Efficient Machining Solutions in Titanium Alloys

David J Wills
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 Alloy materials.
In collaboration throughout ATI, our goal is to improve our customers’ machining efficiency in Titanium & specialty steel alloys providing:

- Reduced processing cost
- Increased machine capacity
- Reduced production lead-times
- Increased bottom line profitability
Critical Aerospace & Defense 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 Machining Challenge:

*Transition from Aluminum to Titanium*

- Titanium mill products are not fly away parts.
- Dramatic increase of future aircraft demanding complex Titanium components.
- Most parts require machining, up to 90% 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.
Typical Titanium Aero-Structure Component Cost Build

- 44% Material Costs
- 36% Machining Costs
- 26% Finishing Costs
Machinability Scale:

- **ATI 6-4™** (15) – Difficult
- **ATI 718™** (35)
- **Steel 180Hb** (100)
- **Aluminum 120Hb** (250) – Easy

### Machined Weight per Cutting Edge

<table>
<thead>
<tr>
<th>Material</th>
<th>Machinability</th>
<th>lbs/edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Temperature alloys, titanium base, ATI 6-4™</td>
<td>1.95</td>
<td></td>
</tr>
<tr>
<td>High Temperature alloys, nickel base, ATI 718™</td>
<td>2.26</td>
<td></td>
</tr>
<tr>
<td>High Temperature alloys, ironbase, ATI 800™</td>
<td>2.81</td>
<td></td>
</tr>
<tr>
<td>Alloyned steel 300HBN, 4340</td>
<td>9.13</td>
<td></td>
</tr>
<tr>
<td>Stainless steel ATI 316™</td>
<td>11.49</td>
<td></td>
</tr>
<tr>
<td>Aluminum, 16%, 6061 T6</td>
<td>12.44</td>
<td></td>
</tr>
<tr>
<td>Grey Cast Iron SAE J431</td>
<td>15.04</td>
<td></td>
</tr>
<tr>
<td>Unalloyed steel&lt;180HBN, 1010</td>
<td>17.01</td>
<td></td>
</tr>
</tbody>
</table>
Machinability

- Coolant Mix and Delivery
- Cutting Tool Material
- Cutting Edge Temperature

Environment

- Machine Tool
  - Stiffer M/c Structure
  - Higher Torque Spindles
  - High Pressure, High Volume Coolant

Titanium Component Material

- Strength / Hardness
- Toughness / Ductility
- Modulus
- Chemical Reactivity

Machining Conditions

- Tooling
- Tool Path
- Cutter Geometry/Cutting Forces
- Feedrate
- Cutting Speed
- Depth of Cut
Advanced Tooling Solutions for Titanium Alloys and Specialty Steels

- Faster Cycle Times
- Maintaining Tool Life Security
- Increasing M/c Tool Capacity

Current Methods

Cost $ vs. Metal Removal Rate Cu In / Min

New Solutions

Advanced Tooling Solutions for Titanium Alloys and Specialty Steels

ATI Stellram 2010. All Rights Reserved.
Using specific machining techniques, it is possible to improve the cutting tool performance and time life:

- **Address Heat Generation!** – *(arc of engagement)*
- **Control Cutting Forces** *(stability)*
- **High Feed Technology** *(a good example of controlling cutting forces)*
- **Trochoidal Toolpaths** *(slotting & profiling)*
- **Helical Interpolation** *(hole making and pocket entry)*
- **Plunging** *(directing cutting forces)*
Titanium Alloys Heat Dissipation

- Temperature diffuses more quickly when the cutter engagement increases.
- Mandates use of low radial engagement to allow the highest cutting speeds and/or a longer time life.

Heat Transfer

<table>
<thead>
<tr>
<th>Component</th>
<th>Steel Machining</th>
<th>Titanium Machining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Cutting Edge</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Steel Machining</td>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>
Cutting Edge Temperature

CONTROLLING CUTTING EDGE TEMPERATURE IS A BALANCE

- Engagement / Arc of contact (Radial depth of cut)
- Chip Section ($A_D$) – Effective Feedrate
- Surface Speed
- Feed
- Chip Creation (Thick to Thin)
- Coolant (volume pressure temperature)
- Tool Geometry
- Tool Wear Consistency
Cutting Edge Temperature

Relation between Material, Speed and Temperature

- **Material**
  - ATI 5553™
  - ATI 6-4™

- **Vc (fpm)**
  - 115
  - 197

- **Wet (° F)**
  - 130
  - 150

- **Dry (° F)**
  - 500
  - 560

Ap: 0.060 in  F: 0.008 ipr
Surface Speed Relative to Arc of Engagement  
(*length of contact during chip creation*)

- 15% (45°)
- 50% (90°)
- 100% (180°)

- Control temperature @ cut point!

Cutting speed:
- 25m/min: 80fpm
- 150m/min: 450fpm
RADIAL ENGAGEMENT (Ae) Effect on cutting temperature...

100% CUTTER ENGAGEMENT...

50%

10%

RELATIVE HEAT “DIFFUSING” INTO INSERT...
Advanced Substrate X-Grade™ Technology

- X-Grade™ X700 Milling Grade
- X-Grade™ X500 Milling Grade
- X-Grade™ X22 Milling Grade

X-Grades feature ruthenium in the substrate.

Ruthenium in WC-Co substrates:
- Improves the resistance to thermal cracking
- Improves the resistance to plastic deformation

Hard, wear resistant CVD or PVD coating:
- Significantly increases wear resistance
- Provides a thermal and chemical barrier during machining

© ATI Stellram 2010. All Rights Reserved.
**X-Grade™ Advanced Substrate Technology**

**X-Grade™ Advanced Substrate**

Minimizes Thermal Crack Propagation (~275 µm)

**Standard WC-Co Substrate** (Non-ruthenium grade)

Extensive Thermal Cracking (~600 µm)

Ru. minimizes thermal crack propagation
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.
Evolution of Insert Geometry

Test comparison our standard geometries -42 : -46 and the new geometry 48
Material: ATI 6-4™ 320HB  Cutter Dia.: 50.8mm - 2inch
Ae: 20mm - 0.78inch  Ap: 6mm - 0.236 inch
Vc: 50m/min - 164fpm  Fz: 0.12mm/Z - 0.00472ipt

Insert definitions and chip formation:

<table>
<thead>
<tr>
<th>Insert Definition</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>APHT1604PDTR-42</td>
<td><img src="42.png" alt="Image" /></td>
</tr>
<tr>
<td>APHT160408ER-46</td>
<td><img src="46.png" alt="Image" /></td>
</tr>
<tr>
<td>APET1604PDER-48</td>
<td><img src="48.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Chip Thickness at Different Approach Angles

- \( h_m \) @ 90 degrees
- \( h_m \) @ 45 degrees, \( 0.707 \)
- \( h_m \) @ 12 degrees, \( 0.208 \)

New \( fz \): maintaining \( h_m \)

Patented Hi-Feed Insert
**7792VXD Hi-Feed Milling**

*A New Solution for Profiling and Pocketing with small radial engagement*

Material: ATI 6-4™
2.0” Diameter
180'/min (sfm)
RPM = 325
0.030” per tooth ~ 0.150” per rev
AE = 40% - 70% engagement
AP = 0.080”
5-Teeth
MMR = 6.1 in³ / min
15% Spindle Load

**video**

US Patents 7,220,083 / 7,600,952
Pocketing ~ Insert Engagement

- Constant cutting section irrespective of position in pocket
- ‘Near-square’ sidewall
- Vibration free cornering
- Excellent surface finish

VRD Button Tool

VXD High-Feed Tool
Advanced Cutter Designs

7792VXD High Feed Milling

Material = ATI 6-4™
Cutter Dia. = 2.0” with 5 pockets
Insert = XDLT120508EN-D41 X500
Speed = 145'/min (sfm)
RPM = 293
Feed = 0.036” ipt
    = 52.7 ipm
Ap = 0.040” in one full 360 degree revolution
MRR = 4.216 in³/min.

video
US Patents 7,220,083 / 7,600,952
Advanced Cutter Designs

7792VXE High Feed Milling

ATI 6-4™ Material

\[ V_c = 197 \text{ sfm} \]
\[ n = 240 \text{ rpm} \]

\[ f_z = 0.0315 \text{ ipt} \]
\[ f_n = 0.189 \text{ ipr} \]
\[ V_f = 45.36 \text{ ipm} \]

\[ a_p = 0.138'' \]
\[ a_e = 2.95'' \]

\[ \text{MRR} = 18.5 \text{ in}^3/\text{min} \]

7792VXE-A080Z06R
XELT160512ER-D41 X500

US Patents 7,220,083 / 7,600,952
Advanced Cutter Designs

5230VS12 – Long Edge Milling tool

Material = ATI 6-4™
Cutter Dia. = 3.15”
Speed = 213’/min (sfm)
Feed = 0.0047” ipt
  = 6.10” ipm
Ap = 3.930”
Ae = 0.98”
MRR = 23.66 in³/min.
Heavy Hogging

Material: Ti-6AL-4V
Number of Tools: 1
Cycle Time: 3 minutes
Machine Used: T4
Notes:
- Ø3.15" (80mm), 5 flute cutter
- MRR: 30.6 in³/min (501 cc/min)
- ap: 2.05" (52mm)
- ae: 3.08" (78.4mm)
Advanced Cutter Designs

RSM Solid Carbide Endmills

Material = ATI 6-4™
Cutter Dia. = 1.00”
RPM = 1,556
Speed = 360'/min (sfm)
Feed = 0.0028” ipt
   = 43” ipm
Ap = 1.00”
Ae = 0.020”
<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rmax [μm]</td>
<td>3.50</td>
<td>3.10</td>
<td>3.08</td>
<td>3.32</td>
<td>2.77</td>
</tr>
<tr>
<td>Ra [μm]</td>
<td>0.618</td>
<td>0.542</td>
<td>0.527</td>
<td>0.595</td>
<td>0.529</td>
</tr>
<tr>
<td>Ra [μinch]</td>
<td>24.72</td>
<td>21.68</td>
<td>21.08</td>
<td>23.80</td>
<td>21.16</td>
</tr>
</tbody>
</table>
### Advanced Cutter Designs

#### XE Aerospace Solid Carbide Endmills

<table>
<thead>
<tr>
<th>Material</th>
<th>ATI 6-4™</th>
<th>ATI 5553</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutter Dia.</td>
<td>0.500”</td>
<td>0.500”</td>
</tr>
<tr>
<td>Speed</td>
<td>197/min (sfm)</td>
<td>95’/ min (sfm)</td>
</tr>
<tr>
<td>Feed</td>
<td>0.004” / tooth</td>
<td>0.002” / tooth</td>
</tr>
<tr>
<td></td>
<td>= 25.6” Linear Feed</td>
<td>= 5.95” Linear Feed</td>
</tr>
<tr>
<td>Ap</td>
<td>0.600” Depth</td>
<td>0.800” Depth</td>
</tr>
<tr>
<td>Ae</td>
<td>0.500” Radial Depth</td>
<td>0.200” Radial Depth</td>
</tr>
<tr>
<td>MRR</td>
<td>7.68 in³ / min</td>
<td>1.00 in³ / min</td>
</tr>
<tr>
<td>RPM</td>
<td>1600</td>
<td>726</td>
</tr>
</tbody>
</table>

**Video**
ATI 64™ X-Grade™ Technology

Rough Machining Improvements

- 1980s ~ 1in³/min
- 1990s ~ 2 in³/min
- 2000s ~ 6 in³/min
- 2010 ~ 30.6 in³/min

Finish Machining Improvements

- 1980s ~ 0.01in³/min
- 1990s ~ 0.10in³/min
- 2000s ~ 1.00in³/min
- 2010 ~ 5.50in³/min
SUMMARY

We have presented our machinability knowledge of Titanium Alloy materials.

Identified machine strategies and machining techniques to significantly reduce customers cost and improve productivity.

Reviewed our X-Grade™ advanced cutting tool grades and cutting tool solutions.

Questions?