ADVANCED DRY GAS SEAL BY THE DYNAMIC ION BEAM MIXING TECHNIQUE

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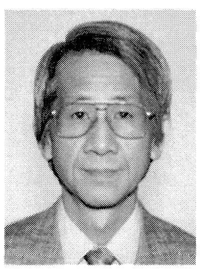

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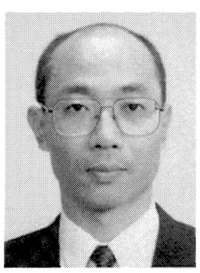

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ABSTRACT

Ductile materials have been used for dry gas seal mating rings to replace conventional sintered materials that have experienced occasional brittle fracture. The ductile materials require a coating to make them suitable for dry gas seal designs.

This paper describes the dynamic ion beam mixing (DM) technique as an improvement in coating technology. Excellent tribological properties of thin titanium nitride (TiN) films formed by the dynamic ion beam mixing technique (DM/TiN) are demonstrated. Further, performance of a dry gas seal provided with a mating ring comprising a martensitic stainless steel substrate, having a DM/TiN coating formed thereon, is demonstrated, while making a comparison with the performance of a dry gas seal utilizing conventional materials. Considerations necessary for

designing the ductile mating ring, its durability under abnormal and severe conditions, testing of the DM coating, and results of field experience are also discussed, together with problems accompanying the use of ductile materials.

INTRODUCTION

In a dry gas seal under normal operating conditions, a stable gaseous film is formed between sealing surfaces, so that there is no contact between the sealing surfaces. However, during starting and stopping, sliding contact between solids occurs, therefore the materials used for the sealing surfaces must have a low friction coefficient and excellent wear resistance. Sintered materials having excellent tribological properties, such as tungsten carbide (WC) and silicon carbide (SiC), have been conventionally used for a mating ring in a dry gas seal. However, these sintered materials have poor mechanical properties (e.g., impact resistance and toughness) and are brittle, leading to fracturing when a stress exceeding a predetermined limit is applied (Mayeux and Feltman, 1996).

As a countermeasure, the use of ductile materials for mating rings, instead of conventional materials, has been proposed (Evenson, et al., 1995). However, it is difficult to obtain a ductile material having tribological properties equivalent to those of sintered materials that is capable of withstanding severe dry friction. On the other hand, the ductile material substrate has a low thermal conductivity and a low modulus of elasticity as compared with the sintered material, and also has a large coefficient of thermal expansion. Thus, the ductile material substrate dry gas seal has low responsivity to a rapid change in operating conditions (Sedy, 1979 and 1980). Therefore, the use of ductile materials for mating rings has been limited.

The dynamic ion beam mixing (DM) technique is a surface-hardening technique that has been recently developed (Satou and Fujimoto, 1983). Using the DM technique, a titanium nitride (TiN) film on the surface of a metal was developed that has an extremely high hardness. A Vickers hardness of from 3,200 to 3,800 was obtained (Nagasaka, et al., 1997). The DM/TiN film on a surface of martensitic stainless steel (AISI420) resulted in a friction coefficient as low as about 1/4 that of WC. The specific wear rate of the mated hard carbon was as low as about 1/20 that of WC.

The DM/TiN technique was initially applied to thrust bearings for down-hole pumps in geothermal power generation, with successful results (Nagasaka and Koizumi, 1997). In Spring 1995, the authors started to work on development of a dry gas seal utilizing the DM/TiN. Several dry gas seals having respective shaft diameters in a range of from three inches to eight inches, each of which is provided with the DM/TiN mating ring, were produced and tested to evaluate their responsivity and durability.

The advanced dry gas seal provided with the DM/TiN mating ring is scheduled to be applied to eight compressors in the first quarter of 1998. Four of them are currently in service.

TRADITIONAL PROBLEMS ON DRY GAS SEAL AND BACKGROUND OF DEVELOPMENT

Natural Gas Compressor Seal Failure

There was an accident at a turbomachinery shop in Japan in April 1994, in which a barrel-type compressor suddenly stopped, with a loud sound, during a mechanical running test. A tandem seal on the drive end side was seriously damaged. When the seal was investigated, it was found that broken pieces of WC, resulting from fracturing of a mating ring in a backup seal, were nipped between the rotary member and the stationary member. Also, part of the shaft sleeve had been melted by heat generated from friction occurring between the seal's shaft sleeve and the rotating shaft. The interior of the seal was severely damaged and deformed from its original shape. It was extremely difficult to determine a cause of the above-mentioned accident. The most conceivable cause of this accident was the absence of driving keys for the spacer sleeve during assembly of the seal, but this could not be confirmed. Fortunately, the rotor and casing of the compressor could be reused after partial repair.

Hydrogen Recycle Compressor Seal Failure

In March 1994, there was an accident in a refinery in Japan, in which the intermediate pressure of a triple seal suddenly increased in a high pressure barrel-type compressor during operation. The compressor was stopped and inspected. Oil mist and dust had adhered to the entire surface of the mating ring on the first stage of the seal. In addition to numerous radial heat checks, a linear through crack having a flat surface was formed at one site of the mating ring in its normal direction. The crack opening had a width of about 1 mm and the outer circumferential surface of the mating ring was in contact with the inner circumferential surface of the sleeve shroud. Damage to the seal occurred mainly because the buffer gas was contaminated with oil mist and dust. This dust accumulated in the hydrodynamic grooves in the mating ring, so that the hydrodynamic effect became insufficient to create a gas film. Consequently, surface contact, heat checks, and through cracking resulting from the heat checks successively occurred.

Failure Investigation and Root Cause Analysis

When fracturing of the mating rings of this kind occurs, in many cases it is observed that a characteristic linear through crack having a flat surface, as shown in Figure 1, is formed at one site of the mating ring in its normal direction. This clearly indicates that cracking of the mating ring occurred due to tangential tensile stress. When the mating ring, which is rotating at high speed, is brought into contact with a primary ring due to some environmental factors, the mating ring develops a very high temperature at its rubbing location (i.e., a hot spot). This causes a highly concentrated stress, which leads to the occurrence and propagation of cracking in a surface of the mating ring. When propagation of cracking exceeds a predetermined limit, a linear crack is generated in the mating ring in its normal direction, due to centrifugal stress in the mating ring (Bond, et al., 1997). A primary crack immediately causes some secondary cracks due to bending. When fragments of the mating ring, resulting from secondary cracking, escape from the sleeve shroud, a fatal accident occurs.

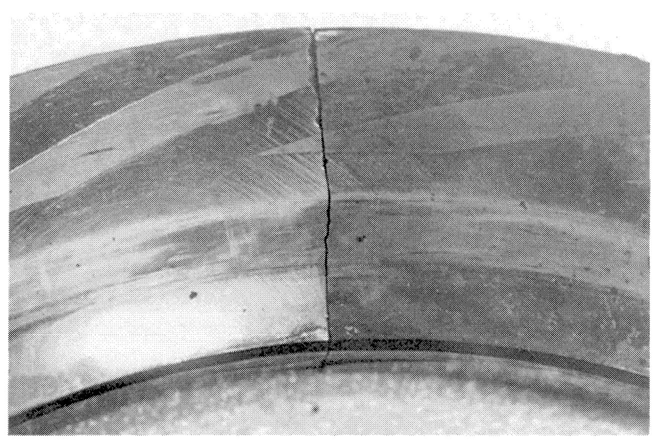

Figure 1. Typical First Crack of the WC Mating Ring.

Conventional Achievements for Improving Gas Seal Reliability

To prevent damage to the seal, it is most important to protect the working environment of the seal, such as its buffer gas system. However, it has been impossible to prevent the occurrence of accidents like ones mentioned above by improving the seal buffering, therefore a number of attempts have been made to improve the reliability of the seal. For example, in 1994, testing conditions for gas seal assemblies at the vendor's shop were changed so that the performance test is conducted at a speed of at least 1.225 times maximum continuous speed (MCS), and a spinning test is conducted at a speed of at least MCS × 1.1 × 1.225. Thus, all products are tested under the tangential tensile stress of at least 1.82 times the stress at MCS.

On the other hand, seal vendors have attempted to employ a mating ring made of a ductile material, so as to completely eliminate the possibility of brittle fracture of the mating ring. A seal that has unique and simple construction made of UNSS17400 (17-4PH) having a nitrated surface is applied to natural gas transportation equipment (Evenson, et al., 1995). Another gas seal utilizing a WC coating was tested for use in a gas turbine at a temperature of 450°C or more. This attempt seems to be ultimately desirable to achieve reliability in gas seals. However, this attempt has not been continuously developed or widely accepted. It is desired that the mating ring for the dry gas seal should have excellent tribological properties. However, such excellent tribological properties are incompatible with the high toughness that is also desired for reliability of the mating ring. Therefore, it is difficult to apply and widely use ductile materials for mating rings.

DRY GAS SEAL DESIGN

The properties necessary for materials for mating rings in dry gas seals are as follows:

• *Excellent wear resistance and a low coefficient of friction in dry contact rubbing*—These properties are necessary for withstanding frequent starting and stopping and low speed rotation, such as operation at turning gear speeds, during which the sealing surfaces do not lift off.

• *Thermal properties for controlling deformation*—Low coefficient of thermal expansion and high thermal conductivity are advantageous in minimizing thermal deformation.

• *High Young's modulus*—This is essential for controlling deformation.

• *High hardness*—High hardness is required to withstand contact rubbing. Further, with respect to coating materials for the mating ring, the following properties must be taken into consideration:

• *The adhesion force to the substrate material*

• *A coefficient of thermal expansion that matches that of the substrate*

• *The hardness, Young's modulus, coefficient of thermal expansion, and the thermal conductivity of the substrate material itself*

On the other hand, when the mating ring is made of sintered WC, the following points must be considered:

• *A method for driving the mating ring that minimizes the stress concentration*

• *An appropriate safety factor for conducting the over-speed test*

With respect to the mating rings, not only performance, but costs are also important for users. In a dry gas seal, the mating ring is a major component accounting for a substantial part of the entire cost. Therefore, the use of inexpensive materials for the mating ring would be attractive.

Dry gas seals with poor tribological properties are likely to have short life or may be damaged when the faces are in contact during starting and stopping, or in prolonged low speed operation. Another difficult operating condition for a poorly composed seal would be the secondary seal of a tandem seal—normally operated without any differential pressure, though the faces are normally separated. On the other hand, when the properties relating to the deformation of the mating ring, i.e., Young's modulus, coefficient of thermal expansion, and thermal conductivity are excellent, a dry gas seal can be easily designed. In a dry gas seal during operation, the factors that cause deformation of the mating ring are pressure, centrifugal force, and heat. Thus, deformation of the mating ring can be prevented by comprehensively analyzing these factors.

The DM/TiN has high hardness, high adhesion force, and excellent tribological properties, such as low coefficient of friction and dry wear resistance, which makes the material promising as a seal face. However, the inferior properties of a ductile material substrate needs more elaborate analysis and optimization for a dry gas seal design.

DYNAMIC ION BEAM MIXING METHOD AND TITANIUM NITRIDE FILM FORMATION

Conventional Surface Modification Methods

Conventional surface modification methods can be roughly classified into a method of modifying a surface layer of the metallic material itself, such as carburizing and nitriding, and a method of providing a coating on the surface of material, such as chemical vapor deposition (CVD), physical vapor deposition (PVD), or thermal spraying and wet plating. With respect to carburizing, nitriding and CVD, these surface-processing techniques have been conventionally employed as surface-hardening techniques for structural members. However, because these techniques utilize thermal diffusion or thermal reaction at a high treatment temperature, a heat gain of the processed base material is high, so problems arise such as deformation and degradation of the substrate. On the other hand, in an ion plating (IP) method (Matto, 1964), a typical film-forming technique of the PVD method, the treatment temperature is relatively low. However, in the IP method, ions have a kinetic energy as low as several hundred eV or less, so that no mixing layer is formed in a substrate/film interface, and therefore, the adhesion force of the formed film is insufficient. When the IP method is applied to the rotary seal ring, damage to the seal ring such as peeling-off of the film due to sliding, is likely to occur.

Surface Modification Techniques by Dynamic Ion Beam Mixing

The DM method is a surface modification technique that forms a thin compound film on a surface of a substrate by conducting ion implantation and vacuum deposition at the same time. The ion implantation is a technique of implanting ions into a surface layer of a substrate by accelerating the ions to high energy. This technique is essential to a doping process for producing semiconductor devices. When the ion implantation technique is applied to mechanical sliding members, however, there have been disadvantages where the processing rate is low and the thickness of the modified layer is too small (< 1 μm). In order to obviate such disadvantages, a hybrid type surface modification technique in which vacuum deposition and ion implantation are combined, that is the DM method, was proposed (Satou and Fujimoto, 1983).

Figure 2 is a schematic diagram of the film formation mechanism by the DM method. The small white dots indicate ions to be implanted, and large gray dots indicate evaporated atoms. Black dots indicate atoms constituting the substrate. The ions imparted with a kinetic energy enter the substrate. Some of the ions collide with the deposited atoms that have adhered to the substrate, thereby imparting a kinetic energy to the deposited atoms. The deposited atoms imparted with a kinetic energy enter the substrate. Thus, the atoms implanted in the form of ions, the deposited atoms, and the atoms constituting the substrate are mixed, thereby forming a mixing layer. When deposition and implantation further proceed, the ions to be implanted do not reach the substrate, and the chemically active ions combine with the evaporated atoms to be accumulated on the surface layer, thereby forming a compound film having new properties. In the DM method, the adhesion force of compound film is extremely high, due to formation of a mixing layer in the substrate/compound film interface. In the DM film-forming technique utilizing a kinetic energy of ions, synthesis of a substance can be conducted in a nonthermal equilibrium state so that the treatment temperature is low. Another characteristic feature of the DM method resides in that the respective feeding rates of the evaporated atoms and the ions to be implanted can be individually controlled without difficulty.

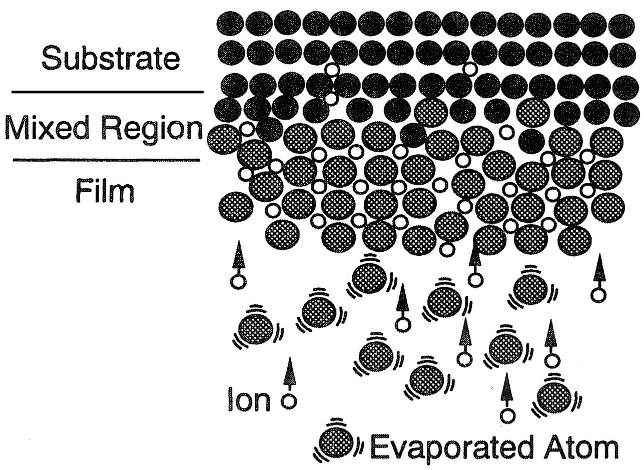

Figure 2. Schematic Diagram of Film F●rmation Mechanism by Dynamic Ion Beam Mixing Process.

The Development of TiN Film by Dynamic Ion Beam Mixing

Using the DM method, a technique for forming a hard film suitable for a sliding member was developed. For selecting a film material suitable for a sliding member, it is important to select a hard material having not only excellent wear resistance, low friction coefficient, and corrosion resistance, but also a coefficient of thermal expansion as close as possible to that of steel. Thus, titanium nitride (TiN) was selected as a film material. A schematic diagram of a DM apparatus is shown in Figure 3. Martensitic stainless steel (AISI420) was used as the substrate material on which a film is to be formed. In order to form a TiN film on a surface of the substrate, vacuum deposition of titanium and implantation of nitrogen ions were conducted at the same time. The irradiation conditions of nitrogen ion beams were: acceleration voltage: 10 kV; current density: 0.2 mA/cm^2; incidence angle: 45 degrees. The N/Ti ratio in the TiN film was changed to various ratios by changing the deposition rate of titanium, while maintaining the above-mentioned irradiation conditions of the nitrogen ion beam. In this experiment, the film-forming process was continued until the thickness of the TiN film became 3 μm. The Vickers hardness of the TiN film and the interplanar spacing of TiN (111) plane as a function of the N/Ti compositional ratio is shown in Figure 4 (Nagasaka, et al., 1993). It can be seen from this figure that the Vickers hardness of the film depends on the N/Ti compositional ratio. For the TiN stoichiometric ratio (the N/Ti compositional ratio of about 1.0), the Vickers hardness of the film is 1200 to 2000. The hardness of the film increases with a decrease in N/Ti ratio. In the case of the N/Ti ratio of about 0.8, a film having an extremely high Vickers hardness (3200 to 3800) was obtained. Within the range of the N/Ti ratio between 0.6 and 0.8, the hardness of the film decreases with a decrease in the N/Ti ratio. In the case of N/Ti ratio of 0.8 or above, a film composed of a single δ-TiN phase having a high orientation in the (111) plane was obtained, and the hardness of the TiN film depends on the interplanar spacings of the (111) planes. It is thought that the lattice strain of the TiN (111) plane is caused by shifting the N/Ti ratio from the TiN stoichiometric ratio, and the lattice strain has an influence on the hardness of the TiN film. At the N/Ti ratio of about 0.6, a film composed of mixed crystals of a preferred ϵ-Ti2N phase and δ-TiN phase was obtained. For N/Ti ratio of about 0.5, a film composed of α-Ti phase was obtained.

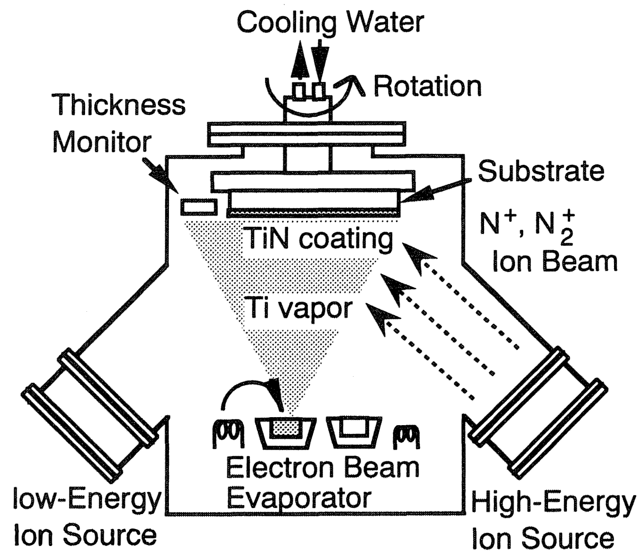

Figure 3. Schematic Diagram of Dynamic Ion Mixing Process.

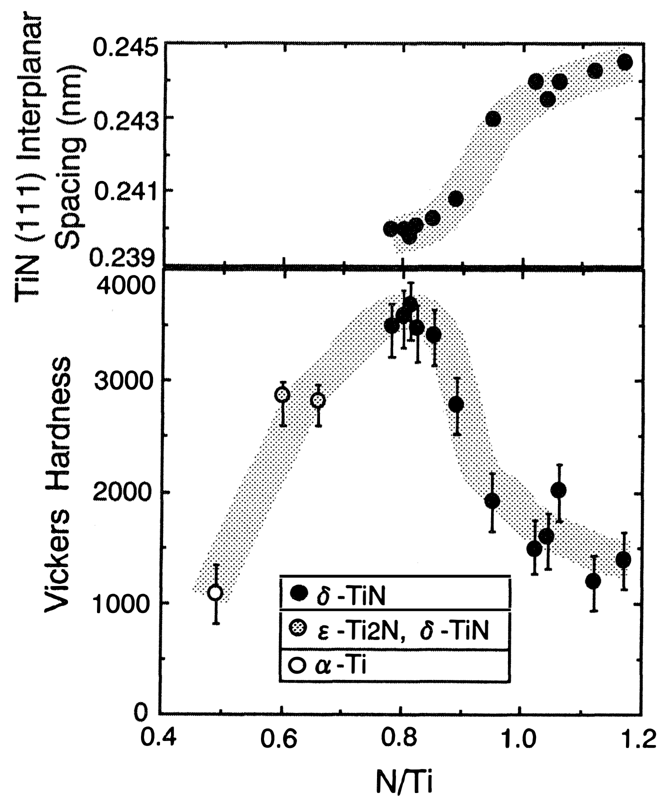

Figure 4. Relationship Between Compositional Ratio N/Ti and Vickers Hardness, TiN (111) Interplanar Spacing.

The hardness and adhesion force of the TiN film obtained by the DM method (DM/TiN) are indicated in Table 1, together with those of the TiN film obtained by the ion plating (IP) method (IP/TiN). The IP/TiN film was produced under conditions where the substrate bias voltage was 400 V and the treatment temperature was 400°C to 500°C. The adhesion force was evaluated by a scratch test (Benjamin and Weaver, 1959) in which the critical load when the film is peeled off the substrate is determined. With respect to the DM/TiN film, both the hardness and the adhesion force were superior to those of a conventional IP/TiN film.

Table 1. Vickers Hardness and Adhesion Force of Titanium Nitride Film.

Deposition Method	Vickers Hardness	Adhesion Force (GPa)
Dynamic Ion Mixing	3500	2.84
Arc Ion Plating	2200	1.35

Tribological Properties of DM/TiN Film

As a material for the substrate of a rotating ring for a sliding test, AISI420 steel was used. A hard TiN film (N/Ti ratio: 0.8; Vickers hardness: 3,500; film thickness: 3 µm) was formed on the substrate by the DM method. The resultant rotating ring was subjected, in combination with hard carbon, to a sliding test to evaluate the sliding properties of the TiN film. Results are shown in Figure 5 (Nagasaka, et al., 1997). For comparison, the IP/TiN film (Vickers hardness: 2000; film thickness: 3 µm) was subjected to the same sliding test, and the results of this sliding test are also shown in Figure 5. The sliding test was conducted using a disk-on-disk testing machine at room temperature in air. The testing conditions were: surface pressure: 1.0 MPa (145 psig), sliding speed: 2.4 m/s; and sliding distance: 5,000 m. With respect to the DM/TiN film, the friction coefficient lowered with an increase in the sliding distance, and became 0.06 when the sliding distance exceeded 1,000 m. Thereafter, the friction coefficient of the film was stable at 0.06 and the film exhibited good sliding properties, until the sliding distance reached 5,000 m. On the other hand, with respect to the IP/TiN film, the friction coefficient was stable until the sliding distance reached around 3,200 m. After the sliding distance exceeded 3,200 m, the friction coefficient drastically changed. Figure 6 shows damage conditions of the sliding surfaces after the frictional wear testing with respect to each of the DM/TiN film and the IP/TiN film. Damage conditions of the sliding surfaces were observed with an optical microscope and measured with a contact type surface roughness tester. With respect to the DM/TiN film, there were no traces of wearing damage on the sliding surface, and the hard carbon constituting the other sliding material suffered extremely slight damage (Figure 6(a)). In contrast, with respect to the IP/TiN film, it was obvious that the film suffered wearing damage, and the hard carbon constituting the other sliding material suffered considerable damage at the maximum depth of 3 µm (Figure 6(b)). As is apparent from these results, the DM/TiN film has excellent sliding properties that are far superior to those of the IP/TiN film. This is because the DM/TiN film is superior to the IP/TiN film with respect to both hardness and adhesion force to the substrate.

Frictional wear testing was conducted with respect to hard materials other than the hard TiN film, i.e., a WC and chrome carbide spray coating. Results are shown in Figure 7. As shown in Figure 7, with respect to the hard TiN film by the DM method, the friction coefficient is low and the specific wear rate of the hard carbon constituting the other sliding material is also low, as compared with the conventional WC, and the sliding properties of the DM/TiN film are satisfactory. From these results, it was confirmed that the DM/TiN film exhibits satisfactory sliding properties, even under severe sliding conditions in a dry environment.

PROTOTYPE DEVELOPMENT

In this study, a DM/TiN dry gas seal was designed by utilizing tapered bidirectional hydrodynamic grooves shown in Figure 8. This configuration was already established and is widely used in a variety of applications, because it is capable of coping with

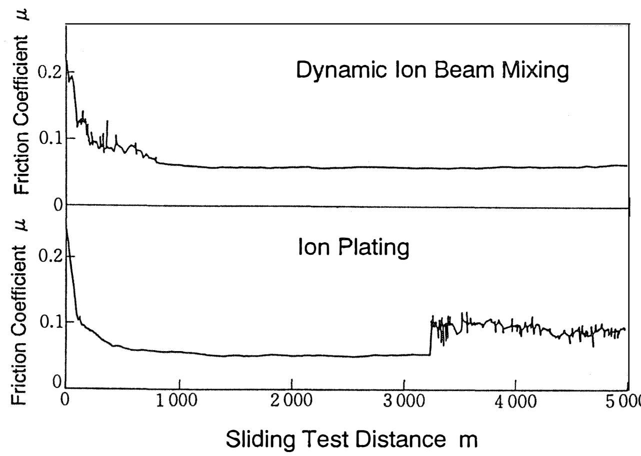

Figure 5. Relationship between Friction Coefficient and Sliding Test Distance.

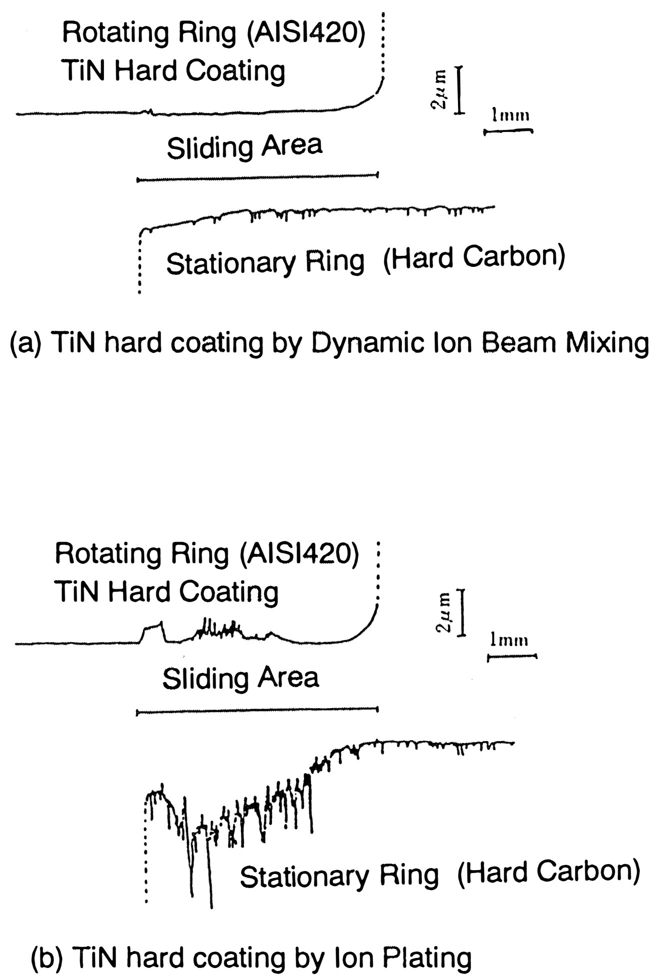

Figure 6. Cross Sectional Profile of Damaged Tracts After Dry Sliding Test.

accidental reverse rotation of the equipment. The performance of the design is found to be equivalent to those of spiral groove dry gas seals (Ito, et al., 1992). The first DM/TiN dry gas seal was designed based on a conventional dry gas seal utilizing silicon carbide (SiC) mating rings. The dry gas seal was produced on a trial basis and tested. The design of the mating ring was optimized by repeatedly feeding back the results of the testing to the design.

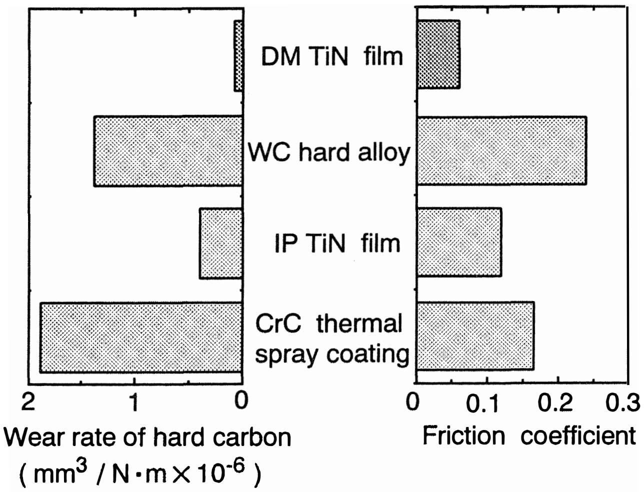

Figure 7. Wear and Friction Properties for Combinations of Various Hard Materials Versus Hard Carbon.

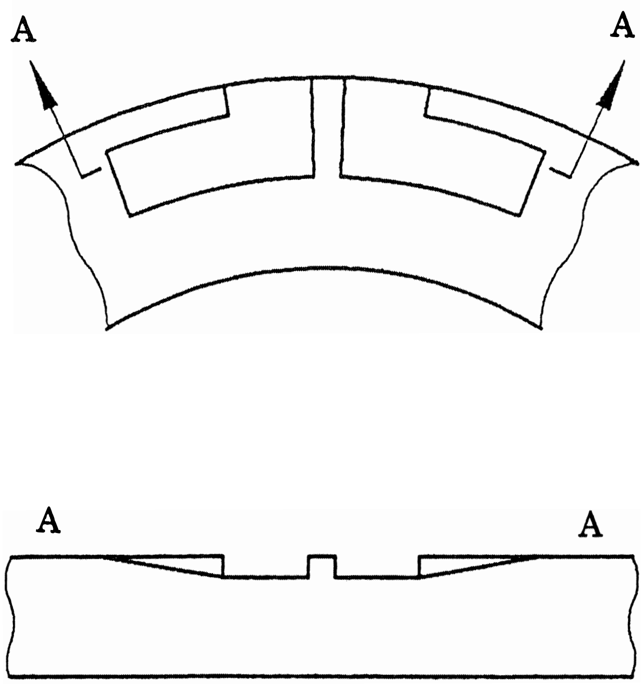

Figure 8. Profile of the Bidirectional Tapered Step on the Mating Ring.

A prototype rotating mating ring for a dry gas seal having a shaft diameter of three inches was first developed. As a base material for a DM/TiN mating ring, type 420 martensitic stainless steel (420SS) having a coefficient of thermal expansion close to that of TiN was selected. When using a composite material for the mating ring, it is important to approximate the coefficient of thermal expansion of the substrate material to the coating material, from the viewpoint of minimizing thermal deformation. Type 420SS is suitable as a mating ring material for a dry gas seal because it is hardenable by heat treatment. Physical properties of some materials are listed in Table 2. The type 420SS blank ring is quenched and tempered, so that its hardness is increased. Subsequently, the ring is machined, the seal face of the ring is ground and lapped, then bidirectional tapered hydrodynamic grooves are formed. Thus, the type 420SS mating ring is almost finished. Then, TiN is coated on the entire seal face, including groove bottoms, by the DM method, to form a TiN film having a uniform thickness of 3 µm. With this film thickness, no finishing process after coating is necessary. The stationary seal ring is made of carbon graphite. For comparison with the 420SS-DM/TiN, a mating ring made of SiC and having grooves identical to those of the DM/TiN coated mating ring was produced and tested.

Table 2. Material Properties.

Material	Tungsten Carbide	Silicon Carbide	TiN by Ion Plating	TiN by Dynamic Ion Beam Mixing	Type 420 SS
Composition (wt%)	WC + 6.5%Co	SiC≧97%	Titanium Nitride		Cr:13% C:0.3% Fe:bal
Apparent Density	14840 kg/m³	3100 kg/m³	5440 kg/m³		7800 kg/m³
Vickers Hardness	1500	2400	2000 ~2200	3000 ~3500	260
Young's Modulus	572 GPa	353 GPa	250 GPa		200 GPa
Thermal Conductivity	109 W/m·K	130 W/m·K	29 W/m·K		25 W/m·K
Thermal Expansion Coef. (1/K)	4.7×10^{-6}	3.5×10^{-6}	9.3×10^{-6}		11.0×10^{-6}
Adhesion Force ※	—	—	1.4 GPa	2.8 GPa	—

※ : Measurement result of scratch tester
Film thickness : 3µm
Substrate material : Type 420 SS

Figure 9 is a photograph showing the test rig. Tandem dry gas seals are mounted on both sides of a driving motor. When these seals are identical to each other, thrusts applied to the main shaft of the test rig by the sealing pressures of both seals are balanced, so that the rig is capable of conducting a test up to high sealing pressure. Therefore, two identical tandem dry gas seals are tested at one time. Figure 10 shows a detail of one shaft end of the rig in which the tandem seal is mounted. Clean nitrogen gas is supplied from bottles through a pressure regulating valve to the primary seal. In this line, a mass flowmeter is provided for measuring the leakage rate from the primary seal. The secondary seal is operated under atmospheric pressure, and the amount of nitrogen gas released from the secondary seal chamber to the atmosphere was also measured by a mass flowmeter. Figure 11 shows the respective leakage characteristics of the conventional SiC dry gas seal and the 420SS-DM/TiN dry gas seal before and after optimization. The 420SS-DM/TiN seal before optimization exhibits high leakage rate probably due to large deformation of the mating ring. In contrast, the leakage rate of the modified 420SS-DM/TiN seal is substantially lower and equal to that of the SiC dry gas seal. Figure 12 shows the deflected seal faces before and after optimization. Before optimization, the seal face of the mating ring shows convex deformation due to heat generated in the sealing surface. After optimization in which the cross section of the mating ring was modified, the seal face is made substantially flat by utilizing centrifugal effect. Thus, in the design with 420SS-DM/TiN, the factors that cause deformation are eliminated. In general, dry gas seals are used under a wide range of conditions. Naturally, deformation of the mating ring is unlikely to occur when the speed and pressure are low, because the centrifugal effect, the thermal effect, and the twisting by pressure are minimal. Optimization of design is attempted to ensure that the mating ring can be satisfactorily operated under heavy duty conditions. Therefore, the 420SS-DM/TiN dry gas seal can be used under a wide range of conditions.

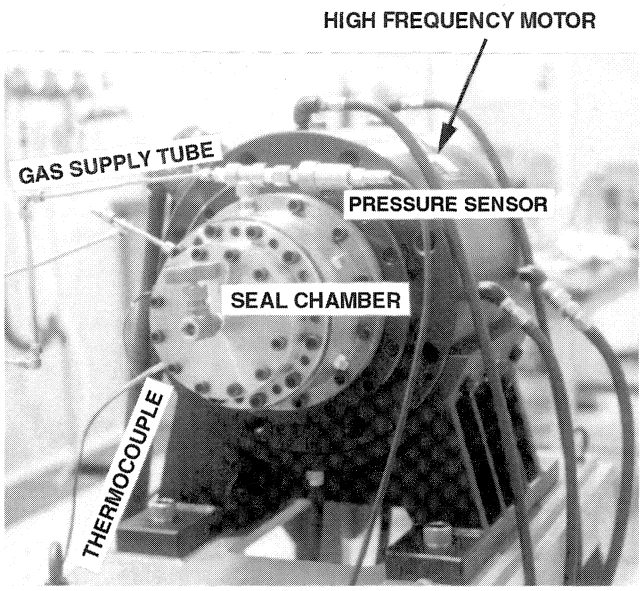

Figure 9. Appearance of the Test Rig.

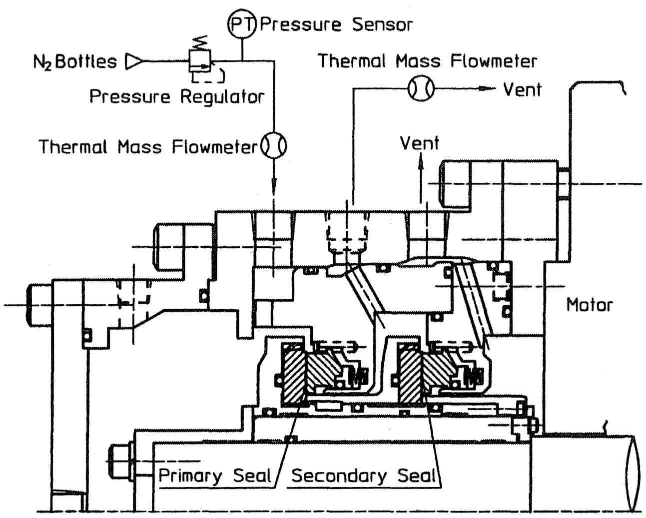

Figure 10. Test Schematic of Three Inch Gas Seal.

Next, using the above-mentioned seal, a low speed test was conducted, simulating the turning operation of turbine driven compressors. During the turning operation, gas seals may be rotated at such low speed that no lift off of the seal faces occurs. In such a case, the dry gas seal is operated with the sealing surfaces in contact with each other for a prolonged period of time. As a mode of testing, high speed dynamic tests are conducted under the same testing conditions before and after the low speed rotation. The conditions of the seal faces were observed before and after the entire test. Also, a comparison was made between the respective leakage rate in the high speed dynamic tests before and after the low speed rotation. In the low speed turning test, the seal was rotated at 18 rpm for 15 hours. The other test conditions are shown in Figure 13. Figure 14 shows a relationship between the pressure and leakage rate in the high speed dynamic tests before and after the low speed rotation. No change was observed with respect to the

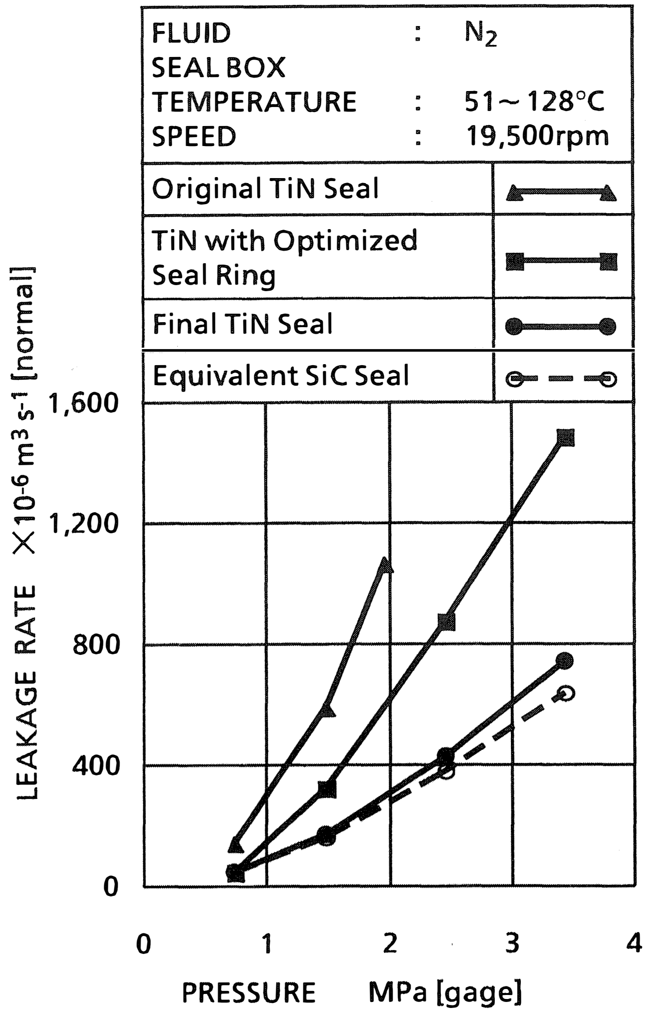

Figure 11. Leakage Optimization of Three Inch Gas Seal.

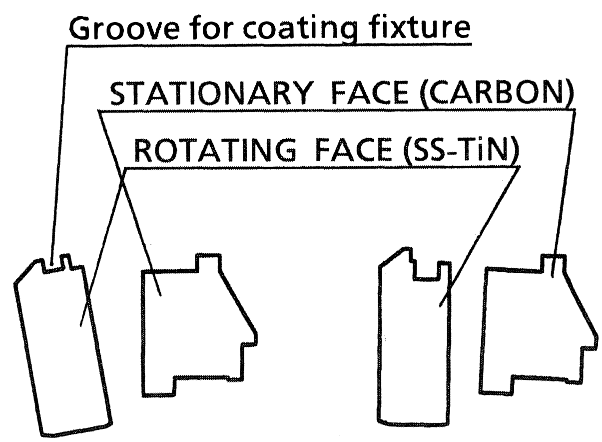

Figure 12. Deformation of Seal Faces (1.47MPa (gauge), 19,500 rpm).

leakage characteristics of the seal after the low speed rotation. When the seal was disassembled, the condition of the seal faces was satisfactory. Figure 15 shows the surface profiles of the seal faces before and after the test. In spite of sliding contact at low speed for 15 hours, the wear rate of the carbon graphite was low, and substantially no change was observed with respect to the TiN surface of the mating ring.

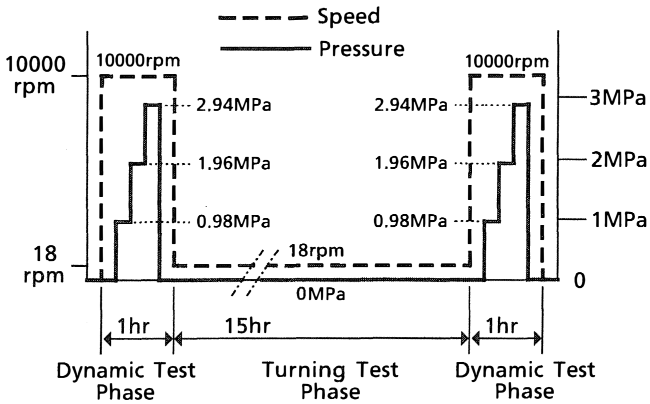

Figure 13. Turning Test Procedure.

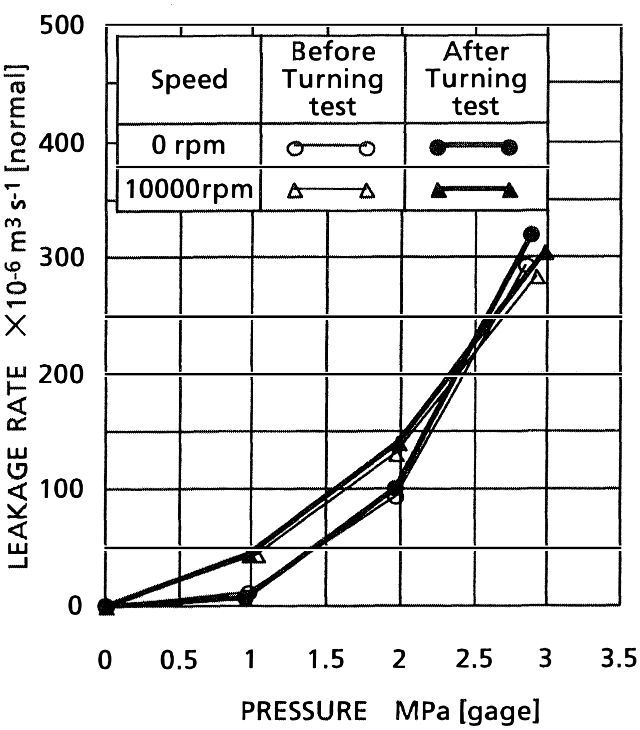

Figure 14. Leakage Rate Versus Pressure (Before and After Turning Test).

HIGH PRESSURE TYPE DEVELOPMENT

A high pressure type of tandem dry gas seal, having a shaft diameter of seven inches, was prepared for testing at a pressure of 12 MPa (1740 psig) at a rotation speed of 11,493 rpm. The average diameter peripheral speed of sealing surface was 133 m/s. Figure 16 shows a cross section of the seal. As in the case of the three inch seal, the rotating mating ring is made of 420SS-DM/TiN and the stationary seal ring is made of carbon graphite. With respect to the construction, stationary components are shaped suitably for withstanding high pressure in consideration of shrinkage under pressure. In this tandem seal, the primary seal bears a pressure of 12 MPa (1740 psig), and the secondary seal is normally operated under atmospheric pressure as an emergency seal. Using the same test rig as was used in the three inch seal test, a full specification test, a severity test using gas contaminated with oil or powder, and a high pressure shutdown test in which the seal was suddenly stopped from full speed operation were conducted to evaluate the reliability and durability of the seal. The test items for the seven inch tandem seal are listed in Table 3. First, in the full specification

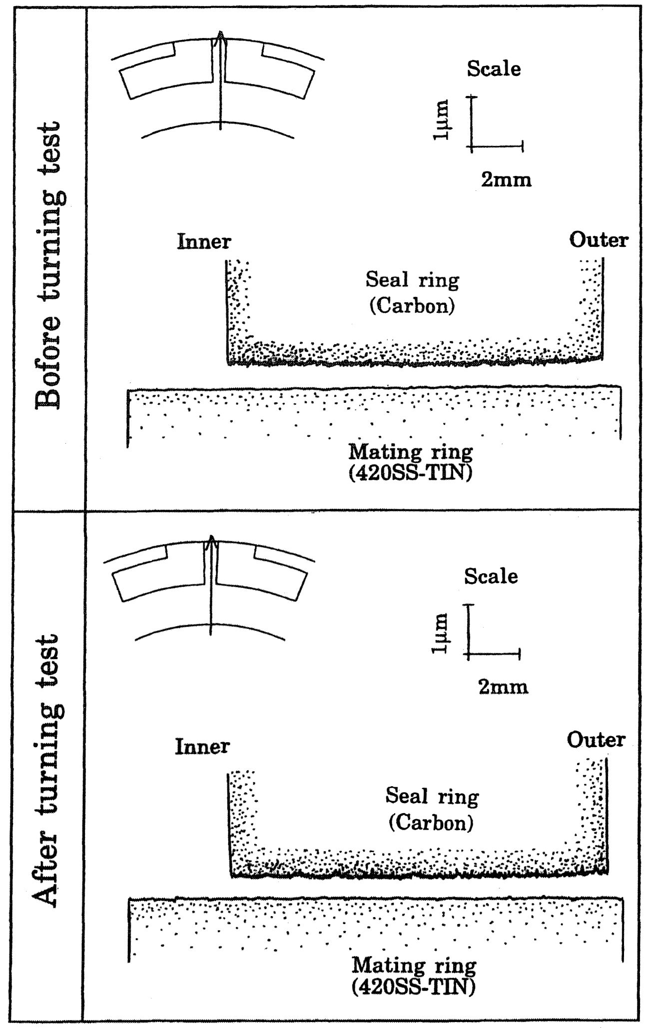

Figure 15. Seal Face Profiles Before and After Turning Test.

test, the gas temperature in the primary seal chamber increased to 139°C due to windage, and the leakage rate from the primary seal was as low as 0.0055 m^3s^{-1} [normal] (12 scfm).

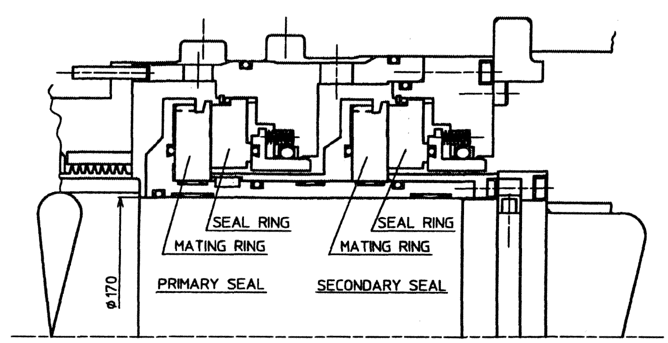

Figure 16. High Pressure Seven Inch Gas Seal.

Next, a severity test was conducted using gas that was contaminated with oil or powder, which represented a malfunction of a buffer gas supply unit and entry of bearing lubricating oil into the seal. This foreign material is put into the seal chamber before pressurization, formed into mist by rotation, and attaches to all the internal surfaces. When the gas contaminated with powder was used in the test, even though some powder passed through sealing

Test Item	Condition	Objective
Full Spec. Test	Helium 12MPa, 11493rpm 85 minutes	To establish baseline performance
Test with Powder & Gas	Helium + Powder (※1) 5MPa, 11493rpm 71 minutes Powder Location : Primary seal box or secondary seal box	To simulate buffer gas supply upset
Test with Oil & Gas	He + Turbine Oil VG32 6MPa, 11493rpm 90 minutes Oil Location : Primary seal box or secondary vent	To simulate buffer gas supply upset or flood of bearing oil
High Pressure Shutdown Test	Helium 10MPa, 11493rpm 101 minutes Deceleration : 150rpm/sec	To evaluate at the possible severest condition

※1 Japanese Industrial Standards Dust Grade 8
Particle size : 0~5µm : 39%, 5~10µm : 18%
over 10µm: 43%
Composition : SiO_2 : 34~40%, Al_2O_3 : 26~32%
Fe_2O_3 : 17~23%

Table 3. Seven Inch Gas Seal Test Item.

surfaces and reached the downstream side, there was no damage to the mating ring. The surface roughness of the carbon seal face changed from 0.3 µm to about 0.4 µm. As shown in Table 3, 39 percent of the powder has a particle diameter of 5 µm or less; therefore, the powder can easily enter the gap between the sealing surfaces.

When the gas that was contaminated with oil was used in the test, an oil film containing worn carbon powder was formed on the sealing surfaces in the primary seal. A small amount of oil drops with worn carbon powder introduced from the atmospheric side by centrifugal force were adhered to the sealing surfaces of the secondary seal. As in the case of the test with powder, there was virtually no damage to the mating ring. With respect to the face of carbon graphite, the surface roughness was as low as about 0.4 µm, and a few traces of wearing damage at a depth of about 1 µm were observed.

The high pressure shutdown test was finally conducted to examine the most conceivable severest thermal responsivity in actual compressors. The seal is operated at full rotational speed of 11,493 rpm under a pressure of 10 MPa (1450 psig) on the primary seal. Then, the rotation speed is decreased by 150 rpm/sec so that the seal is stopped in about 77 seconds. In this case, the heat generation in a gas film between the sealing surfaces and the heat generation by windage rapidly change. When this test was conducted with the first prototype design, contact between sealing surfaces occurred during stopping. However, the improved seal with two modifications described below was safely stopped without contact between the sealing surfaces from the operation at 10 MPa (1450 psig), 11,493 rpm, and 81°C.

The first modification reduced the deformation of the mating ring by changing the position of contact between the back surface of the mating ring and the retaining sleeve. Before the change, the deflected sleeve under pressure pressed the mating ring at a radius outside the centroid of the mating ring cross section. This caused concave deformation of the mating ring. The deformation and interaction of the mating ring and the sleeve, before and after the change, has been confirmed by finite element method analysis.

The dynamic friction of the secondary packing under high pressure was reduced by changing the packing from an O-ring to a spring energized PTFE seal. It had been confirmed that even under a pressure of 10 MPa (1450 psig), no problem arose when the seal was suddenly stopped from the low speed region; therefore, transient thermal responsivity had been noted. However, in a test where contact between sealing surfaces occurred during stopping from high speed rotation, there were no precursory phenomena, such as an increase in torque, until contact. It was suspected that the secondary O-ring had excess dynamic friction. Superiority of the spring energized PTFE seal was confirmed by actual measurement of dynamic friction under various pressure conditions using custom designed tooling. Thus, the spring energized PTFE seal was incorporated in the seal for the test.

By conducting the above-mentioned severity tests, counter measures for possible damage to mating rings in heavy duty conditions were examined and demonstrated on the test rig.

FIELD EXPERIENCE OF THE FIRST PROTOTYPE

In July 1996, the first prototype was mounted on a natural gas fuel booster compressor, shown in Figure 17, in a gas turbine power generation plant in Japan. This compressor is operated at 22,645 rpm by a 720 kW induction motor through a gearbox, under rapid and daily starting and stopping conditions, which are severe for dry gas seals.

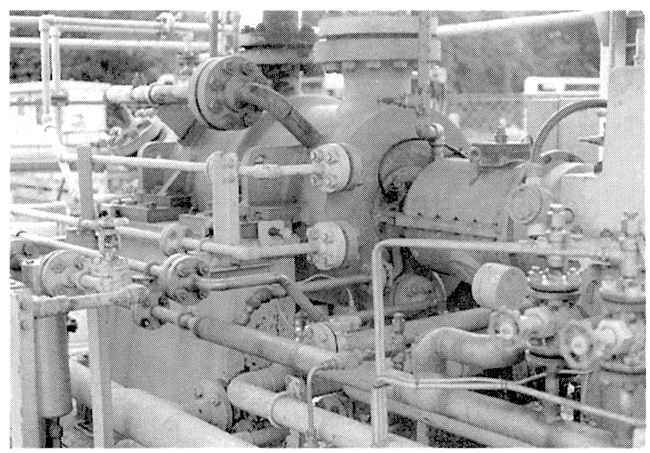

Figure 17. Natural Gas Fuel Compressor Installed First Prototype Seal.

In August 1997, with respect to the above-mentioned prototype seal, oil entry was observed for the first time in the secondary vent lines on both sides. In December 1997, oil entry was found in a primary vent line on the drive end side, and the seal was disassembled for inspection. Until that time, the seal had experienced 153 starts and a total operation time of 1,023 hours. The gas leak in the primary seal was negligible until the seal was stopped.

The investigation revealed that the separation buffer labyrinths on the drive end side and the free end side were damaged by contact with the rotor, and a large amount of lubricating oil had leaked to the gas seal side. On both the drive end side and the free end side, it was observed that oil contamination proceeded through the secondary seal to the primary seal, and oil and carbon powders had adhered to all sliding surfaces. In the secondary seal on the drive end side, the entire sliding area of the surface of the mating ring was worn at a depth of about 25 μm, and no coating or grooves were left. On the other hand, the surface of the mating carbon seal ring was worn at a depth of 0.5 mm. With respect to the other sliding surfaces, although there were traces of wearing damage in the form of concentric circles at a depth of several micrometers on the radially inner side, these sliding surfaces were still usable.

This compressor was tripped by excess vibration due to the gearbox, in February 1997. It was considered that the damage to the separation buffer labyrinths had occurred at that time, and therefore, oil had entered the gas seal side. Heat generation on the sliding surfaces is promoted by oil contamination, leading to the above-mentioned contact between sealing surfaces and damage to those sealing surfaces. However, in spite of the above-mentioned poor conditions, this compressor was able to be operated for a prolonged period of time without any cracking of the mating rings or process gas leakage to the atmosphere or a sharp increase in the amount of leakage. This clearly indicates excellent durability of this gas seal.

CONCLUSION

Ductile materials have been seen as possible candidates for use in mating rings in dry gas seals since their development. The advent of new surface modification techniques marked a new era for development of such attempts. In high speed turbomachinery, needless to say, problems during operation must be avoided. When problems arise, the provision of a failsafe function is of great importance in minimizing damage. From this standpoint, a dry gas seal utilizing the conventional mating ring made of sintered materials is unsatisfactory and the achievements reported in this article suggest one way in which dry gas seals may be improved.

Techniques of designing and analyzing dry gas seals have been improved through experience and research. The use of ductile materials for mating rings can be expanded to cover all application fields without great difficulty. Recent material processing techniques including surface modification techniques will provide new materials superior to the DM/TiN discussed in this article.

Not only the effort of manufacturers and researchers, but also the understanding and cooperation of users will be appreciated, in order to achieve a common goal of improving the reliability of dry gas seals.

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ACKNOWLEDGEMENT

The authors thank the respective companies to which they belong and the Osaka National Research Institute (ONRI), Ministry of International Trade and Industry of Japan, for permitting information to be presented in this report. The authors also thank Joe Sedy for giving them valuable advice on this report.