Wear-Reducing Technologies for Rotary Compressors Using CO_2 Refrigerant

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1. Introduction

We employed a natural CO_2 refrigerant with a high operating pressure in a single rotary compressor. By coating the vane, for the first time in Mitsubishi rotary compressors, we intended to reduce the wear between the top of the vane and the outside of the rolling piston.

1. Application of a Coating to the Vane

Household heat pump water heaters not only use a natural CO_2 refrigerant, which has a high operating pressure, but also require a longer product lifetime than air-conditioning systems or refrigerating machines. In the early stages of development of the compressor, we used vanes prepared by nitriding high-speed steel in the same manner as conventional rotary compressors used for air-conditioning systems with the result that abnormal wear occurred at the top of the vane after operating for less than one-fifth of the lifetime needed. Then, we applied a DLC-Si to the vane, which is a coating of diamond-like-carbon containing silicon.

2. Characteristics of the DLC-Si

DLC-Si is accomplished with a plasma CVD (Chemical Vapor Deposition) method in which the coating forms in a plasma environment created by mixing a hydrocarbon gas and a gas containing silicon. With silicon contained in the film, the coating formed is thicker than general DLC, thus achieving better sliding and rolling characteristics.

Since the top of the vane of the rotary compressor and the outside of the rolling piston make line contact, the stress becomes severe and the contact involves both sliding and rolling phenomena.

When applying the coating to the vane, the adhesion strength between the coating film and the base material must be adequate, otherwise, the coating film may peel off and result in abnormal wear. It is necessary to identify the adhesion strength between the coating film and the base material for the appropriate application of the DLC-Si on the vane of a rotary compressor. We measured the adhesion strength with a micro scratch tester.

Figure 1 shows the relationship between the silicon concentration in the DLC-Si film and the adhesion strength between the coating film and the base material. According to Fig. 1, it is clear that the adhesion strength between the DLC-Si film and the base material depends on the silicon concentration in the coating and is highest at a silicon concentration of approximately 20 wt%. It is also reported that the adhesion strength of the coating film depends on the internal stress developed at the interface and adhesion strength increases when internal stress is controlled properly.[3]

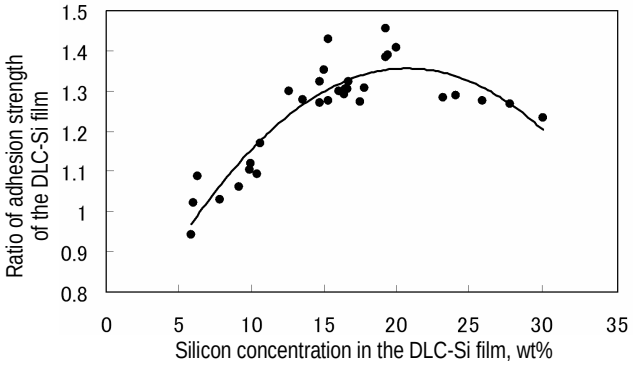

Fig. 1 The relationship between silicon concentration and the adhesion strength ratio of DLC-Si

In accordance with our examination results on the relationship between the silicon concentration in the film and the internal stress of the DLC-Si film applied to the vane of the rotary compressor, we confirmed that the lower the silicon concentration, the higher the internal stress, provided that the silicon concentration is 20 wt% or lower. This generally agrees with the reported characteristics mentioned above.

3. Structure of the Experimental Apparatus and Conditions of the Elemental Test

Table 1 shows the conditions of the wear test on the vane and rolling piston using the experimental apparatus.

Table 1 Conditions of elemental tests

Environment	CO_2
Environment temperature	313K
Lubricant	PAG (VG-100: dropping)
Vane material	High-speed steel (nitriding treatment) High-speed steel (DLC-Si coated)
Rolling piston material	Special cast iron
Pressure loading	450N
Sliding velocity	0.6m/s

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In this elemental test, a vane prepared by nitriding high-speed steel as well as a vane that conforms to treatment condition #5, shown in Table 2, were used.

Table 2 The relationship between silicon concentration and adhesion strength of DLC-Si

Treatment conditions	Silicon concentration	Ratio of adhesion strength of the coating film
1	6wt%	1
2	13wt%	1.3
3	15wt%	1.35
4	17wt%	1.43
5	19wt%	1.46

On the other hand, in the life test (reliability evaluation test), using the rotary compressor as discussed in Chapter 4 below, we used a vane which was prepared by merely nitriding and vanes prepared with DLC-Si having five levels of adhesion strength, in accordance with treatment conditions #1 to #5. As shown in Fig. 1, the adhesion strength of the DLC-Si film changes with the silicon concentration in the film and especially with silicon concentrations between 5 and 20 wt%, the adhesion strength varies greatly with the silicon concentration. As a solution, we changed the hardness of the base material by changing the nitriding pretreatment conditions and the temperature of the plasma environment, as well as the supply of material gas during coating. As a result, the relationship between the silicon concentration in DLC-Si and the adhesion strength between DLC-Si and the base material was secured, as shown in Table 2.

4. Conditions of the Life Test (Reliability Evaluation Test) Using a Rotary Compressor

We conducted a life test on the rotary compressor, under the conditions shown in Table 3.

Table 3 Conditions of reliability evaluation tests

Refrigerant	CO_2
Lubricant	PAG (VG-100)
Ps/Pd	3MPa/14MPa
Stoke volume	4.5cc
Vane material	High-speed steel (nitriding treatment) High-speed steel (DLC-Si coated)
Rolling piston material	Special cast iron

With the pressure inside the rotary compressor's shell at a higher level than the normal operating condition used for household heat pump water heaters and the rotational speed of the motor set at a higher level, which made the sliding conditions between the top of the vane and the periphery of the rolling piston more severe, we simulated an operating period equivalent to the lifetime required for the product in a short period of time.

5. Results of the Elemental Test and Considerations

Figure 2 shows the ratio of the amounts of wear on the nitrided vane and the DLC-Si coated vane. The figure indicates, obviously, that the wear on the DLC-Si coated vane is much lower than that on the nitrided vane. This elemental test showed a tendency for wear on the vane to approach a certain level over time. This is attributed to a decrease in contact pressure due to the change from line contact to surface contact, which results from the increased wear on the top of the vane over a long period of testing time, as the vane slides in continuous contact with the rolling piston. Figure 3 shows the relationship between the contact ratio between the top of the vane and the periphery of the rolling piston, and the ratio of volumetric wear velocity.

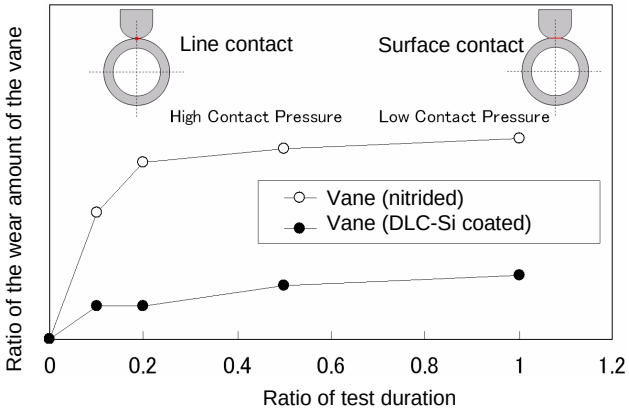

Fig. 2 Wear ratio of the vane in elemental wear tests

From Fig. 3, it becomes clear, with both the nitrided vane and DLC-Si-coated vane, that there is a flexion point where the volumetric wear velocity on the top of the vane increases sharply as the contact pressure between the top of the vane and the periphery of the rolling piston exceeds a certain value. The contact pressure between the top of the vane and the periphery of the rolling piston at the flexion point where the volu-

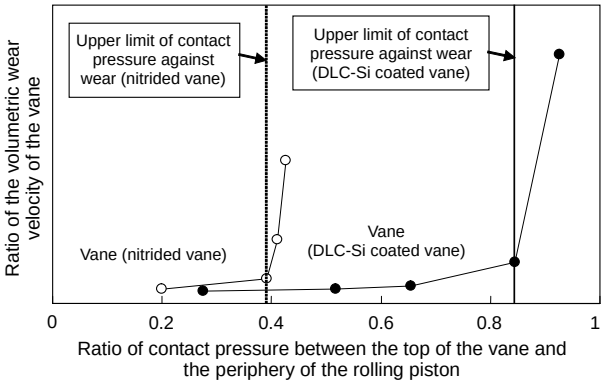

Fig. 3 The relationship between the contact pressure ratio and wear velocity ratio of the vane

metric wear velocity increases sharply is the maximum contact pressure that controls the amount of wear on the vane. Based on the different flexion points shown in Fig. 3, the maximum contact pressure that controls the amount of wear on the DLC-Si coated vane is confirmed to be twice, or more, that of the nitrided vane.

6. Results of the Life Test and Considerations

Figure 4 shows the relationship between the ratio of test duration and the ratio of the amount of wear on the vane in the life test, using the nitrided vane and DLC-Si coated vanes with treatment conditions #1, #3, and #5 shown in Table 2.

For the test on the nitrided vane, the wear amount increased sharply and we suspended the test at the point where the ratio of operational length reached 0.2.

In the test on the DLC-Si coated vanes, the wear amount was most remarkably suppressed on the vane subjected to treatment condition #5, which had the highest coating film adhesion strength. The amount of wear increased on the vane subjected to treatment condition #3, having lower adhesion strength than that of #5. However, these vanes developed slight wear only in the initial period of the operation, which appeared to be mild wear between the vane and the rolling piston. When the operating time was extended, the wear amount did not increase.

In the test on the vane subjected to treatment condition #1, in which the adhesion strength of the DLC-Si film was the lowest, we suspended the test at a test duration ratio of 0.1, when the DLC-Si film started to peel off.

Figure 5 shows the relationship between the ratio of the DLC-Si film's adhesion strength of the DLC-Si coated vanes subjected to treatment conditions #1 through 5, which were used in the compressor life test and the ratio of the amount wear on the vanes. Note that the values at the points where the operation reached durations that were equivalent to the lifetime needed for treatment conditions #2 through #5 and the value at a point where the DLC-Si film started to peel off for treatment condition

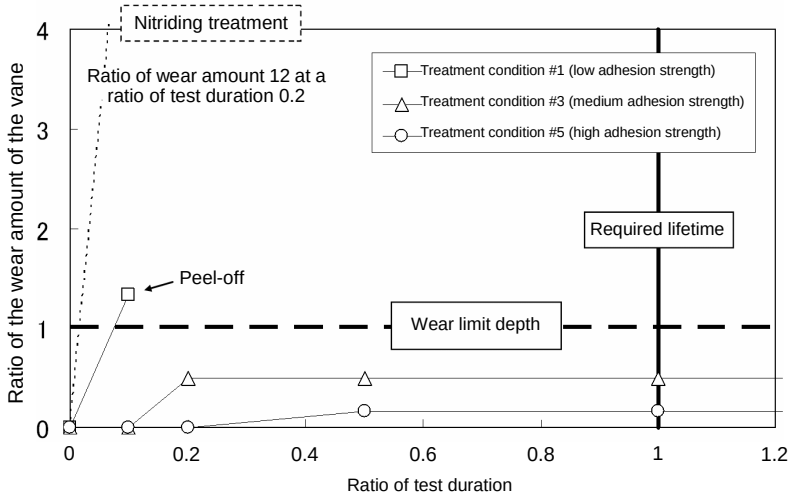

Fig. 4 The relationship between the test duration ratio and the wear volume ratio of the vane

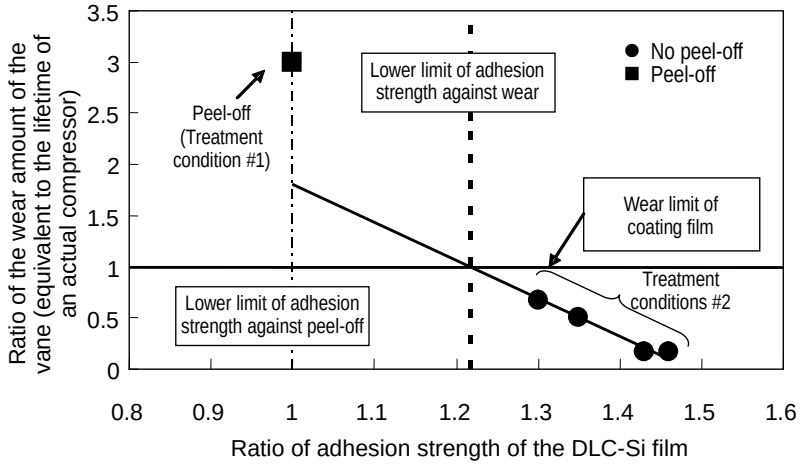

Fig. 5 The relationship between the adhesion strength ratio of DLC-Si and the wear volume ratio of the vane

#1, are indicated in the figure.

The approximate line of the test results of the vanes with treatment conditions #2 through 5 indicates that the amount of wear at the top of the vane increased with decreasing adhesion strength of the DLC-Si film. It also indicates that the film started to peel off when the ratio of adhesion strength was lowered to 1.

6. Conclusion

By applying a DLC-Si to the vane, we developed a single rotary compressor that uses a CO_2 refrigerant for practical application in household heat pump water heaters for the first time in the world.