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cover story

➤ BY BILL KENNEDY, CONTRIBUTING EDITOR

Rough milling of large titanium workpieces requires spindles engineered to handle large cutting forces when running at speeds typically below 1,000 rpm. Here a Mitsui Seiki technician measures the spindle's Z-axis straightness on a Vertex vertical machining center.

Mitsui Seiki

Light-**Heavyweight** MACHINING

Machining centers fulfill demand for heavyweight machining of difficult-to-cut, lightweight workpieces.

Tools evolve in response to changes in the parts they make. Accordingly, machine tool builders develop their machining centers to match trends in product design and engineering. For example, as manufacturers design products for better performance and energy efficiency, they adopt lighter, stronger and more difficult-to-machine workpiece materials. Especially in the aerospace industry, titanium is becoming a material of choice, and a good deal of current machining center technology development is focused on maximizing metal-removal rates—and thereby reducing machining time—when making titanium components.

Cutting titanium alloys quicker, however, is challenging. At typical cutting temperatures of about 1000° C, titanium alloys retain most of their tensile strength; therefore, they require cutting forces about twice those for medium carbon steels. The material's high shear ratio focuses pressure on the cutting edge. In addition, titanium has low thermal conductivity, concentrating heat at the cutting edge. The heat exacerbates titanium's high chemical reactivity, accelerating tool failure and causing built-up edge. The material also workhardens when cut, and recutting hard chips can severely reduce tool life (see sidebar on page 60).

According to Scott Walker, president of Mitsui Seiki (U.S.A.) Inc., Franklin Lakes, N.J., makers of large titanium structural aircraft parts would prefer to machine them the way they've traditionally machined large aluminum parts: "Take a block of material, carve away 98 percent, and what's left is the part you need for the airplane. In aluminum cutting, you crank up the spindle to 20,000 rpm or faster, the feed is very high, you take a light depth of cut and high-speed machine it."

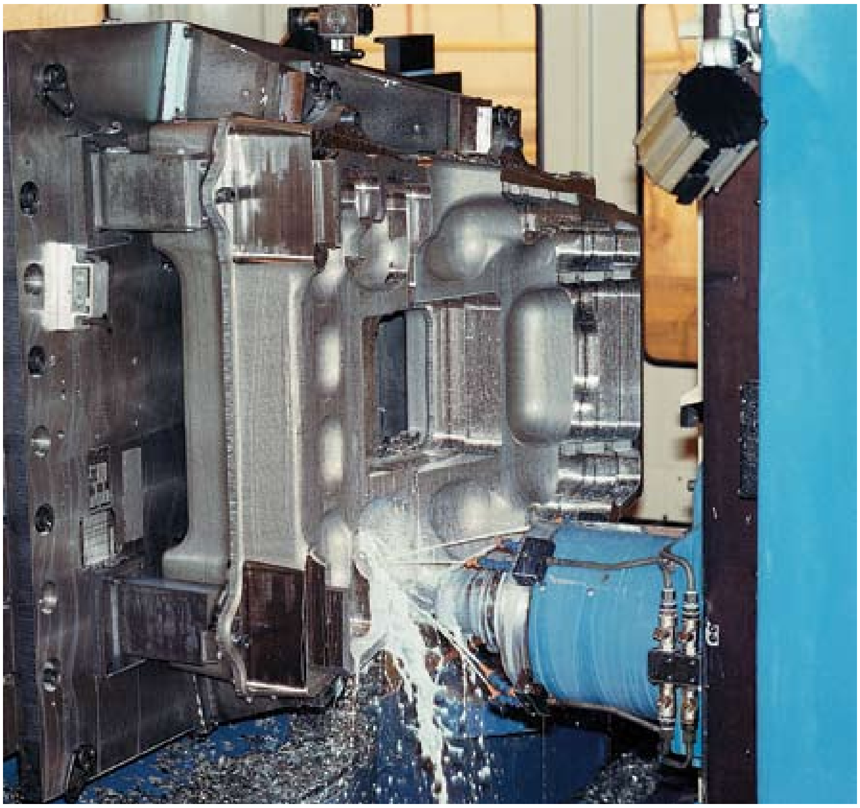
You can't do that with titanium. Its properties require a stiff machine operating at lower cutting speeds—less than 1,000 rpm is typical—to avoid heat buildup. At those speeds, a large DOC is needed to maximize metal-removal rates. Until recently, a majority of demand has been for high-speed machines, but that is changing. "Now you need what I call a heavy-metal, low-frequency machine, so designs have to change," said Walker.


Mitsui Seiki

In addition to maximizing strength and rigidity, the components of machines intended to cut large titanium workpieces are engineered to control resonant frequencies and dampen vibration that can cause chatter during machining operations. Such components include these castings for Mitsui Seiki Vertex 550 5-axis vertical machining centers.

Material-driven machine design must be approached systematically, according to Alan Hollatz, proposal engineer, Makino Aerospace Group, Makino Inc., Mason, Ohio. "When you are cutting any material, the entire system affects the cutting process," he said. "That system includes everything from the material stock to the fixturing, cutters, holders, spindle and machine tool. Particularly when doing heavy cutting on titanium, you must have a strong and rigid setup."

Rigidity is required because machining large titanium parts is a high-torque application, requiring 700 ft.-lbs. or greater. And requirements are growing, according to Gregory A. Hyatt, vice president and chief technical officer for Mori Seiki U.S.A. Inc., Rolling Meadows, Ill. The rise of new beta-phase titanium alloys are driving cutting speeds down and torque requirements up. "It is not due to the material hardness," Hyatt said, "but primarily because we have to run the tools at lower surface footage to achieve adequate tool life. Lower surface footage means lower rpm, so we can maintain productivity only with very high feed forces. We are applying more torque to the machine spindle and much higher feed force with the machines' ballscrews." With newer titanium alloys, such as 5553, he said, torque and feed forces may be in the area of 25 to 35 percent higher than those experienced with more frequently machined titanium alloys.


Makino

When cutting any material, but particularly titanium, the key to high productivity is rigidity of the entire machining system, including fixtures, cutters, toolholders, the spindle and the machine tool. Here a securely fixtured titanium aircraft bulkhead is machined on a Makino 5-axis horizontal machining center, which is part of a large production cell.

Frequently Resonant

Low cutting speeds and aggressive DOCs for titanium produce different machining conditions than those associated with aluminum, including significant low-frequency vibration. Said Hollatz, "Whereas the resonant frequencies generated while cutting aluminum are more likely to be near the resonant frequencies of the part, tooling and fixturing, which causes chatter, cutting titanium, in general, tends to resonate at frequencies more likely to be near the natural frequencies of the entire machine structure."

Walker outlined an example: "Rotate a 1"-dia., 4-flute endmill at

100 rpm, and it will generate a frequency as each cutting edge hits the material. If that frequency is at an excitation range inherent to the mass of the machine, you'll get chatter." Walker said horizontal machining centers typically exhibit low-frequency resonant responses at about 20Hz, 95Hz and 300Hz. In addition, different machine components resonate at different frequencies. For example, a 20Hz resonance typically originates in the machining center's bed, a 95Hz vibration results from column twisting and bowing, and a 300Hz response is from spindle oscillation.

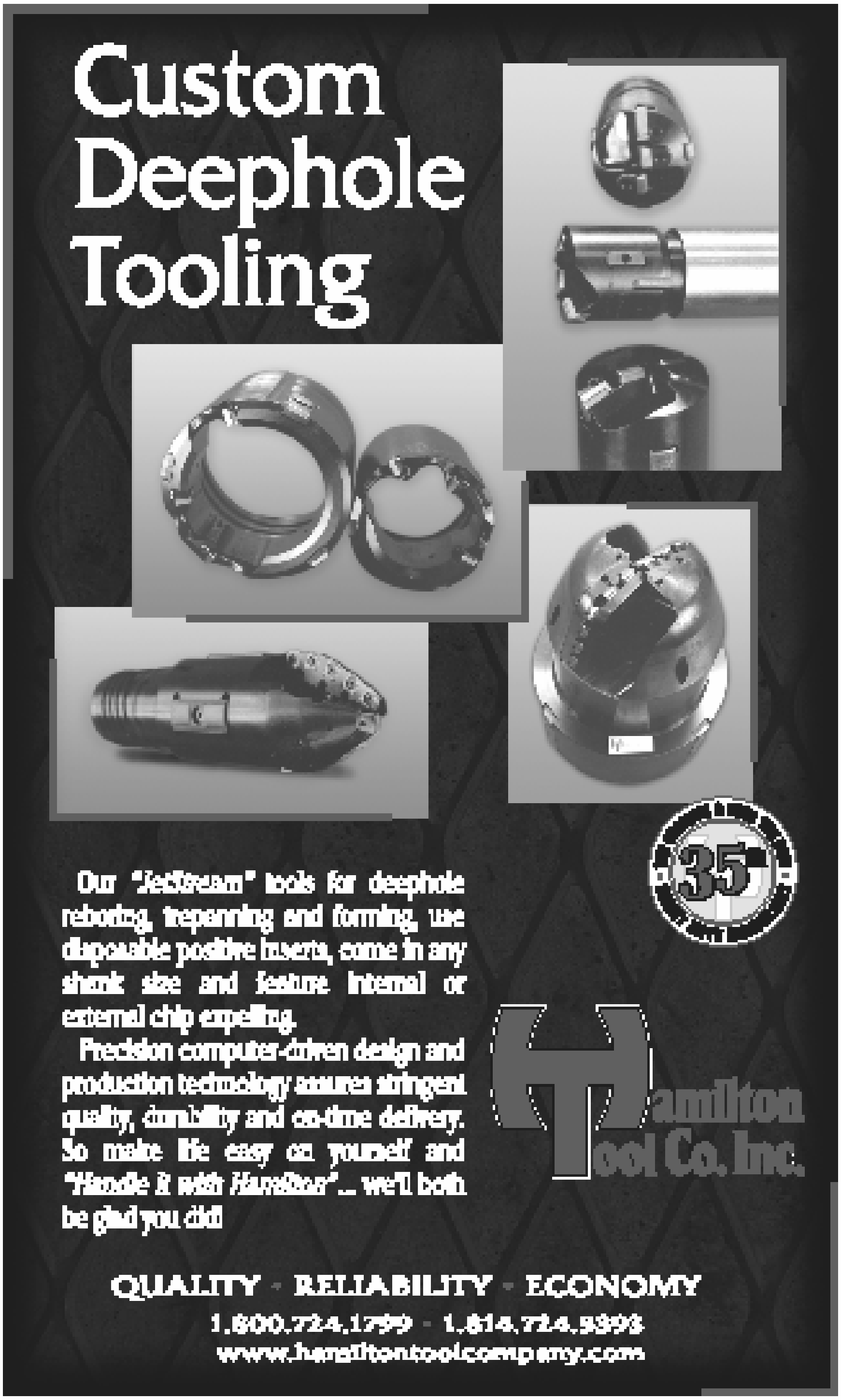
One way to stop chatter on a machine tool is to change the machining parameters in the part program, altering the frequencies generated by the tool so they don't match the machine's excitation ranges. Or, during machine design, the machine structure can be modified to shift its resonant frequencies and dampen vibration. "That can include stiffening the machine base, adding more mass to the top and the bottom of the box column, and changing the retention system that holds the spindle head to shift or dampen resonant frequencies," said Walker.

From a machine tool builder's viewpoint, he added, "The key is to look at the part or family of parts you are going to cut and determine the cutting tool and feed and speed that will give you maximum stock removal and tool life. Then you need to look at the machine tool based on those criteria, and modify the design to accommodate that particular cutting capability."

Walker said impressive time savings are possible when a machine is designed for and dedicated to large-part production. He cited a case where machining time for a nearly 6'-dia. titanium aerospace engine component was reduced from 190 hours to 30 hours using a custom machine.

According to Mori Seiki's Hyatt, off-axis forces can also generate chatter. Large structural parts tend to fill the machine's work envelope, requiring the spindle to cut some distance from the center of the machine table. "The machine tool is essentially a spring," Hyatt said. "Admittedly a very stiff spring, but a spring all the same." When cutting forces are applied away from the machine table's center, "we are storing energy in the structure through its elastic deformation. The elastic deformation of a spring this stiff may be only microns or even submicrons, but there is still a lot of energy stored that is typically released in the form of chatter," he said.

As a result, Hyatt said, "In a typical machine, you may have to program different metal-removal rates at different cutting conditions at the top and bottom of the Y-axis." As an alternative, he said, Mori Seiki has developed its "Driven at the Center of Gravity" design that employs dual ballscrews and box-in-box axes that provide symmetrical support to minimize torsional movement and damp resonances. With that design, Hyatt said, "Once you've



determined the cutting conditions that don't excite the resonances in the work, tool and machine, you can apply them throughout the work envelope."

Not Spindly

Spindle technology is also specialized for heavy cutting. "On the larger titanium parts, we pretty much live below 1,000 rpm," Hyatt said. "There will be finishing and smaller cavity work where we can get up to 8,000 rpm or so, but that is the exception."

Spindles must be optimized for lower-rpm, high-force cuts, requiring high torque to run large tools at only a few hundred rpm. For those applications, Hyatt said, Mori Seiki offers a spindle with 740 ft.-lbs. of torque and a maximum speed of 8,000 rpm. "The standard spindle for the same machine might be 10,000 rpm and the high-speed option 15,000 rpm, with torque in the range of 370 ft.-lbs.," Hyatt said, noting that 8,000 rpm nevertheless is likely fast enough for most large-part titanium applications.

Servomotors and ballscrews that move machine axes for low-speed machining of large parts require unique engineering. "On a high-speed machine, you need high-response servos, not big servos," said Mitsui Seiki's Walker. "On a machine designed for heavy machining of large titanium parts, we'll put on the next servo size up that will provide about 30 percent more thrust capability, because they have to push into really difficult-to-machine material."

Regarding ballscrew design, "In high-speed machines, to boost the speed of axes motion, you'll typically increase the lead of the ballscrew," Walker said. "On a heavy-duty machine, you decrease the ballscrew's lead to increase the mechanical advantage of the screw." He noted that the root path of the ballscrews must be larger, and so must the balls themselves. "On a bigger machine running slow, you need a lot of push capability." Other areas, such as the B-axis, trunnions on 5-axis machines and gib systems, also must be designed

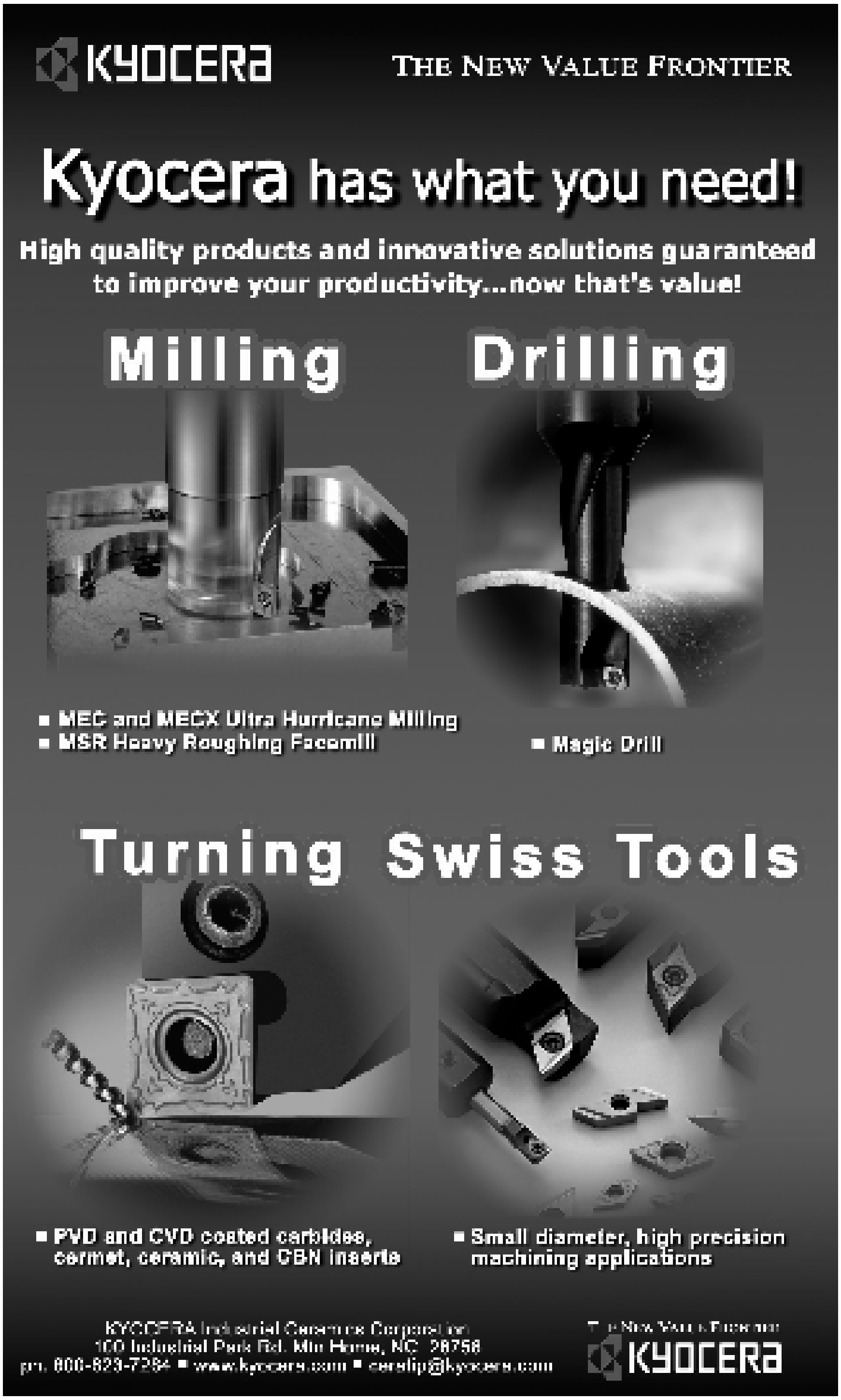
The following companies contributed to this report:

Kennametal Inc.
(800) 446-7738
www.kennametal.com

Makino Inc.
(800) 552-3288
www.makino.com

Mitsui Seiki (U.S.A.) Inc.
(201) 337-1300
www.mitsuiseiki.com

Mori Seiki USA Inc.
www.moriseiki.com
(847) 593-5400



with increased strength to manage heavy cutting loads.

Rugged Toolholding

The tool/spindle retention system is another crucial design element for high-load machining centers. For example, Walker said, a drawbar force of 4,500 ft.-lbs. on a CAT 50 or BT 50 toolholder can withstand about 8,500 in.-lbs. of bending moment before the tool separates from the spindle. An HSK 100 holder under 10,000 ft.-lbs. of drawbar force can provide about 16,000 in.-lbs. of resistance before tool separation occurs.

When cutting titanium, "a ¾" DOC with a 1¼"-dia., 4-flute endmill removing 1.2 in.³/min. will produce about 1,000 lbs. of load," Walker said. "And that's with a sharp tool. If the tool wears 50 percent, the load doubles and you're at 2,000 lbs. of load. Now if you're 7" away from the gage line on the tool interface—assuming that is the total tool length—you're at 14,000 in.-lbs. of load and approaching the strength limit of an HSK 100 tool/taper interface before separation." For reliable operation on structural components involving long tools and high removal rates, stiff tool/taper interfaces such as HSK 125 and 160 are needed, he said.

According to Hyatt, there is no industry consensus regarding choice of steep-taper (e.g., CAT 50) or HSK systems. "We certainly have customers using each successfully," he said. While the HSK connection offers somewhat higher stiffness than steep-taper tooling, in some cases it results in a longer tool and holder combination because HSK's hollow-shank design limits the distance a tool can be set back into the holder. The steep-taper tool can offer an advantage because shorter tools are more rigid and resistant to chatter.

Makino's Hollatz compared fixturing issues when machining titanium and aluminum parts. "Clearly, parameters for cutting a large, monolithic part from titanium are significantly different than with aluminum," he said. More consideration must be given to fixturing requirements for titanium parts. "If possible, we try to use 'self-fixturing' concepts such as back bolts,

Mitsui Seiki

When cutting large workpieces at a low spindle speed, high torque is required to productively remove titanium. This Mitsui Seiki HS6A 5-axis horizontal machining center produces 2,460 ft.-lbs. of torque.

tabbing and window fixtures when machining from plate stock," he said. The high mrr techniques typically employed with titanium put heavy cutting forces into the part and therefore the fixture, requiring proportionally higher strength and rigidity. "In addition," Hollatz said, "due to the high cost of titanium, as the part size increases, it is more likely that the raw material source will be from a forged configuration than it might be for aluminum. Fixturing of forgings can be more problematic and complex than for flat plate work."

Dedicated Power

Walker said that Mitsui Seiki's custom-designed, $1 million-plus machines (distinct from its standard product line) for aircraft OEMs for machining large structural parts aren't suited for high-speed machining of other materials. For example, a high-speed machine with a 1-cu.-m work envelope might have a 20,000-rpm spindle and axes engineered for fast acceleration and deceleration. "The column on that machine typically weighs around 3 tons," he said. For a machine designed for cutting large titanium structures, "the column would weigh 8 tons." The massive column cannot be accelerated as fast as the lighter one. "It's like a dump truck and dragster," Walker said. "You can't have the dump truck do the quarter mile in a couple of seconds, but a dragster won't carry 35,000 lbs. of dirt down the road efficiently."

Tier 1 and other suppliers to aircraft OEMs desire machines that provide more flexibility and require less investment than equipment dedicated to making specific large parts. A balance of titanium and aluminum work can be handled with a "middle of the road" configuration, Hollatz said, citing what Makino calls its "M" series options for HMCs with pallet sizes from 630mm to 1m. The options consist primarily of an 8,000-rpm, 740 ft.-lb. spindle and modified ballscrews to handle increased axis thrust. Makino said a machine thus equipped can provide high productivity in titanium (claiming greater than 25 in.³/min. in Ti-6Al-4V) while also acceptably machining aluminum at 8,000 rpm. He noted that Makino offers larger "MC" series machines with high-torque, low-speed spindle options of 3,000 rpm and 2,700 ft.-lbs. of torque. While those machines can provide significant removal rates in titanium, the lower rpm takes away

most of their utility for aluminum.

Hyatt said Mori Seiki's dual-ballscrew system can handle the high feed forces required for titanium, while its reduced mass permits higher acceleration and enables productive machining of aluminum. When configured with an 8,000-rpm, 740 ft.-lb. spindle, a machine tool is optimized for billet machining. However, some shops prefer a 10,000-rpm or even 15,000-rpm spindles. While these spindle arrangements aren't for heavy hogging of billets, they can be suited to forgings, where the removal rates are lower. At the more moderate removal rates, "We've had success cutting titanium with a 15,000-rpm spindle, which provides productive aluminum machining on the same platform," said Hyatt. △

Where the tool meets the Ti

Just as a sports car needs the right tires to perform well, a machine tool needs the right tools, correctly applied, to maximize productivity in heavy-duty machining of titanium.

To get the most out of a machining center cutting titanium, "you have to customize the way you use tools around the system you are dealing with," said Ken DeRoche, senior program engineer, Kennametal Inc., Latrobe, Pa. "What works on one part doesn't guarantee success on the next. What works on all parts is the complete understanding of the application, or system."

Achieving high removal rates when cutting large titanium billets requires optimized part processing, high rigidity and efficient use of horsepower. In such a high-force situation, the adapter that holds the tool in the spindle "tends to be the weak point," DeRoche said. "If you run faster and harder and exceed the bending moment of that adapter interface or the tool's rigidity, you end up with runout and chatter."

DeRoche advises using the shortest and most rigid adapter and tool combination possible. However, he said, use of longer tools sometimes is unavoidable. "Some aerospace parts have a lot of clamping and fixturing," he said, "and the features [to be machined] may be way inside the part, so the tools have a long reach." DeRoche recommends frequent inspection of the adapter for fretting, bellmouthing and any other signs of premature wear that indicate overloads that can damage spindle bearings.

Part fixturing rigidity should also be maximized, and the work should be as close as possible to the strongest part of the fixture and the spindle.

In a roughing operation, use of Z-axis or plunge milling techniques can help stabilize the system and maximize chip load by concentrating cutting forces vertically into the spindle and workpiece. However, this method can overload older or weaker machines and some gantry configurations. Trochoidal milling, which DeRoche defines as similar to peck drilling but involving radial instead of axial pecking action, may be helpful in situations where long-reach tools are required.

Controlling the heat generated in titanium machining is a major factor in maximizing productivity. DeRoche pointed out that machining temperatures can be higher than those of the tool coating processes and almost as high as carbide sintering operations. "We put some CVD coatings on at about 900° C, and the temperature in the cut when you are cutting titanium is roughly 1,100° C," he said. The high temperatures accelerate tool failure.

"Coolant flow and pressure can really make or break you," DeRoche continued. "If you have minimum coolant flow and/or minimum pressure behind it, you need slower speeds and lighter feeds." Coolant also aids in evacuation of chips, which tend to stick to the cutting edge. DeRoche recommends coolant concentrations of 12 percent or higher, delivered at more than 3 gpm, and 500 psi for through-coolant tools. High-pressure, high-volume, through-tool coolant flow can increase tool life by four times or more when replacing a low-volume, low-pressure setup in titanium machining, he said.

In lower-horsepower, less-rigid situations, higher-axial and lower-radial engagement of the cutter will help reduce side loads while maintaining or increasing the mrr. Radial engagement below 30 percent is desirable, with feed compensated to maintain chip load.

When possible, machinists should apply positive-rake tools with sharp edges and also maintain feed rates high enough to avoid pushing the material, which causes workhardening, rather than cutting it. The chip load produced by the feed rate should be greater than the size of the tool's edge preparation. "I like to stay above 0.003 ipt," DeRoche said. "Feed rate multipliers" and chip-thinning techniques—such as round inserts cutting below their centerline or straight-sided inserts with a high lead angle—can help maintain feed rates. When changes are made, chip load, not necessarily speed, should be increased because boosting speed will generate more heat.

DeRoche added that the operator's own senses can be a great productivity tool for machining titanium:

- sight: watch for chip welding (check coolant flow and edge prep),
- sound: a high-pitched noise indicates chatter (increasing chip load; increasing or decreasing speed; or using variable-pitch cutters can dampen or disturb resonant frequencies), and
- feel: chatter-generating vibrations (correct by altering setup and/or cutting parameters).

—B. Kennedy