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# Roles of mirror-like surface finish and DLC coated piston rings on increasing scuffing resistance of cast iron cylinder liners

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ABSTRACT

This study considers two approaches towards increasing the dry scuffing resistance of grey cast iron (CI) cylinder bore (or liner) surfaces, namely by i) decreasing the initial roughness of the CI liner surfaces and ii) by applying a diamond-like carbon (DLC) coating to the top compression piston rings. CI liners were polished to different surface roughness values ranging between 0.08 μm and 6.83 μm and were subjected to unlubricated reciprocating sliding tests with progressively increasing loads (50–600 N) at a constant frequency of 5.0 Hz (0.15 m/s) using a Cameron-Plint TE77 tribometer. The counterface materials used were CrN coated steel as well as a hydrogenated DLC (H-DLC) coated steel. Microscopic and spectroscopic observations suggested that at low loads a mixed tribolayer comprising of iron oxide ($Fe_2O_3$) and graphitic carbon that was formed on wear tracks maintained low wear rates. At higher loads this tribolayer was removed resulting in metallic contact and leading to scuffing. Mirror-polished CI liner contact surfaces (with an average roughness of 0.08 μm) provided higher scuffing resistance; the critical scuffing load was 300 N compared to 200 N for liners with $>0.25$ μm average roughness. The improved scuffing resistance could be attributed to the lower contact stress experienced by the mirror-polished liners with a bearing ratio of 83% compared to medium-finished liners with a bearing ratio of 69%. CrN coated counterface contributed to scuffing of the CI liners at above 300 N load accompanied by a sharp increase in COF ($>0.4$). The H-DLC coated counterfaces prevented scuffing throughout and maintained a low steady state coefficient of friction (COF) of 0.13 up to 600 N load. The low wear of the CI liners run against H-DLC counterfaces was attributed to the formation of the mixed tribolayer on the CI surfaces that remained intact at all tested loads. The results suggest that the use of DLC coated piston rings and a mirror-polish finish of cylinder liners would avert scuffing and provide low COF values while maintaining low wear rates.

## 1. Introduction

Scuffing is one of the main tribological failure mechanisms that limits the lifespan of automotive components such as cylinder bore-piston ring assembly, bearings, cams and gears. Various working definitions of scuffing have been proposed [1–4]. A commonly used definition of scuffing is “localized damage caused by the occurrence of solid-phase welding between sliding surfaces without local surface melting” [5]. Scuffing can be triggered by high speed, high load and starved lubrication conditions during cylinder bore/liner-piston ring interactions [6]. Extensive plastic deformation of the surfaces in contact [7], rapid increase in coefficient of friction [8], removal of oxide films [9] are among some of the characteristic attributes of scuffing accompanied by an increase in noise and vibration and accumulation of wear debris [10,11]. Cylinder bore/liner-piston ring scuffing is characterized by severe subsurface plastic deformation and formation of large amounts of metallic wear debris [12,13]. Investigations of wear mechanisms responsible for scuffing are important considerations for the automotive industry to avoid premature engine failures.

One of the factors affecting the tribological performance of engines is the cylinder bore finish [14,15]. Surface finish processes such as honing, cross-hatching, polishing and laser texturing that affect the oil retention [16], lubrication regime [17,18] and wear resistance [19] are important parameters while considering the scuffing performance of cylinder bores. Most studies on scuffing have been conducted under the boundary lubrication regime. For example, Rao et al. [20] investigated the effect of surface roughness of cast iron (CI) cylinder liners (0.07–0.50 μm $R_{a)}$ using an engine dynamometer set-up under boundary lubricated conditions at different speeds (100–450 rpm) and reported that smoother surface finish resulted in lower COF. Johansson et al. [21]

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tested the liner surface roughness for lowering friction and showed that under mixed lubricated condition CI liners (0.2–1.2 µm $R_k$, the mean core roughness depth) lower friction force was observed with smoother surfaces tested against Cr coated piston rings. Akalin and Newaz [22] designed a bench friction testing system to investigate the effect of liner surface roughness (smooth; 0.41 µm $R_q$ and rough 0.71 µm $R_q$) on friction under different lubricated conditions. Although piston ring material was not specified in this study, it was observed that both smooth and rough samples manifested the mixed lubrication regime at 70 °C. However, with the lower surface roughness samples a higher tendency for shifting towards hydrodynamic lubrication was observed. Ye et al. [23] explored the influence of the piston skirt ($R_t = 16$ µm (rough) and $R_t = 7$ µm (smooth)) and cylinder bore surface roughness ($R_a = 0.8$–1.0 µm (rough) and $R_a = 0.4$–0.7 (smooth)) values on the cylinder bore–piston ring contact and reported higher scuffing resistance for smoother piston rings. According to the survey presented above, a smoother surface finish of cylinder bore/liner-piston ring would provide lower COF and higher scuffing resistance.

Another aspect of increasing scuffing resistance of cylinder bore/liner-piston assembly is the consideration of piston ring coatings. Wang et al. [24] studied various coatings for piston rings with “rough” and “smooth” finish run against cylinder bores with the same surface roughness values under boundary lubrication conditions. It was reported that both a nickel/ceramic composite (NCC) and iron coated piston rings provided higher scuffing resistance with scuffing loads $> 700$ N than tin-plated coated rings tested against aluminum bores (Al-25%Si, Al 380, Al390). Smoother piston rings resulted in higher scuffing resistance compared to rough finished rings. Ye et al. [23] investigated different ring coatings and reported that piston rings coated with a composite polymer with 15 vol% graphite particles showed the highest scuffing resistance (scuffing load average 1753 N) followed by NCC-plated smooth pistons (scuffing load average 1531 N). The presence of graphite which acted as a solid lubricant at the contact interface provided higher scuffing resistance for the composite polymer coating. The performance of NCC-plated rough pistons were worse than that of the uncoated pistons due to deep plastic deformation zones that were formed during sliding contact. Wang et al. [25] in another study tested composite polymer (CPC) and NCC coated piston rings under boundary lubricated conditions and showed that piston rings with CPC coatings generated lesser wear on CI or aluminum cylinder bores compared to the Ni-P-SiC and Ni-P-$Si_3N_4$ (NCC) ring coatings. Hard anodizing of the piston ring surfaces with the CPCs improved the coating durability with increased scuffing resistance of aluminum cylinder bores. Alzoubi et al. [26] tested the scuffing performance of amorphous carbon coatings under unlubricated conditions with ball-on-flat in a reciprocating sliding setup. Coated SAE H13 type steel tested against SAE 52100 steel balls prevented scuffing up to 200 N as long as the coating remained intact. In summary, the hard piston ring coatings showed high wear resistance however they also led to high COF (0.40–0.50) which may reduce the scuffing performance of the cylinder liner/bores whereas carbon based coatings provide low COF ($\leq 0.15$ [26]) and may improve the scuffing resistance.

The scuffing experiments conducted in this study simulated the initial stages of running of an engine where the surfaces are mostly devoid of lubrication. The dry scuffing experiments are critical in selecting appropriate materials for engine powertrain. The experiments were designed to assess the durability of engine materials during the initial running-in period where the engine may become susceptible to cold scuffing as a result of dry sliding contact [27,28]. Dry sliding tests were conducted using a Cameron Plint TE77 tribometer using the standard loading conditions as per ASTM G-181 [29]. The role of initial surface roughness in increasing the scuffing load has been discussed. A DLC coated counterface was tested against the CI liners and the resulting wear and friction mechanisms were compared with that of a CrN coated counterface to investigate the effects of these piston ring coatings in preventing cold scuffing.

## 2. Experimental procedure

### 2.1. Sample preparation

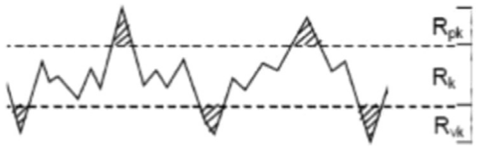
Grey cast iron (type D) liners (CI) with 93 mm inner diameter were used. As received (rough) CI liners were smoothed using a wire cuter (Charmilles Robofil 240 SL wire EDM machine) to remove the initial rough-finished surface. Subsequently, the liners were polished to different surface finishes using a mechanical honing head with SiC papers up to 4000 grit. Oxidation and overheating of the cylinder liner surfaces were prevented by continuously applying ethanol during honing. In the final step, the liners were polished using 3 µm and 1 µm diamond suspensions. The surface texture parameters were determined using a white light optical interferometer (WYKO NT 1100 System) operated in the vertical-scanning interferometry (VSI) mode and are listed in Table 1. 3-D optical profilometer images of the initial surface finishes are shown in Fig. 1a–d. Typical bearing ratio curves, obtained from the initial surface roughness parameters [30,31], are shown in Fig. 1e.

**Table 1**
Initial surface texture parameters of CI liners. $R_a$ is the arithmetic average height parameter, also known as the centre line average (CLA). $R_k$ is the mean core roughness depth, this parameter is inversely related with the bearing ratio of the surface. $R_{pk}$ is defined as the mean of maximum height of peaks obtained for each defined sampling length. $R_{vk}$ is defined as the mean of the maximum depth of valleys obtained for each sampling length.

$$R_{pk} = \frac{1}{n}\left(\sum_{i=1}^{n} R_{p_i}\right)$$

$$R_{vk} = \frac{1}{n}\left(\sum_{i=1}^{n} R_{v_i}\right)$$

Where; $n$ is the number of samples along the assessment length of the profile, $R_v$ represents valleys, whereas $R_p$ are the peaks.



| Surface Finish | $R_a$ (µm) | $R_k$ (µm) | $R_{pk}$ (µm) | $R_{vk}$ (µm) |
|---|---|---|---|---|
| Mirror-finished CI Liner | 0.08 ± 0.05 | 0.24 ± 0.05 | 0.10 ± 0.05 | 0.19 ± 0.05 |
| Smooth-finished CI Liner | 0.26 ± 0.05 | 0.79 ± 0.05 | 0.33 ± 0.05 | 0.57 ± 0.05 |
| Medium-finished CI Liner | 0.48 ± 0.05 | 1.16 ± 0.05 | 0.34 ± 0.05 | 2.06 ± 0.05 |
| Rough-finished CI Liner | 6.83 ± 0.05 | 13.34 ± 0.05 | 0.73 ± 0.05 | 3.5 ± 0.05 |