Process Optimization to Improve Low Friction and Wear Resistance of Compressor Solid Lubricating Coatings

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ABSTRACT

The main causes of compressor performance efficiency and noise reduction are mostly caused by mechanical friction and vibration between parts. This friction and vibration can damage internal parts and cause them to break down, causing compressors and air conditioners to malfunction. In addition, thermal deformation and heavy loads that occur when compressing low-temperature, low-pressure refrigerant into high-temperature, high-pressure gas are also causes of compressor damage. To solve this problem, excellent heat-resistant solid lubricating coatings used in engineering applications such as low friction under medium load, air conditioning, and refrigeration compressors are being applied through deposition of molybdenum disulfide, graphite, and PTFE-based coatings. Solid lubricants such as molybdenum disulfide (MoS2), graphite, and PTFE-based coatings have been shown to have low friction, high wear resistance, and, unlike DLC coatings, are not significantly affected by the environment. Although coating wear increases significantly at high contact pressures, the wear particles generated appear to have a beneficial role in overall wear performance. Due to their excellent tribological behavior under various experimental conditions, the coatings tested in this study can be used in compressor systems and other engineering applications. Critical to compressor development is predicting friction and wear between surfaces in relative motion. In this study, the tribological properties of the sliding surface were investigated using various types of compressor parts simulation specimens. Friction tests were performed under various contact conditions including contact pressure and speed. It was confirmed that the friction and wear characteristics were different depending on the manufacturing process conditions of the solid lubricant coating, and friction and wear tests were conducted depending on the coating according to hardening temperature and time and the presence or absence of post-treatment to find the optimal coating conditions.

1. INTRODUCTION

In the realm of compressor technology, increasing efficiency and reducing operational failures is of utmost importance. This has led to significant focus on the development and application of advanced solid lubricant coatings, which are pivotal in minimizing mechanical friction and wear factors that are notorious for causing compressor performance degradation and failure. Compressors are essential for a wide range of engineering applications, especially in air conditioning and refrigeration systems, so they place stringent demands on their performance and reliability. These systems must operate under a variety of challenging conditions, including high thermal and mechanical loads, which can lead to increased wear, increased noise levels and ultimately failure. To address these issues, recent research has focused on the development and application of advanced solid lubricant coatings. These coatings containing solid lubricants such as molybdenum disulfide (MoS2), graphite, and PTFE-based materials have low friction and high wear resistance, making them suitable for overload applications such as compressors (Sutor, 1991). Unlike existing DLC (diamond-like carbon) coatings, solid lubricant coatings demonstrate resilience to environmental factors, increasing effectiveness in real environments. Several studies have investigated the tribological properties of these coatings under various conditions to optimize their performance (Baumgart and Aurich 2022, Wang et al. 2023, Huang et al. 2023). Recent advances in tribological research have improved our understanding of these coatings. Studies have shown that the performance of solid lubricant coatings can be significantly affected by the specific conditions under which they are applied. In this study, the hardening temperature and hardening time of the solid lubricant coating, and the presence or absence of a post-hardening process of secondary brushing were set as variables to determine the performance and lifespan of the coating. The conditions for this improvement were reviewed. By customizing these conditions, researchers can optimize the coating's properties to specific operating needs, improving the life of compressor components as well as increasing efficiency and reliability. The introduction of these advanced materials into the compressor industry represents an important step toward solving the perennial challenges of wear and efficiency. By reducing friction and wear between moving parts, these coatings contribute to the overall durability and performance of compressors, meeting the increasing demands of modern applications. Moreover, ongoing research and development in this field is expected to drive innovation, provide new solutions to old problems, and pave the way for more sustainable and efficient compressor technology. This ongoing evolution in the field of solid lubricant coatings demonstrates the dynamic nature of compressor technology development, reflecting the industry's commitment to innovation and its critical role in increasing the performance and reliability of critical engineering systems. By conducting friction tests with different contact pressures, speeds, and coating process parameters, the researchers gained insight into the wear behavior and durability of solid lubricant coatings. This knowledge is important for improving compressor efficiency and reliability by selecting optimal coating conditions and predicting friction and wear between surfaces in relative motion.

2. METHODS AND MATERIALS

The sliding friction characteristics simulating various surface conditions inside the compressor were evaluated using a friction tester. Phoenix's TE77 reciprocating friction test equipment was used for testing. After preliminary tests depending on the type of coating, additional tests were conducted to confirm performance differences depending on the coating manufacturing method. Conditions including pressure, speed, etc. were set, and evaluation was conducted according to the manufacturing process conditions of solid lubricant coating. The optimal coating conditions were obtained by analyzing hardening conditions and the presence or absence of a secondary brush.

2.1 Target coating samples; Lubrication, Lubrication + Defric

Fig.1 is the journal bearing structure of a rotary compressor. During the compression process, a reciprocating friction test was conducted by simulating the force, journal, and bearing with a ball and plate specimen as shown in Fig. 2. The upper ball specimen used SUJ2 (bearing steel) with a diameter of 6 mm. The actual compressor bearing material is GC250, which is a material selected because it is soft compared to the journal's GCD550, so it wears out first during the experiment, making the experiment difficult. The load was 30N and the speed was 0.15Hz and 4Hz, respectively. The coating was done on the plate of the lower specimen (GCD550). Table 1 “Test conditions and coating materials for reciprocating friction test” are listed. For accurate comparison, the test conditions and coating materials are the same. To set up a control group for improving manufacturing process conditions, a coating sample (GCD550) without any treatment was selected. Coating samples (lubricated, lubricated + defric) produced by different companies were used. Detailed sample information is listed in Table 2 “Coating Samples”. Through friction tests on samples, results on friction performance and life cycle for each type of coating were obtained.

2.2 Target coating samples; different process conditions

The test results in Section 2.1 are shown in Fig. 2, and among the results, it can be seen that the friction performance of specimen F is significantly superior. However, Specimen G, which has the same manufacturing process, is not very noticeable. Accordingly, in order to analyze the impact of manufacturing process differences between companies, the “Process Sequence and Conditions of Defric Coating by Company” were compared in Table 3 to set test conditions for the impact of process condition improvement on lifespan. Test types according to test conditions are shown in Table 4 "Specimens according to Defric manufacturing process conditions". Manufacturing conditions were differentiated by maintaining or excluding secondary brush treatment, and conditions were classified according to hardening time and temperature.

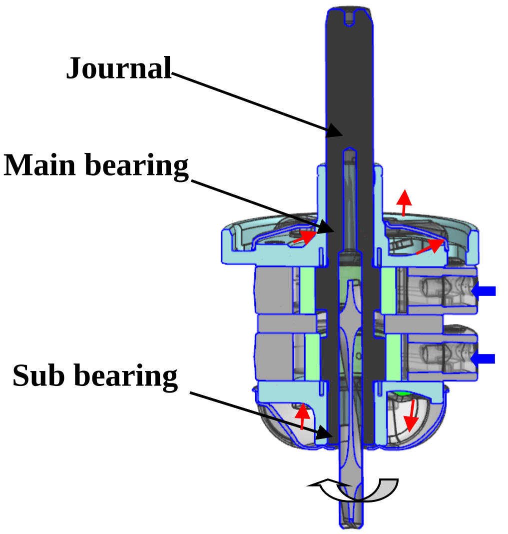

Fig.1 Journal bearing of Rotary compressor

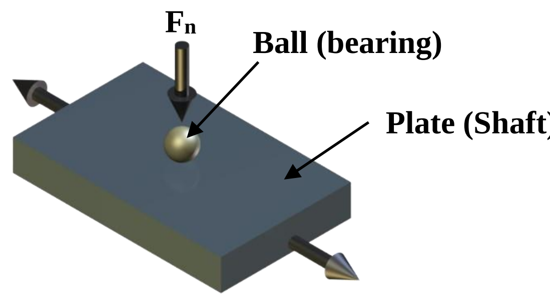

Fig.2 : Friction principle of reciprocating friction test module

Table 1: Test conditions & coating materials of reciprocating friction test.

Condition Variable	Test Condition
Load	30N
Reciprocating Speed	0.15Hz(Low speed), 4Hz (High speed)
Stoke	10mm
Upper test sample (Ball)	SUJ2 Ball / Ø6mm
Lower test sample (Plate)	GCD550 Plate / 58*38*3.9
Oil	NONE
Temperature	Room Temperature
Lubrizing coating	Phosphate coating / thickness 3~5 ㎛
Defric coatig	Solid lubricating coating(MoS2, Graphite, PTFE coating) / thickness 3~7 ㎛

Table 2: Coating condition of test sample

<table>
<tr><th rowspan="2">Test sample</th><th colspan="2">Coating</th><th rowspan="2">Company</th></tr>
<tr><th>Lubrizing</th><th>Defric</th></tr>
<tr><td>A. Not Coated</td><td>X</td><td>X</td><td>-</td></tr>
<tr><td>B._Lub_K</td><td rowspan="2">O</td><td rowspan="2">X</td><td>K</td></tr>
<tr><td>C._Lub_C</td><td>C</td></tr>
<tr><td>D._Lub_Def_K</td><td rowspan="2">O</td><td rowspan="2">O</td><td>K</td></tr>
<tr><td>E._Lub_Def_C</td><td>C</td></tr>
</table>

Table 3: Coating manufacturing process and condition of defric coating company

Manufacturing process	1. Pre-heat 	2. 1st. brushing 	3. spay 	4. 2nd. brushing 	5. Heating & drying 
Company K	Temperature ：120±5℃ Time：30min	Brush：100±10 ㎜ Time：3.0±1.5sec	Temperature ：30-40℃ Spraying ：0.8-1.5sec	Brush : 100±10 ㎜ Time：3.0±1.5sec	Temperature ：**190**±5℃ Time：**40**Min
Company C				X	Temperature ：**170**±5℃ Time：**60**Min

Table 4: Specimens under various defric coating condition

Test sample	**Lubrizing**	**Defric coating conditions**		
		2nd brushing	Temperature	Time
Condition O_170℃_40min	O	O	170℃	40min
Condition X_170℃_40min	O	X		
Condition O_170℃_60min	O	O		60min
Condition O_190℃_40min	O	O	190℃	40min
Condition O_190℃_60min	O	O		60min
Condition X_190℃_60min	O	X		

3. RESULTS

Fig. 3 shows a graph of test results according to the type of coating conditions for each company in Table 1. The friction test measured the number of cycles until the friction coefficient changed rapidly (0.3 or more). A total of three repeated tests were conducted, and a graph showing the number of cycles and friction coefficient for each coating was shown. As a result of the test, the rubbing coating did not show significant differences in lifespan and friction coefficient between companies. Luburizing + Defric coating was found to have a lower friction coefficient and longer life cycle than luburizing coating. In other words, in the case of Defric coating, the lifespan was about 2-23 times longer, and the coefficient of friction was about 0.38 to 0.81 times lower than that of lubrizing one. In addition, the results of D and E samples show that there is a significant difference in performance between companies even if the same lubricating + defric coating treatment is used. In other words, company K lubrizing+defric coating's life cycle decreased by 0.11 times that of company C lubrizing+defric coating's one. This E case was judged to be a factor in the reduction of bearing life and the increase in compressor input. In order to identify these factors, manufacturing process differences (secondary brushing and heating conditions) between companies were confirmed as shown in Table 4, and an additional test was conducted on the D sample under the conditions in Table 2 to identify the controlling factors. The test results are shown in Fig. 4, and the reference data specified at the top and bottom of the graph in the previous test data has a life cycle of 6,335 (D) and 52,666 (E) cycles. Further investigation into the manufacturing processes of each company revealed substantial variations in the lifespan outcomes, which could be attributed to differences in the coating application methods. Modifications in the post-hardening processes, particularly for C Company’s coatings, showed a general increase in durability. The coating manufacturing processes, labeled in Table 4, led to substantial improvements in C Company's coating lifespans, with cycle life readings in three consecutive tests showing considerable variance, yet marked improvement over the original durability metrics. It was confirmed that the life cycle could be improved by 2.2 to 7.4 times depending on the manufacturing process conditions. Through the differences between 170℃ conditions 190℃ conditions, the lifespan tended to increase as the hardening temperature increased. The hardening time does not seem to have a significant effect, and the lifespan is improved by maintaining the secondary brush treatment. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) analyses were employed to examine the coated layers, in Figure 5 and Table 5. The variations in coating thickness and chemical alterations across different manufacturing processes and tests were carefully examined to verify the integrity and success of the experimental trials. This analysis was crucial in determining whether the implemented procedures effectively influenced the properties of the coatings as intended.

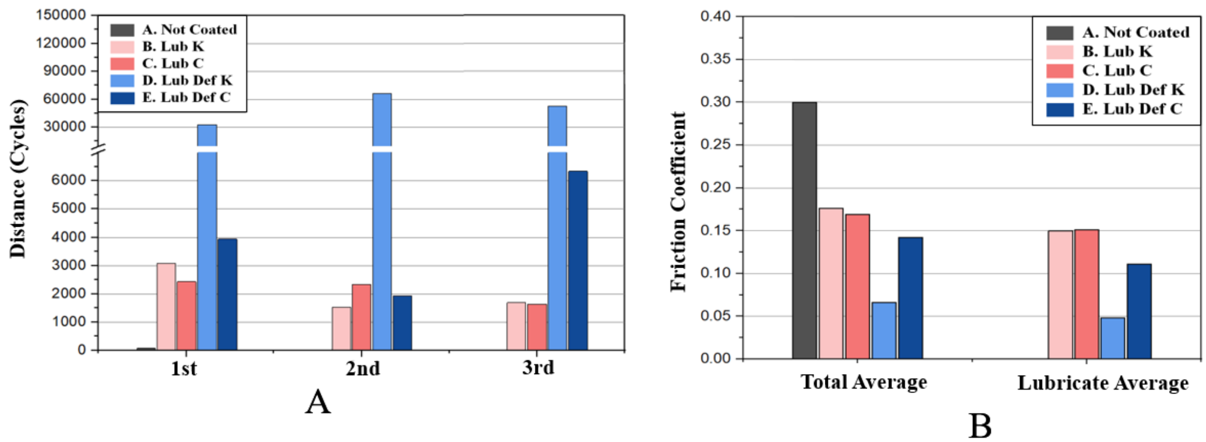

Figure 3: Graph of life cycle comparison according to coating type (A) and average friction coefficient (B).

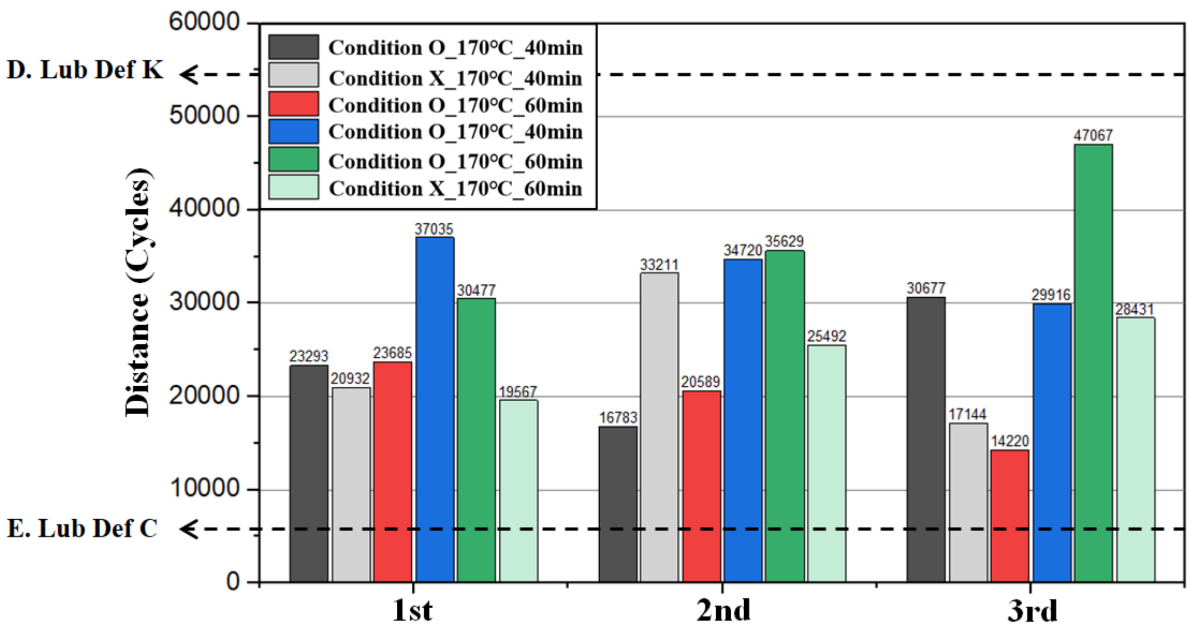

Figure 4: Graph of cycle comparison according to manufacturing process conditions. Data F and G were indicated as reference lines in the previous test

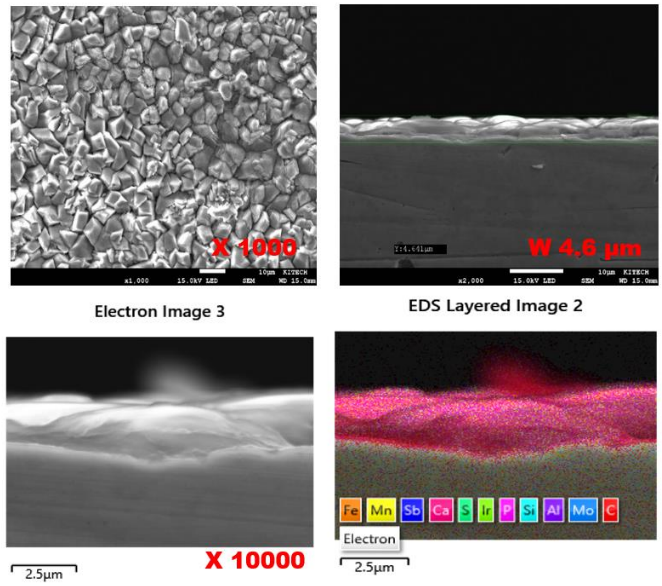

Figure 5: SEM, EDS image of solid lubrication coating

4. DISCUSSION

This study has focused on increasing the operating efficiency of compressors through the application of advanced solid lubricant coatings. Unlike conventional DLC coatings, the solid lubricants used in these experiments showed excellent environmental resilience, confirming their applicability in more challenging industrial environments. Meanwhile, much research is being conducted regarding these solid lubricants. Ouyang et al. (2022) covered the development of high-temperature solid lubricants and their applications across a variety of industries, emphasizing their effectiveness under extreme conditions such as high temperatures and heavy loads. Li et al. (2023) discussed the integration of solid lubricants and plasma surface texturing techniques to improve lubrication in severe operating environments. Chao et al. (2018) explored new MoS2-based coatings reinforced with Cu and Al, focusing on applications in environments where robust lubrication solutions are required. Experimental protocols were meticulously designed to evaluate the performance implications of different manufacturing process for these coatings. Adjustments in hardening temperature, duration and post-hardening processes, such as secondary brushing, were systematically analyzed to determine their impact on the functional properties of the coatings. These manufacturing process changes are important because they directly affect the durability and friction reduction effectiveness of the coating. For example, our results indicate that the post-hardening process potentially extends the operational life of the coating by improving adhesion and surface compliance, which are important for continued performance in dynamic operating environments. Additionally, the study utilized advanced tribological testing techniques to simulate realistic operating conditions, including various contact pressures and movement speeds. This approach not only provided a deeper understanding of the "coating" behavior under different stresses, but also highlighted the importance of tailored application techniques to optimize performance results. Integration of empirical data from these tests with theoretical models allowed for the use of these coatings in compressor systems. The comprehensive analysis performed in this study highlights the pivotal role that meticulous manufacturing process optimization plays in achieving the desired improvements in compressor efficiency and durability. It is clear that precision in their manufacturing process is equally important to realize the full potential of these advanced materials, and as we advance, future research will continue to refine these application techniques and ensure long-term stability of these coatings in a variety of environmental conditions. Such continued research will undoubtedly be essential to verify the operational impact and sustainability of these innovations in industrial applications. This will contribute to the widespread adoption of these technologies to improve lifespan.

5. CONCLUSIONS

Our study demonstrates the important role of solid lubricating coatings in improving compressor performance and durability. Through rigorous testing and analysis, we have demonstrated that the choice of coating material and the applied process manufacturing process have a decisive influence on the tribological properties of the compressor system. It was found that in the case of defric coating, the lifespan was about 2-23 times longer, and the coefficient of friction was about 0.38 to 0.81 times lower than that of lubrizing coating. The results may vary depending on the manufacturing process, and this can have a significant impact on the reliability and efficiency of the compressor. The findings encourage further exploration of these coatings in industrial applications, with a focus on optimizing coating processing conditions to maximize their effectiveness. Additionally, it was confirmed that this test method is very useful in coating performance management. Future research could expand on this work by exploring the long-term effects of these coatings under various operating stresses and manufacturing conditions to further verify their practical benefits and sustainability.

REFERENCES

P Sutor, 1991: Solid lubricants: overview and recent developments, MRS Bull. Volume 16, Issue 5, pp. 24 – 30

Rico Baumgart, Joerg Aurich (2022). Optimization of the Pre-Outlet and Main-Outlet Bores in Scroll Compressors. *International Compressor Engineering Conference*. Paper 2763.

Wei Wang, Wenjuan Chang, Shijie Ding, Yishen Qu, Yuan Gao and Kuaishe Wang, (2023). Preparation and tribological properties of multi-layer graphene/silicon dioxide composites-based solid lubricant coatings at elevated temperatures. *R. Soc.* Open Sci., https://doi.org/10.1098/rsos.220740

Qipeng Huang, Xiaoliang Shi, Yawen Xue, Kaipeng Zhang, Chaohua Wu, (2023). Recent progress on surface texturing and solid lubricants in tribology: Designs, properties, and mechanisms. *Mater.* Today Commun. 35, 105854

JH Ouyang, YF Li, YZ Zhang, YM Wang, YJ Wang, (2022). High-Temperature Solid Lubricants and Self-Lubricating Composites: A Critical Review. *Lubricants* 10(8), 177

Y Li, Z Zhou, Y He, (2023). Solid Lubrication System and Its Plasma Surface Engineering: A Review. *Lubricants* 11(11), 473

M Cao, L Zhao, L Wu, W Wang, (2018). Tribological Properties of New Cu-Al/MoS2 Solid Lubricant Coatings Using Magnetron Sputter Deposition. *Coatings* 2018, 8(4), 134

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