Development of Bearings with Low Temperature-rise and High-speed Performance for Machine Tool Main Spindles

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We have developed an angular contact ball bearing and a cylindrical roller bearing which are superior in low temperature-rise and high-speed performance for machine tool main spindles.

By optimizing the internal design, temperature rise of both bearings has been reduced to approximately half compared with normal types.

These bearings can reduce power consumption for cooling machine tools, which is effective for energy saving. And also, the developed bearings are expected to improve machining accuracy by reducing thermal expansion and improve machining efficiency by increasing high-speed performance of spindles.

Key Words: *machine tool, rolling bearing, temperature rise, high-speed capability*

1. Foreword

In recent exhibitions, best represented by The Japan International Machine Tool Fair (JIMTOF), many machine tools are put out on display which, in addition to high accuracy, high speed, high rigidity and high reliability, are also focused on being energy-saving, environmentally-orientated and user-friendly, with a particular emphasis on being easy for anyone to use. Moreover, regarding the moving parts of machine tools such as the main spindle, table, column and so on, the performance of these moving parts depends greatly on the performance of rolling bearings.

Out of all the moving parts on machine tools, the main spindle is one of the most important elemental parts. Often angular contact ball bearings or cylindrical roller bearings are used for the main spindle. As for lubrication methods, oil-and-air lubrication is adopted for high speed main spindles, while grease lubrication is adopted for low speed main spindles.

JTEKT has commercialized our High Ability Bearing series as bearings for machine tool main spindles. We also have many other product series available to achieve the performances demanded of various machines.

In addition to these products, JTEKT has developed angular contact ball bearings and cylindrical roller bearings with low temperature-rise and high-speed capability in an effort to save energy. This paper introduces the results of such developments.

2. Development Target

The main cause of temperature rise in machine tool main spindles is the heat generated from rolling bearings and the motor. The main spindle undergoes thermal expansion in the axial direction when it heats up which impacts upon the accuracy of machined workpieces. As such, jacket cooling is generally performed to control main spindle temperature.

Figure 1 shows the percentage that various factors influence machining center power consumption.

This figure shows that while the coolant unit is the greatest percentage behind power consumption in machining centers, main spindle cooling is also a major contributing factor at around 16%.

Therefore, by developing low temperature-rise bearings, it is possible to reduce power consumption necessitated by cooling and contribute to saving energy.

Figure 2 shows the relationship between features of the developed bearings and that of machine tools.

This development aims to suppress temperature rise in rolling bearings and improve speed in order to enhance machine tool performance. Specifically speaking, as well as saving energy, the authors aimed to improve machining accuracy by reducing thermal expansion of the main spindle and shortening machining time through high speed rotation of the main spindle.

This development was undertaken with the goal of reducing temperature rise of a high speed rolling bearing using oil-and-air lubrication by half that of a normal bearing.

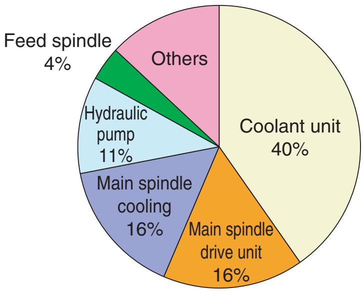


Fig. 1 Example of typical power consumption in machining center by factors

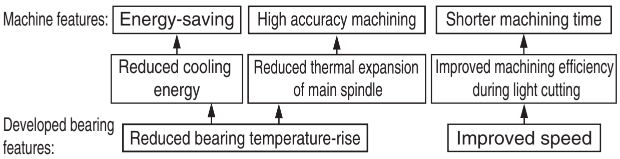


Fig. 2 Features of developed bearings and machine tools

3. Angular Contact Ball Bearings

3. 1 Characteristics of the Developed Bearing

Table 1 shows JTEKT's High Ability Series of angular contact ball bearings for machine tool main spindles.

The High Ability Series includes the high-stiffness Type R, high loading capacity Type C and ultrahigh-speed Type D & F. One of these, Type F has the advantage of high speed due to the two characteristics of two-direction oil-and-air supply (axial and outer ring port) and a rolling contact area design optimal for high speed use. The new type of angular contact ball bearing developed this time was based on this Type F.

Figure 3 shows the appearance and heat generation factors of the developed angular contact ball bearing. The heat generation factors of angular contact ball bearings can be broadly grouped into the heat generated in the rolling contact areas of the inner ring to balls and outer ring to balls, and the heat generated in the sliding contact areas of the cage to outer ring and cage to balls. During the development, each factor was investigated.

It is necessary to consider heat generation reduction and high speed performance to achieve the optimal design of rolling contact areas. Regarding a design that reduces heat generation, because spin sliding occurs in the area where the inner ring contacts the balls during high speed rotation of the angular contact ball bearing, assuming that the product of pressure P and sliding speed V (P･V value) at the contact areas affect its heat generation significantly, therefore the authors aimed to minimize the product of P･V value. Meanwhile, regarding a design that improves high speed performance, in order to raise the critical speed of the main spindle, the bearing that supports the main spindle must be made more rigid. Moreover, it is necessary to avoid the decreasing of the bearing internal clearance due to centrifugal expansion of the inner ring. The rolling contact area of the developed angular contact ball bearing was optimally designed taking into consideration these points.

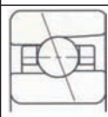
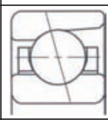
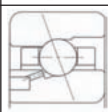
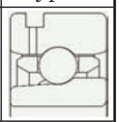
Furthermore, regarding one other heat generating factor, the sliding area of the cage, using the flexible multibody dynamics (FMBD) with cage structure supposed elastic, by estimating the amount of heat which would be generated by each sliding area, the optimal cage design was achieved. In FMBD, the mutual contacting force of bearing components and sliding speed under constant-speed rotation were determined and heat generation was estimated by considering the heat generation amount to be equal to the power of the contact points between the cage and outer ring and that between cage and balls.

Figure 4 shows an example of estimated results of heat generation in the cage sliding area. The X axis shows the *dmn* value which is the value of rotational speed multiplied by the bearing pitch circle diameter (P.C.D). The figure also shows the amount of heat generated due to sliding between the cage and outer ring as well as sliding between the cage and balls (total amount of each generated for each ball area). **Figure 4** gives calculation results under specific load conditions however it was observed that the amount of heat generated between the cage and outer ring was greater than that of heat generated between the cage and balls and tended to increase dramatically with increase in rotational speed.

For the developed bearing, the amount of heat generated was calculated as shown above using the cage design values as parameters, and the cage was designed in a way to reduce heat generation from its sliding area.

Furthermore, the cage material was reviewed for the developed bearing. Seizure of the cage is one of the factors that cause damage during the high speed rotation of angular contact ball bearings. Therefore, PEEK (Polyetheretherketone) was chosen as a resin with the properties required in cages under high speed rotation; namely, high rigidity, heat resistance and a low linear expansion coefficient.

Table 1 "High Ability Bearing Series" angular contact ball bearings for main spindles of machine tools

Type	Type R	Type C	Type D	Type F
Section profiles				
Application	High-stiffness	High loading – capacity	Ultra high-speed	
Lubrication method	Grease/Oil-and-air		Oil-and-air	

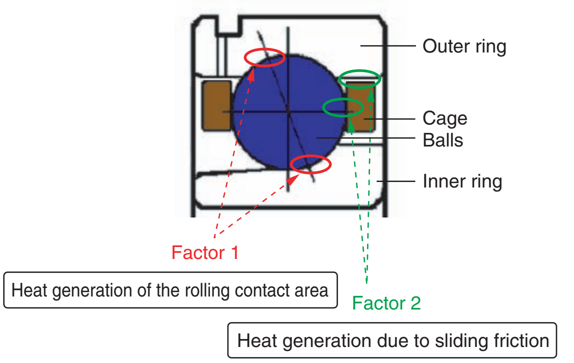


Fig. 3 Appearance and heat generation factors of developed angular contact ball bearing

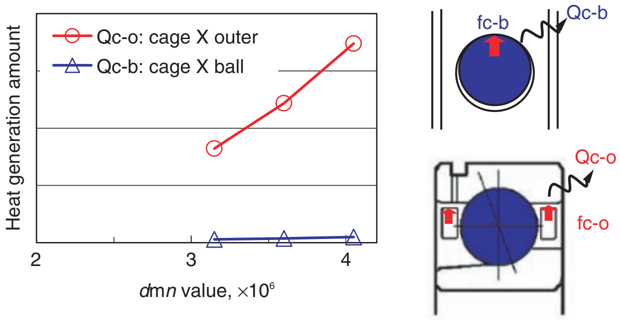


Fig. 4 Example of estimated results of heat generation in the sliding area

3. 2 Performance of the Developed Bearing

This section gives the method used to evaluate performance of the developed angular contact ball bearing and the obtained results.

Figure 5 shows the test apparatus used. In order to make conditions in the test apparatus as close to those of the actual main spindle as possible, a structure imitating the actual machine driven by a high speed built-in motor was used and a jacket cooling device was built. One bearing was used as a sample while a second bearing with a smaller diameter was used as a support bearing, and they were installed with constant preload.

Table 2 shows the test conditions used. The oil-and-air lubrication method was used. Moreover, the developed bearing used the same style of lubrication as High Ability Type F, supplying oil-and-air from both the axial direction and outer ring outside diameter.

During the test, every 1 to 2 hours the rotational speed was increased step-by-step and the saturation temperature of the bearing outer ring at each rotational speed was measured.

Figure 6 shows a comparison of results in temperature rise for the developed bearing and the normal Type F bearing under each rotational speed.

From **Fig. 6** it can be seen that the developed bearing had approximately 45% less temperature rise in its outer ring under each rotation speed compared with the normal Type F bearing, proving there had been improvement.

Also, in contrast to the rotational speed limit for the normal Type F bearing being 3 300 000 *dmn* and seizure occurring at any speed above this, high speed rotation of up to 4 000 000 *dmn* was possible on the developed bearing, confirming that high speed performance had improved.

Next, **Fig. 7** shows the results of an evaluation on the influence of preload on outer ring temperature rise.

From the results, temperature rise of the outer ring at higher preload of 0.83 kN was 3 to 8℃ higher than that at lower preload of 0.42 kN, it was proven that the preload influence to the temperature rise, however even under the high preload condition of 0.83 kN, rotation was still possible without any faults up to a *dmn* of 4 000 000.

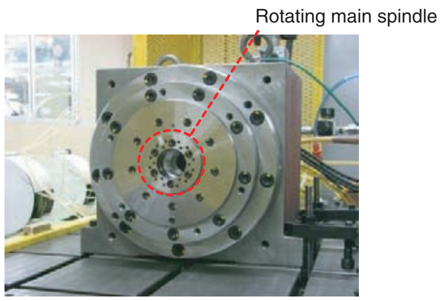


Fig. 5 Test apparatus for angular contact ball bearing

Table 2 Test conditions for angular contact ball bearing

Item		Conditions
Sample main dimensions		$\phi 70 \times \phi 110 \times 20$
Operating conditions	Rotational speed	Max. 45 000 min^{-1}
	Load	Constant pressure preload 420 N
Lubrication conditions		Oil-and-air lubrication VG32 equivalent
Cooling conditions		Jacket cooling

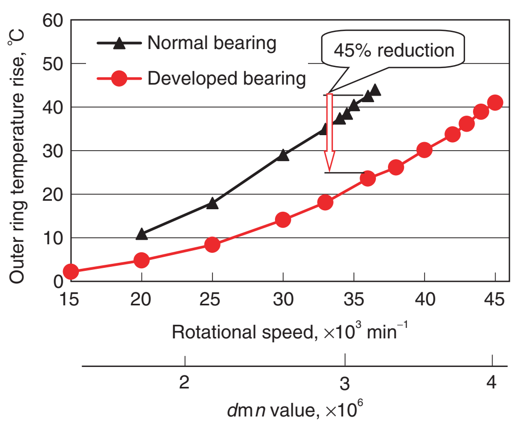


Fig. 6 Comparison results of temperature rise between developed angular contact ball bearing and a normal bearing

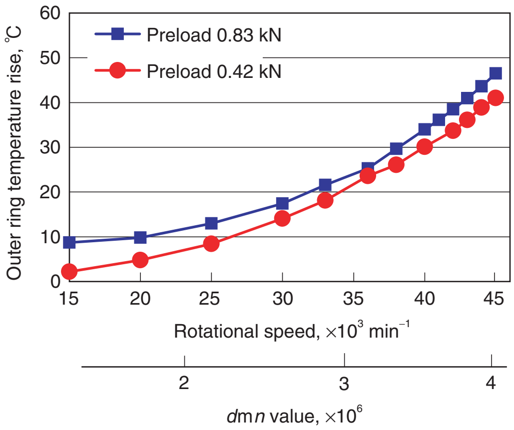


Fig. 7 Temperature rise of developed angular contact ball bearing under two preload conditions

4. Cylindrical Roller Bearings

4. 1 Characteristics of the Developed Bearing

There are two types of using cylindrical roller bearings for machine tool main spindles.

One is using them on the rear of the main spindle and selecting on the basis of allowing for main spindle elongation caused by thermal expansion. In this case, the N-type single row cylindrical roller bearing with a rib on the inner ring side is used as the radial load is small because of just the weight of the main spindle. However, high speed performance is required.

The other is to use a cylindrical roller bearing on the front side of the main spindle in order to support high cutting load. In this case, high speed performance is not required however load capacity and rigidity are required; therefore the NN-type double row cylindrical roller bearing is used.

The developed bearing this time targets the first method of usage at the rear of the machining center main spindle.

Figure 8 shows the appearance and heat generation factors of the developed cylindrical roller bearing.

The heat generation factors of this cylindrical roller bearing can be broadly grouped into (1) the heat generated in the rolling contacting areas of the inner ring to roller and outer ring to roller, (2) the heat generated due to sliding of the inner ring rib and roller, and (3) the heat generated from the sliding areas of the cage.

For the developed bearing, improvement activities focused on the main factor of (3), the heat generated from the sliding areas of the cage, with particular consideration taken towards the design of the cage guide method, cage material and lubrication supply ability.

Normal JTEKT cylindrical roller bearings use the roller guide method for cages, however when this method is used there is contact between the pocket rib and the roller in a wedge shape and it is predicted that this increases the heat generated in ultra high-speed rotation. Consequently, the cage guide method was changed to the outer ring guide type.

Each area of the cage was designed using the Taguchi Method. An evaluation sample was created using five control factors as parameters, and experiments were performed using the oil amount as a fluctuating factor and the outer ring temperature rise as an evaluation property value in order to determine the optimal level.

It is believed this makes the cage more robust.

For the same reasons as the angular contact ball bearing, PEEK was selected as the cage material.

Next, to suppress temperature rise during high speed operation, the lubrication supply performance is one important factor. Therefore, a high speed camera was used to observe the oil-and-air supplying state.

Figure 9 shows the oil-and-air supplying condition using a high speed camera. By increasing the frame rate, the supply interval, supply location and so forth were clearly observed. In this development, the knowledge gained through these observations was helpful in determining the internal design of the bearing from the perspective of improving oil-and-air supply performance.

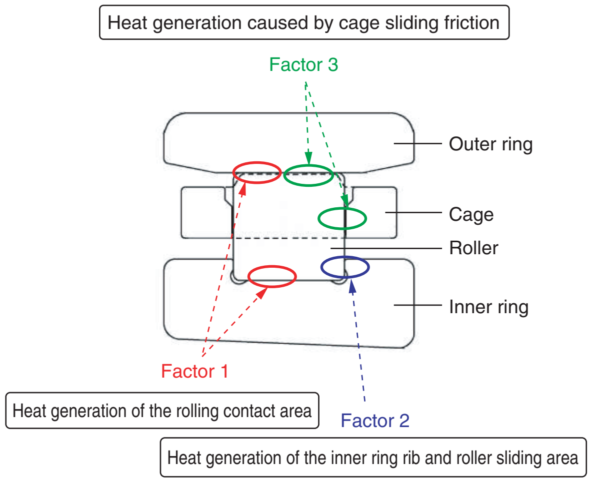


Fig. 8 Appearance and heat generation factors of developed cylindrical roller bearing

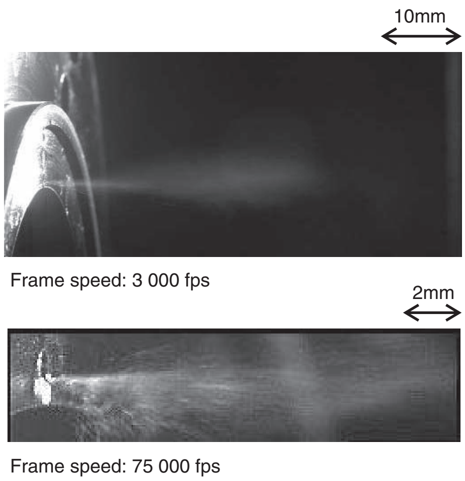


Fig. 9 Observation of oil-and-air supplying conditions

4. 2 Performance of the Developed Bearing

Figure 10 shows the test apparatus used to evaluate performance of the cylindrical roller bearing and **Table 3** shows the test conditions.

The test apparatus has a configuration whereby the sample bearing and a supporting ball bearing with a smaller diameter than the sample bearing, were assembled and external drive was performed using a belt. Because a bearing for use on the rear of the main spindle was targeted in this development, the test apparatus was configured so as to apply no external load to the sample bearing. Moreover, the oil-and-air lubrication method used under high – speed rotation conditions was used for the test.

When the bearing rotates at high speed, centrifugal expansion of the inner ring occurs, reducing the radial clearance. Therefore, the authors believed that the radial clearance upon assembly had a significant influence on temperature-rise performance. As such, the radial clearance upon assembly conditions was made constant across all tests performed using each sample.

In the same way as **3. 2**, test procedures involved increasing the rotational speed step-by-step every 1 to 2 hours and measuring the saturation temperature of the bearing outer ring at each rotational speed.

Figure 11 shows a comparison of results in temperature rise for the developed bearing and the normal bearing (with a polyamide roller guide cage) under each rotational speed.

From **Fig. 11** it can be seen that the developed bearing had approximately 46% less temperature rise in its outer ring under each rotation speed compared with the normal bearing, proving there had been improvement.

Also, in contrast to the rotational speed limit for the normal bearing being 1 500 000 *dmn* and seizure occurring at any speed above this, high speed rotation of up to 3 000 000 *dmn* was possible on the developed bearing, confirming that high speed performance had improved.

Next, the advantage of changing the roller material on suppressing temperature rise was confirmed.

Figure 12 shows the results of a comparison made on outer ring temperature rise for the respective roller materials.

The ceramic roller type had lower temperature rise compared to the bearing steel roller under specific high -speed rotation conditions, therefore confirming that temperature rise was suppressed at high speed.

Changing roller material from bearing steel SUJ2 to ceramic Si_3N_4 is believed to have the advantages of suppressing load on bearing rolling elements caused by heat generation due to a small linear expansion coefficient, as well as suppressing rolling bearing load caused by centrifugal force due to small density.

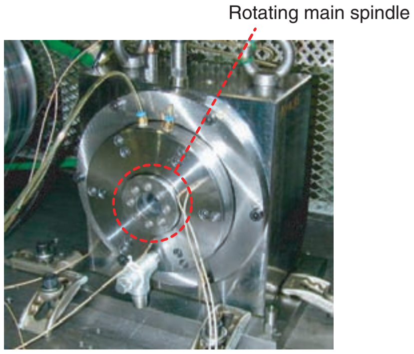


Fig. 10 Test apparatus for cylindrical roller bearing

Table 3 Test conditions for cylindrical roller bearing

Item		Conditions
Sample main dimensions		$\phi60\times\phi95\times18$
Operating conditions	Rotational speed	Max. 39 000 min^{-1}
	Load	no load
Lubrication conditions		Oil-and-air lubrication VG32 equivalent

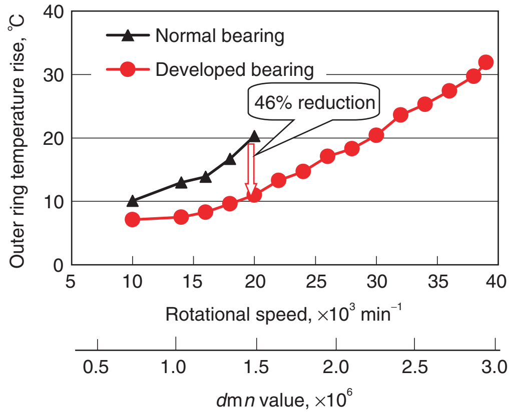


Fig. 11 Comparison results of temperature rise between developed cylindrical roller bearing and a normal bearing

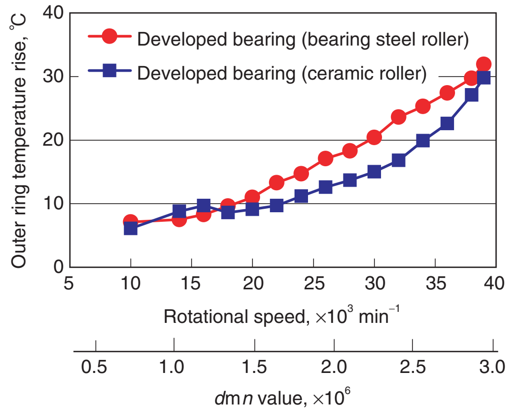


Fig. 12 Comparison results of temperature rise depending on roller materials

5. Conclusion

The new angular contact ball bearing and cylindrical roller bearing for machine tool main spindles developed by JTEKT have a suppressed temperature rise of approximately half compared to normal bearings under oil-and-air lubrication conditions. Moreover, high-speed capability was improved and it was verified that rotations of 4 000 000 dmn (spindle dia. = ϕ70, RPM = 45 000 min^{-1}) and 3 000 000 dmn (spindle dia. = ϕ60, RPM = 39 000 min^{-1}) were possible for the angular contact ball bearing and cylindrical roller bearing respectively.

This type of low temperature-rise rolling bearing is believed to be advantageous for reducing power consumption necessary for cooling of machine tool main spindles and saving energy. Moreover, other advantages can be expected such as better machining accuracy by suppressing main spindle thermal expansion and improved machining efficiency through improved high-speed capability.

JTEKT will continue to exert every effort in improving the performance of rolling bearings to respond to machine tool needs.

*1 High Ability is a registered trademark of JTEKT Corporation.

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