Various kinds of production systems have been established with high efficiency and flexibility in order to respond to the diversification of customer needs and machining cost reduction requests from makers. Manufacturing machines, which are considered to be at the core of the production system, play a very important role in achieving high machining capability and efficiency. Machining centers, which can be considered general purpose manufacturing machines, have recently made rapid advances with regard to their high efficiency. The main spindle is one of the most important parts of a machine tool for achieving this high efficiency, and the main spindle bearings are an essential component for promoting high-speed operation. This paper presents the current status and future technical trends for main spindles and bearings.

1. Introduction

Various kinds of production systems have been established with advanced efficiency and flexibility in order to respond to the diversification of consumer needs and user demands of cost reduction. Manufacturing machinery functions as the core of the production system, and therefore improving capability and efficiency of such machinery is extremely important.

Machining centers are production machinery designed for general use. In recent years there has been striking progress in high-efficiency machining of machining centers. Using multi-thread ball screws or linear motors for feeding the table and main spindle has made feed rates of 60 m/min or more possible. Machining centers having feed rates of 80 to 100 m/min have also been developed and are now being improved for practical use.

In the MAS standard BT40 class, the main spindles for machining work are becoming capable of higher speeds and output. The main spindles of this size are generally operating at speeds between 20,000 to 30,000 min⁻¹.

As a result of progress related to inverters, spindles are being equipped with motors rated at 30 kW of power or higher. For some spindles, automatic tool changing (ATC) time is now less than one second, and the percentage of actual machining time during the total machining cycle time is steadily increasing.

As shown in Fig. 1, when automobile part machining simulation is done, based on the current level of manufacturing machinery, main spindle high-speed operation directly involved in actual machining time is an important factor in high-efficiency machining.

This paper reports on the current status and future direction of the main spindle, one of the important factors for highly efficient machining, and rolling bearings, which contribute to higher speeds.
Table 1 Results of analysis of machine tools exhibited at the 19th Machine Tool Trade Fair, held in Osaka in 1998

| Maker | Machine       | Spindle style | Speed, min⁻¹ | Max spindle diameter, mm | Taper No. | Lubrication method          | Rolling element material | Bearing preload method | Drive system | dn value, x10⁴ |
|-------|---------------|---------------|--------------|--------------------------|-----------|-----------------------------|-------------------------|------------------------|--------------|----------------|----------------|
2. Transition of High-Efficiency Machining

Machine tools have evolved along two parallel routes to meet the production demands of productivity and flexibility. To meet the flexibility requirements of modern industry, the machining center evolved along the first route by taking numerical control (NC) and integrating it with the function provided by the automatic tool changing (ATC). To meet the high productivity demands and thereby address the question of how economical mass production can be, the second path that was followed combined the single purpose machine and the NC special purpose machine based on the process allotment concept and evolved into the transfer machine (TR). Transfer machinery can provide quality assurance with an extremely high productivity rate relative to initial investment. The current trend has manufacturers attempting to control the increase of part types by making common parts for diversified production; however, the number of items continues to increase steadily. In order to settle this problem, Flexible Line Transfer (FTL), or being able to handle various kinds of machining by automatic change of many spindle heads etc., has been developed and has come to be introduced. But FTL is said not to have enough flexibility to satisfy production requirements. Furthermore, the development of machine tools with higher efficiency than present ones is probably desired.

3. Trends Related to High-Speed Main Spindles

3.1 High-Speed Spindles

Increasing the main spindle speed is an important element in raising production efficiency. To study the high-speed spindles, Koyo conducted a study of bearings mainly for machining centers at the 19th JIMTOF held in November 1998. Results corresponding to high-speed spindles are given in Table 1.

Table 1 shows that many spindles can be operated at speeds of 15 000 to 30 000 min⁻¹. Because in this speed range there are problems related to belt and gear drive heat generation, output, vibration, etc. that are difficult to handle, spindles with built-in high-output motors are often used. Also spindles for machining center, not only run at high-speeds but have variable functions for the purpose of increasing machining efficiency. Because of this, machining of 4 000 cc/min or more is possible. An example is given in Table 2.

Table 2 Milling of aluminum (example)

<table>
<thead>
<tr>
<th>Face mill of φ80 with four blades</th>
<th>Cutting volume 4 000 cc/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main spindle speed 11 500 min⁻¹</td>
<td></td>
</tr>
<tr>
<td>Feed rate 18 400 mm/min</td>
<td></td>
</tr>
<tr>
<td>Machining width 50 mm</td>
<td></td>
</tr>
<tr>
<td>Machining depth 40 mm</td>
<td></td>
</tr>
<tr>
<td>End mill of φ32 with two blades</td>
<td>Cutting volume 3 000 cc/min</td>
</tr>
<tr>
<td>Main spindle rotation speed 20 000 min⁻¹</td>
<td></td>
</tr>
<tr>
<td>Feed rate 12 000 mm/min</td>
<td></td>
</tr>
<tr>
<td>Machining width 20 mm</td>
<td></td>
</tr>
<tr>
<td>Machining depth 12 mm</td>
<td></td>
</tr>
</tbody>
</table>

Here, an example of a built-in type high-speed main spindle is shown in Fig. 2.

The spindle has a tapered bore at the end to mount a tool holder, but recently manufacturers are switching from the retaining system of the tapered part only to the two-surface constraining system that holds the tool holder due to contact at both the inside taper and spindle shoulder. On the tool side, four rows of ceramic angular contact ball bearings with ceramic balls are used for the bearings that support this spindle to increase spindle rigidity, and two rows of ceramic angular contact ball bearings are similarly used for the rear. Angular contact ball bearings that have little bearing internal loss and enable high precision are commonly used in many cases for high-speed spindles. For these bearings, ceramic balls have low specific gravity and little effect of centrifugal force at high-speed, and are therefore used more often as rolling elements than steel balls. Also, the bearing preload shown in Fig. 2 is a method of constant preload given by springs. In addition, there is also preload given by locating method that controls axial clearance of the bearing. Preload given by the locating method is often used for high speeds.
Both preload methods have their respective characteristics regarding rigidity, temperature rise and vibration, and are properly selected according to running conditions.

Also, the following functions are also required of main spindles for machining centers in addition to high speed performance.

1) Drawbar for automatic tool changing
2) Through tool cooling
3) Small main spindle heat displacement
4) Orientation
5) High power
6) High rigidity
7) Easy main spindle assembly

3.2 Bearings for High-Speed Main Spindle

A summary of Table 1 concerning trends of bearings for high-speed main spindles is as follows:

1. Bearings with ceramic rolling elements are often used for main spindles in which the $dn$ value (bearing inner diameter $mm \times$ rotation speed $min^{-1}$) is in excess of 1,000,000. It can be said that ceramic rolling elements are generally used. With the use of ceramic rolling elements and oil/air lubrication as the lubrication method, a $dn$ value of 2,000,000 ($d, n$ value: approx. 2,500,000, $d, n$ value is bearing P.C.D. $mm \times$ rotation speed $min^{-1}$) has become practical. With the use of ceramic rolling elements and grease as the lubrication method, a $dn$ value 1,000,000 ($d, n$ value: approx. 1,250,000) has become practical.

2. The most commonly used lubrication methods are oil/air lubrication and oil mist lubrication. Because jet lubrication requires a large amount of lubricant and complicated ancillary equipment and has large dynamic loss due to stirring resistance of the lubricant, it tends to be avoided.

3. Roller bearings and hydrostatic air bearings are used to support machine tool spindles. Problems associated with hydrostatic air bearings are low load capacity, low rigidity and high cost. Rolling bearings therefore occupy the majority of the market. Spindles using magnetic or hydrostatic air bearings can be found, and those that install both these bearings to cover the weak points of each other were exhibited.

4. Bearing makers have exhibited prototype spindles with locating method preload, ceramic rolling elements, oil/air lubrication and shaft-center cooling to make rolling bearing speeds of $dn$ value 3,000,000 ($d, n$ value: 3,600,000) possible.

Further means of increasing the speed of rolling bearings include improving centrifugal force, rigidity, heat generation, life and lubrication method. Reduction of bearing centrifugal force is considered from the aspect of internal design. If the ball diameter is made smaller, the effect of centrifugal force is reduced (even more in case of ceramic balls), the sliding of balls is diminished, and heat generation is restrained. Displacement relative to load is also reduced, as shown in Fig. 3.

We have given attention to ball diameter and the number of balls (if ball diameter is larger, the number of balls in the bearing is reduced; if ball diameter is smaller, the number of balls increases; the number of balls is naturally decided according to the ball diameter) and the relationship with rigidity in Fig. 3.

![Fig. 3 Relationship between ball diameter, number of balls and displacement](image)

It is known that if the ball diameter is reduced and the number of balls increases, rigidity goes up. However, if ball diameter becomes smaller, the basic dynamic load rating decreases, and therefore the calculated life is reduced. As a life improvement countermeasure, ceramic, carburized steel, or high refining steel can be used as the material for the raceways or rolling elements, and the rolling surfaces can receive carburizing or carbonitriding treatment. Critical circumferential stress is improved if a carburizing or carbonitriding part is used for the raceway, and therefore such parts are also effective for centrifugal fracture. In addition to supplying oil from the side, lubrication methods to improve bearing lubrication reliability include supplying oil from the outer ring side (see Fig. 4) and under-race lubrication.

By considering these themes, a $dn$ value of approximately 4,000,000 would be possible for rolling bearings.

![Fig. 4 Bearing with an oil inlet hole (example)](image)
4. Conclusion

Items to study in relation to high-efficiency machining include discharge of chips, transfer rate of the main spindle, transfer rate of the work, the blade change rate and the acceleration/deceleration time of main spindle. Of these, raising the main spindle speed is considered most effective.

Using ceramic for the rolling elements and oil/air lubrication for the lubrication of high-speed main spindle bearings has made a dn value 2 000 000 (dmn value: approx. 2 500 000) possible, and using ceramic for the rolling elements and grease for lubrication has made a dn value of 1 000 000 (dmn value: approx. 1 250 000) possible. Furthermore, using the spring preload method and cooling through the center shaft has shown the possibility of enabling a dn value of 3 000 000 (dmn value: 3 600 000).

It is believed that machining speed will continue to increase in the future, but bearings must be improved comprehensively in the areas of centrifugal force (centrifugal fracture, etc.), rigidity, vibration, unbalance, heat generation, life, drive method, lubrication method and simplification of lubrication equipment.

Also, overcoming conflicting items will probably be a theme in the future.

References