Technical Trends of Machine Tools and Spindle Bearings

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Since precision and productivity of machined products directly depend on the performance of a machine tool spindle such as for a machining center, the spindle is an especially important component. So, spindle bearings are always required to have high performance and reliability. Here recent trends in machine tools and their spindle bearings are presented. And then, new technology required for further development of spindle bearing for machine tools is also presented.

Key Words: machine tool, spindle bearing, high speed, high stiffness, high ability

1. Introduction

Machine tools are called "MOTHER MACHINES" as they are "machines that make machines" and play an important role in supporting the basis of industry. For improving machine tool performance, it is essential to improve the performance of components and units of the machine tool. Especially, to improve the performance of the spindle unit is important as it directly affects the machining accuracy as well as the processing efficiency. Thus, to improve the performance of spindle bearings is very important.

This paper presents recent trends of machine tools, spindle bearing technology that has contributed to the progress of machine tool. It also presents an outlook of spindle bearing technology that will be required for further advancement of machine tools.

2. Technical Transition of Machine Tools and Spindle Bearing

2.1 Machine Tools and Spindle Bearing Technology before the Spread of Machining Centers

Figure 1 shows the technology overview of spindle bearings along with the trends of machine tools. Before 1980s when the machining centers spread, machine tools that operated at low speed under heavy loads such as lathes or milling machines had dominated the market, whereas those that operated at high speed were used for relatively limited areas like internal grinding. For the spindles of the lathes or milling machines, which were not required to operate at high speed, bearing arrangements providing high-stiffness were often employed. On the other hand, for the spindle of the internal grinding machine whose machining resistance is low, bearing arrangements providing high good-high speed performance were often employed since stiffness was not so much required.

Thus, requirements for machine tool spindles before the spread of machining centers were either focused on high-stiffness or high-speed performance. Thus, standard bearings could be applied by selecting appropriate bearing types or preloading methods.

2.2 Machining Centers and Spindle Bearing Technology

A machining center is a numerically controlled machine tool and various machining process can be performed with one machine by automatically changing tools according to the work plan. In other words, as the machining center is required to perform various machining processes ranging from heavy cutting at low speed to light cutting at high speed, the spindle has been required to provide both high-stiffness and high-speed performance. As shown in Fig. 2, however, high-stiffness performance and high-speed performance are contradictory requirements on the spindle bearings and it is sometimes hard to satisfy both requirements with standard bearings.

In order to satisfy both the high-stiffness and the high-speed performance, either a high-stiffness bearing may be made to cope with high speed, or a high-speed bearing may be made to handle the high-stiffness requirement. High-stiffness bearings, however, are not suitable for high-speed operation since their friction loss tends to be large depending on the contact conditions between the raceways and the rolling elements.

On the other hand, an angular contact ball bearing with high-speed capability provides low stiffness in a single row due to point contacts between the raceways and the rolling elements. However, it is possible to increase the stiffness by employing a proper multiple row arrangement.
Fig. 1 Technical trends of spindle bearings for machine tools

<table>
<thead>
<tr>
<th>Performance requirements on spindle</th>
<th>1970s</th>
<th>1980s</th>
<th>1990s</th>
<th>2000s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-stiffness-oriented or high-speed-oriented</strong> (polarized)</td>
<td>Lathe, milling machine</td>
<td>Internal grinding machine</td>
<td>Both high-stiffness and high-speed are necessary</td>
<td>To cover wide range of works is necessary: from heavy cutting at low speed to light cutting at high speed</td>
</tr>
<tr>
<td><strong>Development of oil &amp; air lubrication</strong></td>
<td></td>
<td>Development of ceramic bearings</td>
<td>Development of high-speed angular contact ball bearing (ACH bearing)</td>
<td>Development of high performance angular contact ball bearing (High-ability bearing)</td>
</tr>
<tr>
<td><strong>Prevailing machine tools and typical bearing arrangements</strong></td>
<td>Double row cylindrical roller bearing + Double direction angular contact thrust ball bearing + Double row cylindrical roller bearing</td>
<td>Angular contact ball bearings only (Constant-pressure preloading) Internal grinding machine</td>
<td>Angular contact ball bearings (Position preloading) + Single row cylindrical roller bearing</td>
<td>Machining centers</td>
</tr>
<tr>
<td><strong>Main technology for spindle bearings</strong></td>
<td>Development of oil &amp; air lubrication</td>
<td>Development of ceramic bearings</td>
<td>Development of high-speed angular contact ball bearing (ACH bearing)</td>
<td>Development of high performance angular contact ball bearing (High-ability bearing)</td>
</tr>
</tbody>
</table>

Fig. 2 Stiffness and rotational speed of spindle bearings
and proper position preloading.

However, when the bearings are used with position preloading, the preload can be increased by thermal expansion due to heat generation or centrifugal force acting on the rolling elements, which may eventually cause such a bearing failure as seizure at high-speed rotation.

In an attempt to improve high-speed performance under position preloading, therefore, it is imperative to restrict the increase of preload during operation. To this end, it is effective to reduce the thermal expansion or the centrifugal force acting on the rolling elements.

Ceramic bearings (incorporating a ceramic material for the rolling elements) developed in 1984 contributed to the restriction of preload increase by reducing both the thermal expansion of the rolling elements and the centrifugal force acting on the rolling elements thanks to the smaller coefficient of linear thermal expansion and lower density of the ceramic material (see Table 1). In addition, the higher Young’s modulus of the ceramics also increased the bearing stiffness (by a factor of approximately 1.1 compared to conventional steel one according to a test result in-house).

Furthermore, the high-speed angular contact ball bearing (ACH Bearing) developed in 1985 contributed to the restriction of preload increase by further reducing the centrifugal force associated with smaller-diameter rolling elements. Furthermore, stiffness of single ball bearing was also improved (by a factor of approximately 1.1 compared to conventional ones according to a test result in-house) because the smaller rolling element diameter allowed the bearing to accommodate a greater number of rolling elements.

Adoption of ceramics and high-speed angular contact ball bearings (ACH Bearing), combined with the spread of oil & air lubrication, has enabled extremely high-speed operation under position preloading. This has in turn realized both high-stiffness and high-speed performance simultaneously in machining center spindles.

### Table 1 Comparison of properties between ceramics and bearing steel

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit</th>
<th>Ceramics</th>
<th>Bearing steel</th>
<th>Benefit of ceramics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat resistance</td>
<td>°C</td>
<td>80</td>
<td>180</td>
<td>Adaptable to high temp. environment</td>
</tr>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>32</td>
<td>78</td>
<td>Reduction of centrifugal force</td>
</tr>
<tr>
<td>Coefficient of linear thermal expansion</td>
<td>1/°C</td>
<td>3.2×10⁻⁶</td>
<td>125×10⁻⁶</td>
<td>Reduction of thermal expansion</td>
</tr>
<tr>
<td>Vickers hardness</td>
<td>HV</td>
<td>1 300~2 000</td>
<td>700~800</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>GPa</td>
<td>32</td>
<td>28</td>
<td>Increased stiffness</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>–</td>
<td>0.29</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>W/(m·K)</td>
<td>29.3</td>
<td>41.9~50.2</td>
<td></td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>–</td>
<td>Good</td>
<td>No Good</td>
<td></td>
</tr>
<tr>
<td>Magnetism</td>
<td>–</td>
<td>Non magnetic material</td>
<td>Ferromagnetic material</td>
<td></td>
</tr>
<tr>
<td>Electric conductivity</td>
<td>–</td>
<td>Insulant</td>
<td>Electric conductor</td>
<td>No electric pitting</td>
</tr>
<tr>
<td>Bonding form of material</td>
<td>–</td>
<td>Covalent bond</td>
<td>Metallic bond</td>
<td>Improved anti-seizure</td>
</tr>
</tbody>
</table>

With increased demands for high efficiency processing, higher machining speed for reduced processing time, and improved acceleration/deceleration for reducing non-processing time has become indispensable for spindle bearings.

With the rise of built-in motors on the spindle, heat generation in the spindle has increased, necessitating a cooling system around the spindle housing. Installing a cooling system tends to increase the temperature difference between the inner and outer raceway rings of the bearing, from which an excessive preload can result. Because of this problem, the development of a new spindle bearing design not susceptible to external thermal factors has become necessary.

Recently more emphasis has been placed on the minimization of such environmental burdens as oil scattering, noise or energy consumption.

In response to these demands, High Ability Bearings\(^2\) have been developed. The High Ability Bearings are angular contact ball bearings, which have had their internal geometry optimized in terms of ball diameter, raceway diameters, contact angle, etc. This has had a significant influence on the bearing performance (e.g. limiting speed has been improved by a factor of 1.3 compared to conventional ones according to test results in-house).
Figure 3 summarizes the results of a high-speed test conducted on a grease-lubricated High Ability Bearing and an oil & air-lubricated ACH bearing (high-speed angular contact ball bearing predecessor of High Ability Bearings). It has shown that the grease-lubricated High Ability Bearing, having equivalent or better high-speed capability, can replace an oil & air-lubricated spindle unit with a grease-lubricated spindle unit. Utilization of grease lubrication on the spindle has not only reduced environment burdens, such as oil scattering and noise, but also helped to reduce the cost by doing away with lubrication apparatus as well as simplifying of the spindle structure.

Figure 3 Result of high-speed test for High Ability Bearing

3. Prospect of Bearing Technology

Recently, as seen in the exhibitions of machine tool manufacturers at the Japan International Machine Tool Fair (JIMTOF), the development of multifunction machines and the downsizing of machine tools have been actively pursued in the machine tool market.

A multifunction lathe, which is a typical multifunction machine, combines a turning function and a main spindle to perform milling operation (hereinafter called mill spindle). As the machine can cut complex shapes of workpieces without a loading and unloading operation, it is effective in shortening production lead-time. As this mill spindle is required to change its position over many angles within a limited space, it expected to be compact and simple (i.e. contain no piping for lubrication).

The downsized machines, on the other hand, have contributed to the enhancement of productivity per unit of area on the factory floor. In these cases, too, the spindle should desirably be compact and simple.

In order to realize such a spindle, it would be effective to use grease-lubricated bearings since additional lubrication apparatuses or piping is not necessary. It would also be beneficial for lowering cost and reducing of environmental burdens through limited oil scattering, low noise and energy saving operation.

Thanks to the development of the High Ability Bearings, the potential application range of grease-lubricated spindle bearings has been significantly expanded. However, because the grease itself has a certain service life, it is difficult to use grease-lubricated bearing at high speed for long time without re-lubrication.

In such background, JTEKT has worked on developing an All-in-One Bearing as shown in Fig. 4, in which a self-sustained lubrication system is integrated. As it will be able to supply a minimal amount of lubricant only where and when it is required, the All-in-One bearing is expected to have the following advantages compared to the currently prevailing oil & air lubrication systems:

- Simplified spindle structure (Lubrication piping is not necessary)
- Compact machine size (External lubrication apparatus is not necessary)
- Low cost (External lubrication apparatus and holes for piping are not necessary)
- Minimum oil scattering (Minimum lubricant is used)
- Low noise (Compressed air is not necessary)
- Energy saving (Compressed air is not necessary)

4. Conclusion

Spindle bearing technology and machine tools have been advancing in close correlation. Now that JTEKT has been formed, further in-depth cultivation of technology in this area is expected as the fundamental technology.

From now on, it is expected that more first-hand data from the field machine tests and evaluations will be fed back effectively into the development of bearings. This will enable the targets of the development to be defined more clearly, and the development period to be shortened. In doing so, we will continue our efforts not only to further improve the bearing technology, but also to enhance the analysis method of viewing the bearing as a part of subsystem of a machine (e.g. analysis of...
relationship between bearing accuracy vs. installation conditions and work accuracy). In doing so, we will continue to contribute to the development of the bearing technology for machine tools.

In the future, we would like to develop such a fascinating product as a self-tuning spindle bearing unit that incorporates a real time monitoring device which can optimize the preload and lubrication parameters according to the monitored conditions utilizing sensor technology.

References