Investigation on the Performance Improvement of the Scroll Compressor by DLC Film

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Abstract. The material property of orbiting scroll surface, mainly affects the life and performance of scroll compressors. Generally, the anodic oxide film (AOF) is used in the surface treatment of the domestic orbiting scroll, which has numerous drawbacks such as poor adhesion of the film-substrate and easy wear failure. In this paper, a process producing the diamond-like carbon film (DLCF) on the surface of an orbiting scroll by unbalanced magnetron sputtering technology was proposed based on the mechanical characteristics of the scroll compressor and the surface treatment method of the orbiting scroll. The friction coefficient, microhardness, film-substrate adhesion and other performances of the AOF and DLCF were analyzed from the data measured by various test facilities. The refrigeration capacity, power and volumetric efficiency of compressors with different coatings were analyzed and compared by tests under different operating conditions with fixed values of refrigerant charge and oil content. The surface morphology of the coatings was then studied by scanning electron microscope to identify the microstructure after the operation. The results showed that a more even and dense surface was obtained by the DLCF compared with the AOF, which improved the wear resistance of the surface. The surface friction coefficient was only 0.11 as the Cr transition layer markedly enhanced the bonding strength. The DLCF displayed more properties of graphite with the thickness of only 0.73 μm. The volumetric efficiency of the compressor under the nominal operating condition increased by 5.8%.

1. Introduction

Scroll compressors are widely used in the refrigeration of automobile air conditioning due to their simple and compact structure, high energy efficiency, low vibration and noise, compared with other volumetric compressors. There are 4 friction pairs closely related to the orbiting scroll in 7 friction pairs, which leads to the large friction power consumption and the reduced energy efficiency ratio [1]. Different from the previous concentrated study on the design of the orbiting scroll, more researchers pay great attention to the surface treatment of vulnerable parts and application of wearing resistant materials recently for reducing the impact of wearing.

Hoon ChoaSung got that high hardness TiAlN and a diamond-like carbon film (DLCF) plated on the rotor surface of rotary compressor wear seriously compared with the lower hardness WC/C films and the TiN film shows better wear resistance [2]. L. Swadžba discovered that CrN and Cr-CrN coated by physical vapor deposition had great corrosion resistance [3]. Q. Yan put forward to plate TiN film on the piston rod of CNG compressor by column arc ion plating to improve the adhesion of film base, but the friction coefficient is large [4]. Y. Liao found that the slider coated with DLC film can obviously reduce the power consumption of compressor [5]. D.J.Wang et al. observed that TiN film
coated by magnetron sputtering has low bonding strength and high friction coefficient by the experimental study [6]. Liping Wang et al. plated Ti/TiN/Si/ (TiC/a-C:H) composite film on aluminum alloy surface effectively by combined with plating and magnetron sputtering and considered that DLCF can significantly improve the bearing capacity of the aluminum alloy [7]. Lifang Xia et al. prepared four different interlayers on the 2024 aluminum alloy sample coated with DLC film and got the stable friction coefficient approximately 0.1, but different the sliding period of the stable friction coefficient [8].

The above papers show that DLCF can achieve the desired effect of reducing friction and improving efficiency compared with many other special materials. As clearly reported in some papers about properties of DLCF, it has low friction coefficient under 0.2, self-lubricating characteristic, high hardness, good thermal stability and adhesion strength with Si [9-14]. However, in actual production, the orbiting scroll is made of aluminium alloy whose main surface treatment is anodic oxidation [15]. There are many defects in anodic oxidation, such as uneven film thickness, surface flow mark, a loose oxide film, surface burn, the poor binding ability of film base and so on [9]. What’s more, very few researchers apply DLCF on scroll compressors due to so many complicated control factors, such as suitable base materials, reasonable coating method and so on [16-20].

The present paper reports the results of a comparative experimental investigation of the scroll compressor performance with the orbiting scroll coated by the DLCF and the anodic oxide film (AOF). The DLCF was plated by unbalanced magnetron sputtering technology. The friction coefficient, microhardness, film-substrate adhesion and other performances of the AOF and DLCF were analyzed from the data measured by various test facilities and then completed the performance test experiment of the scroll compressors with the AOF and DLCF to verify the feasibility of reducing friction and improving efficiency by DLCF.

2. Experimental procedures

2.1. Preparation of the DLCF and the AOF

In this paper, the DLCF was prepared on the surface of the domestic orbiting scroll by unbalanced magnetron sputtering technique to improve the surface defect of it. Before plating the films, ultrasonic cleaning of acetone and ethanol was used to remove grease and residual dirt on the sample surfaces of the orbiting scroll. Then glow discharge cleaning was the next necessary step to remove carbon and hydrocarbon impurities on the surface. Cr was placed between the DLCF and the orbiting scroll as the bond layer to increase the adhesion between film and substrate.

Anodic oxidation process with the aluminium or aluminium alloy in the sulfuric acid solution as the anode was used to treat the surface of the dynamic orbiting scroll of the compressor as the contrast term of the DLCF. This process included both the electrochemical formation and dissolution process of the film. By controlling the concentration of sulfuric acid, the temperature of the bath, the applied voltage, the current density, the stirring of the bath and the oxidation time, etc. it could be guaranteed that the growth rate of the film is faster than its dissolution rate to obtain the AOF. The dynamic orbiting scroll of the compressor before and after optimization is shown in Fig.1. As shown in Fig.1, the dynamic orbiting scroll with AOF is on the left side and with DLCF is on the right side.

![Figure 1. The dynamic orbiting scroll with AOF and DLCF.](image)
2.2. Characterization of the DLCF and the AOF

In the friction coefficient test, the two samples with DLCF and AOF and Al₂O₃ ball with the diameter of 5mm were ground separately for ten thousand revolutions under a certain load. As for the film thickness and surface morphology, the AOF thickness was measured by ball pit thickness gauge and the thickness of the DLCF by the scanning electron microscope (SEM). MH-VK microhardness test system was used to measure the samples’ hardness. The adhesion strength was measured by the scratch method in the quantitative method with different loads made on the samples’ surfaces, using the scanning electron microscope to look for the spalling points.

The phase composition of the sample surface was analyzed by D/max-3A X-ray diffractometer (XRD). In order to analyze the composition of the thin films in more detail, the surface and section composition and content of the two samples were analyzed by energy dispersive spectrometer (EDS) and energy spectrum.

| Table 1. Structural parameters of the two-phase reciprocating expander. |
|-----------------|-------|---------------|
| Parameters      | AOF   | DLCF          |
| Load (revealing exfoliation) /N | 60    | 90            |
| Friction coefficient | Increase with the rotational speed increasing, minimum value is 0.15 | 0.11 |
| Thickness /µm | 4     | 0.73          |
| MH-VK microhardness/ HV | 254.1 | 206.7         |
| Surface morphology | porous and rough | uniform and compact |

The results shows that the adhesion strength of the DLCF with Cr as the bond layer is better than that of the AOF. The friction coefficient of the DLCF is much lower than that of the AOF. The surface of the DLCF is uniform and compact, which improves the surface defect of the orbiting scroll to some extent. The hardness of the DLCF is lower than that of AOF because there are fewer SP³ bonds and more SP² bonds in the DLCF. Finally, the DLCF presented graphite properties.

2.3. Experimental principle and apparatuses

The compressor performance test bench simulates the automobile air conditioning system. In addition, the control and acquisition system is added in the operation, which can not only satisfy the variable working condition adjustment of the compressor but also collect the parameters of each position at any time and calculate the refrigerating capacity, input power and energy efficiency ratio of the compressor. As shown in Fig.2, the principle of the refrigeration system is mainly composed of the evaporator, scroll compressor, condenser, motor, dry filter, mirror, mass flowmeter, thermal expansion valve and so on. The parameters of two main apparatuses are listed in Table 2-Table 3.

Figure 2. The principle of the compressor performance test system.
Table 2. The parameters of the scroll compressor

| Type          | Displacement /cc | Voltage/V | Refrigerant | Oil        |
|---------------|------------------|-----------|-------------|------------|
| ATC-086-F10  | 86               | 12        | R134a       | PAG56      |

Table 3. The parameters of the Coriolis force mass flowmeter

| Type          | Medium           | Flow rate /kg·h⁻¹ | Pressure /MPa | Temperature /°C | Precision | Voltage /V |
|---------------|------------------|-------------------|---------------|-----------------|-----------|------------|
| DMF-1-3A     | R134a(liquid)    | 0~220             | 0~4.0         | -50-150         | ±0.2%     | 24         |

2.4. Experimental operation and condition

First of all, the sealing test using nitrogen should be carried out. After sealing test, extracted vacuum to 100Pa and held for more than 20min, then opened the pressure-balancing valve and filled in a certain amount of refrigerant, finally opened the compressor. By observing suction pressure gauges, if suction pressure dropped and exhaust pressure rose, the system started normally. Otherwise, the compressor was abnormal operation and needed to be checked the starting part of the connection and pipeline valve opening. After the operation of 5min, the refrigerant charge amount was adjusted.

The evaporation and condensation temperatures were adjusted by the heat transfer on the evaporation and condensation side respectively. The condensation pressure and the degree of subcooling were adjusted by the cooling water flow rate whose temperature was 16°C. The degree of superheat at the outlet of the evaporator maintained at 10±0.5 °C was regulated by the thermal expansion valve. Since the filling of refrigerant and the oil volume in the system can affect the experimental results, the optimal values are 1210 g and 217.8 g respectively after repeated debugging. The data of performance contrast experiment were recorded after keeping steady for more than 0.5 hours. The experimental working conditions are shown in Table 4 and Table 5.

The Pt100 thermal resistance temperature sensor with A precision is used in the temperature measurement. The temperature measurement range is -50-200 °C, which meets the requirement of the application. The temperature of each measuring point is collected at each time with the temperature patrol instrument. The measuring error is ±0.5% F·S±1. And the compensation error of the additional cold side is ±1 °C. The precision of the suction pressure gauge is 0.4 with the 0 ~ 1.6 MPa measuring range. The exhaust pressure gauge’s precision is 1.6 with the 0 ~ 4 MPa measuring range. They are both resistant to the high temperature and vibration.

Table 4. Variable rotational speed operation conditions

| Numbering | Speed/r·min⁻¹ | Evaporation temperature/°C | Condensation temperature/°C | Superheat/°C |
|-----------|---------------|----------------------------|-----------------------------|--------------|
| Condition 1 | 1200          | -1                         | 57.9                        | 10±0.5       |
| Condition 2 | 1400          | -1                         | 57.9                        | 10±0.5       |
| Condition 3 | 1600          | -1                         | 57.9                        | 10±0.5       |
| Condition 4 | 1800          | -1                         | 57.9                        | 10±0.5       |
| Condition 5 | 2100          | -1                         | 57.9                        | 10±0.5       |

Table 5. Variable pressure ratio operation conditions

| Numbering | Speed/r·min⁻¹ | Evaporation temperature/°C | Condensation temperature/°C | Superheat/°C |
|-----------|---------------|----------------------------|-----------------------------|--------------|

4
3. Results and discussion

3.1. Performance comparison of compressors with the DLCF and AOF

According to the above analysis, the system can satisfy the variable working conditions experiment under 1210 g refrigerant and 217.8 g oil. In order to facilitate the experimental research and analysis, the experimental scroll compressor under different working conditions was numbered: No.1 compressor: 217.8 g oil, the scroll compressor with the dynamic orbiting scroll coated by the AOF; No.2 compressor: 217.8 g oil, the scroll compressor with the dynamic orbiting scroll coated by the DLCF.

The variable speed and pressure ratio performance tests of No.2 compressor were carried out and compared with the tests of No.1 compressor. The performance parameters of the measured refrigeration system are shown in Table 6.

| Condition category       | Speed/r·min⁻¹ | Pressure ratio | Mass flow/kg·h⁻¹ | Motor Power/kW |
|-------------------------|---------------|----------------|-----------------|---------------|
| Variable rotational speed | 1200          | 5.670          | 67.050          | 1.838         |
|                         | 1400          | 5.670          | 75.550          | 2.055         |
|                         | 1600          | 5.670          | 83.420          | 2.140         |
|                         | 1800          | 5.670          | 88.100          | 2.300         |
|                         | 2100          | 5.670          | 88.030          | 2.640         |
| Variable pressure ratio | 1800          | 5.670          | 90.410          | 1.610         |
|                         | 1800          | 3.601          | 88.250          | 1.783         |
|                         | 1800          | 4.108          | 88.480          | 1.957         |
|                         | 1800          | 4.668          | 88.585          | 2.195         |
|                         | 1800          | 5.283          | 88.255          | 2.550         |

Based on the experimental data, the calculated refrigerating capacity, compressor power, volumetric efficiency of No.1 compressor and No.2 compressor under variable rotational speed is shown in Table 7. It can be seen that the refrigerating capacity and volume efficiency of No.2 compressor are higher than those of No.1 compressor under low rotational speed test and the power consumption is lower than that of No.1 compressor, which is due to the decrease the flow resistance loss of the working fluid with the flat surface and low friction coefficient of the DLCF. When the rotational speed is high, the refrigerating capacity of the No.2 compressor is 0.5% lower than that of No.1 compressor, the power consumption increases by 0.4%, while the volume efficiency decrease by 3.6%. According to the previous analysis, the DLCF’s thickness in this experiment is smaller than that of the AOF, so it will
cause the internal leakage of the compressor to increase, the refrigerating capacity of the system to reduce and the volume efficiency to decrease. Because the hardness of the DLCF prepared in this experiment is not high, the orbiting scroll’s wear of No.2 compressor is more serious at high rotating speed, which results in the increase of power consumption and the obvious internal leakage.

**Table 7.** Comparison of performance experiment results (variable rotational speed)

| Programs                  | Rotational speed/r·min-1 | 1200 | 1400 | 1600 | 1800 | 2100 |
|---------------------------|---------------------------|------|------|------|------|------|
| Refrigerating capacity (kW) |                           |      |      |      |      |      |
| No.1 compressor           |                           | 2.299| 2.602| 2.886| 3.032| 3.271|
| No.2 compressor           |                           | 2.334| 2.629| 2.903| 3.066| 3.154|
| Percentage increase       |                           | 1.5% | 1.1% | 0.6% | 1.1% | -0.5%|
| No.1 compressor           |                           | 1.313| 1.555| 1.656| 1.761| 1.978|
| No.2 compressor           |                           | 1.341| 1.548| 1.613| 1.744| 1.985|
| Percentage increase       |                           | -0.9%| -0.5%| -2.5%| -1.0%| 0.4% |
| Power (kW)                |                           |      |      |      |      |      |
| No.1 compressor           |                           | 82.7%| 80.2%| 77.9%| 72.2%| 67.2%|
| No.2 compressor           |                           | 83.9%| 81.2%| 78.4%| 73.0%| 64.8%|
| Percentage increase       |                           | 1.5% | 1.3% | 0.6% | 1.1% | -3.6%|

According to the comparison results, the performance parameters of the system under variable pressure ratio is drawn in Fig.3. The experimental data points in the diagram are fitted by the least square method. It can be concluded that volumetric efficiency are increased by 5.8%. When the pressure ratio is 5.283 and 6.389, the compressor power increases slightly, it is mainly because the low hardness of the orbiting scroll surface with the DLCF makes the compressor fatigue wear, which increases the power consumption of the compressor.
Figure 3. The system performance parameters comparison under variable pressure ratio
(a) Refrigerating capacity; (b) Compressor power; (c) Volumetric efficiency

3.2. Comparison and Analysis of the dynamic orbiting scroll after operating
In this paper, in order to explore the effect of the DLCF on the orbiting scroll wear resistance, the orbiting scroll’s surface wear states of different compressors are compared and analyzed, as shown in Fig.4 and Fig.5 respectively.

Figure 4. The dynamic orbiting scroll of No.1 compressor
(a) Suction side; (b) Discharge side

Figure 5. The dynamic orbiting scroll of No.2 compressor
(a) Suction side; (b) Discharge side
By observing the surface wear of the orbiting scroll, it can be seen that the surface of the two compressors’ orbiting scroll has a certain scratch and wear, which was especially serious at the suction and discharge sides. The scratches on the surface are due to the impurities mixed in the system. Fig. 5 shows that the orbiting scroll wear coated with DLC film is more obvious and the serious wear phenomenon occurs at the discharge side. In contrast, the wear with the AOF is not obvious, but there are also wear marks on the discharge side. This is mainly because of the large force and thermal deformation at the discharge side of the scroll compressor. If the hardness is not high or the surface is rough, it is easy to produce wear phenomenon.

After being analyzed by the optical microscope, the samples were extracted at the suction side of No.1 and at both sides of the No.2 compressor respectively. The surface morphology of the sample was observed by the electron microscope, as shown in Fig. 6-Fig. 8.

**Figure 6.** No.1 compressor suction side orbiting scroll’s surface morphology after operating
(a) 60 (amplified factor);(b) 100

**Figure 7.** No.2 compressor suction side orbiting scroll’s surface morphology after operating
(a) 150;(b) 240

**Figure 8.** No.2 compressor discharge side orbiting scroll’s surface morphology after operating
(a) 500;(b) 1000;(c) 2000
As can be seen from Fig. 6, due to the entrance of impurities, in the variable working condition experiments, the orbiting scroll surface of No.1 compressor produces abrasive wear mainly scratched. It can be found from Fig. 7 and Fig. 8 that the orbiting scroll surface of No.2 compressor produces fatigue wear mainly stripped and falling off. This is because the discharge side is the area where the orbiting scroll most obvious heat deformation and subjected to force exists. In addition, the hardness of No.2 compressor’s film is low and the film layer is thin. As a result, friction and wear are serious relatively.

4. Results and discussion
This paper proposes to use the unbalanced magnetron sputtering technique to prepare the DLCF on the surface of the orbiting scroll to study the feasibility of reducing friction and improving efficiency by DLCF. Through the performance contrast experiments between two scroll compressors with the DLCF and AOF, the main conclusions are as follows:

(a) Aiming at the disadvantages of porous roughness, high friction coefficient and easy wear failure caused by the AOF, an unbalanced magnetron sputtering technique is proposed to prepare DLC film on the surface of the orbiting scroll. By using Cr as the bond layer and then preparing DLC film, the adhesion strength of the DLCF was improved significantly and better than that of the AOF.

(b) The DLC film has obvious improvement in friction and wear. The surface friction coefficient of the DLCF is 0.11, which is much lower than that of the AOF. The thickness of the AOF is 4 μm and of the DLCF is 0.73 μm. Compared with the porous AOF, the surface of the DLCF is uniform and compact, which improves the surface defect of the orbiting scroll to some extent.

(c) The hardness of the DLCF prepared in this experiment is lower than that of the AOF. The main reason is that there are fewer SP² bonds and more SP³ bonds in the DLCF, which makes the DLCF presents graphite properties.

(d) Under the nominal test conditions, the compressor performance with the DLCF is much better than that with the AOF. The volume efficiency are improved by 2.4% and 5.8% respectively. At low rotational speed, the performance of the compressor with the DLCF is improved significantly. When the rotational speed is high, the compressor performance with the DLCF is slightly lower than that of the compressor with the AOF. The main reason is that the surface hardness of the orbiting scroll increases and the internal leakage is obvious.

(e) From the analysis of the surface morphology of the compressor suction side, due to the entrance of impurities, the orbiting scroll surface of the compressor with the AOF produces abrasive wear mainly scratched and with the DLCF produces fatigue wear mainly stripped and falling off. By observing the orbiting scroll surface morphology of the discharge side, two kinds of surfaces both produce fatigue wear. The wear of the orbiting scroll with the DLCF was more serious because of its low hardness and the thin film layer.

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