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TRIBOLOGICAL STUDIES OF COATED PISTONS AGAINST CYLINDER LINERS IN LABORATORY TEST CONDITIONS[1]

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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 prevent premature wear. However, while there may be low friction and wear resistant coatings suitable for use in pistons, some coatings may have high wear rates hindering the tribological performance of the parts by changing the lubrication regime from boundary to mixed, 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 nickel-polytetrafluoroethylene (Ni-PTFE) coating, a graphite-resin coating and a diamond-like carbon (DLC) coating and were tribologically tested using a reciprocating laboratory test rig against gray cast iron liner segments also extracted from a commercial system. The tribological tests were conducted in commercial synthetic motor oils and basestocks at temperatures up to 120°C with a 2 cm-stroke length at a reciprocating frequency of 2 Hz. Results showed that the graphite/resin coating is a good break-in coating when used in formulated oil, but wears quickly, leading to morphological changes and subsequent changes in tribological performance. The Ni-PTFE coating showed a friction reduction in formulated oil, while the DLC coating showed little wear. However, in the basestock oil, while friction reduction was achieved through morphological changes, excessive wear of the graphite-resin and DLC coatings was observed.

Keywords: Piston skirt; Coatings; Friction; Wear.

ESTUDOS TRIBOLÓGICOS DE PISTÕES REVESTIDOS CONTRA CAMISA DE CILINDRO EM CONDIÇÕES DE TESTES LABORATORIAIS

Resumo

Revestimentos e a topografia de superfícies têm um importante papel no desempenho tribológico de componentes deslizantes. Dependendo do revestimento utilizado, é possível reduzir o atrito e/ou prevenir o desgaste prematuro. Todavia, embora possam existir revestimentos com baixo atrito e resistência ao desgaste, adequados para o uso em pistões, alguns revestimentos podem ter altas taxas de desgaste; impedindo o desempenho tribológico das partes, alterando o regime de lubrificação de limítrofe para mista, ou prevenindo elementos aditivos da função planejada por meio de mecanismos químicos. Neste trabalho, os segmentos de saia de pistão foram extraídos de um pistão de liga de alumínio comercial; recobertos com um revestimento base de níquel-politetrafluoroetileno (Ni-PTFE), uma camada de resina de grafite e filme de carbono tipo diamante (DLC) e tribologicamente testados, utilizando ensaios de bancada laboratoriais recíproco-linear contra segmentos de camisa de ferro fundido cinzento, também extraído de um sistema comercial. Os testes tribológicos foram realizados com óleos sintéticos de motor e óleos-base em temperatura de até 120°C, com deslocamento recíproco de 2 cm e freqüência de 2 Hz. Os resultados mostraram que a camada de resina de grafite é um bom revestimento atenuador quando utilizado em meio a óleos formulados, porém desgasta-se rapidamente, levando a alterações morfológicas e subsequente mudanças no desempenho tribológico. O revestimento de Ni-PTFE apresentou redução no atrito em meio ao óleo formulado, enquanto o DLC apresentou baixo desgaste. Entretanto, nos óleos-base, enquanto a redução do atrito foi obtida através de mudanças topográficas, o desgaste excessivo da resina de grafite e do DLC foi observada.

Palavras-chave: Aba do pistão; Revestimentos; Atrito; Desgaste.

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1 INTRODUCTION

The piston-cylinder assembly 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 significant.(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. A coating on the piston may offer advantages such as friction reduction and better scuffing resistance and wear protection,(7) while reduced clearance due to the coating thickness may improve 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.(8)

In this work, skirt segments extracted from a commercial piston, either uncoated, coated with a Ni-PTFE co-deposited coating, a graphite-resin coating or a diamond-like carbon (DLC) coating were tribologically tested using a reciprocating laboratory test rig. The 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 MATERIALS AND METHODS

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.

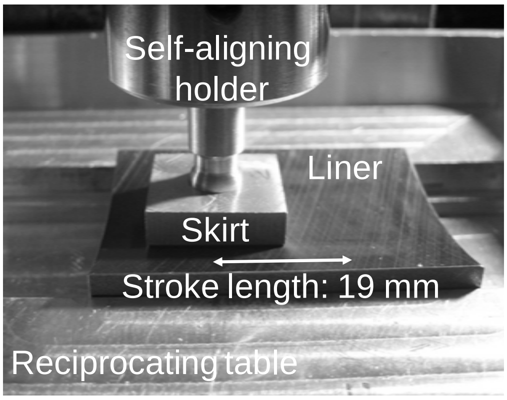

Figure 1 – Photograph of samples used in this work.

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 was plateau honed (R_q= 1 μm). The specimens were either uncoated or coated with Ni-PTFE, a graphite-resin coating or DLC coating. The Ni-PTFE coating is a dispersion blend that provides up to 28 vol. % of PTFE. The graphite-resin consists of a high temperature resistant resin with graphite that is applied by spray or silk screen print. The DLC was an amorphous hydrogenated carbon (a-C:H) that was deposited by plasma assisted physical vapor deposition (PVD). The liner segments were made of gray cast iron. The back surface of the skirt specimens was machined flat with a 0.16 mm spherical radius groove so that when the ball ended holder that fit into the groove would allow self-alignment during testing ensuring a proper conformal contact. The cylinder liner was mounted onto a reciprocating table on the bottom of the test rig while the piston skirt was stationary. The reciprocating frequency was 2 Hz. Two oils were used. Namely, a fully formulated synthetic 10W30 oil and poly alpha olefin oil (PAO10; 65.8cSt at 40^{o}C and 9.97 cSt at 100^{o}C) at 120^{o}C and 20^{o}C, respectively. The test times for these tests were different. The fully formulated 10W30 oil tests were 1-hour long and the PAO10 tests were 20mins. These tests were used to evaluate friction. Additional 1-hour long tests were performed using PAO10 using the test samples previously used in that oil to show the influence of morphological changes over longer duration tests. Four specimens for each test were used to ensure repeatability. 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 was applied with a pneumatic spring and measured with a force transducer while the friction force was measured using a different force transducer, using computerized data acquisition.

In a bench top apparatus that uses actual samples 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. **Figure 2** (a) shows that the contact was not uniform. In this case, the skirt segment was contacting the liner on the sides leaving the middle area untouched. Typically, samples that produced conformal contact such as that shown in **Figure 2** (b) were sought after in order to produce consistent results. An alternative to producing conformal contact is to use samples after a break-in period. However, it should be noted that by doing so the results between samples that have been worn-in and samples that produced a uniform contact patch “as-is” cannot be compared since the initial surface topography will be different and surface changes will have an effect on the tribological behavior. New liner samples were used for each test. **Figure 2** (c) shows the skirt segment that produced the contact patch in (a), while **Figure 2** (d) shows the skirt segment that produced the patch of **Figure 2** (b).

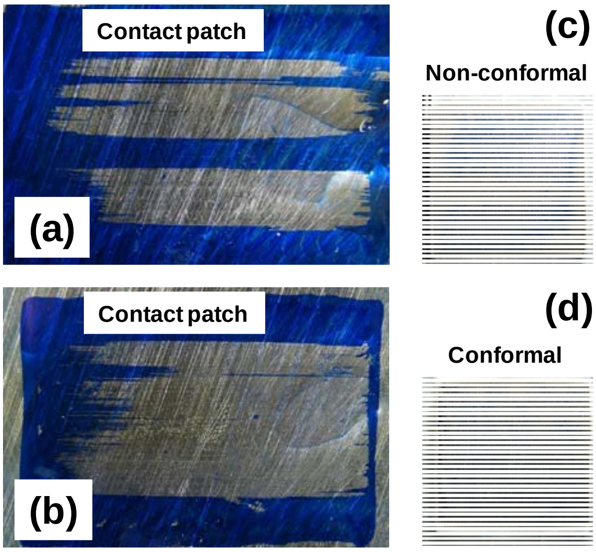

Figure 2 - Photographs of (a) liner segment showing a contact patch produced by non-conformal contact, (b) liner segment showing a contact patch produced by conformal contact, (c) skirt segment corresponding to (a), and (d) skirt segment corresponding to (b).

3 RESULTS

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.

Table 1 – Materials and coatings used in this work

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

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.

Figure 3 shows a microscope image and a 2-D profilometric measurement for the original skirt segment before testing (**Figure 3** (a) and **Figure 3** (b)), respectively and for a non-coated worn sample using PAO10 after 1hr and 20minutes of testing (**Figure 3** (c) and **Figure 3** (d), respectively.

Figure 4 shows friction coefficient variation with time for all coated samples including an uncoated sample as well. Using fully formulated 10W30 oil at 120^{o}C

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(**Figure 4** (a)), during run-in (10 minutes), the highest friction coefficient was observed for the non-coated sample while the lowest friction coefficient was observed for the sample coated with graphite-resin. After run-in, the highest friction coefficient is observed for the non-coated sample. The lowest friction coefficient was observed for the sample coated with Ni-PTFE. The most stable friction behavior is observed for the DLC coated sample. Similar behavior was noted during run-in in PAO10 at 20°C. However, a pronounced lowering in the friction coefficient was noted for the non-coated and graphite resin samples.

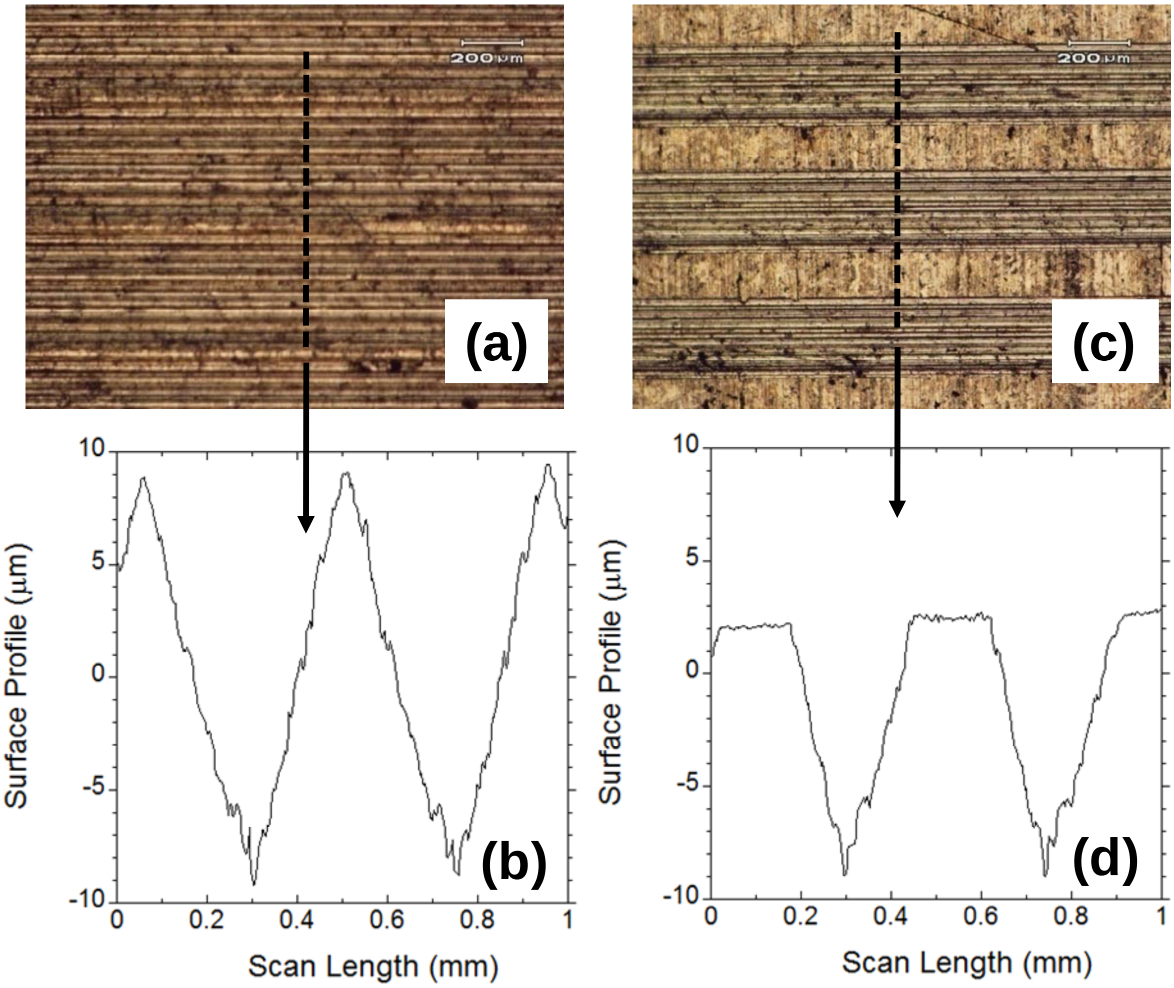

Figure 3 – Optical micrographs and 2-D profilometric measurements for (a)-(b) original surface and (c)-(d) worn using PAO10 after 1hr and 20 minutes of testing at 20°C. Black lines denote scan length.

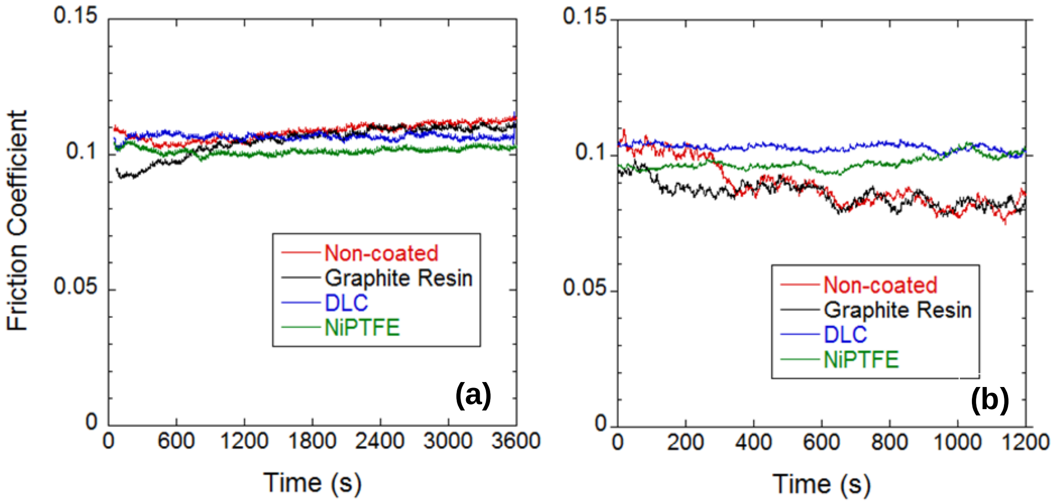

Figure 4 – Friction coefficient as a function time for all samples tested using a load of 250N in (a) fully formulated 10W30 oil at 120°C for 1 hour and (b) PAO10 oil at 20°C for 20 minutes.

Figure 5 shows microscope images of all samples tested in fully formulated 10W30 at 120°C while **Figure 6** shows microscope images of all samples tested in PAO10 at 20°C. In both cases, the most wear occurred in the graphite resin coated sample followed by the non-coated sample and Ni-PTFE while the lowest wear was observed for the DLC coated sample.

Figure 7 shows friction coefficient graphed as a function of time over 1-hour long tests for an non-coated sample and a sample coated with DLC. A gradual friction decrease was observed for the non-coated sample while a spike in the friction coefficient and a subsequent decrease were observed for the sample coated with DLC.

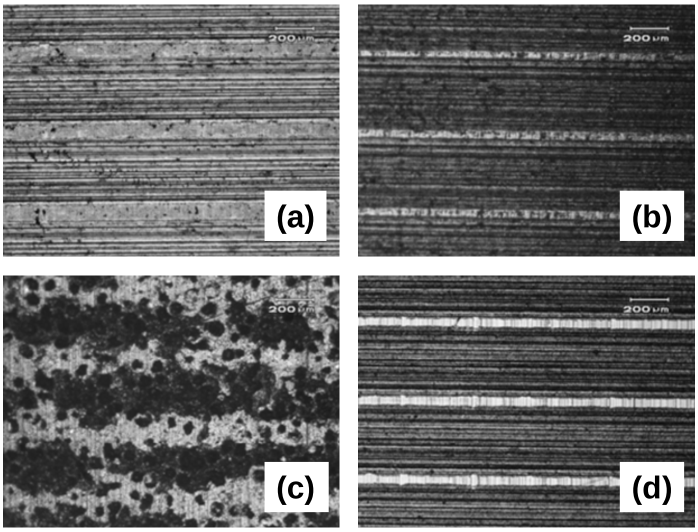

Figure 5 – Microscope images of all samples tested using fully formulated 10W30 oil at 120°C, using a load of 250N: (a) Non-coated, (b) DLC, (c) Graphite-resin, and (d) Ni-PTFE.

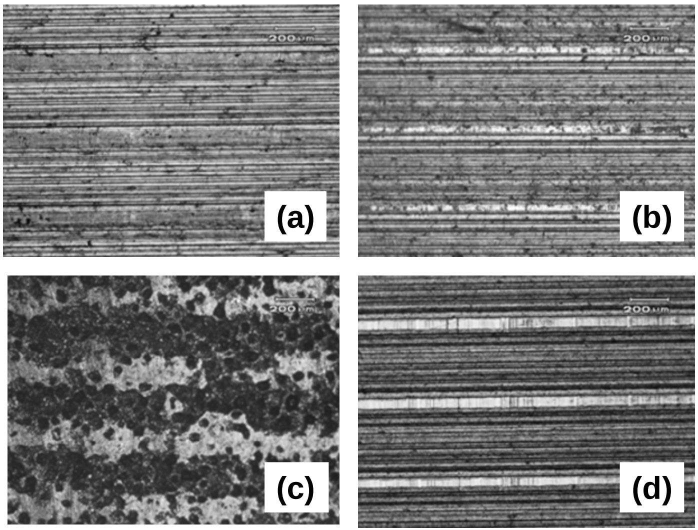

Figure 6 – Microscope images of all samples tested using PAO10 at 20^{o}C, using a load of 250N for: (a) Non-coated, (b) DLC, (c) Graphite-resin, and (d) Ni-PTFE.

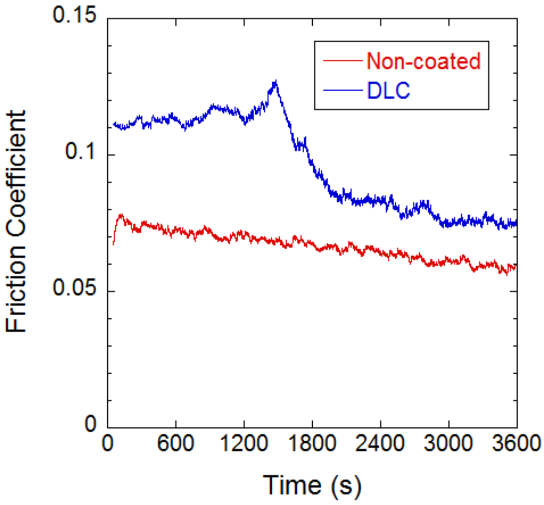

Figure 7 – Friction coefficient versus time for the non-coated and the DLC coated samples tested using PAO10 oil at 20^{o}C for 1 hour.

4 DISCUSSION

Coating thickness and uniformity should be taken under consideration. For example, a soft, break-in type of coating could have a beneficial role as it may offer a uniform transition in friction, whereas a thin and wear resistant coating may be worn through after a certain period of time leading to an unpredictable evolution in friction coefficient and sudden failure.

Since graphite is a solid lubricant, its presence on the surface may be responsible for the initially low friction coefficient measured for the graphite-resin sample as shown in **Figure 4**(a). After run-in, the highest friction coefficient was observed for the non-coated sample while the lowest friction coefficient was observed for Ni-PTFE. The most stable friction behavior was observed for the DLC coated sample. The friction coefficient of the sample coated with graphite-resin gradually increased. Graphite debris was evident at the end of the test, so removal of graphite may explain this increase. In **Figure 4**(b) a lowering in the friction coefficient was noted for the non-coated and graphite resin samples. That can be attributed to topographical changes; the topmost peaks are worn off leading to subsequent change in the lubricating regime, i.e. transition from boundary to mixed regime. Relatively stable friction behavior was observed for the DLC and Ni-PTFE coated samples because of lower wear rates and a possible lack of change in lubrication regime.

Figure 5 shows microscope images of all samples tested in fully formulated 10W30 at 120^{o}C. Similar results were obtained when PAO10 at 20^{o}C was used as seen in **Figure 6**. However, it should be noted that the time duration is shorter in this case. The most wear occurred for the graphite resin coated sample. Removal of graphite particles can be seen from the topmost topographical features which appear as bright areas. Graphite is not very well adhered onto the surface. Lower wear was observed for DLC and Ni-PTFE. PTFE is well bonded in the Ni-PTFE co-deposit. It is interesting to note that the topographical changes that occurred after testing using the same load of 250 N and reciprocating frequency in fully formulated 10W30 oil at 120^{o}C for 1–hr long tests (**Figure 5**) and PAO10 oil at 20^{o}C for 20-minute long tests (**Figure 6**) are very similar, which indicate that the contact was more severe when PAO10 was used. It is known that fully formulated oils contain anti-wear additives, which may be temperature sensitive. Changes in friction behavior can be due to topographical changes or due to the presence of coating. That was the reason different oil temperatures were selected in this work when using the formulated oil and the basestock.

Figure 7 shows friction coefficient versus time in PAO10 oil at 20^{o}C over 1-hr long tests for a non-coated and a DLC coated sample. It should be noted that these were additional 1-hour long tests that were performed using PAO10 using the test samples previously used in that oil to show the influence of morphological changes. Prior to the tests shown in this figure it was hypothesized that the friction reduction was due to topographical changes and subsequent changes in lubrication regime. This was previously observed for the non-coated and the graphite resin coated samples (**Figure 4** (b)). In **Figure 7** we can see that there was a gradual decrease in the friction coefficient with time for the non-coated sample. The DLC coated sample was selected because it had previously exhibited the most stable friction behavior (**Figure 4**). While the wear for the DLC coated sample was lower than the rest of the coated samples for short test durations it was to be expected that the coating would eventually fail because its thickness was only 1.2 μm. For the DLC coated sample a sudden increase in the friction occurred after approximately 25 minutes followed by a gradual decrease in the friction as shown in **Figure 7**. The sudden increase corresponds to wearing through the DLC coating at the grinding ridges while the subsequent decrease is due to the topographical changes of the surface. The friction coefficient plots seem to converge to similar values. However, the nature of the wear debris should be taken into consideration as based on the way loose particles are entrained in the contact could account for difference in the friction values. For example, the worn DLC particles may become abrasive affecting the friction behavior. Therefore, the combined effect of having morphological as well as well as changes in lubrication regime due to entrained particles may all determine the friction and wear behavior. The microscope image and 2-D profilometric measurement of the penetrated DLC sample resemble those of **Figure 3** (c) and (d), respectively. From the geometry of **Figure 3** (d) it is clear that the 1.2 μm-thick DLC coating was penetrated since wear was in the order of 7 μm.

5 CONCLUSIONS

While coatings can be beneficial, their selection should be based on surface roughness, clearance, and piston skirt design and operational specifications of the engine. The Ni-PTFE coating used in formulated 10W30 oil showed a small friction reduction compared to the non-coated sample. Graphite-resin provided the lowest friction during run-in, but offers no wear protection and the effect of entrained graphite should be taken into consideration. Nevertheless, it is a good break-in coating. The DLC coating exhibited stable friction throughout with less wear. However, longer test durations led to coating penetration and showed coating thickness plays an important role. Since the DLC coating is thin it may be penetrated after a certain period of time leading to an unpredictable evolution in friction coefficient. Finally, the effect of changing surface topography is emphasized as friction reduction was seen in PAO10 oil at the expense of wearing the high peaks of the original profile, and therefore the original roughness of the commercial piston skirt may not be effective for lubrication and a smoother surface topography may be desirable.

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