Evaluation of Extra-Small Ceramic Ball Bearings

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Koyo started developing ceramic bearings at an early stage and 15 years ago and became the world's first company to succeed in mass-producing ceramic ball bearings. Ceramic ball bearings have been used for various applications, such as in machine tools, semiconductor manufacturing equipment and vacuum apparatuses.

However, in recent years we have been requested to make extra-small hybrid ceramic bearings more reliable in order to use them in turbochargers, HDD (hard disk drive) spindles, etc.

This report shows that the general properties of ceramic materials (physical and mechanical properties, load rating, fatigue life, etc.) make ceramic bearings suitable for practical use and extra-small hybrid ceramic ball bearings have sufficient reliability for all applications by showing our test results regarding fatigue and vibration life.

1. Introduction

As a material for rolling bearings, silicon nitride has many superior characteristics: It is lightweight, heat-resistant, and wear-resistant. Because of these characteristics, Koyo developed silicon nitride ceramic bearings, which are used in various types of equipment including machine tools and semiconductor manufacturing equipment[1–8].

We have been attempting to expand the use of these ceramic bearings to products such as turbochargers and HDD spindles in response to recent needs. Extra-small hybrid ceramic ball bearings are used to improve the performance of such products (low torque, low vibration, and low temperature rise) during high rotational speed and enhance life and long-term reliability related to vibration and noise[9], [10].

At this point the authors have compared ceramic bearings with steel bearings and shown that there is no problem with ceramic bearings in regard to general data (physical properties, load rating, life, and strength). In the second half of the report are given the results of life testing (rolling fatigue life and life by increase of vibration) conducted on extra-small balls bearings.

2. Characteristics of Ceramics

Characteristics of ceramics (silicon nitride, or Si₃N₄) and high-carbon chromium bearing steel (SUJ2) are given in Table 1.

Ceramic bearings have a wider range of possible application due to the superior characteristics of ceramics (silicon nitride).

For example, the superior heat resistance of ceramics enables ceramic bearings to be used at high temperatures, and its low density is effective in reducing bearing weight and the centrifugal force of the rolling elements (balls or rollers) under high-speed conditions. Ceramics furthermore forms covalent bonds, so it can be used to improve anti-seizure performance under oil starvation conditions during high-speed rotation[10].

3. Load Rating and Life of Ceramic Bearings

Because ceramics (silicon nitride) has a higher Young's modulus than that of high-carbon chromium bearing steel, the contact surface stress between the raceway and rolling elements of ceramic bearings is higher than that of steel bearings.

Dynamic and static load ratings of Koyo ceramic bearings are defined in Table 2. These are based on the results of various bearing life tests, load limit tests done on ceramic materials under static load, and evaluation of the elastic deformation of high-carbon chromium bearing steel[7].
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3.1 Rolling Fatigue Life of Ceramic Bearings

Specifications of sample bearings used in the life test and test conditions are given in Tables 3 and 4. Test equipment is shown in Fig. 1 and the life test results are given in Fig. 2. The surface of a flaked ceramic ball that reached the end of its life is shown in Fig. 3.

**Table 2** Load rating of ceramic bearings

<table>
<thead>
<tr>
<th>Bearing Type</th>
<th>Dynamic load rating</th>
<th>Static load rating</th>
<th>Philosophy of static load rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-ceramic bearing</td>
<td>Same as steel bearing (SUJ2)</td>
<td>Same as steel bearing (SUJ2)</td>
<td>Load at which cracking occurs</td>
</tr>
<tr>
<td>Hybrid ceramic bearing</td>
<td>Same as steel bearing (SUJ2)</td>
<td>0.85 times steel bearing (SUJ2) value</td>
<td>Load at which permanent deformation occurs</td>
</tr>
</tbody>
</table>

**Table 3** Test bearings

<table>
<thead>
<tr>
<th>Bearing No.</th>
<th>Materials (inner and outer rings, balls)</th>
<th>Dimensions, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC6206</td>
<td>Si₃N₄ (ceramics)</td>
<td>30 × 62 × 16</td>
</tr>
<tr>
<td>6206</td>
<td>SUJ2 (bearing steel)</td>
<td>(inner diameter × outer diameter × width)</td>
</tr>
</tbody>
</table>

**Table 4** Test conditions

<table>
<thead>
<tr>
<th>Items</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial load</td>
<td>5 800 N/bearing</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>8 000 min⁻¹</td>
</tr>
<tr>
<td>Lubricant</td>
<td>Aeroshell turbine oil 500</td>
</tr>
<tr>
<td>Temperature</td>
<td>70 ± 2°C</td>
</tr>
</tbody>
</table>

**Fig. 2** Rolling fatigue life test results

**Fig. 3** Surface appearance (flaking on the ball (a) and inner raceway (b))

From the test results, it was confirmed that the service life of ceramic bearings was more than that of steel bearings and predicted values.

Flaking was observed in the ceramic bearing that had reached the end of its life, as shown in Fig. 3. The flaking had the same appearance as that generally observed in steel bearings due to rolling fatigue.

From these results, it was found that the dynamic load ratings of steel bearings can be used for ceramic bearings of the same dimensions.
3.2 Static Load Rating of Ceramic Bearings

In the case of steel bearings, the allowable load that can be statically applied is established as the basic static load rating by JIS B1519.

JIS defines basic static load rating of steel bearings as follows: “The basic static load rating is the static load corresponding to the following calculated contact stresses in the center of the place where the raceway makes contact with the rolling elements under the maximum load.”

- Self-aligning ball bearings: 4,600 MPa
- Other ball bearings: 4,200 MPa
- Roller bearings: 4,000 MPa

In the case of ceramic bearings, because ceramics (silicon nitride) is a brittle material, almost no permanent deformation can be expected. The JIS static load rating therefore cannot be used as it is.

3.2.1 Static Load Rating of Full-Ceramic Bearings

Ceramics is ultimately destroyed by excessive load, but cracking occurs prior to destruction.

The authors gave their attention to the cracking that occurs in ceramics and investigated the static load rating for full-ceramic bearings having ceramic inner and outer rings and balls.

The method of measuring the load at which cracking occurs is given in Fig. 4, and the results are given in Fig. 5. The test results were compared with the static load rating of steel bearings (maximum contact stress calculated as 4,600 MPa).

From the results, the load at which full-ceramic bearings crack is high enough in comparison with the static load rating of steel bearings. It is shown that the static load rating of steel bearings can be used for full-ceramic bearings as well.

3.2.2 Static Load Rating of Hybrid Ceramic Bearing

In the case of the static load rating of hybrid ceramic bearings (inner and outer rings made of high-carbon chromium bearing steel and rolling elements of ceramics), because the inner and outer rings of steel bearings are permanently deformed, the philosophy of static load rating for steel bearings can be adopted.

The results of measuring permanent deformation (depth indentation) when high-carbon chromium bearing steel balls and ceramic balls respectively are pressed against a plate of high carbon chromium bearing steel by the method shown in Fig. 6 are given in Table 5.

The results showed that permanent deformation was not observed in the ceramic balls, and that the permanent deformation produced on the steel plate when ceramic balls were used was approximately 1.2 times of the combined permanent deformation produced on the ball and the plate when steel balls were used.

Thus the static load rating of hybrid ceramic bearings is limited by the deformation of steel races.

Koyo therefore uses 0.85 times the static load rating of steel bearings as the rating for hybrid ceramic bearings.
Concerning the strength of ceramic bearings under impact load, the authors conducted a static crushing test and impact crushing test on ceramic balls as shown in Figs. 7 and 8.

The impact crushing test was done by dropping a weight on the top of a holder that held two ceramic balls. Test results are given in Fig. 9.

The results showed that ceramic bearings have sufficient strength against impact load as well, and that the strength is almost the same as that against static loads.

5. Results of Rolling Fatigue Life Test for Extra-Small Hybrid Ceramic Ball Bearings

The results of the rolling fatigue life test for extra-small hybrid ceramic ball bearing 696 with 7/64" (φ2.778 mm) ceramic balls are as follows.

5. 1 Test Method and Conditions

The test bearings were shown in Fig. 10. They were extra-small hybrid ceramic ball bearings with high-carbon chromium bearing steel (SUJ2) inner and outer rings, ceramic (silicon nitride) balls and a resin cage. The bearing contained seven 7/64" (φ2.778 mm) ceramic balls.

The test equipment is shown in Fig. 11. The basic structure is the same as that shown in Fig. 1 but has a more compact design in order to handle the smaller diameter of the test
bearings. Four test bearings were mounted on a single shaft. Rotation was applied via coupling. A radial load was applied by lifting the housing of the two bearings in the center with a loading coil spring.

Test conditions are given in Table 6. The life test was conducted under a heavy 0.9 kN radial load (max. contact pressure of 5.6 GPa) per bearing (a little more than 50% of basic dynamic load rating for steel ball bearings). The sudden death test method which was suspended at 400 hours (n=4) was used. Life was set at five times the initial vibration value.

5.2 Test Results

Results of the life test are given in Fig. 12, and typical examples of surface conditions for the inner race and ceramic balls after the tests are shown in Figs. 13 and 14.

1) The life tests were conducted ten times. In four tests out of ten tests, the bearings survived more than 400 hours.

2) For the remaining six tests, the bearings arrived at lives. All the damage was flaking on the inner race (see Fig. 13). There was no damage on the ceramic balls (see Fig. 14).

3) All the bearings surpassed the predicted life of 47 hours. Even the shortest one was more than 2.5 times the predicted life.

4) The Weibull slope was 2.7, L10 life was 249 hours, and L50 life was 496 hours.

5) L10 life was at least five times predicted life.

Table 6 Test conditions

<table>
<thead>
<tr>
<th>Items</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>Forced oil circulation</td>
</tr>
<tr>
<td>Oil type</td>
<td>Spindle oil (JIS machine oil # 7)</td>
</tr>
<tr>
<td>Temperature</td>
<td>Room temperature</td>
</tr>
<tr>
<td>Kinematic viscosity</td>
<td>6.1~7.5 × 10^-6 m²/s (40°C)</td>
</tr>
<tr>
<td>Radial load</td>
<td>0.9 kN/bearing</td>
</tr>
<tr>
<td>Max. contact pressure</td>
<td>5.6 GPa</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>1 200 min⁻¹</td>
</tr>
<tr>
<td>Predicted life</td>
<td>47 h (contact pressure is considered)</td>
</tr>
<tr>
<td>Test method</td>
<td>n = 4, sudden death</td>
</tr>
<tr>
<td>Suspension time</td>
<td>Terminated at 400 h</td>
</tr>
<tr>
<td>Damage determination</td>
<td>Vibration value &gt; 5 times the initial value</td>
</tr>
<tr>
<td>method</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 12 Results of rolling fatigue life test
6. Results of Vibration Life Test for Extra-Small Hybrid Ceramic Ball Bearings

Results of vibration life testing done on extra-small hybrid ceramic ball bearing 695 containing φ2 ceramic balls which oil or grease lubrication are as follows.

6. 1 Test Method and Conditions

The test bearing and bearing specifications are given in Fig. 15, and the test conditions are given in Table 7.

Vibration was measured on the combined two bearings. (7 200 min⁻¹, room temperature)

6. 2 Test Results

The results of the oil drip lubrication test are given in Fig. 16, and the results of the grease lubrication test are given in Fig. 17. Examples of surfaces of steel balls and ceramic balls of bearings that had completed the oil lubrication test are shown in Figs. 18 and 19.

1) Oil lubrication (very little oil lubrication)

(1) All steel ball bearings locked before 1 000 hours. The life of hybrid ceramic ball bearings was more than three times longer than that of steel ball bearings.

(2) Whereas the surface of the steel balls (Fig. 18) had damage (peeled skin, discoloring, adhesive wear, etc.), the ceramic balls (Fig. 19) were not damaged.

2) Grease lubrication

(1) Whereas the vibration of steel ball bearings at 10 000 hours were about three times greater than the initial value, the vibration of hybrid ceramic ball bearings increased less than 10%.
From these results, it was found that hybrid ceramic ball bearings exhibit superior durability particularly in poor lubrication. This is thought to be due to the fact that there is no metal contact under the poor lubrication conditions and adhesion can be avoided.

7. Conclusion

The following items were clarified in regard to the use of ceramic balls in order to expand the application of extra-small hybrid ceramic ball bearings.

1) There is no problem with the basic characteristics, such as load rating and strength. Concerning rolling fatigue life, the life is at least five times longer than the predicted life.

2) Vibration life

   (1) The life of hybrid ceramic ball bearings was at least three times longer than that of all-steel bearings when oil lubrication is insufficient.

   (2) The vibration increase of hybrid ceramic ball bearings was maximum 1/30 for that of steel ball bearings under grease lubrication condition.

As described above, extra-small hybrid ceramic ball bearings exhibit superior characteristics and are suitable for practical use. Their application is expected to increase significantly in the future.

References