Ceramic Bearings for Special Environments

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ABSTRACT
Compared to steel, ceramic materials offer superior corrosion and heat resistance, higher dimensional stability, and lower density, which facilitates high speed. NSK’s silicon nitride bearings have been used with successful results in machine tool spindles for more than 10 years. Recently, NSK has developed ceramic bearings for special operating conditions including corrosive, vacuum, high-temperature, clean, non-lubricated and seizure-prone environments.

NSK’s ceramic bearings are made of silicon nitride, silicon carbide or partially stabilized zirconia, depending on the application. The superiority of these bearings was demonstrated in endurance tests in water, acid solutions, high-temperature vacuum conditions and an oil shut-off test, as well as on a hot-dip galvanizing line.

1. Introduction
Research on ceramic rolling bearings has been ongoing for more than 30 years.1,2) As shown in Table 1, ceramics are superior to steel in heat and corrosion resistance, and are lightweight and extremely hard as well. Consequently, ceramic rolling bearings can be used in environments where conventional steel bearings cannot. Accordingly, NSK has long been engaged in research and development of ceramics for rolling bearings. This paper describes the latest advances in ceramic materials for rolling bearings and evaluates the performance of ceramic bearings in various conditions and environments.

2. NSK Ceramics and Bearing Composition

2.1 NSK Ceramics
NSK has developed three types of ceramics: silicon nitride, silicon carbide and partially stabilized zirconia.

2.1.1 Silicon nitride
Silicon nitride bearings are used in high-speed applications like machine tools and aircraft engines, and in oil- and liquid-lubricated machinery operated under heavy load. As shown in Table 1, silicon nitride is superior to bearing steel (AISI 52100) in physical and mechanical properties such as density, strength and heat resistance. It is also satisfactory in terms of rolling fatigue life, making it an outstanding material for rolling bearings. Silicon nitride bearings have been used with successful results in machine tool spindles for more than 10 years.

2.1.2 Silicon carbide
In especially harsh conditions, such as environments where highly corrosive agents are present, even silicon nitride can be corroded. For these environments, NSK’s silicon carbide is the most suitable. NSK’s silicon carbide bearings have self-lubricating cages and are used in film and semiconductor cleaning systems.

2.1.3 Partially stabilized zirconia
Compared with the other two types of ceramic bearings,
NSK’s partially stabilized zirconia bearings have the longest rolling fatigue life in water and can be manufactured at the lowest cost. They are widely applied in the silicon wafer polishing process.

The corrosion resistance and cost of NSK’s three types of ceramics are compared in Table 2.

2.2 Composition of ceramic bearings

Ceramic bearings are either all-ceramic or hybrid (Fig. 1). Cages are made from either polyamide resin or self-lubricating material and lubrication is oil, grease or solid lubricant depending on the operating environment.

3. Rolling Performance of Ceramic Bearings

3.1 Corrosive environments

3.1.1 Endurance life in water

Fig. 2 is a Weibull plot of the results of life tests in water of silicon nitride and stainless steel 6206 deep groove ball bearings. The test load is 980N and rotating speed is 1000 rpm. Compared to stainless steel bearings, hybrid and all-ceramic bearings lasted three and 20 times longer, respectively. It is presumed that water readily adheres to silicon nitride and forms a better lubrication film, leading to extended bearing life.

Fig. 3 presents results of endurance life tests in water of all-stainless steel bearings and hybrid bearings made from various ceramics including aluminum oxide (AO), partially stabilized zirconia (PSZ) and silicon nitride (SN). The hybrid bearings with stainless steel rings and SN balls and stainless steel rings and PSZ balls demonstrated longer life than the all-stainless steel bearings and are therefore suitable for water environments. The hybrid bearings with stainless steel rings and AO balls had shorter life than the all-stainless steel bearings and are therefore not a feasible alternative.

Fig. 4 compares the life in water of all-ceramic bearings made from silicon nitride, silicon carbide and partially stabilized zirconia.
stabilized zirconia with a hybrid bearing with silicon nitride balls and an all-stainless steel bearing. The partially stabilized zirconia bearing demonstrated the longest life of all the bearings, including the silicon nitride and silicon carbide ones. It can therefore be concluded that all-ceramic bearings made from partially stabilized zirconia are most suitable for water environments.

### 3.1.2 Performance in corrosive agents

Generally silicon nitride has excellent corrosion resistance. However, corrosion resistance varies depending on the type and quantity of sintering additives, and certain corrosive agents decrease in hardness and flexural strength.

Fig. 5 shows the results of flat washer endurance life tests of silicon nitride under oil lubrication both before and after 100 hours of immersion in a 3 mol/dm³ hydrochloric acid solution at 90°C. Silicon nitride with CeO₂-MgO as the sintering additive demonstrated equal endurance life before and after immersion in the acid solution (Fig. 5a). On the other hand, the same type of ceramic with Y₂O₃-Al₂O₃ as the sintering additive demonstrated a significant decrease in endurance life as a result of immersion in the acid solution (Fig. 5b). The sintering additive, Y₂O₃-Al₂O₃, in the silicon nitride grain boundary was eroded by the acid, resulting in deterioration of the binding strength of the sintering additive.

Fig. 6 presents the results of an endurance life test under exposure to a 10% sulfuric acid aqueous solution. In this solution, the carbide-based ceramic bearing proved the most effective.

### 3.1.3 Performance on a galvanizing line

All-silicon nitride ball bearings with tantalum cages were tested in the steel plate transfer rolls on an actual galvanizing line. Establishing a new high for service life in this application, the bearings operated continuously for about a month while suppressing bearing vibration substantially and improving plating accuracy.

Table 3 summarizes the corrosion resistance of stainless steel bearings and NSK’s three types of ceramic bearings. NSK’s silicon carbide bearings are the most appropriate for corrosive environments with strong acid solutions while the partially stabilized zirconia bearings are most suitable for water and weak acid solutions.
3.2 Performance with poor lubrication

3.2.1 Endurance life without oil or grease lubrication

As ceramics are extremely hard and have outstanding wear resistance, they outperform other materials in bearing life without lubrication. Results of an endurance life test of steel, hybrid and all-silicon nitride bearings operating without lubrication are presented in Fig. 7.6 The steel bearing seized within a short period while the hybrid and all-ceramic bearings, though sustaining wear, did not. As shown in the figure, the all-ceramic bearing sustained considerably less wear than the hybrid bearing, indicating that its endurance life is much longer.

3.2.2 Performance in high-temperature vacuum

An all-silicon nitride ball bearing with a self-lubricating laminated cage (mainly composed of MoS2) and with MoS2-coated rings and balls proved superior in durability in a high-temperature vacuum environment. Fig. 8 shows the change over time in the dynamic frictional torque of various bearings in 10^-4 - 10^-6 Pa at 300°C.7 The all-ceramic bearing rotated continuously for 3810 hours. Compared with the hybrid bearings, the all-ceramic bearing was superior in both dynamic frictional torque and life.

3.2.3 Particle generation

Among ceramics, partially stabilized zirconia used in combination with steel is known to generate the fewest particles. As shown in the test results presented in Fig. 9, hybrid bearings with partially stabilized zirconia balls generated fewer particles than stainless steel bearings with fluoride grease or stainless steel bearings with a gold coating.8 The combination of dissimilar materials is an effective means to reduce particle generation.

3.3 Performance under oil lubrication

3.3.1 Rolling fatigue life

The rolling fatigue life (ISO 281) of silicon nitride bearings under oil lubrication is at least longer than the basic rating life of steel bearings. Fig. 10 shows the results of life tests of all-silicon nitride and silicon nitride hybrid bearings relative to the basic rating life of steel bearings.9 All-silicon nitride bearings demonstrated rolling fatigue.
life equal to or a little longer than the basic rating life of steel bearings while the hybrid bearings eclipsed the basic rating life of steel bearings by a factor of four. The failure mode for all of the bearings in the test was flaking.

As the rolling fatigue life of steel bearings is more than ten times their basic rating life in good lubrication, silicon nitride bearings are inferior to steel bearings. The principal reason is that silicon nitride bearings sustain higher contact pressure because they are less elastic than steel. Still, because the rolling fatigue life of silicon nitride bearings is at least longer than the basic rating life of steel bearings, silicon nitride bearings are feasible for some applications. Note that the most important feature of all-silicon nitride bearings is their superior performance in applications where lubrication is poor due to extreme temperatures, water-ingress or vacuum conditions.

3.3.2 High-speed performance

NSK produces high-speed bearings specifically designed for machine tool spindles. Because the density of silicon nitride is only 40% that of steel, substituting steel balls with ceramic ones greatly facilitates high-speed rotation. In a machine tool spindle under position preload, the centrifugal force acting on ceramic rolling elements is substantially lower, resulting in suppression of heat generation between the balls and outer ring. The result is superior high-speed performance. Hybrid bearings have demonstrated excellent high-speed performance not only with grease lubrication, but also with oil-air lubrication. NSK’s recently developed ROBUST Series for machine tool spindles includes hybrid bearings.

3.3.3 Seizure resistance

High-speed performance is also required for aircraft engines. At the same time, seizure resistance is extremely important for safety reasons. This critical performance attribute was assessed in an oil shut-off test in which aircraft engine conditions were closely replicated. Fig. 11 shows the temperature rise of M50 heat-resistant steel and hybrid bearings (M50 rings and silicon nitride balls) after the supply of lubricating oil was shut off. The PV value, which is an index that reflects the risk of seizure, was kept constant for both bearings. In the test, the hybrid bearing demonstrated excellent high-speed performance, reaching a value of 3.1 million. After the oil supply was shut off, the steel bearing seized before reaching the 30-second re-lubrication point while the hybrid bearing returned to stable operation after being re-lubricated and did not sustain any damage. The superior seizure resistance demonstrated by the hybrid bearing can be attributed to two factors: the disinclination of two different materials to adhere to each other and the smaller increase in preload that results from the low linear expansion coefficient of the ceramic balls.

For applications in aircraft engines, bearings must not only meet requirements for high performance, but also strict safety standards. NSK has developed a unique non-destructive ultrasonic flaw detection method for hybrid ceramic bearings for aircraft engines. This method can detect surface and subsurface defects that shorten rolling fatigue life. Fig. 12 presents the results of rolling fatigue life tests of silicon nitride balls that were tested with the...
new method. The balls that were deemed defective through this method demonstrated shorter rolling fatigue life, while every one of the balls that passed the inspection lasted until the test was suspended after 2,000 hours, nearly eight times the basic rating life of steel bearings.17) NSK’s ultrasonic flaw detection method was thus shown to be an effective non-destructive means of inspecting ceramic balls.

4. Life Equation for Ceramic Bearings

NSK has performed life tests under various environments as described in Section 3. Estimating the life of ceramic bearings can be carried out as follows:

\[ L = \alpha_{CL} \cdot a_{CM} \left( \frac{C_r}{P} \right)^3 \]

where,

- \( L \): Basic rating life (90% reliability life), 10^6 rev
- \( C_r \): Basic dynamic load rating of steel bearings of the same size, N
- \( P \): Dynamic equivalent load, N
- \( \alpha_{CL} \): Lubrication coefficient
- \( \alpha_{CM} \): Material coefficient

Table 4 lists the lubrication and material coefficients.

5. Conclusion

The characteristics of NSK’s ceramic materials for rolling bearings and the results of recent performance tests of ceramic bearings in a variety of environments have been described. Ceramic bearings are believed to have additional superior performance attributes. NSK will conduct further research and development to meet the needs of the market.

References: