Spindle Design Technology for High Speed Machine Tools

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ABSTRACT

The spindle unit is core parts in high precision machine tools. Diverse static, dynamic and thermal charateristics of spindle unit are needed for special purpose of machine tools. Compromise between those charateristics will be done in concept design phase. High static stiffness at spindle nose may be very important performance for heavy cutting work. High dynamic stiffness is also useful to high precision and high speed machine tools. Improvement of thermal charateristics in spindle lead to high reliability of positioning accuracy. For high speed spindle structure, the design parameter such as, bearing span, diameter, bearing type and arrangement, preload, cooling and lubrication method should be in harmony.

Key Words : High Speed Spindle, Bearing Type & Arrangement, Spindle Optimization, Static & Dynamic Weak Point, Thermal Deformation, Bearing Preload Control, Cooling System, Built-In Motor Spindle, Sensor Bearing, Cutting Force Monitoring

1. Introduction

High speed machining techniques to shorten machining process time and machining costs significantly alter the characters of machine tools(Fig.1). Cutting forces are lower than in conventional machining processes because higher spindle speeds are used, thickness of chips is very thin. So, High speed machining process is now used for not only aluminum alloy materials but also for difficult cut quenched steel(Fig.2). On the other hand, axis feed rates and accelerations / deceleration are significantly higher than conventional machining processes. As a result, the dynamic loads placed upon the machine can be very high. Beyond the loads of ballscrew and support bearings by high speed table, loads of spindle unit must also be considered.

Because the spindle unit is composed of relative weak bearings with point or line contact between spindle and housing, the dynamic loads play an larger role in the design of high quality spindle units. With the magnitude of dynamic loads, the excitation frequency generated by cutting can not be neglected. High speed cutting work can easily become a source of unwanted vibration for spindle units. To achive high static and dynamic stiffness, rotational accuracy, good damping, thermal stability in high speed spindles, many difficult problems, such as selection of bearing type and arrangement, optimization of spindle design parameter, control of bearing preload, selection of lubrication and cooling methods will be discussed through examples.

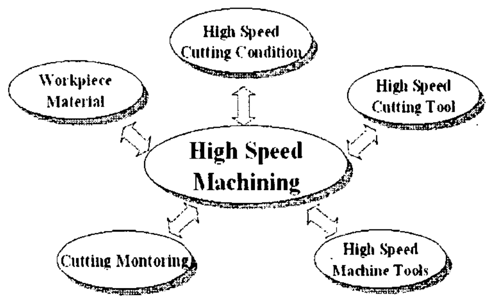


Fig. 1 Component Technology of High Speed Machining

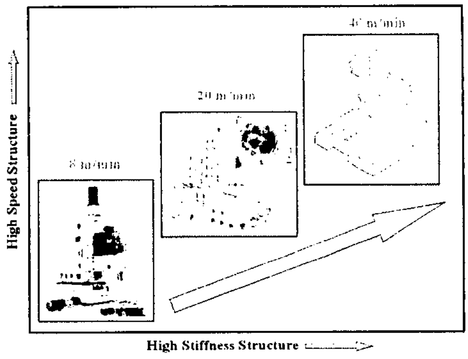


Fig. 2 High Speed and High Stiffness Design Trend of Modern Machine Tools

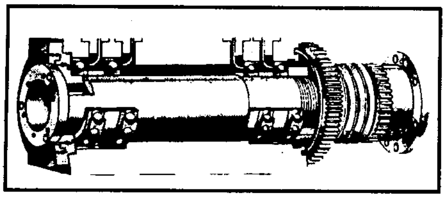


Fig. 3 Machine Tool Spindle with Ball Bearings for Lathe (SKF)

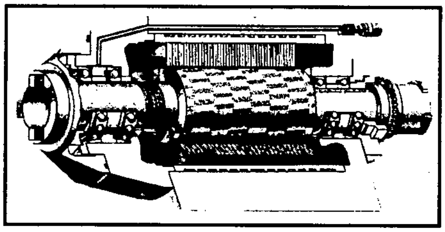


Fig. 4 Machine Tool Spindle with Ball Bearings and Built in Motor for Machining Center (SKF)

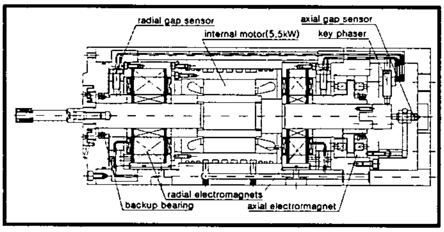


Fig. 5 Machine Tool Spindle with Magnetic Bearings for Internal Grinding Machine (KIMM)

2. Selection of spindle bearings type and arrangement

The Spindle unit is weak interface with points or lines contact between the workpiece and the machine tool. So, spindle play a critical role in high precision and high speed machine. First, selecting the right spindle bearing type and arrangement is necessary to strengthen the stiffness, to increase load capacity and to stabilize thermal characteristics of spindle structures. In order to select best bearing type , the magnitude and direction of cutting force, rotating speed, spindle shape, impact state, enviromental condition must be considered. Since, as a rule, the main demand for spindle bearing in high speed machine tool is more speed and accuracy than load capacity and stiffness, the angular contact ball bearing with steel balls or ceramic balls(for high stiffness) is popular(Fig.3), together with aero static bearings and active magnetic bearings(Fig.5). But, because the aero and magnetic bearings have low radial stiffness and damping, non standard dimsion and high maintenance cost property, for general high speed machine tools those bearings are not suitable. Until recently, most spindle system was composed of rotating shaft and outside motor connected by belt. Now, as the use of belt driven spindle is limited by rotating vibration (at about 12,000 rpm), the built in motor spindle is used for high speed(Fig.4). In this case the cooling system in spindle is inevitable to reduce the internal heat of rotor and stator. The maximum temperature rise in rotor without cooling system is generally 110°C.

The bearing arrangements often adopted for high speed machine tool spindles are back-to-back or tandem duplex / four-row angular contact ball bearing in fixed end, duplex angular contact ball bearing / cylindrical roller bearings (high stiffness in rear side) in free end. The change of static stiffness at spindle nose related to selecting bearing arrangements is not small. But bearing arrangements must be selected and compromised in consideration of static and thermal properties of spindle systems.

3. Optimization of spindle structure and improvement of weak point

The spindle system is composed of two kind parts, standardized parts such as bearings, bolts, shank and nonstandardized parts such as spindle shaft, cooling jacket. The design dimension of spindle in concept phase depend on discrete standardized parts that is manufactured in noncontinuous dimension. So, dimension of spindle unit should not be changed continuously in design range to get optimal properties.

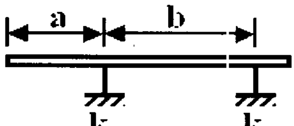
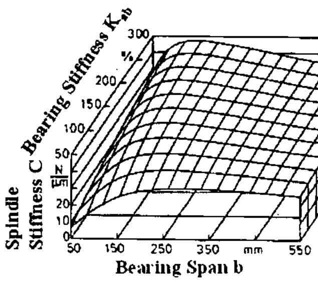


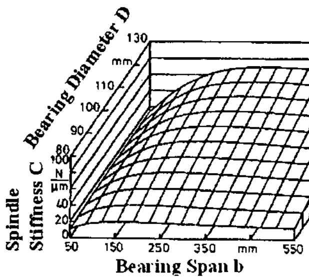
Fig. 6 Simplified spindle model with front and rear Bearing

To optimize spindle structure, three design parameters for example bearing span b between front and rear bearing, bearing stiffness $k_{a,b}$, bearing diameter D are usually used(Fig.6). The static deformation y_1 and stiffness C at spindle nose is described mathematically below

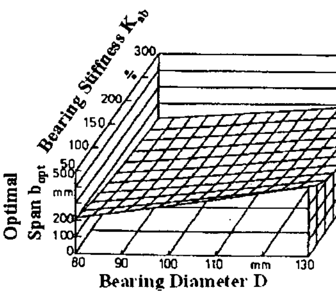
$$y_1 = \frac{F(a+b)a^2}{3EI} + \frac{F}{b^2}\left[\frac{a^2}{K_b} + \frac{(a+b)^2}{K_a}\right] \qquad C = \frac{F}{y_1}$$



a) Stiffness according to span, diameter



b) Stiffness according to span, bearing stiffness



c) Optimal span according to diameter, bearing stiffness

Fig. 7 Static stiffness at spindle nose and optimal bearing span according to spindle diameter, bearing stiffness

As shown in Fig.7(a), the spindle stiffness at nose is changed according to bearing span. When a small or large span is chosen, the spindle stiffness is small. In case of choosing middle size span, the stiffness is bigger. It implies that optimal bearing span is in existence, so that spindle stiffness is maximum at optimal span. With increasing bearing stiffness, the spindle stiffness increases step by step and the optimal span is reversely smaller. When bearing diameter increases to 160%, the spindle stiffness increases to 300%. Fig.7(c) depicts that the optimal span decreases when bearing stiffness increases and bearing diameter decreases. Hence compact spindle unit can be designed with small optimal bearing span.

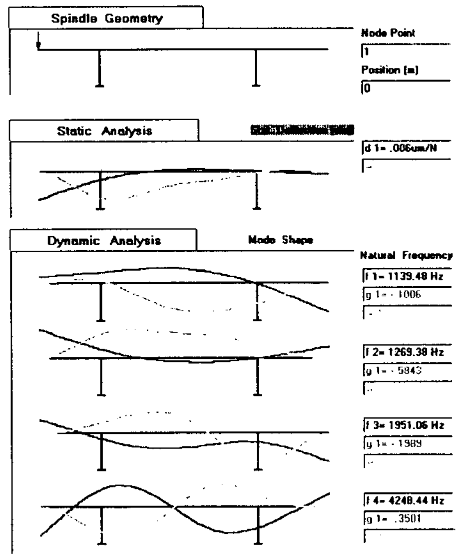


Fig. 8 Static and dynamic deformation analysis (black), allocation of static and dynamic weak points in spindle system (grey)

The optimization of spindle by bearing span is done. Change of bearing span help strengthen spindle stiffness. However, the weakest point of spindle is still in existence. To improve the weak point in spindle, the bending curve of spindle is analyzed in consideration of load point. This method is very useful to selection of improved points, which can be modified under design boundary in practice. Fig.8 show the weak points analysis for static and dynamic deformation. In this case, the static weak point is the area near front bearing, where the magnitude of grey curve is big. The improvement at weak point is suggested by the increase of spindle diameter in some length. The dynamic weak points are very different depending on natural frequency and mode shape of spindle. So, the improvement at some frequency is bed spindle modification for another frequency. Usually, first natural frequency and mode shape are very important for resonance vibration related to operation speed of spindle, which is near to first natural frequency. When the operation spindle speed is near to some natural frequency, the some mode shape should be selected for dynamic weak point analysis. In Fig. 8, the dynamic weak point is the spindle area between front and rear bearing at first mode shape.

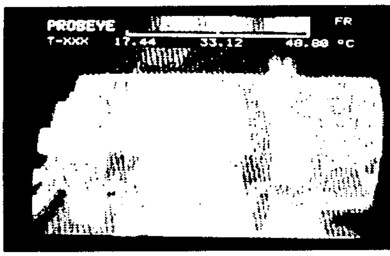


Fig. 9 Temperature distribution of built in motor type high speed spindle

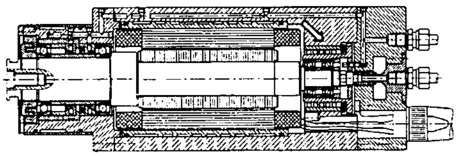


Fig. 10 Constant pressure preload control unit (GMN)

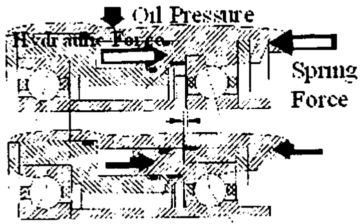


Fig. 11 Constant pressure preload control unit with hydraulic power(2)

4. Low heat generation in high speed spindles

Whether spindle is motorized, belted or geared, all spindle change temperature during operation. Spcially, high speed spindle generate heat very much in bearings, which rotate over 8,000 rpm with increase of gyroscopic moment and centrifugal force(Fig.9). The heat in spindle causes thermal expansion and contribute to inaccuracy in machining. To reduce the centrifugal force, miminizing the density of rolling elements, ball diameter and contact angle are effective. Ceramic bearing is generally used for high speed spindle. Ceramic balls have high heat resistance, high corrosion resistance, low density. In addition, a bearing using not only ceramic rolling elements but also a ceramic inner / outer race has been develolped to reduce deformation of the inner race by centrifugal force and to have small coefficients of thermal expansion. Air-Oil or Jet lubrication is used to lubricate the high speed spindle. Air-Oil lubrication supplies the lubricant at the rate of 0.003-0.004 cm^3 /min per bearing, minimizing heat generation. In contrast, Jet lubrication supplies lubricant at a rate of 2,000-4,000 cm^3 /min, emphasizing the cooling effect. This method spend high cost due to the requirement of a large capacity cooling system. Air-Oil lubrication has therefore been adopted for many case now.

The Expansion of balls, inner and outer races by bearing heat generation causes excessive preload in angular contact ball bearing pairs. In worst cooling case, the outer race of bearing is cooled, and only the outer race shrinks. So, preload between bearing pairs increases rapidly, causing metal welding in bearings. The excessive preload can not be absorbed by conventional constant position preload method. Another preload method is constant pressure preload. This preload is produced usually constant by springs(Fig.10). The big preload in high speed operation can be absorbed fully by this method. To control the preload of bearing, new method is developed, using hydraulic force for increase and springs back force for decrease(Fig.11).

The cooling system of spindle unit must be controlled in consideration of bearing inner / outer race temperature balance and operation time. The cooling of rotor in integrated motor can be achived by blasting cooling air on the rotor.

5. Conclusion

High speed machining lead to the requirement change for machine tool design and control. Specially, modern machine tools spindle must be more geometrically accurate and speedy over the working process than conventional spindles, and must possess a high degree of thermal stability.

To achieve high precision and speed, first of all the best selection of bearing type and arrangement are needed. Secondly optimization of spindle structure is done to lead spindle to high static and dynamic stiffness by the selection of optimal bearing span. Thirdly the weak points of spindle structure after optimization are allocated and improved to strengthen stiffness. Fourthly the automatic preload control unit is designed to reduce heat generation of bearings at high rotational speed and to control spindle radial stiffness for heavy cutting work. The thermal deformation by bearing friction heat should be harmful to positioning and rotation accuracy of spindle.

Also the improper thermal deformation cause to suddenly big heat generation or reduction of spindle stiffness.

Modern spindle unit must be not only accurate and speedy but also intelligent. The cutting state and tool monitoring can be done by sensor bearing in spindle unit. In future the role of spindle unit in machine tools should be more important and compact.

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