Machining turbomachinery parts pushes endmills to the max.

Turbocharged Endmilling

▶ BY BILL KENNEDY, CONTRIBUTING EDITOR

Every dreamer eventually faces reality. Design engineers create exciting designs, but manufacturing engineers have to turn them into tangible parts. Good examples are endmilled prototypes for turbomachinery.

As researchers explore gas flow, power production and efficiency, they experiment with dramatic part contours as well as exotic materials.

It takes a special blend of tooling, machine tool technology, software and experience to make these designers' dreams come true. What follows is how three shops deal with these challenges daily in endmilling turbomachinery parts.

The Stuff Dreams are Made of

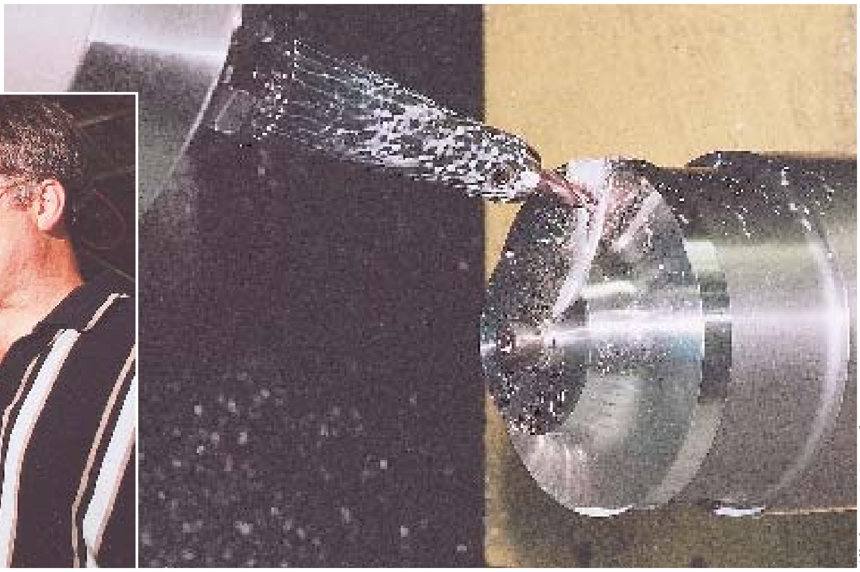
Describing aerospace designers' ideas, John Bressoud, vice president for product engineering at Turbocam Inc., Dover, N.H., said, "Some of it is really oddball looking stuff, but apparently it works."

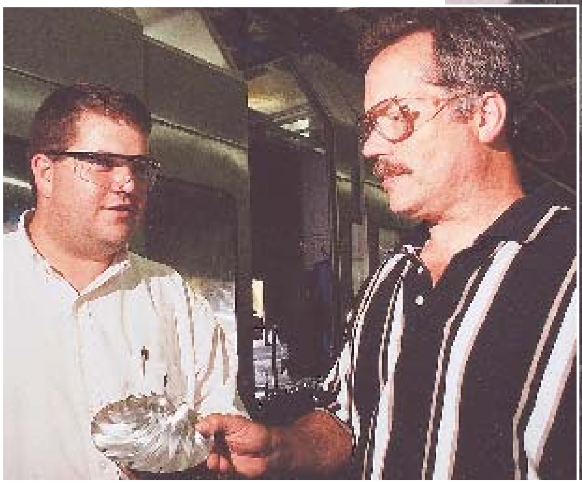
Turbocam 5-axis machines bladed parts for turbomachinery. Its customers include OEMs and university research programs. A typical job is machining a rotor and stator assembly, representing one stage in a turbine engine's compressor, for R&D testing.

Bressoud said most of Turbocam's work involves precipitation-hardening stainless steels, titanium and nickel alloys. Many of the workpieces possess high-temperature strength that enables them to endure the harsh environment of gas turbines but also makes them difficult to machine. Bressoud said, "With other materials, you generate heat in the cutting zone, and the material's strength drops as you put energy into it. Then you can pull a chip off the work face. But with many exotic alloys that doesn't happen."

The key is to use sharp tools with positive geometries to shear the material and minimize friction that boosts temperatures even higher, he said.

The acute contours of turbine parts for R&D compound machining difficulty. The shapes often have deep cavities ending in small radii. "We're really pushing the length-to-diameter ratios," Bressoud said. While it's routine to ma-





All photos: B. Kennedy

Turbine-related components are often machined by Tech Development Inc. with solid-carbide ballnose endmills and corner-radius endmills on a 5-axis, twin-spindle Parpas machine. Manufacturing engineer Andy Sherman (left, inset) and manufacturing engineer and programmer Mark Albert (right, inset) examine a completed impeller.

chine with an endmill having a length-to-diameter ratio of a 4:1, "we're often at 10:1 or 20:1," he explained. "In addition, we apply some very tiny tools—0.020" or 0.030" in diameter."

Small diameters, deep cavities and high L/D ratios raise tool-stiffness concerns. How fast the tool can be fed and how well it cuts depend on its tendency to deflect.

Turbocam uses a lot of ballnose endmills. Bressoud said: "To make the contours, especially when you're removing less stock, you have to use a ball endmill. Once in a while, we'll get a part that has big enough cavities that we can use a flat endmill to do some roughing. Or we use what we call a 'bullnose cutter,' which is a flat endmill with a 0.020" radius on the corner. Those can take some punishment. The farther up the side of the ball endmill you cut, the better your speed, as far as ipr. When you get to the bottom, your speed drops to zero, because you've got zero radius, and you create problems."

Coated 4mm, 4-flute ballnose endmills are used at Tech Development to machine complex internal contours on aerospace parts. The cutters are held in shrink-fit toolholders (inset).

The shop applies custom solid-carbide endmills almost exclusively, many of which are made by regional fabricators.

Bressoud said indexable-insert endmills don't fit Turbocam's needs for small-diameter tools. "There are people who make them small, and I'm sure they can show test results that they're great, but they're usually one flute. At one flute per revolution vs. four flutes per revolution, the feed rate really decreases."

Another challenge, he said, is concentricity. "In aerospace prototype work especially, designers want the leading edge to have a 0.003" total profile tolerance. If you've got 0.002" runout on your insert, you're just throwing away two-thirds of your tolerance," he said.

Reflecting the company's roots in manufacturing software, Bressoud said, "It's how we program the part that makes the difference between productivity and frustration. Most of the time we get out of a machining problem by tool vectoring."

Vectoring involves optimizing the tool's relationship to the workpiece and the motion of the machine tool. In 5-axis milling, the ideal situation is for the direction of travel to be perpendicular to the axis of the tool.

Turbocam's 5-axis machining centers, from Mikron Bostomatic Corp., provide flexibility to machine complex contours.

Turbocam tailors its machining programs to minimize finishing operations. "If we have a severe surface-finish requirement, something better than 32µin., then we might use some finishing techniques," Bressoud said. "We get very good results, sometimes better than ±0.001" blade profile tolerance, depending on the size of the part."

Turbocam developed its own software to generate NC toolpaths.

"It might take us a little longer, but when we actually get to cutting metal, we're producing surface finishes on parts that customers say are too pretty to assemble," Bressoud said.

Out of this World?

Another manufacturer that produces turbomachinery is the aerospace group of Tech Development Inc. The Dayton, Ohio, company specializes in the design, testing and manufacture of turbine-related components. In addition to job shop work, its custom engineering capabilities enable it to offer advanced products such as long-life, low-friction magnetic bearings.

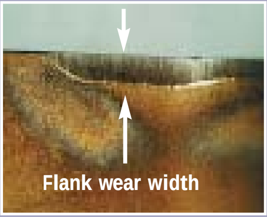
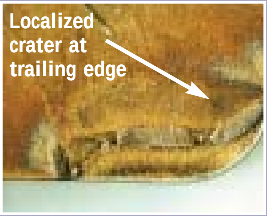
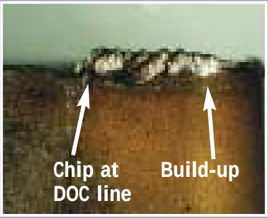
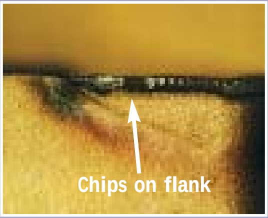
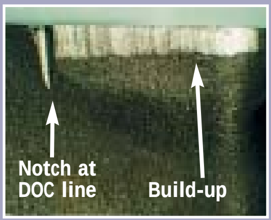
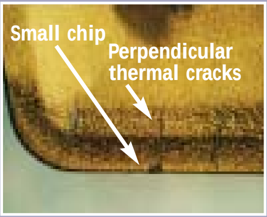
Site manager Tom Jacobs pointed out that Tech Development's thorough familiarity with the design process—in addition to its manufacturing expertise—allows the company to provide customers added value in the form of feedback on process alternatives and costs. An example is concurrent engineering. Tech Development uses information released early on during a project to develop tooling and order materials. This significantly streamlines the overall process.

Tech Development employs 5-axis machining technology to produce complex contours. In addition to 5-axis Bostomatic machine tools, the shop also has a big 5-axis machine from Parpas America Corp.

Five-axis technology enables users to avoid zero tool speed when cutting complex parts. "You can orient the tool so you're not cutting on the center of a

Troubleshooting tool wear when milling

While all inserts eventually wear if any type of metal is milled long enough, tool wear is more pronounced when milling difficult-to-machine materials, such as high-temperature alloys. Presented here are some of the common problems carbide inserts experience, as well as the possible causes and solutions. To look for these typical failure modes on your milling inserts, use a 10x magnifier.

<table>
<tr><th>PROBLEMS</th><th>CAUSES</th><th>SOLUTIONS</th></tr>
<tr><td>Flank wear
</td><td>• Excessive heat
• Incorrect carbide grade</td><td>• Reduce the cutting speed
• Increase chip load to carry away heat
• Apply coolant
• Select a more wear-resistant coated grade</td></tr>
<tr><td>Crater wear
</td><td>• Excessive heat
• Excessive cutting forces</td><td>• Select a more heat-resistant grade coated with Al_2O_3
• Reduce the cutting speed
• Flush with coolant
• Reduce the feed rate</td></tr>
<tr><td>Built-up edge
</td><td>• Insufficient cutting temperature causes chips to adhere to the insert</td><td>• Increase the cutting speed
• Apply coolant to aid lubricity
• Use inserts with sharp edges
• Select a high-lubricity grade</td></tr>
<tr><td>Chipping
</td><td>• Insufficient edge prep
• Grade not tough enough
• Excessive cutting forces
• Recutting of chips</td><td>• Use a tool with a hone or T-land
• Select a tougher grade
• Decrease the feed per tooth
• Apply a cutter with chip gullets large enough for adequate chip clearance
• Remove chips using high-pressure air or coolant</td></tr>
<tr><td>DOC notching
</td><td>• Milling high-workhardening materials</td><td>• Avoid cutters with a 0° lead angle; choose tools with a larger lead angle
• Apply a more wear-resistant grade
• Reduce the feed per tooth
• Reduce the cutting speed
• Use a tool with a T-land
• Vary the DOC</td></tr>
<tr><td>Thermal cracking
</td><td>• Heat stresses due to temperature variation</td><td>• Reduce the cutting speed
• Select a cutter with a more positive geometry
• Discontinue coolant application</td></tr>
</table>

Valenite

Troubleshooting information provided by Valenite, Madison Heights, Mich. For more information about Valenite's cutting tools, visit www.valenite.com or call (800) 544-3336.

ball endmill," said Mark Albert, manufacturing engineer and programmer.

The machines also permit use of advanced cutting strategies, such as helical entry into the part, which is easier on the cutter than direct entry. Albert noted that on a 5-axis machine "you're not going to hog like you can on a 3-axis machine with a big C-frame and a CAT 50 spindle."

Tech Development primarily uses solid-carbide, TiAlN-coated, ballnose endmills and corner-radius endmills.

"Occasionally, if we have fairly heavy roughing to do on a 3-axis machine with sufficient power, we will use an HSS endmill. In some applications they hold up better," Albert said. "They're a little more resilient; you're not going to cut very fast, but you can take a fairly hefty DOC."

Aerospace production supervisor Kenny Magee believes certain brands of HSS tools work better when machining high-temperature alloys, not necessarily because they're better endmills but because they're ground better. "It's the geometry," Magee said.

Knowing what works is a continual learning process. In addition to "familiar" exotics, some customers provide their own proprietary alloys. "We nickname some of them 'Roswell 47,' because they act like they came from an alien spacecraft," Albert said.

Toolholding technology also is im-

Endmill selection 'an art'

According to Steve Abrams, product market manager for the endmills and carbide round tools group of Kennametal IPG, Evans, Ga., the selection and application of tools in a turbomachinery job shop is "an art." And different shops, machining the same materials, may have widely differing tool needs.

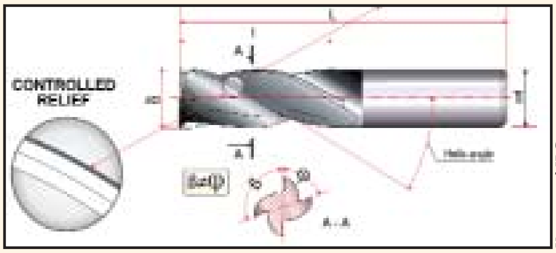
For example, Abrams said, a shop with state-of-the-art equipment might need a productivity-oriented selection of tools, while another operation with older machines and controls might require tools geared more for toughness than absolute speed.

He said a shop's goals also play a role. One operation might decide that its competitive advantage lies in supplying a certain surface finish right off the machine, while another might focus on producing four parts in the time that it formerly took to produce two. Again, the tools required to fulfill those goals will be different.

"Depending on what's available, the 'artist' uses different things along the way in optimizing processes," Abrams said.

Endmilling components made of titanium alloys, such as these aerospace parts machined by Tech Development, requires tools with high helixes and rake angles to minimize friction.

In general, materials such as aerospace-grade titanium alloys require tools with higher helixes and higher rake angles, because they "bite" the material and minimize friction. Continuous cutting speeds—eliminating the peaks and valleys that generate extra heat—can also facilitate the machining of some alloys. "The total amount of machining time is always the key," he said.



Kennametal IPG

The constant, unequal flute spacing of Kennametal IPG's Hanita Cutting Tools VariMill endmill eliminates resonance vibration to optimize high-speed machining.

Abrams said Kennametal IPG's Hanita Cutting Tools brand includes a series of endmills designed to reduce machining time when roughing and finishing high-temperature alloys and stainless and hardened steels. The VariMill combines a parabolic core and offset division of flutes, with a patent-pending controlled relief design. The constant, unequal flute spacing eliminates resonance vibration to provide chatter-free machining at high speeds, Abrams said.

Scott Walrath, vice president at endmill maker Dura-Mill Inc., Malta, N.Y., said that every case is different when it comes to machining exotics.

To help users find reasonable starting parameters, Walrath said Dura-Mill offers a tool users guide on its Web site (www.duramill.com). The guide leads users through a five-step process defining material, operation, tool selection, and radial and axial DOC. Then, at the end, it recommends starting speeds and feeds. The results illustrate the different machining characteristics of various alloys.

For example, when applying a 3/8"-dia., TiAlN-coated carbide endmill in Inconel 718 (hardness above 32 HRC), at radial and axial DOCs of 0.125", the guide recommends a feed of 2 ipr and a surface speed of 60 sfm. On the other hand, machining Inconel 600/625 (hardness below 32 HRC), the recommended speed is more than 50 percent faster (96 sfm) than that used with the harder alloy at the same feed and DOCs.

Walrath stressed that the recommendations are starting points. "We don't know how rigid the user's setup or machine tool is, and we have to play conservative to begin with. We start them at the bottom. If you get through several parts and the cutter appears to be running fine, doesn't show wear and sounds good, then you can bump it up, say, 20 percent. The goal is to get to a sweet spot where there is optimum tool life and machining times that enable the user to make money on the job."

—B. Kennedy

The following companies contributed to this article and the sidebar:

Dura-Mill Inc.
(800) 444-6455
www.duramill.com

SGS Tool Co.
(330) 688-6667
www.sgstool.com

Tech Development Inc.
(937) 898-9600
www.tdiairstarters.com

Kennametal IPG
(888) 434-4311
www.gfii.com/it

Stellex Paragon Precision Inc.
(661) 257-2557
www.paragon-precision.com

Turbocam Inc.
(603) 749-6066
www.turbocam.com

portant. On some finish passes, where there is not as much pressure on the tools, the shop employs shrink-fit toolholders. "We used tapered ball mills previously, but they are somewhat expensive, and the manufacturing tolerances on them may not provide the quality we require," Albert explained. "For jobs where we use just the tip of the ball mill but need more length, we use a shrink holder and a 3mm- or 4mm-dia. ball endmill. The shrink holders run more concentric, and there is the advantage of 360° contact between the holder and tool. It enables us to achieve better surface finishes."

Shrink-fit holders often can be modified to eliminate the interference that sometimes occurs between the part and holder when 5-axis machining a complex part.

Jacobs cited the unique pressures of machining such components in the R&D environment: "We have one time to do it right and satisfy the customer. We don't have the latitude of developing the process. There is a fixed development schedule involving the design and testing of the component."

Materially Relevant

Time is a little less critical for Stellex Paragon Precision Inc., Valencia, Calif., which produces turbomachinery hardware, including impellers and stators.

Doug Verill, vice president for business development, said the shop handles a nearly limitless range of materials. "Starting with 6061 aluminum up through Waspaloy, Hastelloy, Haynes 188—even ceramic—if it's out there, we'll cut it."

The priorities of the R&D environment affect Paragon's selection of tools. Productivity is important, but reliability and quality get the greatest emphasis.

Terry Barker, senior engineering programmer, said "We deal with exotics, but not on a long-term basis. Time isn't an issue on these jobs; it's quality. So we just go with standard coated-carbide tools and don't push them to the limit."

Ninety percent of the time (or more) for complex parts, Paragon uses ballnose endmills whose flutes are as short as possible. This ensures adequate tool strength.

"With exotic metals, you have to make sure you take a cut and don't rub, or you will workharden the workpiece," Barker said. "We approach it from an HSM point of view: small cuts, as fast as you dare, without banging the cutters up."

Machinist and manufacturing engineer John Shilling said some of the alloys generate an enormous amount of heat when machined. As a result, Paragon has to consider the type of coolant most appropriate to meet its goals. Some coolant formulations will cool the tool and reduce wear but won't stop friction, whereas others will minimize friction but won't extend tool life.

Barker emphasized the importance of the operator in determining final machining parameters. "Depending on the job, I might program the roughing of a passage of an impeller at 10 ipm and finishing at 20 ipm. But when it gets to the machine, the operator may override that feed rate by 30 or 40 percent," Barker said.

Shilling said experience is the key. "You know pretty much that you don't want to be taking 1"-deep cuts with a negative-rake tool if you're running Inconel, or that you can't go drilling with a ball endmill," he said.

Experience also guides Barker's toolpath programs. He has developed procedures for blades, disks and rotors over a long career.

Shilling stressed Paragon's focus on quality. "We deal with costly pieces of merchandise and will take 5 more minutes to make the thing in light of the 1-year turnaround for some parts we make."

However, when there is an opportunity to increase productivity, Paragon does. For example, by switching the size and style of one endmill, Shilling said, Paragon reduced the time of a roughing operation from 4 hours to less than 30 minutes.

Instead of applying a ⅜"-dia. ball tool to rough an Inconel part, he employed a ⅝"-dia., coated micrograin-carbide tool (from SGS Tool Co.), with a corner radius ground in the shop. Shilling said the larger mill removed nearly twice as much material per pass.

Regarding the ongoing challenges of aerospace machining, Shilling said, "Sometimes it's a head scratcher, but most of the time I really enjoy it."

Turbocam's Bressoud added, "The aero designers design impossible parts, then we manufacture the impossible. There are some jobs we threw a bazillion tools at and a bazillion machine hours at.

"We don't dream them up. We just make them."