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ABSTRACT

The ductile cast iron crankshaft provides an effective alternation to grey cast iron crankshaft in the rotary compressor. In this research, several manganese (Mn) phosphate coatings and molybdenum disulfide (MoS_2) coatings of ductile cast iron crankshaft are studied compared to grey cast iron crankshafts. The coating surface was observed with Scanning Electron Microscope (SEM) and analyzed with Energy Dispersive X-ray Spectroscopy (EDX). In the scratch test, the critical load characterizing the coating scratch resistance was measured by Micro-Tribometer with electrical contact resistance (ECR) measurements mainly. In the wear test, the friction coefficient and wear life was evaluated by Micro-Tribometer. As the results, we developed the technology of Mn phosphate coating and MoS_2 coating of ductile cast iron crankshaft with higher adhesion and wear characteristics.

1. INTRODUCTION

In the rotary compressor, the manganese (Mn) phosphate coating and molybdenum disulfide (MoS_2) coating provide elevation of wear resistance and lower friction coefficient for the ductile cast iron crankshafts as well as the grey cast iron crankshafts, resulted in better efficiency of the compressor.

The Mn phosphate coating and MoS_2 coating are used to improve lubrication and decrease the metal contact. Mn phosphate coating deposited onto the iron substance is a dense and wearable grey-black coating. The coating has good sliding characteristics because its layer is a porous crystalline that can absorb and hold lubricating oil and has oil-film forming capability during sliding (C. T. Hu, *et al*., 1997, Y. Yoshimi, *et al*., 2006). And MoS_2 is considered as solid lubrication films as its excellent friction and wear characteristics.

2. EQUIPMENTAL

The samples were deposited of the Mn phosphate coating of PF-5004 and PF-M1A respectively. Then the MoS_2 coatings were deposited with two different technologies. The HMB-2 MoS_2 coating was immersed and the MOLY CS MoS_2 coating was sprayed to the substructure respectively before they are hardened and polished.

The surface structure of the phosphate coating and MoS_2 coating were investigated with a Scanning Electron Microscope (SEM, S-3400N), and the coatings specimens were analyzed with Energy Dispersive X-ray spectroscopy (EDX, HORIBAEX 450). The adhesion of both coating was measured in the scratch test with Micro-Tribometer (UMT-3), which consisted of linearly increasing applied load to 4N, while slowly sliding the tungsten carbide micro blade at 0.025mm/sec. And the friction and wear properties of the coatings were investigated by ring-on-block tests with the Micro-Tribometer in the dry friction condition, with test load setting to 30N and speed 800RPM.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Surface structure and mechanical properties of the coating

Fig.1 shows the surface structure of the Mn phosphate coating observed through Scanning Electron Microscope (SEM, 500 times magnification). And the sizes of Mn crystal are as follows, (a) PF 5004-ductile cast iron, 2.81um, 4.47um, 5.36um, (b) PF-M1A -ductile cast iron 2.1um, 2.8um, 4.98um, (c) PF-5004-grey cast iron 2.75um, 4.04um, 4.55um, (d) PF-M1A -grey cast iron 4.41um, 4.44um, 4.57um.

From the Figure 1 and Mn crystal size, there are some gaps on the Mn phosphate coating of ductile iron and these sizes are smaller. The gaps around manganese particles of PF-5004 are relatively larger, and the uniformity is relatively less. In contrast, the Mn phosphate coatings of gray iron are more complete and even, while the sizes of particles are larger.

The results reveal that the Mn phosphate coating is consisted of a series of different size crystal. There is small cracks porous structure on the formation of crystal connection points. They can improve the corrosion resistance, adhesion and abrasion resistance of ion surface in the oil lubrication conditions (Z.G. Liu, *et al*., 2007)
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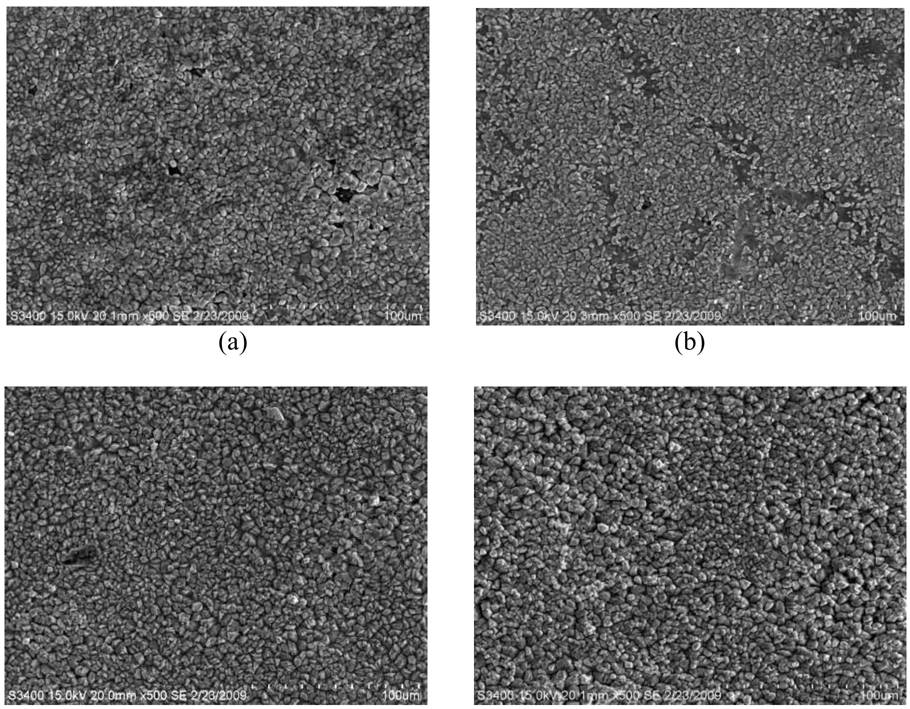
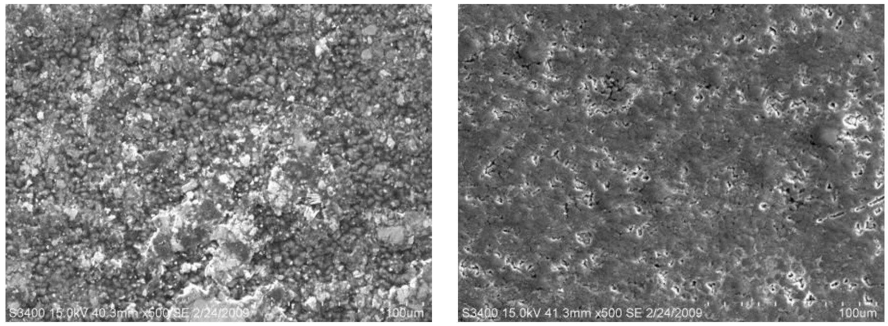


(a) (b) (c) (d)

Figure 1: SEM image of the manganese phosphate coating: (a) PF-5004-ductile cast iron; (b) PF-M1A -ductile cast iron; (c) PF-5004-grey cast iron; (d) PF-M1A -grey cast iron

The PF-5004 Mn phosphate coating + HMB-2 MoS2 coating and PF-M1A phosphate coating + MOLY CS MoS2 coating are observed and analyzed by Energy Dispersive X-ray spectroscopy (EDX). The results are showed in the following figure (Figure 2) and table. The HMB-2 MoS2 coating on the Ductile iron crankshaft has a clearer coverage, however has the void space to the underlying Mn phosphate coating, and leading to the roughness increasing. The roughness of MOLY CS MoS2 coating decreased because of the different pesticides and polishing process. Part of MoS2 particles are embedded in the Mn phosphate coating, and the edges of Mn particles were polished.



(a) (b)

Figure 2: SEM image of coatings: (a) PF-5004 Mn phosphate coating+ HMB-2 MoS_2 coating and (b) PF-M1A phosphate coating + MOLY CS MoS_2 coating

Table 1: EDX of Mn Phosphate Coating and MoS_2 Coatings

PF-5004 Mn phosphate and HMB-2 MoS_2 coating				PF-M1A phosphate and MOLY CS MoS_2 coating		
Element	Mass(%)	Atom(%)		Element	Mass(%)	Atom(%)
C	37.2	62.29		C	10.71	18.24
O	22.68	28.52		O	49.43	63.21
P	2.86	1.86		Na	0.42	0.38
S	0.29	0.18		Si	0.3	0.22
Mn	2.63	0.96		P	11.69	7.72
Fe	2.49	0.9		S	0.23	0.15
Mo	0.55	0.12		Ca	0.26	0.13
Sb	31.29	5.17		Mn	14.74	5.49
				Fe	12.21	4.47

3.2 Adhesion of the coatings

For scratch-adhesion tests, the adhesion of the different coatings of crankshaft is measured by the critical load. Since the coatings are non-conductive and the ion substrate is conductive, the electrical contact resistance (ECR) together with friction was measured to receive the result. The effective use of the ECR and friction is illustrated in Figure 3 below. In this example, the critical threshold of breaking can be determined by the sharp drop in electrical resistance, and is fully supported by the increases in friction.

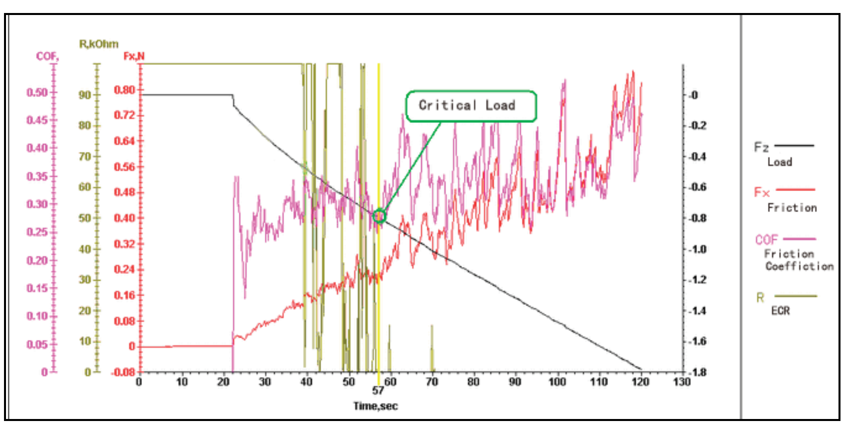


Figure 3: illustration of scratch test: multi-sensor determination of coatings failure

The scratch test data reveals that PF-M1A Mn phosphate coating + HMB-2 MoS2 coating has the highest adhesion, both on the ductile iron and gray cast iron crankshaft.

Table 2: Results of the Crankshaft Coatings Scratch Test

Crankshaft	No.	Technologies of Coatings	Critical Load（N）		
			Short shaft	Eccentric position	long shaft
Ductile Cast Iron	1	PF-5004 Mn + HMB-2 MoS_2	1.4	1.8	1.7
	2	PF-5004 Mn + MOLY CS MoS_2	0.9	1.3	1.5
	3	PF-M1A Mn+ HMB-2 MoS_2	**2.6**	**2.4**	**2.3**
	4	PF-M1A Mn + MOLY CS MoS_2	1.9	2.1	1.0
Grey Cast Iron	5	PF-5004 Mn + HMB-2 MoS_2	1.2	1.0	0.9
	6	PF-M1A Mn + MOLY CS MoS_2	**2.4**	**3.1**	**2.0**

3.3 Wear behavior

Ring-on-Block tests （grey cast ion block on crankshaft sample ring）use wear life to compare the wear characteristics of coatings, which is the time (hours) of continuing friction before the coatings wearing out and the metal surface exposed, as well as the friction coefficient increasing.

The results of wear tests are showed in Figure 4, to compare the wear characteristics among the several technologies of Manganese phosphate coating and MoS2 coating, as well as coatings thickness and average critical load. We found it is unanimous among thickness, critical load and wear life that PF-M1A Mn phosphate coating + HMB-2 MoS2 coating has the highest characteristics. Besides, the coating friction coefficient basically unchanged.

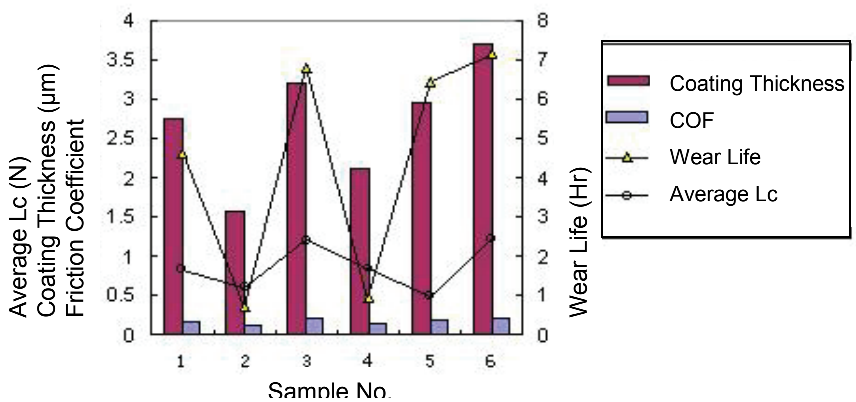
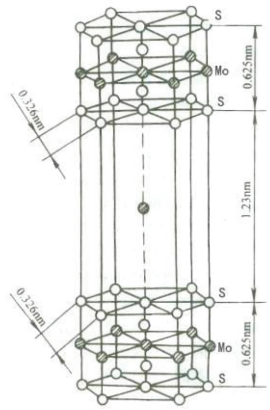


Figure. 4 Friction and Wear test results

In the wear tests, the MoS2 coating reduces the friction and wear characteristics of the crankshafts. As the figure 5 showed, MoS2 is a hexagonal layer compound made of one molybdenum atom and two sulfur atoms, and the crystal was composed of S-Mo-S three layers. Each Mo atoms positioned diagonally with two sulfur atoms by covalent bond with high bonding energy. While the neighborhood Mo layers are separated by S layers, and the bond between S-S is formed by Van der Waals force which is weaker than the covalent bond and easily slips under shear force. These slipped layers transformed the friction between two metal contacted to the slipping between MoS2 layers. As the result, the MoS2 coating diverted between two friction parts (Figure 6) and the friction and abrasion is reduced.



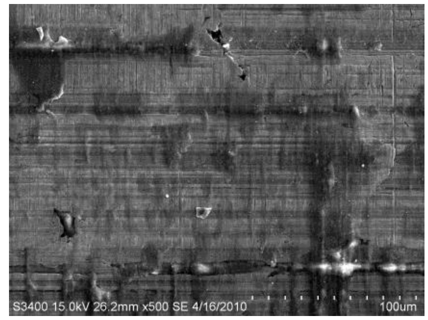


Figure 5: Schematic of MoS_2 crystal structure (D.T. Wang *et al*., 1998)

Figure 6: SEM image of the block after 1 hour wear test

Table 3: EDX of the block after 1 hour wear test

Element	Mass(%)	Atom(%)		Element	Mass(%)	Atom(%)
C	11.52	30.13		S	0.57	0.56
O	13.21	25.94		Mn	4.67	2.67
Si	1.41	1.58		Fe	63.36	35.63
P	2.82	2.86		Sb	2.43	0.63

4. CONCLUSION

The results were obtained in this research as following:

1. PF-M1A Mn phosphate coating + HMB-2 MoS_2 coatings have the highest characteristics of thickness, adhesion and wear in the research.
2. The MoS_2 coatings can reduce the friction coefficient and wear in the friction. The HMB-2 MoS_2 coating has a clearer coverage to MOLY CS MoS_2 coating, however less evenly.
3. The next work is planed to be focused on the friction and wear characteristics of Mn phosphate coating and MoO_2 coating in oil lubrication condition, especially in boundary lubrication condition, in order to investigate and simulate the two coatings work in the rotary compressor.

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