Development of Eco-friendly Oil Jet Lubricated Angular Contact Ball Bearings for Machine Tool

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The lubrication system is critical for the high-speed operation of a machine tool. In 1992, NTN developed a complex lubrication system with oil jet lubrication and an under-race lubrication system for angular contact ball bearings with \( d_{mn} \leq 390 \) million (\( d_m = \) ball pitch circle diameter, \( n = \) speed). In order to increase the speed limit of angular contact ball bearings, the “Eco-friendly Oil Jet Lubrication System” was developed. In this paper, the eco-friendly jet lubricated bearing and the lubrication system are introduced. This paper summarizes a test that measured the power loss and temperature of bearings (70mm bore, \( d_{mn} \) value = 500 million) using this new lubrication system.

1. Introduction

Faster rotation of machine tool main spindles is needed to improve the surface quality and machining efficiency of machine tools. The key technologies to accomplish this will increase the speed and accuracy of the rolling bearings that support main spindles. NTN has already established a technology that analyzes the relationship between the accuracy of the bearing components and the bearing vibration under preload \(^1,2,3\). This technology makes it possible to study how to reduce bearing vibration. The speed of rolling bearings for machine tool main spindles depends on lubrication methods which include, in the ascending order of the limiting speed, grease lubrication, air-oil lubrication, oil jet lubrication, and under-race lubrication. In 1992, NTN combined oil jet lubrication and under-race lubrication mechanisms into an angular contact ball bearing of 100mm bore and achieved a \( d_{mn} \) value of 3.9 million \(^4,5,6\). The oil jet lubrication system supplied a jet of lubricant through a nozzle that was facing the inner ring raceway from the outer ring spacer. The under-race lubrication mechanism supplied a lubricant jet from the outer ring spacer to the cylindrical surface of the scoop, which was formed by enlarging the ID of the inner ring end surface. This scoop is connected to the lubricant supply hole leading to the inner ring raceway through the axial through-hole in the inner ring, thus accomplishing supply of the lubricant. Both lubrication mechanisms lubricate the bearing. At the same time, the oil jet lubrication contributes to the cooling effect of the outer ring and the under-race lubrication to the cooling of the inner ring.

As mentioned above, adoption of oil jet lubrication and under-race lubrication increased the speed of the bearings. However, if even faster bearings are desired, these lubrication mechanisms require a driving unit of larger capacity to compensate for the power loss on the bearings caused by a large amount of lubricant that passes through the bearings. This paper describes a new eco-conscious oil jet lubrication mechanism that has reduced the power loss of the bearing and achieved ultra high-speed rotation.

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2. Eco-friendly oil jet lubrication mechanism

The technical issue to be resolved in achieving higher speeds with rolling bearings is reduction in power loss and preload fluctuation. In the oil jet lubrication mechanism, reduction in power loss would require a reduction in the drag against the rotation of the rolling elements aside from the friction torque of the rolling elements at their contact surfaces. To do this, the technology that controls the amount of lubricant inside the bearing is important. Additionally, high-speed operation of a bearing causes the bearing to produce heat, which leads to thermal expansion of the outer ring and inner ring raceways. Furthermore, centrifugal force causes the inner ring raceway to expand and increases preload. Oil jet lubrication cools the outer ring, but its cooling effect on the inner ring is low. Therefore, the oil jet lubrication requires a cooling mechanism for the inner ring.

To resolve these issues, the eco-conscious oil jet lubrication mechanism shown in Figs 1 and 2 was developed. Lubricant supplied to the outer ring spacer is injected towards the scoop formed at the inner ring end surface through the nozzle. Inside the scoop, centrifugal force of the rotating inner ring causes the lubricant to stick to the inner diameter of the scoop. Then the lubricant, moves from the inner ring end surface to the conical surface by centrifugal force and surface tension. At the conical surface of the inner ring, a portion of the outer ring spacer has a ring that creates clearance to allow oil passage. A portion of the lubricant on the inner ring passes through this clearance into the internal structure of the bearing, while the remaining lubricant cools the inner ring. If then flows along the inner diameter, shown on the right side in the figure, of the ring that establishes the clearance. The outer ring spacer consists of a bearing side spacer with a nozzle and a counter bearing side spacer. As shown in Fig. 2, only the nozzle portion of the bearing side spacer protrudes towards the inner diameter and the remainder forms an annulus ring of a larger diameter than the inner diameter of the nozzle. Consequently, the lubricant moving along the inner diameter of the smaller annulus ring moves towards the counter bearing side spacer as shown in Fig. 2.

A special lubrication device is typically installed for the bearings of machine tool main spindles. Fig. 2 shows the lubrication system used for this study where a jacket-cooling device for the machine tool was used as a lubrication device. Here, the oil from the cooling oil delivery device is filtered and fed to the outer ring spacer for lubrication. Oil that has cooled the inner ring is pumped out from the outer ring spacer, and oil that has lubricated the bearing, cooled the outer ring, and then come out of the bearing is returned to the oil recovery tank by the discharge oil pump. The discharged oil is returned from the oil recovery tank back to the cooling oil delivery device for circulation. The lubrication system shown in Fig. 2 does not require any special lubrication devices other than the filter and the discharge oil pump. Thus, this lubrication system incurs less power loss as compared to the traditional oil jet lubrication system, and it requires no cost for the peripheral equipment. That is why this system is called an eco-friendly oil jet lubrication mechanism.
3. Test results

3.1 Test conditions and test equipment

The outer ring temperature of a bearing and power loss of a motor were measured at different bearing speeds using a 70mm bore angular contact ball bearing equipped with the eco-friendly oil jet lubrication mechanism. Fig. 3 shows the structure of the test spindle and Photo 1 shows the appearance of the test equipment. A built-in motor powered the spindle. The spindle was supported by two test bearings and two support bearings. The inner diameter of the support bearings was 35mm. Lubricant was supplied to the test bearings through the orange oil hole at the top indicated in Fig. 3, and it was discharged through the orange discharge hole at the bottom. The test equipment also supplied jacket-cooling oil to the test bearings, motor, and the support bearings. For lubrication of the support bearings, eco-friendly air-oil lubrication was used. A constant preload was used. To compare the test lubrication mechanism to the air-oil lubrication mechanism, the same performance test was conducted on the air-oil lubrication mechanism. The air-oil lubrication was established by 0.03cc/3min of oil and 30NL/min of air.

The primary test conditions are shown in Table 1.

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<th>Table 1 Test conditions</th>
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<td>Test bearing</td>
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<td>Contact angle</td>
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<tr>
<td>Lubricant</td>
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<tr>
<td>Initial preload</td>
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<td>Jacket-cooling rate</td>
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<td>Jacket-cooling oil temp</td>
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<tr>
<td>Race material</td>
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<tr>
<td>Ball material</td>
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<td>Cage material</td>
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Fig.3 Schematic construction of test spindle

Photo 1 Test spindle
3.2 Test results

The test spindle was set at predetermined rotational speeds starting with the lowest speed using an inverter controlled built-in motor. When the bearing speed stabilized, the motor’s power loss and the outer ring temperature were measured. After the measurement, the rotational speed was raised to a pre-determined speed and the test continued until a \( d_{mn} \) value of 5 million was reached. For the air-oil lubrication mechanism, the test was terminated when a maximum speed of 2.5 million in the \( d_{mn} \) value was reached.

Fig. 4 shows a comparison of the motor’s power loss between eco-friendly oil jet lubrication and air-oil lubrication. The delivery rate of the oil jet lubrication was 3L/min. The measured power loss values included friction torque of the support bearing. However, when comparing the eco-friendly oil jet lubrication to the air oil lubrication mechanisms, the differential between the two is simply the differential between the two lubrication methods for the test bearing. In the same figure, the power loss of eco-friendly oil jet lubrication is about the same as that of air-oil lubrication. The test for the air-oil lubrication mechanism finished at the \( d_{mn} \) value of 2.5 million, but even if the measured value is extended up to 5 million in the \( d_{mn} \) value, the power loss in the eco-conscious oil jet lubrication is about the same as that of the air-oil lubrication. The support bearings were smaller in size as compared to the test bearings. If the power loss in the support bearings is zero, the power loss in the eco-conscious oil jet lubrication at the \( d_{mn} \) value of 5 million was below 8kW.

A quantitative discussion of the preload changes associated with the rising rotational speed would require measurements of the outer ring and the inner ring temperatures as well as calculations of the centrifugal expansion of the inner ring. In this test, however, the outer ring temperature in the eco-conscious oil jet lubrication method was verified to be within the operating temperature range.

Fig. 5 shows a comparison of the temperature rise of the outer ring between the eco-friendly oil jet lubrication and the air-oil lubrication methods. The delivery rate of the eco-friendly oil jet lubrication mechanism was 3L/min. In this figure, it is clear that the eco-friendly oil jet lubrication method is superior to the air-oil lubrication method in terms of the temperature rise in the outer ring. Also confirmed was the fact that the temperature rise in the outer ring for the eco-friendly oil jet lubrication mechanism at a \( d_{mn} \) value of 5 million was below 60°C.

For the eco-friendly oil jet lubrication method, the amount of the lubricant delivered inside the bearing seems to determine the friction torque of the bearing as well as the cooling capability of the outer ring. Fig. 6 shows the measurements of power loss for the eco-friendly oil jet lubrication method with different oil delivery. In this figure, the delivery rate of the eco-friendly oil jet lubrication mechanism was measured at the nozzle, and it was not the amount of the lubricant that passed through the bearing. The discussion of the measurement results, however, assumed that the oil flow through the bearing is proportional to the delivery rate at the nozzle. Fig. 6 shows that the more oil was delivered inside the bearing, the larger the power loss values.
power loss. It also shows that, at higher revolutions, the rate of power loss became greater as the oil delivery increased.

Fig. 7 shows the temperature rise of the outer ring at different lubricant delivery rates using the eco-friendly oil jet lubrication method. The outer ring temperature dropped as the lubricant delivery increased. At low revolution rates, increase in the lubricant delivery rate did not significantly cool the outer ring, but as the revolution rate became higher, the cooling effect on the outer ring increased. In the figure, the delivery rates in the air-oil lubrication at $d_{an}$ 0.9 million and $d_{an}$ 1.8 million were plotted as being close to zero. However, since these points are almost on the extension lines of the measurements of oil jet lubrication, we can say that the amount of lubricant delivered into the bearing determines the cooling efficiency of the outer ring.

Since the relationship of the lubricant delivery rate for oil jet lubrication and friction torque on the bearing is opposite that of the lubricant delivery rate for oil jet lubrication and cooling efficiency, the optimal lubrication conditions for machine tool main spindle bearings can be determined by selecting a proper lubricant delivery rate for the eco-friendly oil jet lubrication mechanism.

4. Conclusion

To meet the needs for increased speeds in main spindle bearings for machine tools, we have developed an eco-friendly oil jet lubrication mechanism with less power loss and fewer changes in bearing temperatures. This lubrication mechanism was successfully applied to a 70mm bore angular contact ball bearing at an operating speed of $d_{an}$ 5 million. It is our hope that this lubrication mechanism will contribute to the development of faster machine tools.

References

4) M. Mori and M. Niina, NTN TECHNICAL REVIEW No.60(1992)41, (in Japanese)