



Design and Configurations for Machine Tool Spindles

An Online Continuing Education Course for Engineers

Course Number: M-4068

Credit: 4 Hours / 4 PDH / 4 CPD

Design and Configurations for Machine Tool Spindles

Jyoti Mukherjee, P.E., DEng, M.S., MBA, PGDBM

1. Introduction

Fundamentally, a spindle of any machine rotates about its own axis, called the axis of rotation. The job may be mounted on the spindle, or tools could be mounted on the spindle. When the job is held by a spindle, as in a lathe, the tool remains stationary or rotating. When the tool is rotating and held by the spindle, the job is held fixed with respect to the rotating tool, or it could have a curvilinear motion about its own axis. The cutting power is transferred through the spindle, and the relative motion between the job and tool helps to remove metal from the job. Various types of spindles are in use in various machines, as listed below:

1. Lathe spindle
2. Machining center spindle
3. Conventional Milling spindle
4. Motorized or built-in spindle
5. Grinding spindle for holding the grinding disc
6. Boring spindle used for enlarging inner diameters
7. Drilling spindle for drilling holes in metal blanks
8. Threading spindles for threading purposes
9. Hobbing spindle used for gear hobbing machines
10. Air spindles used for dental work
11. Electric spindle for machining centres or computer-controlled lathes
12. Jig boring spindle
13. Internal grinding spindle

The spindle has a shaft supported by bearings to transfer cutting loads from the job or tool to the machine housing. This shaft is called the spindle. The spindle assembly consists of the shaft or spindle, support bearings, holding devices, and an actuator, which is used to hold the job or tool. When the tool rotates, it is normally referred to as shaping, milling, drilling, or grinding operations. In common terms, a spindle consists of a chuck and a hydraulic actuator that operates the chuck. The bearings separate; the front and rear bearing support the spindle assembly (i.e., shaft, chuck, and actuator) from the spindle housing. We will discuss mostly angular contact bearings for spindle applications.

For a very slow rotary motion, journal bearings or hydrostatic bearings could be used to support the spindle. Various types of bearings could be used for spindles, as mentioned below:

1. Angular Contact Bearings
2. Radial Contact Bearings
3. Combination of angular and radial contact bearings
4. Taper Roller Bearings
5. Cylindrical roller Bearings
6. Pneumatic Bearings
7. Hydrostatic Bearings
8. Hydrodynamic Bearings
9. Magnetic Bearings

In the following sections, spindle design and bearing design will be discussed in detail. Spindle housing configurations could also be numerous, i.e., horizontal, vertical, and angled. Spindle housing also could be of different configurations: bolted housing in lathes, cartridge type in machining centres, housing integrated with the bed, etc. So, any spindle assembly for a lathe consists of the following:

1. Support housing
2. Support Bearings
3. Spindle shaft
4. Chuck holding the job
5. Actuator activating the chuck in a fly or a stationary position
6. Belt or gear drive
7. Encoders for spindle speed monitoring

For a lathe, for example, there could be a headstock or main spindle, and there could be a tailstock spindle, which helps to hold a very slender part between the chuck and tailstock center. There could be a single-spindle or multi-spindle configuration for a lathe. The machine with a multi-spindle configuration is also called a multi-spindle automat or lathe. Similarly, for gang drilling machines, a central shaft rotates several spindles simultaneously to drill many holes at the same time. For a lathe, the main spindle and tailstock spindle rotate at the same time and in the same direction. Spindles could be different depending on the types of machines, such as grinding spindles, electric spindles, hybrid spindles, very high-speed spindles, etc. So, spindles could be mechanical or electrical spindles.

The spindle could be mechanically driven by belts of gears, etc. Lathe spindles are of these types. Some recent lathes also have an electric spindle for high-speed operations. The belt-driven spindles could run as high as 6,000 to 8,000 revolutions per minute (RPM). For higher speed ranges, electric spindles or integrated spindles are used, and these spindles do not have belts or gear drives. The modern CNC lathes could run as high as 10,000-12,000 RPM. The low-speed spindles are meant for heavy chip removal per unit time, provided enough horsepower is available. The design of spindles and their speed and power capabilities depend on the nature and type of machines. Typically, CNC milling machine spindles run at a much higher speed than CNC lathe spindles in general. The belt-driven spindles cost ways less than electric or hybrid spindles.

The different but typical combinations of spindles for various machineries could be described as follows:

1. A lathe has a main spindle unit inside the headstock, and a sub-spindle called the tailstock spindle. A separate motor could power the tailstock, called a sub-spindle. (See Fig. 2.4 and Fig. 2.5).
2. For machining centres, milling machines, or drilling machines, the main spindle holds the tool, and the job is relatively fixed on a fixture. The spindle holds the tool through a taper nose and is pulled through the center of the spindle by an actuating cylinder or actuator. (See Figure 2.1)

2. Spindle Design Parameters

The first step of spindle design is to obtain the sub-system design parameters that the spindle has to satisfy. The sub-system design parameters for the spindle stem are derived from system parameters. The design parameters also depend on the type of machine, i.e., turning machine, milling machine, external grinding machine, internal grinding machine, fine boring machine, etc. The spindle design has really no standards and predominantly depends on design legacy and requirements. The design parameters and their metrics for the spindle design could be as follows:

1. Type of machine
2. Turning machine
3. Machining center
4. Grinding machine
5. Drilling machine
6. Etc.
7. Housing characteristics
8. Integral to the machine bed
9. Bolted on the machine bed
10. Cartridge type
11. Integral to the machine gearbox
12. Other relevant factors
13. Space limitations
14. Method of mounting
15. Tool mounting methodology
16. Size of chuck or tool size
17. Spindle nose requirements for chuck or tool mounting
18. Operating maximum and minimum speed
19. Maximum spindle horsepower of the machine
20. Noise level and maximum speed
21. Maximum torque at base speed and the highest speed of the machine
22. Desired surface finish
23. Thermal considerations
24. Duty cycle life for the spindle
25. Type of external loadings or forces

26. Spindle cooling requirements
27. Type of lubrication required
28. External or Internal coolant supply methods
29. Speed control mechanism
30. Machine accuracy or precision requirements
31. True Indicated Reading for the machine (TIR)
32. Maximum deflection allowed at the tool point
33. Axial movements due to thrust

For air-lubricated spindles, external load capacity is normally low, but the speed capability is very high. For dental work, air air-lubricated spindle might have speeds higher than 60 thousand revolutions per minute (RPM). Whereas conventional grease-lubricated bearings are meant for very high external loads and comparatively lower speeds. For extremely low RPM and high load cases, hydrostatic bearings are also used. There is no fixed method of lubrication for spindle bearings. It depends on speed and external load conditions. I have designed several spindles for CNC lathes, machining centers, and grinding machines during my professional career. The specifications for a high-speed computer-controlled lathe, termed as spindle sub-assembly, could be written as follows:

1. Main Spindle Power: 10 HP
2. Maximum Revolution: 6000 revolutions per minute (RPM)
3. Chuck Size: 6 inch
4. Spindle Nose Size: A2-6
5. Configuration: Hollow Spindle for draw bar
6. Hole Through Spindle: 1.25 inch
7. Maximum Bar Capacity: 2 inches
8. Chuck Jaw Clamp mechanism: Hydraulic Actuator
9. Grease Lubricated Bearings for Life
10. Minimum Bearing Life: 10,000 hours
11. Maximum Axial Drilling Thrust: 2000 pounds
12. Maximum Bearing Temperature: 110 degrees F
13. Maximum True Indicated reading @ spindle nose: 0.0002 inch
14. Spindle Runout @ spindle nose: 0.0001
15. Spindle Cooling: Normal Air cooling

Machine tool spindles depend heavily on the applications, load duty cycles, power, and speed requirements. The design also depends on the legacy of spindle design in the company. Next, we are going to explain some spindle design applications for various types of machines. During my machine tool career, I have successfully designed several types of spindles for lathes, machining centers, and grinders. Several typical machine tool spindle designs will be explained next to understand the differences in design for such spindles.

3. Characteristics of spindle design applications

Upright Drilling Machine Spindle (See Fig. 2.1)

The spindle has to reciprocate up and down vertically to perform the drilling operations. The spindle unit, also called a quill, houses the spindle and support bearings. In addition, it has serrated teeth on the outside of the quill, called a rack. The up and down motion of the quill is achieved through this rack and a pinion mechanism, which is not shown in the sketch. Moreover, the rotation of the drill is possible using a spline at the end of the spindle. Hence, motion is obtained through the rack and pinion, and power transfer is possible through the spline. The spindle has rotary and axial feed motions to carry out the drilling operation. The drilling operation requires a lot of axial thrust for the drill to penetrate into the metal. The quill-down motion, called feed motion, creates the thrust force. In addition, it also has radial or transverse force. Hence, the spindle bearings have to sustain axial and radial forces. The accuracy of the drilling operation is not that important as long as the spindle has sufficient power to carry out the drilling operation. The axial thrust and torque required depend on the metal being cut and the type of drilling operation, such as spade drill or flute drill. The cutting tool or drill is mounted at the end of the spindle using a more taper mechanism.

The considerable axial thrust developed during the drilling operation is taken up by the thrust bearing, as shown in the sketch. In addition, it has two radial ball bearings to take the radial loads. For high-speed drilling machines, the thrust bearing and radial ball bearing could be combined, and angular contact bearings are used instead. The angular contact bearings are good for very high speeds, axial loads, and radial loads. If the axial load is very high and the speed is low, thrust bearings or taper roller bearings could also be used. The rear end of the spindle also has a thrust bearing and radial ball bearings. In recent days, mostly angular contact bearings are being used for almost all the spindles due to higher speed and load capacities for these types of bearings. The thrust loads are transmitted to the housing through the thrust bearing collars, which are pressed against the housing as shown in the sketch. For this particular design, the radial ball bearings are placed between the thrust bearing and the spindle housing. So, the axial load goes through the thrust bearing and ball bearings to the housing.

Internal Grinding Machine Spindle (See Fig. 2.2)

Figure 2.2 shows a schematic for the internal grinding spindle. The characteristics of the internal grind spindle are very high speed, low radial and axial loads. The spindle has to have very high stability so that the high finish requirement is satisfied. The radial stiffness of the spindle should be very high. The front and rear of the spindle have a duplex tandem set of angular contact bearings. Normally, for high-speed applications, 15-degree contact angle angular contact bearings are used, where radial stiffness is much higher than axial stiffness. The tandem pairs are mounted in a back-to-back condition. Moreover, the rear set is opposed to the front set. In order to increase the radial stiffness of the spindle, i.e., higher radial rigidity, the front bearings are preloaded with the help of compression springs circumferentially. Normally, 10-12 springs are put to create the preload, and bearings cannot unload during grinding conditions. The springs are equally placed around the circumference of the bearing to create uniform

preloading conditions. The amount of compression of each spring determines the initial preload for the bearing. Total preload required depends on the temperature rise of the bearings, which are grease lubricated for life. More initial preload means higher axial stiffness, but it also increases the temperature of the bearings. Very high temperature at high speed might seize the bearings.

The bearings are normally greased for life using Kluber or shell grease (Vectra 2 or equivalent), suitable for high-temperature applications. The bearings are protected from the coolant using labyrinth seals in front and back. The coolant entry destroys the bearing in a very short time. The bearings used are very high-precision bearings with EP7 class bearings. Very high-speed applications requiring 30,000 RPM or higher might need even EP9 class bearings. The characteristics and specifications of these bearings will be discussed afterwards. For extreme high-speed applications, the lubrications might have to be changed to oil-mist or lubricated air types. EP9 bearings work better with oil mist lubrication. If the axial load exceeds the total spring preload on the front, it might unload the front bearing and at that point, the rear bearings will be destroyed instantly. For extreme high-speed applications, the bearings should not unload at any time during operation.

External Cooling

The front bearing is located between the spindle and the workpiece. The bearings are preloaded to provide axial stiffness on the spindle configuration. The bearings on the spindle are necessary for the spindle. The bearing is vertically located the spindle. The growth of the spindle is controlled so that the tolerances of the spindle are controlled so that the spindle is greased with high-speed bearings or tilted pads. The modified such a spindle

To view the remainder of the course material and to take the quiz for PDH credit, you must purchase the course.

Close this window and click "Add to cart" on the product page.

is captivated through the bearings. The bearings cause the radial and axial stiffness of the spindle. Overtightening the bearing set to accommodate thermal growth. So, the bearings must be preloaded and they are life-long oil lubricated. The bearings are serviced and modified such a spindle

CNC Lathe Tailstock Spindle (See Fig. 2.4)

In a conventional lathe machine, the tailstock center is fixed and cannot rotate. For automated computer and numerically controlled (CNC) lathes, it is necessary to have a live center so that the center can rotate along with the main spindle rotation. Hence, the tailstock center is supported on bearings as shown in Fig. 2.4. The center is supported by a quadruplex set of angular contact bearings having 20-degree or 25-degree contact angle. The front three bearings are mounted in tandem configuration and one opposed fashion, which could be called a preloading bearing. The front three bearings are fixed between two surfaces and take the axial force mostly in addition to the radial force due to part weight and cutting loads. These three bearings in the front take all the axial thrust, and the axial loads will tend