Approaches for Bearings with Low Temperature-rise for Machine Tool Main Spindles

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Low temperature-rise is an important technology in bearings for machine tool main spindles.

Bearings with low temperature-rise enable energy saving by reducing power consumption cooling system for machine tools. This is effective in improving machining accuracy as it reduces thermal extension. It is also effective in improving machining efficiency as it increases the high-speed capability of the spindle.

Although we are creating a lineup of the angular contact ball bearing and cylindrical roller bearing, which had low temperature-rise and were excellent in high velocity rotation performance when used by machine tool main spindles, we would like to incorporate further low temperature rise technology in order to improve product appeal.

Key Words*: machine tool, rolling bearing, temperature rising, thermography, fluid simulation*

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1. Introduction

Improving the performance of the units and individual components which a machine tool is configured from is essential to improving the performance of the machine tool itself. The main spindle is of particular importance, as it directly affects machining accuracy and efficiency, therefore the standard required from the market has grown increasingly higher in recent years. The performance requirements of machine tools include the reduction of processes and man-hours as well as a higher capability to machine difficult-to-machine material. Therefore the performance of the main spindle in regards to high-speed, low temperature and so on, has been raised as a key item. Up until the year 2000, bearings used in the main spindle were required to have a maximum rotation performance of around 3 million dmn but in recent years this has risen to 3.5 million dmn or higher. Low temperature-rise is another important technology that a main spindle bearing is required to possess. The less heat a bearing generates, the less thermal expansion occurs on the main spindle; which is extremely effective in improving machining accuracy, the most important feature of a machine tool. This also contributes to energy-saving as it is possible to reduce power consumption for cooling. In other words, high performance bearings are essential to achieve high performance main spindles.

JTEKT offers a product series featuring high-speed angular contact ball bearings and cylindrical roller bearings with an excellent low temperature-rise characteristic for application in the main spindles of machine tools. In order to achieve even higher performance, we are engaging in the development of low temperature-rise technology. This paper introduces examples of approaches for the bearing internal temperature measurement technology which uses thermography and a simulation of the airflow inside the bearing under oil/air lubrication.

* dmn: Pitch circle diameter (P.C.D.) of the bearing's rolling element (mm) × rotational speed (min^{-1})

2. Approaches for achieving low temperature-rise of main spindle bearings

2. 1 Visualization of bearing internal temperature

Despite low temperature-rise being a key technology of not only bearings for machine tool main spindles, but bearings in general, not much was known regarding the internal temperature of bearings during rotation.

The areas of the bearing which generate heat are each sliding contact portion between the inner ring and rolling element, cage and outer ring (in the case of outer ring guide cage type bearings) and cage and rolling element, as well as each sliding contact portion of each rolling contact portion between the outer ring and rolling element. All of these areas are extremely difficult to measure.

Table 1 shows the measuring apparatus generally used to measure the temperature of rotating bodies such as bearings. This method uses a slip ring and transmits a thermocouple signal through brush contact therefore is limited in regards to the rotational speed it can be used at. Moreover, while the inner ring temperature can be measured, it was unable to measure the individual temperatures of internal components such as the cage and rolling element.

When measuring using an infrared thermometer, it is difficult to set measurement points in narrow areas such as the cage and rolling element, therefore measuring temperature proved to be a challenge.

This is why JTEKT has used high-sensitivity thermography and built a system which can measure the internal temperature of bearings. This system has helped to clarify the heat-generating factors and parts within the bearing and through combination with the FEM heat generation forecast method, made it possible to reduce heat generation within the bearing[1)].

In general, angular contact ball bearings and cylindrical roller bearings are used in the main spindle of machine tools therefore measurements of internal temperature were conducted on these bearings as per shown in the below table and low temperature-rise was accomplished based on the results.

Table 1 Measuring method for rotating body temperature

Measurement device	Measured portion			Problems
	Inner ring	Rolling element	Cage	
Thermocouple, slip ring	○	×	×	Has limitation regarding maximum rotational speed
Infrared thermometer	○	×	△	Difficult to measure narrow portions
Highly-sensitive thermography	○	○	○	–

○···Measurement possible
△···Measurement difficult
×···Measurement impossible

2. 2 Reduction of heat generated inside angular contact ball bearings

In order to clarify the factors behind internal heat generation of angular contact ball bearings which use ceramic rolling elements, we used a system which utilizes the high-sensitivity thermography mentioned earlier and measured the bearing internal temperature. **Figure 1** shows the apparatus used in measurement. This apparatus adopts DDS motor drive and a constant preload method and is of a structure which resembles the main spindle of machine tools. Moreover, a large opening has been made at the end of the spindle in order to observe the inside of the bearing.

Thermography measures the infrared strength (infrared dosage) and converts this to temperature therefore if there is disturbance such as reflection, it is difficult to obtain an accurate temperature measurement. As such, we have devised various ways to remove disturbance from bearings and enable accurate temperature measurement.

Table 2 shows the samples measured and test conditions used. These are general usage conditions for machine tools.

Figure 2 shows an example of the actual measurement results for a standard bearing. The results show that the temperature of the rolling element is the highest of all the components within the bearing. The red dots in **Fig. 3** indicate the points where temperature was measured on the outer ring, cage and rolling element. These measurement results were established as representative values and the rotational speeds were set as parameters. **Figure 4** gives the results of temperature measurements at various portions inside the bearing. Across all rotational speeds, the temperature of the rolling element was the highest and rose as rotational speed increased.

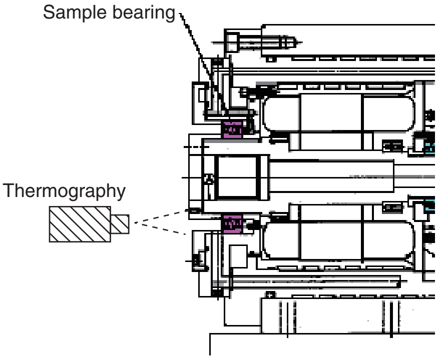


Fig. 1 Test apparatus for angular contact ball bearing

Table 2 Test conditions of angular contact ball bearing

Sample conditions	Type	Angular contact ball bearing
	Main dimensions, mm	$\phi70\times\phi110\times20$
	Rolling element pitch diameter, mm	90
	Rolling element material	Si_3N_4 (ceramic)
Test conditions	Preload method	Constant-pressure preloading
	Rotational speed, min^{-1}	Max. 30 000
	dmn	Max. 270×10^4
	Lubrication method	Oil/air lubrication

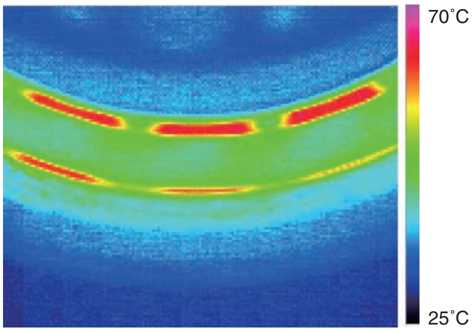


Fig. 2 Bearing temperature (standard, 30 000 min^{-1})

As it was possible to confirm the internal temperature of the standard bearing, we then performed the heat generation forecast mentioned previously and **Fig. 5** shows the results of a measurement after the bearing was optimized by improving the cage design and respective clearances. Compared with the results of **Fig. 2**, there is less warm color, confirming that the bearing internal temperature has dropped. In other words, through optimization of the bearing based on heat generation forecast, we confirmed a reduction in bearing temperature rise and verified the validity of our technique for analyzing heat generation forecast.

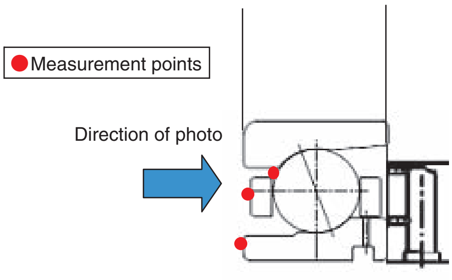


Fig. 3 Photography direction and the point of measurement

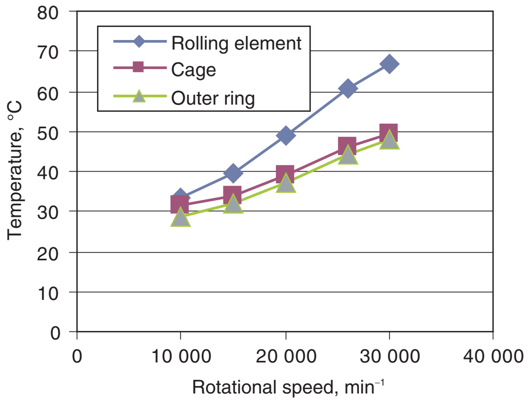


Fig. 4 Bearing temperature (standard)

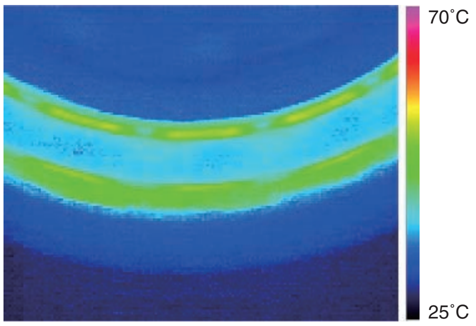


Fig. 5 Bearing temperature (Optimal design, 30 000 min^{-1})

2. 3 Reduction of heat generation inside double row cylindrical roller bearings

It is a known phenomenon that when double row cylindrical roller bearings are rotated at high speed, they heat up rapidly from a certain rotational speed onwards. We investigated this phenomenon using this system.

For this investigation, we used the bearing stand-alone test apparatus shown in **Fig. 6** and made an opening at the end of the spindle in order to measure the bearing internal temperature, as was done for the abovementioned test apparatus shown in **Fig. 1**.

The bearing used was a ϕ100 I.D. double row cylindrical roller bearing with a brass cage as shown in **Table 3**.

The left half of **Fig. 7** shows the result of measuring bearing internal temperature when abnormal temperature rise occurs. Compared with the result of the right half of **Fig. 7**, where there is no abnormal temperature rise occurring, temperature rise of the cage is significant and it is believed that this heat effects the entire bearing, therefore the phenomenon of increased temperature rise at high-speed rotation is surmised to be caused by this heat generation of the cage.

As such, we established the design elements of the cage as parameters and performed an investigation using cage samples with differing lengths as per **Table 3**.

Figure 8 shows the plotted results of the cage rib temperature by rotational speed for each sample. Cage temperature is shown on the Y axis, while rotational speed is shown on the X axis, and it can be seen that depending on the differences in cage rib length, there is a tendency for the cage temperature to rise rapidly once a certain rotational speed has been reached. In other words, the phenomenon of rapid temperature rise when a double

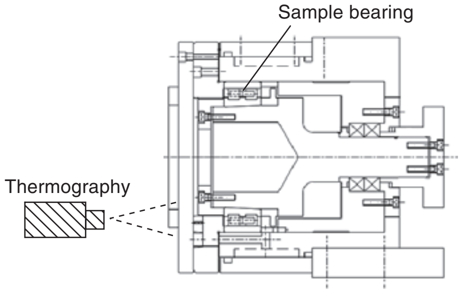


Fig. 6 Test apparatus for cylindrical roller bearing

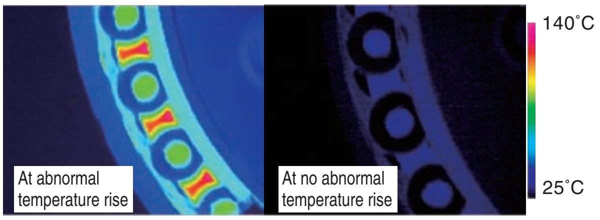


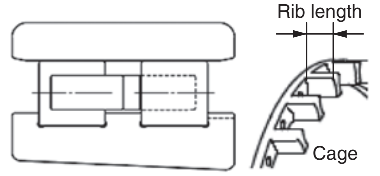
Fig. 7 Cage temperature (8 000 min^{-1})

row cylindrical roller bearing is rotated at high speed is believed to be due to heat generation in the cage rib portion.

Rapid temperature rise of the rib portion is thought to be related to the volume of the rib portion and the rotational speed. This is surmised to be due to the centrifugal force which is applied to the rib portion. We performed an FEM analysis regarding the deformation of the rib portion caused by centrifugal force. The top half of **Fig. 8** shows the results of a deformation analysis while **Fig. 9** shows an image of such deformation.

As shown in the top half of **Fig. 8**, the longer the ribs (bigger the volume), the more deformation occurs on the outer ring due to centrifugal force accompanying the rise in rotational speed. Moreover, the longer the ribs are, the greater the tendency for deformation to begin at low-speed rotation.

Table 3 Test conditions of cylindrical roller bearing

Type	Double row cylindrical roller bearing		
Main dimensions, mm	$\phi 100 \times \phi 150 \times 37$		
Cage material	Brass		
Sample #	#1	#2	#3
Rough shape			
Rib length	Long	Medium	Short
Rotational speed, min^{-1}	3 000 to 12 000		

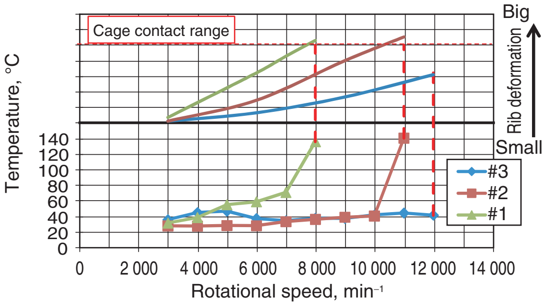


Fig. 8 Cage temperature and a cage deformation FEM analysis results (#1-3 correspond to **Table 3**)

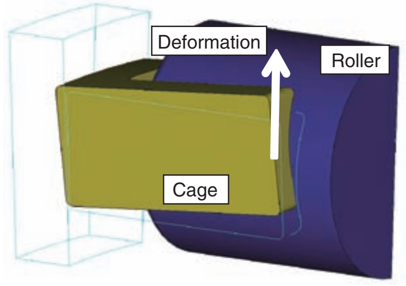


Fig. 9 Deformation of the cage by centrifugal force (FEM)

Comparing the top and bottom halves of **Fig. 8**, there is good consistency between the rotational speed at which rib deformation exceeds the cage contact range and the rotational speed at which the cage temperature rises rapidly, as shown in the bottom half of the figure.

From the above, it can be said that by measuring the temperature of a cage during rotation it is possible to verify the FEM analysis result with actual measurement.

By utilizing FEM analysis and minimizing rib deformation at the same time as optimizing design to also consider the impact on other performances, it was possible to achieve a double row cylindrical roller bearing with an even better low temperature-rise property.

3. Approaches for high-accuracy fluid simulation technology

Bearings for the main spindles of machine tools primarily adopt either the oil/air or grease methods of lubrication. High velocity rotation spindles in particular adopt the oil/air lubrication method. Oil/air lubrication is a method whereby minute amounts of oil controlled at a fixed amount are supplied and delivered together with compressed air to each bearing. Compared with grease lubrication, oil/air lubrication has small mixing resistance and better air-cooling results utilizing compressed air, making it suitable for high velocity rotation. **Figure 10** gives an overview of the oil/air lubrication system.

However, due to the characteristic of oil/air lubrication that it supplies oil to the inside of the bearing from externally with compressed air, not all of the oil/air supplied reaches the inside of the bearing. This is surmised to be because, as **Fig. 11** shows, an air curtain forms between the oil/air discharge port and the bearing during high velocity rotation causing a portion of the oil/air to be pushed back thereby decreasing the ability to supply to the inside of the bearing. In a separate confirmation test, we attempted supplying only oil directly inside the bearing in order not to be effected by the air curtain and by doing so confirmed that equivalent rotational performance could be obtained with only 1/1 000 of the oil supplied during oil/air lubrication. This point differs to the grease lubrication method whereby lubricant is present within the bearing from the beginning.

Based on the above results, in order to clarify the air flow/air curtain behavior within the bearing and determine the best grease nozzle shape and location to effectively supply lubrication inside the bearing, we are collaborating with Toyota Central R&D Labs., Inc using their high accuracy fluid simulation technology[2)] to build a behavior analysis system for the air flow/air curtain behavior within bearings. **Figure 12** shows the simulation results of flow velocity distribution inside a bearing. The flow velocity distribution of **Fig. 12** does not take the nozzle into account however we are gradually clarifying the flow direction and volume of the oil/air ejected from each nozzle in bearings which rotate at high velocity.

Through the knowledge obtained using this system, we will make a proposal for an optimal oil/air supply method with better cooling efficiency in the near future and anticipate it will contribute to achieving even better low temperature-rise bearings.

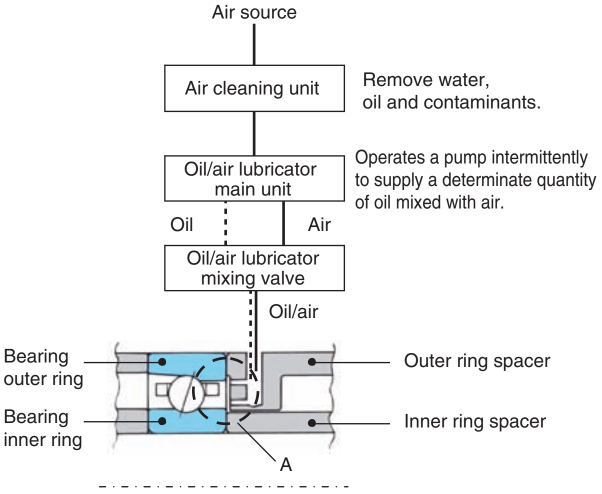


Fig. 10 Oil/air lubrication system

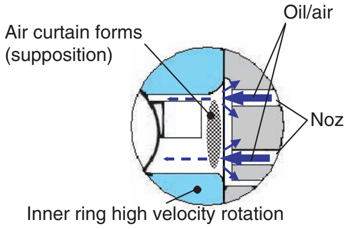


Fig. 11 The air curtain of bearing side (A section)

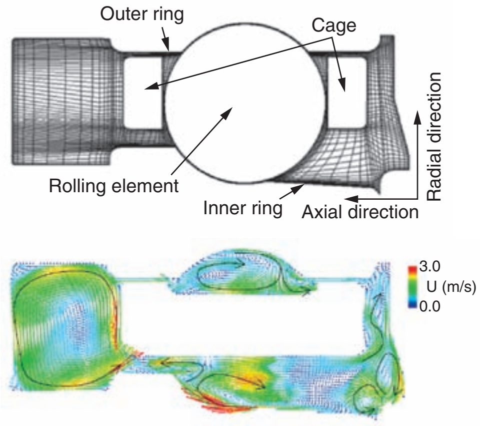


Fig. 12 Flow velocity distribution inside bearing

4. Conclusion

This time, by applying high-sensitivity thermography, we established a technology to accurately measure bearing internal temperature (rolling elements, cages) unable to be measured in the past. By combining this measurement technology with FEM heat generation forecasting we made great progress in regards to reducing bearing heat generation and clarifying the seizing mechanism, which we believe is useful for the design of bearings used in machine tool main spindles and reduction of heat generation in bearings used across all fields.

Moreover, by establishing a high accuracy fluid simulation technology, we will continue to strive for even better low temperature-rise performance and improved product appeal.

By developing low temperature-rise bearings, we believe we can contribute to better machining efficiency and improved quality and accuracy through improving the machining accuracy and high-speed potential of machine tool main spindles. We can also anticipate this will have energy-saving benefits due to a reduction in the power necessary for main spindle cooling.

It is JTEKT's wish to continue developing bearings which can be used by our customers with peace-of-mind and contribute to energy-saving initiatives.

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