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Effect of iron oxides on sliding friction of thermally sprayed 1010 steel coated cylinder bores

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ABSTRACT

In-situ Raman spectroscopy was performed on 1010 steel coatings thermally sprayed on an Al-Si alloy on A 380 (Al-9.0% Si) cylinder bore and subjected to reciprocating sliding against various coated rings to investigate the progression of iron oxide formation during sliding. The coatings evaluated for the top compression ring (TCR) included diamond-like carbon (DLC) and chromium nitride (CrN). The reciprocating tests were conducted under unlubricated and boundary lubricated conditions. During unlubricated sliding, a running-in period was observed with increasing coefficient of friction (COF) values which corresponded to the conversion of the initial FeO, present in the as-deposited coating, to Fe_3O_4 and then to Fe_2O_3 as identified by changes in Raman spectra obtained at short intervals during the test. Once a Fe_2O_3 layer was formed, a steady state regime was obtained with a COF of 0.4 that was accompanied by the adhesion of the oxide debris generated during sliding to the counterfaces. The DLC coated TCR provided low steady state COF (0.18) and volumetric wear of 1010 steel, with negligible debris formation. Boundary lubricated sliding tests, with an initial period of unlubricated sliding, resulted in low steady state COF value of 0.10 for DLC and 0.16 for CrN. The low friction and wear of 1010 coatings observed during boundary lubricated sliding against DLC coated TCR was due to a composite tribolayer consisting of an amorphous carbon layer on top of an oil residue layer that was formed on the sliding surfaces.

1. Introduction

Mass reduction strategies for automotive components have received significant attention in recent years for improving fuel economy and decreasing emissions. In this context the use of linerless Al-Si alloys in internal combustion engines is notable. Early efforts to develop linerless cylinder blocks consisted of the use of a hypereutectic Al-Si alloy A390 with ~18 wt% Si [1,2] where the presence of a high volume fraction of large (50–100 μm) primary Si particles provided wear resistance and extended engine durability [3]. These alloys, however, have the drawback of being difficult to cast and machine [4]. Hypoeutectic Al-Si alloys with 6–10% Si on the other hand contain no primary Si, which makes them easier and more economical to manufacture but provide insufficient wear resistance [5]. While most hypoeutectic aluminum engine blocks use an iron liner to meet durability requirements for wear, eliminating the mass of an iron liner and the cost associated with it has been a significant goal in lightweight engine technology [2]. The wear resistance of hypoeutectic Al-Si alloy engine blocks may be improved by using low carbon ferrous coatings deposited by thermal spray techniques [6]. Plasma transfer wire arc (PTWA) process, for example, produces coatings that have a lamellar structure consisting of iron splats, resulting from flattening of molten metal droplets as they hit the surface, separated by iron oxide (FeO) stringers [7].

The unlubricated sliding wear mechanisms of PTWA low carbon (1020) steel coatings deposited on 319 Al alloy at different velocities, loads and relative humidity (RH) levels against M2 high speed tool steel have been studied [8–10]. The COF values of the 1020 steel coatings varied with changing RH–at 12% RH the COF was 0.62 which decreased to 0.48 at 90% RH. This was attributed to the "polishing" effect, on increasing RH, by hydrated iron oxides being trapped between the contact surfaces. Oxidative wear occurred by Fe_2O_3 formation at low loads (< 20 N) and low sliding velocities (< 1 m/s) with the thickness of surface oxide layer generated during sliding increasing with increasing the loading conditions. At high loads and low sliding velocities, the wear rates were high due to severe plastic deformation of the splat tips

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leading to fracture and fragmentation. It was suggested [7] that the low fracture toughness (0.2–1.0 MPa $m^{1/2}$) of the interfacial oxide phases in the thermal spray ferrous coatings could cause splat delamination during sliding contact. On increasing the sliding velocity, at high loads, the wear mechanisms shifted from mechanical to oxidation wear causing a decrease in the wear rates.

Self-mated plain carbon steel pins and disks tested under unlubricated sliding are known to reduce the wear rates over a critical speed due to the surface hardening [9] as a result of frictional heating of the asperities in contact causing ferrite-to-austenite phase transformation and subsequent quench hardening as also observed in the case of PTWA 1020 steel coatings samples in the load range between 40–80 N and velocity range of 1.5–2.5 m/s [10,11]. Hwang et al. [12] studied the wear behaviour of plasma spray deposited ferrous coatings, with varying oxide (FeO) contents, against SAE 9254 V spring steel under lubricated conditions. The ferrous coatings hardened by the addition of Al_2O_3-ZrO_2 powders showed low wear rate at high loads (200 N) which was attributed to the high cohesive bonding between the coatings and the matrix. Nickel aluminum thermal wire-arc sprayed coatings [13] tested against SAE 52100 steel pins under lubricated conditions, using hydraulic oil, showed high wear resistance and low friction which was attributed to the formation of a transition lubricating film and porous microstructure assisting in lubricating oil retention—although no direct evidence was provided for the same.

For extending the durability of the cylinder bore and piston ring assembly it is also important to consider the wear and friction behaviour of the counterface piston ring. A standard piston ring pack consists of a set of two compression rings, a scraper ring and a bottom oil-control ring [14–17]. The top compression rings (TCRs) serve as the gas seal between the combustion chamber and the crankcase and are often subjected to demanding tribological conditions (high loads and temperatures) and dry scuffing [15]. Traditionally, gray cast iron has been used as TCR material. In the past two decades, CrN and flame spray/plasma sprayed molybdenum coated steel rings have become popular. Scuffing resistance of piston coatings was studied against a 390 Al bore under lubrication starvation conditions at 12 Hz, 120 N load and 360 K [17]. It was found that while a physical vapour deposited (PVD) diamond-like carbon (DLC) coating showed moderate scuffing resistance the Ni–P–BN coating produced least wear and highest scuffing resistance. Amorphous diamond-like carbon coatings coated steel rings are becoming popular as coatings for commercial TCR [18].

The DLC coatings consist of a mixture of sp^2 and sp^3 hybridized carbon atoms and have two principal grades: hydrogenated DLC (H-DLC) with typically 40 at% H and non-hydrogenated DLC (NH-DLC) with <2 at% H [19]. One of the factors determining the friction reduction of DLC coatings is the formation of a transfer layer on the counterface [20–22]. In the case of hydrogenated DLC (H-DLC) coatings with 40 at% H, the H-terminated carbon bonds in the coating have led to low coefficient of friction (COF) and wear, an effect that was more prominent in vacuum tests [23]. Unlubricated sliding of H-DLC coatings against M50 steel balls under 5.0 N load and in a dry N_2 atmosphere showed low COF values of 0.03–0.07 which was attributed to the formation of carbon rich transfer layers on the steel counterface were observed [24]. Tung and Gao [25] studied the wear and friction behaviour of Cr-plated and DLC coated rings tested against a cast iron cylinder segment under boundary lubricated conditions and observed that a lower running-in friction was observed for DLC coated rings compared to Cr-plated rings which was attributed to the solid lubricant properties of carbon films.

From the above review, it can be seen that further wear and friction studies on the roles the piston rings against thermal spray coatings on engine bores, especially under lubricated sliding conditions are needed, and will prove to be useful for the automotive industry to assess the performance of the spray coatings. In this study, we report the friction and wear behaviour of thermally sprayed low carbon steel 1010 coating, deposited on Al 380 cylinder bore, sliding against selected top compression rings (TCR), namely, DLC coated, and CrN coated piston rings. The evolution of microstructure and compositions of the contact surfaces during sliding has been characterized using Raman spectroscopy. The friction and wear reduction mechanisms were delineated. This study also provides dry scuffing and durability evaluation of the ring coatings to be used against the ferrous thermal spray coatings.

2. Experimental

2.1. Spray coatings

A cylinder bore made of cast hypo-eutectic (Al 380) Al-9.0% Si was mechanically roughened and periodic dovetail grooves were machined. The low carbon ferrous thermal spray coatings were deposited on the Al 380 bores using plasma transfer wire arc (PTWA) technology. This technology is a single wire based rotating spray process using an arc spray applied on the internal surface of the Al–Si engine bore. The wire stock was low carbon steel with nominal ANSI 1010 composition. The deposited coatings were 200 ± 25 μm thick measured from the apex of the machined grooves. The cross-hatched honed surfaces had an average surface roughness of $R_a = 195 \pm 20$ nm as measured by an optical profilometer.

2.2. Tribological tests

In order to simulate a reciprocating bore/piston ring sliding contact from an internal combustion engine, an Anton-Paar (formerly CSM) linear module reciprocating tribometer was used. The 1010 spray coated cylinder bores were sectioned and tested against piston rings while measuring friction. Two types of commercial piston rings were selected as counterfaces: DLC coated and CrN coated rings. The DLC coating is a plasma vapour deposited (PVD) hydrogenated coating with a 2.5 μm thick top carbon-rich layer on a 2.4 μm tungsten rich layer and a 0.1 μm Cr-interlayer. The PVD deposited CrN coating had an average thickness of 24 ± 1 μm.

Reciprocating tests were performed at different stroke lengths in the range 2.0–40.0 mm under a constant load of 5.0 N, corresponding to 2.0–5.0 MPa Hertzian contact pressure. The frequency was maintained between 5.0 Hz to 8.0 Hz, covering a velocity range of 0.02–0.60 m/s. The test conditions used in this study were selected according to the reciprocating testing standards [26,27]. Each reciprocating test was performed using a coated TCR and was repeated three times whereby the average value was reported. The conformal contact of the bore and the piston rings was carefully maintained for all the tests to avoid edge wear. The volumetric wear loss measurements from different regions of the coating wear track were determined using optical profilometry techniques (Wyko NT1100) as described in [28–31].

Both dry (unlubricated) and lubricated reciprocating wear tests were performed. The unlubricated wear tests were performed in ambient air (25–35% relative humidity, RH) while the lubricated tests were performed using a commercial engine oil, SAE 5W-30 (ILSAC GF-5). For all lubricated tests, 1 ml of oil was added onto the sample surface at the beginning of the test. The lubrication regime, determined from the ratio (λ) of minimum film thickness (h_{min}) to the r.m.s roughness (r^*) of the contacting surfaces was calculated using Eqs. (1)–(3) [32]:

$$\frac{1}{E^*} = \frac{1-\nu_{1010}^2}{E_{1010}} + \frac{1-\nu_{DLC}^2}{E_{DLC}} \quad (1)$$