A Study of Ceramic Bearing for Vertical Pumps*

(Friction Coefficients of Submersible Bearings in Air and Water)

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Friction coefficients in air and water of various sleeve-type submersible bearings for vertical pumps were investigated with respect to a variety of bearing materials including SiC-sintered ceramics, WC-cemented carbides, self-fluxing alloys and conventional bearing materials such as rubber, resins, PTFE # and soft sintered alloys. The test equipment simulated the frictional conditions of actual vertical pump shafts, that is, the shaft of the testing apparatus precessed against the bearing. The results showed that when silicon carbide was used as a stationary bearing, lower friction coefficients could be obtained, regardless of the material used for the rotating sleeve. In slurries, the abrasive particles adversely affected the friction coefficients of conventional bearings, however, owing to superior hardness, ceramic bearings maintained low friction coefficients. In air, a combination of silicon carbide and tungsten carbide displayed a low friction coefficient. Also, the results confirmed that dry starting of vertical pumps is also possible when using this combination of materials.

Key Words: Hydraulic Machine, Friction Coefficient, Submersible Bearings, Ceramics, Vertical Pump, Diffuser Pump, Hardness, Slurry

1. Introduction

Rubber bearings, resins, copper-based sintered alloys, or carbon sleeve bearings are generally used as the intermediate shaft bearings of diffuser type vertical pumps. In cases where these bearings are lubricated by the pumped liquid itself, abrasion by the solid particles contained in the liquid frequently renders the pump unusable within a short period of time. Moreover, since the water level of the suction inlet prior to starting is generally at about the upper portion of the diffuser casing, the intermediate shaft bearing, which is located above the water level, is in air, i. e., in a dry state. Therefore, during the period between starting and the instant when the pumped water reaches the bearing, lasting from several seconds to several tens of seconds, the bearing undergoes dry rotation, and consequently, depending upon the material composing the bearing, even seizure may occur. The measure ordinarily adopted to deal with

this situation consists in enclosing the shaft and bearing in a shaft enclosing tube and passing clean lubricating water through this tube. However, this requires the installation of a lubricating water unit, complicating operation and maintenance of the pump. This suggests the desirability of developing a long-life bearing which would permit dry starting even without protective tubes and lubricating water units. Recently, in order to realize such a dry bearing, considerable research has been done on the application of ceramics to sliding parts.

As pointed out in a previous paper⁽¹⁾, the elimination of the shaft enclosing tube and lubricating water unit requires a combination of materials which possesses superior wear resistance properties and also a friction coefficient sufficiently low as to ensure that seizure does not occur during the period of dry rotation immediately following startup or during subsequent running under lubrication by pumped water.

Considerable research has already been conducted in connection with the friction coefficients of ceramic materials, however, most measurements have been performed using a pin-on-disk arrangement, with the pin being pressed against the rotating compo-

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nent from a fixed direction, as in the reports of Iwasa⁽²⁾ and Ishigaki⁽³⁾. However, the friction coefficients of ceramic materials appear to depend, to a considerable extent, upon the form of the frictional surfaces, and few reports have appeared concerning the friction coefficients in air or water of bearings in contact with precessing shafts such as those of vertical pumps.

Accordingly, the authors have performed measurements of friction coefficients in air and water of various bearing materials, with emphasis upon ceramics, using testing apparatus such that the shaft precesses in the same manner as that of an actual vertical pump. The results obtained will be briefly described below.

2. Nomenclature

- F : bearing load N
 m : mass of unbalance weight kg
 N : rotational speed min^{-1}
 r_1 : bearing radius mm
 r_2 : distance from center of shaft of testing apparatus to centroid of unbalance weight mm
 l_1 : distance from center of ball bearing of testing apparatus to center of tested bearing mm
 l_2 : distance from center of ball bearing of testing apparatus to centroid of unbalance weight
 T : torque meter reading Nm
 v : peripheral velocity of bearing
 $=10^{-3}r_1\omega/\text{s}$
 ω : angular velocity of sleeve
 $=2\pi N/60 \text{ rad/sec}$
 μ : bearing friction coefficient
 Al_2O_3 : alumina
 Cr_2O_3 : chromium oxide
 PTFE : polytetrafluoroethylene
 SFCA : self-fluxing cobalt base alloy
 SiC : silicon carbide
 SUS 316 : austenitic stainless steel
 WC : tungsten carbide
 ZrO_2 : zirconia ceramics

3. Experimental Apparatus and Procedures

The apparatus used for measurement of friction coefficients is shown in Fig. 1. The rotating shaft is supported by the antifriction bearing at the top and the tested bearing inside the tank, and is driven by a variable speed motor via the torque meter. The test bearing is composed of a stationary cylindrical bearing and a rotating sleeve, which can be surrounded by air, clean water or slurry as the experimentally condi-

tions may require. Also, an unbalance weight is attached to the shaft, so that during rotation the centrifugal force of the weight causes the shaft to precess against the test bearing and at the same time creates a load F on the test bearing in accordance with the following formula.

$$F = mr_2\omega^2 l_2 / l_1 \times 10^{-3} \quad (1)$$

Thus, the sliding condition of the test bearing closely simulated that of the bearing in an actual vertical pump. Also, the friction coefficient was calculated from the reading of the torque meter in accordance with the following relation.

$$\mu = \frac{T}{10^{-3}Fr_1} \quad (2)$$

The bearing specifications and conditions of the tests are indicated in Table 1. The tested materials, in addition to hard materials (principally fine ceramics), also included various soft materials which might be used in dry bearings. The austenitic stainless steel SUS 316 was used for the sleeve when soft bearing materials were tested.

The mechanical properties of the hard materials used in the tests are shown in Table 2, and the composition of the abrasive particles used in the slurry was

Table 1 Bearing specifications and test conditions

Item	Specification
Bearing Diameter	60 mm
Radial Load	20 ~ 1300 N
Speed	500 ~ 1300 min^{-1}
Peripheral Velocity	1.6 ~ 4.1 m/s
Diametral Clearance	0.134 ~ 0.196 mm
Max. Surface Roughness Height	3.2 μm
Slurry Temperature	20 ~ 40 $^{\circ}\text{C}$

Fig. 1 Testing apparatus

Table 2 Mechanical properties of tested bearing materials (reference values)

		SiC	WC	ZrO ₂	Al ₂ O ₃	Cr ₂ O ₃	SFCA
Vickers Hardness		2500 ~ 3000	1470	1400	1600	1200	600
Density	g/cm ³	3.1	14.7	6.1	3.9	4.7	9.0
Bending Strength	MPa	867	2000	1100	390	-	-
Young's Modulus	MPa	4.04×10^5	6×10^5	1.96×10^5	3.43×10^5	-	2.4×10^5
Thermal Expansion	1/K	3.9×10^{-6}	3.3×10^{-6}	8.3×10^{-6}	$7 \sim 8 \times 10^{-6}$	6.8×10^{-6}	12.6×10^{-6}
Thermal conductivity	KW/mK	0.08	0.08	0.003	0.029	-	0.015
K _{1C}	MPam ^{1/2}	5.6	12	8 ~ 10	5	-	-

Fig. 2 Friction coefficient in clean water ($v=1.6$ m/s)

Fig. 5 Friction coefficient in clean water ($v=4.1$ m/s)

Fig. 3 Friction coefficient in clean water ($v=2.2$ m/s)

Fig. 4 Friction coefficient in clean water ($v=2.8$ m/s)

the same as that indicated in our previous report⁽¹⁾.

4. Experimental Results and Analysis

4.1 Friction coefficients in clean water

The precession of the shaft in vertical pumps creates a strong local thrust against the edge of the bearing. Thus, load support by a liquid film is difficult, and the bearings are driven in a state of solid contact. Consequently, the conventional approach to the estimation of friction coefficients on the basis of classification into fluid lubrication or boundary lubrication, etc., according to the Sommerfeld number, is not applicable, and the friction coefficients depend to a great extent upon the sliding characteristics of the materials.

Figures 2 to 5 show the experimental results obtained by varying the bearing load and measuring the friction coefficients in clean water at various sliding velocities. The values of bearing loads and peripheral velocities investigated were chosen as representing the range of conditions encountered in actual practice when using vertical pumps. Combinations with silicon carbide as the stationary bearing displayed uniformly low friction coefficients, regardless of the material used for the sleeve, moreover, when the bearing load exceeded 100 N, the friction coefficients assumed an almost constant value, irrespective of the peripheral velocity. On the other hand,

when tungsten carbide was used as the stationary bearing, then for some sleeve materials, the load dependence of the friction coefficient was considerable, i. e., when the sleeve was composed of zirconia or SFCA, the friction coefficient rose sharply with increasing load. Furthermore, when the sleeve was composed of Cr_2O_3 , the friction coefficients also rose abruptly when the sliding velocity and load conditions became severe.

The dependence of friction coefficient upon bearing load for various fixed values of the peripheral velocity is shown in Fig. 6, while Fig. 7 shows the variation of friction coefficient with peripheral velocity for a fixed value of the bearing load. Although the data display some dispersion, the results shown here indicate that the friction coefficient is almost independent of peripheral velocity. Using a four-ball friction testing rig, Kin et al.⁽⁴⁾ have measured the friction coefficients of paired alumina surfaces in turbine oil, and found that the friction coefficient was almost unaffected by the sliding velocity; the results of the present study were similar in this respect.

Figure 8 shows the experimental results of measurements of friction coefficients of a silicon carbide-tungsten carbide combination along with those of various conventionally used soft bearing materials.

Fig. 6 Variation of friction coefficient with bearing load

Fig. 7 Variation of friction coefficient with peripheral velocity

Silicon carbide-tungsten carbide combinations displayed lower friction coefficients than conventional submersible bearing materials in clean water, and the results indicated that such combinations were quite adequate for use in the submersible bearings of pumps.

4.2 Friction coefficients in slurries

As was pointed out in our previous report⁽¹⁾, when the pumped water itself is used for lubrication, sand or other abrasive particles may exert a considerable effect upon the friction coefficient. Accordingly, in the present study, the friction coefficients of bearings in slurry were also investigated.

The experimental results of friction coefficient of various bearing materials in clean water and in a 3000 ppm slurry are shown in Fig. 9. A density of 3000 ppm corresponds to the turbidity of a river in flood. Not only PTFE and rubber but also the tungsten carbide-SFCA combination displayed markedly increased friction coefficients in slurry as compared with clean water, and the absolute values of the friction coefficients in slurry were also conspicuously high. In the case of PTFE or rubber, this is attributed to the entry of hard silica particles into the bearing surface, causing abrasive wear of the stainless steel sleeve which effectively increases the friction coefficient. Similarly, in the case of the tungsten carbide-SFCA combination, since the hardness of SFCA is lower than that of silica, the SFCA also undergoes abrasive wear, again resulting in increased friction coefficients.

On the other hand, in the case of silicon carbide-

Fig. 8 Comparison with bearings composed of soft materials

Fig. 9 Friction coefficients in slurry

tungsten carbide combinations, since both components are harder than silica, the latter presumably acts more as a lubricant than as an abrasive, which would explain why the friction coefficients of such combinations did not increase in slurries. Thus, the fact that silicon carbide-tungsten carbide combinations can maintain low friction coefficients even in slurries indicates that these materials could provide excellent sliding properties for submersible bearings.

4.3 Friction coefficients in air

Figures 10 and 11 show the experimental results obtained by maintaining a constant peripheral velocity and measuring the friction coefficients of hard materials in a dry condition with varying loads. The observed friction coefficients in a dry condition, i. e., in air, were more than ten times higher than the corresponding values measured in clean water.

Using the pin-on-disk method, Ishigaki et al.⁽³⁾ have investigated the effects of relative humidity upon the friction coefficients of ceramics, and obtained results indicating that the friction coefficients of these materials in water are of comparable magnitude or even higher than the corresponding values in air. This might be attributable to an increase in friction coefficients which is manifested in the pin-on-disk method because of changes in mechanical strength due to adsorbed water. However in the sliding motion between concentric cylinders under water observed in the present experiments, although solid contact between the surfaces does occur owing to intense local contact, some lubricating action does arise from the wedge effect of the water film, which presumably explains the great reduction of friction coefficients in water as compared with air.

Fig. 10 Friction coefficients in air ($v = 3.5$ m/s) Fig. 11 Friction coefficients in air ($v = 4.1$ m/s)

When silicon carbide was used for the stationary bearing component, low friction coefficients were observed irrespective of the material used for the sleeve, and the dispersion of the data was also comparatively small. When tungsten carbide was used for the stationary component, the friction coefficient tended to rise for large bearing loads, and as a whole the absolute values of the friction coefficients were also large for this bearing material. However, seizure such as occurs in the case of rubber bearings did not occur when any of these combinations were tested, demonstrating that the use of bearings composed of these hard materials would permit dry starting in vertical pumps.

Figure 12 shows the temporal changes in friction coefficients observed for varying bearing loads when the peripheral velocity was fixed at 2.8 m/s. The bearing loads considered were within the range of values anticipated for the dry operation of actual vertical pumps. The maximum running time considered was 5 minutes, which corresponds to a total sliding distance of 840m. As shown by Fig. 12(a), for a bearing load of 90N, when the bearing material was tungsten carbide, the friction coefficient con-

Fig. 12 Temporal changes of friction coefficients in air

tinued to display a high value of approximately 0.5 from the moment immediately after starting, but when the bearing material was silicon carbide, the friction coefficient remained stable at the comparatively low value of 0.3. On the other hand, as seen from Fig. 12(b), when the bearing load was fixed at 120 N, the friction coefficient of the silicon carbide-zirconia combination displayed a rise of about 0.55 after 3.5 minutes. When the fixed value of the bearing load was further increased to 180 N, then, as shown by Fig. 12(c), all the materials tested except for the silicon carbide-tungsten carbide combination continued to display a high friction coefficient of about 0.5 from the moment after starting, but even under this severe bearing load the silicon carbide-tungsten carbide combination maintained a low friction coefficient between about 0.3 and 0.4 up to 3.5 minutes after starting, demonstrating that within the range of conditions considered in the present experiments, this combination provides the best performance with respect to dry start.

Tsuya⁽⁵⁾ has shown that reduction in the friction coefficients of ceramics is effective in preventing damage and wear. Although the duration of dry operation of bearings for vertical pumps is only a few seconds per run, nevertheless, taking wear and accumulation of damage into account, the selection of material combinations with friction coefficients as low as possible is clearly desirable. In particular, since the silicon carbide-tungsten carbide combination can maintain low friction coefficients over a wide range of sliding conditions, the results described above demonstrate that this is in fact the most suitable combination of materials for dry pump operation among all those tested in the present experiments.

5. Conclusions

Using a testing apparatus with a precessing shaft, the friction coefficients of various types of bearing

materials were measured in water, slurries and air, and the following results were obtained.

(1) As regards combinations of hard materials, when silicon carbide was used as the bearing material, then the friction coefficient in water was almost constant, independent of the material used in the mated component.

(2) When tungsten carbide was used as a bearing material, the friction coefficient in clean water displayed a considerable dependence upon the material used in the mated component as well as the bearing load. In particular, when tungsten carbide was combined with zirconia of SFCA, the friction coefficients were comparatively high and their load dependence was pronounced.

(3) The friction coefficients of bearings composed of conventionally used soft materials such as rubber or PTFE measured in clear water differed greatly from those measured in slurries. This demonstrated that the conventional submersible bearings are greatly affected by the abrasive particles suspended in slurries. By contrast, the silicon carbide-tungsten carbide combination displayed low friction coefficients in high-density slurries as well as in clean water, indicating that this combination permits efficient operation almost unaffected by the presence of abrasive particles.

(4) The friction coefficients between pairs of hard materials in air were more than ten times greater than the corresponding values in clean water, but nevertheless no seizure of the kind occurring in rubber bearings was observed when these materials were tested, indicating that they could serve as bearings for vertical pumps under dry starting conditions.

(5) The silicon carbide-tungsten carbide combination maintained low friction coefficients over a wide range of dry sliding conditions, and within the scope of the present experiments, this combination

appeared to be optimal with respect to use in pumps subject to dry starting.

References

- (1) Wakigawa, A., Aiyoshizawa, S., Takagi, K., Konno, D., A Study of Ceramic Bearings for Vertical Pumps. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 53, No. 491 (1987), p. 2094.
 - (2) Iwasa, M., Tribological Properties of Silicon Nitride Ceramics. Jpn. Soc. of Lubr. Eng., (in Japanese), Vol. 31, No. 7 (1986), p. 449.
 - (3) Ishigaki, H., Friction of Ceramics. Jpn. Soc. of Lubr. Eng., (in Japanese), Vol. 30, No. 9 (1985), p. 627.
 - (4) Kim, S., Kato, K., Horikirikawa, L., Seizure and Wear in Alumina Ceramics. Jpn. Soc. of Lubr. Eng., (in Japanese) Vol. 31, No. 5 (1986), p. 329.
 - (5) Tsura, Y., Wear Control of Fineceramics. Jpn. Soc. of Lubr. Eng., (in Japanese), Vol. 28, No. 11 (1983), p. 815.
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