Chapter

Headstock for High Speed Machining - From Machining Analysis to Structural Design

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Abstract

The progressive technological growth in developed industrial countries is characterized by the increasing range of manufactured parts, the variety of their shapes, and the development and usage of new non-traditional materials. At the same time, demands for high quality and production efficiency must be fulfilled. The essential function of machine tools is to make workpiece surfaces with the required geometry and with the required surface quality under economically efficient conditions. A significant benefit in increasing the efficiency and quality of machined surfaces was the development of high-speed machining. With the application of this machining method, the overall concept of the machine tool and the construction of its individual nodes have changed. The headstock has a significant impact on the quality of the final product and the overall productivity of the machine tool. Machine tools with integrated drive headstocks offer the users much greater performance and reliability. The aim of the presented chapter is the analysis of high-speed machining technology, a description of the structures of high-frequency headstocks and their individual parts, along with the design of a headstock with an integrated drive for the specific case of a machine tool.

Keywords: headstock, high-speed cutting, ball bearings with angular contact, design, testing

1. History, development, and advantages of speed machining

Machining with high cutting speeds is associated with the name Carl Salamon [1]. This German researcher in the 1920s milled, for example, steel with cutting speeds at 440 $m.min^{-1}$, and aluminum at up to 16,500 $m.min^{-1}$. The trials ended in German Patent No 523594 of 1931, creating a series of diagrams describing the impact of the cutting speed on the cutting temperature (**Figure 1**). The experiment focused on machining non-ferrous metals, such as aluminum, copper, and brass, respectively [1]. The theory assumes that at a certain cutting speed (5–10 times higher than in conventional machining), the chip removal temperature at the cutting edge will start to decrease.

His experiments overturned Taylor's theory on "maximum cutting speeds," above which machine damage would occur. Salomon showed that for each tool-work piece couple, there exists a critical speed range at which machining is not

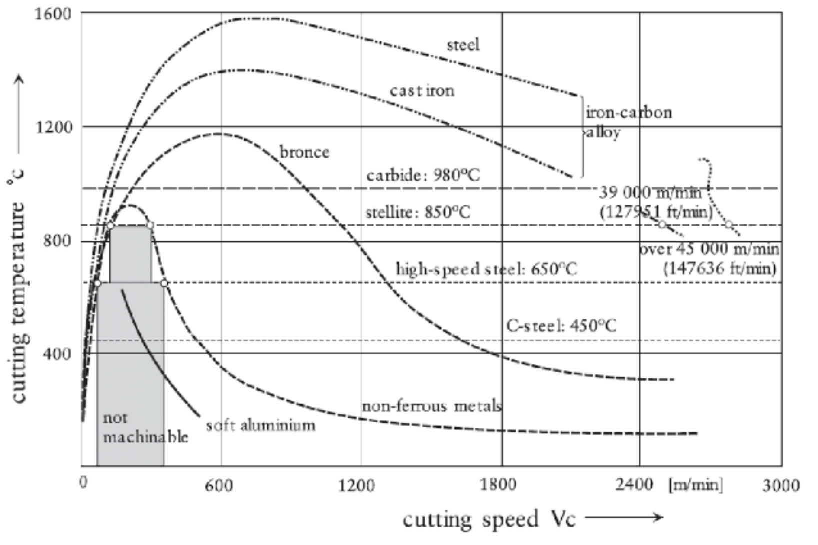

Figure 1.
Machining temperatures at high speeds.

possible. After overcoming this area, we can continue to work, while the temperature of cutting will drop significantly. In the early 1950s, research in the USA carried on from his results. For cutting thin-walled aircraft parts, the Lockhead and Boeing corporations, on a spindle mounted on rolling bearings (n_{max} = 18,000 min^{-1}, P_{elm} = 18 kW), achieved a milling speed of 3000 $m.min^{-1}$, [1–3]. In 1978 in Germany, and a year later in the USA, extensive research focused on the practical usage of high-speed machining was begun. In Germany alone, more than 40 leading firms participated on a project. On the basis of this cooperation at the beginning of 1980 at a university in Darmstadt was constructed an integrated milling spindle unit with asynchronous drive, with a spindle mounted on active magnetic bearings and cutting speeds of 2000–10,000 $m.min^{-1}$ [4]. Over the next 3 years,, an economic variant on a roller bearing was constructed. Partial results from ongoing research confirmed the following advantages of high-speed milling:

- at increased cutting and feed speeds, the cutting force is significantly reduced, [3, 4]. This makes possible the machining of thin-walled parts without special preparations. A drop in cutting forces reduces the demands for rigidity of the whole machine;

- a large part of the heat emerging in the machining process is taken away by chips. This significantly increases the durability of the machine, the work piece remains cold, and the roughness of its surface is decreased with equal or better dimensional precision, which leads to a saving in finishing operations;

- a significant increase in cutting power leads to saving production time so as to save of production costs; and

- high-speed cutting machine provides higher quality surface finish due to the reduced cutting pressure.

A comparison of the advantages and disadvantages of conventional and high-speed machining is shown in the following table (**Table 1**).

Technology of classical machining	High-speed machining technology
The contact time between tool and work is large	Contact time is short
Less accurate work piece	More accurate work piece
Cutting force is large	Cutting force is low
Poor surface finish	Good surface finish
Material removal rate is low	Material removal rate is high
Cutting fluid is required	Cutting fluid is not required

Table 1.
Compare technology of classical machining a HSC technology.

2. Parameters of high-speed machining

Cutting speed values in chip machining are dependent on technology, the material make-up of the cutting machine, and of the machined pieces. Therefore, there exists no unequivocal and general classification of machining according to cutting speeds. In professional literature, we most often encounter the concepts of classical, high-speed, and ultra-high-speed machining. It should be noted, however, that the classifications of the individual authors are considerably different or contradictory. According to individual machining technologies, König is probably the most systematic classification of cutting speeds [3, 4]. This author divides machining into classic and high speed (**Figure 2**). Back in the 1950s, Kronenberg carried out experiments with ultra-high cutting speeds of 9000–720,000 $m.min^{-1}$. In **Figure 2**, it can be seen that for stretching technology, the area of high-speed machining is in the 30–70 $m.min^{-1}$ range, whereas in this area, cutting speeds from about 5000 to 12,000 $m.min^{-1}$ are used for grinding.

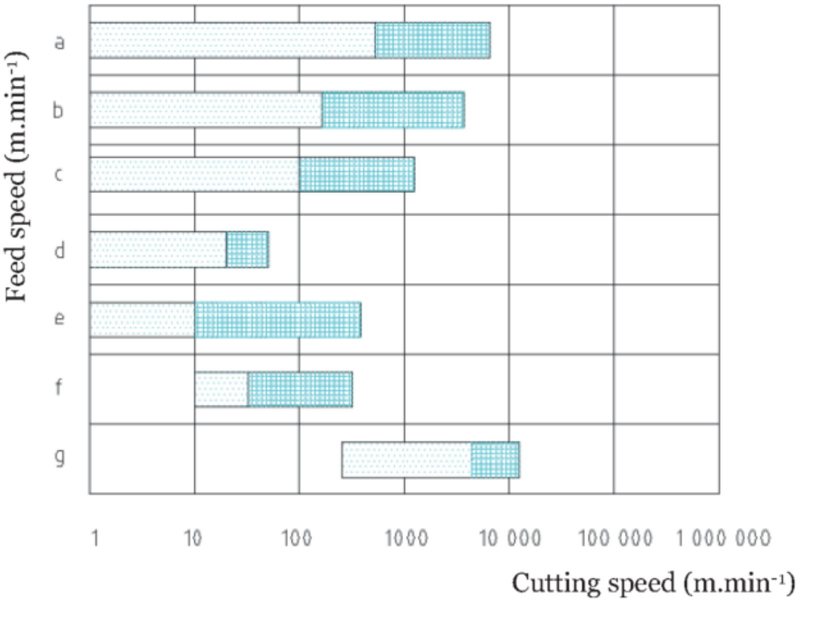

Figure 2.
Cutting speed ranges for chip machining operations. (a) Turning, (b) milling, (c) drilling, (d) stretching, (e) reaming, (f) sawing, (g) grinding, (▢) classic machining, and (▢) high-speed machining.

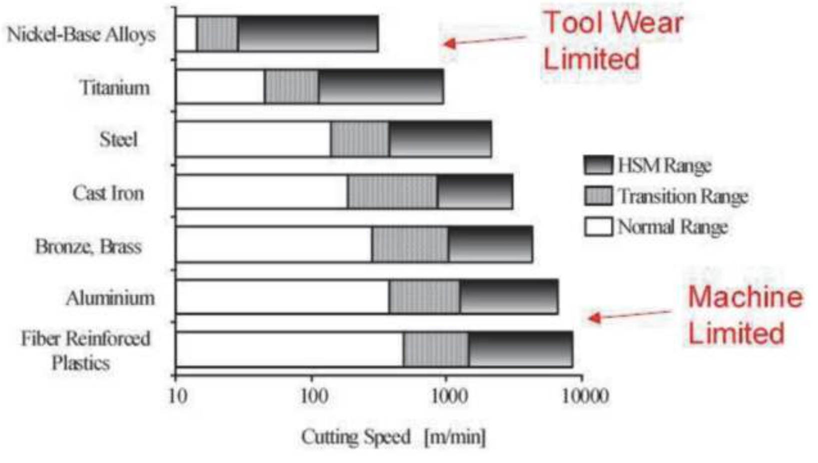

Figure 3.
Cutting speed ranges for milling.

The dependence of cutting speed for individual types of machined material is shown in **Figure 3** [4]. It is clear from the figure that the lowest cutting speed is when milling nickel and its alloys and the highest when milling aluminum and its alloys.

It must be remembered that cutting speed is also a function of the cut material and other accompanying machining conditions (cooling, etc.). To create the most general idea of cutting speed values, we can break down machining according to **Figure 4**.

3. Headstock—heart of machine tool

The issue of high-speed machining is very expansive. It is suitable therefore to divide this area into the conception of the machine as a unit and the development of its individual constructional nodes and elements.

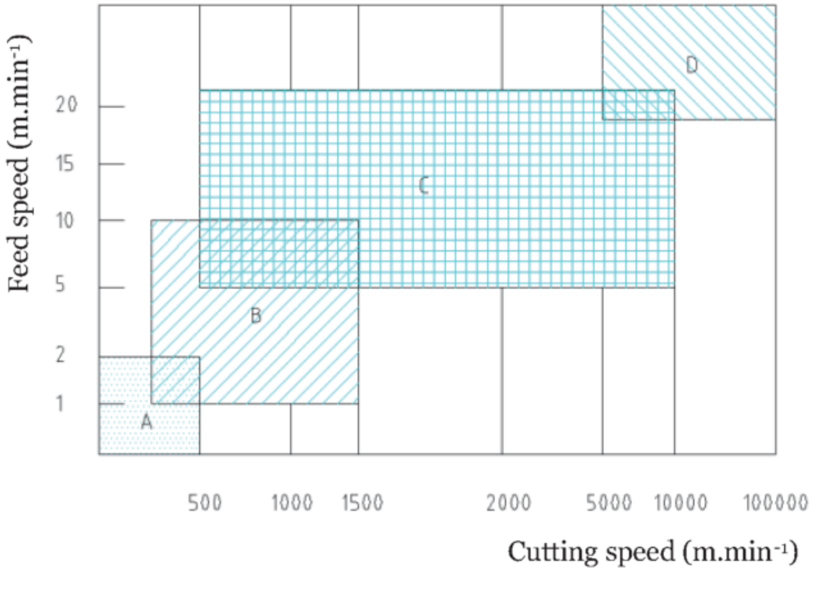

Figure 4.
Outlining of cutting speed ranges for speed machining: (A) classic machining, (B) transitional area, (C) high-speed machining, and (D) ultra-high-speed machining.

Modern machine tools have become more flexible capable of performing a range of programmed tasks.

In the conception of a machine, it is necessary to bring into consideration these factors:

- in the design of a machine's frame, it is important to place emphasis on rigidity and damping capacities. It is very advantageous for this purpose to select the machine frame in high-strength concrete;
- the working area of the machine must be perfectly shroud covered, with good chip transfer and with a suitably selected cooling and control system;
- feed units must be designed with consideration of maximum speeds (vr—15-20 m. min^{-1}), with very short time constants and high strengthening factors (kv ›1.8). This means on one side reducing to a minimum the weight of the moving parts, and on the other, securing maximum rigidity. We can solve this compromise by using high-strength lightweight materials; and
- also important are the aspects of the modularity of the machine construction, together with the rapid replacement of the spindle unit and other machine nodes.

The headstock, as a construction node, has an important position in the overall machine concept. This is for the following reasons:

- the spindle should rotate with the high degree of accuracy. The accuracy of rotation is determined by the axial and radial run out of the spindle nose and these must not exceed certain permissible values that are specified depending upon the required machining accuracy. The rotational accuracy is influenced at the most by the stillness and accuracy of the spindle bearings, particularly the one located at the front end;
- the spindle unit must have high static stiffness. The stiffness of the unit is made up of the stiffness of the spindle unit proper and the spindle bearings. Machining accuracy is influenced on bending, axial as well as torsional stiffness. In series configurations of individual machine nodes, headstock is usually the weakest construction node, which is a limiting member to achieve the required rigidity of the entire machine concept, as a criterion for ensuring the required standstill accuracy;
- the spindle unit must have high dynamic stiffness and damping. Poor dynamic stability of the spindle unit adversely affects the dynamic behavior of the machine tool as a whole; and
- the maximum rotational frequencies of the headstock is a limiting factor of the maximum cutting speed of machine tools and thus of the overall machine production. These maximum rotational frequencies can no longer be ensured for HSC by conventional indirect drives with gear or belt. It should be emphasized that these two factors, stiffness and maximum speed, act in opposite directions.

For high-speed machining, headstocks with integrated drive—"Electrospindles"—are usually used (**Figure 5**) [5]. This has solved the problem of providing rotational frequencies for high cutting speed.

Figure 5.
Spindle unit with integrated drive (SKF) [5].

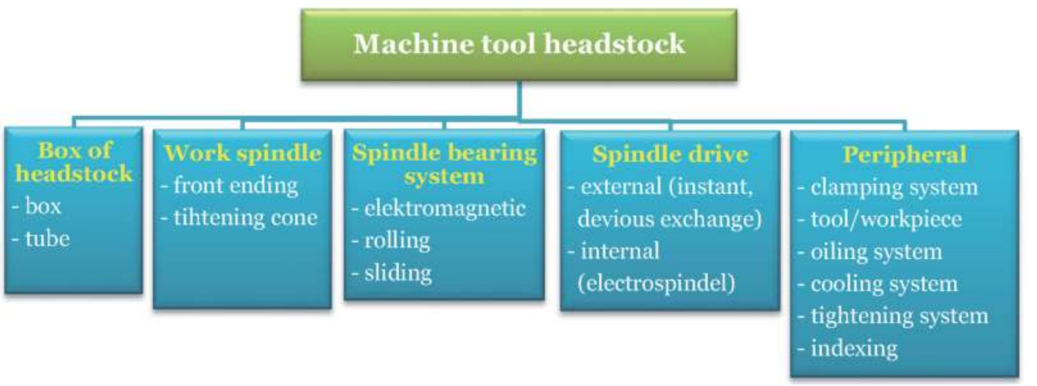

Figure 6.
Headstock morphology.

The electrospindle consists of the particular parts and external peripheries, which together provide the required functions of the whole assembly group (**Figure 6**) [6]. The essential headstock parts include the spindle, bearings system, the tool clamping system or the work piece chucking system, and the body of the headstock. The peripheral devices can include integrated or external systems determined to drive the spindle, lubricate the bearings, provide cooling, spindle indexing, and monitoring.

4. Box of headstock

For high-speed machining, tubular shapes of headstocks like box type are more used. Recently, in addition to tubes made of steel, bodies with a tube wound from fiber composites have recently been used. These include headstocks from Weiss or Step-tech. Based on the elasticity and rigidity knowledge, it is possible to form the approximate solution of every headstock type. Requirements put on the headstock body boxes are:

- maximum symmetry—for the reasons of symmetrical thermal expansions;
- minimum quantity of holes—holes decrease rigidity; and
- statically predestined design—it increases rigidity.

5. Work spindle

The requirements put on the spindle are concentrated on the spindle geometric rigidity, selection of design material, and shape configuration of diameters. The selection of design material for the spindle is conditioned particularly by mechanical properties of the essential core structure, which are by the modulus of elasticity E and by the coefficient of relative damping D. The spindles made of steel comply with the requirements of high static rigidity. The relative spindle quality measure is its specific rigidity, that is, the spindle nose rigidity compared with the spindle weight. The spindle natural frequency and the dynamic characteristics of the headstock are also connected with it. Composite materials (graphite epoxide) start to be used for high-speed spindles. This spindle is lighter, and it does not require such a big diameter [7].

The shape configuration of diameters shall be simple to the maximum possible extent. Those configurations are rational, where the minimum number of graduated diameters can be found and the difference between diameters is determined only by the types and dimensions of applied bearing models.

The spindle end that protrudes from the headstock body is called the front spindle nose. When designing the spindle, the great attention must be paid to the suitable adaptation of the spindle nose so that it can provide the optimum tool clamping (through the clamping shank) or the optimum work piece chucking (e.g., by means of the chuck) [8]. This connection must be a quick, precise, rigid, and reliable one. The type execution and the shape of the spindle nose depend on the technology, type, and size machine tool and on the required accuracy of working.

6. Spindle bearing system

A limiting factor determining cutting speed is bearings. At high frequencies, it must be sufficiently rigid, accurate, and with high durability. The selection of the bearing type in particular supports in the bearing system of the machine tool spindle is always the matter of a compromise among the high rigidity, maximal frequencies of rotation, and offered possibilities of the utilizable building area in the headstock body. In particular, electromagnetic and rolling bearing nodes made of radial angular contact ball bearings are used for receiving spindles for high-speed machining. High revolutions may be achieved by the application of an aero-static bearing whose very low rigidity makes it suitable only for grinding operations.

6.1 Electromagnetic bearings

In the mid-twentieth century, a successful magnetic levitation bearing was successfully demonstrated. This first successful magnetic bearing utilized electromagnets to provide attractive forces in the five degrees of freedom (with rotation being the sixth). Active servo control stabilized the system by using feedback signals from position sensors in each axis of control to vary the currents flowing through the various electromagnets.

Several individual electromagnets, usually from 8 to 12, were arranged in a north-south-north-south configuration around each end of a levitated shaft to provide radial support. This design approach, which results in a multiplicity of magnetic flux reversals around the circumference of the shaft, is known as heteropolar. Most commercially available magnetic bearing systems utilize this technology. A typical heteropolar magnetic bearing system is shown in the below **Figure 7** [9].

The stator, composed of an array of stationary electromagnets, generates powerful attraction forces that suspend the ferrous rotor shaft in the center of the magnetic field (with the help of an active servo-control unit). The active magnetic bearings are divided into radial, axial, and conical bearings (**Figure 8**).

In addition to the zero mechanical passive resistances, these active bearings have the property that they can determine, for example, the cutting force value, thanks to the active check of the bearing. The reached maximum speed is up to 100,000 min^{-1} and at small special spindles up to 150,000 min^{-1}. The spindle seating on active magnetic bearings uses attractive forces. The spindle position sensors provide the back response for the control system. The sensors send the linear output signal, and they can work in a wide range of operating temperatures. The correct bearing function is ensured by costly control electronics, which prevents faster application of these bearings in the practice. Roller "emergency" bearings are also used in the machine tool spindles carried in the active magnetic bearings (**Figure 9**). The main task of these bearings, which do not work at the normal spindle run, is to provide the trouble-free spindle stop in the case of the sudden electricity blackout.

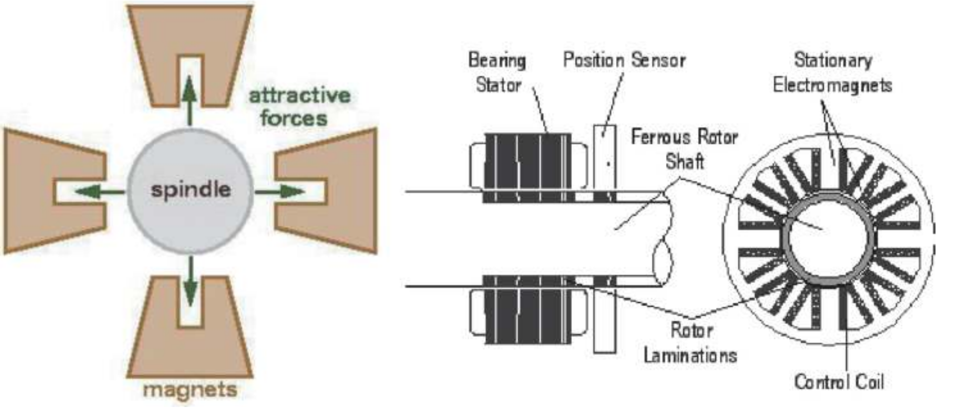

Figure 7.
Principle of electromagnetic bearings.

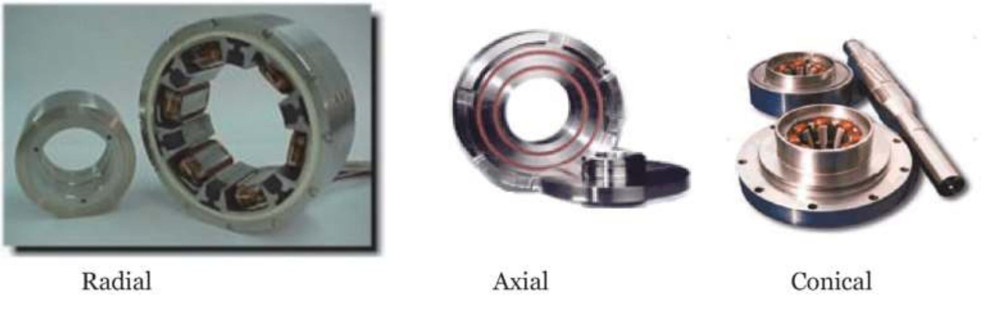

Figure 8.
Type of magnetic bearings.

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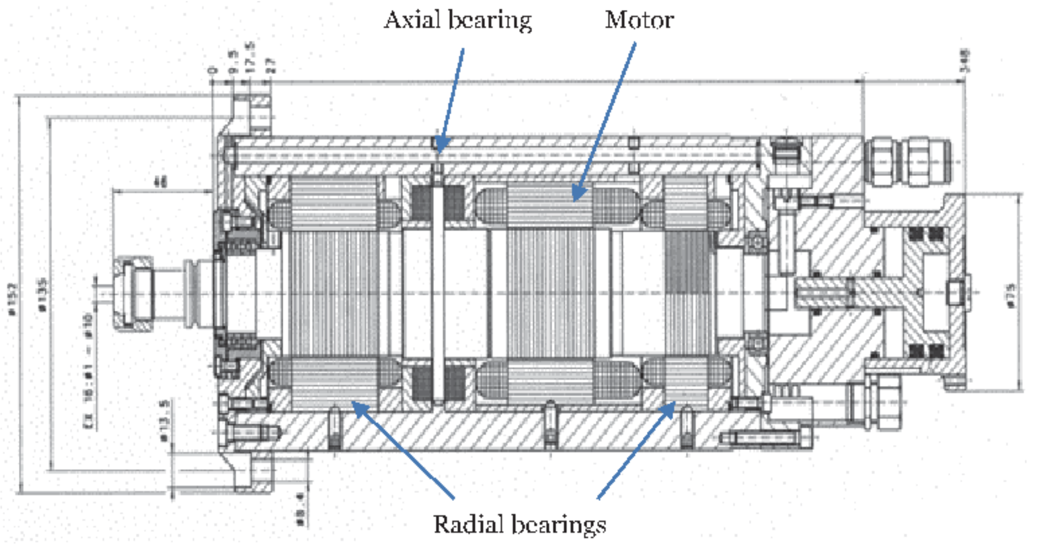


Figure 9.
Electrospindle with electromagnetic bearings (Ibag, HF 120 MA 80 K, n_{max} *= 70,000 min*$^{-1}$*, and* P *= 11 kW,* M_k *= 1.5 nm), [10].*

6.2 Roller bearings

Radial angular contact ball bearings are used almost exclusively for high-frequency spindle bearings with integrated drive [11]. It is generally valid, that radial ball bearings with angular contact are recently unequivocally the most often used bearings for mounting of high-speed machine tool spindles. The reason is that their different design, their dimensional range, the contact angle values, the preload intensity, and the way of bearing arrangement in the assemblage provide the greatest scope of possibilities how to solve the compromise between the limit speed and maximum rigidity. "Spindle" bearings are manufactured in different dimensional ranges (72, 70, 719, 718) with the design of antifriction body guiding on the inside ring (B) or on the outside ring (A), with different contact angle values (12°, 15°, 25°, and 26°), with the polyamide cage (TB), with the required accuracy (P2, PA9, SP, UP), with various arrangement ways (DB, DF, DT and their combinations), with light (UL), middle (UM), or heavy preload (US) [5]. The bearings made with the higher accuracy degrees are used to seat the spindles. The axial loading capacity of the bearing increases proportionally when the contact angle increases, but the value of limit rotation frequencies decreases. It order to catch bigger radial or axial forces, the bearings are mounted in assemblages created from three, four, or five bearings. Radial load is distributed to all bearings in the group (shape arrangement), and axial load is distributed to all bearings joined behind each other (direction arrangement).

6.2.1 Observed parameters of the bearing groups

The important parameters of the bearing groups specified to seat the working spindles at machine tools are:

- run accuracy;
- durability;

- rigidity;
- high-speed run; and
- temperature.

6.2.1.1 Run accuracy

The run accuracy spindle bearing system is limited by the accuracy of bearings and by the accuracy of bearing surfaces—connection parts. The accuracy of antifriction bearings is understood as the accuracy of their dimensions and run. The limit values for the accuracy of dimensions and run are mentioned in ISO 492 and ISO 199 standards. The accuracy of connection parts is understood as geometric shape and position deviations which can be admissible at the manufacture of the spindle and headstock box. The bearing manufacturer prescribes the admissible geometric shape and position deviations of bearing surfaces (**Figure 10**). At the assembly of bearing, it is necessary to observe matching of inside and outside bearing diameters to provide the required radial preload.

6.2.1.2 Durability

The calculation of bearing durability is generally known [6]. It is described by the international ISO 281/l standard. When durability is calculated, we usually use the modified equation of durability that expresses the durability in operation hours. The following relation is used for the bearing durability in hours:

$$L_{h10} = \left(\frac{C_d}{P}\right)^p \cdot \frac{10^6}{60.n_s} \ [\mathrm{h}] \tag{1}$$

where P is the equivalent dynamic load [N];
C_d is the dynamic loading capacity of the bearing [N];
exponent: $p = 3$, for ball bearings;
$p = 10/3$, for needle, spherical-roller and tapered roller bearings; and
n_s is mean frequencies of bearing rotation [min^{-1}].

The equivalent dynamic load P at roller bearings corresponds to the intensity of reactions in the particular supports. However, the methodology is not unified how to calculate the equivalent load at bearing groups made of the radial angular contact ball bearings.

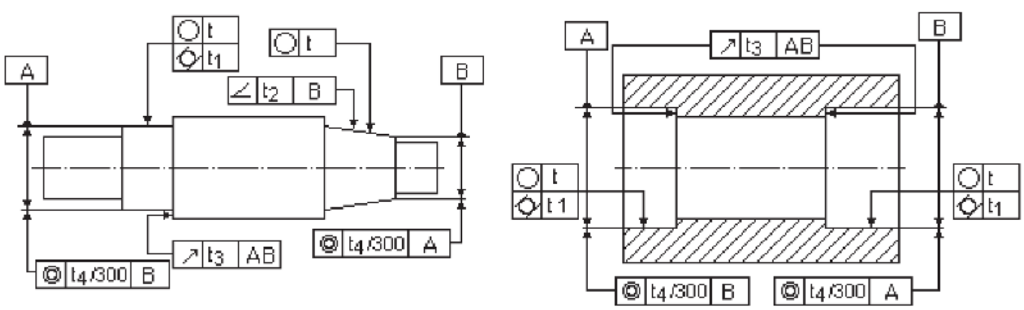


Figure 10.
Prescribed shape and position deviations (SKF).

The spindle bearings transfer the combined radial-axial load. When the selected bearing type (selected bearings) is calculated, the combined radial-axial load is recalculated to the so-called equivalent dynamic load:

$$P = X.F_r + YF_a \text{ [N]} \tag{2}$$

where
F_r is the radial force [N];
X is the radial coefficient;
F_a is the axial force [N]; and
Y is the axial coefficient.

6.2.1.3 Rigidity

The significance of the bearing rigidity in the particular supports is considerable at the spindles having a bigger diameter, where the rigidity of the bearing assemblage in the particular supports is the limiting factor necessary to reach the required rigidity of the complete seating, as the tool how to provide its accurate operation. The total rigidity is the criterion of the body resistance against the influence of external forces.

The rigidity of the bearing assemblage made from the radial angular contact ball bearings can be described mathematically as the multiple parametric function [11].

$$C_{r,a} = f\left(i, z, d_w, \alpha, F_p, (\delta_{ps}), F_{r,a}, F_n, T\right) \tag{3}$$

It depends on the number of bearings i, dimensional rank, size and design of bearings z, d_w, contact angle α, preload size F_p, or deformations due to preload δ_{ps}, and frame conditions (bearing accuracy, assembly, and cooling).

Three essential states can generally take place in the bearing assemblage made from the radial ball bearings [6]:

- the preload state [e.g., the assemblage joined from two shape-arranged bearings (**Figure 11a**)];
- the preload axially loaded state [the TBT assemblage loaded by the axial force (**Figure 11b**)]; and

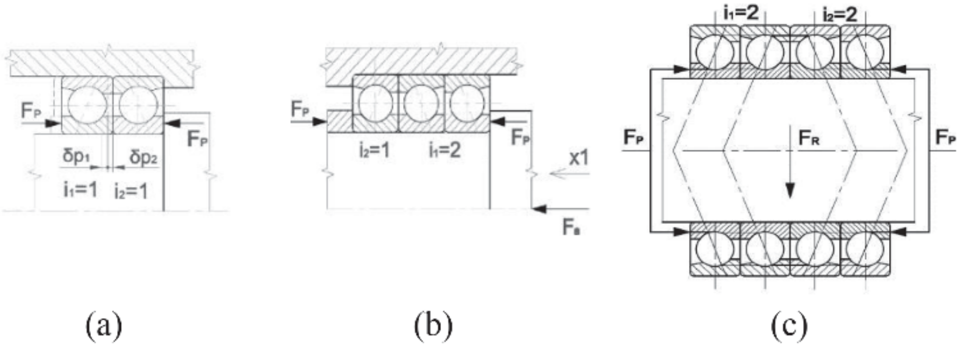


Figure 11.
Essential states of bearing assemblages: (a) DB preload state, (b) TBT preload—axially loaded state, and (c) QBC preload -radially loaded state.

- the preload radially loaded state [the QBC assemblage loaded by the radial force (**Figure 11c**)].

Preload of the spindle bearings at the spindle assembly enables to increase the working accuracy and rigidity of the whole seating. On the other hand, the increased preload initiates the temperature origination in the bearing, which has the negative influence on critical rotation frequencies of the bearing or of the bearing assemblage. Two angular contact bearings are preload by the force F_p according to ČSN/STN 024615,

$$F_p = k.C_d.10^{-2} \tag{4}$$

The preload value for more bearings will be increased depending on the relation:

$$F_{ps} = k.C_d.i^{0,7}.10^{-2} \tag{5}$$

6.2.1.4 Axial rigidity

The axial rigidity importance comes to the foreground especially at facing, milling, drilling, and grinding. In the system "spindle-bearing," the axial forces are almost always caught by the point-contact bearings. The axial rigidity is then given by the relation:

$$C_a = \frac{F_a}{\delta_a} \tag{6}$$

The following is valid for the approximate axial rigidity value according to [11]:

$$C_{az} = \frac{3.10^{-3}}{2} z^{\frac{2}{3}} \cdot k_\delta^{\frac{2}{3}} \cdot i_1^{\frac{2}{3}} \cdot F_p^{\frac{1}{3}} \cdot \sin^{\frac{5}{3}}\alpha_1 \left[1 + \frac{i_2^{\frac{2}{3}} \cdot \sin^{\frac{5}{3}}\alpha_1}{i_1^{\frac{2}{3}} \cdot \sin^{\frac{5}{3}}\alpha_2}\right] \tag{7}$$

After the omission of the contact angle change due to the axial force and under the presumption that the contact angles are the same ones at both joined groups, the relation becomes the simplified form:

$$C_{az} = \frac{3.10^{-3}}{2} z^{\frac{2}{3}} \cdot k_\delta^{\frac{2}{3}} \cdot i_1^{\frac{2}{3}} \cdot F_p^{\frac{1}{3}} \cdot \sin^{\frac{5}{3}}\alpha_1 \left[1 + \frac{i_2^{\frac{2}{3}}}{i_1^{\frac{2}{3}}}\right] \tag{8}$$

6.2.1.5 Radial rigidity

$$C_r = \frac{F_r}{\delta_r} \tag{9}$$

For the reason that the load is not distributed equally, the rigidity calculation is rather difficult and it cannot be almost realized without application of computer technology. It is necessary to determine theoretically and to verify experimentally the deformation course on the load at the preload point-contact bearing groups. The research of the bearing groups made from the radial angular contact ball bearings [12] showed that the deformation course is almost linear at the preload bearing groups up to the certain critical load. For the calculation and testing of radial ball bearings arrangement to nodes, we have developed an expert mathematical model allowing calculation of stiffness, limit frequencies, and bearing node durability.

Based on this knowledge, the simplified equations for the calculation of the mean rigidity value were deduced in works [12, 13].

6.2.1.6 Directional rigidity

$$C_{\mathrm{rsi}} = \frac{3.10^{-3}}{4} . z^{2/3} . k_{\delta}^{2/3} \cdot i^{2/3} \cdot \mathrm{F}_{p}^{1/3} \cdot \frac{\cos^{2}(\alpha)}{\sin^{1/3}(\alpha)} \tag{10}$$

The resulting radial rigidity of the bearing group with the shape-arranged bearings will then be:

$$C_{\mathrm{rz}} = C_{\mathrm{rs1}} + C_{rs2} \tag{11}$$

The following relation was deduced according to [13] for the approximate radial rigidity value of the bearing assemblage made from two shape-arranged groups:

$$C_{\mathrm{rz}} = \frac{3.10^{-3}}{4} \cdot z^{2/3} \cdot k_{\delta}^{2/3} \cdot i_{1}^{2/3} \cdot \mathrm{F}_{p}^{1/3} \cdot \frac{\cos^{2}(\alpha_{1})}{\sin^{1/3}(\alpha_{1})} \cdot \left[1 + \frac{i_{2}^{2/3} \cdot \cos^{2}(\alpha_{2}) \cdot \sin^{1/3}(\alpha_{1})}{i_{1}^{2/3} \cdot \cos^{2}(\alpha_{1}) \cdot \sin^{1/3}(\alpha_{2})}\right] \tag{12}$$

At the omission of the contact angle change due to the axial force and under the presumption that the contact angles are the same ones at both joined groups, the relation becomes the simplified form:

$$C_{\mathrm{rz}} = \frac{3.10^{-3}}{4} \cdot z^{2/3} \cdot k_{\delta}^{2/3} \cdot i_{1}^{2/3} \cdot \mathrm{F}_{p}^{1/3} \cdot \frac{\cos^{2}(\alpha_{1})}{\sin^{1/3}(\alpha_{1})} \cdot \left[1 + \frac{i_{2}^{2/3}}{i_{1}^{2/3}}\right] \tag{13}$$

where k_{δ} we can calculate according to the equation

$$k_{\delta} = \sqrt{1,25 d_{w}} \tag{14}$$

Under the presumption that the contact angles $\alpha_1 = \alpha_2$ **are the same ones at the shape-arranged bearings in the group or** $i_2 = 0$ for the direction-arranged bearings in the group, the relationship between radial and axial stiffness is simplified as:

$$C_{rz} = \frac{C_{az}}{2} \cdot \frac{1}{tg 2\alpha} \tag{15}$$

6.2.1.7 High-speed run

The high-speed run criterion is the quality criterion of the node regarding to the reached frequencies of rotation. Regarding to the high-speed run of the bearing nodes, the node systems are analyzed in work [6]. The particular designing solutions of the existing seating are divided into three essential groups in this work. The high-speed run parameter can reach the value K = (2–2.7).106 mm. min^{-1} at the special high frequency groups. For the limit values, it is suitable to use the special bearings with the optimized design, high accuracy, and with the utilization of materials having the favorable physical and mechanical properties (e.g., silicon nitride Si_3N_4).

$$K_r = n_z \cdot d_s \left[\min^{-1} \cdot \text{mm}\right] \tag{16}$$

The following relation is used for the determination of the critical frequencies of the bearing groups n_z.

$$n_z = n_{l\,\max} \cdot f_1 \cdot f_2 \cdot f_3 \cdot f_4 \dots \dots f_n \left[\min^{-1}\right] \tag{17}$$

where $n_{l\,\max}$ is the critical frequencies of the bearing rotation and f_i is the coefficient describing the bearing group and conditions of its work (the number of bearings, preload, accuracy of bearings, kinematics, heat removal, lubrication, etc.). Their importance is different in dependence of the particular sources.

The reduction of antifriction body dimensions results in the decrease of the centrifugal force, for which the following is valid:

$$F_o = m \frac{d_s}{2} \cdot \omega^2 \tag{18}$$

where m is the antifriction body weight and d_s is the bearing mean diameter.

Such bearings are economical and reliable. The issue of decrease in centrifugal forces at high-frequency rotations is solved by reducing the weight of the rolling elements. This is achieved by changing the dimensional series of bearings and by changing the ball material.

Using bearings with smaller cross-sections, for example, 718, 719 instead of bearings with bigger cross-sections (70, 72), reduces the diameter of the balls. Reducing the diameter of the rolling elements makes it possible to increase the high frequency of rotation of the bearing (**Figure 12a**) and at the same time increases the number of balls to achieve higher bearing stiffness (**Figure 12b**) [5]. With constant external diameters, the internal diameter of the bearings increases, which is suitable from the standpoint of reducing spindle deflection, increasing its drilling, and increasing the critical revolutions of the spindle.

Roller bearings as well as ball bearings can be made as so-called "hybrid ones," which means that the bearing rings are made of steel and antifriction bodies are ceramic. The advantage of hybrid bearings by the same size compared to steel bearings is their lower centrifugal forces, frictional moment, and higher radial and axial stiffness (**Figure 13**). Disadvantages include the high manufacturing costs

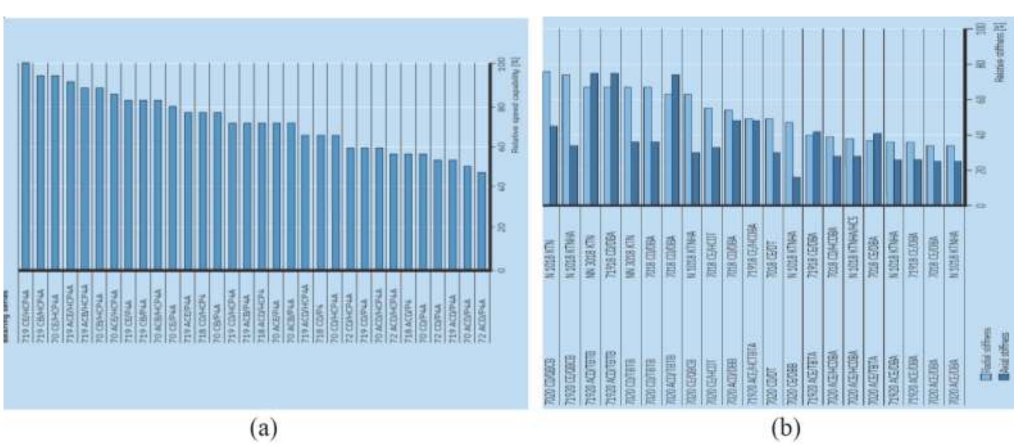


Figure 12.
Changing the dimensional series of bearings—contact ball bearings (SKF) [5] (a) relative speed capability, and (b) relative stiffness.

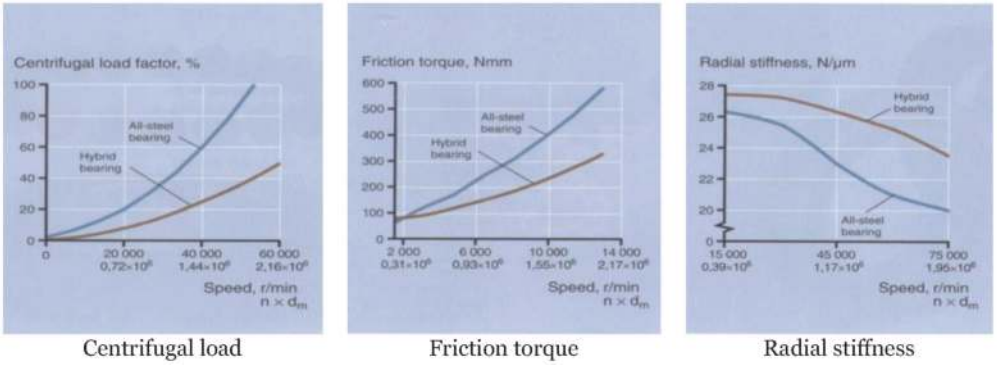


Figure 13.
Hybrid bearings (SKF).

(up to 10 times) of rolling elements, still persisting problems with the homogeneity of ceramic materials, and the identification of failures.

6.2.1.8 Temperature

In the bearing groups, where no external heat sources act, the shaft temperature, the spindle temperature as well as the temperature of inside bearing rings and of the antifriction bodies are higher than the temperature of external bearing rings and of the headstock body sleeve. Due to the heat drop at the same expansibility coefficient, the dilatation of the spindle, bearing rings, and balls is bigger than the expansibility of the surrounding parts in the radial direction as well as in the axial direction. According to [11], its value is described by the equation:

$$\Delta l_{r,a} = \upsilon_t \cdot l_{r,a} \cdot \Delta t \tag{19}$$

For headstocks where high demands are placed on the range of rotational frequencies or temperature, it is advantageous to vary the amount of bearing preload directly during work. In order to increase the speed ranges and the service life of the spindle bearing, due consideration must be given to temperature optimization of the bearing when designing the spindle. The temperature of the bearing system varies depending on the temperature gradient, type and arrangement of the bearings (DB, DF, DT), assemblies, contact angle, bearing size, and the distances of bearings in the note and of the individual supports. There are known systems of active control of bearing preload of high-frequency headstocks and peripheral

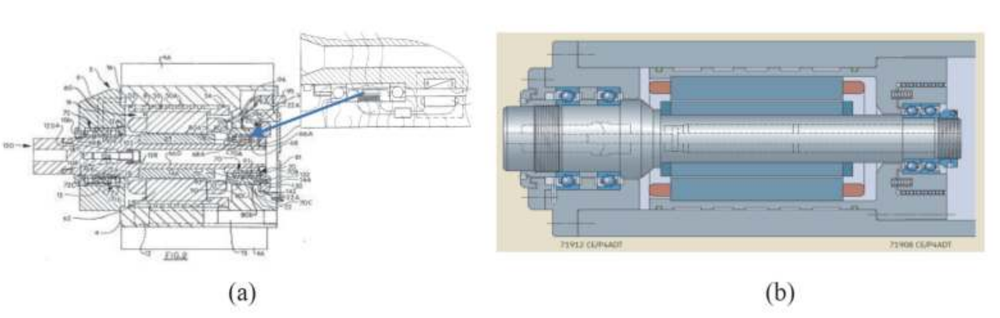


Figure 14.
Temperature change compensation. (a) US06422757; Active piezoelectric spindle bearings preload adjustment mechanism*, [14]. (b) Motor spindle SKF with movable rear support [5].*

devices and sensors of important parameters, the monitoring of which has a decisive influence on ensuring correct operation of the spindle. The solution may be, for example, active piezoelectric spindle bearings preload adjustment mechanism (**Figure 14a**) [14]. Bearings in the rear support must also allow thermal expansion of the entire spindle. Advantageously, it is possible to minimize the change in bias in the bearing by resolving the bearing arrangement in the individual supports (**Figure 14b**) [5].

7. Spindle motor

Desired performance and revolution characteristics place ever increasing demands on the construction of the spindle unit. The type of propulsion and bearing is the decisive component for providing the stated characteristics. Incorporating the drive directly into the spindle unit has successfully solved transmission problems at high speeds. In this way, the stress from the drive forces onto the spindle is eliminated and its accuracy is increased (**Figure 15**).

Both single-direction and alternating drives can in principle be used for integrated spindle units. Despite very good control properties, DC drives have known operational and technical drawbacks resulting from mechanical commutation devices—the commutator. For eliminating this deficiency, electronic commutation (Stromag and Bosch companies) is suitable. The use of synchronous frequency controlled drives is conditioned on the development of new hard magnetic materials [6]. In addition to the known Alnico alloys and hard ferrites, cobalt-based alloys characterized by high permanent induction (0.8–1 T) and high density are being developed, while the demagnetization curve is almost straight. An Italian company Polymotor is producing ring drives for integrated spindle units on a base of $SmCO_5$ alloy. In an effort to reduce the consumption of rare earths and hence the cost of permanent materials, materials that do not contain rare earth are being developed. Mn-Al-C alloys are well known, as are materials containing CO, Cr, and Fe.

At the present time, the majority of manufacturers of integrated drive spindle units use asynchronic frequency controlled drives due to their advantages (**Table 2**).

For securing the drive parameters, it is necessary to choose a suitable frequency shifter, which processes the frequency of the 50 Hz network with an output frequency of up to 3000 Hz. They are thyristors or transistors with sinusoidal output. The main advantage of static converters compared to rotary converters is in

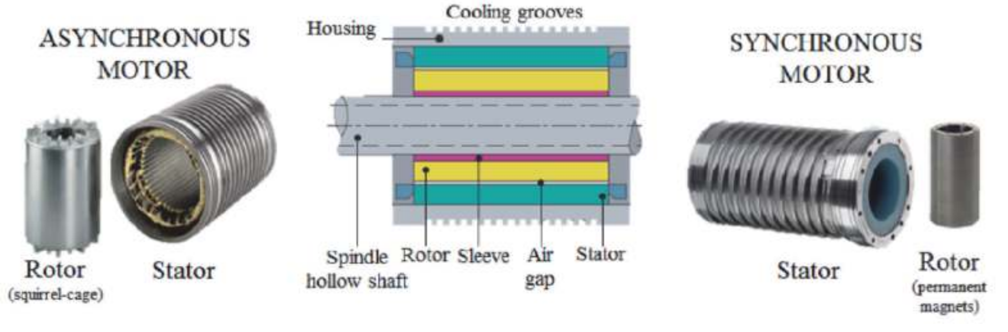


Figure 15.
Electric spindle motors (SIEMENS).

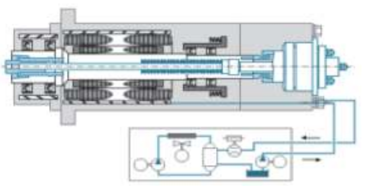
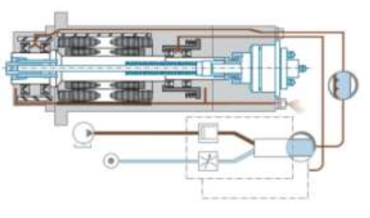
Lubrication method	Scheme		Describe
Grease		Advantages	• Low price • General purpose application • Maintenance-free operation over long periods,
		Disadvantages	• Lower speed • It does not remove heat • Grease has smaller durability than oil
Oil-mist (oil-mist lubrication)		Advantages	• No worsening of lubricant quality • Water cannot get to the bearing area (oil mist forces it out)
		Disadvantages	• Ambient contamination • Oil quantity depends on temperature and viscosity
Oil-jet (oil-jet lubrication/ cooling)		Advantages	• Stable bearing temperature • Water cannot get to the bearing area
		Disadvantages	• High friction moment • Higher price • Oil leakage at vertical application
Oil-air (oil-air lubrication)		Advantages	• It is environmental friendly • Water cannot get to the bearing area • No worsening of lubricant quality • Stable bearing temperature • Low generation of heat from excess of lubricant
		Disadvantages	• High price • Difficult determination of oil quantity

Table 2.
Comparison of lubrication methods for spindle bearings [6].

continuous speed change control. Acceleration and braking work in a very short time without thermal load on the engine. There is no slip during braking, which is very advantageous for precise positioning of the spindle.

8. Peripheral

8.1 Clamping system

High-speed machining is associated with the development of new cutting materials such as cutting ceramics, synthetic polycrystalline diamond, and cubic boron nitride. In addition to the development of cutting materials with the new physico-mechanical and chemical properties, increased attention must also be paid to the optimization of machine geometry with regard to chip removal at high machined material volumes. It will be necessary to design new holder and clamper constructions in light of the frequency of revolution, rigidity, and the flow of cooling liquids.

In addition to the demands that are placed on clamping systems used in high-speed spindle units are the following constructional and technological requirements [15, 16]:

a. small clamp dimensions limited by spindle dimensions;

b. low weight, ensuring low centrifugal forces;

c. balancing, providing resistance to high frequencies; and

d. quick automatic tool or work piece exchange.

Interfaces are used for HSC machining centers: steep taper ISO, SK, BIG PLUS (taper 7:24) and especially short taper HSK (taper 1:10), Kennametal/Widia KMTS KM4X.

Clamping of the tool holder in the spindle cavity is usually done by pulling it in by means of restressed disc springs (**Figure 16**). The release is then a hydraulic cylinder (**Figure 17**). The advantage of the HSK type for high speed is that the centrifugal forces cause the collet to open, which rests on the internal cavity surface of the shank (**Figure 18**). Rotary turrets replace tools in less than 1 second and accuracy positioning is max. ± 3 μm.

Since HSC technology uses around 50,000 rpm, tools must have radial runout max. 0.003 mm and with interchangeable cutting plates (VRP) max. 0.01 mm. All tools used must be perfectly balanced.

In HSC technology, the following are most commonly used as tool holders:

- thermal fixture; and
- hydroplastic clamp.

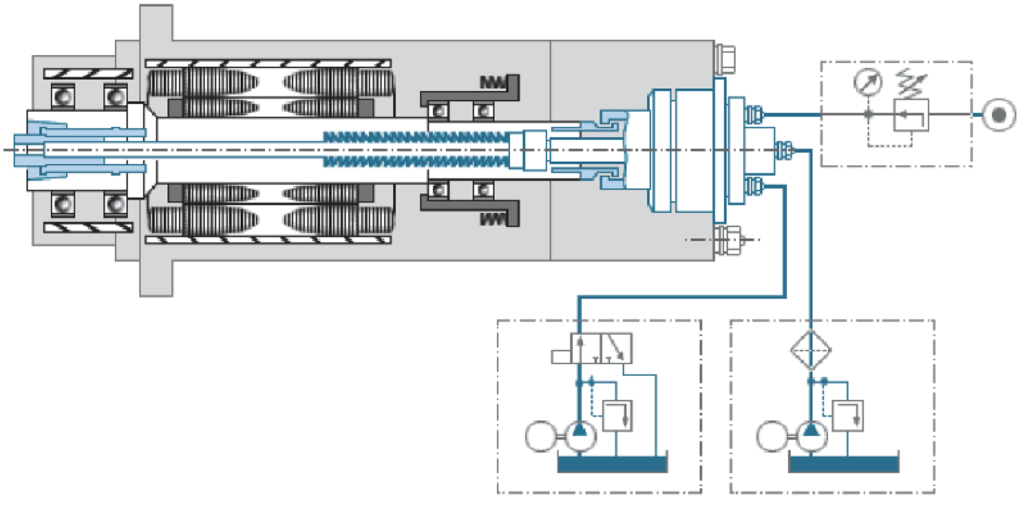


Figure 16.
Holder and clamper constructions (GMN).

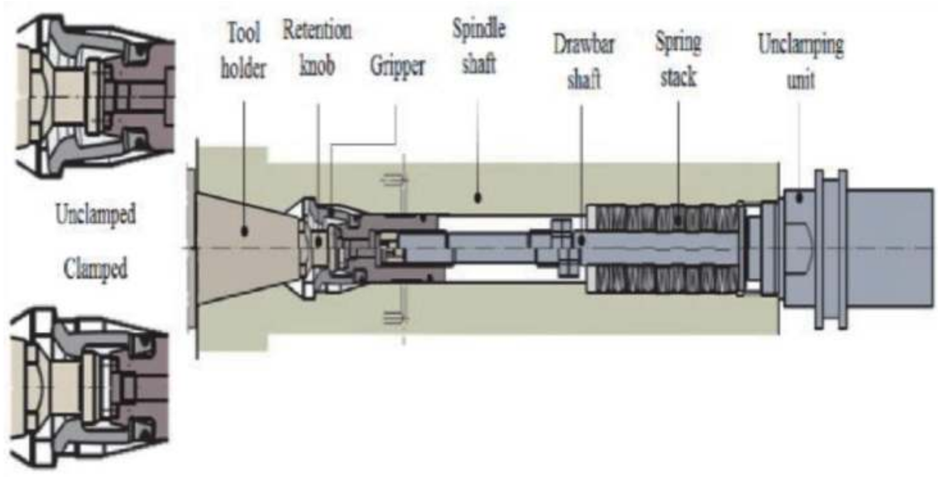


Figure 17.
End of spindle for clamping through the clamping shank [8].

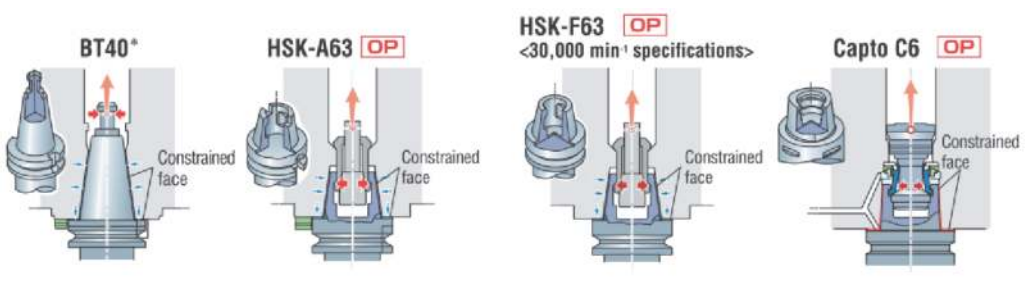


Figure 18.
Unsuitable and suitable clamping systems for high-speed spindles [DMG/Mori].

The thermal clamp allows quick clamping and unclamping of tools from the fast cutting steel, including sintered carbide. Tools are exchanged with a high-frequency generator that quickly warms up the tool holder and releases it tool. The following functions are used for the correct function of the tool: monitoring the tool holder contact in the spindle cavity, checking the temperature and force of the clamping system, checking the position of the clamping cylinder and the gripper, as well as checking the suction and temperature.

In the case of a hydroplastic clamp, the replacement is carried out using a hydraulic pump that squeezes the holder. Here, Pascal's law on the spread of uniform pressure is used, which ensures even clamping of the tool in the holder.

Advantages of these clamps:

- rapid shrinkage and release of the holder;
- the rigidity of the clamping ensures high quality of the machined surface;
- good bending and radial stiffness;
- clamping tools with shank h6;
- circumferential runout less than 3 μm; and
- use at maximum speed.

8.2 Lubrication and cooling system

In addition to the bearings themselves, the bearing parameters depend on the material and the quality of the surrounding parts, correct installation, and the choice of appropriate lubrication and cooling systems. These are lubrication and cooling of the contact point of the tool and work piece, lubrication and cooling of the bearings in the individual supports, and cooling of the motor and the headstock shell.

The correct choice of lubricant, method of lubrication, cooling liquid, method of cooling is as important for the proper operation of the bearing as the selection of the bearing and the design of the associated components. The methods used to lubricate and cooling the spindle bearings system at machine tools are shown in **Table 2**. Lubrication of bearings prolongs their life; it reduces the risk of their failures due to the mechanical damage at high speed; and it leads away generated heat. The lubrication method of spindle bearings at machine tools depends on the particular operation conditions.

The lubricating film thickness depends on the natural frequencies of rotation, operation temperature, and lubricant viscosity. In addition to the lubricant film thickness, it is necessary to assess the lubricant durability.

Grease for lubrication consists of 90% mineral oil or petroleum oil and 10% thickener. Lime soap, soda soap, lithium soap, or barium soap is used as the thickener. Grease durability depends on its quantity, sort, the bearing type, frequencies of rotation, and temperature in the assembled state. The bearings must be run in after their lubrication, and after a certain time period, they must be again lubricated. At running in, it is also necessary to take into account that grease can be well distributed on the whole bearing, which results in equalizing of temperatures generated by mechanic losses [6].

If the big accuracy is required at the spindle run, it is necessary to reduce heat. Passive friction moments that change to heat are influenced by the selected lubrication way and by the bearing design. The total passive friction moment is given:

$$M = M_0 + M_1 \quad [\text{N.mm}], \tag{20}$$

where M_0 is the friction moment dependent on the bearing design; and
M_1 is the friction moment dependent on loading (reaction).

The friction moment given by the bearing design and by the lubrication way is as follows:

$$M_0 = f_0 . 10^{-7} . (\nu . n)^{2/3} . d_{s^3} \ [\text{N.mm}], \tag{21}$$

where
f_0 is the coefficient given by the bearing design (0.7–12);
ν is the operation viscosity of oil or grease [$\text{mm}^2.\text{s}^{-1}$];
n is the frequency of spindle rotation [min^{-1}]; and
d_s is the mean spindle diameter [mm].

Lubrication by oil is used mainly in those cases where operation frequencies of rotation also require removal of generated heat from the bearing. At lubrication of the precise spindle bearings, it is necessary to use a small oil quantity to reach the high-quality bearing lubrication. The most widely used lubricating methods are:

- oil mist lubrication—the oil mist is produced in an atomizer and conveyed to the bearings by an air current. The air current also serves to cool the bearings and the slightly higher pressure prevents contamination from penetration;

Producer	Performance range [kW]	Revolutions range [min^{-1}]	Lubrication	Cooling	Drive	Technological operations
ENIMS	6.5	48–5200	Oil mist	Air liquid	AC	Tu
OMLAT	4.5–48.5	5000–40,000	Oil mist grease	Air	AC	Mi, Dr., Gr
IBAG	3–42	3000–80,000	Oil-air grease	Air liquid	AC	Mi, Dr
GMN	3–40	9000–60,000	Oil mist Oil-jet grease	Liquid	AC	Mi, Dr., Gr
FAG	2.5–20	20,000–45,000	Oil-jet minim. amount	Liquid	AC	Gr, Dr., Mi
SZM	10–15	20,000–75,000	Oil-jet grease	Air	AC	Mi, Gr
ITW	15	22,000–36,000	Oil mist	Air	AC	Mi, Gr
SKF	5.5–16	10,000–30,000	Oil mist Oil-air	Liquid	AC	Gr, Mi
MODIGS	1.4	70–2160	Grease	Liquid	DC	Gr, Mi
FORTUNA	0.45–15	12,000–18,000	Oil mist	Liquid	AC	Gr, Dr., Mi
SETKO	3.7	400–10,000	Grease	Liquid		Fr, Dr
PRECESI	0.17–6	7500–12,000	Oil mist	Liquid	AC	Fr, Dr., Gr

Machine units with AC integrated drive, DC, direct drive; Tu, turning; Mi, milling; Dr, drilling; Gr, grinding.

Table 3.
Components and peripheral devices used by selected manufacturers of electric spindles.

- oil-air lubrication—the oil is conveyed to the bearing in droplets by compressed air. The droplet size and the intervals between two droplets are controlled; and

- Oil-jet lubrication (cooling lubrication)—considerable amounts of oil are carried through the bearing by injection, the frictional heat generated in the bearing is dissipated. The cooling of the oil is achieved, for example, with an oil-to-air heat exchanger.

Table 2 describes various lubrication technologies and **Table 3** gives an overview of the individual components and peripheral devices used by selected manufacturers of electric spindles (**Table 3**).

9. Realized outputs

The spindle unit is determined by the structural parameters of the machine tool.

In accordance with the growing requirements for production and precision of machine tools, the requirements for the design and technical execution of machine tool headstocks are increasing. The headstock of a machine tool is now a mechatronic, highly sophisticated system in which internal systems with external peripherals must interact. The design, research and development of new types of headstocks is not possible today without high-quality computing and simulation software, high-performance computing, testing equipment, and the necessary experience. For our headstock design, we have developed:

- special software that enables the calculation of the load, stiffness, and durability of rolling bearings used for the bearing of machine tool spindles [11–13]. Our methodology of calculation of bearing nodes associated from radial ball bearings angular contact is original. At the same time, the software enables to calculate the optimal distance of bearing supports with respect to overall maximum stiffness, running accuracy, and thermal expansion according to the arrangement of bearings in individual nodes as well as thermal expansion of the whole spindle bearing system; and

- special testing equipment for measuring the accuracy of running, temperature, and stiffness of bearing nodes made of radial ball bearings with angular contact. The experimental bench (**Figure 19**) enables the determination of required parameters of nodes arrangement by up to 5 bearings [6, 11]. Testing is carried out under different operating conditions.

The results of our work are designed more headstocks of machine tools. At our institute, we developed headstocks for CNC machine tools for the companies TOS Lipník and TOS Kuřim. The headstocks developed for SBL CNC lathes manufactured by the company Trens Trenčín deserve special attention [17]. The headstocks of the 300, 500, and 700 series developed at our workplace and the first lathes SBL was first time at the exhibition in Nitra 2000 and at the exhibition in Düseldorf 2004 presented. The SBL series lathes with the listed headstocks are still produced and are successful in the market.

Well known is our design of high-speed headstock with two drives. The advantage of the original solution is the possibility of using a high torque moment at low revs, as well as the principle of achieving high resultant revolutions of a double-mounted spindle driven by two drives [11]. The headstock is applied to a wood lathe in the company Šustrik.

An example of a new functional model of an electric headstock for a grinding machine is shown **Figure 20** [18]. It is a design of a headstock designed on the basis of modular components of an AC motor (stator, rotor, and metering system) and compact control system of the IMB Indramat drive. The functional model is preferably used in our laboratories for ultrasonic grinding.

When designing all headstocks, we use the V-2.16 headstock application software. The technical parameters of the rolling bearing nodes, such as axial and radial

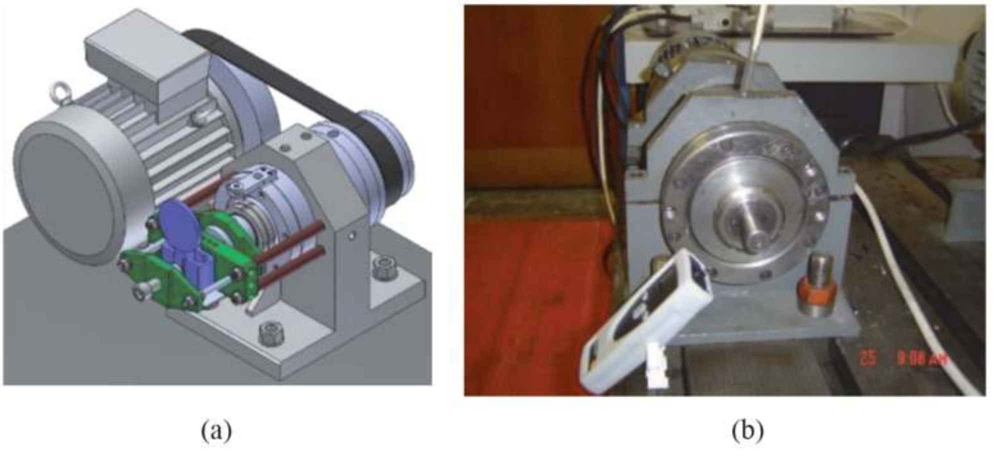


Figure 19.
Laboratory for measuring: (a) testing equipment for measuring bearing nodes; and (b) test bench for testing functional models.

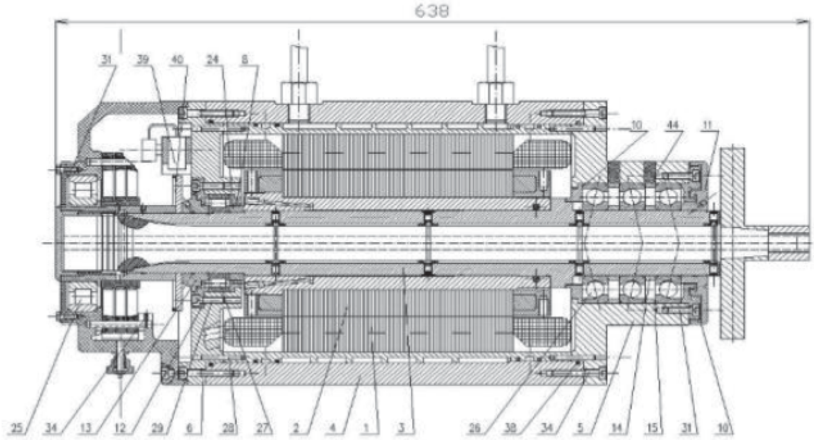


Figure 20.
Motor spindles for grinding machine tool [18].

stiffness, maximum speed, temperature, and running accuracy, are tested in our laboratories. Both the software and the experimental stand were developed at our workplace.

10. Conclusion

The technical level of fully automated flexible production systems has reached a degree at which accompanying working times and instruments are reduced to a minimum. Further increases in output are therefore possible by reducing the main production times.

This is possible by increasing cutting speeds—high-speed machining. Research in the field of high-speed cutting shows that, along with the reduction of lead times, cutting accuracy, productivity and machined surface quality are significantly improved.

In the chapter, requirements, characteristics, and development tendencies of the whole concept of construction of a machine, as well as construction nodes and elements of machine for high-speed cutting are described. With respect to the individual technological operations and the range and diversity of the required parameters, it is clean that at this time, it is not possible to design and universal machining unit—headstock. This requires a modular construction of the machining tool and individual peripheries that make possible a rapid change of the machining unit with the required revolution and performance characteristics.

The headstock is a determining structural node affected technological parameters machine tool. For high-speed machining, headstocks with built-in drive are used “Electrospindles.”

The results of the analysis showed that electromagnetic and rolling spindles are used to accommodate the spindles of high-speed headstocks. Exceptionally with lower rigidity requirements, an aero-static bearing can also be used. The most widely rolling bearings used machine tool spindle support are nodes—formed from radial ball bearings with angular contact. They are reliable enough, cost-effective and, given the wide range of combinations, they can optimally meet the contradictory requirements of stiffness and maximum speed. Hybrid ball bearings are used for the highest rotational speeds but are very expensive.

In terms of drives, both single-direction and alternating drives can be used in the principle for integrated spindle units. Despite very good control properties, DC drives have known operational and technical drawbacks resulting from commutation devices. They are used less than AC drives. From the point of view of lubrication, the oil-air system is used for the highest rotational frequencies, while grease lubrication is still used for the lowest rotational requirements.

The headstock is a complicated mechatronic node with a system of internal elements and external peripherals. Designers must, in addition to complicated computer systems, perfectly master the demands placed on the headstock and the interoperability of individual elements and peripherals. New non-traditional materials (SI3N4, SmCO5 alloy) as well as progressive design technologies and design solutions are used to achieve the best technical parameters of these headstocks. At the end of the chapter, we present our results and experience in the design of headstocks of machine tools.

Acknowledgements

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