

## Machining Advanced Materials for Aerospace

### Next-generation alloys and composites pose new challenges for aircraft builders

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As demand for lighter, faster aircraft grows, aerospace component manufacturers are machining more titanium, Inconel, Hastelloy, and Waspalloy alloys and composites to meet the needs of airframe and aircraft engine builders. High-profile commercial aircraft such as the Boeing Dreamliner 787, as well as defense programs like the F-35 Joint Strike Fighter, are using nearly all-composite airframe designs, necessitating innovative new processes for machining workpieces that are often composed of both composites and harder metal alloys.

**Machining titanium and other difficult alloys** typically requires using rigid machine tools capable of high torque, as well as using the latest in cutting tools, high-pressure coolants, and machining processes. Offering those elements in a turnkey approach makes customers more productive, notes Dan Cooper, product manager, Cyclo Cut cutting tools, at Productivity Solutions (Hebron, KY), a subsidiary of MAG (Hebron, KY). “We specialize in total solutions: new machine tools, retrofits or rebuilds, along with process development and a complete line of cutting tools and fluids that deliver high chip removal rates. Optimum chip removal and part quality requires a balance of all the inputs to the process.”

Stiffer machines, larger spindle interfaces with HSK100 or 125, high-pressure coolant flushes, and the use of horizontal designs, like MAG’s recently introduced H4000 horizontal profiler, can offer process improvements when cutting titanium and other difficult alloys. Larger spindle motors and geared spindles also are an advantage in cutting difficult alloys, Cooper adds. “Titanium with its low thermal conductivity and high elasticity is very tough to cut. It’s very prone to

chatter, and chatter is one of the worst things you can encounter because it impacts part quality, tool life, and machine life.”

**Aerospace tooling applications** for cutting composites, titanium, and other hard alloys cover a very broad range, notes Chris Mills, manager, aerospace development, Sandvik Coromant (Fair Lawn, NJ). “We have specific tools for the nickel-based alloys, solutions for titanium, and we’re just coming out with tooling for the composites.

“Composites by volume is increasing the most, but then that doesn’t necessarily represent the amount of machining to be done on it,” Mills adds. “The most difficult materials to machine are nickel-based alloys within the engine.” In the front of the turbine engine, the fan and the high pressure compressor are titanium, while the hot combustion section in the turbine uses nickel-based alloys that can tolerate extremely high temperatures.

“Titanium can withstand temperatures to about 800°C, whereas the nickel-based can operate at temperatures above 1400°C,” Mills says. “Nickel-based alloys are the most difficult material to machine but, of course,

they’re only used where necessary. Titanium is much lighter, so titanium’s used as much as possible.



Aerospace profiler from MAG cuts titanium workpiece.

Nickel-based alloys, including Inconel, Waspalloy, and René 41, are generally grouped as Nickel-High Temperature Alloys, or Nickel High Temp Alloys, Mills adds. Most of the titanium machined is Ti-64, or titanium 6Al-4V, which is 6% aluminum and 4% vanadium, Mills explains. “You’ve got different alloying elements, and that changes the metal’s strength. The alloy that causes people the most headaches is titanium 5553, or titanium 5Al-5Mo-5V-3Cr,” he adds. “It’s a

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new material for the Boeing 787, and it's now accelerating with the ramp-up of the production of the 787, with more and more machining of Ti-5553 to be done.

"We generally have benchmarked everything off 6Al-4V, and we find that the same tool, the same grades, and the same programming methods are key. The difference is that you have to go down to 50% of the cutting speeds with 5553 compared to Ti-64. Many people may have run into problems because they've quoted work basing it on a typical 6Al-4V production, whereas it's going to take twice as long because the machinability is decreased 50%. If you were running at 150 fpm (46 m/min) in Ti-64, you're going to have to be down at 75 fpm (23 m/min) in 5553."

**With Ti-5553**, machine shops must optimize processes to deal with the lowered machinability of the newer alloy, Mills notes. "It really magnifies the best practices that you have to adopt with these difficult materials, in terms of the whole machine, process rigidity, setup, coolant flow, and also programming methods. The more difficult the material gets, the more programming is highlighted. Fixturing and setup is important, because you have much higher cutting forces, and any sort of vibration will create difficulties with the tool. You operate at low rpm, because of the very low cutting speeds, so you need to have good torque and power at low rpm. People are using big horizontal machines, and also coming out with dedicated machines just for titanium machining."

To cope with the reduced machinability of Ti-5553, Sandvik recently introduced two new inserts, the S30T and S40T grades aimed specifically at titanium applications, Mills says. The S30T offers higher cutting speeds and longer tool life for titanium milling and it features micrograin cemented

carbide and a thin PVD-TiAlN coating. The S40T, which has a fine-grained, tough, cemented carbide and a thin CVD coating, is aimed at operations that demand toughness, and has increased tool life and security in the most demanding areas of titanium milling.

**Another way to machine** nickel-based alloys is to employ creep-feed grinding on the harder alloys, notes Greg Hyatt, vice president of engineering and chief technical officer, Mori Seiki USA Inc. (Hoffman Estates, IL). "With the nickel-based materials, we're using more and more grinding on our machines, because as the machinability of the material gets down into the single-digit range, grinding becomes a very viable alternative," Hyatt states, "and in some cases, we can actually achieve higher metal-removal rates by grinding than with milling and turning."

By using very specialized processes developed specifically for the nickel-based materials, manufacturers are able to remove metal at much higher rates than with traditional grinding techniques, notes Hyatt. "These are creep-feed grinding processes, so we're using large wheels, taking depths of cut of 1 and 2 mm at a pass," he adds. "It's not the light reciprocating grinding associated with finishing grinders. It's a heavy-hogging process, where we're using full machine power."

The new beta-phase titanium alloys, such as 5553, are abrasive, Hyatt adds, leading to much shorter tool life. "It requires somewhat higher torque, and, for the most part, the increase in torque is required to protect tool life, even with approved tools, such as those Sandvik is now offering, with recommended cutting speeds that are usually even lower than the recommended speeds for 6804B and the more typical alloys. These speeds were already low for cutting titanium—now they're getting even lower, so the only approach really is high torque, low speed. It's a challenge for both the machine tool and the cutting tool."

**Advanced tooling designs** give aerospace manufacturers ways to address the inherent difficulties of abrasiveness when machining nickel-based superalloys. "When you machine steel, you bend the chip across the top of the insert very quickly, consequently that chip turns red-hot, and a red-hot steel is a relatively soft steel," notes Don Graham, manager, turning products and educational services, Seco Tools (Troy, MI). "Therefore, it does not put a lot of pressure on the top of the insert. The danger there is that you dissolve the cutting insert. We can protect that cutting insert with coatings, and therefore it won't dissolve in steel."

"In superalloys, you bend that same chip. It gets redhot but it does not soften. That's why it works so well in a jet engine—it retains a large fraction of its mechanical strength at very high temperatures," Graham explains. "So now when you're machining superalloys, you're putting a lot of pressure on the tool, trying to deform it."

Besides needing heat resistance in the tool, manufacturers must contend with premature tool wear. "These superalloys are abrasive, particularly as they're heat-treated, so they grind away at the edge. These superalloys are very tough, and therefore it's difficult to break a chip. In other words, chip control is somewhat difficult. Another problem associated with the toughness of nickel-based materials is built-up edge. Eventually that build-up is going to be pulled away, and you've chipped the edge of the cutting tool."

For these alloys, Seco Tools addresses cutting problems with geometry, tool chemistry, and proper selection of speeds and feeds, Graham notes. "In the most general terms, we prefer positive-rake geometries to decrease cutting force and minimize built-up edge. We prefer micrograin carbide, because it resists the pressure that a superalloy puts on the edge of an insert, more so than conventional carbide. And the micrograin carbide also has very good resistance to abra-

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sion. Another thing we do that's associated with the chemistry of the tool is to use PVD coatings. Such coatings prevent built-up edge and provide a bit of abrasion resistance."

**Chip-control improvements** also are offered with Seco's Jetstream Tooling, a toolholding system that directs high-pressure coolant at the cutting edge. Developed for an aerospace customer working with Ti-64, the system helped reduce titanium chip size from about 1 m down to 0.25" (6.4-mm) long chips. "Chips on Ti 64 were dangerous, expensive to dispose of, and very difficult to handle," Graham recalls.

"The problem is that titanium is not a good conductor of heat, and what that means is you can cool the top of the chip, but the bottom of the chip is still hot, and therefore still tough and difficult to break. Jetstream Tooling is a toolholder system to hold a turning insert that delivers coolant to the area underneath the chip. It helps form a hydraulic wedge that lifts the chip, quenches the chip, bends the chip, breaks the chip, and blows the chip out of the way."

Flute density and micrograin carbides are other advancements that can help shops with tool wear when cutting materials like titanium, notes MAG's Cooper. "Typically, the finishing tools are almost always solid carbide," he notes. "We have a product called a Max-Flute where we'll take a cutter, for example, a 3/4" (19-mm) solid-carbide end mill, and we'll put sixteen flutes in it, compared to the old days where you'd have four flutes. With the higher flute density, you would feed four times faster in finishing operations, reducing cycle time while providing higher quality and more accurate parts.

"We've reduced the grain structure for higher strength and better tool life," he adds. "We have an ultra-fine submi-

crograin carbide, which uses 0.4-0.6µ grain size on the cutting edge. This gives you a stronger carbide, because your particles are smaller, and there's more surface area for bonding. With the finer-grain carbide, you're also able to get sharper cutting edges."

**Proper tooling** on rigid machines is critical when cutting titanium, notes Wayne Reilly, application manager, Haas Automation (Oxnard, CA). "To be successful you need sharp, rigid tools that are going to be able to evacuate the chips very well. Particularly when cutting titanium, a sharp tool is probably the key to being successful. As soon as it starts to get dull, things quickly deteriorate."

"The key is having a rigid machine, a rigid spindle and very high-end cutting tools with the right geometry," adds Jochen Reichert of Methods Machine Tools Inc. (Sudbury, MA). "We've definitely seen an increase in cycle time, speeds, and surface footage in the last couple of years in hard-to-machine materials like titanium and Inconel."

A contract manufacturer and spindle builder, Dynamax Inc. (Mundelein, IL) machines aerospace components in composite, aluminum, titanium, and Inconel, according to Dynamax CEO Rich Zic, PhD, Material Sciences and Metallurgy. "For aerospace work, we mostly machine titanium, Inconel, stainless, and those types of materials," Zic says, "but mainly we focus on titanium metal removal, because it's a little bit different than standard machining of any material that people normally machine. We cut a great deal of the alpha beta titanium alloy, which is very widely used in aerospace."

"With titanium, we need to have rigid equipment, because if the machines we are using don't have sufficient rigidity, the surface finish does not turn out to be good, and tool life is tremendously shortened," Zic says. "Also, we have to move across the cutting surface within a certain speed band. We need to employ proper feed rates;

you need to cut that material—you can't rub it. If the machine stops at any a given point, it will introduce thermal stresses into the material."

Dynamax machines primarily titanium structural parts, including support members employed where the engines are mounted. "For jet engines in particular, builders want to have reduced weight and increased strength, and the strength levels of titanium are equal to most of the other steel alloys, at half the weight," Zic notes. "Aerospace is always looking to reduce weight. Every ounce costs fuel."

**Producing threaded holes for aerospace** in harder alloys continues to be a challenge for manufacturers. "The area where we've had the most development for aerospace is where they have problems producing internal threads in materials such as 15-5 ph stainless, 17-4 ph, 6AL-4V titanium, and 718 Inconel," says Mark Hatch, thread milling product manager, Emuge Corp. (West Boylston, MA).

Many aircraft parts are difficult to machine due to their chemical makeup and the specialized heat-treating the materials go through, Hatch notes. "Generally we have to machine stainless steels and Inconels in prehardened condition, so typically we could be working in ranges of 38 to 48RC. One of the primary issues you have with these material categories in aerospace is not only high hardness, but the chemical makeup, which can create a squeezing characteristic to the material. You find that tap manufacturers have to create specialized geometries with a lot of relief in them to correct for this squeezing behavior. Tap breakage continues to be a chronic problem in aerospace applications, but aerospace is shifting to is thread milling, wherever possible in these difficult materials."

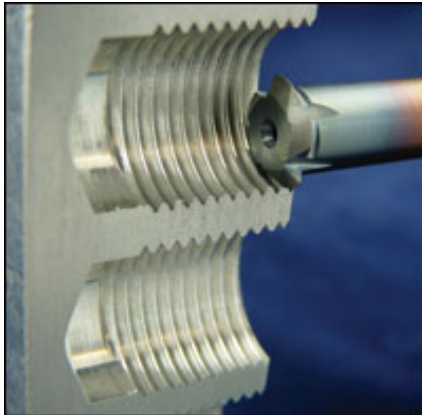
Using threadmills saves cycle time for users, he adds. "Our geometry is designed with an extended milling section up to 2X deep, which is a

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characteristic unique to our tool. In aerospace, manufacturers have very demanding requirements for the internal thread, J-series threads. They call them safety-critical threads that must be held to a 3-B tolerance for the pitch diameter, and this means they have very high quality standards when it comes to producing general threads. Our threadmills lend themselves well to controlling these tolerances.”

Aircraft parts require close tolerances on safety-critical threads, shown here cut with an Emuge threadmill.

**In composites machining**, the biggest process problems often involve delamination of composite stacks comprised of differing materials, including composite and titanium layers. “Our primary focus is on aerospace. We help Boeing and defense



Aircraft parts require close tolerances on safety-critical threads, shown here cut with an Emuge threadmill.

contractors who are using our tools in commercial and military aircraft mill and drill the parts,” says Drew Strauchen, vice president, engineering, OSG Tap & Die Inc. (Glendale Heights, IL). “We focus primarily on two different tools, routing for the trimming of the material, and drills for holemaking.

“The hole processing is the most difficult aspect and the most common. For every milling cutter they use, they probably use 100 drills. There are a lot of fasteners in the airplanes—a lot

more drilled holes than there are milled parts,” Strauchen notes. “The challenge we found is delamination and hole sizing—being able to drill a hole with one drill, as opposed to using two and three drills to make one quarter-inch hole. Our specialty is designing double-angle and triple-angle drills for CFRP [Carbon-Fiber-Reinforced Polymers] to process the hole in one shot, to prevent delamination, and to produce consistent hole size.”

With OSG’s solid-carbide double and triple-angle drills, longer tool life is achieved because of the company’s patented diamond coating, Strauchen says. The drills, which are offered only as specials, feature a CVD diamond coating.

“The direction of the fibers in the CFRP dictates the angles that are required in the design of the drill,” Strauchen observes. “Delamination often occurs because the drill successfully cuts the CFRP layers going in one direction, but as soon as it gets to the layers going in a different direction, it tends to push them instead of shear them. Then you get additional pressure pushing the layered laminate out. That’s why there are multiple angles in our tools. The angles are there to address the different directions of the fiber in the CFRP layout.”

New CFRP tool designs also are available from tooling supplier Kennametal Inc. (Latrobe, PA), which has conducted extensive research in CFRP tools and alternative processes with its partner, orbital drill developer Novator AB (Spanga, Sweden). The Kennametal SPF drills control delamination on hole entry and exit by design.