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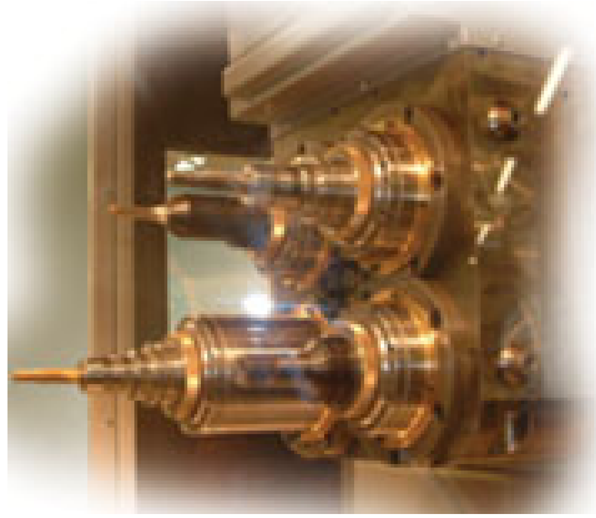
Spindles Are the KEY TO HSM



Linear toolchanger from Licon is designed for high-speed tool change in volume production.

What determines rpm?

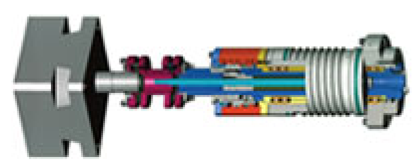
Robert B. Aronson, Senior Editor

Spindle performance, an essential element in HSM, has been under constant pressure for ever higher spindle speed as a means of increasing productivity. Improvements in drive motors, lubricants, bearings, and heat management have all contributed to higher rpm numbers. Here's how several major players have responded to the challenge.

"Spindle growth compensation is one fairly new development at our company," explains Corey Johnson, president, Fischer USA (New Brighton, MN). "We have a sensor in front of the shaft that monitors thermal and mechanical growth. A signal goes from the senor to the control allowing compensation down to micron tolerances [±2 µin. for 100 mm diam]. Each spindle has to be tuned by type to the conditions of the customer's application. For milling aluminum, our customers seem to be using spindle speeds ranging from 18,000 to 40,000 rpm, while grinding applications go up to 150,000 rpm using mechanical bearings.

"This sensing arrangement is part of our Smart Vision package, similar to a "black box" used on aircraft. It records all critical performance data, such as bearing and motor temperatures, power consumption, vibrations, tool changes, and thermal growth. Analysis of this data can help detect problems before they occur and to establish a preventive maintenance program. This helps customers get the most use out of their spindles prior to rebuilds.

"Regarding grease lubricant limitations, the nDm factor is a standard calculation used to determine how fast you can go using grease-packed bearings," says Johnson [nDm is a grease speed capability metric that equals bearing bore diameter in millimeters plus OD diameter divided by two × rpm.] "High bearing temperatures over a prolonged period of time can break down the properties of the grease, which prevents proper lubrication." Grease bearings are preferred by customers cutting composite material, because oil dripping on their part can damage it.



Hurco spindle uses direct drive motors.

For high-rpm spindles, we use an oil-based DLS (direct lubrication system). This system essentially places the oil directly on the ball of the bearing which enters through the outer race of the bearing. This system is best for the most demanding jobs requiring high power and high speeds.

"Compact, high-power, integral motors are what we are best known for. Most of our designs use asynchronous motors; however, synchronous motors are also used. Another trend is more powerful motors. For example, we have a 150-hp motor that mounts in a 260-mm housing achieving material removal rates [MRR] in excess of 488 in.3/min. [continuous power rating] for heavy aluminum machining.

"These are vector-controlled motors so that from zero rpm to the base speed you have full torque, and from base speed to top speed you have full power. Nonvector-controlled motors typically have a linear-type power rating, which often times limits what the customer can use the spindle for at various speeds."

“Customer education is very important if high-speed machining is to advance. The user has to take several things into consideration when determining if high-speed machining is right for them. First, you can’t just add a high-speed spindle and not change any of your practices. Consideration must be given to: balancing of tools, optimization of the cutting process, determining spindle and tooling harmonics, etc. A good analogy is taking a car with a stock 350 engine and dropping in a 454 supercharger with nitrous oxide. It needs some special tuning and optimization before it works well. But if customers are willing to do this, they can improve their productivity exponentially.”

For very light duty, NSK America (Schaumburg, IL) supplies both electric-motor and air-driven spindles. The electrics run at up to 80,000 rpm, and the air-driven to 325,000 rpm. They are most often used in Swiss-type machine tools.

“Our customers use our spindles for very light milling and grinding with much of the work in the medical area,” says Executive Vice President, Hirohiko Mursae. “A typical job would be 1 or 2-mm holes in a titanium part. We use three types of bearings, depending on the application: angular contact, ceramic hybrid, and air.

“Cooling is done by air. For the air-driven spindles, the air is supplied by an integral fan, for the electrics there is a separate air source.

“We offer straight spindles for CNC lathes, and shank-type spindles for milling applications.”

Bearing preload plays a big part in spindle performance. At Yasda Precision America (Elk Grove Village, IL) their machines maintain a constant bearing preload regardless of speed. This design provides three advantages: greater rotation accuracy over the entire operating range, longer tool life, and longer bearing and spindle life.

“Some high-speed spindles have problems with preload change,” explains Yasda president, Hutch Hachiuma. “At higher speeds, the spindle bearings heat and transfer the heat to the spindle. To avoid too high a preload at higher speeds when the spindle expands, many designs set the initial preload quite low. The downside is that at lower speeds, spindle stiffness is less than optimum.”

Yasda achieves constant preload though a patented bearing preload self-adjusting system. Because the spindle has a constant stiffness, it works well with heavy, slow cuts as well as fine, high-speed cuts.

“This mechanical system consists of an inner race made from the same steel as the spindle shaft, and an outer race made from a nickel alloy, which has an expansion coefficient about 1/3 that of the inner race,” says Hachiuma. “Therefore, as the spindle begins to heat and grow there is a differential action that automatically maintains a constant preload.

“This is especially important for hard-milling applications where tool life is a big consideration. The constant preload can increase tool life 100% or more. It also means longer bearing life as well as spindle life.”

Collar above the spindle on this Hurco installation directs coolant to the work area.

Bearings are key to spindle performance and life. There have been a number of improvements in bearing rolling elements, raceways, and lubricants. “We have a new design that has been very successful for us in high-speed applications,” says Chris Hetzer, assistant general manager, SKF-Grafton, formerly Russell T. Gilman Inc. (Grafton, WI). It’s a single-row, tapered-bore cylindrical roller bearing with ceramic rollers. It has a special cage made of “peek” (poly-ether-ether-ketone).

“With grease it can run at 1.4 million nDm [ID+OD/2 × rpm]. With oil, we can achieve 2 million nDm.

“This bearing is mounted at the back of the spindle with rigid bearings forward. This allows the back bearing to move smoothly to compensate for spindle-shaft growth, eliminating the need for sliding bushings that can compromise spindle system stiffness.

“To prolong the lubrication life of a high-speed spindle system, we have developed a greasing device, built into a spindle, which can give spindle bearings an accurately measured amount of grease at specific intervals.”

“Ever higher speed is a constant customer demand,” says Pete Baechle, manager, machine tool design, Hurco Companies, Inc. (Indianapolis, IN). “Five years ago our top speed for metal machining spindles was 8000 rpm, three years ago it was 10,000 rpm, and today it’s 15,000 rpm, with higher speeds available.

“We currently offer a 20,000-rpm unit for graphite machining with a 30,000-rpm option. These spindles can be turned faster because of the lighter loads when cutting graphite.

“To achieve these higher speeds, we improved the bearings, made the entire unit to higher tolerances, and designed for better balance. One of the ways to improve balance was to eliminate all keyways and threaded sections from the spindle shaft. Both these features can induce vibration at higher speeds. In addition, bearings are held in place by a shrink-fit collar so there are no nuts to induce imbalance. We also went to a 30-taper from our previous 40 and 50 designs.

“All of our spindles have lifetime-grease lubrication because the quality of the grease has greatly improved. This eliminates the extra hardware and maintenance necessary for mist lubrication.”

“To avoid contamination we use an air purge at both ends of the spindle,” explains Himat Patel, general manager. “Shop air is used, but has to be carefully adjusted so the flow is strong enough to keep debris out, but not strong enough to blow out the grease.

“To provide high torque at both ends of the operating spectrum, we use double-wound motors. Base speed can be as low as 400 rpm with full torque. Almost all of our spindles are belt-driven with a herringbone-type belt.

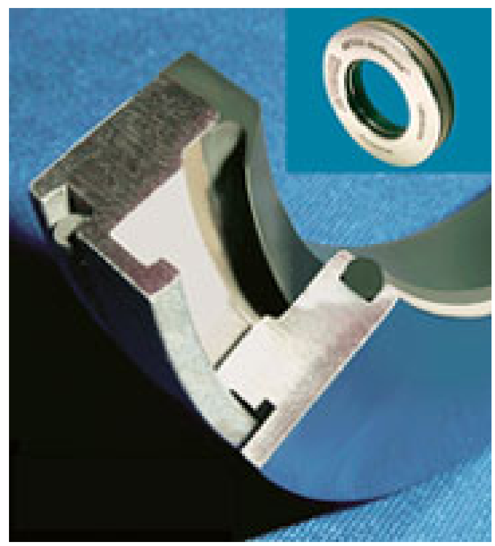
“Coolant may be through-the-tool or from a collar with multiple nozzles that fit around the spindle nose.

“For greater tool security, the spindle holds the tool with gripper fingers, not the more commonly used ball collar,” Patel concludes.

“High-speed spindles are our only product,” explains John Easley, VP/GM, Business Operations, Precise Corp. (Racine, WI). “The maximum speed of our slowest spindle is 20,000 rpm and our fastest is 200,000.”

“As to trends, the market is demanding more power and speed in a smaller spindle package. Our engineers have met this challenge chiefly through the use of permanent magnet synchronous motors. These spindles can provide more than twice the power and torque of previous designs,” says Easley.

“One of the main drivers behind this change is to help the machine tool builder save cost. There is less stress on the machine’s axes, as well as less need to build-in more structural mass, for a spindle to provide the same torque and power at half the size as in the past,” he says.



Pressurized air and labyrinth seals protect SETCO spindles. Keeping solid and liquid contaminants out of the spindle is a prime consideration in the SETCO design.

“Another trend is the use of permanent grease bearings on more than 80% of our spindles. This is chiefly because of the ease of maintenance, less cost, plus the fact that you do not want oil to drip on the part when machining graphite,” explains Ryan Brath, VP/GM, Technical Operations for Precise.

“To avoid damage from contamination we use a good labyrinth seal that is pressurized.”

To get the longest spindle life and best performance, Brath suggests the following:

- Don’t clean the spindle nose with compressed air. This just blows contaminates into the spindle.
- Check air quality used with the spindle to be sure it is not contaminated in the first place. He recommends a 5 μin. filter.
- Proper maintenance is critical. Bearings inevitably need to be replaced over time, and this cost should be considered in the overall maintenance plan.
- Most important is to be aware of the system’s natural frequency. Every system has an inherent natural frequency which will result in high vibration. Balance is a very important factor. At 8000-10,000 rpm you might be able to ignore it, but at higher speeds balance is both a performance and safety issue. “We are not talking just about the spindle, but the entire system and the specific work situation. This includes the spindle, the tool, the runout, and the method of mounting. We had a case where a customer was cutting Styrofoam, but the tools were turning to spaghetti at high speed. Obviously the load was not the problem, but the tool was 18" long and improperly secured. Tool length is particularly influential, especially when exposed length goes beyond five times tool diameter. Natural frequency isn’t difficult to calculate, you just have to do it,” concludes Brath.

“Precise is one of the few remaining American spindle manufacturers,” says Easley. This gives us a competitive advantage in the US market to rapidly respond to customer requests and provide application engineering expertise to help work with the customer to optimize and ensure a reliable high-speed machining process.” “In high-volume operations, chip-to-chip time, not spindle speed, is often the critical issue,” explains Lothar Koerner, director, Licon (Ann Arbor, MI).

“When thousands of parts are involved, seconds can add up to a significant amount of time out-of-cut.”

“Our company offers the LTC [Linear Tool Changer] multiple-spindle system in which tool-to-tool time is down to 0.8 sec and chip-to-chip time is between 1 and 1.5 sec. The system can consist of multiple three-axis LTC units, with each LTC carrying four to six powered, horizontally mounted spindles. When the workpiece is in position opposite a LTC unit, individual spindles are advanced and retracted hydraulically for tool clearance, and then brought to the machining location via the three-axis CNC slides. Up to six machining operations can be performed per LTC. One machine may have up to six LTCs or stations, so up to 20 or 30 powered spindles are available.”

One system of this type is currently being used by Volkswagen to make steering knuckles. In this installation, the machine has three LTC units, each carrying six HSK63 spindles. Each spindle is powered by a 20-hp (15-kW) motor and runs up to 10,000 rpm (15,000 optional). Multiple machines then accommodate capacity requirements. Because the features being machined are only a few inches apart, the chip-to-chip time is about 1 sec.

Despite the publicity about high-speed machining, SETCO planners see a strong market developing in the mid-speed range. “Often the tradeoff in spindle design is speed for robustness,” says Bob Hodge, vice president, engineering, development, and quality, SETCO (Cincinnati). “We found that customers were having problems with the fragile nature of some high-speed spindle designs.”

“High-speed processing needs are only a tiny segment of the machine tool market. Our customers are looking for spindles that operate at a more practical level, usually in the 18,000-24,000-rpm range. We are, therefore, offering a new line of spindles which have a maximum speed of 24,000 rpm. Initially there will be three barrel sizes: 170, 230, and 300-mm. They are all integral-motor units.

“Among the positive trends has been better grease composition so that the initial grease pack lasts the entire life of the spindle. These newer greases are allowing us to stay away from air/oil lubrication, along with the associated problems of added expense, reliability, and maintenance. We have greases that will run at 20,000 rpm at 40°C.

“Bearing improvements include the use of high nitrogen steel for the raceways. To preserve spindle stiffness and accuracy, our bearings are solidly preloaded up to 18,000 rpm or 1.25 million DN. [The DN factor (or speed factor) for grease is maximum bearing speed allowable for that grease. DN=(ID+OD/2.] Forward bearings can be duplex, triplex, or quad-set mountings. Spring loading is a common way to compensate for preload variation due to temperature increases at high speed. But when you spring-load a spindle you loose stiffness. With our solid-preload-bearing setup we can run at 1.25 million DN and more.

“We typically handle high torque at low speed with a synchronous belt drive spindle configuration. Other systems such as two-speed planetary spindle drives are available, but are quite costly. We have a very reliable and cost-effective line of belt-drive spindles for 15,000 rpm and under.

“Motor spindles are becoming more powerful and more compact. Our permanent- magnet brushless DC motors give you a lot of power and torque in a small package. As a comparison, a 5-hp [3.75-kW] brushless dc motor is about ¼ the size of the ½ hp [0.4-kW] induction motor. One application where this smaller size is a benefit is on gang drills where there is a need to control the individual drills. You can put one drive on each drill as opposed to gearing them together with one drive motor.”

Fischer spindles specialize in high-precision applications.

As a follow-on to their successful air seal, SETCO now offers the Universal AirShield as a performance upgrade for spindle rebuilds. It’s an aftermarket device that can be added to about 90% of all existing spindles, and offers the same contaminant protection as the original product.

GM’s Spindle Needs

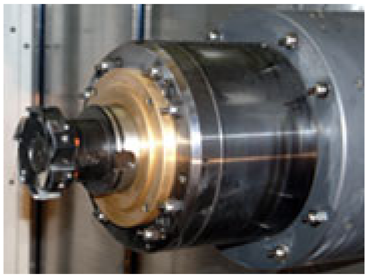
Probably GM is the world’s biggest user of machine tool spindles, buying up to 200 machining centers per year for new engine and transmission programs. To support this operation, the company has an extensive program of spindle-performance monitoring.

“We choose machine tools based on past performance,“ says John Agapiou, staff research engineer, GM Research and Development, Manufacturing Systems Research Lab (Warren, MI). ”The supplier is responsible for the entire system. We don’t specify the individual components, but we do give guidelines.”

GM uses two types of spindles. For transfer lines, the spindle is usually a belt-driven, constant-speed unit. For the more numerous CNC operations with variable-speed applications, the drive unit is an integral synchronous motor.

“We normally buy a lot of commodity machines, often as many as 50-machine batches,” says David Stephenson, GM Technical Fellow, GM Powertrain Central Manufacturing Engineering. “But we want them to do everything.”

“Currently for GM ‘high speed’ means over 10,000 rpm with the majority of work being done at or below 8000 rpm. This is because in CNC operations on complex parts, the time gained by cutting at high rpm is lost in the acc and dec time. Possibly motor manufacturers could look more strongly into that issue. Therefore, the selection of machining centers should be based on the total time required to finish a part, rather than on the machine spindle and/or slide speeds. The total time to finish a part depends on the machine motion time, the tool-change time, the number of workpiece setups [the fixturing approach], the available number of axes, and the pallet-change time.



At GM, the Manufacturing Systems Research Lab keeps close watch on the performance of the spindles they use. Long life is a prime consideration.

“We also want the same machine to handle low speeds, around 800 rpm,” said Stephenson. “For this type of work we would like to see more kick at 800 rpm, or more torque characteristics over the entire power range. We want to avoid multiple passes.”

“It is not so much ‘power versus speed,’ but ‘torque versus speed’ that is important,” says Agapiou.

In evaluating performance, Agapiou notes that spindle manufacturers have been constantly improving their products, but there are still opportunities for improvement. “Most of the problems we have are related to cleanliness. First is tramp oil, coolant, and other contaminates getting through the seals and into the bearings. Although this problem has become less significant through the years, we would like to see more efficient seals. Also, there are sometimes problems with chips and debris getting into the toolholder-spindle interface flange. In other words, chips or debris get in-between the spindle face and the toolholder flange during an automatic toolchange. Even a small bit of debris can cause imbalance at higher speeds, which can lead to unsafe machining, and inaccuracy or quality variations," he explains.

He suggests some means be developed that would ensure the cleanliness both of the toolholder and the spindle-tool gripping mechanism. Every toolchange should be preceded with an effective coolant shower and a strong air blast as the tool rapidly travels away from the part to the tool-change position. The machine flushing system and the processes must be designed to guarantee the cleanliness of these toolholder assemblies and the surrounding machine workspace before toolchanges. Coolant through the spindle should be kept clean to prevent dirt accumulating around the hollow tool shank and the fingers system of the drawbar. The flushing system through the spindle should be designed to be effective, especially in the high-speed spindles. In addition, an air-gage check at the face of the spindle for proper face contact with the toolholder is extremely important in a production environment. In some reported cases, the toolholder did not seat on the spindle face, and the machine controller allowed the spindle to rotate, resulting in holder breakage.

"The spindle taper nose should be gauged periodically [every three to six months] for possible wear," he suggests. "In addition, the spindle nose should be cleaned periodically depending on the number of toolchanges, coolant through the spindle, coolant filter size, and the material cut [cast iron vs. aluminum].

"One of the changes has been greater use of grease as a lubricant," says Stephenson. "It offers the advantages of lower maintenance and fewer environmental problems, and it is easer to seal against contaminants. This often requires hybrid bearings [with ceramic balls] to obtain high DN value of up to 1,500,000 for higher speeds.

"Bearing preload is usually not an issue on transfer lines where spindles run at a constant speed, but in CNC operations bearing preload can vary. GM specifies a compensation system, which is usually in the form of a spring preload. The variable preload allows thermal growth and heavier preload at lower speeds, which increases stiffness and allows higher cutting forces. We look for 20,000-hr bearing life," Stephenson says.

Motors have, for the time being, been standardized on AC synchronous. However, despite an ability to operate over a wide speed range, GM engineers would like to see higher torque capability at low speed for face-milling applications and sufficient torque at higher speeds for holemaking. Permanent-magnet brushless DC motors (PMB-DC) are used in higher speed and performance applications.

Another improvement we would like to see is more monitoring of the spindle in operation. "We would like to know temperature, vibration, and balance so we can avoid inaccuracy and failure," says Agapiou.

"The tool-retention system is also important. The clamping force for the automatic tool-change system was found to vary tremendously among different clamping systems. For example, the range of the clamping forces is between 10 to 30 kN for the HSK-A-63 interface, while the recommended level by the DIN standard is 18 kN. Manual clamping systems [using two, three, or four-point clamping] are used in transfer lines. The level of the clamping force is a function of the torque applied on the differential screw. For example, the clamping forces of about 60 HSK-A-63 manual clamping spindles using an identical finger system were measured by applying a 19 N•m torque on the differential screw. The average and three standard deviations for the clamping forces were 27 kN and 6 kN, respectively. The large clamping force scatter was probably due to the low accuracy and repeatability of the torque meter and the sizable spindle nose manufacturing variation. We would like to see more consistency in the clamping force among spindle manufacturers.

"The spindle tapered bore should be gaged to conform to the DIN or ANSI STD using the proper gaging equipment. The CAT or 7/24 taper can be checked easily compared to the HSK 1/10 taper that requires the removal of the drawbar fingers before it can be checked.

"Lastly, the spindle manufacturers should provide the static, modal, and dynamic characteristics of the spindle. Such characteristics are important to make sure that the minimum natural frequency exceeds the cutting speed or tooth pass frequency."