High-speed machining: A strategic weapon

Exceeding 30,000 rpm gives many manufacturers an edge

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Contributing Editor

Deploying machining centers that cut at speeds faster than 30,000 rpm might be considered extravagant at many machine shops, but not at Boeing Co (Chicago). To the aerospace giant, fast machining centers are a mainstay of its competitive arsenal.

High-speed machining is a strategic part of making F/A-18E/F tactical fighters

The benefits of using such machines go far beyond shorter machining cycles and better surface finishes. The machines have made it possible for Boeing to change its strategy for producing the sophisticated high-performance jet fighters defending America today. Its shops now cut many of the thin-walled monolithic parts inside these airplanes completely from one block of material, rather than joining a number of smaller sheetmetal parts and extrusions.

The ramifications have been enormous. The St Louis facility, for example, slashed total production costs of the 4R avionics shelf going into the F/A-18E/F tactical fighter by 73%. Using a 40,000-rpm machining center, Boeing produces the shelves from only one machined billet and five other pieces, instead of 44 formed sheetmetal parts, extrusions, and other pieces. Consequently, the aluminum components now weigh 8.5 lb, need only five tools in their construction, and spend only 38.6 hr in manufacturing. Beforehand, they weighed 9.5 lb, required 53 tools, and spent 1028 hr in manufacturing.

When manufacturing engineers and machine shop owners come across reports of such fantastic increases in productivity, many wonder whether their operations can reap the same benefits. The answer is yes, if you can justify the right machine for the job and learn to use it correctly. In fact, it is easy once you understand that high-speed machining is different from conventional machining and that you must adopt a completely new philosophy to make it work, according to Adam Schaut, a manufacturing engineer at Boeing's St Louis facility.

He explains that this understanding begins with the definition of high-speed machining. Rather than using the conventional definitions based on spindle speeds (rpm), tool-tip speeds (sfm), or bearing ratings (DN), he and his colleagues prefer to define it in terms of frequency. As disciples of Dr Scott Smith, a researcher at the University of North Carolina (Charlotte), they say that high-speed machining occurs when the tooth-pass frequency approaches a substantial fraction of the dominant natural frequency of the machine and tool system.

Smith developed his definition after showing a relationship between this natural frequency and the frequency of chatter, which is the vibration induced by the regeneration of waviness as a tooth recuts a portion of the work already cut by the previous tooth. Because the wavelength of chatter increases with cutting velocity, there is less friction along the clearance face of the tool to damp the vibration. Consequently, Smith and his followers deduced that high-speed machining involves more than just high spindle speeds and requires a definition that accounts for this fact.

A definition based on tool-pass frequency gives engineers and machinists a tool for eliminating chatter and its deleterious effects on tool wear, surface finish, and machine life. Given the direct relationship between the chatter frequency and the dominant natural frequency in the running machine, the goal is to match the chatter frequency with the tooth-pass frequency of the tool, according to Schaut at Boeing. An example he offers is one of a process with chatter frequency of 2000 Hz. For a two-tooth cutter, the optimum spindle speed would be 60,000 rpm; 2000 Hz x 60 sec/min/2 teeth.

What if your high-speed machine has a 40,000-rpm spindle? In this case, Schaut recommends finding another region of stability by dividing the optimum spindle speed by an integer. The next best region would be 30,000 rpm, which is found by dividing 60,000 rpm by 2. To find the optimum spindle speed for the highest material removal rate possible, increase the depth of cut until a new chatter limit is encountered and repeat the process of measuring the chatter frequency and calculating the best spindle speed.

Schaut emphasizes that the procedure works for chatter in the machine and tool system. Users must eliminate any vibration in the workpiece through appropriate workholding and good toolpath programming.

Because the tooth-pass frequency depends on the dynamics of the machine and the cut-

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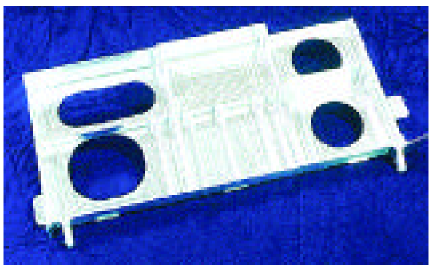
ting process being in tune, there is no such thing as a general-purpose machine once spindle speeds exceed 30,000 rpm. Machine dynamics are too critical to performance. High-speed machines, therefore, must be built for the application.

"A set of dynamic characteristics might be quite suitable for one application, but unacceptable for another," explains Greg Hyatt, manager, Product and Process Development Group, Makino Inc (Mason, Ohio), a supplier to Boeing. "When machine tool designers start to design a machine, especially a high-speed one, they need to know its intended application: the kind of parts, the cutting speeds, and the materials."



With help from a 40,000-rpm machining center, Boeing Phantom Works now produces 4R avionics shelves for the F/A-18 from only one machined billet and five other pieces, instead of 44 formed sheetmetal parts, extrusions, and other pieces. Total production costs of the shelf are down by 73%

The problem is that machine dynamics have not received adequate attention from many machine tool builders in the past. The power, torque, thrust, and other traditional elements of machine tool design are still important for machining centers designed for machining at speeds greater than 30,000 rpm. "They just weren't enough alone if machine dynamics were ignored," says Hyatt. He notes, however, that builders have done significant work in the computer-aided modeling of machine dynamics and dynamic stiffness over the last 20 years.

The result is a number of different designs that have emerged for various kinds of high-speed work. The machining centers that Makino, for example, builds for cutting structural airframes look drastically different from those producing dies and molds. "The servodrives for positioning the table are different, the spindle designs are different, and the torque-power curves are different," says Hyatt. "Such a design will generate power at very high speed because relatively small tools are used." A spindle that generates high torque at low speeds is unnecessary.

Because these machines cut large-envelope parts made from aluminum billets, rather than forgings or castings, most will move the spindle across the workpiece, rather than move the workpiece under the spindle. "You often eliminate 90 to 95% of the mass of the workpiece," observes Hyatt. "The spindle, on the other hand, has a constant inertia during the cut and from one workpiece to another. So you can tune the performance of the machine more precisely by keeping the workpiece stationary and moving the spindle through at least three axes."

Most of these machines will drive the axes with linear motors because typically these motors outperform ballscrews as travel grows. "The performance of a linear motor is insensitive to the length of travel," explains Hyatt. "So a linear motor with 1 meter of travel will have the same acceleration and achieve the same velocities as one with 10 meters of travel." The performance of ballscrew drives, on the other hand, depends very much on the length of travel and wanes as the length increases.

Although early versions of the high-speed machines made for cutting airframes were gantries, Makino has recently introduced a line of horizontals for this application. The smallest, the MAG 4, has a travel of 4 m. Among the advantages to the horizontal arrangement is the exploitation of gravity to remove chips. Because the chips fall onto a conveyor below, the arrangement eliminates the need for an operator to push a broom across the table to prevent the recutting of chips. It also supports automatic work changing more readily, which boosts utilization.

Besides designing high-speed machines for niches, builders also are introducing lines of "compromise" machines to broaden their application a little. For example, some aerospace shops cutting aluminum are preparing for the pending conversion to titanium. To avoid having their machine tools become obsolete in five years, they are investing in machines that might offer 95% of the productivity of the ultrahigh-speed machines built exclusively for aluminum but have the characteristics for cutting titanium.

Many machine shops supplying components that might undergo the conversion are buying 24,000-rpm ballscrew-driven machines, which might accelerate at 0.6 g, rather than 1.0 g. "They're giving up a little in acceleration, but gaining a great deal in damping, rigidity, robustness, and thrust for taking the heavier cuts in titanium," says Hyatt. "A 0.6-g machine offers 85% or 90% of the speed of a 1.0-g machine, not 60%, which might be the intuitive expectation."

Moldmaking, a different look

Because the working envelopes required for making molds and dies is small by airframe norms, machining centers for this application also are much more likely to drive the axes with ballscrews than with linear motors. "There is little or no difference in the acceleration potential of ballscrews and linear motors in the smaller envelopes," continues Hyatt.

He also points out that the range of machine dynamics tends to be much more important in die and mold work, especially today. The trend among toolmakers is to abandon the old strategy of roughing a piece of steel, hardening it, finishing and grinding it, making electrodes, eroding features impossible to cut with an endmill, and polishing the important surfaces. Now that high-speed machines can create excellent surface finishes that need little or no polishing, toolmakers prefer to machine their products completely in one fixture to eliminate time-consuming operations and setups.

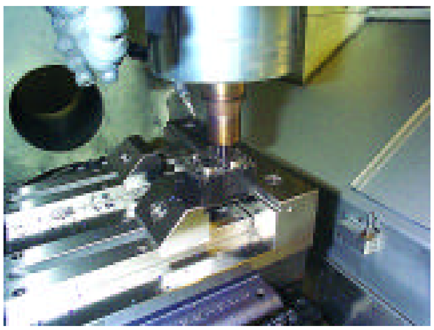
The Boeing facility in Wichita, Kan, uses a high-speed machining center from Makino to make window frames

Because this means roughing, semifinishing, and finishing hardened steel, its practitioners want a spindle with high enough speed to allow fine stepovers for finishing and with a reasonable amount of torque for roughing cavities with larger tools. Consequently, builders fit machines for this work with spindles that have large bearings and a power curve shifted towards the lower end of the speed range. Although maximum speed might be the same, power tends to drop as the spindle reaches top speed.

Among the growing number of high-speed specialty machines designed for hard milling are two models from Roeders of America Inc (Orangeburg, NY). The ballscrew-driven machines can cut steel as hard as Rc 68 and feed as fast as 1200 ipm or 2400 ipm, depending on the model. “Not many people have this ability,” says Victor Pfister, president. He attributes the ability to the new generation of spindles on these machines. “They have both the rigidity and power for this kind of work.”

Robust spindles mandatory

This builder offers a choice of three spindles: a 30,000-rpm, 34-hp model; a 36,000-rpm, 25-hp model; or a 42,000-rpm, 19-hp model. Eventually, the builder will be phasing out the 30,000-rpm model. The 36,000-rpm spindle is new and will be replacing the 30,000-rpm spindle because it’s an HSK 50 and is more rigid. The 36,000-rpm model has everything that the 30,000 offers and then some.



As roughing in this test piece proves, 42,000-rpm spindles can be stout enough for cutting a Rc 50 tool steel that is similar to H13. The 10-mm tool is spinning at 9000 rpm on a Roeders RFM600 machining center and traveling at 120 ipm in a 0.025-in. cut

Roeders’ applications engineers usually recommend the 36,000-rpm spindle for heavy roughing of hardened materials and roughing for long periods. For example, they like to fit large machines with these spindles because such machines typically cut big workpieces and use large-diameter tools. “Its power and torque curves also are almost straight throughout the entire speed range,” says Pfister. “It produces similar torque at 35,000 rpm as it does at 8000 rpm.”

Although the 42,000-rpm, 19-hp spindle can perform a fair amount of roughing in hard materials, it is not the best spindle for this kind of work. “It has a bit of a spike in the power curve,” explains Pfister. “Power spikes at about 30,000 rpm. The low and high ends [of the speed range] don’t have as much [power].” The extra 6000 rpm, however comes in handy for work requiring mostly small tools, such as cutting small features and generating fine finishes.

When deciding which spindle to specify, Roeders’ engineers generally consider the kind of work that the machine will perform and the amount of material that it will remove. Despite their ability to specify an optimum spindle for the job, they recommend not sticking on a point that is not critical. “There’s not much of a difference between 36,000 and 42,000 rpm,” he says. “You’re only gaining or losing 6000 rpm.”

Builders also urge users not to fear high-speed spindles because of stories about their fragility and short lives. “We have run machines in graphite at 40,000 rpm for long periods of time without any spindle damage,” claims Hans Berlinger, president, Hansco Technologies Inc (Montvale, NJ), an importer selling the German-made Digma hard-milling and graphite machining center. He admits, however, that longevity depends on the precision and care that the builder applies.

A well-constructed high-speed spindle used correctly could last longer than a conventional spindle, according to Hyatt at Makino. The reason is that fast rotational speeds allow achieving high power without generating the high torque and tangential loads that degrade bearings and shorten spindle life. For example, a 100-hp cut at 30,000 rpm involves a tenth the torque and machining forces as a 100-hp cut at 3000 rpm and a hundredth the torque and machining forces as a 100-hp cut at 300 rpm.

Mapping surfaces and finding features with the Z-axis probe from Datron takes about 1.5 sec per point. Rather than fitting in the spindle, the probe sits on a pneumatically driven arm that unfolds to make measurements. Tool changes are unnecessary

“Rolling element bearings are more sensitive to load than to speed,” notes Hyatt. “In fact, the factor for load is cubed and speed is only squared. So, assuming adequate cooling, the fatigue life of the spindle bearings will be longer at high speeds, than at low speeds.”

The problem, however, is that some high-speed spindles, especially old designs, have inadequate cooling, which causes inordinate failure rates. “It’s not a mechanical-wear or fatigue problem in these cases,” says Hyatt. “It’s a matter of inadequate heat dissipation causing things to bind or seize because of designers cutting corners and costs.” Makino, therefore, keeps its spindles cool by providing under-race lubrication and routing chilled oil through the spindle.

No hardening and less time in polishing on an EDM are the advantages of milling mold cavities on high-speed hard-milling centers. This cavity was cut from prehardened steel on the Vibra-Free machining center from Compumachine

Another reason for the perception that high-speed spindles are delicate is that they typically use smaller bearings and shafts to achieve the high rpm. Although the fatigue life of the bearing is better than those in low-speed versions, their small size makes the potential damage in crashes more likely to be catastrophic for the spindle than for the work. “It’s like comparing the results of a Formula I car and a garbage truck hitting a wall,” says Hyatt. “In one case, the car breaks. In the other, the wall gets broken.”

Stability important, too

As one might imagine, stable castings are important for the new class of machines built for hard milling. The need for a rigid design is greater in these machines than in those for most aerospace parts for two reasons: the workpiece will be hardened steel instead of aluminum, and volumetric accuracy tends to be much more critical in toolmaking. Stability also must include accommodating the large amount of heat generated while moving at high speeds and feeds.

“In the old days, people would put a high-speed spindle in a regular machine and expect it to perform,” says Dave Shaby, president, Compumachine Inc (Wilmington, Mass), a builder offering the 42,000-rpm Vibra-Free hard-milling center designed by FMC (Niigata, Japan). “Anybody who’s serious about high speed today doesn’t have a C-frame.” Instead, this and other machines in this class are closed-bridge designs with a solid backside to reinforce the bridge and prevent it from rocking.

The comparable Digma machine that Hansco offers uses the closed-bridge design for the same reason. Berlinger adds that the design also eliminates the cross-table arrangement in which one table runs on another. "You don't want a cross-table arrangement in which one table moves along the X axis and another on top of it moves along the Y because it lacks rigidity," he says. "Rigidity is very important for tool life and accuracy," especially in hardened materials.

Stability of many machines in this class also comes from the head's weight distribution and the ribs reinforcing the casting. "The sides of the Vibra-Free's columns have fins emanating from them like stars for thermal dissipation, rigidity, and vibration damping," says Shaby. "If you go behind the machine and put your hand on the way guide while the axis is traveling at 800 ipm, you won't feel the machine shake."

The shape of the casting and arrangement of its fins also help to control thermal growth and dissipate heat. Builders often supplement good design by cooling the cores of spindles and ballscrews, using software to compensate for thermal growth, installing scales, or combining a number of these.

Other builders add stability by preloading the linear guideways and casting the base directly from a polymer concrete, rather than filling a steel weldment with the polymer. The Digma machine, for example, has both. "The polymer composite has greater temperature stability and vibration damping than cast iron," claims Berlinger at Hansco. "The preload ensures that there is no slack anywhere, and the casting is designed not to give when the linear guideways are under pressure."

More than molds

Although builders aim this class of machine at making molds and dies from hardened steel, the machines also find other uses. They have the speed and stability for cutting graphite electrodes, for example. The rigidity at high cutting speeds lets these machines make electrodes for producing sharp corners and small holes with unusual shapes much faster and with better surface finishes than possible on conventional machines.

In fact, producing electrodes for electrical discharge machines (EDMs) is often the first use of these machines in tool and die shops. "Users like the idea of having machines that they can try and get into hard milling slowly," says Berlinger. "Meanwhile, they are busy producing loads of electrodes for their EDMs." He points out that no matter how many operations that high-speed machining eliminates, many tools will continue to need finishing with electrodes.

For this reason, builders typically fit their machines with special devices for evacuating graphite dust. Hansco's Digma machine, for example, sucks the dust from the cutting zone as it is created. Berlinger says that the suction is strong enough to prevent abrasive dust from entering the ways. Other builders blow air into the ways to create a zone of slightly higher pressure that blows the dust away from the ways continuously.

Despite their strong suitability for tool and die shops, this class of machines is finding use in other industries wanting to mill hardened parts. Although Compumachine initially concentrated on the moldmaking business, "we stumbled onto some specialty high-speed production that has actually been bigger than the mold business," says Shaby. This collection of niches includes cutting composites in the electronics industry and hard alloys in the gas-turbine business.

While cutting seven 17-in. gas turbine vanes made from 17-4 PH stainless steel, the Vibra-Free machine produces a nearly polished finish, which eliminates a time-consuming finishing step. "Because 17-4 PH is a gummy material, machining it at 8000 or 10,000 rpm will not produce a fine finish," says Shaby. "So vanes made on conventional CNC machines generally need polishing." Machining at high speed not only improves finish, but also shortens overall manufacturing time.

The machine produced one 14-in. vane in only 65 min. Roughing took 20 min with a 10-mm ballnose endmill cutting at 16,000 rpm and 160 ipm, and finishing took 45 min with a 3-mm ballnose endmill cutting at 28,000 rpm and 125 ipm.

The biggest challenge has been the blending of the root and blade of the airfoil. Because of their limited block-processing capacity, CNCs of the past often could not interpolate the axes fast enough for machines' to run at the feeds necessary to exploit extremely high spindle speeds. Moreover, finish depends on the toolpath and the skill of the programmer. "You can give the same CAD file to two shops with good machines, yet the test cuts will be very different," notes Shaby.

The computing capacity of today's CNCs has eliminated these problems. "We almost never use NURBS because block-processing time is not an issue," says Shaby. "We don't care how long the file is." There is plenty of memory and computing power to apply good programming technique for developing a toolpath that keeps cutting forces constant and look ahead and plan for navigating around features.

Datron Dynamics Inc (Milford, NH) also exploits the computing capacity of modern CNCs to monitor the machine dynamics. "There's a lot of communication going on in the machine," says Dr Walter Schnecker, president. "The CNC knows when the spindle is standing, its temperature, and the temperature in every servodrive in the machine. It also watches motor current. If you crash the machine, you might break your tool, but you'll never bend a ballscrew."

Despite a meeting of the minds on CNCs, Datron takes a radically different approach to high-speed milling. Rather than building the stout, 42,000-rpm machines that excel in hard milling, this builder offers a lighter-weight, 60,000-rpm gantry machine for cutting mainly aluminum and other nonferrous materials. If the cuts are light, such as those taken with carbide engraving tools, the Raptor M-8 machine also can cut molds made of hardened steel and stainless steel.

Because the builder is aiming for intricate work requiring small tools rotating at extremely high speeds, chip loads are small. "So the machine doesn't require the torque that a conventional vertical machining center would have to provide, which means the machine needn't be built to withstand it," says Schnecker. "Because we're really interested in responsiveness, we designed the machine lighter to minimize the inertia in the moving parts to aid the high-speed agility."

Nevertheless, enough stiffness to minimize deflection is important for accuracy and repeatability over a 30 by 40-in. bed. For this reason, the builder's design engineers specified a welded-steel bridge filled with a polymer concrete. "Cast iron is too heavy [to be responsive]," says Schnecker. The lighter polymer concrete provides the desired stiffness and vibration damping without creating unwanted inertia. The tradeoff, however, is that it fractures relatively easily. Thus, the steel case is necessary to absorb any loads to protect the concrete core.

Even though the machine costs $120,000, it comes with productivity devices, such as an integrated chip conveyor under the bed and a tool-length sensor on the bed, to keep the spindle busy. As the toolchanger retrieves a tool from the 32-station magazine, it pushes the tool into a mechanical switch to measure and check it and load the length into the CNC's tool library. "You don't have to know where the tip of a new tool is; the machine will measure it," says Schnecker. "You can look at it as an on-machine tool setter."

An option is a Z-axis probe that gives the machine the ability to map surfaces and find features of a part. "To write a name on the backside of a spoon, for example, the machine would scan the round surface of the spoon and engrave the name inside with the constant depth over that curve," says Schnecker. The probe also can find features such as edges and the center of a boss and help the machine account for the slight curvatures common on large aluminum control panels. Other engraving machines compensate for changing surface with a floating head, which cannot mill cavities.

Unlike edge finders and other similar devices on the market, Datron's probe does not fit in the spindle. Instead, it sits at the end of a pneumatically driven arm mounted under the spindle. The arm unfolds to make measurements and folds back into place so the spindle can resume cutting without having to wait for a tool change. The mapping process takes roughly 1.5 sec per point, which means scanning time is usually 20 to 50 sec. Actual time, however, varies with the size of the part and resolution of the grid.

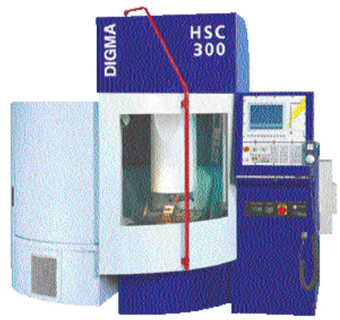
Kinematics for automotive

Because the automobile industry is keen on cutting aluminum and magnesium parts at ever-faster speeds, Lamb Technicon (Warren, Mich) also has designed a horizontal machining center for cutting these materials at high speeds. A clever use of hybrid kinematics gives this ballscrew-driven machine the ability to accelerate and travel at velocities comparable to those found on machines fitted with linear motors.

Called the Bobcat, the machine exploits the principle of kinematic advantage. Two high-pitch ballscrews lying parallel in the direction of the X axis generate all movement throughout the X-Y plane. By means of a crank-like linkage, the spindle and its carrier move both in an arc and in a line to reach all targets in the plane. Consequently, even cutting a straight keyway parallel to the Y axis would require two-axis interpolation.

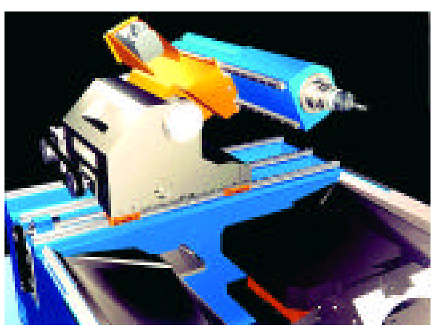
Because all motion is a function of two inputs, speed is much faster than it would be otherwise. "The spindle is farther from the pivot than the input side of the Y-axis ballscrew," explains Phil Szuba, director, research and product development. "So if you move the ballscrew 1 in., the kinematic multiplier might let you generate 1.5 in. of motion. The machine is moving faster in all of the areas of the workzone than it could with the conventional ballscrew rotating at the same speed because of this multiplier."

He adds that the Z-axis motion is no different than it would be on a conventional three-axis machine. The difference, however, is that he and his colleagues adopted a similar strategy as their counterparts at Hansco and designed the machine to be lightweight. The main moving members are weldments, not castings. "So we can use very thin ribs and walls that you normally can't cast," says Szuba. "Less mass means less inertia… and faster speeds and acceleration for the same torque output of the servos."



The latest generation of high-speed hard milling centers excels at cutting graphite. A Digma 300 from Hansco cut this electrode in 43.5 min with maximum speeds and feeds of 35,000 rpm and 118 ipm

The machine, therefore, can accelerate at 1.5 g in X and Y, and 2.0 g in Z and cruise as fast as 80 m/min in all three axes. Moreover, it does so without sacrificing accuracy. It moves to any location within ±0.005 mm and repeats bidirectionally within ±0.004 mm.



The Bobcat from Lamb Technicon exploits hybrid kinematics to accelerate at 1.5 g. Two high-pitch ballscrews lying parallel in the direction of the X axis generate all movement throughout the X-Yplane. They move the spindle and its carrier both in an arc and in a line. The resulting kinematic advantage multiplies velocity and acceleration

During nine months of beta testing at a DaimlerChrysler plant in Germany, the machine made about 10,000 alternator attachment brackets. According to Szuba, feedback from the automaker's engineers was positive. They liked the machine's kinematics, but suggested a few modifications to the packaging of the machine, such as in the pallet changer for stand-alone models. Because the three axes are under the spindle, the machine already plugs into transfer lines easily.

Although the machines can run faster spindles, Lamb will be fitting the first generation of Bobcats with a 16,000-rpm cartridge spindle. The reason is that the company serves automakers and their Tier One suppliers. These manufacturers tend to use large diameter tools to mill cylinder heads and similar parts. "Because the tool diameter is so much larger, you must run it slower [compared to some other high-speed applications]," says Szuba. "Our automotive customers rarely need anything much faster."

That is not to say that Lamb would not consider fitting the machine with a faster spindle. "If somebody wanted us to modify the machine for some application, we would definitely look at putting one in," says Szuba.

Don't buy blind

Most builders agree that, no matter the design, machining at speeds greater than 25,000 rpm requires an enormous investment and that shops should know what it can and cannot do for them. For example, the machines not only are expensive but also are not versatile. "Because the spindles have no torque whatsoever at low speeds, you can't really tap or put a decent size tool in them," says Kanovic. "You're typically limited to finishing work and small-diameter tools." Consequently, users contemplating the purchase of one of these machines must have enough work for endmills smaller than 1/4 in.

Nevertheless, he notes that the philosophy can pay handsome dividends. In California one shop using an Okuma machining center with a 35,000-rpm spindle was able to slash the cycle time for cutting aluminum plates used in producing silicon chips. The 6-hr job took only 2 hr on the new high-speed machine.

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