2008

Wear-Less Technology for Rotary Compressor Using CO2 Refrigerant

Naotaka Hattori
Mitsubishi Electric Corporation

Hideto Nakao
Mitsubishi Electric Corporation

Tomoo Takayama
Mitsubishi Electric Corporation

Ikenaga Kaoru
NDK Incorporated

WEAR-LESS TECHNOLOGY FOR ROTARY COMPRESSOR USING CO_2 REFRIGERANT

Naotaka Hattori[1*], Hideto Nakao[2], Tomoo Takayama[3], Ikenaga Kaoru[4]

[1]Mitsubishi Electric Engineering Corporation Shizuoka Engineering Office
3-18-1, Oshika, Suruga-ku, Shizuoka-City, Japan
Tel: +81-54-287-3112, Fax: +81-54-287-3127, Postcode: 422-8528
E-mail: Naotaka.Hattori@zt.MitsubishiElectric.co.jp

[2]Mitsubishi Electric Corporation Advanced Technology R&D Center
8-1-1, Tsukaguchi-Honmachi, Amagasaki-City, Hyogo, Japan
Tel: +81-6-6497-7582, Fax: +81-6-6497-7291, Postcode: 661-8661
E-mail: Nakao.Hideto@dr.MitsubishiElectric.co.jp

[3]Mitsubishi Electric Corporation Manufacturing Engineering Center
8-1-1, Tsukaguchi-Honmachi, Amagasaki-City, Hyogo, Japan
Tel: +81-6-6497-7528, Fax: +81-6-6497-7601, Postcode: 661-8661
E-mail: Takayama.Tomoo@dx.MitsubishiElectric.co.jp

[4]NDK, Incorporated
3-10-14,Miyasimo Sagamihara-City,Kanagawa,japan
Tel: +81-42-774-1233, Fax: +81-42-773-1674, Postcode:229-1112
E-mail: k-ikenaga@ndkinc.co.jp

ABSTRACT

We have developed a new CO_2 heat pump water heater compressor with a single rotary mechanism in practical use for the first time in the world. CO_2 refrigerant doesn't destroy the ozone layer, and the global warming potential (GWP) is less than 1/1000 in comparison to hydro-fluorocarbon refrigerants. However the operating pressure of CO_2 refrigerant is approximately three times as high as that of R410A refrigerant. Therefore, it is important to secure the reliability of sliding portions under high operating pressure conditions.

The single rotary mechanism is used in mainstream R410A refrigerant air conditioning systems. However, CO_2 refrigerant has not been used practically for CO_2 refrigerant systems due to the difficult issue of securing the durability against vane wear. We worked on this issue of reliability for the sliding portion between the vane tip and the periphery of the rolling piston, by applying a coating DLC-Si to the vane. As a result, even after a long duration, the DLC-Si coated vane is hardly worn-out, only the surface roughness is smoothed. We were able to achieve an excellent level of wear durability, which we call "WEAR-LESS".

1. INTRODUCTION

In Japan, the heat pump type water heater (Figure 1) that uses a natural refrigerant CO_2 has been rapidly spreading, after it was commercialized in 2001. The single rotary mechanism has been the mainstream of R410A refrigerant air conditioning systems, because of it is simple mechanism and high efficiency. However, the operating pressure of the CO_2 refrigerant is approximately three times as high as that of R410A refrigerant. It is difficult to secure the reliability of the sliding portion between the vane tip and the periphery of the rolling piston under high operating pressure conditions. Therefore, it had not been able to be used practically. We worked on securing the reliability against the vane wear. As a result, we started mass production of the single rotary compressor using CO_2 refrigerant in October, 2005

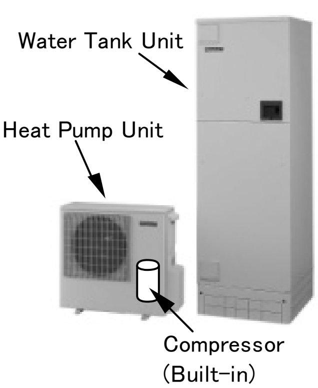

Fig. 1 Appearance view of Water Heater Unit

2. ROTARY COMPRESSOR

2-1. Single Rotary Compressor using CO_2 refrigerant

Table1 shows the specification of the single rotary compressor using CO_2 refrigerant. It is used for our heat pump water-heater units of 4.5kW, 6.0kW and 7.2kW. Figure 2 shows a cross-sectional view of the Mitsubishi CO_2 compressor. The structure of the compressor is designed to withstand high pressure CO_2 refrigerant. The compressor uses a "Joint-lapped" brush-less DC motor that is used in our compressor installed in conventional refrigerant air conditioners.

Table 1 Specification of the CO2-Single Rotary Compressor

Model Name	KXB045F
Compressor Type	Single Rotary
Displacement	4.5cc
Usage	HP Water Heater4.5/6.0kW/7.2kW
Size	ϕ122×278mm
Motor	BLDCM(Joint-Lapped Motor)
Weight	12.7Kg

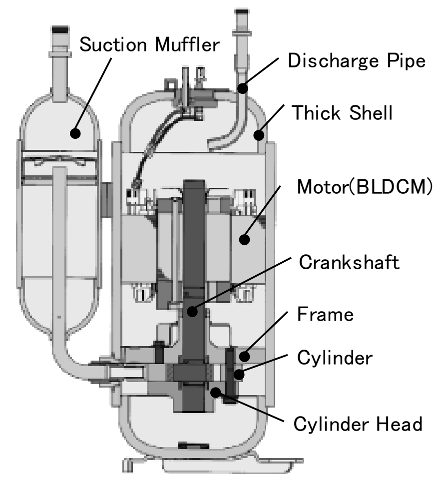

Fig. 2 Single Rotary Compressor for CO2

2-2. Rotary Mechanism

Figure 3 shows the compression movement of the rotary mechanism. The rotary compressor mechanism consists of a rolling piston that rotates eccentrically in its cylinder and a vane installed in a vane slot in the cylinder, which reciprocates along the slot causing the vane to move along the periphery of the rolling piston. As a result of the vane's movement, suction and compression chambers are formed inside the cylinder and the volume of each chamber changes in accordance with the rotation of the crankshaft to provide compression. When the compression chamber gas equals the discharge pressure, a discharge valve is opened, and compressed gas is discharged.

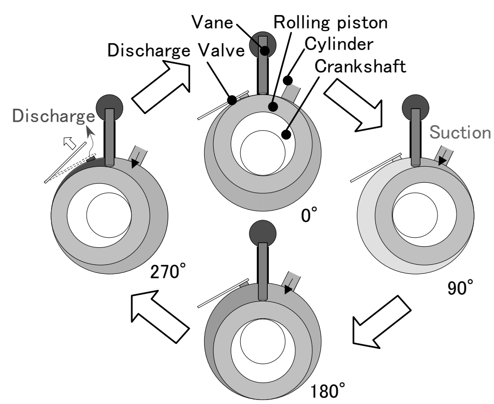

Fig. 3 Mechanism of rotary type

2-3. Issues in applying the single rotary mechanism for CO_2 refrigerant

The rotary mechanism has a simple structure, and it has light weight in comparison with other compression methods. Component-parts of rotary compressor have an advantage, as they are easy to machine because their shapes are based on cylinders and plane surfaces. Therefore it is the mainstream type of compressor for conventional R410A refrigerant air conditioners. However, since the vane tip and the periphery of the rolling piston slide while receiving the load pressure, it is difficult to maintain the lubricating oil in this sliding portion, so the sliding condition is harsh. Figure 4 shows the sliding portion of the vane and the rolling piston. As shown in Figure 5, the operating pressure of the CO_2 refrigerant is approximately three times as high as R410A refrigerant. Therefore, it is too harsh to secure the reliability of the vane with a rotary mechanism.

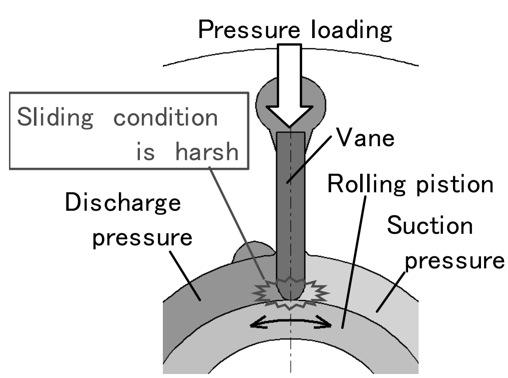

Fig. 4 Sliding portion of the vane

Figure 6 shows the life test results of rotary compressors with CO_2 refrigerant in the early stages of development. A nitrided vane was used which implemented the conventional rotary compressor for R410A refrigerant air conditioners. The axis of abscissa shows the life test period ratio, and the axis of the ordinate shows wear ratio of the vane. The required life time is 1.0, and the wear tolerance-limit of the vane is 1.0. The result of the experiments, wear amount of the nitrided vane exceeded the wear tolerance-limit by 1/5 of the required life time. Therefore, this result shows how difficult it was to establish a specification for practical use of CO_2 refrigerant by the single rotary mechanism. We think that was necessary to develop a new technology.

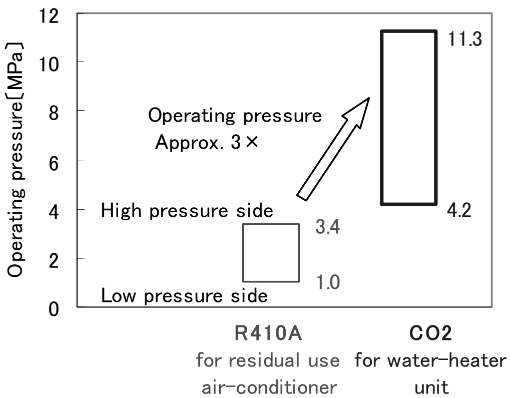

Fig. 5 Comparison of operating pressure

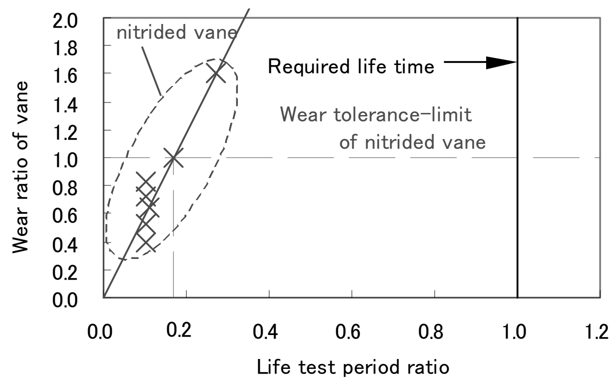

Fig. 6 Life test result of nitrided Vane

3. IMPROVEMENT OF SLIDING DURABILITY AT THE VANE TIP

In the history of refrigeration units, there were some turning points when rotary compressors needed to improve the specification of sliding durability at the vane tip, such as increasing sliding speed by applying inverter control and increasing operating pressure by changing refrigerant from R22 to R410A. As an improvement action, we changed the material of the vane, and added a surface treatment to the vane. However, these methods merely decreased the amount of wear on the vane. We achieved “WEAR-LESS”, the reliability of the sliding portion by coating DLC-Si to the vane.

3-1 “WEAR-LESS” coating DLC-Si to the vane

Figure 7 shows the life test results of DLC-Si coated vane. Results of the life tests, DLC-Si coated vane is hardly worn-out, and the surface roughness only becomes smooth. Therefore the DLC-Si coated vane is effectively “WEAR-LESS”. The rolling piston does not wear out equally either. Figure 8 shows the surface profile of a DLC-Si coated vane before and after the life test, and was compared with nitrided vane. The surface profile of nitrided vane was coarse. However, the surface profile of DLC-Si coated vane was still smooth and not worn. It is understood that the DLC-Si coated vane has excellent sliding characteristics.

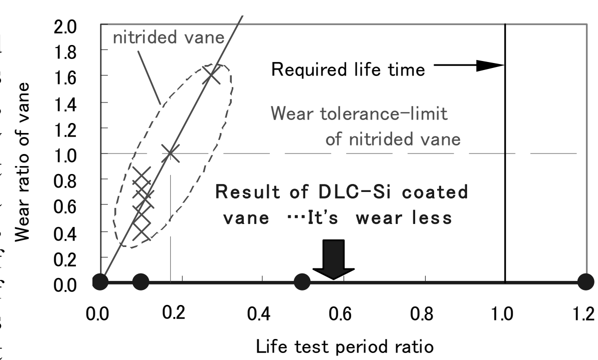

Fig. 7 Life test result of DLC-Si coated vane

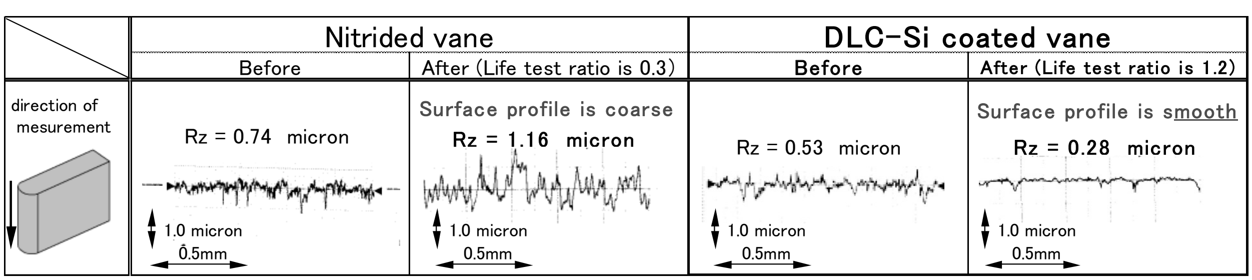

Fig. 8 Surface shape of vane before and after the life test

3-2 DLC-Si coated vane

DLC-Si is the term for "Diamond-Like Carbon-Silicon", which is a film of DLC containing silicon. Figure 9 shows the structure of the DLC-Si coated vane. The nitrided layer is formed on the base material, and the DLC-Si film is coated on top of it. The characteristic of the DLC film is hard with a crystal structure similar to a diamond, so the DLC itself is not worn out. Moreover, the other part is not worn out by the characteristic of DLC such as flexible graphite and solid lubricity. The DLC-Si film has the high adhesion strength by containing the silicon compared with conventional DLC that does not contain silicon. Coating technologies such as DLC have existed for some time to reduce friction and wear. We evaluated several coating technologies. However, there were many issues that were wearing out the rolling piston and peeling off the coating film. Figure10 shows the result of rolling piston wear ratios when the CrN coated vane was tested compared to the DLC-Si coated vane. The DLC-Si coated vane does not wear out the rolling piston compared with the CrN coated vane.

Conventional DLC film that does not contain silicon was developed in the 1970's. And it has been used for tools, metal molds and other applications. However, practical use of conventional DLC came later, because of two issues, the first issue is the low adhesion strength, and the second issue is that it was impossible to coat a high thickness film. We tried to evaluate the life test of a conventional DLC coated vane. As a result, it peeled off in the early test period because of low adhesion strength. Figure11 shows a picture of a peeled off the film. The adhesion strength of the DLC-Si film is approximately twice as high as that of conventional DLC film. Moreover, the film thickness of conventional DLC film was only 0.5-1.0 micron, however it is possible to produce more than 5micron thickness film in the case of the DLC-Si film.

DLC-Si film improved the demerit of conventional DLC film by containing the silicon, and it sliding characteristics were improved.

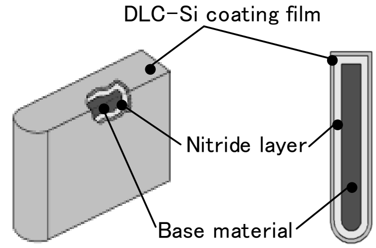

Fig. 9 Structure of DLC−Si coating Vane

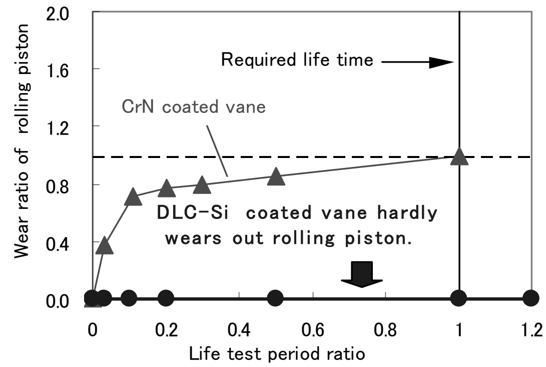

Fig. 10 Life test result of rolling piston wear ratio

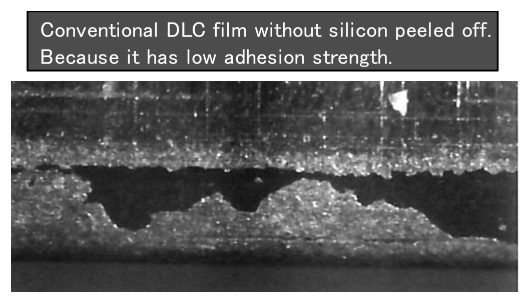

Fig. 11 Result of life test for conventional DLC

3-3 Optimization of adhesion strength by controlling the silicon content

When coating DLC-Si to the vane of the rotary compressor, it is necessary to secure enough adhesion strength against peeling off the film. In this paragraph, I will describe the optimization of adhesion strength of the DLC-Si film by the silicon content.

The peeling patterns of the DLC-Si coated vane of the rotary compressor are roughly divided into two groups as follows:

Pattern A) Peeling at the surface film
Pattern B) Peeling at the interface between the DLC-Si film and the base material

The peeling pattern of "A" has a lot of small damage called "micro-picking". The peeling pattern of "B", the base material surface is exposed in a wide area. In both peeling patterns, adhesion strength relates to the silicon concentration in the DLC-Si film. The adhesion strength characteristics of the DLC-Si films are changed by silicon concentration. We optimized the silicon concentration in the DLC-Si film and secured the adhesion strength of the film. Figure 12 shows the relationship between silicon concentration and the adhesion strength ratio. Figure 13 shows the relationship between silicon concentration and the residual stress ratio. Figure 14 shows the relationship between silicon concentration and the ratio of Young's modulus.

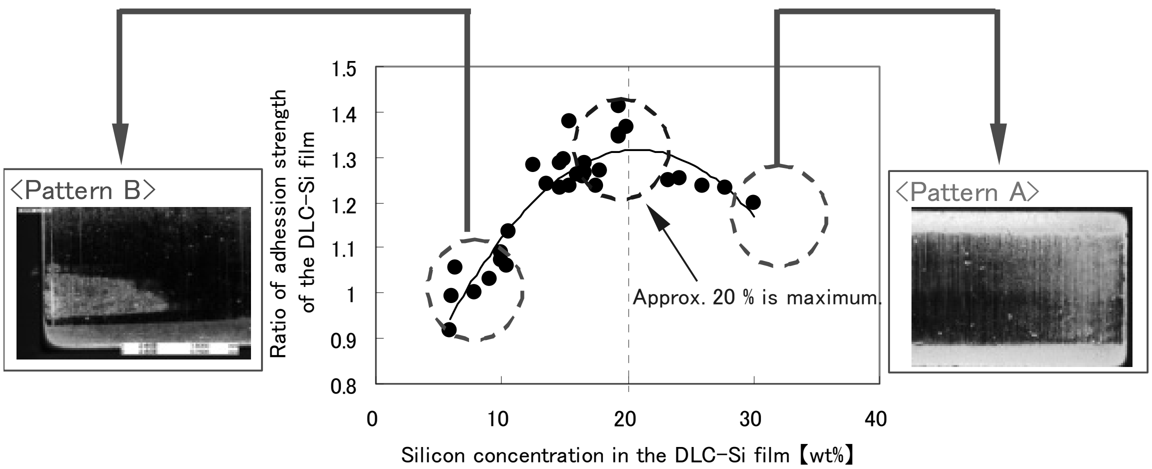

Fig. 12 The relationship between silicon concentration and the adhesion strength ratio of DLC-Si

As shown in Figure 12, The adhesion strength of the DLC-Si film depends on the silicon concentration. Adhesion strength of DLC-Si film is maximized when the silicon concentration is approximately 20 %. If the silicon concentration is lower or higher than 20 %, either way the adhesion strength declines. Adhesion strength decreases seriously when the silicon concentration becomes 10 % or less, resulting in peeling "pattern B". In this case, it is considered that the low adhesion strength is cased by the high residual stress due to the mismatch of the crystal structure between the film and the base material. As you can see from Figure 13, when the silicon concentration is low, the residual stress increases. Therefore, We assume that the residual stress of the film depends on the silicon concentration. In the case of low silicon, high residual stress generates at the interface between the DLC-Si film and the base material. The film peeling pattern by high silicon concentration is "pattern A". From Figure 14, we can see when the silicon concentration is high, the Young's modulus decreases. We assume that a high silicon concentration film is fragile and peels off at the surface of the film. Thus we controlled the silicon concentration of DLC-Si coated film to approximately 20 %.

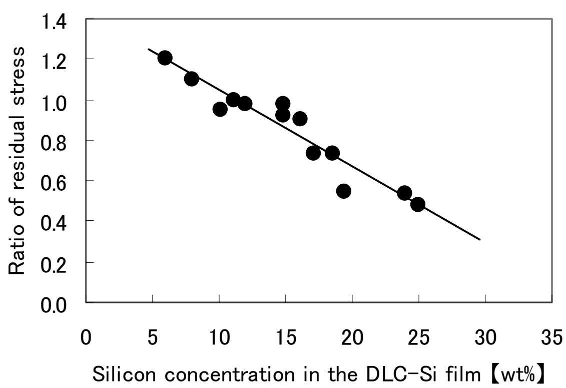

Fig. 13 The relationship between silicon concentration and the residual stress ratio of DLC-Si

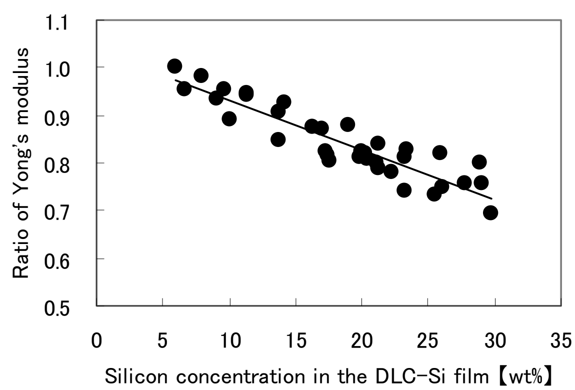

Fig. 14 The relationship between silicon concentration and the Young's modulus ratio of DLC-Si

3-4 Deposition of DLC-Si to the vane

DLC-Si is deposited by the plasma CVD (Chemical Vapor Deposition) method with gases of CH_4 and a silicon gas such as $Si(CH_3)_4$. Mass production of DLC-Si coated vane is processed by NDK Incorporated Japan. Figure 15 shows the processing equipment for mass production. By mass production processing, the vane can be processed at the rate of several hundred pieces per one batch. We developed the specification of the vane stage, the gas supply pipe, flow rate of gases, and processing temperature to secure the characteristics such as film thickness or adhesion strength for exclusive use in this application.

Fig. 15 The processing equipment of DLC-Si (A product made in NDK,Incorporated)

4. THE WEAR-OUT DURABILITY OF THE DLC-Si COATED VANE

The vane tip of the rotary compressors comes in contact with the periphery of the rolling piston, and slides. It involves both sliding and rolling actions. If the load of this sliding portion is higher than the wear limit of the material, the vane tip and the periphery of the rolling piston wears out. However if the sliding portion is less than the wear limit of the material, it does not wear out. Therefore, it is possible to grasp the wear-out resistance of the vane by obtaining the load that corresponds to the wear out limit rate and comparing the maximum load rate for practical use. We obtained the load that corresponds to the wear-out limit rate through experiments with an abrasion tester (Figure 16). In Figure 16, the vane comes in contact with the rolling piston through the load from the back, as the rolling piston rotates by the motor drive. Therefore the contact formation of the vane tip and the periphery of the rolling piston is a sliding action only. Table 2 shows the conditions of the experiments, and figure 17 shows the result of experiments that compares the nitrided vane with the DLC-Si coated vane. The experiment result shows a relationship between the experimental time and the ratio of the vane wear. The wear amount of DLC-Si coated vane is much lower than that of the nitrided vane. Both wear amount of vanes have a tendency to be saturated by progression of the test time. This is attributed to a decrease in contact pressure due to the change from a line contact to a surface contact, as the wear of vane increases.

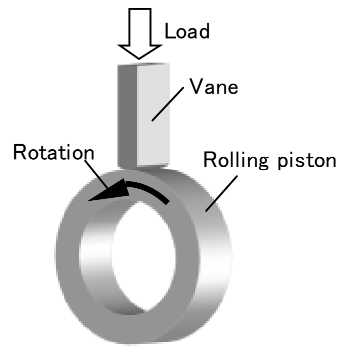

Fig. 16 Wear tester

Table 2 Condition of the wear test

Environment	CO_2 refrigerant	
Case	1	2
Vane material	DLC-Si coated vane	Nitrided vane
Rolling piston material	Special cast iron	
Lubricant	PAG	
Load	Maximum load of CO_2 refrigerant(constant)	
Sliding velocity	0.6m/s	

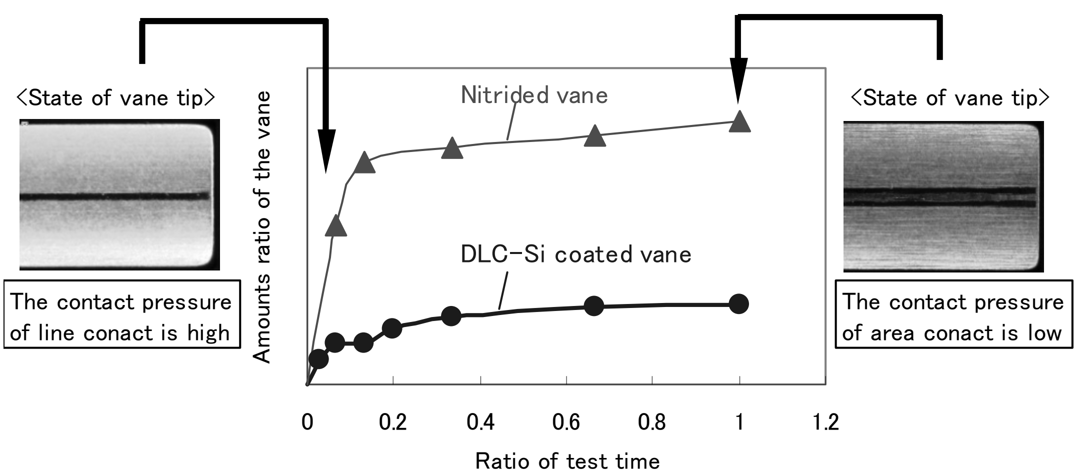

Fig. 17 Wear ratio of the vane in wear tests

Figure 18 shows the relationship of the contact pressure ratio between the vane tip and the periphery of the rolling piston, and the velocity ratio of the vane wear progression. The velocity of the wear progression is defined by the amount of wear with the equivalent time.

From Figure 18, it is clear that in both the nitrided vane and the DLC-Si coated vane, there is contact pressure where the velocity of vane wear, increases sharply, and this contact pressures varies as shown by the material of the vanes. Contact pressure where the progression velocity of the vane wear increases sharply is defined as contact pressure of wear-out limit. The contact pressure of the wear-out limit of DLC-Si coated vane is about two times higher than that of the nitrided vane under the sliding conditions of CO_2 refrigerant.

In the case of using the nitrided vane with CO_2 refrigerant, the contact pressure wear-out limit is lower than the maximum contact pressure in practical use. However in the case of using the DLC-Si coated vane with CO_2 refrigerant, the contact pressure of the wear-out limit is higher than the maximum contact pressure in practical use. Therefore we are able to achieve a significant level we call "WEAR-LESS" durability with all the conditions of CO_2 refrigerant by coating DLC-Si to the vane.

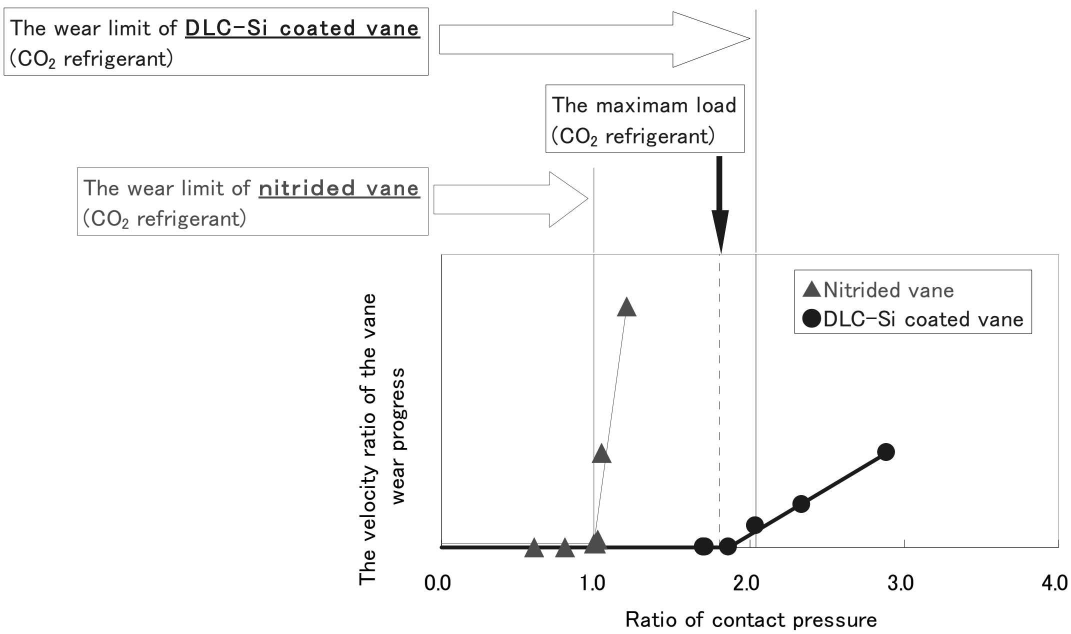

Fig. 18 The relationship between the contact pressure ratio and wear velocity ratio of the vane

5. CONCLUSION

We were able to achieve a significant level of durability we call "WEAR-LESS", by coating DLC-Si to the vane, and we have developed a new CO_2 compressor with a single rotary mechanism. In applying DLC-Si for practical use of the vane, we optimized the silicon content in the DLC-Si film and secured the adhesion strength of the film. By using the technology of coating DLC-Si to the vane, we were able to apply it to use in other products with harsh sliding portions. We believe this application will contribute to the development of the new products.

REFERENCE

[1] Hideaki Maeyama, Tetsuhide Yokoyama, Hideto Nakao, 2006, Development of the Compressor for CO_2 heat pump with the single rotary mechanism, Proceedings of the 2006 International Compressor Engineering Conference at Purdue: C056

[2] Hideto Nakao, Naotaka Hattori, 2007, Wear-Reducing Technologies for Rotary Compressors Using CO_2 refrigerant, Proceedings of the 2007 Mitsubishi Electric ADVANCE December 2007: p.13-16.

[3] Hideaki Maeyama, Shinichi Takahashi, 2007, Rotary Compressor for a CO_2 Heat Pump water Heater, Proceedings of the 2007 Mitsubishi Electric ADVANCE December 2007: p.9-12.