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Tribology of Protective Hard Coatings for use in Oil-Less, Piston-Type Compressors

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ABSTRACT

Compressors have been operating at increasingly severe conditions in order to raise efficiency, requiring them to function under starved lubricated conditions. With the use of HFC refrigerants, which deteriorate natural protective "films," materials with enhanced tribological properties have become necessary. Extensive research has been conducted on the tribological performance of protective hard coatings, though very little in compressor simulated environments. Controlled pin-on-disk experiments imitating the wrist pin-connecting rod interface were performed using a High Pressure Tribometer under unlubricated (oil-less) conditions. Test specimens included 52100 steel wrist pins coated with either WC/C or multi-layer WC/C + DLC and cast iron disks. Analysis of experiments investigating temperature effects and performance in various refrigerants including R134a, R410a, and R600a, was completed using energy dispersive x-ray microanalysis and surface profilometry. Based on the research presented, it is concluded that coatings will become an essential component of modern compressors operating under starved and possibly oil-less conditions.

1. INTRODUCTION

The transition from chlorofluorocarbon (CFC) refrigerants to more environmentally friendly refrigerants such as hydrofluorcarbons (HFC), hydrocarbons (HC), and CO_2, for use in compressors, has necessitated the quest for wear resistant and low friction materials and interfaces. Because of the absence of chlorine which forms ferrous chloride layers on iron surfaces, the contact pressure limits allowed by HFCs have decreased from those of CFCs [Sung , 1998; Lee and Oh., 2003]. Furthermore, interfaces must be able to withstand severe operating conditions caused by smaller clearances and increased speeds and loads of current and future compressors. Also, the state of lubrication in many compressor components is limited and usually is in the boundary and mixed lubrication regimes [Pergande *et al*., 2004]. Additionally, an interest in transitioning towards oil-less compressors is desired to eliminate the negative effects on the thermodynamic efficiencies of refrigeration cycles. Under these dry sliding conditions, one cannot rely on oxide formation and other surface reaction layers alone for enhanced tribological performance, and some form of protective coatings will be necessary.

There is little research on the application of coatings in compressors and simulated environments and none was found to specifically investigate reciprocating motion such as that of a piston-type compressor. In this study, the use of hard coatings is investigated for use in piston-type compressors at the connecting rod-wrist pin interface. Specifically, actual 52100 steel wrist pins from a compressor were coated with single-layer WC/C or multi-layered WC/C + DLC. These coatings were chosen for their advertised and widely known low friction characteristics, high relative hardness, low surface energy, and, therefore, expected reduced adhesive and abrasive wear. The areas of investigation presented in this paper are coating performance under severe conditions with temperature variation up to 120°C including the amplified effects of running-in at elevated temperatures, and coating performance in various refrigerants and inert environments.

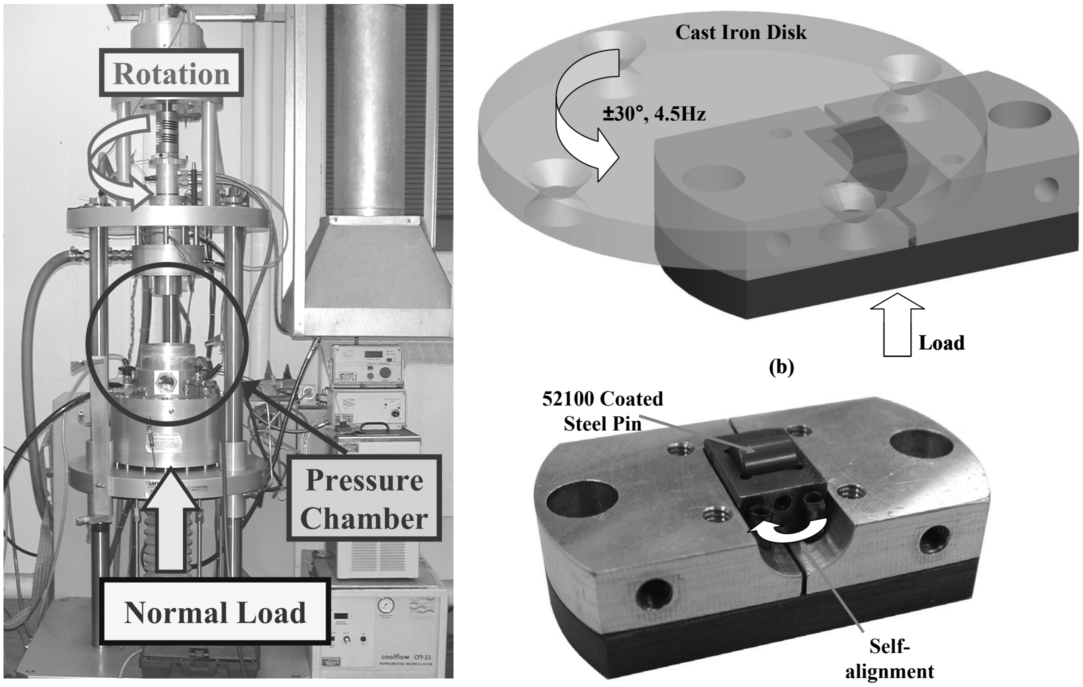
2. EXPERIMENTAL PROCEDURE

2.1. High Pressure Tribometer

A specialized high pressure tribometer (HPT, Figure 1a) was used in this study to perform controlled tribological experiments and evaluate friction and wear characteristics while simulating typical operating conditions found in air conditioning and refrigeration compressors. It uses an upper rotating spindle to which the disk is securely attached and a stationary lower fixture that holds the pin. A power screw mechanism adjusts the vertical position of the lower fixture to open or close the pressure chamber and apply a controlled normal load ranging from 45 N to 4450 N. The lower fixture is mounted to a 6-axis force transducer which measures the forces in the x, y, and z linear directions to calculate the coefficient of friction for eccentric contacts or frictional torque for concentric contacts. Rotary or theta-axis control regulates upper spindle oscillation amplitude and frequency up to 5 Hz for oscillatory motion or up to 2000 rpm for unidirectional motion.

The chamber temperature of the HPT can be varied from -20 to 140°C by pumping a heat transfer fluid through the upper spindle which is temperature regulated by an external unit. The chamber can also be vacuum evacuated and subsequently pressurized up to 1.72 MPa. The HPT is computer controlled and acquires data including in-situ normal load, friction coefficient, near contact temperature of the stationary specimen (approximately 2 mm below the surface), and electrical contact resistance while exporting the data for analysis. A detailed description of the HPT can be found in Yoon *et al.* (1998).

The contact used in this study is a pin-on-disk geometry, where the disk is the upper rotating sample, and the pin is the lower stationary sample. The pins are oriented to create a line contact as illustrated in Figure 1b and are 8 mm in diameter and 8 mm long with a 1 mm diameter hole for miniature thermocouple insertion. Disks are 75 mm in diameter and 6.4 mm thick. The pin is fixed within a special holder (Figure 1c) which is then placed in the fixture such that it is allowed to self-align to the disk surface ensuring a uniform contact. Specimen holders can be fitted to the machine to simulate many different contacts at any diameter on the disk.

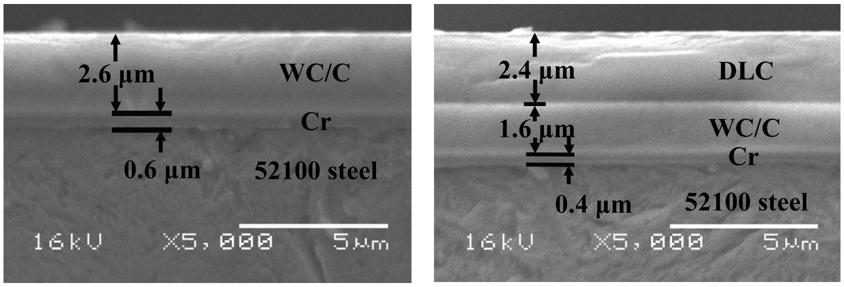


(a)

(b)

(c)

Figure 1: (a) High Pressure Tribometer (HPT), (b) illustration of pin-on-disk line contact, and (c) self alignment pin holder



(a) **(b)**

Figure 2: X5,000 cross-sectional SEM image of (a) WC/C and (b) WC/C + DLC coatings on 52100 steel pins

2.2. Test Specimens and Coatings

Single-layer WC/C and multi-layer WC/C + DLC coatings were acquired from a leading coating manufacturer for this testing. WC/C, an amorphous metal-carbon coating (a-C:H:W), was chosen based on its successful application in areas where low friction ($\mu < 0.2$) is required. Although the performance of coatings usually varies due to the adhesion layers used, the deposition method, and their surface roughness, according to the literature, WC/C has been found to perform similarly to harder, pure DLC coatings in terms of frictional characteristics and wear resistance [Meerkamm *et al.*, 1999]. Furthermore, the abrasive wear resistance of WC/C coatings has been found to be as high as TiN, a common coating unsuitable for low friction applications with a friction coefficient of 0.4 or higher [Wanstrand *et al.*, 1999]. Good wear resistance is a result of the alternating tungsten carbide and carbon phases in layers a few atoms thick, which can also provide good running-in characteristics.

Multi-layer coatings are often used to improve tribological performance of the individual constituents. They can provide increased adhesion, increased load capacity, decreased surface stresses, and resistance to crack propagation [Holmberg *et al.*, 2000]. The WC/C + DLC coating was chosen due to the low friction and high wear resistance of each individual coating. However, it has also been shown that the DLC/WC pairing performs particularly well where cyclic loading is prevalent, such as gears and bearings [Holmberg *et al.*, 2000], making it a good candidate for piston-type compressors. To promote coating adhesion to the substrate in all cases, a chromium interlayer was applied with a nominal thickness of 0.5 µm. The thickness of the single-layer WC/C coating was 2.6 µm while WC/C + DLC was 1.6 µm + 2.4 µm, respectively. Thickness verification measurements of each coating were determined by cross-sectional SEM, and such measurements are depicted in Figure 2.

Nanoindentation measurements on the coated and uncoated pins were also performed to measure their nanohardness and reduced Young's modulus values. A Hysitron TriboScope® nanoindenter was used in conjunction with a Berkovich indenter tip to obtain contact depths of 50-200 nm and mechanical properties were determined using the Oliver and Pharr method [Oliver and Pharr, 2004]. The nanohardness and reduced modulus of bare 52100 steel were 12 GPa and 205 GPa, respectively, but higher than the bulk hardness of 7.3 GPa (converted from a hardness of 62 HRC). WC/C hardness was similar at 10.5–12.5 GPa while its reduced modulus ranged from 90-125 GPa. The hardness of the WC/C + DLC coating is equal to that of just the DLC overcoat and ranges from 25-27 GPa while the reduced modulus was between 200 and 220 GPa. The hardness values of the substrates and coating are summarized in Table 1 and also agree with published values and manufacturer specifications [Guo and Warren, 2005; Gubisch *et al.*, 2005].

Table 1: Mechanical properties and roughness of substrates and coatings

Material	Hardness (GPa)	Reduced Modulus (GPa)	Roughness, Rq (nm)
Uncoated 52100 Steel	12	205	36
Dura-Bar G2 gray cast iron	1.5-3[1]	124[2]	300-500
WC/C	8-10	90-125	55
WC/C + DLC	25-27	200-220	45

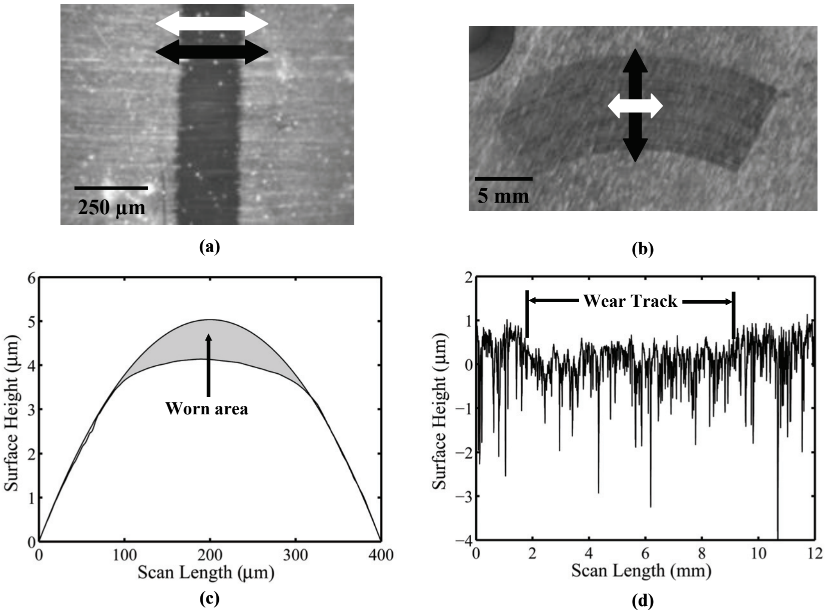
[1] Converted from Brinell hardness; [2] Bulk tensile modulus

2.3. Tribological Testing

Prior to and following testing, specimens were ultrasonically cleaned in acetone for 10 minutes and subsequently rinsed with 2-propanol. All tribological experiments were performed under a constant normal load and oscillating frequency in order to evaluate wear and running-in. Due to the high wear resistance of WC/C, it was necessary to use higher contact pressures to obtain measurable wear with accelerated experiments. Thus, tests were conducted with loads of 445 N to produce a maximum Hertzian contact pressure of 623 MPa. All tests were performed at a frequency of 4.5 Hz, amplitude of 30 degrees, and an average wear track diameter of 47.6 mm to produce average and maximum linear velocities of 0.21 m/s and 0.33 m/s, respectively. To investigate the use of this coating in oil-less compressors, tests were primarily performed in R134a at 172 kPa environmental pressure and no lubricant while WC/C + DLC was also tested in R410a, R600a, and N_2 at the same pressure to investigate environmental effects.

As a baseline, uncoated experiments were performed at a lower normal load of 200 N for 10 minutes, to avoid scuffing. Using coated pins, test durations of 21 minutes were performed, excluding tests at 23°C, which were run for 30 minutes. These times provided measurable wear from which performance distinction could be made without observing scuffing failures. For the first minute of each test with a coated pin, the normal load was set to half that of the remaining test load to aid running-in. In the absence of this initial lower load at the beginning of the running-in process, several immediate coating failures had occurred.

At tested chamber temperatures above 60°C, a progressively increasing running-in period was observed where friction coefficients of up to 0.4 were measured, and to study this behavior, WC/C was tested at 120°C and 222 N for 5, 10, and 21 minutes. Following all tests, wear was quantified using two profilometric scans on each disk and pin, of which typical representations are shown in Figure 3, along side micrographs of tested specimens. As shown in the figure, to precisely determine pin wear, the worn pin profile was subtracted from the original measurement of the cylindrical pin shape. The areas of the two scans were averaged and multiplied by the pin length to determine the wear volume. Also following testing, specimen roughness scans were completed to correlate roughness to the running-in process.



(a) (b) (c) (d)

Figure 3: Images and profilometric scans of typical worn (a) pin and (b) disk. The white arrows on the pin micrograph denote the scan directions of Figure 7 while the black arrows indicate the sliding direction.

3. RESULTS AND DISCUSSION

3.1. Temperature Variation

To obtain a baseline from which to compare coating performance, tests were performed with uncoated pins at room temperature. The aim was to determine at which load the uncoated tests could be run without scuffing failure. Uncoated pins were only able to support a 200 N normal load for ten minute tests and exhibited steady-state friction coefficients of ~0.34. Steady-state was reached after four minutes of a lower friction running-in period with an initial friction coefficient of ~0.2. The cause of this running-in period is likely a result of adhesive wear increasing roughness of both surfaces and subsequently the abrasive wear and friction coefficient as evidenced by material transfer to the pin as well as significant wear debris from the disk. No measurable pin wear was observed as mostly material transfer from the disk occurred. Disk wear depths ranged from 1-2 μm, in contrast to the behavior exhibited in the coated experiments, where measurable disk wear was not observed.

Due to insignificant disk wear produced in coated experiments (depths < 0.5 μm, indistinguishable from the disk roughness) while pin wear became significant, only pin wear was quantified. Steady-state friction coefficient values and wear rates, defined as wear volume per total distance, are depicted in Figure 4 where error bars represent the minimum and maximum values for a given condition. As the error bars indicate, test repeatability was high. Steady-state friction coefficients are shown to decrease with temperature while wear rates initially decrease and then increase at the highest temperature tested. At room temperature, no significant running-in period was observed, with initial friction coefficient values of 0.13. This is likely due to low adhesive wear from the low surface energy of the coating while the disk surface was quickly polished. Wear is significantly less for WC/C + DLC than WC/C due to the multi-layer coating's higher hardness and, therefore, resistance to abrasive wear.

At temperatures of 60°C and above, however, adhesive wear begins to increase, increasing the pin wear rate. As wear of the pin increases with temperature, it is postulated that a transfer film on the disk from the coating begins to form, more so with WC/C that WC/C + DLC, causing the steady-state friction coefficient to decrease, which is in agreement with the literature [Erdemir *et al.*, 1995; Holmberg *et al.*, 2000]. Also contributing to the friction decrease is a higher polishing rate of the disk surface at increased temperatures. It is important to note, however, that disk wear is still not measurable while pin wear rates decreased by 9% in the transition from room temperature to 60°C for WC/C and 11% for WC/C + DLC. An even higher wear rate decrease is exhibited from 60°C to 80°C for WC/C, but steady-state friction coefficients remained similar. Increased wear and similar friction is due to a transition period from abrasive to adhesive wear in this temperature range. An increase in temperature to 120°C produces a lower steady-state friction coefficient for WC/C while the transition to adhesive wear increases the pin wear rate by over 50% from values at 80°C. The increase in adhesive wear is evidenced by greater material flow on the coating surface at higher temperatures, observed with SEM, which also causes pronounced running-in periods.

3.2. Running-in at Elevated Temperatures

It was desired to complete all tests with a load of 445 N, but at 120°C, instant failure occurred. To obtain tests of the same duration as those discussed previously, the normal load was reduced to 222 N. During these tests, a very pronounced running-in period was observed with friction coefficients reaching in excess of 0.4, but would then attain steady-state values of less than 0.05. To study this running-in behavior, additional tests were performed that

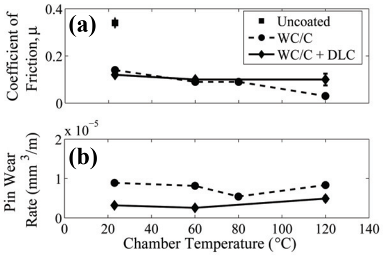


Figure 4: (a) Steady state coefficient of friction and (b) pin wear rate versus temperature. Error bars represent maximum and minimum values for a particular condition.

were stopped at the friction coefficient peak (5 minutes) and at the end of the running-in period (10 minutes). Tests were repeatable and plots are shown with load and friction evolution in Figure 5, exhibiting the same trend of high values in running-in and attaining steady-state thereafter. Notice also in Figure 5 that friction immediately reaches steady-state at 23°C, while running-in friction coefficients increase with temperature.

As postulated, nearly all pin wear occurred during the running-in period. The pin wear volume of the 10 minute test was nearly identical to those of the 21 minutes tests at 2.35 x 10^{-3} mm^3. Pin wear volume at 5 minutes, was slightly less at 1.67 x 10^{-3} mm^3, suggesting that the majority of the wear occurs during the first half of the running-in period. Illustrating material transfer to and from the disk, SEM images captured at the edge of the pin wear are displayed in Figure 6. The image taken after the 5 minute test shows that only polishing of the pin occurred with possibly some material transfer from the coating to the disk. However, the SEM image taken after the 21 minute test shows possible coating material flow or material transfer from the disk. In all cases investigated in this work, the coating was never fully worn through.

To further examine running-in, profilometric scans of the pins and disks were taken perpendicular to the sliding direction within the central 4 mm of the wear scar. In Figure 7, the profile of a virgin pin is shown for reference along with scans taken after the 5 minute and full length tests. A difference is clearly seen in that during the first 5 minutes, pin micro-roughness significantly decreases through the shearing of asperity peaks, while an increase in pin micro-roughness is observed at 21 minutes due to conforming to the disk. However, overall roughness decreased from Rq = 87 nm at 5 minutes to Rq = 73 nm at 21 minutes as a result of polishing. A similar but less pronounced trend is apparent from the 5 to 10 minute tests.

Profile scans of the disks provide further insight as to the cause of running-in with similar justifications as with the pin profiles. Specifically, the virgin roughness and skewness of the disks in the wear track area (measured perpendicular to the sliding direction with a 4 mm scan length) were Rq = 300 nm and Sk = -0.69. After the 5 and 10 minute tests, the negative skewness increased significantly to -2.62 and -2.85, respectively, indicating the removal of asperity peaks (polishing). At 21 minutes, the negative skewness increased slightly to a value of -2.92 while the Rq value decreased to 270 nm. These values along with the evolution of the pin wear profile demonstrate that pin and disk surfaces must conform to each other through polishing and material transfer to reduce abrasive friction and complete the running-in process. To reduce the length of the running-in period, it is recommended that the contacting surfaces be polished before and after coating for actual engineering applications, such as that in a compressor, or the coating may not survive the running-in period to achieve steady-state.

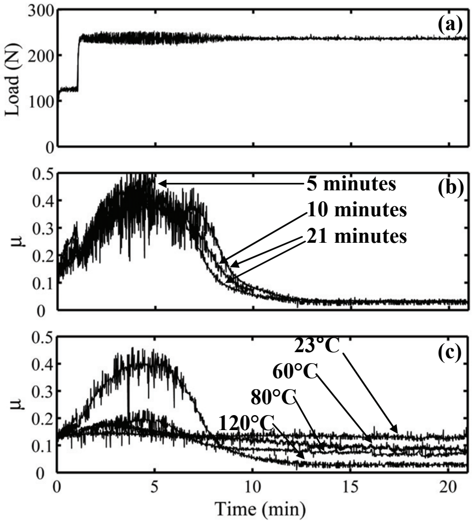


Figure 5: (a) Load and (b) friction coefficient, μ, evolution for WC/C with test durations of 5, 10, and, 21 minutes (full length). (c) Comparison running-in characteristics in terms of the friction coefficient of WC/C for each temperature tested. Note the test repeatability and apparent noise caused by oscillatory motion.

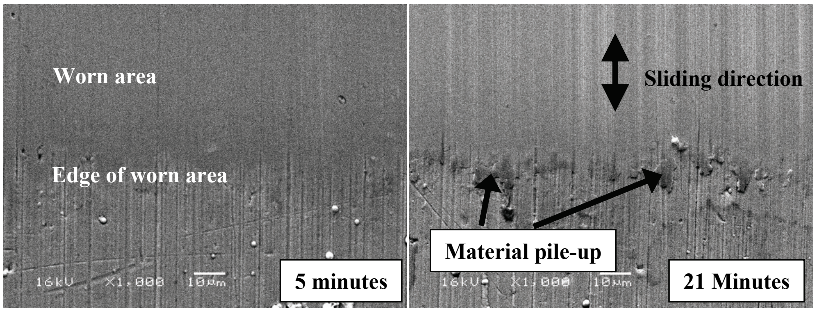


Figure 6: X1,000 SEM images at the edge of pin wear for 5 minute test and full length, 21 minute test at 120°C.

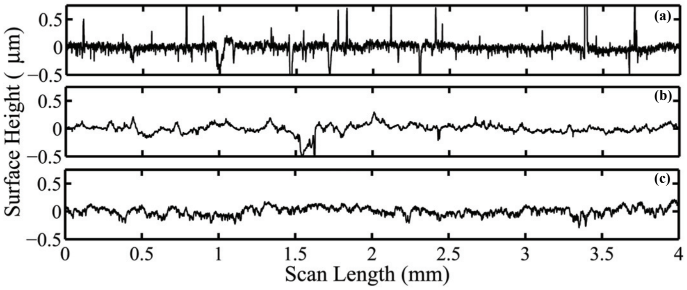
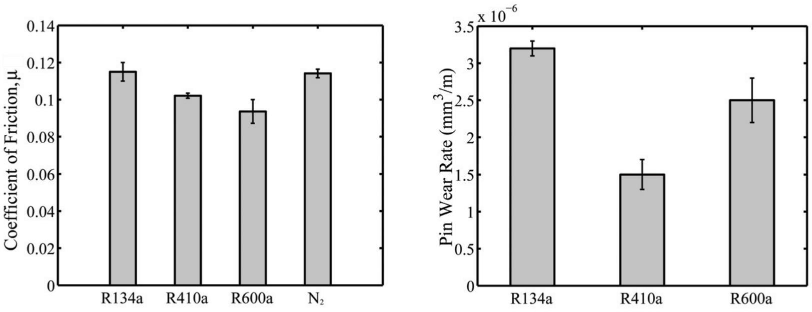


Figure 7: Representative (a) virgin pin, (b) pin wear after 5 minutes, and (c) pin wear after a full length, 21 minute test. Scans were performed perpendicular to the sliding direction.

3.3. Refrigerant Variation

Due to the absence of published literature on refrigerant comparison in tribologial applications, it was unsure how each refrigerant would perform relative to each other. It was found that friction coefficients for R134a, R410a, and N_2 are similar in the first few minutes with the WC/C + DLC coating, but then scuffing occurred in the N_2 environment at a little over four minutes. At around five minutes, the R410a interface exhibits decreasing friction indicating that it was in a state of running-in. It reaches steady-state with slightly lower friction than in the R134a environment, but the friction in the R600a environment remains the lowest for the entire test. Steady-state friction coefficients for each environment are displayed in Figure 8a. Note that the friction coefficient for N_2 is the average prior to scuffing. Chemical analyses were not performed to detect compounds that may improve friction characteristics, but R600a has the highest percentage of hydrogen atoms per unit volume and Fontaine *et al.* (2004) reported that H_2 has a healing effect on hydrogenated DLC coatings in tribological testing. Conversely, R410a produced the least amount of wear with R600a being the second best. Reasons for this are unknown until further chemical analyses are completed. Relative pin wear rates are given in Figure 8b. Also, note that wear is not reported for N_2 due to extreme material transfer with scuffing failure.



(a) (b)

Figure 8: (a) Average friction coefficient and (b) average pin wear rate produced with each environment. Error bars represent maximum and minimum values for a particular condition.

4. CONCLUSIONS

An experimental investigation of a single-layer WC/C and multi-layer WC/C + DLC coating for oil-less compressors at various temperatures and in multiple environments was performed. Unlubricated, uncoated experiments exhibiting high friction and wear suggest that protective films such as hard coatings are necessary to enable the use of oil-less compressors for increased efficiency.

The coatings used in this study enhanced tribological performance greatly by reducing the friction coefficient by factors of 3.5 and almost ten for WC/C and WC/C + DLC, respectively, at high temperatures and virtually eliminating wear of the uncoated disk. WC/C + DLC consistently showed the least wear while friction for WC/C is slightly higher at lower temperatures, a trend that is reversed at elevated temperatures. The friction coefficients decreased with temperature while wear decreased and then increased following a critical point in temperature where running-in wear becomes more severe. Following running-in, minimal additional wear occurs, indicating the advantage of using coatings with good running-in characteristics and reducing the initial roughness of the interface as much as possible. Experiments in R410a produce the least amount of wear, whereas those in R600a have the lowest friction, possibly due to the abundance of hydrogen in the environment.

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