Angular Contact Ball Bearings for High-Speed and Heavy-Cutting Machine Tools

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NTN has developed new angular contact ball bearings, well suitable for machine tool spindles especially taking advanced multi-tasking which is the latest trend of the manufacturing field. The bearings perform 30% higher basic load rating and higher allowable axial load through internal design optimization. Thus the bearings support the well balanced machine tools show high-speed and heavy-cutting capability. In this document, we introduce the design points and test data.

1. Introduction

Recently, requirements for higher machine tool performance are increasing in order to address the diverse needs of different industries.

The recent trends of these requirements include (1) "increase of machining and cutting of difficult-to-machine material and hard material like titanium, and requirement of a more rigid main spindle to deal with them," (2) "integration and multi-functionality of machining process for higher efficiency," (3) "requirement of five-axis tool for machining complex shapes with high precision" and (4) "requirement for smaller machine tools to adapt to the size of workpiece." To cope with these trends, "one chucking for the entire process," which is to process the workpiece from heavy cutting in mid to low speed rotation of the main spindle to refined cutting in high speed rotation by one machine tool, is demanded. As a result, the bearing for the main spindle of machine tool needs to provide a high level of both high-speed capability and high rigidity, which are in a trade-off relationship (Fig. 1)1).

Also, efforts for reducing non-cutting takt time are in progress to "further increase productivity," which is an important factor for machine tools; consequently, the speed of the main spindle and table feed rate of recent machine tools is increasing. In addition, recent machine tools are required to process more complex shapes. With these changes, unexpected collision events between the tools attached to the tip of the main spindle and workpieces are recently increasing.

The impact load applied to the bearings of the main spindle due to collision may produce indentation on the raceways of the bearing inner/outer rings depending on the magnitude of the load, which impedes smooth and high precision rotation of the main spindle. Therefore, bearings of the main spindle are also required to have high load resistance to prevent/mitigate occurrence of indentation. To respond to these trends and requirements, NTN has developed bearings for main the spindle to support high-speed rotation and heavy cutting based on the high-speed angular contact ball bearing "HSE Type."

In this article, we describe the features and the evaluation test results of the developed product.

Fig. 1 Technical trend of machine tools and spindle bearings1)
2. Background of development

NTN’s high-speed angular contact ball bearing HSE Type adapts for broad usage from high-speed to ultra high-speed range. Consequently, many units have been adopted for main spindles of machine tools for a long time. However, machine tools are expected to evolve with even higher speed of main spindle rotation for further productivity gain. Under these circumstances, adoption of the HSE Type is expected to expand.

As another approach of productivity increase, machine tools actively incorporating integration of machining processes, multi functionality, and heavy-cutting capability are recently increasing. In these cases, \( d_{mn} \) value\(^*1\) of the main spindle rotational speed is approximately 1.2 million and the bearings for the main spindles are required to have both high-speed capability and rigidity, which are in a trade-off relationship. Therefore, as shown in Fig. 2, the challenge of the bearings for main spindles is to fulfill both high-speed capability and high rigidity at an elevated level.

In addition, impact load (large axial load) may be applied to the main spindle and bearings of main spindles of machine tools due to unclamping load while exchanging tools during off-operation or unexpected collision of tool attached to the tip of the main spindle and the workpiece (Fig. 3).

When the impact load exceeds the tolerance, indentation may occur on the raceway, impeding smooth and highly precise rotation. This axial load limit is called permissible axial load (stationary) and NTN defines it as the load leading to any of the following\(^*2\):

- The end of the contact ellipse produced between the rolling element and the raceway overtakes the shoulder either in the inner ring or outer ring (Fig. 4).
- The contact surface pressure of the raceway reaches 3,650 MPa\(^*2\) on either the inner or outer ring.

In order to prevent/mitigate indentation, permissible axial load (stationary) needs to be increased and tolerance against collision must be enhanced.

\*1 \( d_{mn} \) value expresses the rotational performance of bearings. \( d_{mn} \) (diameter of rolling element (mm)) \( \times \) \( n \) (rotational speed (min\(^{-1}\)))

\*2 Contact surface pressure 3,650MPa is a value to produce permanent deformation of 0.00002 to 0.00005 times the rolling element diameter.
3. Features of developed product

3.1 [Support of heavy-cutting (1)]

increase of load capacity

The developed product optimized the internal design such as larger rolling element diameter, in order to support heavy-cutting capability while still maintaining the high-speed capability of the aforementioned HSE Type (hereafter, conventional product) (Fig. 5). The developed product improved the load capacity, increasing the rated load by approx. 30% (Fig. 6).

This load varies depending on the magnitude of the “lag-lead” of rolling elements and the magnitude of the load applied to the rolling elements (hereafter, rolling element load). Since the developed product uses larger rolling elements than the conventional product, as mentioned above, the rolling element load is likely to increase. In addition, for heavy-cutting, a relatively larger machining load is applied. Therefore, a large load may be applied to the cage, as well. Therefore, an enhanced cage with larger cross section than the conventional product was adopted to increase reliability of the cage strength (Fig. 7).

3.2 [Support of heavy-cutting (2)]

improvement of cage strength

The rolling elements of rolling bearings rotate with so-called "lag-lead" which is a very small difference of relative speed due to geometrical accuracy of the bearing, installation accuracy onto shaft and housing, external load, etc. The rolling elements with relatively faster rotational speed tend to shift forward in the cage pocket (traveling direction). The rolling elements with relatively slower rotational speed tend to shift backward in the cage pocket (opposite side of the traveling direction). Consequently, the rolling elements make contact with the cage pocket to apply load on the cage.

3.3 Increase of permissible axial load (stationary)

The permissible axial load (stationary) of the developed product is increased by approx. 30% compared to the conventional product by optimizing the internal design (Fig. 8). This will prevent/mitigate indentation on the bearing raceway surface when impact load is applied.
4. Evaluation test of developed product

4.1 Test condition

We have conducted high-speed operation tests of the developed product. The configuration of the tester is shown in Fig. 9 and the test conditions are shown in Table 1.

This test used a bearing of inner ring inner diameter 70 mm, which is widely used for main spindles of the machining center. Assuming main spindles where high rigidity is required such as heavy cutting, a four-row back-to-back arrangement (DTBT) fixed position preload was used, setting 1,400 N of preload after incorporation of bearing into the main spindle, which exceeds medium preload of the conventional product. In addition, the enhanced type of Fig. 7 was adopted for the cage of the developed product and with phenolic resin material.

<table>
<thead>
<tr>
<th>Test bearing</th>
<th>( \Phi 70 \times \Phi 110 \times 20 \times 4 ) rows (DTBT) Equivalent to SS-2LA-HSE014 (Ceramic ball, contact angle 20°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cage</td>
<td>Conventional product</td>
</tr>
<tr>
<td>Preload method</td>
<td>Fixed position preload</td>
</tr>
<tr>
<td>Preload after incorporation</td>
<td>1,400N</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>0～18,000min^{-1}</td>
</tr>
<tr>
<td>Lubrication method</td>
<td>Air oil lubrication</td>
</tr>
<tr>
<td>Supply oil amount</td>
<td>0.03mL/8min</td>
</tr>
<tr>
<td>Amount of air</td>
<td>35NL/min</td>
</tr>
<tr>
<td>Lubricating oil</td>
<td>ISO VG32</td>
</tr>
<tr>
<td>Outer cylinder cooling</td>
<td>Yes</td>
</tr>
<tr>
<td>Attitude of axis</td>
<td>Horizontal axis</td>
</tr>
</tbody>
</table>

Fig. 9 High-speed running test spindle

4.2 Test results

Test results are shown in Fig. 10 and 11. The developed product shows rise of temperature similar to the conventional product while increasing the load capacity. It was verified that the operation exceeds \( d_{mn} \) value of 1.2 million, shown in Fig. 2, up to \( d_{mn} \) value of 1.62 million (18,000 min^{-1}) (Fig. 10). It was also verified that the bearings other than row C also showed a stable rise in temperature (Fig. 11).

![Graph showing test results](image-url)

**Fig. 10** High-speed running test result (C-row bearing)

![Graph showing test results](image-url)

**Fig. 11** Outer ring temperature rise in spindle rotation speed 15,000 min^{-1}

4.3 Permissible axial load (in operation)

Based on the temperature data obtained in the aforementioned test, permissible axial load (in operation) was calculated for each bearing in the range of \( d_{mn} \) value of approximately 1.2 million. The result indicated that when \( d_{mn} \) value is 1.17 million (13,000 min^{-1}), the developed product was \( F_a = 9.8 \) kN compared to the conventional product of \( F_a = 6.8 \) kN, verifying that the external load applicable to the main spindle is increased by approx. 30%. In addition, similar result was obtained for \( d_{mn} \) value of 1.35 million (15,000 min^{-1}) (Fig. 12).
5. Application of injection molding plastic cage

5.1 Material of plastic cage

In the previous section, we verified that the developed product shows equivalent rise in temperature as the conventional product by optimization of the internal design. In this test, phenolic resin (hereafter, PF) was used for the cage. Since the phenolic resin is thermosetting, it has the advantage of higher tolerance against a rise in temperature due to high-speed rotation of the bearing. On the other hand, consideration is required for productivity and cost since it is fabricated by machining. In this section, adoption of injection molded cage, which has an advantage in productivity and cost, is also considered.

For high-speed operation of injection molded cage, research using high-melting point polyamide resin (hereafter, high melting point PA) shown in Table 2 has been conducted.

Table 2 Characteristics of resin cage material

<table>
<thead>
<tr>
<th>Material</th>
<th>Phenol (PF)</th>
<th>High-melting point polyamide (high-melting point PA)</th>
<th>Polyamide (PA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Thermosetting</td>
<td>Thermoplastic</td>
<td></td>
</tr>
<tr>
<td>Glass transition temperature</td>
<td>—</td>
<td>158°C</td>
<td>58°C</td>
</tr>
<tr>
<td>Melting point</td>
<td>—</td>
<td>158°C</td>
<td>260°C</td>
</tr>
<tr>
<td>Production method</td>
<td>Cutting</td>
<td>Injection molding</td>
<td></td>
</tr>
</tbody>
</table>

5.2. Evaluation test

Enhanced cage was fabricated with high-melting point PA in Fig. 7, and high-speed operation test of the developed product was conducted under the conditions of Table 3. The test conditions were the same as Table 1 except that the cage specification is different.

The test result revealed that the developed product with high-melting point PA cage also showed a rise in temperature similar to the conventional product. It was verified that the operation is possible, in addition to $d_{mn}$ value of 1.2 million, shown in Fig. 2, up to $d_{mn}$ value of 1.62 million (18,000 min$^{-1}$) (Fig. 13). It was also verified that the bearings other than the row C also showed a stable rise in temperature (Fig. 14). In this test, conventional product with ordinary polyamide resin (hereafter, PA) cage was also evaluated. The result showed an unstable rise in temperature at $d_{mn}$
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value of 1.35 million (15,000 min⁻¹) and could not support the high-speed/heavy-cutting range (da/n value 0.9 - 1.5 million). We will proceed with volume production of the developed product, considering adoption of the high-melting point PA cage, as well.

6. Summary

We have developed “Angular Contact Ball Bearings for High-Speed and Heavy-Cutting Machine Tools” in order to meet new trends such as integration of machining processes and multi-functionality of machine tools. The developed product optimizes the internal design based on the conventional high-speed angular contact ball bearing "HSE Type," by increasing load capacity and permissible axial load by approx. 30% while maintaining high-speed capability. In addition, adoption of high-melting point polyamide resin (high-melting point PA) with advantageous productivity and cost was also studied for the developed product. We will also conduct performance evaluation with grease lubrication.

We are poised to continue working on the improvement of bearing performance in order to support higher functionality of machine tools.

References

2) NTN Catalog: Precision Rolling Bearings, CAT. No. 2260-VII/J. 16.11.03 21.
3) Atsushi Tokuda, Takumi Hayashi: Impact of Heat Resistance of Plastic Cage for High-Speed Operation of Angular Contact Ball Bearing, Japanese Society of Tribologists, Tribology Conference 2017 Fall Takamatsu

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