1996

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A STUDY OF OVERALL TRIBOLOGICAL PROBLEMS IN DEVELOPING R407C ROTARY COMPRESSOR WITH POLYOLESTER OILS

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ABSTRACT

In this paper, overall tribological problems were investigated in developing an rotary compressor using R407C as an alternative refrigerant with polyolester(POE) oils. Real compressor life tests were conducted with several POE oils. Accelerated bench wear tests were also performed, and their results were compared with the life tests. To prevent severe wear in the vane and the roller components, several hard coatings were applied in the vane surface and their tribological performances were evaluated. Too hard coatings such as TiAlN, DLC_1 are not suitable since it produces high friction and severe wear. DLC_2 coating showed good tribological properties by forming a soft and easily shearable tribo-film on the mating surface. TiN coated vane itself showed good wear resistance property, while it produced high friction. Ion nitriding is not suitable since durability of ion nitride layer is not enough to sustain cyclic contact stress.

INTRODUCTION

To protect the ozone layer depletion, the HCFCs will be phased out by 2020 according to the Montreal Protocol. Several alternative refrigerants have been proposed for replacing HCFCs with HCFs. Among those, R407C is a possible candidate due to its similar thermodynamic characteristics, non-flammability and non-toxicity. However, since conventional mineral oil is not miscible with R407C, the use of R407C brings about problems of developing new refrigerant oils which are compatible with R407C. POE is considered to be adapted as the lubricant because of its good electrical insulation properties and good miscibility with R407C. There are various problems, however, in the actual application of the mixture of R407C-POE oil to compressor. R407C which contains no chlorine shows inferior lubricity or antiwear capability compared to HCFC22 [1,2]. Also POE oil which has high hygroscopicity tends to form acids by hydrosis, resulting in corrosive wear in the compressor. Therefore improvement of durability and reliability of compressor is a major concern when the mixture of R407C-POE oil is used [3]. This study was aimed to find and solve the tribological problems in developing compressor using R407C-POE oil mixture. Real compressor life test was conducted with several POE oils which are different in chemical structures and additives for finding a suitable POE oil. Also a accelerated wear test was conducted and those results were compared with those of life test. After tests, severe wear between the vane and the roller has been observed. To increase the wear resistance, several surface treatments or coatings has been applied to the vane surface and their performance were evaluated.

EXPERIMENTALS

Real compressor life test

The compressor life test was conducted for 4000 hours with rotary compressor used in air conditioner to evaluate lubricity of several POE oils with R407C. The compressor was a model currently used with R22. 6 POE oils were used which have different kinds of chemical structures and additives. Total 5 sets of compressors were used for each oil and the results were averaged.. Test in environments of R22-mineral oil was also conducted for comparisons.

Accelerated wear test

The accelerated bench wear test machine used was a Falex multi-specimen wear tester. The tester has a pressurized chamber which is capable of providing pressures up to 9kg/cm². Temperature of the chamber is raised by cartridge heater which is controlled by a microprocessors. To simulate the relative motion between the roller and the vane, a vane and disk type geometry was used. The vane material was SKH51 and roller material was Ni-Cr-Mo cast iron which were used in the real compressor. The shape and dimension of the specimens were shown in Fig. 1. The vane was sliding on the disk with a rotation speed of 700 rpm(1.04 m/s). The normal load applied was 180 Kgf. As calculated by Hertzian contact stress, these conditions are 10 times higher in load and 2 times higher in speed than those of encountered in the real compressor. The test was run in 5 hours with oil temperature of 70℃ and chamber pressure of 9kg/cm². The friction force was monitored continuously throughout the test and wear on the vane was obtained by measuring the wear scar width by an optical microscope. Additional qualitative information on the nature of wear was obtained with SEM and EDX (energy dispersive X-ray spectroscopy), and wear particle ferrography analysis.

RESULTS

Lubricity of POE oils

Severe wear was observed between the roller and the vane, the flange and the cylinder after real compressor life test. Interestingly there was no scuffing or significant wear between the shaft and the bearing which had been often occurred in the compressor using R22. The vane wear width for each oil was shown in Fig. 2. The wear resistance of POE oils tested in a R407C is much lower than mineral oil in R22. Fig. 3 shows the vane wear width measured in the accelerated bench wear test. Those wear results shows close correlation with the life test results except for R22-mineral oil mixture. In the accelerated tests, R22-mineral oil mixture did not show superior wear resistance to R407C-POE oil mixture contrary to the life test results. These findings suggested that intrinsic properties of refrigerant-oil mixture in the inside of the real compressor, such as miscibility, wettability, and oil return property, are important factors to be considered. After life test, the worn surfaces of the flange faces tested in some POE oils were observed to be very shinny. SEM examination revealed that the shinny surface was produced with abrasion or polishing by very fine wear particles, which is called buffing wear. Those fine wear particles can be generated from corrosive wear or destruction of molecular seive desiccant. After life test, it was observed that molecular seive was destructed, even though not for all POE oils tested, and traces of the molecular seive components were detected both in oil and in the capillary tube. The exact causes of destruction is not clear at this point. However, it suggests that development of a new molecular seive compatible with formulated POE oils as well as R407C should be necessary [4].

Evaluation of Vane Coatings

In order to apply a suitable coating to the vane surface, wear mechanism between the vane and the roller was studied. SEM examination of worn surfaces of the vane and the roller after the life test showed that wear was produced mainly by progressive adhesive wear as well as abrasive wear resulting from wear debris and contaminants including particles of molecular seive. Furthermore, since the vane was made of SKH51(high speed tool steel), several hard coatings, which are effective in abrasive wear and mainly adapted in the tool steel, were selected and evaluated in this experiments. The coatings tested are: TiN, TiAlN, DLC_1 (Diamond-Like-Carbon), DLC_2

Ion nitriding. Also aluminum carbide (Al_4C_3) vane, which namely known as a Carbon vane, was tested for reference purpose. In order to evaluated the effects of deposition method, TiN was deposited by Arc Ion Plating and RF Magnetron sputtering respectively. Some pertinent data for various coatings tested are given in Table 1. All coatings were supplied by several commercial surface coating companies.

The test conditions for coating evaluation test are: a load of 45 kgf, speed of 200 rpm, oil temperature of 70℃. Those conditions were more closely simulated the real contact conditions between the vane and the roller. The tests ran 10 hours in R407C-POE oil mixture. Lubricant used in the test was a pure POE oil which contains no additives. The compressor life test of adapting various coating vane is underway. The wear widths for various coating vane were shown in Fig. 4. All coated vanes showed better wear resistance than the uncoated original vane. Carbon vane, however, produced higher wear than the original vane. TiAlN, DLC_2 coating showed better wear resistance than

DLC_1 and Ion nitriding. TiN_I showed less wear than TiN_II. Fig.5 displayed the friction data. The ion nitriding showed the lowest friction coefficient. TiAlN, which showed the least wear, and Carbon vane showed the highest friction. Wear of the disk surface can not be measured since no measurable wear could be obtained in this test. However, ferrography analysis of wear debris revealed that hard coating such as TiAlN, TiN, DLC_1 produced a large amount of wear debris. Especially for DLC_1 case, a heavy deposit of fine particles at the exit end of the ferrogram was observed as in Fig.9, indicating that the corrosive wear was occurred.

To better understand wear resistance performance of the coatings, another set of wear test was conducted in only R407C environments without oil. Fig.6 showed the wear width tested under load of 4 5 kgf, speed of 70 rpm and 1 hour test duration. Scuffing had occurred for TiAlN, DLC_1 and Ion nitriding while DLC_2 and TiN_I displayed good wear resistance. As shown in Fig.7, however, TiN showed high friction and DLC_2 and carbon vane showed low friction.

The worn surfaces of the vane and the disk was examined with SEM and EDX. SEM pictures of vane wear scar was shown in Fig.8. Compared to the unworn surface, generally the wear surface became more smooth. For TiN_I coating, the worn surface is very smooth. However, the fracture of coating was occurred in some areas as shown in Fig.10 . Even though not shown in this paper, the edge of contact area becomes sharp for the test without oil. For TiN_II coating, the large grooves were produced and EDX analysis showed no trace of Ti in the grooves, indicating the coating was spalled off. For TiAlN coating, the original coating exhibits a rough surface topography, and edge of worn surface is very sharp. As shown in Fig.11, the wear particles embedded in the edge of contact area were observed. Those rough surface and hard TiAlN wear particle entrapped between contact surfaces may be responsible for high friction. EDX analysis also revealed that coating was removed extensively. DLC_2 coating showed much low wear and friction. SEM pictures of the worn surface exhibited very smoothening of asperity. EDX analysis of the disk surface, the mating surface, showed that the carbon was transferred to disk surface and formed a easily shearable tribo-film which gives low friction and consequently contributes low wear. However, plate-like spalling of coating in some areas was observed as shown in Fig.12. This is a kind of delamination fracture which is caused by propagation of cracks running parallel to the surface, at the interface between coating layer and substrate under action of the repeated cyclic stress. It is attributed to poor adhesion between coating and substrate. The worn surface of DLC_1 vane show similar wear type with that of DLC_2 which is consisted of smooth surface and spalling of coating. However, DLC_1 coating did not provide enough wear resistance compared to DLC_2. Ion nitride did not show sharp edge either embedded wear debris on the worn surface. The SEM pictures of the vane cross section (not shown in this paper) exhibited several cracks perpendicular of the sliding direction in the nitride surface layer, indicating that durability of ion nitride layer is not enough to sustain cyclic contact stress. Carbon vane which is softer than the roller was worn much despite of good lubrication property. Those loose wear particles will be collected around the molecular seive, resulting in deterioration of the molecular seive.

Discussion

In compressor adapting R407C-POE oil, three types of wear can be occurred: mild adhesive wear, abrasive wear, corrosive wear. Therefore, in case of considering surface modification of the vane, a number of concernings must be dealt with in order to choice the best surface modification method: hardness, adhesion force to substrate, chemical stability, surface roughness and thickness, etc. Generally, the coatings applied for tool material require high hardness. However, as shown in the tests, too hard coatings such as TiN, TiAlN and DLC_1 resulted in high friction which is detrimental for energy efficiency of compressor. Furthermore, scuffing is likely to occur mainly by severe wear of the roller surface. Adhesion force to substrate is also important. Once the coating is spalled off, wear will be accelerated, and those hard coating fragments will facilitate severe abrasion. In addition to proper hardness and adhesion property, the tribo-film forming ability is found to be very beneficial to improve tribological performances. DLC_2 coating produced a continuous and easily shearable film on the mating surface which reduces friction significantly, therefore decreases the chance of severe wear.

CONCLUSIONS

Development of HFC compressors had faced with many tribological problems. The following conclusions were drawn from the compressor life test and the accelerated wear test.

1. In compressor using R407C-POE oil mixture, wear occurred mainly between the roller and the vane, the flange and the cylinder. The type of wear observed was mild adhesive wear, abrasive wear and corrosive wear. The compatibility of molecular seive with POE oils as well as R407C should be considered, otherwise the fragmented particles of molecular seive will accelerated the wear.
2. Too hard coatings such as TiAlN and DLC_1 are not suitable for the vane coating since it produced a severe wear of the roller.
3. TiN coated vane itself showed good wear resistance property, especially when deposited by ion plating compared to magnetron sputtering. However, it produced high friction.
4. DLC_2 coating showed the best tribological performances among the coatings tested, by forming a durable and easily shearable tribo-film on the mating surface.
5. Ion nitriding is not suitable since durability of ion nitride layer is not enough to sustain cyclic contact stress.

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Table 1. Properties of various coatings

Vane	Hardness (HV)	Roughness (Ra μm)	Coating thickness (μm)	Deposition Method
Original	950	0.1658	-	-
TiN_I	1900	0.1155	2	Arc Ion Plating
TiN_II	1600~1800	0.1770	1.5~2	RF Magnetron Sputtering
TiAlN	2700	0.3410	1.2	Arc Ion Plating
DLC_2	1000	0.1538	2.4	Magnetron Sputtering
DLC_1	2000	0.1802	2	Dual Ion Beam Sputtering
Carbon vane	458	0.2686	-	-
Ion nitriding	1150	0.2905	150~200	Pulse Plasma Nitriding

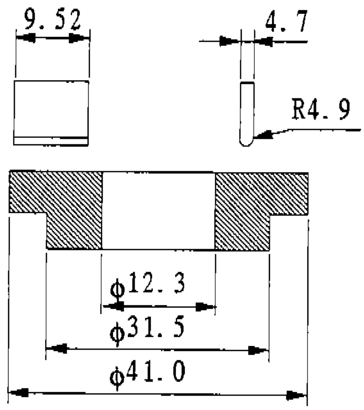

Fig.1 Shape and dimension of specimen

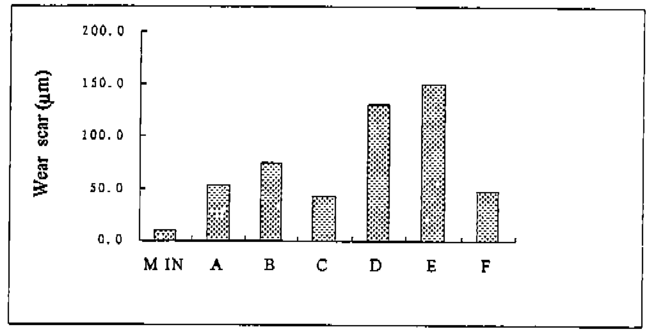

Fig.2 Vane wear width in compressor life test

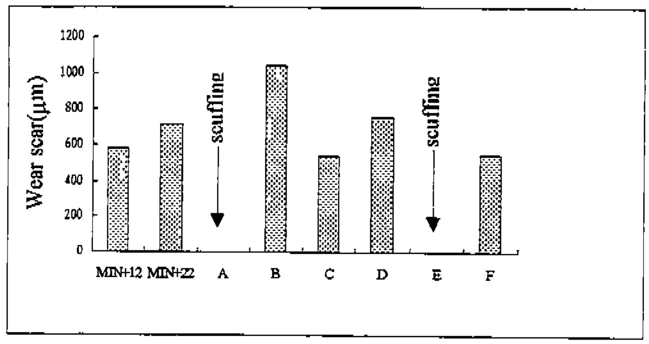

Fig.3 Vane wear width in accelerated wear test

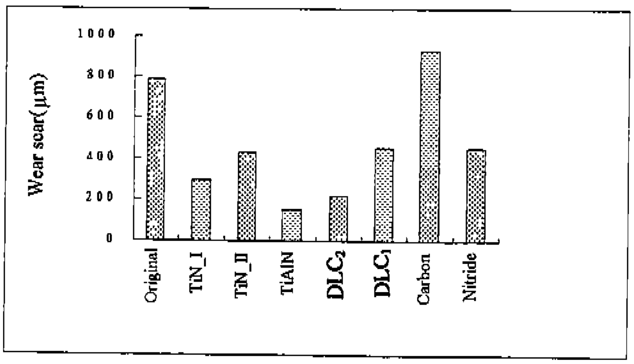

Fig.4 Vane wear width for various coatings

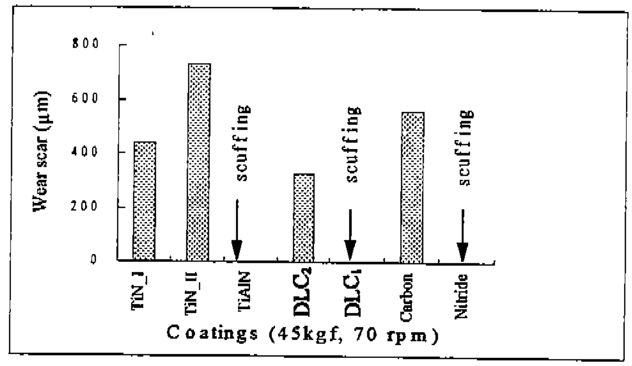

Fig.6 Vane wear for tested in refrigerant only

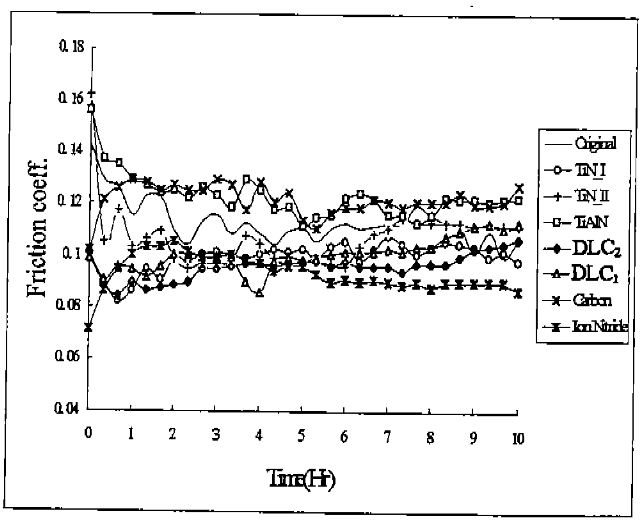

Fig.5 Friction data for various coatings

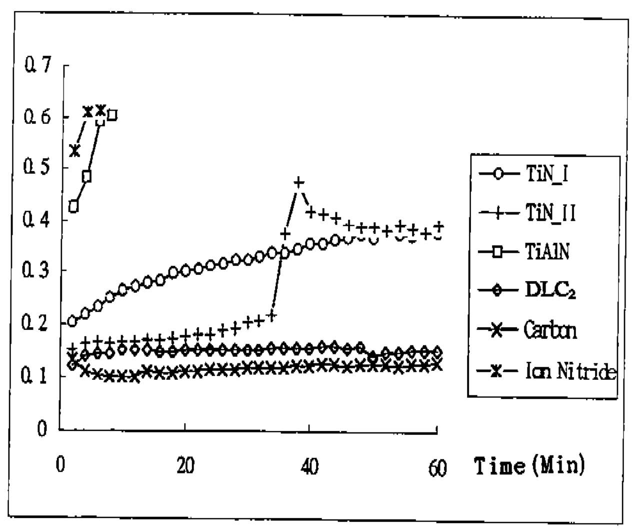

Fig.7 Firction data tested in refrigerant only

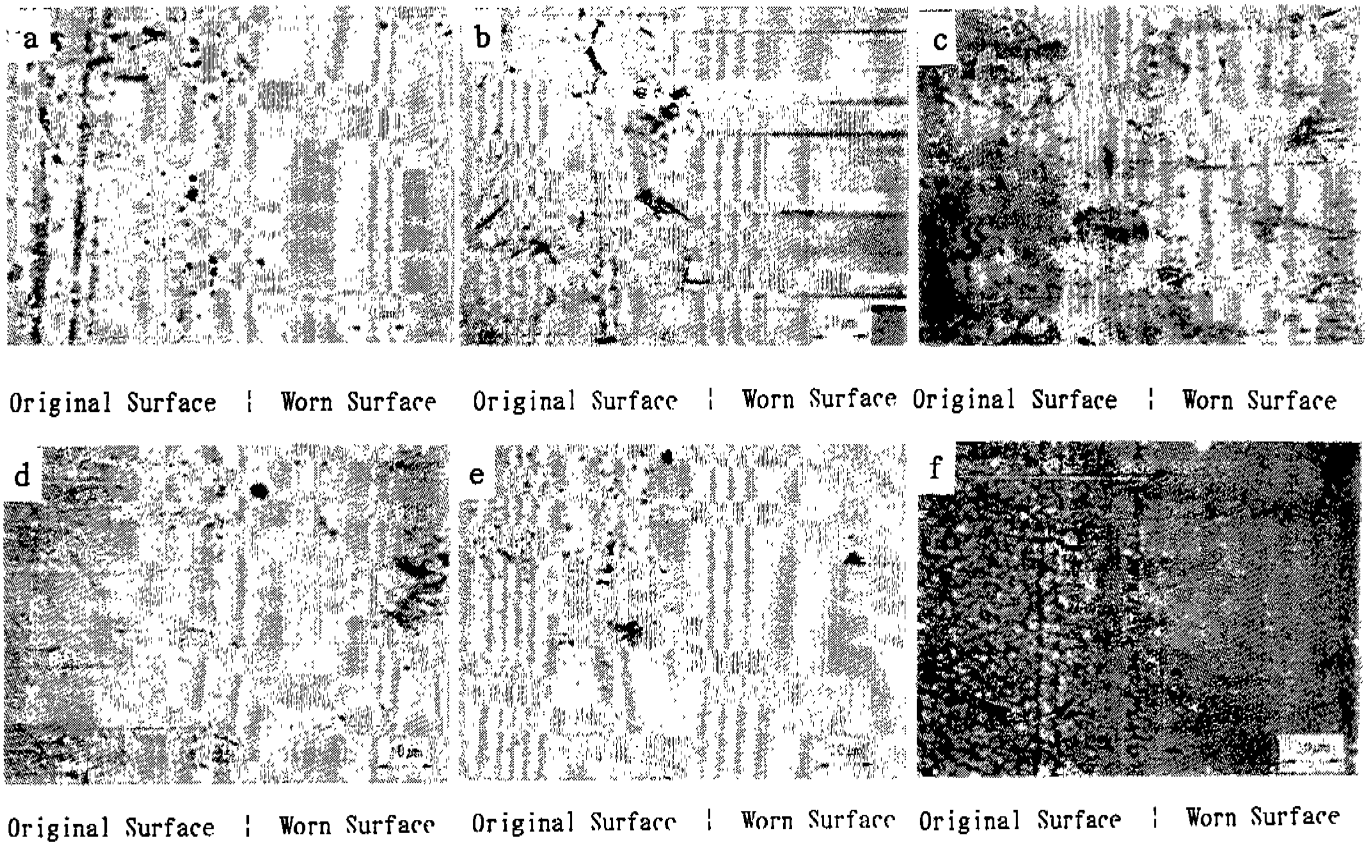

Fig. 8 SEM pictures of the wear on the vane for various coating
(a) TiN_I, (b) TiN_II, (c) TiAlN, (d) DLC_2 (e) DLC_1 (f) Ion Nitriding

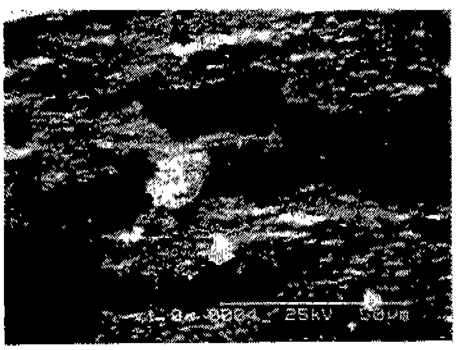

Fig. 9 Wear Debris for DLC_1 coating test

Fig. 10 Wear Track of TiN coating

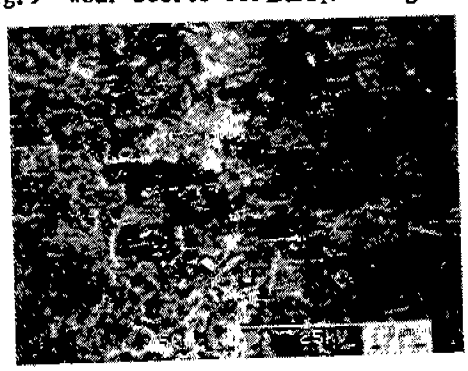

Fig. 11 Wear Surface of TiAlN coating

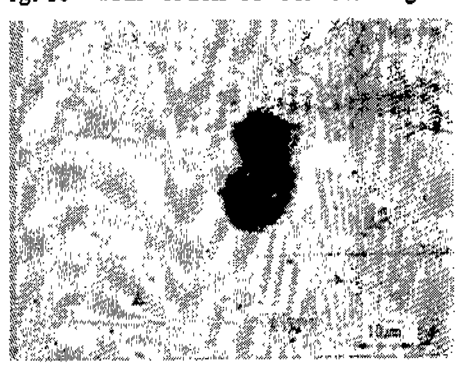

Fig. 12 Wear Track of DLC_2 coating