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Difficult-to-machine materials, such as titanium, require the use of special cutting tools, such as this C7710VRD antirotation button cutter.

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TITANIUM Takes Off

The art and science of milling titanium to make aerospace parts.

Titanium and composites are replacing traditional aluminum alloys in many aerospace applications. Today, the aerospace industry consumes roughly 42 percent of all titanium produced globally, with double-digit demand growth expected to continue throughout the rest of this decade.

Both commercial and military markets are driving demand for titanium as new generation aircraft take full advantage of the properties titanium offers. The Boeing 787, the Airbus A-380, the F-22 Raptor and the F-35 Joint Strike fighter (also called Lightning II) all include significant titanium content.

The Titanium Advantage

Titanium alloys provide high strength, high fracture toughness, good corrosion resistance and good weldability. As airframes move toward higher structural composite material content, titanium substructures assume a much greater proportion of the airframe because titanium bonds to composites much better than aluminum. For example, titanium alloys can increase airframe structural life up to 60 percent compared to aluminum.

Titanium's high strength-to-density ratio (20:1, or up to 20 percent improvement in weight) provides significant weight savings in large components—a key challenge for aircraft designers. Additionally, the inherent corrosion resistance of titanium relative to steel reduces aircraft operating and maintenance costs.

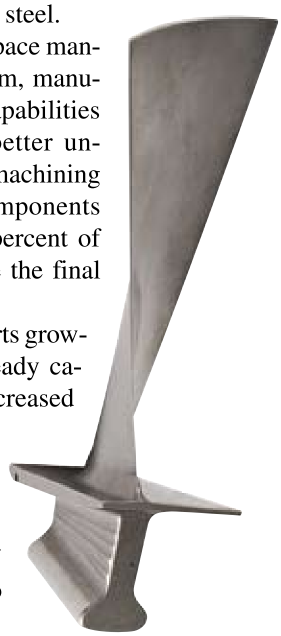
More Machining Capacity Required

Because it is more difficult to cut than common steel alloys, titanium is considered a difficult-to-machine material. Typical titanium metal-removal rates are roughly 25 percent of those seen for more common steel and stainless steel alloys, so it takes about four times as long to machine a component in titanium as it does in steel.

With growing demands on aerospace manufacturers to machine more titanium, manufacturers need to increase their capabilities and capacities. This requires a better understanding of effective titanium machining strategies. Typically, titanium components start as forgings where up to 80 percent of the material is removed to achieve the final component shape.

With the market for aerospace parts growing rapidly, manufacturers are already capacity-constrained. Add to that increased demand for slower-to-machine titanium components, and machining capacity is clearly under stress. Several leading aerospace companies have wondered publicly if the machining capability exists to handle all the new titanium parts.

These parts are often made of new alloys, changing the machining methods and tool material requirements.



Finished aircraft engine blade machined from a proprietary titanium material using X-Grade technology.

Airframe component in Allvac Ti-5-5-5-3 alloy titanium. Pockets were rough milled with high-feed facemills and finished with solid-carbide endmills.

Titanium Ti-6Al-4V

There are three structural types of titanium alloys: alpha, alpha-beta and beta. Commercially pure titanium and alpha alloys of titanium are not heat treatable but are generally very weldable. Alpha-beta alloys are heat treatable and most are weldable. Beta or near-beta alloys are fully heat treatable and are generally weldable.

The most common alpha-beta titanium alloy in turbine engine and airframe structural applications is Ti-6Al-4V (Allvac Ti-6-4 alloy, or Ti-6-4 for short). The short version of ATI Allvac alloy designations are used in this article because the company is a major supplier of titanium. *(Editor's Note: ATI Allvac recently signed a long-term, $2.5 billion*

Internal synergy leads to new solutions

Allegheny Technologies is a diversified manufacturer that includes business units in both metallurgy and metalcutting. Being in these two fields provides the company with an advantage in developing new approaches for machining advanced materials, such as titanium.

ATI Stellram receives all new materials developed by ATI Allvac. Machinability tests are then conducted to determine the best insert design, tool geometry, substrate and coating combination and machining parameters to economically machine the material before it is sold on the open market. In addition, representatives from Allvac, Stellram, primary aerospace manufacturers and Tier 1 suppliers that machine aerospace components meet to collaborate on requirements for both workpiece materials and cutting tools.

The knowledge of the inherent material structures provides ATI Stellram with an advantage in engineering unique formulations for cutting tool substrates, according to the company. One result is X-Grade technology, which ATI Stellram says is a proven and reliable solution for machining difficult-to-machine materials.

X-Grade technology was developed through R&D to discover a carbide grade that thrives in unstable conditions while providing very high metal-removal rates in difficult-to-machine materials, according to ATI Stellram.

X-Grades (substrate and coatings)

Using a ruthenium/cobalt alloy substrate, X-Grade inserts resist thermal cracking and propagation and allow a higher mrr. This substrate creates a stronger bonding matrix, thereby yielding improved edge toughness. Coupling this with new geometries and coatings produces an excellent combination for machining aerospace alloys, according to ATI Stellram. The company reports that X-Grade technology inserts can:

- Double the mrr,
- Triple tool life, and
- Improve surface finishes by 30 percent.

X-Grade inserts are available in three grades (X400, X500 and X700), each designed for specific difficult-to-machine applications. They are available in standard insert styles, and many fit the pockets of standard tool bodies.

However, according to ATI Stellram, the best solution is to use cutters specifically designed to optimize the performance of X-Grade technology inserts. These cutters feature flute designs for maximum chip evacuation, reinforced pockets and maximized cooling. Two such cutters are:

- The 7710VR antirotation button cutter, which features round inserts with a patented locking indexation system to prevent insert movement under heavy feed rates.
- The 7792VX high-feed cutter, which improves mrr by as much as 100 percent compared to conventional cutters, according to ATI Stellram. In addition to high-feed facemilling, the 7792VX family is capable of pocketing, slotting and plunging. Cutting forces are directed axially into the spindle, lessening spindle wear and improving stability.

—CTE Staff

titanium supply agreement with The Boeing Co., Chicago.) In addition, ATI Stellram, which works with ATI Allvac to develop machining solutions, uses these alloy designations to describe machining requirements. (ATI Stellram is a business unit of ATI Metalworking Products, an operating company of Allegheny Technologies.)

Ti-6-4 has a good combination of strength, fracture toughness and fatigue resistance in various product forms. Annealed Ti-6-4 has broad use in structural components, and slight variations in the Ti-6-4 chemistry and thermomechanical processing can produce components for a wide range of applications.

Titanium Ti-5Al-5V-5Mo-3Cr

A new titanium alloy penetrating the market is Ti-5Al-5V-5Mo-3Cr, or Ti-5-5-5-3 for short. This is a near-beta titanium alloy that offers fatigue and fracture toughness in aircraft structural applications requiring superior tensile strength compared to beta-processed alpha-beta titanium alloys.

Its ability to be forged into complex shapes and heat treated to above 180 ksi (thousands of lbs. per square inch) ultimate tensile strength makes Ti-5-5-5-3 a promising material for advanced structural and landing gear applications, compared to traditional titanium alloys, such as Ti-6-4 and Ti-10-2-3.

The mechanical properties of Ti-5-5-5-3 are developed by solution heat treating below the beta transus or beta annealing (above the beta transus) and subsequent appropriate aging to control grain size and precipitation in wrought microstructure. The beta transus is a composition specific temperature where the alloy transforms from an alpha plus beta (α/β) microstructure to a completely beta (β) microstructure. Variance of the chemistry and microstructure gives titanium alloys the wide range of property combinations and thus wide applicability in aerospace structures. Ti-5-5-5-3 is roughly 30 percent more difficult to machine than Ti-6-4, so component manufacturers using this new alloy are racing to find technologies to machine it without shortening tool life and extending production time.

The material's hardness is a critical issue in machining titanium. If its hardness is low (below 38 HRC), the titanium will be sticky and built-up edge may occur. With a higher hardness value (above 38 HRC), the material will be abrasive and wear the cutting edge. Selecting the right speed, feed and cutting tools is critical (Table 1).

Cutting Tool Requirements

New workpiece materials and part designs increase the pressure on aerospace component manufacturing teams to meet cost, quality and on-time delivery demands. Machining these new materials changes cutting tool requirements. High mrr, long tool life, high product quality and predictable tool life without tool breakage are crucial to efficient, safe manufacturing.

"Difficult to machine" is a relative rather than absolute term. With the right combination of cutting tools and machining parameters, machinists can achieve effective production rates.

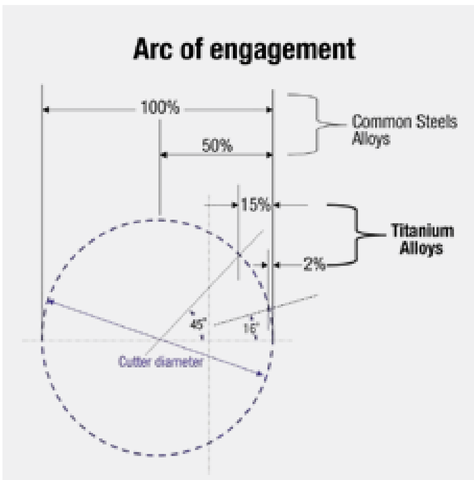
Cutting tool manufacturers have improved tool capabilities by increasing the density of substrates, designing specific geometries, using precise edge honing techniques and developing new coating technologies to manage heat at the tool/workpiece interface when machining aerospace-grade alloys.

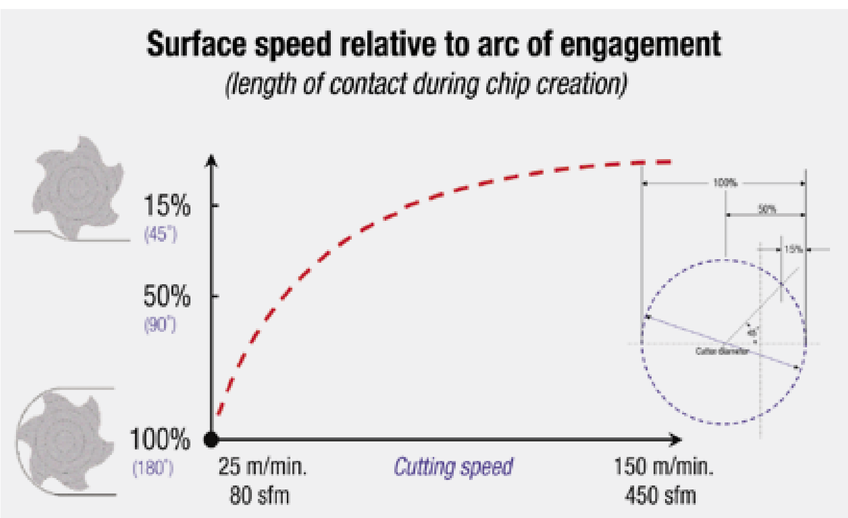
In milling operations, titanium's most significant property is its poor heat conductivity. The temperature generated when machining titanium is very high (up to 1,200º C when not controlled) due to the material's high strength and poor thermal conductivity. Heat is concentrated at the cutting edge instead of evacuating with the chip or being absorbed by the workpiece. Too much heat will shorten tool life.

Using specific machining techniques, it is possible to improve tool performance and life. (Controlled temperature using proper machining techniques reduces the temperature to between 250º C to 300º C).

Reducing Heat Generation

Reducing the radial and axial engagement of the cutting tool can control heat generation. With titanium alloys, the application window (regarding speed, feed, radial and axial engagement) is small before excessive





Figures 1a (top) and 1b: Titanium alloys require a maximum of 15 percent "arc of engagement" compared to 50 to 100 percent for common steels.

heat build-up begins.

For proper tool life, titanium alloys require a maximum of 15 percent "arc of engagement" compared to 50 to 100 percent for common steels (Figure 1a). Speed can be increased by reducing the arc of engagement, allowing for higher metal-removal rates without loss of tool life (Figure1b).

Using an approach angle of the cutter equal to 45º or less thins the chip. This increases the length of the cutting edge in contact with the chip (Figure 2). Therefore, localized heat is reduced and the cutting edge lasts longer. This also allows machines to cut faster.

Insert Geometry

When machining titanium using inserts, it is vital to apply periphery ground inserts to minimize cutting pressure and friction with the surface

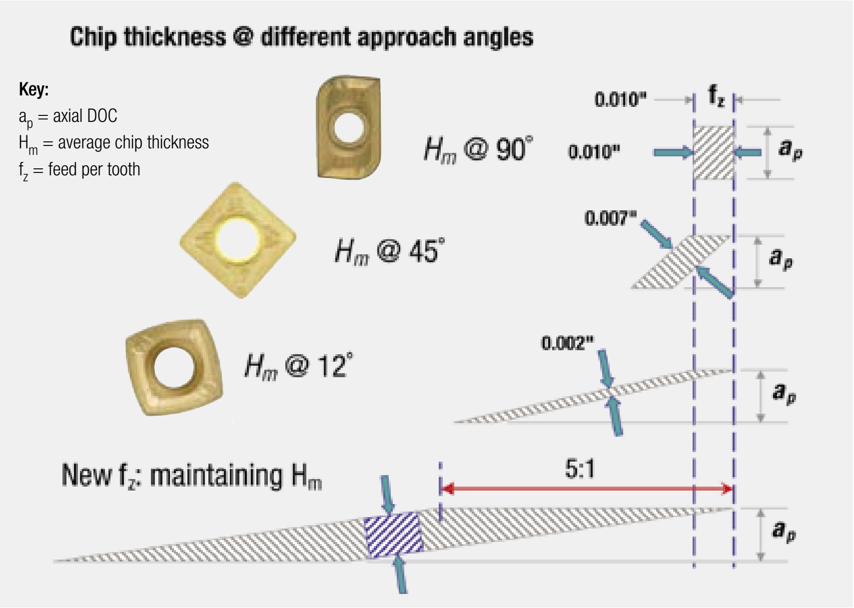


Figure 2: Using an approach angle of the cutter equal to 45º or less thins the chip. This increases the length of the cutting edge in contact with the chip.

Family	Commercial name	Allvac designation	Hardness HRB or HRC	R_m N/mm^2	K_c 0.6 N/mm^2	v_{cmin} sfm	v_{cmax} sfm	v_{cmin} m/min	v_{cmax} m/min
Titanium α	Ti-5Al-2.5Sn	5-2.5 Alloy	36 HRC	1,130	2,400	156	329	48	100
Titanium α	Ti-6Al-4Zr-2Mo-2Sn	6-2-4-2 Alloy	28 HRC	900	1,500	168	355	51	108
Titanium α	Ti-8Al-1Mo-1V	8-1-1 Alloy	35 HRC	1,100	2,400	156	329	48	100
Titanium β	Ti-11.5Mo-6Zr-4.5Sn				2,200	90	190	27	58
Titanium β	Ti-13V-11Cr-3Al				2,200	90	190	27	58
Titanium β	Ti-3Al-8V-6Cr-4Mo-4Zr	38-644 Alloy	32 HRC	1,000	2,200	90	190	27	58
Titanium β	Ti-8Mo-8V-2Fe-3Al				2,200	90	190	27	58
Titanium β	Ti-13V-11Cr-3Al	13-11-3 Alloy	40 HRC	1,270	3,400	78	165	24	50
Titanium β	Ti 10.2.3	Ti-10V2Fe3Al Alloy	35 HRC	1,100	3,000	72	152	22	46
Titanium β - α β	Ti 5Al-5V-5Mo-3Cr	Ti-5-5-5-3 Alloy	40 HRC	1,270	3,400	78	165	24	50
Titanium α β	Ti-6Al-4V	Ti-6-4 Alloy	36 HRC	1,130	2,400	156	329	48	100
Titanium α β	Ti-6Al-5Zr-0.5Mo-0.25Si				2,400	132	279	40	85
Titanium α β	Ti-6Al-5Zr-4Mo-Cu-0.2Si				2,400	132	279	40	85
Titanium α β	Ti-6Al-6V-2Sn	6-6-2 Alloy	35 HRC	1,100	2,400	144	304	44	93
Titanium α β	Ti-7Al-4Mo				2,200	132	279	40	85
Titanium α β	3-2.5	3-2.5 Alloy	24 HRC	820	1,600	168	355	51	108
Titanium α β	6-4ELI	6-4ELI Alloy	32 HRC	1,000	2,200	162	342	49	104
Titanium α β	6-2-4-6	6-2-4-6 Alloy	36 HRC	1,130	2,300	156	329	48	100
Titanium α β	Ti-17	Ti-17 Alloy	38 HRC	1,200	2,500	144	304	44	93
Titanium α β	Ti-4Al-4Mo-2Sn-0.5Si	4-4-2 Alloy	35 HRC	1,100	2,400	132	279	40	85
Titanium α β	Ti-4Al-4Mo-4Sn-0.5Si				2,400	132	279	40	85
Pure Titanium	Ti 99.5	70,Ti CP-4 Metal	100 HRB	780	1,450	240	507	73	155
Pure Titanium	Ti 99.6	55,Ti CP-3 Metal	90 HRB	600	1,450	264	557	80	170
Pure Titanium	Ti 99.7	40,Ti CP-2 Metal	80 HRB	510	1,450	288	608	88	185
Pure Titanium	Ti 99.8	30,Ti CP-1 Metal	70 HRB	430	1,450	312	659	95	201

Table 1: Range of speeds for machining titanium alloys. The range v_{cmin} to v_{cmax} covers roughing to finishing.

being machined. Insert geometry must be positive, but this is not enough to ensure effective performance. If the first part of the cutting edge is reinforced by a stronger small primary angle, then a higher secondary angle for more positive clearance is the best geometry to resist pressure and extend tool life.

Next, a small hone helps protect the cutting edge, but its size must be consistent in the manufacturing process and held to a tight tolerance. When machining titanium, a sharp cutting edge is required to shear the material, but too sharp of a cutting edge will chip the tool, reducing tool life. The proper size hone protects this cutting edge from premature chipping. These parameters lead to longer tool life and increased productivity with less stress and pressure on the material.

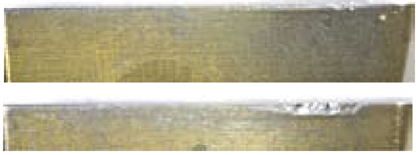
The cutting angle of the cutter body and insert must be positive to achieve a progressive cutting action and avoid hitting the cut with the entire cutting edge rather than achieving the desired shearing effect. If this is not done, the workpiece's structure may be modified, making machining impossible.

In machining titanium, cutter bodies and inserts must use very positive cutting angles to achieve progressive cutting action and avoid impact.

Pocketing and Helical Interpolation

During pocketing and helical interpolation operations, machinists should use through-coolant tools and, when possible, apply the coolant at constant pressure. This is especially important for deep pockets or holes.

For deep pocketing, best results are achieved by using tungsten heavy-



Using correct cutting parameters, inserts used to machine titanium exhibit regular wear and have a standard evolution and offer predictable machining life (top). When applied cutting energy is too high, inserts exhibit excessive wear and are prone to premature failure (bottom).

alloy extensions with modular cutting heads to improve rigidity and minimize deflection.

The coolant's function is to clear the chips from the cutting area to avoid recutting them, which can cause premature tool failure. At the same time, coolant helps to lower the temperature at the cutting edge, resulting in less geometric deformation on the workpiece and longer tool life.

Helical interpolating holes with milling tools can eliminate the need for other tools—such as drills—in the tooling magazine, allowing machining of different sizes holes with one cutter diameter.

As the use of titanium in aerospace grows, so too will the metalworking technology that supports efficient machining. With the high demands that titanium places on machining capacity, machine shops and manufacturers that use the most efficient technology will be first in line to benefit from surging demand for titanium parts. △

About the Authors

This article is the result of a collaboration among specialists at Allegheny Technologies (ATI), a leading producer of specialty metals. Participants include Dave Watson, vice president, cutting tools, ATI Stellram; Dr. Tom Bayha, director of titanium technology research and development, ATI Allvac; Tom Hofmann, global product milling manager, ATI Stellram; and Gilles Festeau, technical and development manager, ATI Stellram. For more information, go to www.alleghenytechnologies.com or www.atistellram.com.

Aerospace case studies

The following are two cases studies involving metalcutting using ATI Stellram cutters tooled with X-Grade inserts.

Titanium Shell (military)
Material: Ti-6Al-4V (Allvac Ti-6-4 Alloy)
Part size: 110"x18"
Description: The part is machined with an ATI Stellram 7792VX high-feed milling cutter with XDLT-D41 indexable-insert geometry utilizing X-Grade technology to achieve tool life of 156 minutes during roughing.
Cutter: C7792VXD12-A3.00Z5R
No. of pockets: 5
Insert: XDLT120508ER-D41
Grade: X500 (X-Grade technology)
Axial DOC (a_p): 0.080"
Radial WOC (a_e): 2.100"
Speed (v_c): 131 sfm
Feed (f_z): 0.023 ipt
Feed: 19.2 ipm
Tool life: 156 minutes per index (4 indexes per insert)

Turbine Blade for Military Aircraft (new application)
Material: Proprietary titanium alloy
Blade size: 23.6"x11.8"
Description: The airfoil is machined using an ATI Stellram 7710VR milling cutter tooled with indexable antirotation round inserts utilizing X-Grade technology to achieve tool life of 110 minutes during roughing.
Cutter: C7710VR12-A2.00Z5R
No. of pockets: 5
Insert: RPHT1204MOE-421-X4
Grade: X700 (X-Grade technology)
Axial DOC (a_p): 0.080" to 0.100"
Radial WOC (a_e): 0.800" to 1.37"
Speed (v_c): 265 sfm
Feed (f_z): 0.0086 ipt
Feed: 21.8 ipm
Tool life: 110 minutes per index (4 indexes per insert)