10.1 Introduction

This review is organized into the following sections: 1) Machine Construction Materials, 2) Slideway Design, 3) Spindle Bearing Design, 4) Spindle Drives and, 5) Machine Component Systems. It is intended to be a brief overview of each area. Additional, independent study in each area is recommended to properly prepare for the certification exam.

The design of a machine tool is a complex process. It requires a full spectrum of knowledge in mechanical, electrical and electronic engineering. In evaluating the design of a machine tool the question must first be asked, "What is the purpose of the machine?" In machine design what's good for one machine may not be good for another machine. Each machine is designed to meet the goals of its application. Design considerations for machine tools include some of the following:

- Quality & Reliability.
- Economics of production.
- Strength and rigidity
- Accuracy
- Stability
- Space & weight limitations
- Life expectancy
- Legal & industry codes
- Safety enclosures and labeling
- Waste removal – (i.e. dust & chip flow, collection systems)
- Part conveyance (i.e. pallet changing or work piece loading systems)
- Operator ease (i.e. access to the spindle or toolholders for setting tools)
- Workholding – (i.e. rotary tables, chucks, angle plates, bar feed)
- Sound abatement and noise level controls
- Flood/Mist/high pressure coolant systems and coolant recovery systems
- Installation provisions and foundation needs if required.
- Ease of maintenance and required maintenance provisions.
- Availability of standardized spare parts for necessary maintenance.
- Styling
- Selling price

The machine tool design engineer must carefully consider the types of part pieces that will likely be produced on the machine and make provisions for vital features, accessories. The designer must also consider environmental and safety issues.
10.2 Glossary

**Backlash** - The relative motion of interacting mechanical parts resulting from looseness and deflections.

**Ball screw** - See lead screw.

**Bar capacity** - The maximum diameter of bar stock which can pass through the spindle hole of a center or turret lathe or of an automatic bar machine.

**Bar feed** - A feeding attachment used to advance bar stock into the main spindle of an automatic lathe.

**Base plate** - A metal plate used as a foundation for a machine.

**Bed** - A horizontal frame provided with one or more precisely machined slideways on which moves another machine element or table. These machine ways also support or align other machine parts.

**Bearing Preloads** - Preload is the application of pressure to one set of bearings in a set of opposed bearings supporting a shaft supplying rotary motion. It is a force applied along the axis of the shaft against the moveable bearing. Too much force could lock the bearings while too little force could produce unwanted endplay movement in the shaft.

**Bearing, roller and ball** - An anti-friction bearing in which the rolling elements are rollers (roller bearing) or balls (ball bearing).

**Coefficient of Friction** - The relationship between force of friction and normal force.

**Column** - A machine frame or main part or a frame, whose height greatly exceeds its width and its depth. If the frame has two vertical main parts, they are usually called "standards"; if only one main part, the term "column" is preferred.

**Counterbalance** (counterweight) - A device or system that counterbalances the original load (i.e. Counterbalance weight for the vertically moving headstock on a horizontal boring mill).

**Creep** - The flow or plastic deformation of metals that are held for long periods of time at stresses lower than the yield strength.

**Cross slide** - A part of a machine tool that allows the tool to move at right angles to the main direction of travel. A slide, which moves on the saddle at right angles with respect to the bed.

**Cross turret** - A turret that moves horizontally and at right angles to the lathe guides.
**Damping** - A built-in characteristic of mechanical systems, which prevents rapid or excessive corrections that might lead to instability and oscillation.

**Deflection** - Bending or displacement of the workpiece or machine member from its normal position.

**Flywheel** - A heavy wheel whose purpose is to store Kinetic energy.

**Force** - That influence on a body, which causes it to accelerate; quantitatively it is a vector, equal to the body's time rate of change momentum.

**Frame, machine** - A structure made of metal or composite material, which the various parts of a machine are assembled.

**Friction** - A force, which opposes the relative motion of two bodies whenever such motion exists or whenever there exists other forces which tend to produce such motion.

**Friction, rolling** - The resistance (force) to the relative rolling motion of the surfaces of two bodies in contact.

**Friction, sliding** - The resistance (force) to the relative sliding motion of the surfaces of two bodies in contact.

**Guideway** - See slideway.

**Headstock** - 1. The machine member, which contains the main revolving spindle and its drive mechanism. 2. The moveable head of certain machines.

**Hexapods** - A machine designed in a fashion similar to the Stewart platform used in flight simulators. One common version is a stable truss type octahedron, composed of triangular elements and a vertical spindle housing and requiring advanced controller architecture and use of algorithms when programming.

**Horsepower** - A unit of power (inch system) for measuring the power of motors or engines, equal to a rate of 33,000 foot pounds per minute (the force required to raise 33,000 pounds at a rate of one foot per minute). Equivalent to 0.746 kilowatts.

**Hydraulics** - The technique of control that uses a liquid (oil) to perform sensing, control, information processing and actuation of functions.

**Hydrostatic bearing** - A sleeve bearing in which high-pressure oil is pumped into the area between the shaft and the bearing so that the shaft is raised and supported by an oil film.

**Kilowatt** - A unit of electrical power equivalent to 1,000 watts or 1.34 horsepower.

**Lead screw** - A high-precision slide feed screw, used to convert rotation to longitudinal motion, which imparts the feed or axis motion. A ball screw uses a precision spiral-ground screw with a recirculating ball bearing nut.
**Linear Motors** - Literally a rotary motor “laid out flat” where the rotor is a fixed slideway and the stator is a flat plate type-moving element. Each element has electrical windings, thus the slideway needs no drive motor to initiate displacement.

**Multi-Function Machines** – Machines labeled as “Multi-function”, “Multi-tasking”, “Multi-axis” or “Integrated” machines usually combine several machine types such as a lathe and a mill.

**Nutation** – The rocking, swaying or nodding in an axis of rotation. This term is used to define any tilting axis on a 5-axis machine tool that is not at a right angle to a linear axis.

**Overhang** - The unsupported length of a machine part which projects from its support.

**Pneumatics** - The technique of control that uses air to perform sensing, control, information processing and actuation of functions.

**Ram, machine** - A reciprocating slide, which carries either, the tool post of a shaper or slotter, or a press tool and which carries out the main movement of the machine.

**Rib (strengthening)** - A projection from a wall whose purpose is to reinforce that wall.

**Rigidity** - The quality or state of resisting change in form.

**Rolling friction** - The force resisting a body rolling on a surface.

**Rotary table** - A work table, circular or rectangular, which has a rotary feed or indexing motion through not less than 360 degrees.

**Saddle** - The slide of a tool-carrying device that slides directly upon the bed or cross slide.

**Slideway** - Bearing surfaces used to guide and support moving parts of machine tools; commonly designed as flat, round, V-shaped, dovetail or rectangular.

**Spindle** - The main shaft of a machine tool, usually hollow, on which the working energy is available. The spindle receives the workpiece or the cutting tool.

**Spindle nose** - The free end of a spindle, projecting slightly from the frame of the machine and receiving clamping devices for the workpiece or cutting tools.

**Static load** - A load acting on a non-rotating bearing.

**Stiction** - The static or breakaway friction.

**Stress** - A constraining force or influence. A force exerted when one body or body part presses on, pushes against, or tends to compress or twist another body or body part.

**Tail stock** - A part of a lathe that holds the end of the work not being shaped, allowing it to rotate freely.
**Tensile strength** - The resistance of a material to being torn apart; the maximum tensile or pulling stress it can withstand. Tensile strength tests may measure the tensile stress a material can support without yielding, or without breaking.

**Thrust** - 1. The force exerted in any direction by a powered screw. 2. The weight or pressure applied to a tool bit to make it cut.

**Thrust bearing** - A bearing which sustains axial load and prevents axial movement of a shaft.

**Torque** - The tendency to produce rotation or torsion; it is expressed as the product of a force and its distance from the axis of rotation.

**Transfer Line/Machine** - Group of work stations closely connected together by an automated material handling system and designed for high-volume production of a single part or similar parts.

**Turret** - A tool-carrying block which can be swiveled so as to bring several tools successively into working position. It can replace the simple tool post. On CNC machines the part program can control it.

**Vector** - A quantity that has magnitude and direction and is usually represented by a directed line segment whose length represents the magnitude and whose orientation in space represents the direction.

**Viscosity** - A fluid's resistance to shear or motion (internal friction).

**Way** - See slideway
# 10.3 Machine Construction & Materials

## Structural Components

Major machine structural components such as beds, base plates and columns come together to form the load-carrying structure the machine. The terminology for the various structural components varies by machine design. Here are the more common terms.

<table>
<thead>
<tr>
<th>Structural Component</th>
<th>Lathe &amp; Turning Ctr.</th>
<th>Milling Mach &amp; Machining Ctr.</th>
<th>Multi-Function Machines</th>
<th>Cylindrical Grinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base/Bed</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Column</td>
<td>Some</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Headstock / Spindlehead</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-Spindle or Second Spindle</td>
<td>Some</td>
<td>Some</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carriage</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Cross Slide</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Saddle</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Table</td>
<td>+</td>
<td>+</td>
<td>Some</td>
<td>+</td>
</tr>
<tr>
<td>Wheelhead</td>
<td></td>
<td></td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Workhead</td>
<td></td>
<td></td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Tailstock</td>
<td>+</td>
<td>Some</td>
<td>Some</td>
<td>+</td>
</tr>
<tr>
<td>Footstock</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
</tbody>
</table>

While each machine design is different, several examples of structural components are presented for consideration. Consult with the machine manufacturer regarding structural component nomenclature.

Fig. 1 – Lathe Structural Components (Courtesy Hardinge, Inc.)

Fig. 2 – Vertical Machining Center Structural Components (Courtesy Hardinge, Inc.)
Fig. 3 – Multi-Function Turn/Mill
(Courtesy of DMG / Mori Seiki USA)

Fig. 4 – 5-Axis Vertical Machining Center
(Courtesy of DMG / Mori Seiki USA)

Fig. 5 – Cylindrical Grinder Structural Components
(Adapted from Gardner Publications)
While construction designs and techniques vary among machine manufacturers, one common denominator is the need for precise geometric alignments. In other words, the machine’s structural components must be held square and parallel with each other. Also, the machine’s slides must perform within acceptable specifications of roll, pitch and yaw throughout their entire length of travel. Other requirements such as flatness will apply to the mating surfaces of structural components as well as tabletops. The sales engineer should discuss the issue of geometric alignments with the machine tool manufacturer and know the specification limits as well as their effect on workpiece quality.

**Multi-Function Machines**

Multi-function machines (also called Multi-tasking, Multi-Axis or Integrated machines) combine two or more single machine designs into one machine. For example, combining a lathe and a milling machine together in a single machine could be called a Turn/Mill machine if the primary structure resembles a lathe. If the primary structure resembles a mill, with added lathe functions, the designation would be a Mill/Turn design. These machines will have more axes of movement and incorporate machine components of both lathes and mills.

Machine designers are now integrating grinding, gear-cutting and broaching into multi-function machines. These machines can reduce setups, floor space and cycle time. They may also allow for machining more complex parts with higher accuracy.

**Five-Axis Machining Centers**

Five-axis simultaneous machining centers have been around for many years; however, their popularity is increasing. Five-axis machining center designs normally follow one of three common structural designs:

1. Two rotary axes in the head (head/head).
   a. Fork or
   b. Nutated fork (one axis is not perpendicular to a linear axis)
2. Two rotary axes in the table (table/table).
   a. Rotate/swivel or
   b. Rotate/swivel nutated (one axis is not perpendicular to a linear axis)
3. One rotary axis in the head and one rotary axis in the table (head/table).

The popularity of five-axis machining centers is being driven by several factors:

1. Machining of parts with complex features that require machining at compound angles and surface geometry not obtainable with 3 or 4 axes.
2. Machining of less complex parts where five sides can be machined in a single setup.
3. Machining of parts where shorter, more rigid, tools can be used due to tilting the head or table.

Additional information on 5-axis machining centers is discussed in the “CNC Technology and Machine Control” chapter.
Fig. 6 – 5-Axis Machining Center Configurations (Courtesy of Siemens)
STRUCTURAL MATERIALS

The materials that are chosen for these components play a key role in the machine's integrity and performance. Construction materials are chosen based on the properties of the material and the component's function. Here is a chart of material properties with respective influence on performance:

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Performance Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>Avoids plastic deformation &amp; fracture</td>
</tr>
<tr>
<td>Specific Density</td>
<td>Mass distribution, static &amp; dynamic performance</td>
</tr>
<tr>
<td>Modulus of elasticity, torsion or stiffness modulus</td>
<td>Static &amp; dynamic performance</td>
</tr>
<tr>
<td>Dampening properties</td>
<td>Dynamic performance</td>
</tr>
<tr>
<td>Coefficient of friction &amp; hardness</td>
<td>Frictional and wear performance of moving surfaces</td>
</tr>
<tr>
<td>Residual stress, creep, relaxation properties</td>
<td>Long-term retention of geometric shape</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, specific heat, coefficient of thermal conductivity</td>
<td>Thermoplastic characteristics and repeatability</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>The resistance of a material to being torn apart; the maximum tensile or pulling stress it can withstand. Tensile strength tests may measure the tensile stress a material can support without yielding, or without breaking.</td>
</tr>
</tbody>
</table>

No single construction material has it all; therefore, material properties and performance must be balanced. Become familiar with the above characteristics by looking them up in a metal's handbook and comparing the various machine construction materials. The most common materials used in machine frame construction are:

1. **Cast iron**
2. **Steel**
   - Weldments
   - Castings
3. **Composites & Combinations**
   - Concrete
   - Concrete in cast iron frame
   - Steel reinforced concrete
   - Concrete with epoxy resin
   - Epoxy/Plastic
   - Glass/fiber (reinforced plastic)
   - Carbon/fiber (reinforced epoxy)
   - Granite slab
   - Epoxy/Granite

**CAST IRON & STEEL**

**Cast Iron**

Cast iron is one of the most popular materials used in machine tool construction. It yields good static and dynamic performance along with excellent dampening, stability and long-term retention of shape when properly cast and aged. Machinability is very good. It can vary in material specification and consistency from casting to casting is difficult to guarantee.
Gray iron castings are produced from molds made with wooden patterns. Due to the complexity of gray iron workpieces “core boxes” are used in and with the pattern to make more complex interior sections of the casting.

The use of gray iron as the base metal for machine tool structures is based on the combination of cost, reliability, casting strength, machinability and the vibration absorption ability of cast iron structures. Machine tool gray iron has combinations of carbon and silicon to suit the application and desired machinability. In addition, alloys of gray iron may include elements of nickel, chromium, manganese and chromium to provide added strength or improve machinability.

Generally, gray iron castings can be classified by tensile strength, which is defined as the force required to fracture a test bar when pulling the opposed end of the bar. Tensile strength varies from 20,000 pounds to 35,000 to 40,000 pound and the traditional nomenclature is a “20,000 pound iron.” Generally, higher tensile strength iron can be harder to machine, but offers more rigidity and strength in the resulting structure. Many machine tool builders advertise “Meehanite” castings, which are basically cast iron but alloyed and poured under a special process licensed under the trade name “Meehanite.” Use of different grades or types of cast iron depends upon the design engineering and machining objectives of the machine tool builder.

Procurement drawbacks can include increasing costs and long lead times. Foundries are experiencing higher costs due to environmental concerns. Finding quality foundries may force builders to deal with out-of-state sources with higher shipping costs. Also, initial mold costs must be written off over a large quantity of castings.

**Steel**

Steel can either be cast or welded to form suitable machine components.

**Steel castings** are used in limited applications due to cost and less machinability. They have similar characteristics to cast iron but have greater tensile strength and stiffness.

**Steel weldments** have grown in popularity as designers and fabricators work to overcome shortcomings of early designs. Weldments offer excellent static and dynamic performance with dense mass. Cost and availability are also desirable with some builders fabricating weldments in-house. Without expensive molds, they offer potential for quick production and are frequently used on custom or low volume machine designs. High tensile strength easily withstands machining forces and deflections without being permanently deformed. Generally, steel weldments have a slightly higher coefficient of thermal expansion than cast iron, which means that they grow more with heat. (Depending on the specific type of steel or cast iron, the thermal expansion ranges of these two metals can actually overlap in rare cases). However, the welding process can introduce stresses that must be relieved before...
machining and assembly. Design challenges include the proper addition and placement of reinforcements. Since steel has less dampening abilities than cast iron some manufacturers may fill the weldment with concrete and/or composites.

**COMPOSITES**

In the early 1960's alternatives were sought to traditional cast iron and steel fabricated parts. The 1970's saw the development of castable polymer composites, which were mixtures of aggregates, fillers and active resin binders. Since concrete was the primary aggregate the term polymer concrete is frequently used. Composites are now being used in machine tool construction and have made a place for themselves as a reliable and noteworthy material. Concrete is also used, alone or mixed with resins, as a dampening filler with cast iron and steel. It has excellent dampening qualities and has been used where volume is needed with a low cost. It can be mixed and molded in the builder's facility after molds and processes have been developed.

Other composites include Glass-fiber (reinforced plastic), Carbon-resin (reinforced epoxy) and epoxy/granite slabs and components. Typical mixtures of aggregate gravel, resin and concrete are poured into a wood mold and allowed to harden. Composites can offer superior vibration dampening, greater rigidity and ease of manufacture. The dampening qualities are claimed to increase tool life and improve workpiece surface finish. Thermal expansion is usually lower than cast iron. Other considerations for composite materials are:

1. Does the geometric form and application of the structure lend itself to composite molding?
2. What are the pattern or mold costs?
3. Will the machining costs increase?
4. Will the design require metal plates or inserts for mating and mounting components?
10.4 Guideway Design

The purpose of the guideway (or slideway) is to accommodate the axis movement of the machine slides, worktables and spindles. The guideway also provides the geometric alignment (parallelism, perpendicularity, roll, pitch and yaw) for the axis. The surface must support the static and dynamic loads (including machining forces) with as little friction as possible, but at the same time dampen the effect of a movable joint on the machine.

**Standard Guideway Geometries** - The guideway configurations or geometries most commonly used are:

1. **Round** – Limited used on surface grinders as well as feeding spindle bars (e.g. boring mill).
2. **Flat** – This guideway is used for alignment only – normally outboard from the machine’s spindle. Found on a wide range of machines including grinding machines.
3. **Vee** – Cylindrical grinders may have vee ways. They are outboard from the grinding wheel and are used primarily for alignment.
4. **Dovetail** – This guideway is seldom seen on today’s machine tools. However, it has some application in tool slides (e.g. gang tool slide on a Swiss-type turning machine). It features extremely good rigidity and alignment characteristics. It is an expensive guideway to produce.
5. **Box** (square/rectangular) – This is a common guideway on machining centers and lathes. It is used in heavy machining (e.g. milling) applications. The box can either be a bolted-on steel rail or an integral part of the machine’s casting. When they are integral, the cast iron surface is flame or induction heat-treated and then ground and/or hand scraped.
6. **Ball or roller** – Prepackaged ball and roller packs can be purchased in a variety of sizes and ratings for general application on a wide range of machine guideways. A version of this concept is the Linear Motion guideway discussed below.

Not shown above are rolling element linear motion (LM) bearings or Linear Guideways. This design combines the moving and non-moving elements of a slideway in a prepackaged unit that uses one or more of the above geometries. LM guideways have become a standard feature for...
most CNC machine tools and is as much of a basic guideway design as the above sketches.

**Linear Motion Guideways** are pre-packaged, pre-ground elements packaged for use with most, if not all, slideway configurations. The benefit in their use is the reduced friction encountered in the typical configuration shown below. As design and manufacturing capability has improved linear motion guideways, their use in machine tool applications has increased. These units normally offer designers cost savings. Special engineering handbooks permit a machine tool design engineer to “customize” a standard design for a specific use. Also bearing packs and guide rails may be ordered to fit almost any application. For certain, critical applications, special linear motion guideways with higher rigidity and accuracy can be utilized. A machine tool design engineer will consider the following factors before deciding on which form of linear motion guideway to use.

- Use of balls or rollers
- Shape of the guideway contact surface
- Recirculating or non-recirculating ball/roller elements
- Bearing spacing

Generally, balls are more accurate, suitable for lighter loads and have less potential skidding sideways. Ball-type designs may also allow faster machine axis traverse rates. Rollers have twice the load capacity of balls in a given circular arch. In short-stroke precision applications, non-recirculating balls are generally used. For heavier, longer travels rollers are more likely to be used. As in all machine tool design, trade-offs exist and no one solution is best for every application.

There are three basic types of rolling element linear motion bearings:

1. Non-recirculating balls or rollers.
2. Recirculating balls.
3. Recirculating rollers.

Shown above is a typical runner block mounted on a rail and a cross-section of a typical 4-ball, unit cross-section.
Guideway Installation & Alignment is a critical factor in the performance of the machine tool. The guideway top surface geometry must be square, parallel and flat with respect to the moving axes of the machine. If the guideway is a bolt-on unit (e.g. steel box way or linear motion guideway), then the machine surface under the guideway must also be square, parallel and flat before mounting.

The top and mounting surfaces are normally prepared by either: 1) finish milling, 2) grinding or 3) hand scraping. A combination of these techniques is often employed.

Hand Scraping

Cast iron, mild steel and Turcite can be hand scraped. Scraping is the controlled removal of metal, by hand, from a part, either to improve the surface quality or change its shape or both. An oversimplified process is as follows:

1. Rub a known flat surface (e.g. straight edge or master block) over the surface of the object to be scraped. A white or blue dye material is used between the surfaces.
2. After the “rub”, the dye material is worn off the high spots and the remaining shiny spots on the part indicate where metal is to be removed by scraping.
3. The scraper hand uses a “scraper bar” (a long bar fitted with a High Speed Steel or Carbide tip) to selectively cut (shave) down the high spots.
4. The process is repeated until the shiny spots are uniform across the surface.

Scraping is usually identified with the hand scraper or power scraper tools, but other metal removal tools such as files, stones, and emery cloth may be used. The techniques used in manipulating these tools and the methods for determining exactly were metal should be removed are part science and part art. A craftsman skilled at scraping is called a scraper hand. Scraper hands often develop their own techniques. Scraping requires patience, intelligence, coordination, mechanical reasoning skills, and a great deal of practice.

When small pockets of relief are added to a bearing surface it is called “flaking.” Flaking is used to enhance surface lubrication and reduce contact friction. Flaking is normally applied as a regular pattern on a surface and has a uniform, distinctive appearance. When done only for ornamental purposes it is called frosting. Flaking does not improve geometry or fit of the surface. This uniform pattern is frequently seen on machine tabletops.

Scraping is a highly precision process. Fit and geometry tolerances in the millionths of an inch are common. It is normally more accurate than machining or grinding because the metal is removed very selectively with the part in an unclamped state.
Scraping is traditionally done with a hand tool with all the power driving the tool coming from the scraper hand. Power tools can greatly speed up the scraping process. While power scraping can be just as accurate on open surfaces as hand scraping, more control over the finish can be exercised with a hand scraper.

For more information and pictures on hand scraping refer to www.machinerepair.com.

**Slideway Design Criteria** - Important design criteria for slideways are:

1. **Static and Dynamic Characteristics**
   The slideway must have adequate characteristics for both static (parked) and dynamic (moving) performance. An example of needing good static performance is during precision boring operations when slides are parked. Dynamic characteristics are important for the cutting and traversing motions of the slide.

2. **Alignment**
   The design must provide a straight path for the machine slide. Cast iron constructed slideways can be brought into flatness and alignment by finish milling, grinding and/or hand scraping. A cast iron slideway has the advantage of being an integral part of the machine instead of being bolted-on. When used as a slideway surface it is usually flame hardened and used with a non-metallic liner on the matching surface. Steel slideways are ground flat and parallel, then mounted (bolted) onto the machine structure. The machine structure surface where steel ways are mounted is usually precision ground and/or hand scraped for flatness and alignment. Steel slideways are extremely hard and feature long life. They can be used with a non-metallic liner material or roller bearings.

3. **Bearing Surfaces & Lubrication**
   To reduce friction between the matching slideway members some type of bearing must be incorporated. Bearings fall into three categories: 1) sliding, 2) rolling and 3) pressurized (oil or air). The surface of the slide must provide stability and strength for the transfer of machining forces but also have minimal friction. These two characteristics are not always easily achieved together.

   **Metal-to-metal** way surfaces were the first to be used on machine tools. Lubricating oil becomes the anti-friction agent between the moving slide members. Lubrication is either passive (drip/gravity) or under pressure. Hand-scraped surfaces provide natural pockets for the lubrication oil.

   **Non-Metallic** (Turcite® type) liners are a popular synthetic material that is applied with epoxy-based adhesive to flat machine surfaces. It offers maximum surface area contact with a low coefficient of friction. The broad surface-to-surface contact provides excellent stability and dampening. Non-metallic liners can be used on flat, Vee, dovetail and rectangular way
designs. Both metal-to-metal and non-metallic lined ways require excellent chip protection and lubrication filtration systems.

**Lubrication** of slideways can be accomplished by one of the following systems:

1. **Hydrodynamic** - Lubricant (oil) applied with little or no pressure.
2. **Hydrostatic** - Lubricant (oil) applied with pressure.
3. **Aerodynamic** - Lubricant (air) applied with little or no pressure.
4. **Aerostatic** - Lubricant (air) applied with pressure.

Some machines use a combination of air and oil under pressure. It should be understood that when a lubricant is used, its ideal purpose is to coat the surfaces and form a separating film.

Lubrication theory is a complex subject. Even the terms can be confusing. For instance, take the terms "hydrostatic" and "hydrodynamic." The word "static" sounds like it means "no pressure" and the word "dynamic" sounds like it means "pressure or action." In fact this is not the case at all.

The problem comes from the fact that the term "hydrodynamic" is a term from physics that describes what is happening between the moving surfaces and the lubricant. The hydrodynamic phenomena acts a little differently depending if you are talking about flat surfaces or rotating shafts with journals. It can either be pressurized (normally on flat surfaces at low-pressure flow) or naturally drawn between the moving surfaces (normally rotating shafts & journals). Here is a definition taken directly from the Automotive & Industrial Lubricants Glossary:

**Hydrodynamic Lubrication**

"A lubrication regime characterized by a fluid film between two moving surfaces. The most common example is the type of lubrication, which occurs in lubricating journal bearings. The movement of one surface (the shaft or journal) "pulls" lubricating oil into the space between the journal and the bearing. This action causes a high pressure in the fluid, which completely separates the two surfaces. By contrast, in boundary lubrication, there is only a partial fluid film separating the two surfaces and some surface-to-surface contact occurs."

The pressure spoken of in the above definition is caused, not by an external pump, but by the viscosity, drag flow and wedging effect on the lubricant between the moving surfaces. This "hydrodynamic" effect causes a separation of the moving surfaces with a solid fluid film between.

The other type of lubrication is called "hydrostatic." Here is a description from the book "Hydrostatic Lubrication" by Bassani & Piccigallo (Publisher - Elsevier Science Ltd. 1992)
Hydrostatic Lubrication
"Hydrostatic Lubrication is characterized by the complete separation of the conjugated surfaces of a kinematic pair, by means of a film of fluid, which is pressurized by an external piece of equipment. Its distinguishing features are lack of wear, low friction, high load capacity, a high degree of stiffness, and the ability to damp vibrations."

Here is a comparison of the relative benefits of roller bearings compared to plain bearing surfaces lubricated with oil.

<table>
<thead>
<tr>
<th>Damping:</th>
<th>Roller bearing</th>
<th>Hydrodynamic bearing</th>
<th>Hydrostatic bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running accuracy:</td>
<td>Poor/Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Speed range:</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Wear resistance:</td>
<td>Fair</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Power loss:</td>
<td>Fair</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Installation costs:</td>
<td>Good</td>
<td>Poor</td>
<td>Fair</td>
</tr>
<tr>
<td>Cooling capacity:</td>
<td>Fair</td>
<td>Fair</td>
<td>Poor</td>
</tr>
</tbody>
</table>

| Approximate coefficients of friction for common combinations of lubricated slide-way materials are as follows (the lower coefficient means less friction): |

- Cast iron to Cast iron 0.21
- Cast iron (or steel) to Non-metallic liner 0.07
- Steel to Ball (or Roller) 0.05
- Steel (or Iron) to Air (or Oil) 0.03

Technology in bearing design is moving ahead at a rapid pace. Stay in contact with the machine tool manufacturers for the latest in slideway bearing benefits.

4. Support of Machine Members
Machine designs are characteristic of a series of movable machine components built one upon another, with a movable joint between each component. Each movable joint is equipped with a slideway, which should provide adequate support and strength to support the subsequent machine component. When evaluating a machine design, picture the path (direction) the forces must travel back to the machine foundation. Designers call this a force-flow diagram and it can tell a lot about the structure and slideways. When slideways are overhung or unsupported, rigidity suffers.
10.5 Spindle Bearing Design

SPINDLE DESIGN REQUIREMENTS

The transmission of power to the spindle depends upon many factors. Two distinct spindle applications exist on today’s machine tools – 1) rotating partpiece or 2) rotating cutting tool. For instance, on a Lathe the part generally rotates. On a Machining Center the cutting tool rotates. Design considerations in both cases include:

- The horsepower required for the cutting operations.
- The end thrust (forces directed along the axis of the spindle) and lateral forces (forces perpendicular to the axis of the spindle) on the spindle during cutting operations.
- The minimum and maximum RPM required for the range of material to be machined.
- The mounting method used for adapting cutting tools to the spindle for milling/drilling or to attach the workpiece for lathe operations.
- Thermal stability required for the tolerances expected from the machining operations.

From the accurate definition of these conditions the machine tool designer has to decide how to support the rotary motion of the spindle within the housing or spindle head. In the case of turning machines where the rotation of the workpiece is a function of the machine tool spindle, the weight of the workpiece is a determining factor in the selection of the spindle bearings. Conversely, the size and weight of cutters, tool adapters and tool holders must be carefully considered in machining center spindle design.

When the above factors are combined, they present certain tradeoffs, particularly in general-purpose lathes and machining centers. These tradeoffs, generally found in the type of bearings used to support the rotary motion of the spindle, relate to:

- Speed and acceleration limits.
- Applied loads.
- Accuracy in the workpiece to be machined.
- Preload required to provide the required stiffness in the spindle drive.
- Vibration and shock resistance.
- Dampening or the ability to absorb vibrations involved in the machining process.
- Friction in moving elements and the resulting thermal performance of the spindle and spindle drive.

SPINDLE BEARING TYPES
Spindle bearings present considerably more design challenges than do slideway bearings. The spindle bearings affect every aspect of the machining process including both heavy cuts and finish cuts needing premium surface finish.

Today's machine spindles have high-speed, precision bearings specifically developed for machine tools. There are many design types, each having different benefits in the areas of speed and stiffness. Basic mechanical designs include 1) ball, 2) tapered roller, 3) parallel roller, 4) hydrostatic (oil) and air suspension and, 5) magnetic levitation. These are used in a variety of combinations to obtain optimum results in a particular machine. Looking at three typical design types we find some general characteristics and applications.

<table>
<thead>
<tr>
<th>Bearing Type</th>
<th>Characteristics</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tapered Roller</td>
<td>High stiffness</td>
<td>Turning &amp; milling</td>
</tr>
<tr>
<td></td>
<td>Good running accuracy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower rotational speed</td>
<td></td>
</tr>
<tr>
<td>Double-Row Parallel Roller</td>
<td>Very good radial stiffness</td>
<td>Turning, milling, drilling &amp; grinding</td>
</tr>
<tr>
<td></td>
<td>Medium rotational speed</td>
<td></td>
</tr>
<tr>
<td>Angular Contact Ball</td>
<td>Lower stiffness</td>
<td>Grinding, turning &amp; milling</td>
</tr>
<tr>
<td>&gt; High contact angle</td>
<td>High rotational speed</td>
<td></td>
</tr>
<tr>
<td>&gt; Low contact angle</td>
<td>Good axial loading</td>
<td></td>
</tr>
<tr>
<td>&gt; High accuracy</td>
<td>Good radial loading</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ABEC 9 w/High preload</td>
<td></td>
</tr>
</tbody>
</table>

Keep in mind that spindles can use a combination of roller and ball bearings to achieve design goals. Stiffness usually increases with larger diameter bearings while speed increases with smaller diameter bearings. Bearings are normally preloaded to prevent any slop or movement - this increases stiffness and rigidity. However, as the speed increases, the preload can make the bearing run hot. To solve this problem, designs often incorporate automatically adjustable preload allowing the best stiffness at desired speed. When analyzing a machine spindle design, determine what class of bearings is used. For instance, ball bearings are classed by the ABEC (Annular Bearing Engineers Committee) as ABEC -1 to -9, with the highest number being the most accurate.

Today, increased speed and stiffness requirements are pushing bearing technology to new limits. Speed and stiffness are constantly improving on all bearing types. The recent introduction of ceramic roller bearings combines the rigidity of a roller bearing with the speed of a ball bearing. Ceramic roller bearings are expensive, but demonstrate the benefits of ever-changing technology. Magnetically levitated spindles eliminate the bearing by suspending the spindle shaft in a magnetic field. They allow very high speeds but the added costs of associated controls and lower radial loads make them a specialty application.
The above figure demonstrates the radial and axial capabilities of three typical spindle-bearing designs. Radial loads are loads applied to the side of the spindle, while axial loads are those applied directly into or out of the spindle face. Each type of load is characteristic of different machining processes.

**Design A** – Tapered roller bearings at front and rear. This spindle would be good for heavy duty machining operations such as milling (radial forces). It would also be good for heavy axial loads typical of spade drilling. However, top speed would be limited.

**Design B** – Roller bearings and angular ball bearings at front and roller bearings at rear. This is good spindle for all-round work. Good axial and radial capability is available with the combination of both angular ball and roller bearings.

**Design C** – Angular ball bearings at front and roller bearings at rear. This spindle would be capable of higher speeds that design A or B. Caution would be advised for heavy-duty operations. However, a spindle with ball bearings at front and rear could be rated at an even higher rpm range.
HIGH-SPEED SPINDLE DESIGN

Special design considerations are required when considering high-speed spindle designs (generally over 10,000 RPM). The design tradeoffs are many; however, speed and stiffness are the most dominant. A spindle that needs to have the maximum speed possible will normally have to sacrifice some stiffness.

Angular-contact ball bearings are the most common designs in current high-speed applications. The main design considerations in high-speed applications are:

- Maximum RPM (loaded and unloaded)
- Bearing type
- Bearing preload
- Lubrication method
- Spindle loading

Most manufacturers use a simple rating system when classifying a high-speed spindle called the dN number. The dN number is determined by multiplying the bearing bore diameter by the rated speed in RPM. For example, a spindle utilizing ball bearings can attain a dN number as high as 1,500,000. Angular-contact ball bearings are available with 12, 15, and 25-degree contact angles. Generally, a high-speed design will dictate a 15-degree or lower angle. Bearings are rated in different classes of precision. The American Bearing Engineers Committee (ABEC) standard ranges from ABEC 1 to ABEC 9. High-speed spindles will use an ABEC 9 rated bearing. Bearings are assembled and preloaded (pre-stressed) to prevent distortion and backlash once installed. Bearings with higher preloads are stiffer. However, when operated at high speed, high-preload bearing will experience significant heat and wear. Therefore, high-speed bearings will have a lighter preload.

Ceramic balls are replacing steel balls in today’s high-speed spindle systems. They are commonly found in systems rated above 15,000 RPM. Ceramic balls have 60% less mass that steel, which reduces rotational inertia. They also feature better surface finish, which aids in reducing friction and heat. They are less affected by vibration and have higher rigidity than traditional steel ball systems.

While high-speed spindles can use several different lubrication methods, the highest speed applications will dictate either an oil mist or oil jet pressurized system. Maintenance and cleanliness of the lubricant is critical to these applications. Most lubrication systems will also incorporate a chiller unit to control bearing heat growth.

Another, more technical approach to high-speed spindle design utilizes either magnetic levitation or fluid bearing systems. These high technology systems are “non-contact” which allow for very high speeds with no wear. Currently, the cost and application limitations prevent their widespread use.
SPINDLE LUBRICATION

Proper lubrication minimizes power loss and extends spindle life. Components are lubricated by splash, oil-flow or oil-spray techniques. Some spindle bearings have permanent grease lubrication. Circulating lubrication systems serve two purposes. First, they lubricate gear and bearing contact surfaces and secondly, they remove heat. Hydrostatic lubrication is commonly used because it provides forced lubrication to the spindle. Maintaining the oil film on component contact surfaces at high spindle speeds has always presented a special challenge to designers. When using high-speed precision spindle bearings, oil viscosity must be carefully selected and good filtration is critical.

SPINDLE TEMPERATURE & GROWTH

Machine spindles are probably the greatest heat-producing element on the machine tool. Excessive heat in the spindle head causes unwanted axial growth, bearing stress and headstock/column growth. These conditions directly affect the workpiece. Heat is produced from 1) power losses (friction) in the gear train, 2) power losses (friction) in the bearings, 3) power losses (friction) from the drive motor, 4) ambient temperature and, 5) heat transferred from the cutting process (chips and coolant).

Solutions include: 1) circulation of chilled lubricant or coolant around the bearings and/or headstock, 2) spindle growth compensation routines that adjust the axis position using touch probes and CNC adjustments, 3) relocation of gear trains outside of the headstock and, 4) use of direct-drive AC spindle motors. Today, most CNC machines use direct drive AC spindle motors with temperature control for the spindle lubricant.

Most direct-drive AC motors are integral with the spindle, using the spindle shaft as the motor rotor. Improved computer technology is improving the inherent low RPM limitations of direct-drive AC motor designs. More information on spindle drive systems can be found in Chapter 7, titled “CNC Technology & Machine Control.”
SPINDLE FACE CONFIGURATIONS - LATHES

Most lathes will be fitted with a chuck or workholding device. The spindle face configuration is, therefore, critical in making a correct match to chucks and workholding devices. Several sizes of lathe faces are available. The following chart is for reference only. Each application should be evaluated for correct chuck application.

<table>
<thead>
<tr>
<th>Nose Nomenclature</th>
<th>Primary Chuck Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2-4</td>
<td>6” dia. Chuck</td>
</tr>
<tr>
<td>A2-5</td>
<td>6” or 8” dia. Chuck</td>
</tr>
<tr>
<td>A2-6</td>
<td>8” dia. Chuck</td>
</tr>
<tr>
<td>A2-8</td>
<td>10” dia. Chuck</td>
</tr>
<tr>
<td>A2-10</td>
<td>12” dia. Chuck</td>
</tr>
</tbody>
</table>

Fig. 16 - Spindle Nose Configuration
(Courtesy Decision Technology, Inc.)
10.6 Spindle Drives

A major machine component is the spindle drive. It provides the power necessary to rotate the tool or workpiece. Without adequate speed, horsepower and torque the machine tool will fail at its intended purpose. Most machine tools require variable-speed spindle drives to meet changing metal cutting conditions. Each machine type has its own requirements for speed, torque and horsepower.

SPINDLE DRIVE TYPES

Spindle motors can be of two types: 1) direct drive integral and 2) direct drive external (reference figure below).

- **Integral** (Configuration #1) where the rotor of the electric motor becomes the main spindle shaft. This is a common type of spindle drive system on CNC machines. The integral design allows for reduced vibration and noise while increasing top rpm and efficiency. In contrast to “geared” designs, the “integral” design will have different horsepower/torque characteristics. These units develop full horsepower at a higher rpm than a geared design. Some integral designs use dual winding motors to increase the speed range, thus creating the effect of an
“electronic gearbox.” The most common dual winding motors used in CNC machine tools are called “Wye/Delta” which represents the physical shape formed by the wire connections to the windings.

- **Benefits** – Eliminates gears, belts and pulleys and the associated power loss and vibration. Smaller machine footprint. Higher RPM’s are normally possible.
- **Limitations** - Heat buildup in spindlehead requires a chiller which adds cost. Repair or replacement of spindle motor can be harder than an external motor. However, cartridge-style spindles are a relatively easy replacement. They may not be able to deliver full HP at lower RPM’s.

**External – Direct In-Line Coupling** (Configuration #2) where the motor drives the main spindle shaft by means of a directly-coupled external motor. In contrast to “geared” designs, the direct in-line design will have different horsepower/torque characteristics. These units develop full horsepower at a higher rpm than a geared design. Some integral designs use dual winding motors to increase the speed range, thus creating the effect of an “electronic gearbox”.

- **Benefits** – Eliminates gears, belts and pulleys and the associated power loss and vibration. Motor repair or replacement is easy.
- **Limitations** – Coupling misalignment. With no gear ranges, lack of full HP rating at lower RPM’s. The in-line design requires more dimensional length in the machine design. Some heat may be transferred from the motor to the spindle bar through the solid coupling.

**External – Belt System** (Configuration #3) where the motor drives the main spindle shaft by means of a belt and pulley to an external motor.

- **Benefits** – Eliminates gears and the associated power loss and gear vibration. Motor repair or replacement is easy. Low cost. Heat transfer is minimized.
- **Limitations** – Belt stretch, wear and vibration. Some systems are a single gear range while others offer multiple gear ranges through a variable pulley scheme. The machine may require a larger footprint or height.

**External – Gear System** (Configuration #4) where the motor drives the main spindle shaft by means of gears and shafts to an external motor.

- **Benefits** – Provides a wider speed range and full horsepower at lower RPM’s. Gear ranges can accommodate a wide range of machining applications.
- **Limitations** – Some power loss and vibration. Gear systems generate heat. The gear train requires maintenance and lubrication.

Note: Some machines are designed with a combination of external gear and belt systems.

**SPINDLE PERFORMANCE**

The sales engineer should take every precaution not to sell the wrong machine for the application. An area of particular concern is torque and power. Speed, torque and power
curves should be closely reviewed with the customer to verify needed torque (pound-feet or Newton-meter) and power (horsepower or kilowatts) for machining operations.

A complete discussion of spindle performance and interpretation of power curves can be found in Chapter 7 - CNC Technology & Machine Control.

While the perfect spindle drive for all conditions does not exist, designers are constantly optimizing spindle drive performance. For instance, a lathe cutting large diameters on hard workpieces requires high torque at low spindle speeds, but when turning small diameters with soft material it requires high spindle speeds. The machine tool sales engineer will need to understand the relationship between speed (RPM), horsepower and torque when evaluating an application and quoting a machine tool. The relationships of speed, horsepower and torque are as follows:

\[
\text{HP} = \frac{\text{TN}}{5252}
\]

Based on this formula, the following relationships must exist.

<table>
<thead>
<tr>
<th>Constant Torque Drive:</th>
<th>Horsepower increases with speed increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Horsepower</td>
<td>Torque decreases with speed increase</td>
</tr>
</tbody>
</table>

In past years the only way to solve the problem of maximizing horsepower and torque at any given speed was to provide a drive with multiple gear ranges. Today's microprocessor controlled AC spindle drives provide excellent "low speed/high speed" ratios with fewer gear ranges. This allows the performance at the higher spindle speeds required to utilize the newer cutting tool materials. Today’s AC motors are of brushless design and provides higher torque for its size than previous DC motor drive designs. On most machine designs the AC motor has the potential of being integrated into the spindle head design, using the spindle as the motor's rotor. The microprocessor-controlled system also can provide the control necessary for the spindle drive to be used as a servo drive on machines requiring this feature.

**DUTY RATINGS**

Electric motors have the characteristic of being able to operate at a continuous power rating without interruption. They can also be run at a higher power output for short periods of time. The main limitation is heat. Therefore, manufacturers have a choice when rating the horsepower of the spindle drive. They can be rated at a “continuous” rating (lower hp) or at a “peak” rating (higher hp). When rated at “peak” or “intermittent” they must state the time period or duty cycle. For example, the same motor might have the following possible ratings:

- 10 hp  Continuous rating
- 15 hp  Peak - 30 min. rating (called MTDR – Machine Tool Duty Rated)
- 21 hp  Peak - 15 min. rating
- 28 hp  Peak - 7 min. rating
The above ratings above are only for illustrative purposes as each motor will have its own “continuous” and “peak” characteristics. For years, motors in the machine tool industry were rated at the MTDR (30 minute) duty cycle. However, marketing pressures have caused many manufacturers to create their own peak ratings at non-standard duty cycles in order to boost the perceived hp rating of the machine. Be sure to clarify the rating of the machine you are quoting to be sure it is suitable for the customer’s application. Also, be aware of your rating versus that of the competition.
10.7 Machine Component Systems

The machine tool sales engineer should be familiar with the other components found on machine tools. These include hydraulic and pneumatic, ball and leadscrew, gear train and basic electrical systems. CNC, PLC and motion control systems are covered elsewhere in Volume II. Machine literature and basic machine design manuals will provide a resource for these term and application.

GUIDEWAY DRIVE MECHANISMS

Machine tools have both linear and rotary axes. The linear axes (e.g. X, Y, Z, W) of a machine tool move in a straight or linear path. The rotary axes (e.g. A, B, C) rotate around an axis. The available driving mechanisms for these slideways are shown below.

<table>
<thead>
<tr>
<th>Linear slideways can be powered by:</th>
<th>Rotary slideways can be powered by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Leadscrews – manual</td>
<td>• Worm gears – manual &amp; motorized</td>
</tr>
<tr>
<td>• Leadscrews / ballscrews – motorized</td>
<td>• Other geared configurations – manual &amp; motorized</td>
</tr>
<tr>
<td>• Dual ballscrews - motorized</td>
<td>• Direct connect - motorized</td>
</tr>
<tr>
<td>• Rack and pinion – motorized</td>
<td></td>
</tr>
<tr>
<td>• Hydraulic cylinders</td>
<td></td>
</tr>
<tr>
<td>• Linear motors</td>
<td></td>
</tr>
</tbody>
</table>

Leadscrews & Ballscrews

Leadscrews and ballscrews are the most accepted driving mechanism for slideway motion. They provide a convenient, cost effective method of converting motor rotation into linear motion. They provide this conversion with relatively high resolution and force. In some cases, there are speed limitations.

Leadscrews

On basic, manual machine tools, a linear slide is positioned by the use of a handwheel attached to a leadscrew. The leadscrew turns in a nut (metal-to-metal fit), which is attached to the machine slide. When the operator or machinist turns the handwheel the leadscrew converts rotary motion into linear motion and the slide advances. The machinist can control the distance (position) and speed (feedrate) of the slide by adjusting the motion of the handwheel. Leadscrews typically use a non-precision Acme (square) thread.
A vernier scale (pointer and dial) on the handwheel mechanism or a digital readout is used to tell the operator the exact position of the slide at any given time.

Conventional leadscrews consisting of solid nuts loosely fit onto a leadscrew offer low-cost, low-repeatability linear motion. The addition of an anti-backlash leadscrew and friction nut results in a higher repeatability system, at low additional cost. Leadscrews can be hand- or motor-driven.

**Rolled Ballscrews**

Rolled ball screws are formed by precision thread rolling, unlike the more expensive ground threaded shafts. Balls roll in the threaded groove, providing high efficiency and requiring one-third less torque than conventional leadscrews. These units feature simplified lubrication, high-speed operation and superior resistance to wear. They are generally less accurate and repeatable than precision ground ballscrews. These ballscrews can be found in applications such as robotic, pick and place loading systems.

**Precision Ground Ballscrews**

Precision ball screws are the preferred choice in high accuracy machine tool applications. Most units have recirculating balls that reside in the ball nut. They travel a few turns on the screw and are then picked up and deposited at the other end of the nut. Three methods of recirculation are used in today’s ballscrew applications: 1) Internal channel, 2) Internal crossover and 3) External pipe. By recirculating the balls, wear patterns are avoided and accuracy maintained.
Some machines use dual ballscrews to drive critical machine axes. The design is credited with:

- Moving the ballscrews closer to the balanced centerline of the axis thus reducing any skewing/crabbing and vibration of the driven axis during motion.
- Increasing rigidity.
- Increasing accuracy.

Key ballscrew design and application factors are:

**Shaft diameter** – A larger diameter will increase stiffness and reduce prevent whip, however it may also require more power to turn. Longer travel machines will require larger diameter screws.

**Ball contact area** – The thread shape and number of balls in contact are important design factors. Thread shapes are either circular or gothic. Gothic designs generally allow more balls to be in contact with the screw. Stiffness increases with more ball contact area.

**Lead** – The thread lead is defined as the distance the nut advances with each rotation of the ballscrew. A high-lead thread will produce more nut travel, but may not be as good for low-speed positioning. Today, some machines use two ball screws on a single axis – a high-lead and a low-lead to maintain high accuracy and repeatability as well as high axis traverse rates.

**Precision class** – Ball screw precision is rated in precision classes. For instance, the lead accuracy of a precision ball screw (class C5 or higher) is generally < 0.001" for lengths of 1000 mm. This is normally needed in CNC applications.

**Preload** – The ball nut and screw will have some backlash unless a preload is applied. This stiffens the ball nut and screw tolerance and actually puts pressure on the balls causing them to distort slightly. Therefore, when the system is under operation the initial ball distortion has already taken place and reduced backlash is the result. However, these ball screws require more power to rotate.

**Heat** – The friction between the balls and the screw/nut produce heat in the screw. This can cause ballscrew growth, which is undesirable and can affect positioning accuracy. Some high-speed applications utilize ball screws with liquid coolant passages in the ball screw to normalize ballscrew temperatures.

**Supports** – Ballscrews can be supported at each end in several different ways. The more rigid is a dual-supported design, where the ballscrew has a bearing support at the motor end and the opposing end. A cantilever design is only supported at the motor end, but not the opposing end. This design is more susceptible to end whip, but does allow the ballscrew to grow with heat expansion. The end bearing supports are called pillow block bearings.
Hydraulic Cylinders
Hydraulic cylinders or pistons provide slide movement where there is need for high power with low positioning accuracy. Simple positioning systems that require repetitive positioning operations are a good application. High production machines with fixed machine cycles typical of “slide-in” and “slide-out” use hydraulic pistons. This is an inexpensive solution for slide movement.

Rack & Pinion
This type of slide positioning system is used in non-precision applications that require long travel distances. Some long-travel double gantry machines use rack and pinion drives on each gantry base. Backlash is one potential issue with these positioning systems as well as axis skew when multiple rack and pinions are used on one axis, typical of a double-gantry system.
ROTARY AXES & TABLES

Many machine tool designs incorporate rotary or tilting axes. In some cases, a rotary table can be added as a third-party retrofit, thus expanding the capability of the machine.

The most common rotary axis is the rotary table typical of that found on horizontal machining centers, boring mills, vertical machining centers and milling machines. A rotary table can take many forms. Here are the most common:

- 4 to 72 discrete position indexing
- 360 degree discrete positioning
- 360,000 position servo driven
- Full rotary contouring axis (coordinated with other linear machine axes)

The discrete position tables are application sensitive and can only move to the number of specified positions. However, these tables tend to be very rigid due to the rugged indexing mechanisms. The full rotary, servo driven tables are very flexible with regards to application, however, cutting forces must be carefully calculated as not to exceed the rated torque (feeding and holding) capabilities of the table.

A full rotary axis can also be incorporated into the spindle rotation on some machines to accommodate precise positioning and/or feeding of spindle rotation. In these cases, the spindle drive motor effectively acts as both a drive motor as well as a servo positioning motor. Increasingly, rotary table designers are moving to direct-drive servo motors instead of geared drive systems.

Tilting axes are also found on some machines. The tilting mechanism can either be on a machine table or a spindle. The advantages are normally to: 1) machine at odd workpiece angles and 2) reduce tool reach on some complex workpieces. Observe the figure at the right where the tool length can be shortened, providing a more rigid tooling situation. This will allow heavier cuts, faster processing and higher workpiece quality.
10.8 Machine Tool Accessories

The proper selection of application-dependent accessories will make or break the eventual success of a new machine tool installation. These items are best determined by careful understanding of:

- The intended application.
- The operating environment.
- The maintenance capability of the end user.
- The training and skill of the operators and supervisors.
- Possibility of changes in the use of the machine tool.

By taking the above factors into consideration, the list of accessory items would likely include:

1. The type of flood or mist-coolant system, if any, required for control of cutting temperatures and chip control. A coolant filtration system may be required.
2. Chip collection and disposal:
   - Conveyor systems must be matched to the specific application which may include the type of material being cut, the shape of the chips and the type of coolant system.
   - Filtration must be specified to the appropriate micron level.
   - Self-cleaning feature may be specified where needed.
   - Coolant pressure is a consideration. A high-pressure coolant system may be required for some applications.
     - Selection will include pressure and volume. Some systems provide multiple pressures or variable pressures based on tooling needs.
     - The machine tool must be capable of handling a high pressure system.
3. Enclosures for chip control and operator protection.
4. Lathe accessories such as:
   - Special chucks:
     - Chuck power:
       - Hydraulic.
       - Air.
     - Jaw types.
     - Collet chucks.
     - Eccentric chucks.
     - Custom work holding devices and fixtures.
   - Steady rests and turret steady rests
• Bar feeders and feeder accessories.
  • Magazine style.
  • Automated bar load system.
  • Spindle liners (Polyurethane materials allow shape-specific liners).
  • Quick change spindle liners.
• Tool and part probe measurement devices.
• Tooling packages.
• Load monitoring systems (tool preservation).
• Tool ID systems (chip & scan)
• Fire suppression systems (oil applications).
• Robotics
  • Part and tool transfer.
  • Chip vacuum for special applications.
• Automated gantry loaders.

5. Machining center accessories such as:
• Palletized work changers or set up changers.
  • Linear and rotary pallet exchange systems.
  • Multiple port hydraulic palletized fixtures.
• Workholding and specialty workholding.
• Rotary tables (single and multiple-axis types) or fixed position index tables.
• Special tool changer size and capacity requirements.
• Cutting tool presetting equipment.
• Tool and part probe measurement devices.
• High speed spindle adapters.
• Angle blocks or special flat work support devices.
• Special set-up holding or fixture devices with pre-machined locations.
• Tooling packages.
• Load monitoring systems (tool preservation).
• Tool ID systems.
• Fire suppression systems (oil applications).
• Robotics
  • Part and tool transfer.
  • Chip vacuum for special applications.
• Automated gantry loader.

6. CNC control options
• Refer to the Chapter titled “CNC and Machine Control”

Application support staff and machine tool accessory suppliers can assist with the selection of accessories based on machine type and metalcutting applications.
10.9 Machine Tool Selection Factors

Each type of machine tool has a long list of features and specifications. However, there are key selection factors that are generally more important than others when sizing and selecting a machine.

The selection factors listed below are typically the most important when discussing machine selection with customers because they define the basic machine work envelope, speed and power capabilities.

**Key Selection Factors - Lathes & Turning Machines**

All Lathes
- Chuck diameter (in or mm)
- Swing over bed ways (in or mm)
- X-axis travel (in or mm)
- Z-axis travel (in or mm)
- Turning distance, max. (in or mm)
- Horsepower (hp or kW)
- Axis traverse and feed rates (ipm or mpm)
- Spindle speed range (rpm)
- Tailstock – required or not required

CNC Lathes (additional to above):
- Bar, Chucking, Universal or Swiss type machine
- Tool turret – number of tool stations?
- Live tools for milling or offset drilling?
- Single or dual turrets?
- Bar capacity (through-hole in spindle) (in or mm)
- Sub spindle – required or not required?

**Key Selection Factors - Vertical Milling, Horizontal Boring & Machining Centers**

All machines shown above:
- X-axis travel (in or mm)
- Y-axis travel (in or mm)
- Z-axis travel (in or mm)
- Table size – Length and width (in or mm)
• Table load capacity (lb or kg)
• Spindle taper type and size
• Axis traverse and feed rates (ipm or mpm)
• Horsepower (hp or kW)
• Spindle speed range (rpm)
• Number of gear ranges on spindle

Machining centers (additional to above):
• Tool changer – Number of tools & max. weight
• Tool change time (sec.)
• Pallet size (in or mm)
• Tool change and pallet change time (sec.)

**Key Selection Factors - Cylindrical Grinders**

All Cylindrical Grinders
• Swing over bed ways (in or mm)
• Grinding length capacity (in or mm)
• X-axis travel (in or mm)
• Z-axis travel (in or mm)
• Wheel diameter size (in or mm)
• Horsepower (hp or kW)
• Wheelhead type – straight, angular or universal
Additive Manufacturing

Glossary

1.0 Purpose The intent of this document is to provide a resource to assist in discerning how to define Additive Manufacturing equipment or systems. The prerequisite for applicability of this document for such purpose is that the AM equipment or system in question must be classified as an “Additive Manufacturing System.”

2.0 Background The fundamental definitions have been developed by the ASTM F42.91 Terminology Subcommittee and have been adopted by the ASTM F42 Committee on Additive Technology and ISO Technical Committee (TC) 61 on Additive Technology. Supplemental information has been provided as an “AMT Discernment” point of clarity. These points of clarity are not to supersede, substitute or otherwise make irrelevant the currently approved definitions. The intent of the points of clarity is only to help AMT provide discernment for AMT-related business.

3.0 Summary AMT recognizes the seven (7) additive processes as defined by ASTM Designation F2792−12a and also includes an additional process to cover hybrid offerings designated as “Multi-Functional.” The following are the eight (8) categories that AMT recognizes for types of Additive Manufacturing Equipment:

1. Binder Jetting
2. Directed Energy Deposition
3. Material Extrusion
4. Material Jetting
5. Powder Bed Fusion
6. Sheet Lamination
7. Vat Photopolymerization
8. Multi-Functional

4.0 Detail Definitions – General

4.1 Additive Manufacturing (AM), n—a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.
AMT’s Discernment: The AM layer upon layer methodology is generally followed without relying on molds, casts or patterns, as opposed to subtractive manufacturing methodologies whereby material is removed from a pre-existing workpiece.

4.2 Additive Systems, *n*—machines used for additive manufacturing.

5.0 Detail Definitions – Additive Manufacturing Processes

5.1 Binder Jetting, *n*—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

5.2 Directed Energy Deposition, *n*—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. DISCUSSION—“Focused thermal energy” means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.

AMT’s Discernment: Directed Energy Depositions occur where there is simultaneous introductions of material and focused thermal energy, effectively interacting, during the process of deposition.

5.3 Material Extrusion, *n*—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.

AMT’s Discernment: Extrusions occur where a continuous filament material is heated (usually to a semi-molten state) and then selectively dispensed through a nozzle or orifice.

5.4 Material Jetting, *n*—an additive manufacturing process in which droplets of build material are selectively deposited. DISCUSSION—Example materials include photopolymer and wax.

5.5 Powder Bed Fusion, *n*—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

5.6 Sheet Lamination, *n*—an additive manufacturing process in which sheets of material are bonded to form an object.

AMT’s Discernment: “Bonded” could also include any permanently assembled objects by means of joining mechanically (e.g. fasteners), adhesively (e.g. paste, gel adhesives) or with appropriately timed exposure to heat or pressure.

5.7 Vat Photopolymerization, *n*—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.
5.8 1**Multi-functional**, *n*—an additive manufacturing process in which more than one methodology is included within a single machine solution.

AMT’s Discernment: Multi-functional could refer to more than one additive process as well as an additive process that includes another non-additive process for the purposes of object fabrication; examples of items included would be: additive metal deposition with a secondary milling operation all within the same additive manufacturing system. Examples of additional processes not included would be: inspection or validation processes within a single machine solution (again multi-functional refers to the fabrication processes).

---

1 Multi-Functional is not an approved ASTM F.42 term. This was an AMT addition to account for the multi-functional systems currently or anticipated to require classification.
Defining Additive Manufacturing

Sometimes known as “3-D printing,” additive manufacturing uses emerging technologies to fabricate parts by building them up layer-by-layer. It allows rapid transformation from "art" (CAD model) to "part" (manufactured product), and shows great promise for applications as diverse as lightweight aerospace structures and custom biomedical implants.

How does it work?

Metallic, plastic, ceramic, or composite materials are laid down one thin layer at a time and placed precisely as directed from a digital file. Frequently, the raw materials used are in the form of powders or wires that can be melted and shaped by a laser, in a fashion somewhat akin to welding.

An example application for the medical industry would be the creation of an artificial jawbone. A 3-D computer model of a jawbone is created based on a person’s bone structure, and this model is sliced into many layers. The computer then feeds the information into the additive machine, which could generate the complex bone structure substitute out of metal.

How does additive manufacturing impact the economy?

Additive manufacturing is largely an emerging technology that shows promise for the defense, energy, aerospace, medical and commercial sectors. Its ability to build up objects directly makes it a good alternative to conventional machining, forging, molding and casting for rapidly making highly customized parts. While additive manufacturing is most attractive for making complex parts in relatively small volumes, it can be used for rapidly making tools and dies used in large volume manufacturing. The technology also shows promise for creating parts in situ, such as at forward-stationed military bases. Because of its potential, many companies are experimenting with the technology. The field of companies using the technology to make commercial products today is relatively small, but growing, and includes the makers of machine parts and aircraft cabin components.

The expected long-term impact is in highly customized manufacturing, where the technique can be more cost-effective than traditional methods. According to an industry report by Wohlers Associates, by 2015 the sale of additive manufacturing products and services could reach $3.7 billion worldwide, and by 2019, exceed $6.5 billion.

What is the administration doing to support additive manufacturing?

The Obama Administration is committed to supporting additive manufacturing research and enhancing America’s manufacturing capabilities. The National Network for Manufacturing Innovation (NNMI), which President Obama announced in March 2012,
is just one of these initiatives. The NNMI will accelerate innovation and increase U.S. manufacturing competitiveness by bringing together federal agencies, industry, universities and community colleges, and the states to invest in industrially relevant manufacturing technologies with broad applications. An interagency team chose additive manufacturing as the focus of the NNMI pilot institute, which will have a physical incubation hub in Youngstown, Ohio. The pilot institute will bring together a regional network of 14 research universities, community colleges, at least 40 industry partners and 10 non-profit organizations and professional societies from Western Pennsylvania, Eastern Ohio and West Virginia, with the goal of building a national presence and network. With a nearly $40 million match to the $30 million federal investment, the private sector response is a strong indicator of interest in a successful public-private partnership.

10.11 Review Questions

These review questions are provided for study purposes only and are not on the CMTSE certification exam. Correctly answering these questions does not guarantee a passing exam grade.

1. Which of the following produces the most heat on a machine tool?
   1. Ballscrew
   2. Spindle head
   3. Slideways
   4. Counterweight

2. A design material that would be the least affected by changing temperatures would be:
   1. copper.
   2. steel.
   3. cast iron.
   4. aluminum.

3. The coefficient of thermal expansion for cast iron is .00000655 in./degree. How much will a 60 inch long machine slide increase in length with a 10 degree increase in temperature?
   1. 0.0007"
   2. 0.00039"
   3. 0.0039"
   4. Less than 0.0001"

4. In most cases, spindle bearings with larger diameters have:
   1. slower rotational speed.
   2. decreased stiffness.
   3. higher positioning accuracy.
   4. less bearing mass

5. Which of the following is least associated with slideway alignment?
   1. Pitch
   2. Yaw
   3. Hand scraping
   4. Bearing preload

6. In selecting lubricating oil for high-speed bearings, which of the following characteristics is the most important?
   1. Resistance to thermal deterioration
   2. Oxidation prevention
   3. Viscosity
   4. Thermal absorption capability
7. Slideways with dovetail geometry have what primary advantage over a ‘V’ configuration?
   1. Faster traverse rates
   2. Better geometric alignment
   3. Greater resistance to dynamic machining forces
   4. Easier to install and service

8. Turcite is a synthetic material that is best applied as a/an:
   1. high-speed spindle bearing material.
   2. slideway liner bearing material.
   3. thermally Insulating material for the spindle housing.
   4. anti-vibration base plate pad material.

9. The Annular Bearing Engineers Committee (ABEC) provides the ball bearing industry with a classification for bearing accuracy. Which of the following denotes the lowest accuracy?
   1. ABEC 9
   2. ABEC 7
   3. ABEC 1
   4. ABEC 0

10. Which drive types are most commonly used for machine tool slides?
    1. Linear motor drive
    2. Hydraulic piston drive
    3. Pneumatic piston drive
    4. Motor-powered screw drive

11. Linear guideways out-perform more traditional machine tool guideways by:
    1. supporting heavier loads.
    2. allowing faster positioning speeds and greatly reduced friction.
    3. reducing machine harmonic vibrations.
    4. providing for higher servo motor rpm.

12. Which best describes the action of a “nutated” axis on some 5-axis machining centers?
    1. parallel.
    2. right angle.
    3. swaying.
    4. pulsating.
ANSWERS TO REVIEW QUESTIONS

1. (2)
2. (3)
3. (3)
4. (1)
5. (4)
6. (3)
7. (3)
8. (2)
9. (3)
10. (4)
11. (2)
12. (3)