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Abstract

The presence of coatings and surface topography play an important role in the tribological performance of sliding components. Depending on the coating used, it is possible to reduce friction and/or reduce wear. However, while there may be low friction and wear-resistant coatings suitable for use in pistons, some coatings may hinder the tribological performance by changing the lubrication regime, or by preventing additives from their intended function through chemical mechanisms. In this work, piston skirt segments extracted from a commercial aluminum alloy piston were coated with a diamond-like carbon (DLC) coating, a graphite-resin coating or a nickel-polytetrafluoroethylene (Ni-PTFE) coating, and were tribologically tested using a reciprocating laboratory test rig against commercial gray cast iron liner segments. The tribological tests used commercial synthetic motor oil at a temperature of 120^{o}C with a 20 mm-stroke length at a reciprocating frequency of 2 Hz. Results showed that the graphite/resin coating, while it may serve as a good break-in coating, wears rapidly. The Ni-PTFE coating showed friction reduction, while the DLC coating wore off quickly due to its small thickness. Furthermore, the higher hardness of the DLC coating relative to the cast iron liner surface led to pronounced changes on the liner counterface by polishing. In contrast with the uncoated piston skirt segments, all of the coatings prevented the formation of a visible tribochemical film on the cast iron surface.

KEYWORDS: Piston skirt, Cylinder liner, Coatings, Friction, Wear

1. Introduction

The piston-cylinder system is a significant source of mechanical friction in internal combustion (IC) engines. It has been shown that the piston skirt contribution to the total friction losses of the piston/cylinder system is substantial [1-3]. Improved tribological characteristics have been achieved by coating the piston [4-6]. Studies have focused both on the piston ring/cylinder liner interface and piston skirt/cylinder interface. However, somewhat limited experimental work has been done on coated piston skirts in laboratory conditions simulating closely the conditions found inside the engine [7]. A coating on the piston may offer advantages such as friction reduction and better scuffing resistance and wear protection [8], while reduced clearance due to the coating thickness may reduce oil consumption and engine noise. Although oil viscosity and oil film thickness affect the operating lubrication regime between the piston skirt and cylinder liner and are important, the friction between them will also be affected by clearance and surface roughness, and hence are not to be overlooked [9].

Nickel/ceramic composites applied via conventional electroplating over piston skirts slid against aluminum and cast iron bores have been investigated [6]. These coatings varied in thickness depending on the coating and particles used in suspension during electroplating. Coating thickness between 6 μm and 25 μm were investigated with hardnesses of 5-6 GPa. It was found that Ni-P-BN has better self-lubricating properties than Ni–P–SiC or Ni–P–Si_3N_4 coatings and exhibits low wear when slid against cast iron and aluminum liners. Counterface wear was reduced when commercially available composite polymer coatings were used. These coatings were applied onto the piston skirts by either screen printing or a spray process and their thickness was approximately 25 μm. Their tribological properties were investigated over hard-anodized piston skirt surfaces and it was found that the anodizing plays an important role to durability of the coating under starved lubrication conditions.

In this work, skirt segments, extracted from a commercial piston, either uncoated, coated with a Ni-PTFE co-deposit, a graphite-resin coating, or a diamond-like carbon (DLC) coating were tribologically tested using a reciprocating laboratory test rig. The effect of roughness of the skirt was not explicitly studied; however, the importance of it is emphasized and projections based on our findings have been made.

2. Experimental details

The specimens used in this work were extracted from commercial heavy-duty diesel engine components. During all machining operations the original surfaces of both piston and liner were protected in order to retain the original surface roughness and pattern. The skirt specimens were 19 mm in length, 19 mm in width, and had a thickness of 6.35 mm, while the liner segments were 50 mm in length, 38 mm in width and had a thickness of 8.5 mm. A photograph of the samples as assembled in the test rig is shown in Figure 1.

The material of the skirt specimens was an aluminum alloy. Circumferential grooves were present on the surface of the skirt segments as an outcome of the manufacturing process. The liner segments were made of gray cast iron. The liner was plateau honed (R_q= 1 μm). Three-dimensional maps of the surface of a liner and a skirt segment are shown in Figure 2 (a) and (b), respectively. The back surface of the skirt specimens was machined with an 8.0 mm socket so that a ball-ended holder would enable self-alignment during testing ensuring a proper conformal contact. The specimens were either uncoated or coated with DLC, graphite-resin, or Ni-PTFE. The DLC was an amorphous hydrogenated carbon (a-C:H) that was deposited by reactive sputter deposition using a carbon target and an Ar/CH_4 gas plasma. The Ar and CH_4 flow rates were 70 and 12 sccm, respectively. The graphite-resin consists of a high temperature resistant resin with graphite that is applied by spray or silk screen print. The Ni-PTFE coating is a dispersion blend that provides up to 28 vol. % of PTFE. The hardness of the materials used and each of the coatings as determined by microindentation and/or nanoindentation (for the DLC) is shown in Table 1. The thickness of each coating, determined by cross-section microscopy, is also shown in this table. Both the Ni-PTFE and DLC coatings showed uniform coverage and a constant thickness that followed the surface topography of the original samples. The graphite-resin sample varied in thickness. The cylinder liner was mounted onto a reciprocating table of a test rig while the piston skirt was stationary. The reciprocating frequency was 2 Hz.

Fully synthetic SAE10W30 engine oil that meets ILSAC GF-4 specifications formulated for spark ignition engines was used at 120°C. The duration of these tests was 1 hour, but each test was interrupted every 20 minutes in order to perform profilometric and mass loss measurements. The oil offers protection against wear due to the anti-wear additives present in the oil. The reciprocating table had embedded heating elements and the temperature was controlled using a temperature control unit. A small amount of oil (0.3 ml) was applied at the interface of the samples at the start of each test. A normal load of 250 N (approximately 0.7 MPa) was applied with a pneumatic spring and measured with a force transducer while the friction force was measured using a lateral force transducer, using computerized data acquisition.

In a benchtop apparatus it is important to conduct tests with samples that produce conformal contact and closely simulate the contact conditions found in the engine. For this reason, blue ink was used before the samples were tested. Once in contact, a single pass revealed which spots were rubbing against each other, if there was misalignment, and if the contact was conformal. Only samples that produced a near conformal contact were used in order to produce consistent results. New liner samples were used for each test.

3. Results and Discussion

Friction

Figure 3 (a) shows a graph of coefficient of friction as a function of time for an uncoated skirt specimen. The three curves shown in this plot correspond to 20-minute time intervals. Even though the same set of samples was used for these tests, the used oil was replaced with fresh oil before each test, thus they have been plotted individually for clarity. The coefficient of friction started out at approximately 0.12 followed by a very slow gradual decrease during the test between 0-20 minutes as show in this figure. The curve corresponding to the second test between 20-40 minutes starts lower and approaches the same value. The reason for this is believed to be due to the presence of wear debris generated during the first 20 minutes. In fact, as the result of wear, the oil becomes dark. The color may be due to a combination of the aluminum skirt wearing and graphitic exfoliation from the gray cast iron. The wear debris generated can change the nature of the contact. For example, particles entrained into the contact could change the lubricating regime leading to third-body interactions, so when the oil containing the wear particles is replaced with fresh oil, this eliminates interactions leading to a lower coefficient of friction. At the end of the 20-40 minute test the oil appeared slightly cloudy from wear debris. However, compared to the 0-20 minute test, the oil was relatively clean. The last 20 minutes of the test (40-60 minutes) started at approximately the same value as where the previous test ended due to the lesser wear debris generated after the 20-40 minutes. The fresh oil replaced oil that was not heavy in wear debris and therefore there is little difference between the two tests.

Figure 3 (b) shows coefficient of friction as a function of time for the DLC coated sample. Even though the coefficient of friction is initially lower than the previous case, a slight gradual increase was observed. The reason for this might be due to the presence of the wear debris generated between 0-20 minutes. However, unlike the case of uncoated sample, the DLC wear debris is hard, so when entrained into the contact, changes the lubrication regime, and leads to higher coefficient of friction. It should be noted that only two curves are shown in this plot. The reason for this is that the DLC was only 1.2 microns-thick and therefore wore-off from the top of the grooves. Hence, any subsequent test would not be evaluating the performance of the DLC coating, but the Al substrate.

Figure 3 (c) shows coefficient of friction as a function of time for the graphite resin coated skirt specimen. The coefficient of friction for the test between 0-20 minutes attained a value of approximately 0.13 initially followed by a slow gradual decrease. The curve corresponding to the second test between 20-40 minutes starts at approximately the same value. Examination of the oil revealed significant wear of the coating as the oil turned dark. The 40-60 minute showed very similar behavior. It is interesting to note that for both the 20-40 minute and the 40-60 minute test, the coefficient of friction gradually increased in contrast with the 0-20 minute tests. For the latter case, graphite present at the surface of the sample acts as a solid lubricant and therefore would be responsible for the initially low coefficient of friction. However, as graphite is depleted, the surface is dominated by the resin matrix and therefore the coefficient of friction in the absence of solid lubricant shows an increase.

Figure 3 (d) shows coefficient of friction as a function of time for the Ni-PTFE sample. The friction starts out low and decreases to below 0.1, which is lower than all of the previous cases. However, the wear debris generated, similarly to what was described above, leads to a gradual increase in the coefficient of friction which attained a value of approximately 0.12 at the end of the test. The coefficient of friction for the 20-40 minute test starts at approximately 0.12, but then decreases to approximately 0.1 and then reaches a steady-state. The coefficient of friction for the 40-60 minutes test behaved in a nearly identical manner. That could be due to PTFE particles in the Ni matrix filling in the valleys in the cast iron disk, creating a smoother surface compared to the original surface, which would move the contact into the mixed regime and therefore lower friction. It may also be possible that a loosely adherent transfer film on the cast iron liner surface is forming. Because PTFE has a very low coefficient of friction, the sliding contact is a PTFE film on the cast iron against the Ni-PTFE coating on the piston skirt sample, and therefore friction reduction is observed. From the optical inspection it was not possible to see whether the formation of such transfer is evident and either electron microscopy or spectroscopic techniques might be necessary to investigate this. A more plausible explanation might be that the PTFE particles that wear out are incorporated into the oil at which point the viscosity of the oil would increase, leading to an increased lambda ratio creating a hydrodynamic effect, which in turn would result in a decrease in coefficient of friction.

Measurements of coefficient of friction as a function of time at 300 Hz data acquisition rate were made. The "waveforms" for an uncoated skirt specimen in 10W30 are shown in Figure 4 (a), (b), and (c) for reciprocating speeds of 1, 2 and 3 Hz, respectively. The position of the skirt specimen with respect to the liner segment is also graphed in this figure and appears as a sinusoid. The minima and maxima of the sinusoid correspond to ends of the stroke. The static coefficient of friction value is obtained at the end of the strokes or equivalently at each edge of the wear track while the kinetic friction value is obtained at the center. It is obvious that during tribological sliding between the piston-skirt specimens and the cylinder-liner segments the contact is mostly in the boundary lubrication regime. The friction waveforms are symmetrical, confirming that the sample used was in good conformal contact with the liner.

Wear

Wear was quantified in terms of mass loss for all skirt samples. Figure 5 shows cumulative mass loss as a function of time for all tests. As seen in this figure, the DLC-coated skirt sample has the lowest mass loss for the first 20 minutes of testing, followed by the uncoated sample. The Ni-PTFE and the graphite-resin have similar mass loss during the first 20 minutes, and higher than both of the uncoated and the DLC coated specimens. The highest mass loss was observed for the graphite-resin coating as time increased. The Ni-PTFE coating exhibited a gradually slow mass loss beyond the 20 minutes. The uncoated sample behaved similarly. The DLC coating was worn off completely after 20 minutes and therefore only a single data point was generated. It is interesting to note that most of the wear for all of the samples, except for the sample coated with graphite-resin, happens at the beginning of the tests up to 20 minutes, and little mass loss is accumulated beyond that.

Figure 6 shows micrographs of all samples before and after 20 and 60 minutes of testing, except for the DLC, which is shown after 40 minutes (since the DLC coating was worn off completely during the 20-40-minute test, the last segment of 40-60 minutes was not run). Pronounced machining marks can be seen in this figure. The machining marks are transverse to the sliding direction (left-to-right). Figure 6 (a) shows the uncoated sample in its original state as well as after 20 minutes and 60 minutes. Removal of the topmost asperities that come into contact can be seen in this figure; they appear as flat regions along the vertical direction. In fact, flat regions appear almost immediately after the sample comes into contact with the liner. At the end of the 40-60-minute test similar plateaus can be seen on the microscope image of Figure 6 (a). No significant "widening" of the flat regions was observed, supporting the cumulative mass loss measurements of Figure 6. Similarly, for the DLC coated skirt sample, the original surface resembled that of the uncoated skirt sample, but has a slightly different hue to it. Removal of the topmost asperities that come into contact can be seen in Figure 6 (b). At some point between 0-20 minutes of testing, the DLC coating started to wear off, but it is only partially removed and therefore some bright areas that correspond to the Al substrate are visible in this figure. In the 20-40-minute test, the DLC coating was almost completely worn off and the topmost features appear uniformly bright. The surface of the piston skirt samples coated with graphite resin have a very different appearance under the microscope that the previous samples. A relatively uniform distribution of black particles can be observed on the original surface, as seen in Figure 6 (c). After 20 minutes of testing the graphite particles seem to be rearranged or deposited within the grooves, and the flat regions seem to be depleted from it exposing the resin matrix. After 60 minutes little graphite is present on the surface compared to that of the original sample. After all tests a significant amount of graphite was removed as evidenced in the darkening of the oil at the end of each test. This was supported by the cumulative mass loss measurements shown in Figure 5. Figure 6 (d) shows the surface of a Ni-PTFE coated skirt sample. The surface features resemble those of the uncoated and the DLC coated samples in their original state as well as after 20 minutes and 60 minutes. As the flat regions start to form they appear bright under the microscope. At the end of 60 minutes they have a brown hue possibly because with the removal of PTFE more Ni is exposed and a tribochemical film is allowed to form.

Profilometric measurements for all samples are shown in Figure 7. The 2D profilometric measurements were 1.4 mm long perpendicular to the machining marks and flat regions (for the worn samples). The original profiles of each of the samples were superimposed in each of these plots. Removal of the topmost asperities of the uncoated sample can be seen on Figure 7 (a). Initially, little wear was observed for the DLC coating as it offered protection against wear. However, its thickness was only 1.2 μm. Therefore, since wear was in the order of 5 μm as seen in Figure 7 (b), it can be concluded that the DLC coating was worn off. The morphology of the graphite-resin coated sample looks very different than the previous cases as seen in Figure 7 (c). The triangular shape of the piston is not present in this case and it is difficult to distinguish between the valleys and actual roughness. The Ni-PTFE, similar to the DLC coating, showed little wear as shown in Figure 7 (d). PTFE coatings are relatively soft and tend to suffer from poor wear characteristics. Therefore, for tribological applications they are typically blended with other materials in order to improve their mechanical properties [10,11]. The Ni-PTFE used in this work was hard (4-6 GPa) due to PTFE incorporated into a Ni matrix, and took advantage of the low friction characteristics of PTFE without exhibiting excessive wear.

Figure 8 shows microscope images of the cast iron liner samples. The sliding direction for the liner counterfaces is left-to-right in this figure. Figure 8 (a) shows the surface of an untested cast iron liner. Machining marks are evident from the plateau honing process. It is known that fully-formulated oils contain anti-wear additives, which are thermally activated. As a result, during sliding a tribochemical film with beneficial role usually forms on metallic surfaces. Such film is evident on the surface of the cast iron tested against the uncoated sample as shown in Figure 8 (b). The tribochemical film has a blue-brown appearance. There is no significant wear on the surface of the cast iron liner in this case, but some visible scratches are present in the sliding direction as a result of rubbing. All of the machining marks and finer cross-hatching pattern left from the plateau honing are still visible on the surface. Figure 8 (c), corresponding to the liner segment tested against the DLC coating, contrary to the previous case, shows polishing wear. The surface looks shiny as a result. The topmost asperities of the cast iron surface have been polished and most of the finer grooves of the plateau honing have disappeared. Furthermore, there is no visible tribochemical film on the surface. It is possible that a tribochemical film cannot form because it is continuously removed during contact. Figure 8 (d) shows the surface of the liner tested against the sample coated with graphite-resin. Uniform, light burnishing is evident on the surface along the sliding direction as seen in this figure. The formation of tribochemical film is also evident by the different colors present on the surface. Figure 8 (e) shows the surface of the cast iron dick tested against the sample coated with Ni-PTFE. A faint tribochemical film can be seen on the surface, but unlike the other cases where some damage in the form of light scratches, severe polishing or simple burnishing, was evident, the surface of the cast iron liner in the case of the Ni-PTFE looks unharmed. That may be due to the presence of PTFE in the Ni-PTFE coating which is known to form a transfer layer providing easier sliding and could responsible for the lower coefficient of friction as it was observed in Figure 3 (d).

4. Conclusions

While coatings can be beneficial, their selection should be guided by surface roughness, clearance, piston skirt design, and operational specifications of the engine. The Ni-PTFE coating used in formulated 10W30 oil showed a friction reduction compared to the uncoated sample. Graphite-resin provided a steady coefficient of friction and can serve as a good break-in coating. The DLC coating exhibited stable friction throughout with little initial wear. However, longer testing produced complete coating removal due to wear. Furthermore, due its higher hardness and possible harder wear debris, it caused polishing wear of the gray cast iron counterface. It was found that most of the wear for all samples, except for the sample coated with graphite-resin, occurs at the beginning of the tests up to 20 minutes, and little mass loss is accumulated beyond that. Coating thickness would play an important role in the tribological behavior or components and the original profile of the commercial piston skirt may not be the most effective for lubrication, and a smoother surface topography may be desirable.

Acknowledgements

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Material	Hardness (GPa)	Thickness (μm)
Graphite Resin	0.28	20-30
Ni-PTFE	4-6	15
DLC	7-8	1.2
Gray cast Iron	2.0	No coating
Al alloy	1.4	Substrate

Table 1 – Materials and coatings used in this work

17x7mm (300 x 300 DPI)

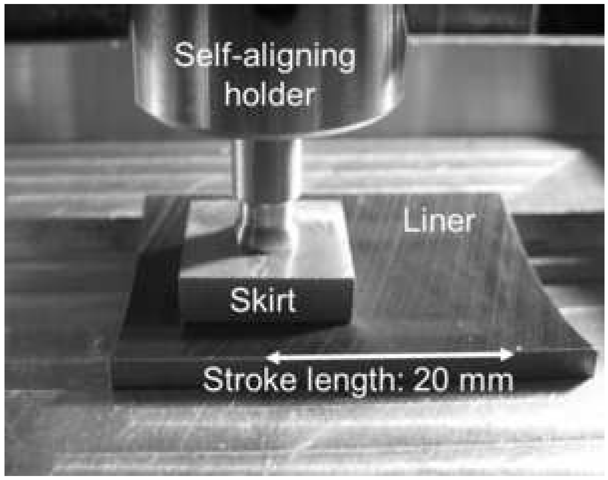

Figure 1 – Photograph of samples used in this work

25x19mm (300 x 300 DPI)

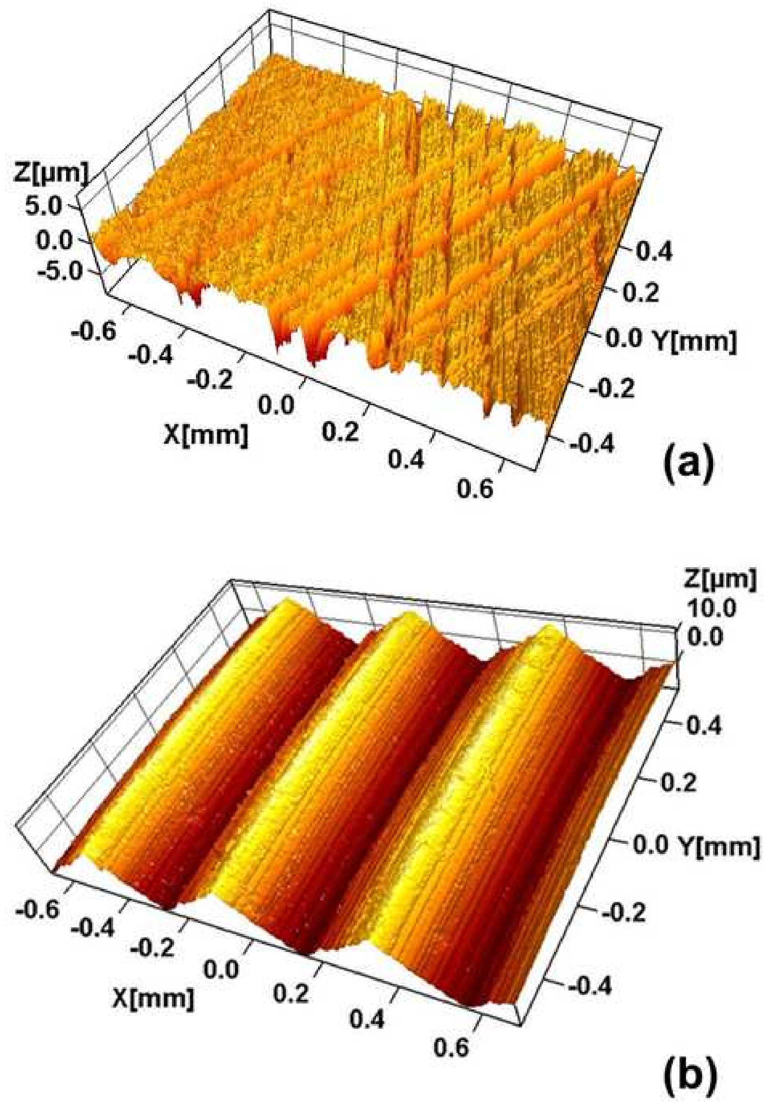

Figure 2 – Original surface 3-D maps of: (a) cylinder liner and (b) piston skirt

47x63mm (300 x 300 DPI)

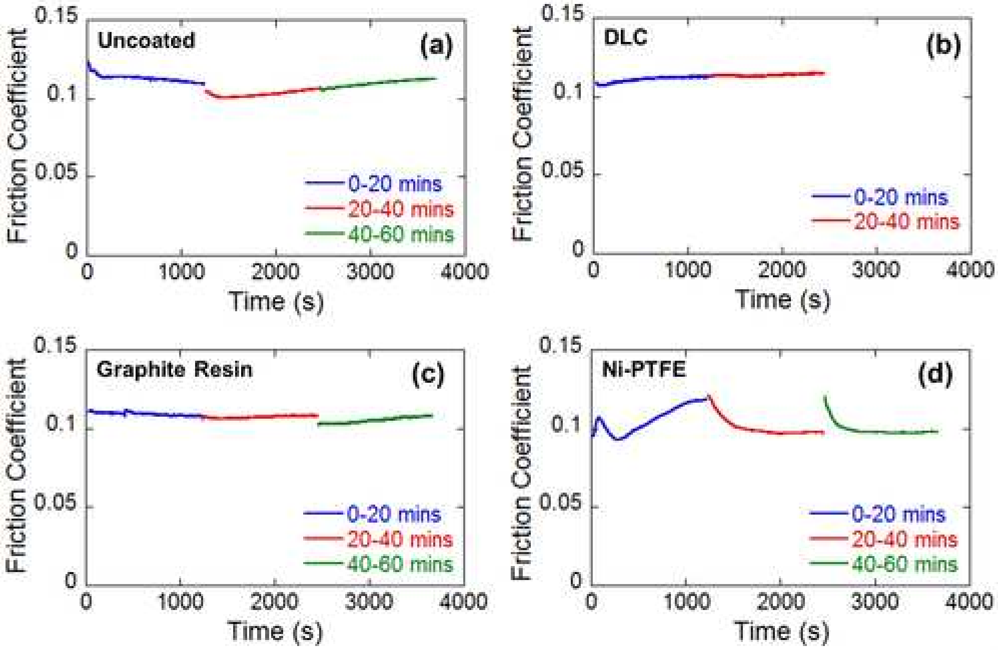

Figure 3 – Graphs showing coefficient of friction as a function of time for: (a) uncoated, (b) DLC, (c) graphite resin, and (d) Ni-PTFE samples

42x28mm (300 x 300 DPI)

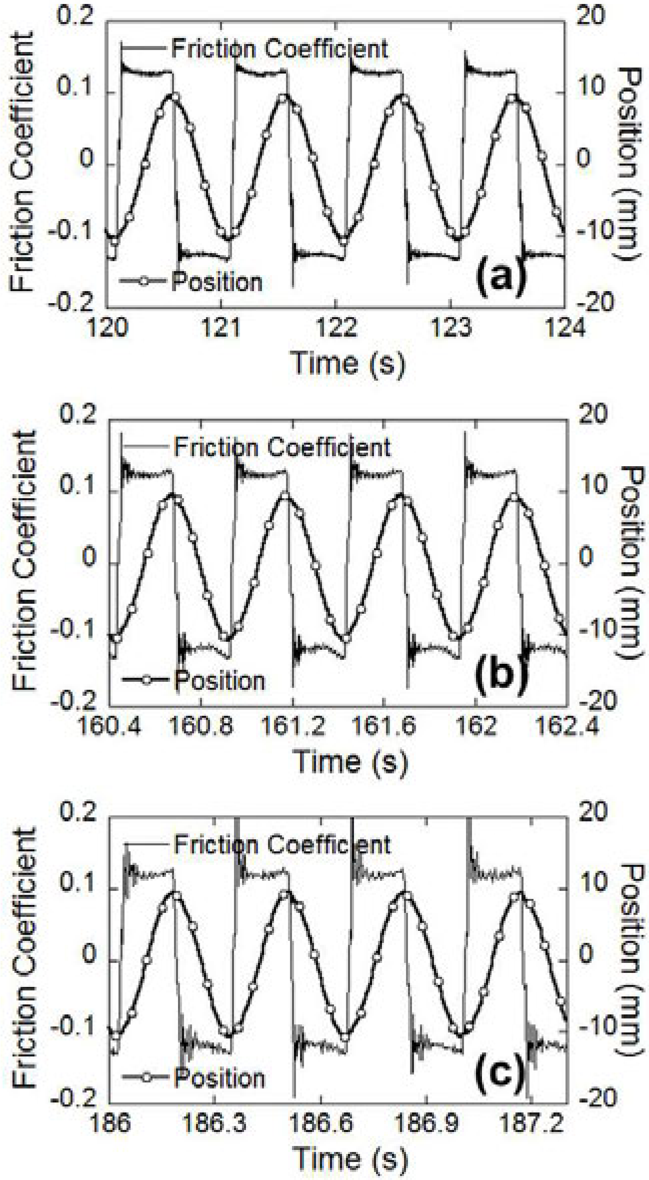

Figure 4 – Graphs showing coefficient of friction and sliding position as a function of time for an uncoated skirt-liner segment against a cylinder liner for reciprocating frequencies of: 1Hz, (b) 2 Hz, and (c) 3 Hz

47x87mm (300 x 300 DPI)

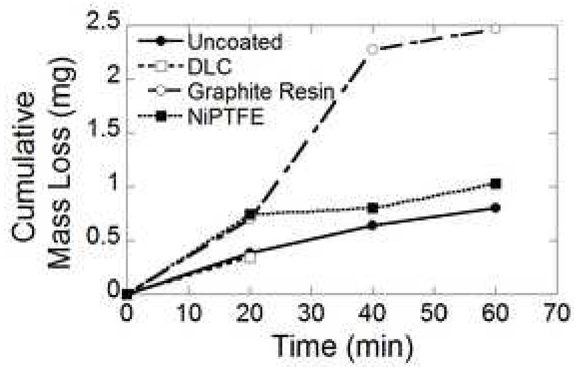

Figure 5 – Graph showing cumulative mass loss as a function of time for: (a) uncoated, (b) DLC, (c) graphite resin, and (d) Ni-PTFE samples

24x15mm (300 x 300 DPI)

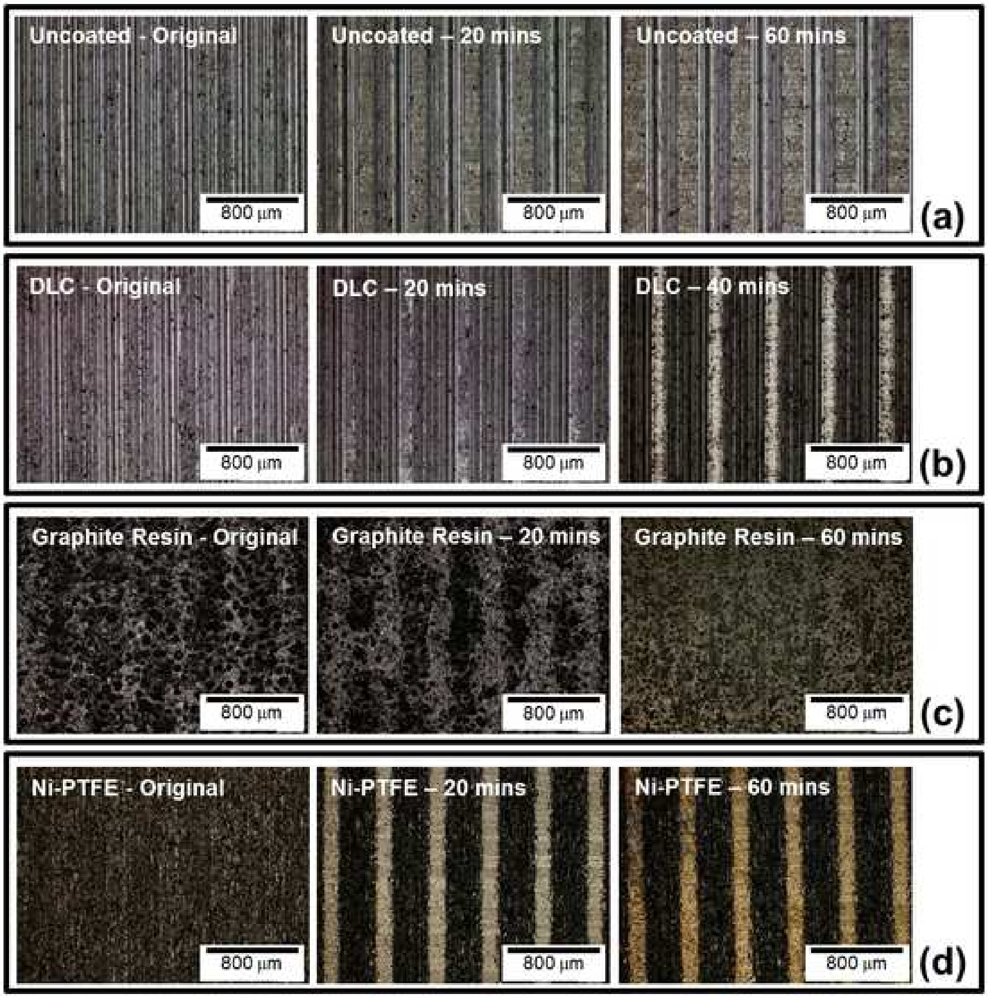

Figure 6 – Micrographs of: (a) uncoated, (b) DLC, (c) graphite resin, and (d) Ni-PTFE samples before and after testing (sliding direction is left-to-right)

47x47mm (300 x 300 DPI)

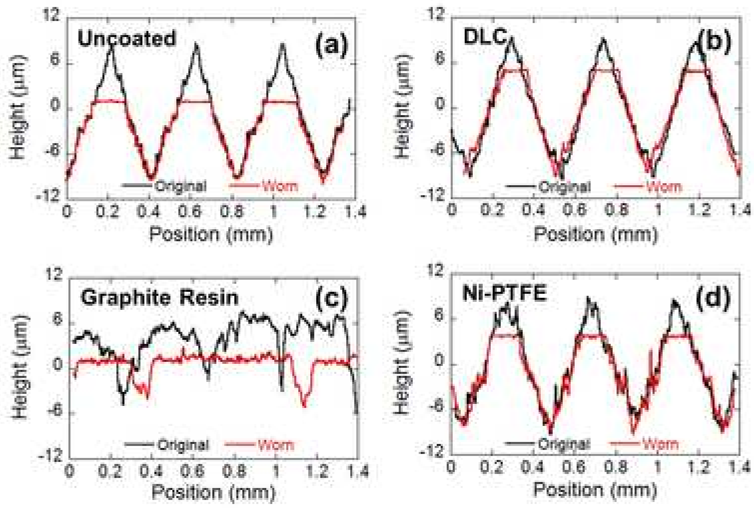

Figure 7 – Graphs showing 2D profilometric measurements of: (a) uncoated, (b) DLC, (c) graphite resin, and (d) Ni-PTFE samples, before and after 20 minutes of testing

32x22mm (300 x 300 DPI)

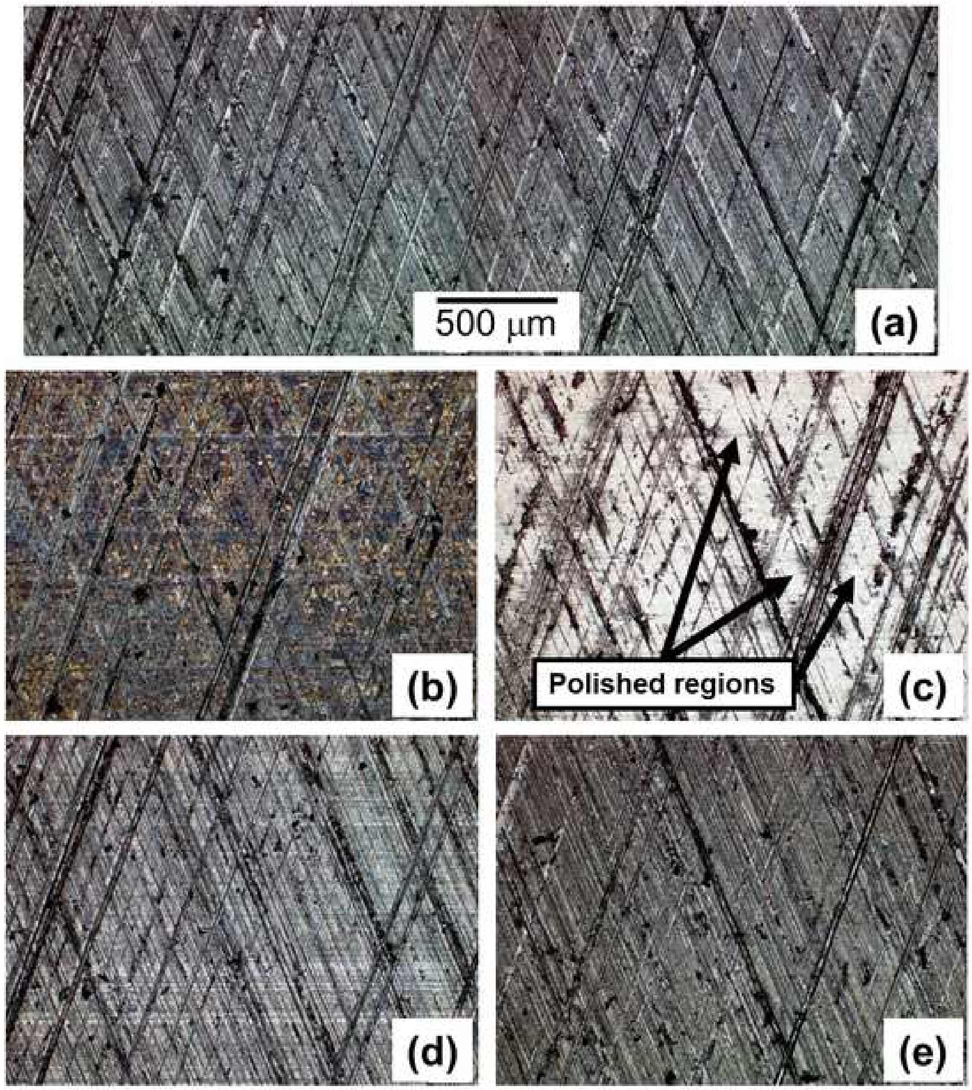

Figure 8 – Micrographs of the surface of liner segments slid against: (a) uncoated, (b) DLC, (c) graphite resin, and (d) Ni-PTFE samples (sliding direction is left-to-right)

47x52mm (300 x 300 DPI)