Effects of Surface Modification on Tribological Performance for Thrust Bearing in Scroll Compressor

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Abstract--Tribological characteristic is crucial to prevent catastrophic failure for thrust bearings in scroll compressors. In this study, tribological performances of gray cast iron (FC25) with and without surface modification were evaluated by wear tests. The three types of surface modification methods are TiC coating, nitriding treatment and MoS_2 spraying. Thickness and quality of coating layers were determined by scanning electron microscopy (SEM) and electron probe microanalyzer (EPMA). Wear tests were conducted by a thrust-washer-type tribometer with CO_2 refrigerant and PAG lubricant oil. A sliding speed of 4.22 m/s, 165 kg normal load and environmental temperature 125 ℃ were applied. After wear tests, the wear loss of specimens were compared and the worn surfaces were observed by SEM. According to the results, FC25 coating with MoS_2 material exhibited optimal wear resistance. However, FC25 coating with TiC film was inferior to FC25 without surface modification.

Keywords: Scroll compressor, surface modification, thrust bearing, wear resistance.

I. INTRODUCTION

A refrigerant compressor is the main component in the air-conditioning industry. The scroll compressor plays a vital role in recent years because of its higher efficiency and reliability than other types of compressors. However, thrust bearings must sustain the axial force generated by the rotary scrolls, which leads to wear phenomena, subsequent lower work efficiency, and even failure.

Currently, numerous researchers are working in tribological fields to enhance the wear resistance of compressor components. Several hard-coating techniques, such as diamond-like carbon coating (DLC) [1], WC/C [2], TiC [3] and TiN [4] may enhance the wear resistance of products by increasing surface hardness. In addition, soft-coating techniques, such as PTFE-based coating [5] and MoS_2 coating [6] are used to increase the lubricating effect to reduce friction behavior. Thus, surface modification may be a suitable and a promising option to enhance tribological performance for prolonging the service lifetime of thrust bearings.

The objective of this study was to evaluate the tribological performance of FC25 without and with surface modification in the CO_2 refrigerant and PAG lubricant mixing environment by thrust washers type. Wear resistance of the tested specimens are discussed to determine the optimal surface modification method for thrust bearings in scroll compressors.

II. EXPERIMENTS

Gray cast iron (FC25) was chosen as the testing material, and three types of surface modification methods, including nitriding treatment, MoS_2 spraying and TiC coating were applied separately. After surface modification, optical microscopy (OM) was used to observe interfaces between coating layer and substrate, and the thickness of the layers was measured and measuring thickness of the layers. Chemical compositions in local regions were detected by energy-dispersive X-ray spectroscopy (EDS) and line-scan analysis of electron probe microanalyzer (EPMA). Hardness of the various coatings was measured by Vickers microhardness tester with 0.2 kg load and 15 s dwell period. Surface roughness was measured by Form Talysurf PGI 1240 with traveling length of 2 mm and cutoff length of 0.25 mm.

Tribological performances of various specimens were conducted by a tribometer with thrust washers type, which was designed for a high-pressure refrigerant environment and equipped with an electrical control system for controlling sliding speeds and chamber temperatures. The sliding speed and chamber temperature were set at 4.22 m/s and 125 ℃, respectively, and a normal load of 165 kg was applied. The test conditions corresponded with the real operating conditions of scroll compressors for industrial applications. The carbon steel SK3, after hardening treatment, was used as the standard counter specimen (rotating washer) with hardness of approximately HRC 50. Stationary specimens, after various coating treatments, were fixed on the low stage, and both specimens were subsequently surrounded by the oil cup to maintain PAG and CO_2 in the chamber. Fig. 1 shows the schematic diagram of the geometry and installation of the wear specimens.

A wear specimen was immersed in acetone before and after each wear test to be cleaned by an ultrasonic machine to ensure that no contamination was present on the contact surfaces. The specimens were weighted by electrical balance with 0.0001 g precision, and the wear loss was subsequently calculated to evaluate wear resistance of various coating specimens.

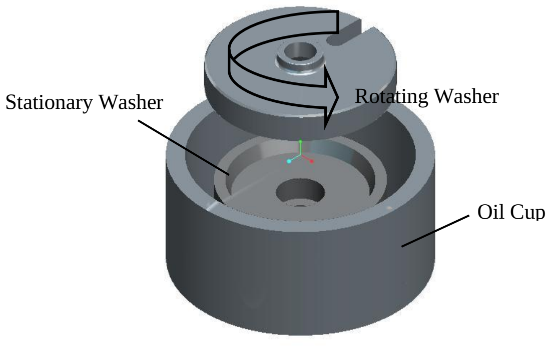


Fig. 1 Schematic diagram of a thrust washers sliding contact.

Table 1 Physical Characteristic of Various Specimens.

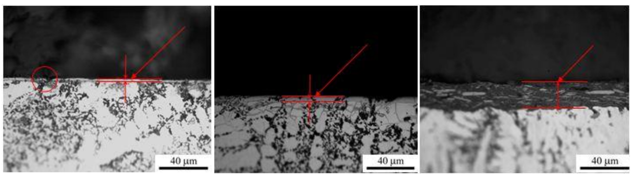
Specimen ID	Surface Modification Treatment	Layer Thickness (μm)	Surface Roughness, Ra (μm)	Hardness (VHN)
FC25	X	X	0.55	200
FC25/TiC	TiC Coating	2.5	0.26	3300~4000 [7]
FC25/N	Nitriding Treatment	5	0.37	910
$FC25/MoS_2$	MoS_2 Spraying	20	0.74	80

A. *Physical Characteristics*

Coating thickness, surface roughness and hardness of various specimens are listed in Table 1. As shown in Table 1, the $FC25/MoS_2$ specimen had the thickest coating layer at approximately 20 μm and the highest surface roughness at Ra=0.74 μm among all specimens. However, its hardness only reached Hv80, which was lower than the substrate, FC25. By contrast, the film thickness of FC25/TiC specimen was only 2.5 μm and the surface roughness, Ra, was 0.26 μm, which were the thinnest and smoothest. Although hardness of FC25/TiC could not be measured exactly for considerably thin thickness by the Vickers microhardness tester, the hardness of TiC may reach over Hv3200 [7]. Therefore, the film hardness of FC25/TiC is higher than that of FC25/N and $FC25/MoS_2$.

B. *Interface of Coatibg Film*

Fig. 2 presents the cross sections of various specimens. As shown in Fig. 2(a), FC25/TiC exhibits small pits in the circle-marked region, and is regarded as the defect in TiC coating film. Fig. 2(b) reveals that the average depth of the nitriding layer in FC25/N was measured at approximately 5 µm, and that nitrides diffused into the subsurface along the grain boundaries to form the diffusion zone. This finding indicates that FC25 and nitriding layer have excellent metallurgical bonding and benefits adhesion between the substrate and the coating layer, effectively enhancing wear resistance. Fig. 2(c) reveals that the MoS_2 coating layer of $FC25/MoS_2$ is considerably thicker than that of the others, and that a clear interface was observed between the substrate and the coating layer.



(a) (b) (c)

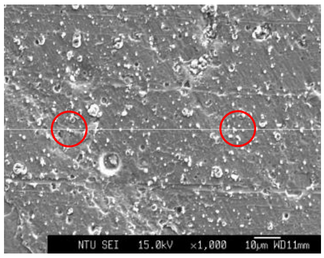
Fig. 2 Cross-section of (a) FC25/TiC. (b) FC25/N. (c) $FC25/MoS_2$ specimen.

C. *Morphology Observation*

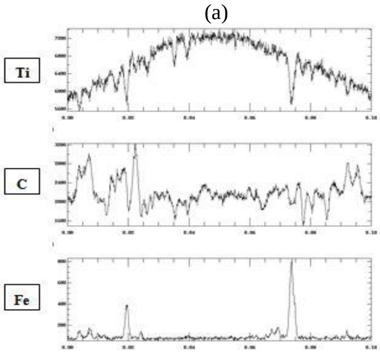
The surface morphology and EPMA line-scan result of FC25/TiC are shown in Fig. 3. The line-scan result indicates that two peaks of the Fe element occurred, the positions of which are marked with circles. The line-scan presents a Fe-rich and Ti-free result at these points. Therefore, these positions are defects in TiC coating film, where the coating film has been spalled off. The result is consistent with the cross-sectional observation in Fig. 2(a).

The metallographic morphology of FC25/N is presented in Fig. 4. As shown in Fig. 4, nitrides diffused into ferrite grain along the grain boundaries, forming a vein-pattern appearance, which confirms high quality bonding between the nitriding layer and the substrate.

Fig. 5 shows the morphology of MoS_2-sprayed surface and chemical compositions of $FC25/MoS_2$. According to the EPMA line-scan result, the bright regions have molybdenum (Mo) and sulphur (S) elements. The result confirmed that these areas contained MoS_2 particles. In addition, the dark regions in which antimony (Sb) was detected were used as the binder for adhering to the substrate and MoS_2 layer.



(a)



(b)

Fig. 3 FC25/TiC specimen (a)Top-view. (b) Line-scan result.

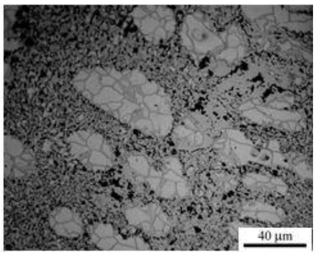


Fig. 4 Microstructure of FC25/N specimen.

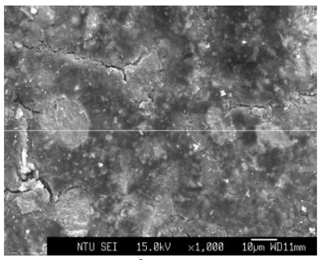
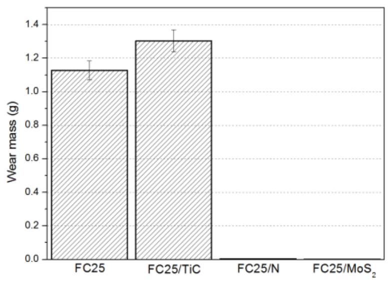


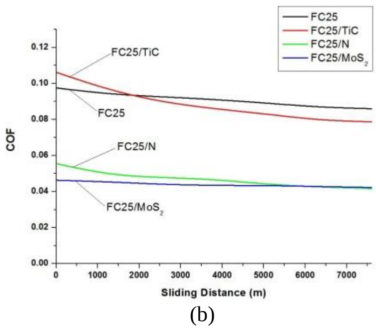
Fig. 5 Top-view of $FC25/MoS_2$ specimen.

D. *Wear Test*

The wear loss and friction coefficient of each specimen is shown in Fig. 6. Fig. 6(a) indicates that the wear resistance of FC25/TiC was inferior and $FC25/MoS_2$ was superior. Moreover, the wear loss of $FC25/MoS_2$ approached zero. This result is unusual for specimen hardness. In general, higher hardness represents a higher wear-resistant ability that is correct for the most abrasive wear mechanism. However, this criterion is not obeyed in other wear conditions, at least in this work. This phenomenon can be explained by subsequently analyzing the worn surfaces. Fig. 6(b) displays the friction coefficient variation for the various specimens during wear tests. The result indicates that FC25/MoS_2 has the lowest friction coefficient, and the highest friction coefficient was for FC25/TiC during the beginning of wear tests. The result demonstrates that the lubrication condition of FC25/TiC wear test was dominated by boundary lubrication during run-in process and caused considerable wear. MoS_2 is often used as the solid lubricant in industry for decreasing friction and enhancing the lubrication effect. It was considerably quiet for FC25/MoS_2 during wear tests. However, FC25 and FC25/TiC were noisy because of inferior lubrication, which can be verified by the higher friction coefficient. In addition, along with the increasing sliding distance, except for FC25/MoS_2, the friction coefficient was gradually reduced, which was caused by the tapered-bore geometry of the stationary washer. When the specimens wear away, the contacting area between the rotating and stationary washer specimens is increased to reduce contact stress, which enhances the hydrodynamic effect and causes a decrease in the friction coefficient. This phenomenon is more conspicuous for FC25/TiC because its higher wear loss causes a larger contact area, in which the hydrodynamic effect is more obvious.



(a)



(b)

Fig. 6 Various specimens (a) Wear loss. (b) Friction coefficient.

The typical worn surface of FC25 is shown in Fig. 7. The parallel wear scars on the worn surface of FC25 exhibit typical abrasive wear and adhesive wear. Its anti-penetration ability is inferior because of the soft surface and the debris generated during wear tests can penetrate the rubbing surface easily. Thus, the material of the worn surface was removed by microcutting to cause considerable wear loss.

The worn surface and the EDS result of FC25/TiC are shown in Fig. 8 (a). Regarding friction, a higher friction coefficient generates higher temperature during rubbing processes, which causes materials to soften. Therefore, plastic flow is discovered on the worn surface. A slight titanium element was detected in the EDS result, which indicates that the TiC coating film was removed, where no hard films can protect the substrate from wear. Because of geometrical discontinuity of small pits of the coating film, local stress concentration occurs in these regions, in which the failure originates. Thus, the TiC coating film was plowed by the asperities or debris and the spalled TiC debris can cause two- or three-body abrasion. Subsequently, the substrate and SK3 make direct contact and adhesive wear is caused on the rubbing surfaces. The schematic illustration is shown in Fig. 8 (b).

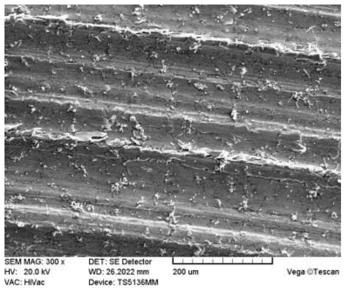
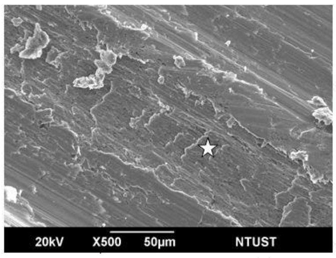
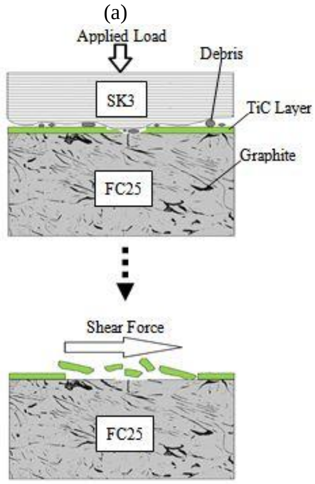


Fig. 7 Worn surface of FC25 specimen.



Element	Wt. (%)	At. (%)
C K	19.32	51.18
O K	5.7	1.78
Ti K	0.30	0.2
Fe K	76.70	43.69
Totals	100	100

(a)



(b)

Fig. 8 FC25/TiC wear specimen (a) Worn surface and EDS result. (b) TiC film peeling-off schematic diagram.

The worn surface of FC25/N is shown in Fig. 9. Regarding the morphology, the machining-processed patterns remained after the wear tests, which were more evident than the wear scars. The result indicates that the nitriding layer effectively improves wear resistance of FC25. According to the interface observation of FC25/N in Fig. 2(b), the nitriding atoms diffused into the substrate, which resulted in optimal bonding between the nitriding layer and FC25, and the nitriding layer cannot be peeled off during the rubbing process. Hence, the hardened surface layer may resist penetration, resulting in the superior wear resistance of FC25/N.

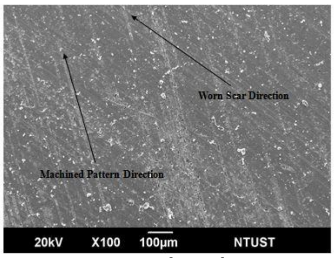


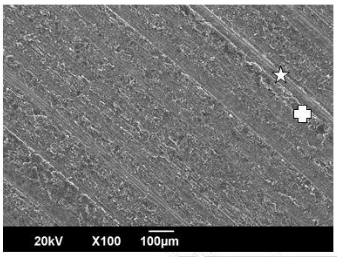
Fig. 9 Worn surface of FC25/N.

The worn surface and the EDS result of FC25/MoS_2 are shown in Fig. 10 (a). The worn surface exhibits mild abrasion. For the EDS result, the area with the star mark exhibits an iron element only, which indicates that an MoS_2 layer is not present at this location. However, the area with the plus sign represents the composition of MoS_2, suggesting that the MoS_2 layer remained on the worn surface. In Fig. 10(b), a more detailed wear process of FC25/MoS_2 is illustrated with the schematic figure. As shown in the top-view of Fig. 5(a), a number of cracks were observed on the surface. When the SK3 specimen was applied with normal load, the soft MoS_2 layer deformed to provide a "cushion effect," and these cracks were closed. The soft sprayed layer may bear squeezing by the applied force and flow easily to fill the vacancies between the contact surfaces; thus, the bearing area may be increased to reduce the real contact stress. Because of the lower shear strength than the other two coating layers, MoS_2 layer can flow easily and stick on the rubbing surfaces uniformly. Therefore, it prevents wear specimens from direct contact, leading to lower friction coefficient and wear loss.

III. CONCLUSIONS

The tribological performance evaluation of FC25 for thrust bearings in air-conditioning scroll compressors with and without surface modification was conducted by the thrust-washer type tribometer. The following conclusions are based on the results:

1. The topographic observation indicates that TiC coating film caused defects in the FC25/TiC that resulted in destruction by plowing, which caused FC25/TiC to exhibit inferior wear resistance among the specimens.
2. With surface nitriding treatment on FC25, FC25/N exhibited superior wear resistance because of the high hardness of surface layer and excellent bonding at the substrate-nitriding layer interface.
3. The direct face-contact area between SK3 and FC25/MoS_2 was reduced after surface modification by MoS_2 spraying for FC25, which resulted in a lower friction coefficient and wear loss.



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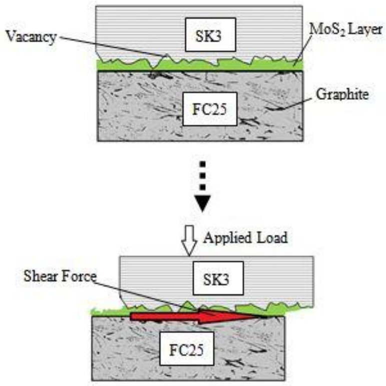
Element	Wt. (%)	At. (%)
Fe K	100.00	100.00
Totals	100	100

✚

Element	Wt. (%)	At. (%)
C K	56.37	79.92
O K	7.80	8.30
S K	15.34	8.15
Mo L	20.49	3.64
Totals	100	100

(a)



(b)

Fig. 10 FC25/MoS_2 wear specimen (a)Worn surface and EDS result. (b) Schematic diagram of MoS_2 layer deformation process during wear test.

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