Increasingly titanium and composite materials are replacing traditional aluminum and steel alloys in many aerospace applications. Today, the aerospace industry consumes roughly 42% of the total titanium produced with double-digit demand growth expected to continue throughout this decade. In fact, experts say we’re in the “Age of Titanium” for aerospace. Both commercial and military markets are driving this demand as the new aircraft take full advantage of the high strength to weight properties titanium provides. The reasons for this transition are many: Titanium alloys provide high strength, fracture toughness, good weld ability and good corrosion resistance. For example, the inherent corrosion resistance of titanium alloys relative to steels reduces operating and maintenance costs for the airline industry. Titanium also bonds to composites much better than aluminum. Titanium’s high strength to density ratio provides significant weight savings of large components, while simultaneously increasing system operating efficiency.

Along with these advantages, however, comes the challenge of machineability. Machining titanium is more difficult than common steel alloys and, for that reason, is considered a “difficult-to-machine” material. For example, typical metal removal rates for Titanium are roughly only 25% of the rates of these other materials, thus taking approximately 4 times as long to machine a component. In addition and typically, titanium components are forgings where up to 80% of the material must be machined away to achieve the final component shape. These new alloys are changing the traditional machining methods and cutting tool material requirements.

Difficult to machine isn’t an absolute term, but a relative one. The use of these new materials does change the cutting tool requirements (metal removal rates, tool life, product quality and machining security – all critical to efficient, safe component manufacturing), however using the right combination of cutting tool designs, speeds and feeds, can result in effective production rates.

This presentation will review various ways to increase machining capability and capacity through a better understanding of how to more effectively machine titanium alloys. This is accomplished through the technology of the tooling as well as how the part is processed on the machine, however, component rigidity, fixturing, coolant, cutting tooling and machining strategy are all factors that need to be balanced for the best result. One additional key factor of this optimization is a thorough knowledge of the inherent structures of the materials which allows one to design the optimum cutting tool system. For example cutting tool manufacturers have improved the capability of their tools by increasing the density of the substrates and developing new coating technologies to manage the heat generated in the machining of aerospace alloys. Heat is one of the main reasons for premature failure of cutting tools when machining the various titanium alloys.
TOM HOFMANN
Global Product Manager - Milling
Acknowledgement

• The following presentation is a result of collaboration of ATI’s metallurgists, scientists and engineers in providing an effective understanding and solutions for improving machinability techniques of Titanium alloys.
Critical Aerospace Industry Concerns:

“Does sufficient titanium machining capability exist?”
Source: From the Boeing presentation “Titanium for Aircraft” ITA 2005 Conference

“Military growth alone will require a doubling of machining tools by 2015.”
Source: From the GKN Aerospace presentation “Titanium in Military Airframes” ITA 2007 Conference
Airframe Production Challenge:
Transition from Aluminum to Titanium

Military Aircraft 9% (F-4)
to 40% on Current Aircraft

Source: From the Boeing presentation "Titanium for Aircraft" ITA 2005 Conference
The Titanium Advantage

- Titanium alloys provide high strength, fracture toughness, good corrosion resistance and weldability.

- Titanium bonds to composites much better than aluminum.

- Titanium’s high strength to density ratio provides significant weight savings.

- Titanium’s corrosion resistance relative to steels reduces operating and maintenance costs.
Airframe Production Challenge: Transition from Aluminum to Titanium

- Titanium mill products are not fly away parts.
- Most parts require machining (up to 93% metal removal).
- Existing machinery, tooling and methods for Aluminum are not suited for Titanium machining.
- Existing machinery suitable for machining large components may have stability and rigidity issues.
- Using existing tooling, machinery and methods could require a tenfold increase in machining capacity.

Why? What makes it so difficult?
Why Titanium is “Difficult” to Machine

- **Low Thermal Conductivity**
  - In Steel 75% of heat generated goes into chip.
  - In Titanium only 25% of heat goes into chip.

- **Low Modulus of Elasticity**
  - Titanium “springy” characteristics
  - Excessive heat generation

- **Work Hardening Tendencies**
  - High cutting pressure
  - High heat generation

- **High Chemical Reactivity**
  - Undesirable chemical reaction at cutting interface
Titanium

Machined volume (in³) by cutting edge

- Aluminium < 16%, 6061 T6: 129.60 in³
- Unalloyed steel < 180HBN, 1010: 60.74 in³
- Grey cast iron SAE J431: 60.18 in³
- Spheroidal-ductile iron, 654512: 51.97 in³
- Aluminium > 16%, 390.0: 51.84 in³
- Grey cast iron, SAE J431: 51.84 in³
- Spheroidal-ductile iron, 654512: 51.84 in³
- Unalloyed steel < 180HBN, 1010: 51.84 in³
- Stainless steel 316: 41.04 in³
- Stainless steel 316: 32.83 in³
- Alloyed steel 300HBN, 4340: 12.05 in³
- HTA titanium base, TA6V: 12.05 in³
- HTA iron base, Incoloy 800: 8.77 in³
- HTA iron base, Incoloy 800: 7.78 in³
- HTA titanium base, 5.5.5.3: 7.65 in³
- HTA nickel base, Inconel 718: 7.65 in³
<table>
<thead>
<tr>
<th>Material Type</th>
<th>Machined Weight (lb) by Cutting Edge</th>
</tr>
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<tbody>
<tr>
<td>Unalloyed steel &lt; 180HBN, 1010</td>
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<td>Spheroidal-ductile iron, 654512</td>
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<tr>
<td>Aluminium &lt; 16%, 6061 T6</td>
<td>12.44</td>
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<td>Stainless steel 316</td>
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<td>Alloved steel 300HBN, 4340</td>
<td>9.19</td>
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<tr>
<td>Aluminium &gt; 16%, 390.0</td>
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<tr>
<td>HTA iron base, Incoloy 800</td>
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<td>HTA nickel base, Inconel 718</td>
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<td>HTA titanium base, TA6V</td>
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<tr>
<td>HTA titanium base, 5.5.5.3</td>
<td>1.31</td>
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</tbody>
</table>

**Titanium**

Machined weight (lb) by cutting edge

[Bar chart showing the machined weight (lb) by cutting edge for various materials, including unalloyed steel, grey cast iron, spheroidal-ductile iron, aluminium, stainless steel, alloyed steel, aluminium, HTA iron base, HTA nickel base, and HTA titanium base.]
Areas of focus for optimized milling of Titanium

- Understanding the workpiece material
- Ensure maximum stability of workpiece / fixturing
- Applying the correct strategy in conjunction with the selected tool design
- Cutter body design
- Insert geometrical design
- Cutting insert substrate
- Coating and the technique of deposition
# Titanium Alloys Range of Speeds

<table>
<thead>
<tr>
<th>Family</th>
<th>Commercial name</th>
<th>Allvac® designation</th>
<th>Hardness HRB HRC HB</th>
<th>Rm N/mm²</th>
<th>Kc 0.6 N/mm²</th>
<th>vmin fpm</th>
<th>vmax fmp</th>
<th>vmin m/min</th>
<th>vmax m/min</th>
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<tr>
<td>Titane α</td>
<td>Ti-5Al-2.5Sn</td>
<td>Allvac® 5-2.5 Alloy</td>
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<td>329</td>
<td>48</td>
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<td>100</td>
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<tr>
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<td>Pure Titan</td>
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<td>312</td>
<td>659</td>
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</table>
Substrate and Coating

It is important to use a substrate formula, such as ruthenium-based substrates, that can withstand very higher temperatures generated during cutting.

It is important to also use coated carbide to prolong the wear process and to have a thermal barrier at the temperature diffusion during machining.
Advanced Substrate Technology

X500

Minimizes Thermal Crack Propagation
Standard WC Co Substrate Technology

*Non Ruthenium Grade*

→ Extensive Thermal Cracking
CVD Coated Ruthenium Based Grade

• Coated with TiN-TiC-TiN by CVD
• Layer thickness 3-5 microns
• Improved edge toughness: For use in difficult conditions on exotic alloys at low cutting speeds
• Contains Ruthenium
PVD Coated Ruthenium Based Grade

- Coated with TiAlN by PVD
- Layer thickness 4-6 microns
- Contains Ruthenium specifically qualified for titanium alloyed and stainless steel materials

US Patent #7,244,519
Titanium and Cutting Geometries

- Sticky material and / or hard, often abrasive

- The geometry needs to be positive, a sharp cutting edge with a small hone protection

- If too high of a cutting pressure results during machining, the material is subject to structural modification by surface overheating resulting in premature damage from chipping, notching or breakage
Geometry Evolution

- The first positive area of the cutting edge needs to be strong to resist cutting pressure, but the geometry then needs to evolve positive / helically, to minimize the cutting forces.

- The profile of the cutting edge is progressive and allows for a smooth transition in the material.
Refractory Alloys and Surface Contact

- The temperature diffuses more quickly when the cutter engagement increases. For this reason it is necessary to use a low radial engagement to allow the highest cutting speeds and/or a longer time life.

Heat Transfer

<table>
<thead>
<tr>
<th></th>
<th>Steel Machining</th>
<th>Titanium Machining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip</td>
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<td></td>
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<tr>
<td>Material</td>
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<td>10</td>
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<td>Cutting Edge</td>
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<tr>
<td>Steel Machining</td>
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</tbody>
</table>
Radial Engagement (Ae): Effect on cutting temperature...

CUTTER ENGAGEMENT...

100%  50%  10%

Relative Cutting Temperature Diffusion...
Surface speed relative to arc of engagement
(length of contact during chip creation)

- 15% (45°)
- 50% (90°)
- 100% (180°)

25m/min  Cutting speed  150m/min
80fpm       450fpm

- Control temperature @ cut point!
## Arc of Contact for milling

<table>
<thead>
<tr>
<th>Material</th>
<th>Mill cutter with indexable inserts</th>
<th>Solid Carbide Endmill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arc of Contact</td>
<td>ae % of Diam</td>
</tr>
<tr>
<td></td>
<td>(°)</td>
<td>(°)</td>
</tr>
<tr>
<td>Steel &lt; 50HRc</td>
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<tr>
<td>Steel &gt; 50HRc</td>
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<td>Iron</td>
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<td>Titanium TA6V</td>
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<td>Titanium 5-5-5-3</td>
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<td>718 Nickel</td>
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<td>Graphite</td>
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<td>41</td>
</tr>
<tr>
<td>Aluminium</td>
<td>90</td>
<td>50</td>
</tr>
</tbody>
</table>
Flute design for maximum chip evacuation

Locking indexation system to prevent insert movement (patented)
Advanced Cutter Designs

Unique patented insert design, approach angle and cutter body ensures the cutting forces are directly axially

Relationship between cutting edge and work piece is at its most stable

Resulting in high feed rates and consistent tool life

US Patent # 7,220,083
European Patent # EP 1 689 548 B1
Tooling Solutions for Titanium Machining

- Faster Cycle Times
- Increased Capacity
- Maintained Security

Cost $ vs. Metal Removal Rate Cu In / Min

Current Methods vs. New Solutions
Solutions for Aerospace Machining

Milling Cutters:
- 7745VOD Octagon Milling Cutter
- 5230VS Chevron Long Edge Cutter
- 7690VA Power Mill 90™
- 7710VR Anti-Rotation Button Cutter, patented design

Insert Grade:
- X500 Patented ruthenium / cobalt alloy insert substrate with improved edge toughness

Landing Gear Component Ti 5553

Result: 90% increase in metal removal
Solutions for Aerospace Machining

Landing Gear Component Ti 1023

Milling Cutters:
- 7792VXD High Feed Cutter, patented design
- 7710VR Anti-Rotation Button Cutter, patented design

Insert Grade:
- X500 Patented ruthenium / cobalt alloy insert substrate with improved edge toughness

Result: 90% increase in metal removal
Solutions for Aerospace Machining

Engine Turbine Blade Proprietary Ti Alloy

Milling Cutters:
7710VR Anti-Rotation Button Cutter, patented design

Insert Grade:
X700 Patented ruthenium / cobalt alloy insert substrate with improved edge toughness

Result: 300% increase in tool life
THANK YOU!