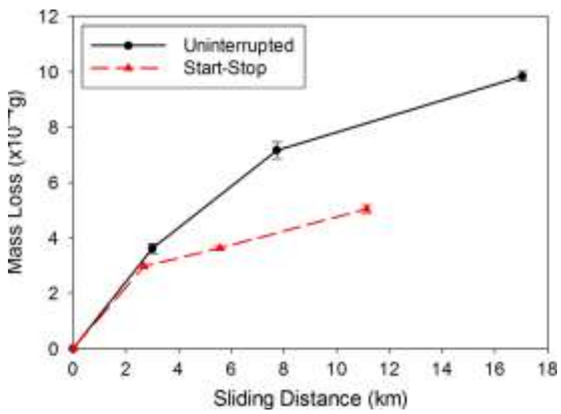


Fig 4: Mass loss vs sliding distance forun-interrupted and start–stop tests[12]

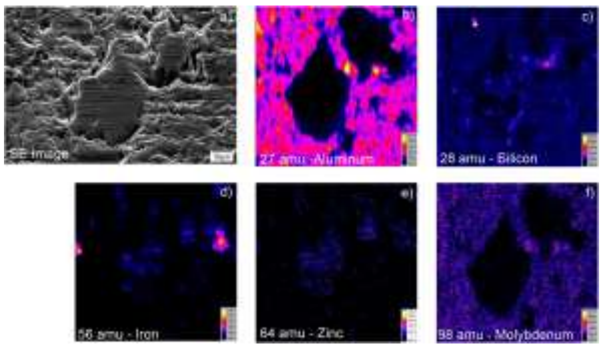


Fig 5: Secondary electron image (a) of surface tribo-films formed on start–stop surface in the mid-stroke region and(b–f)FIB–SIMS chemical maps of aluminium, silicon, iron, zinc and molybdenum, respectively.[12]

M. Priest et al., [17] applied a new model to the piston ring pack of a diesel engine. With the overall aim of evaluating the correlation between theory and experiments, the analysis was divided into two discrete parts. First, the model was used to predict the lubrication performance of measured ring packs before and after periods of running, at constant speed and load, in a Caterpillar 1Y73 single-cylinder diesel engine: the objective being to establish the change in tribological behaviour with observed wear in the engine. Secondly, the model was used interactively to predict the lubrication and wear of the top compression ring from the same engine. This research presented advances in the understanding of piston ring profile evolution with time and its dependence on complex interactions between lubrication and wear.

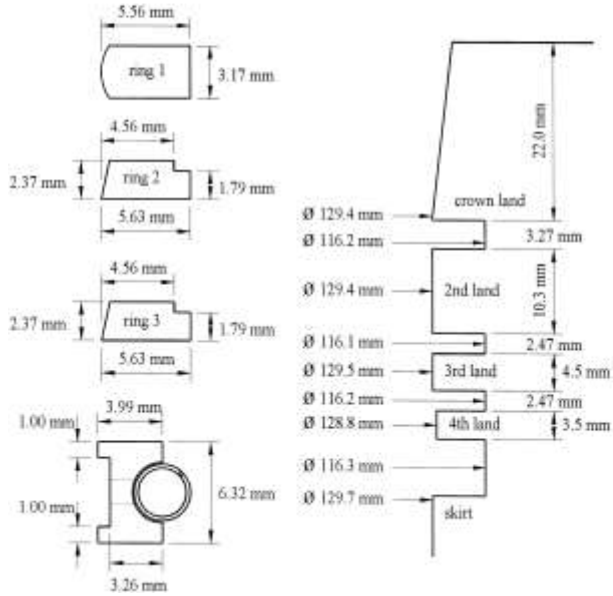


Fig 6: Caterpillar 1Y73 piston and ring pack.[17]

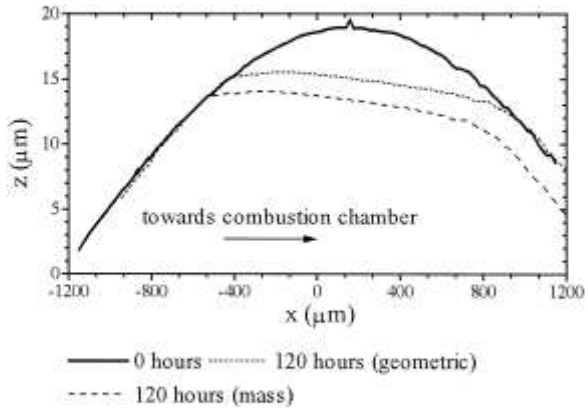


Fig 7: Measured profiles of the new and worn ring.[17]

S. Mezghania et al.,[23] developed a numerical model to investigate the effects of groove characteristics on the lubrication condition and friction at the interface between the piston ring and cylinder liner.

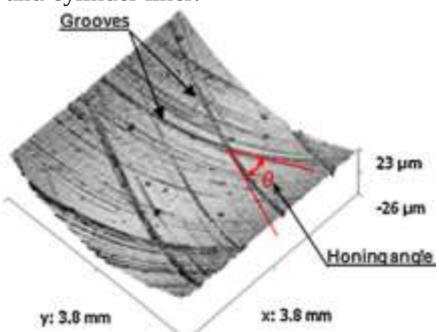


Fig 8: Plateau honed surface of thermal engine cylinder.[23]

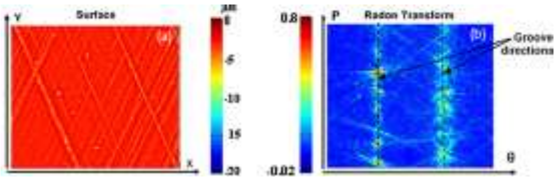


Fig 9: Plateau honed surface (a) and its radon transform (b).[23]

This model was used to solve the average Reynolds equation, which depends on the real surface topographies of the cylinder liner, and describes the influence of surface irregularities on the lubricant flow under hydrodynamic lubrication conditions, considering lubricant film rupture and cavitations. Numerical results helped to determine the optimum lateral groove characteristics to reduce friction and then noxious emissions.

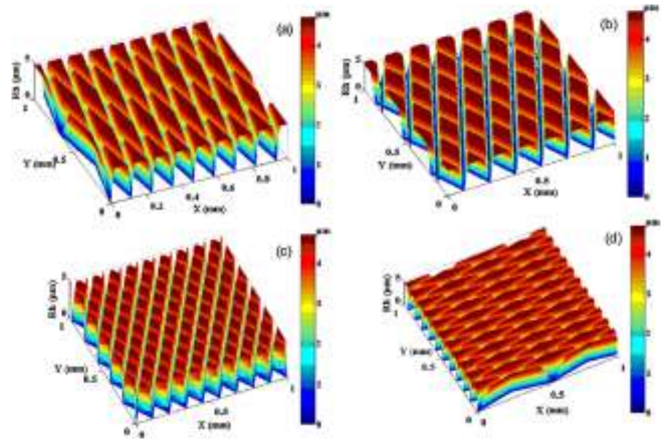


Fig 10: Simulated honed surface with different honing angles: (a) 20◦, (b) 50◦, (c) 120◦ and, (d) 160◦.[23]

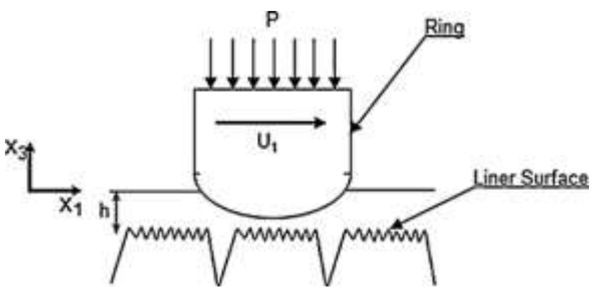


Fig 11: Piston–liner contact description[23]

Luiz G.D et al.,[14] analysed numerically the influence of film thickness and properties on the stress state of thin film-coated piston rings under contact loads.The systems were compared based on the stress distribution, particularly in terms of the intensity and position of the peak stresses in the film and at the film/substrate interface. Results show that (a) in terms of radial stresses in the ring, the stiffer (or thicker) the film, the lower the compressive stresses at the interface immediately under the film-sleeve contact, and the higher the tensile stresses deeper at the ring, while (b) in the coating, the more compliant the material, the more compressive the axial stresses observed. C. Friedrich et al., [4] worked on PVD CrxN coatings for tribological application on piston rings. They concluded from the results: the wear protection of piston rings by PVD coating systems was possible as an alternative to the surface materials used up to now; and as a consequence of the reduced wear rates, the coating thickness can be lower. Carlos Eduardo Pinedo,[5] used selective plasma nitriding on piston rings for performance improvement. Plasma nitriding proved that selective nitriding is possible using a simple mounting system, leading to homogeneous properties on both inner and outer diameter surfaces. Only a diffusion zone, without grain boundaries nitrides, composes the nitrided microstructure. The surface hardness is increased up to 1100 HV0.1. The mechanical tests showed that the performance of selective plasma nitrided rings is superior to the gas nitrided counterpart. The wear rate is 30% higher for the plasma nitrided rings, but acceptable for practical purposes.

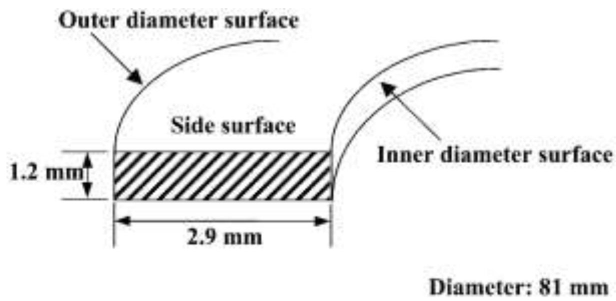


Fig 12: Typical gasoline ring dimensions [5]

R C Singh et al., [22] presented performance behaviors of a commercial diesel engine fueled with diesel and Jatropha based biodiesel (B100) at various loads (up to 100%) and compared using standard (conventional) and three new face profile designs (I, II & III) of piston rings. Face profiles of piston rings had considerable impact on engine's brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and mass flow rate, irrespective of fuels used. BTE of engine fueled with diesel increases 2-8% with new face profile design (III) of piston rings in comparison to standard (conventional) piston rings. BTE enhanceed 8-16% when engine is fueled with biodiesel using face profile design (III) on piston rings. Corresponding to increase in BTE, recorded reduction in BSFC (biodiesel) was 28-34%. Industrial application of the results of this study was useful in saving and conservation of fuels. Dhananjay Kumar Srivastava et al., [6] explained the effect of liner surface properties on wear and friction in a non-firing engine simulator. In their study, a production grade cylinder liner was used and the experiments were conducted using a custom-made non-firing engine simulator. The wear and surface property behaviour were evaluated at several locations in the liner and found that after running-in an engine, surface of cylinder liner exhibits plateau-honed-like characteristic. Energy dispersive analysis (EDS) was carried out of liner and top ring for evaluating materials transfer. Coefficient of friction between three different liner segments and ring was evaluated using an SRV wear tester. Coefficient of friction in the piston ring–liner interface increased with increasing average surface roughness for liner.

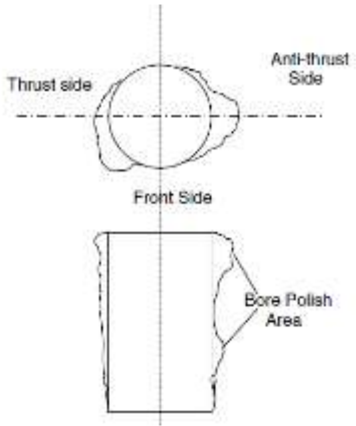


Fig 13: Exaggerated diagram of typical cylinder liner wear [6]

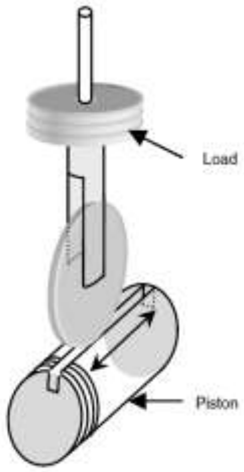


Fig 14: Loading mechanism on the piston [6]

Hanbey Hazar,[10] coated the surface of a piston in a diesel engine with molybdenum nitride (MoN) by using the arc PVD method, and its surface behaviour was subsequently analyzed. Analyses of microhardness, SEM, X-ray and surface roughness were carried out in order to examine surface characteristics of pistons. It is found that the hardness of coated piston is 2000±400 HV while hardness uncoated piston 123 HV. The results showed less deformation and fewer scratches due to wear on the MoN-coated piston as compared to uncoated one. Atul Dhara et al., [2] carried out an investigation of a motored engine in order to validate the sensor and instrumentation and it can be directly employed in a firing engine also. The oil film thickness was measured at different speeds at three different locations, i.e. close to TDC, mid stroke position and close to BDC position and the results were accordingly presented. Lubricating oil film thickness was found to vary between 0.2 and 8_min the motored engine. At a particular position, lubricating oil film thickness varied significantly in upward and downward stroke of the engine due to reversal in direction of piston tilt.

III. SUMMARY

After the detailed study of the published data the following points have been summarized:

i. Lubrication at ring/liner contacts mainly depend on the oil quality, quantity behavior of tribo materials, contour, sliding relative velocity and deformation at the interection due to dynamic action of piston rings.

ii. The frictional loss at the interaction of piston ring and cylinder liner reflect the energy consumption, responsible for wear, and depend on the lubricated conditions of the sliding tribo-pairs.

iii. A steady level of mild wear develops after an initial phase of running-in of the engine. The wear mechanism during running-in depend on two-body abrasion theory. Maximum wear takes place near the top dead centre and the bottom dead centre of the piston motion.

iv. The physics of phase change, gas dynamics, and material scuffing is complex due to the free material liberated from deep scoring between the piston and liner snowballs that changes its phase from solid to molten state and finally makes its path into the inter space of rings. On cooling molten melal locks the rings and thus leading the complete seizure of engine.

v. The lubricating oil film thickness varies significantly in upward and downward stroke of the engine due to reversal in direction of piston tilt in the two strokes. The lubricating oil film thickness increases with increasing engine speed when shifting of lubrication regime from boundary/mixed lubrication to hydrodynamic regime.

vi. Increase the speed of sliding increases the rate of wear as well as the increase in the average roughness, while it is inversely associated with the sliding distance. In a lubricated, the tribology behavior of alloys at sliding distance to steady-state conditions depends on the type of surface preparation.

vii. Building plateau-honed liner at the time of production can control initial wear of the engine and thus reduce the amount of wear debris generation during the initial running-in period. Building-in plateau honedliner surface at the production stage will reduce the initial wear due to running-in. Fatigue will last a problem for long because efforts on fuel consumption reduction and power increase will push to the limit weight reduction that means thinner walls and higher stresses.

viii. The wear rate for plasma nitriding is lower than that found for gas nitrided rings, but still acceptable by the manufacturer and for the application. Plasma nitriding is an alternative process for piston ring production.

ix. When the piston's surface is coated with the arc PVD method, pistons can be used without any need to apply any additional process on the surface after the coating. Surface hardness of the coated piston is higher than the uncoated one and this has positive effects on its resistance against wear. The surface of the coated piston is harder than that of the uncoated one and this contributes to the piston's load capacity.

x. The friction performance in the piston ring/cylinder liner contact is associated with the plateau formation. Both oil consumption and ring-pack failure through scuffing are complex phenomena rather difficult to predict numerically. Engine testing, then will allow the verification of this optimal spatial morphology and will also permit the quantification of the effects of the proposed liner groove texture characteristics on oil consumption and scuffing tendency.

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