EFFECT OF R600a ON TRIBOLOGICAL BEHAVIOR OF SINTERED STEEL UNDER STARVED LUBRICATION

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Abstract

This study aims to develop and characterize wear resistant and low friction tribopairs that are compatible with new ozone-friendly Isobutane refrigerant to run at hermetic compressor bearings. The tribological behavior of 100Cr6 steel pin is investigated under starved lubrication condition in air and R600a environments when running against sintered steel with and without steam treatment. EDS and SEM are carried out on pin and plate samples after wear tests. The results indicate that durability distance is lower for the tests with R600a than those with air. The adverse effect of R600a on wear rate is linked to the change in the viscosity and foaming characteristics of the oil in the presence of R600a as well as the lack of oxides.

Keywords: Sintered steel, starved lubrication, R600a.

Introduction

Common household refrigerators and freezers all utilize hermetic compressor to drive the refrigeration cycle. Such hermetic compressors pressurize a refrigerant and raise its temperature, then discharge it into the refrigerating cycle [1]. As energy costs increase rapidly, compressor mechanical losses attract renewed attention. Various surface treatments and oil-refrigerant compositions have been proposed to decrease friction and wear in closed type compressors [2,3]. On the other hand, research on the stratospheric ozone layer demonstrated the detrimental affects of conventional refrigerants containing halogens. Discharge or leakage of stable refrigerants containing chlorine, bromine, and other halogens affects the stratospheric ozone equilibrium [4], and their use has been restricted by Montreal and Kyoto protocols [5,6].

A conventional closed-type compressor uses CFC (cloroflorocarbon), R12, or HCFC (hydrofloroclorocarbon), R22. Typically these refrigerants work well with Mineral oils to achieve desirable wear life and friction levels. None chlorine substitute refrigerants mean that favorable lubrication properties of R12 or R22 can not be utilized. As conventional refrigerants phased out, Isobutane (R600a) emerged as the main alternative in refrigeration industry. Hydrocarbons (HCs) such as R600a are viable substitutes as they possess favorable refrigerants properties. Their use as refrigerants in domestic refrigerators is very attractive as they are environmentally acceptable and cheap in nature. However, they are flammable. Their compatibility and performance with compressor oils are still worked on.

Transition of refrigerants occurred in two phases. First, CFCs (like R12 and R22) evolved to HFCs (like R134a), then HFCs were replaced with HCs (like R600a). Although there are some published research on HFCs, literature on HC refrigerants is very limited. There is no open literature on friction and wear performance of new HCs for typical compressor bearings. This work, aims to provide information on friction and wear performance of common compressor bearing materials under Isobutane (R600a) atmosphere with common Mineral oil.

With the transition from CFC to HFC on compressors, Solzak and Polycarpou [7] have studied the tribological effects of connecting rod-wrist pin interface with HFC refrigerants. Their experiments with unlubricated and uncoated steel surfaces indicated high friction and wear suggesting the need for protective films to use oil-less compressors with high efficiency. Tribological behavior of some hermetic compressor parts in R134a environment has been studied by a number of researchers [8-10]. The studies show that the wear rate in R134a is significantly lower due to the fact that R134a and PTFE have very similar chemical structure.

Most studies in the literature deal with the performance of domestic refrigerators working with different refrigerant/oil mixtures to determine refrigeration capacity, compressor power and coefficient of performance (COP). Alsaad and Hammad [11 14], Jung et. al [12 15], indicated that mixture of propane(R290)/butane(R600) and propane/isobutane(R600a) could be successfully adopted for the replacement of CFC-12/HFC134a in domestic refrigerators. Wongwises et al. [13,14] studied the application of hydrocarbon mixtures R290, R600 and R600a to replace HFC-134a in domestic refrigerators. The results indicate that various refrigerant mixture ratios show excellent performance and energy consumption when replaced with pure R134a.

There is not enough long term wear and durability information on the use of R600a refrigerant. Garland et.al [15] have studied the tribological behavior of some hermetic compressor parts in R134a, R12, and R600a environments. The results indicated the superior COP for R600a over R134a and R12, yet the long term wear and durability of equipment using this refrigerant is unknown. In another study about thermodynamic properties of R600a by Zhelezny et al. [16] reported that the variation of vapor pressure, density, capillary constant and surface tension as a function of concentration for the isobutane/Azmol solutions can be easily optimized for domestic refrigerators.

Garland and Hadfield [17] investigated the impact of the use of hydrocarbon refrigerants in a domestic refrigerator. Their results indicate that R600a mixture with Mineral oil appeared to be an appropriate long-term candidate to replace R134a.

Although better COP values are achieved with HC refrigerants, wear life related issues need to be resolved since no published data is available. Possible problem areas include motor/crankshaft journals, crank pin/connecting rod bearings, piston/cylinder sliding interface and the inlet/exhaust flapper valves [18].

Most sliding elements are usually fabricated from sintered iron in order to improve lubricant retention. Increasing attention to environmental issues forced the lubricant industry to increase the ecological friendliness of its product. Eco-lubricants, due to the lack of effective but hazardous additives, do not exhibit satisfactory anti-friction properties necessary for parts like connecting rod, piston pin, gears. To improve scuffing resistance, to prevent seizure, and prolong the life of the critical components, steam treatment is implemented to sintered steels. Steam application is a widely applied surface treatment for sintered parts in industrial applications; hence it has been considerably studied in terms of tribological characteristics. The lower wear rate of a steam treated sintered iron compared to the untreated material has been demonstrated.

Sintered iron against 100Cr6 is one of the most common tribopairs used in hermetic compressors. Shedding light on friction and wear performance of 100Cr6/sintered iron tribopairs under R600a atmosphere, this study aims to aid hermetic compressor designers in achieving their extended life goals. With renewed attention to use less and less oil, friction and wear performance under starved lubrication and dry conditions are also presented.

Experimental Details

The sintered disc material was prepared from the iron powder of 5-100 μm grade size at constant compaction pressure of 475 MPa, containing (wt.%) 0.30C, 0.0043S, 2.44Cu, 0.21Si, 0.54Mn, and the remaining being Fe at a density of 6.8 g/cm^3. Sintering process was conducted in a mildly reducing atmosphere of 75% N_2 + 25% H_2 at a constant temperature of 1120^{o}C for 25-30 minutes. Then samples were cooled at 1.0°C/s to room temperature in a H_2 atmosphere with a low dew point. As sintered samples had bulk hardness around 85 HRF. The surface roughness (Ra) of 0.50 μm was measured. Steam treatment involved two hours of pre-heat process at 100^{o}C prior to steam oxidation for one hour at 600^{o}C, and following two hours of cool-down process in the furnace. Steam treated samples had a bulk hardness around 102 HRF.

A standard pin-on-disc test rig was used. A 100Cr6 steel pin (1250 HV), 7.89 mm in diameter and of a 5 mm in length, was rubbed sideways against a rotating sinter disc (Fig1). Prior to each test, samples were cleaned in an ultrasonic cleaner for 15 min. in acetone, followed by 15 min. cleaning in ethanol. Dry sliding tests were conducted in an atmosphere with 60-70% relative humidity and at a temperature around 23°C. For starved oil lubrication tests, Mineral oil, with a viscosity of 7cSt at 40°C, was misted on the sliding surface for 1 second at 30 psi oil pressure through a fully controlled nozzle at the beginning of the each wear test. The amount of oil used at each test was measured to be 100 mg. No other oil was introduced throughout the test. Applied loads of 40 N and 50 N, as well as the speeds of 0.26 m/s and 0.8 m/s were chosen for these tests. New pin and disc were used for each test and the track diameter was kept constant for each sliding speed so as to eliminate this as a further variable. All of the disc specimens investigated in this study were kept in desiccators before and after their friction/wear tests.

The R600a gas pressure and composition inside the tribometer was monitored with a flow regulator. A large isolated Plexiglas cage was used to ensure atmosphere control to observe frictional behavior in isobutane atmosphere. Being heavier than air, R600a refrigerant was introduced from a lower point while excess atmosphere is bled through a higher exhaust to ensure that the entire test system is submerged in R600a atmosphere. To facilitate uninterrupted R600a exposure, refrigerant is continuously fed to the system.

The amount of wear was determined by appropriate measure of the weight of both specimens before and after each test (Table 1). Initial weight of pins and disc were measured after cleaning in acetone and ethanol followed by drying operation using an electronic weighing balance with 0.1 mg. accuracy. The wear rates were obtained by dividing the wear volume by the load and the total sliding distance. Wear tests were conducted at normal loads of 50N. A fresh abrasive surface was used in every test. The surface microstructures of the wear tracks of each specimen and its paired pin were investigated using scanning electron microscope (SEM) with energy-dispersive X-ray spectroscopy (EDS).

Results & Discussion

In order to facilitate easier comparison of various cases, wear tests at identical conditions were conducted in both R600a and air environment. First, friction and wear performance of both pairs under dry conditions were tested [19]. The weight loss measurements were taken for applied loads of 40 N and 50 N. Figure 1 illustrates weight loss against the test time at a constant sliding speed of 0.26 m/s. It is observed that the load increase changes the wear regime, and wear rate was more than doubled with 25% load increase. However, steam treatment had a favorable effect decreasing the wear rates by four-folds as compared to untreated sinter material. The lower wear rate for steam treated sinter sample was due to sealing of pores and formation of oxide layer during steam treatment, which in turn forms a smoother sliding surface. As shown in Figure 2, accompanied by an excessive noise and vibration during testing, the coefficient of friction fluctuated more for the untreated sinter sample.

When dry tests were repeated in R600a environment, it has been observed that wear rate increases (Figure 3). The oxidation of iron contributed significantly to the reduction of wear rate for samples tested in air. The hard oxides form a protective layer, and increase wear life. However, under R600a environment, EDS analysis showed that the oxidation of iron was obstructed (Figure 4). The results clarify that introduction of R600a degrades wear performance of sintered surfaces.

As starved lubrication tests took much longer, test speed had to be raised to 0.8 m/s to achieve longer sliding distances in a shorter test period. Wear performance is established by comparing the sliding distance before the sudden increase and fluctuation of the friction curve. When plotted against the sliding distance the transition in friction coefficient, the transition in friction coefficient is noticeable in Figure 5 for both air and R600a environments. Just as observed in dry test conditions, introduction of R600a during starved lubrication tests resulted in noticeable reduction in wear performance (durability distance).

It is clear that the micro structural features of the sinter material greatly affect the properties of the oil absorbed layer, which in turn influence the durability distance. The observed higher durability distance for untreated sintered steel is attributed to higher porosity levels which resulted in higher oil absorption of pores providing a smoother sliding surface by supplying oil over extended time period. For the steam treated sintered steel this distance was shorter since the oil absorption gets lower due to sealing of the pores during heat treatment process. The adverse effect of R600a on wear regime was noticeable for both untreated and steam treated sintered steel, showing 50% decrease for untreated case, and more than 60% decrease for the steam treated case. The wear rate results in Table 2 point out that 100Cr6 steel have longer life than sintered steel. This is due to the hardness of the 100Cr6 pins, which is greater than that of the sintered steel. As observed in SEM pictures

(Figure 6) predominant wear mechanisms appear to be through material removal by cutting and plowing.

Conclusions

Upon concerns on stratospheric ozone depletion, low cost and ozone-friendly Hydrocarbons like isobutane are replacing other conventional refrigerants. The results of the current study indicate that introduction of R600a refrigerant in to the compressor bearings will have adverse effects on friction and wear performance at critically loaded interfaces. Adverse effect of R600a environment is notable for both dry and starved lubricating conditions. Especially for starved lubrication case, the wear life for both untreated and steam treated sintered steel was almost reduced in half in the presence of R600a as compared to that of in air. Adverse effect of R600a on wear is thought to be due to change in viscosity and foaming characteristics of the oil. Furthermore, EDS analyses of indicate that the oxidation of iron under R600a was blocked, causing an increase in weight loss of no treated sintered iron. Overall, these results raise the question as to how effective the starved lubrication by itself can be in achieving ambitious targets for controlling the wear rate in ambient of R600a.

Acknowledgements

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List of figure captions

Fig. 1. Weight loss under dry sliding at 40 N and 50 N, at RT and 0.26 m/s, (a) Sinter, (b) ST-Sinter.

Fig. 2. Fluctuation in coefficient of friction under dry sliding at 50 N at RT and 0.26 m/s, (a) Sinter, (b) ST-Sinter.

Fig. 3. Weight loss under dry sliding at 50 N, RT and 0.8 m/s for in air and R600a.

Fig. 4. EDS analysis results for sinter iron samples after wear tests in (a) air , (b) R600a

Fig. 5. Transition in friction coefficient under starved lubrication in air and R600a.

Fig. 6. SEM pictures of (a) steam treated, and (b) untreated surfaces under starved lubrication and R600a.

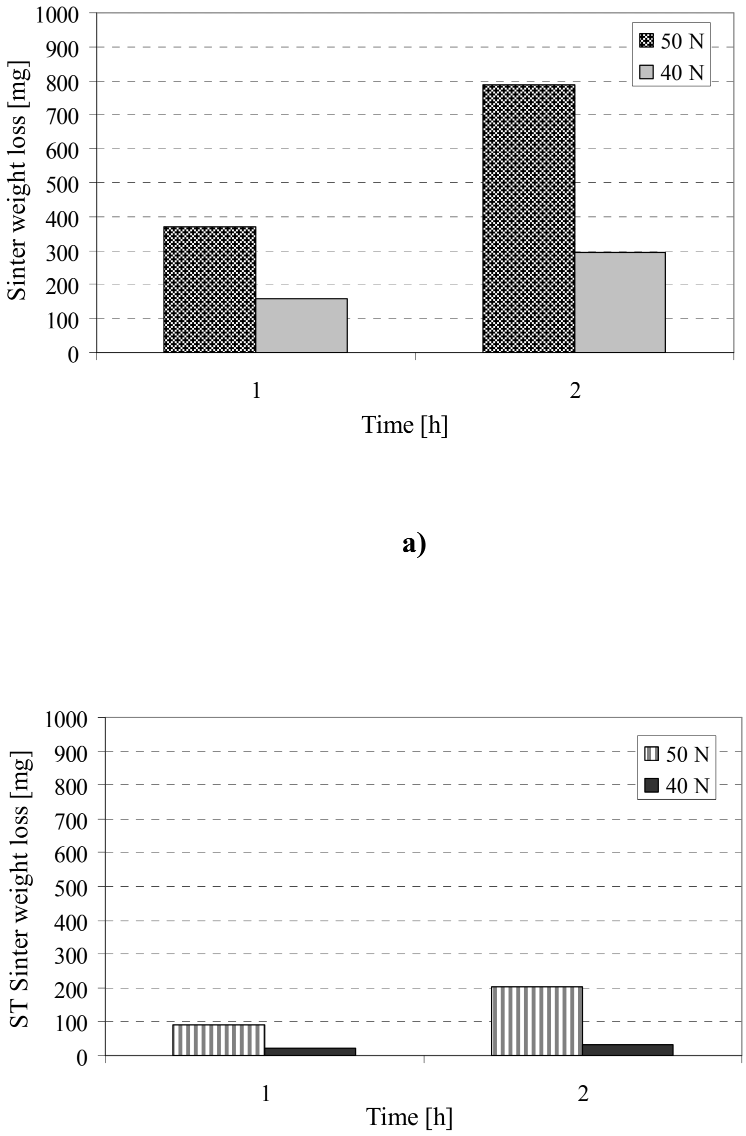
Table I. The test conditions of pin-on-disk tribometer tests

Parameters	**Conditions**
Applied Load (N)	50
Velocity (m. s^{-1})	0,8
Rotational speed of substrate (rpm)	350
P.V. (MPa.m.s^{-1})	8
Wear track (mm)	21,90
Environment	Air , R-600a
Temperature (^{0}C)	23-25
Humidity (%RH)	55-60

Table II. The wear rate and weight loss of steam treated sintered steel (ST), and no steam treated sintered steel (NT) under air and isobutane (R600a) conditions

	Air		**R600a**	
Samples	**Wear Rate ($mm^3.N^{-1}.m^{-1}$)**	**Weight Loss (gr.)**	**Wear Rate ($mm^3.N^{-1}.m^{-1}$)**	**Weight Loss (gr.)**
ST Sintered	1.35×10^{-5}	0,24	4.71×10^{-5}	0,30
NT Sintered	0.76×10^{-5}	0,17	4.52×10^{-5}	0,50
100Cr6 (ST)	4.17×10^{-8}	0,0009	2.50×10^{-8}	0,0002
100Cr6 (NT)	1.46×10^{-8}	0,0004	4.07×10^{-8}	0,0006

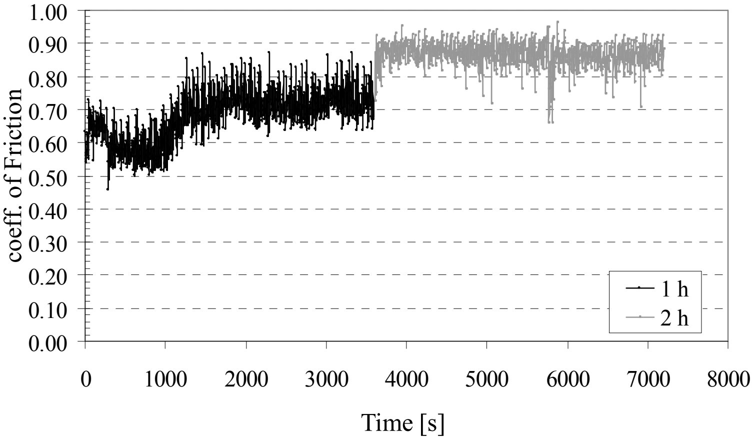
Figure 1


1000
900
800
700
600
500
400
300
200
100
0
Sinter weight loss [mg]
▩ 50 N
▨ 40 N
1
2
Time [h]
1000
900
800
700
600
500
400
300
200
100
0
ST Sinter weight loss [mg]
▥ 50 N
■ 40 N
1
2
Time [h]

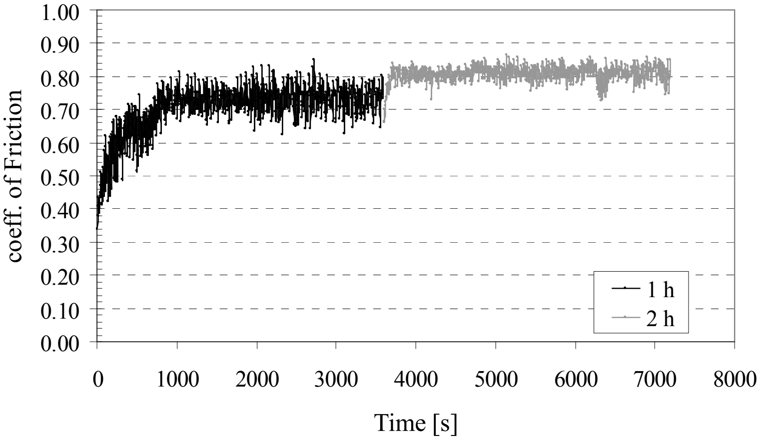
a)

b)

Figure 2


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
coeff. of Friction
0
1000
2000
3000
4000
5000
6000
7000
8000
Time [s]
1 h
2 h

a)


1.00
0.90
0.80
0.70
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0.30
0.20
0.10
0.00
coeff. of Friction
0
1000
2000
3000
4000
5000
6000
7000
8000
Time [s]
1 h
2 h

b)

Figure 3

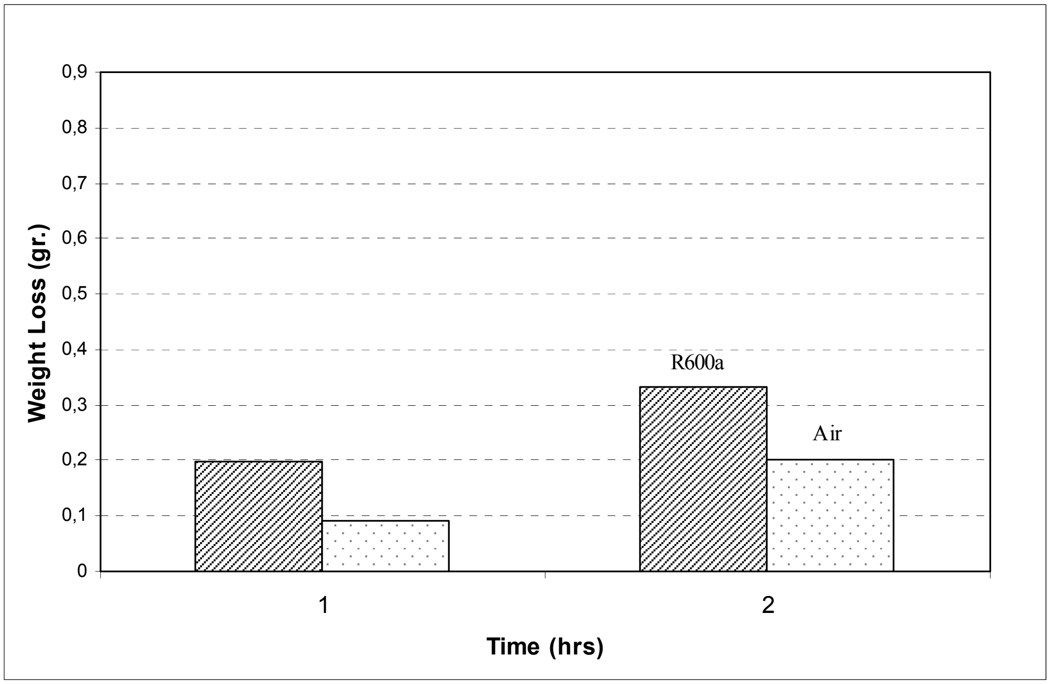
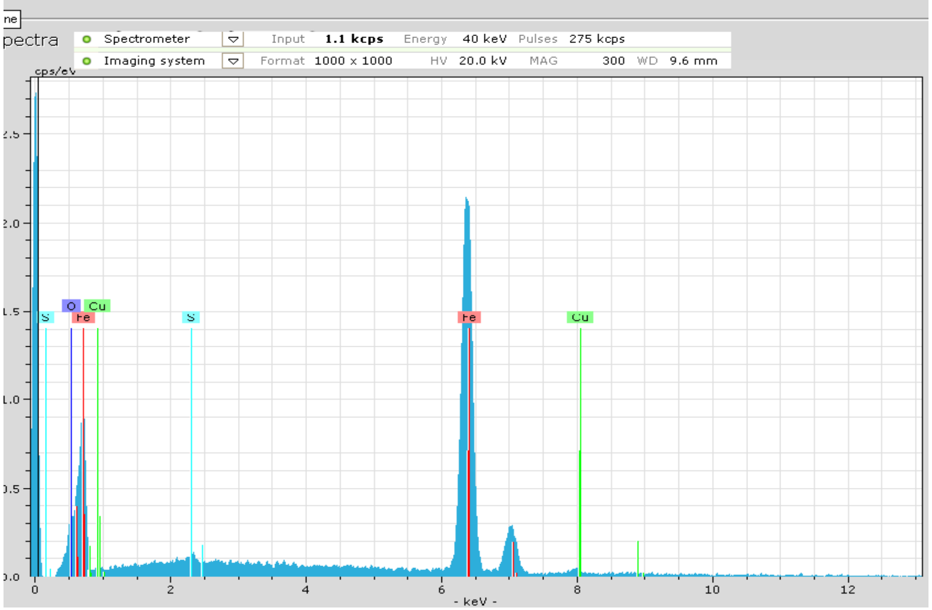


Figure 4



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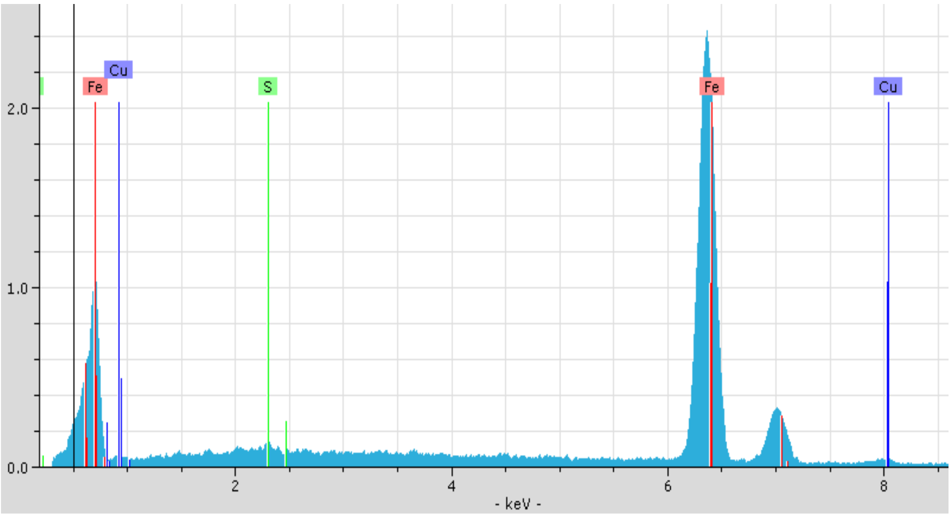
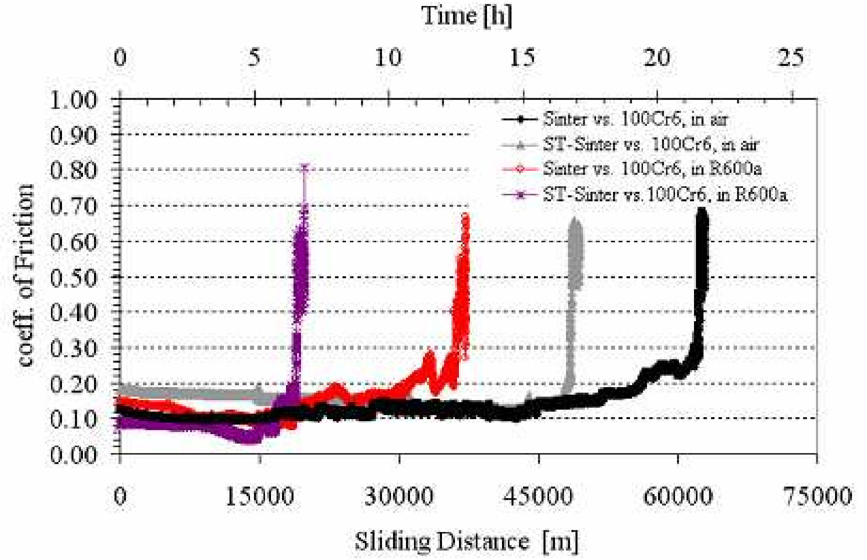
Imaging system Format 1000 x 1000 HV 20.0 kV MAG 300 WD 9.6 mm

(a)



(b)

Figure 5



Time [h]
0
5
10
15
20
25
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
coeff. of Friction
Sinter vs. 100Cr6, in air
ST-Sinter vs. 100Cr6, in air
Sinter vs. 100Cr6, in R600a
ST-Sinter vs.100Cr6, in R600a
0
15000
30000
45000
60000
75000
Sliding Distance [m]

Figure 6