High Performance Ti Machining

Boeing St. Louis Phantom Works

Advanced Manufacturing
Research & Development
OVERVIEW

• The Phantom Works Machining Development Group:
  – Who we are and what we do
  – Team capabilities

• Increase machining capacity through higher throughput:
  – High metal removal rates during roughing
  – High flute count carbide tools for high speed finishing
  – Feature based processes for ribs, webs, and corners

• Weight reduction on titanium parts:
  – Processes for minimum gage
  – Machining techniques for small corner radii

• Controlling machining cost and quality:
  – Cost models that help select cutting tools and machining approaches
  – Weight reduction without manufacturing cost increases
  – High flute count carbide tools for finishing
  – Reduce part deflection and chatter by using step cutting approaches

• Continuous process improvements:
  – Pushing the envelope on titanium finishing (Hollow Cutters, 45 flutes)
  – High feed milling for roughing
  – Glued on tabs for part clamping
  – Light duty machining of titanium part
  – High performance roughing of near net shape parts with light radial immersion
Group Members:
- Mechanical Engineers
- Design Engineers
- Manufacturing Engineers
- Electrical Engineers
- Metallurgical Engineers
- NC Programmers
- Lab Technicians

Group Tasks And Capabilities:
- Supplier Training Workshops
- Advanced Machining Development
- Prototyping
- Turnkey Machining Packages
- High Speed Machining Of Aluminum
- High Performance Titanium Machining
- Alternative Material Preforms
- Kinematic Modeling Of Machine Tools
- Machining Dynamics Testing
- Producability Support
- Cutting Tool Development
- Strategically Aligning Boeing suppliers and cutting tool vendors both foreign and domestic
Machining Workshops Held At Revelli, Moreggia, and Mechachrome

Edge Frame
Key Notes:

- Corner plunge and sweep method utilized to quickly and accurately produce .375 Corner Radii 3.5” Deep.
- Ribs and webs machined to .060” thick using high performance titanium machining techniques and tools.
- Part accuracy was held to + - .005”
ITALIAN MACHINING WORKSHOP HELD IN ST. LOUIS, MO

- TITANIUM HOT STRETCHED FORMED SIDE FRAME
- PART WAS MACHINED COMPLETE IN 3.5 HOURS WITH NO DISTORTION
- WORKSHOP CONSISTED OF BOTH CLASSROOM AND ON THE MACHINE TRAINING
- APPROPRIATE CUTTING TOOL VENDORS ALSO ATTENDED
High Speed Finishing With Carbide

- Tool Life and Tool Wear vs. Deflection
- Step Cutting For Finishing
- Step Cutting Rules
- Examples of Parts
- Tool Requirements
- Cost Models
- Carbide Compared To HSS For Finishing
- Key Notes for High Speed Finishing With Carbide
- Videos
Tool Life And Tool Wear Vs. Deflection

Test Specimens Machined At High Speeds And Feeds With Solid Carbide 10 Flute Tools
Test Specimens

.250" (6.4mm) Thick Rib

Machined Using One Axial Depth Of Cut Of 1 Inch (25.4mm)

.030" (.76mm) Thick Rib

Machined Using 8-1 Depth To Thickness Ratio
Thickness Deviation vs. Tool Wear

- **Thickness Deviation vs. Cutting Time**: The graph shows the relationship between thickness deviation and cutting time for two different thicknesses: 0.25 thick and 0.03 thick.

- **Axes**:
  - Y-axis: Thickness Deviation (ranging from 0 to 0.012)
  - X-axis: Cutting Time (ranging from 0 to 120 minutes)

- **Lines**:
  - Blue line represents 0.25 thick, showing a steady increase in thickness deviation as cutting time increases.
  - Pink line represents 0.03 thick, showing a more erratic increase with fluctuations.

The graph indicates that as cutting time increases, thickness deviation also increases, with the 0.25 thick material experiencing a more consistent and higher increase compared to the 0.03 thick material.
Thickness Deviation vs. Tool Wear

- Thickness Deviation:
  - 0.25 thick
  - 0.03 thick

- Tool Wear:
  - X-axis: 0 to 0.005
  - Y-axis: 0 to 0.012

The graph shows the relationship between thickness deviation and tool wear for two different thicknesses: 0.25 thick and 0.03 thick. As tool wear increases, the thickness deviation also increases.
Step Cutting for Finishing

Conventional Finishing:
- Float-cut to final dimension (.1 in^3/min)
- Slow feed rate 1-3 ipm (25.4-76.2 mm/min)
- 1 slow pass to finish
- Multiple float passes
- Poor thickness control
- Chattered surface finish
- Hand blending required

High Speed Finishing (2 in^3/min):
- High feed rate (46/ipm) (1168 mm/min)
- No float passes
- Good thickness control
- No Chatter
- No Hand blending
- 20-60 X’s faster
Depth (D) / Thickness (T)
Rough (R), Finish (F)
Maintain An 8/1 D/T Ratio

Example
1”DR / .130”TR = 7.7
25.4mm/3.30mm = 7.7

.5”DF / .060”TF = 8.33
12.7mm/1.52mm = 8.33
Step-Cutting Rules of Thumb for Titanium

Example

1"DR / .130"TR = 7.7
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Maintain An 8/1 D/T Ratio

Depth (D) / Thickness (T)
Rough (R), Finish (F)

Level 1
Level 2
Step-Cutting Rules of Thumb for Titanium

**Example**

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12.7mm/1.52mm = 8.33

Maintain an 8/1 D/T Ratio

**Diagram:**
- Depth (D) / Thickness (T)
- Rough (R), Finish (F)
- Thickness
- Finish
- Depth
- Rough

**Levels:**
- Level 1
- Level 2
Step-Cutting Rules of Thumb for Titanium

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Maintain An 8/1 D/T Ratio

Depth (D) / Thickness (T)
Rough (R), Finish (F)

Level 1
Level 2

Thickness
Finish
Depth
Rough

Maintain An 8/1 D/T Ratio
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Level 1
Level 2

Thickness
Finish
Depth Rough
Depth Finish
Thickness
Rough
Step-Cutting Rules of Thumb for Titanium

Maintain an 8/1 D/T Ratio

Example

1”DR / .130”TR = 7.7
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Rough (R), Finish (F)
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Step-Cutting Rules of Thumb for Titanium

Example

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Depth (D) / Thickness (T)
Rough (R), Finish (F)
Maintain An 8/1 D/T Ratio

Level 1

Level 2
Test Parts

.060” (1.52mm) Ribs And Web
5” (127mm) Deep Pocket,
.5” (12.7mm) Corner Radii.

18” (457.2mm) Long Ribs, 4” (101.6mm) Tall
Varying Thicknesses
.005” (.127mm) Tolerance Maintained
Carbide High Speed Finishing

.040” Thick
.060” Thick
.080” Thick
.100” Thick
48"(1219mm) X 110"(2794mm) X1"(25.4mm) X .050"(1.3mm) Titanium

Single Sided
• Total Machining Time was reduced by 77% By Using High Flute Count Carbide Tools (84 hours & 84 Tools To 19.5 hours and 15 Tools

• .030”(.76mm) Ribs And Webs
Hot Stretch Formed Side Frame

Phantom Works Machine Time = 3.5 hrs
Supplier Machine Time = 40hrs
Hot Stretch Formed Crown Frame

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Phantom Works Machine Time = 8hrs
Supplier Machine Time = 70hrs
High Speed Finishing With Carbide

Rib Finishing
- 400sfm (122M/min)
- 1” (25.4mm) ADOC
- .035” (.89mm) RDOC
- 46 ipm (1168mm/min)
- 90 minutes tool life

Web Finishing
- 300sfm (91M/min)
- .03” (.76mm) ADOC
- 34 ipm (864mm/min)
- 60 minutes tool life

Eccentric Relief Required

10 flute solid carbide
### Cost Formulas For Volume And Area

<table>
<thead>
<tr>
<th></th>
<th>Cost for Roughing</th>
<th>Cost for Finishing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(volume Removal)</td>
<td>(Area Removal)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Cost                         | \[
\frac{\text{Cost}}{\text{in}^3} = \left[ \frac{T_c}{T_L} + \frac{R_m}{60} + \left( \frac{R_L}{60} \cdot \frac{T}{T_L} \right) \right] \frac{MRR}{\text{in}^3/min}
\] | \[
\frac{\text{Cost}}{\text{in}^2} = \left[ \frac{T_c}{T_L} + \frac{R_m}{60} + \left( \frac{R_L}{60} \cdot \frac{T}{T_L} \right) \right] \frac{MRR}{\text{in}^2/min}
\] |
| Tool Change Time (min)       | \(T\)              | \(T_c\)             |
| Tool Cost ($)                | \(T_c\)            | \(T_c\)             |
| Tool Life (min)              | \(T_L\)            | \(T_L\)             |
| Machine hourly rate ($)      | \(R_m\)            | \(R_m\)             |
| Labor hourly rate ($)        | \(R_L\)            | \(R_L\)             |
| Metal Removal Rate (in^3/min)| \(MRR\)            | \(MRR\)             |

\(T\) ~ Tool Change Time (min)
\(T_c\) ~ Tool Cost ($)
\(T_L\) ~ Tool Life (min)
\(R_m\) ~ Machine hourly rate ($/hr)
\(R_L\) ~ Labor hourly rate ($/hr)
\(MRR\) ~ Metal Removal Rate (in^3/min)
**Example**

**Finishing Ribs**

<table>
<thead>
<tr>
<th></th>
<th>Finishing Ribs</th>
<th>1.25&quot; dia 6 flute HSS</th>
<th>1&quot; dia 4-flute carbide</th>
<th>1&quot; dia 10-flute carbide</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OVERHEAD INPUTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine Hourly Rate ($/hr)</td>
<td>$100.00</td>
<td>$100.00</td>
<td>$100.00</td>
<td></td>
</tr>
<tr>
<td>Tool change time (min)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Tool Change hourly Rate ($/hr)</td>
<td>$50.00</td>
<td>$50.00</td>
<td>$50.00</td>
<td></td>
</tr>
<tr>
<td><strong>PROCESS INPUTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool Cost ($)</td>
<td>$100.00</td>
<td>$200.00</td>
<td>$270.00</td>
<td></td>
</tr>
<tr>
<td>ADOC (in)</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Feedrate (in/min)</td>
<td>3</td>
<td>6</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>MRR (in^2/min)</td>
<td>6</td>
<td>6</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>Tool Life (min)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td><strong>OUTPUT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Area Machined per tool</td>
<td>540</td>
<td>540</td>
<td>4,140</td>
<td></td>
</tr>
<tr>
<td><strong>OUTPUT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost/in^2</td>
<td>$0.49</td>
<td>$0.67</td>
<td>$0.10</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

1. A cheap tool can cost you more than you think.
2. In this example, cost per square inch is nearly 5 times less using a tool that costs 2.5 times more.
3. Nearly 8 times more area machined in 90 minutes.
Example

Finishing webs

<table>
<thead>
<tr>
<th></th>
<th>1.25&quot; dia 6 flute HSS</th>
<th>1&quot; dia 4-flute carbide</th>
<th>1&quot; dia 10-flute carbide</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OVERHEAD INPUTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine Hourly Rate ($/hr)</td>
<td>$100.00</td>
<td>$100.00</td>
<td>$100.00</td>
</tr>
<tr>
<td>Tool change time (min)</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Tool Change hourly Rate ($/hr)</td>
<td>$50.00</td>
<td>$50.00</td>
<td>$50.00</td>
</tr>
<tr>
<td><strong>PROCESS INPUTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool Cost ($)</td>
<td>$100.00</td>
<td>$150.00</td>
<td>$270.00</td>
</tr>
<tr>
<td>RDOC (in)</td>
<td>1</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Feedrate (in/min)</td>
<td>3.7</td>
<td>6.1</td>
<td>34</td>
</tr>
<tr>
<td>MRR (in^2/min)</td>
<td>3.7</td>
<td>4.575</td>
<td>25.5</td>
</tr>
<tr>
<td>Tool Life (min)</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td><strong>OUTPUT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Area Machined Per tool</td>
<td>222</td>
<td>275</td>
<td>1,530</td>
</tr>
<tr>
<td>Cost/in^2</td>
<td>$0.96</td>
<td>$0.96</td>
<td>$0.25</td>
</tr>
</tbody>
</table>

Notes:

1. Positive rake on end geometry and no gash on corner radius

2. Full tool cost was figured into this example, however, since the same tool for finishing ribs can be used for finishing webs, the tool cost was already accounted for. Even so, you are 4 times cheaper.
Carbide Compared To HSS For Finishing

**Cost Per Area of Material Machined (Finishing Ribs)**

- HSS: $0.50
- 4-flute carbide: $0.40
- 10-flute carbide: $0.20

**Total Surface Area Per Tool (Finishing Ribs)**

- HSS: 1,500 in²
- 4-flute carbide: 3,000 in²
- 10-flute carbide: 4,500 in²

*10 Flute Carbide Compared To HSS*

- 16x more productive finishing ribs
- Cost per square inch material removed is 5x less finishing ribs
- 1 tool removes same amount of material as 8 HSS tools
- Faster cycle times reduce the need for additional machine capacity
1” (25.4mm) Dia. Carbide
10 Flutes
400sfm (122M/min)
.003 ipt (.08mm)
2760 in^2 (70104mm^2)
2 inch Diameter Carbide Finishing

- Economical solution for 2 inch dia (50.8mm) carbide
- Performs well in extension heat shrink holders
High Speed Finishing With Carbide

• **Corner Removal**
  - Treat corners as a separate operation.
  - Corners should be removed before high speed finishing.
  - Never touch a corner, drive a slightly larger radius.

• **Vibration/Deflection**
  - Tools must be ground with eccentric relief.
  - Limit deflection and vibration issues using ratios.
  - Use shorter flute lengths to keep the tool more rigid and this will also keep the flutes from touching a thin surface that has already been finished.

• **Cutter Life**
  - Know your process and cutter life expectancy.
  - Maintain appropriate axial and radial immersion.
  - Account for deflection during roughing by using a high speed sizing pass to remove any deflection.
  - Quality carbide with a sharp grind is important.

• **Rib Finishing**
  - 400sfm(122M/min), .003(.08mm) ipt, 1”(25.4mm)adoc, .035(.89mm)rdoc

• **Process Monitoring**
  - Chip removal during finishing operations is important.
• Plunge and sweep techniques
• Deflection tests
• Tool Geometries
Surface Finish-HSS & Carbide Side Milling, And Carbide Plunging

<table>
<thead>
<tr>
<th>Tools</th>
<th>Surface Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSS SIDE MILLING</td>
<td>150</td>
</tr>
<tr>
<td>CARBIDE SIDE MILLING</td>
<td>50</td>
</tr>
<tr>
<td>CARBIDE PLUNGING</td>
<td>0</td>
</tr>
</tbody>
</table>

5.5/1 L/D
Test Data

DEFLECTION DURING CORNERING

DEFLECTION (IN)

0.05
0.04
0.03
0.02
0.01
0

HSS SIDE MILLING
CARBIDE SIDE MILLING
CARBIDE PLUNGE AND SWEEP

5.5/1 L/D

TOOLS AND TECHNIQUES
Small Diameter Corners

- Extending Small Diameter Corners into Deep Pockets

Eric Stern, Randy Hancock
Boeing - St. Louis Advanced Manufacturing
• **Stabilizing Land**

• **Irregular flute Spacing**

- .004" land
- No land

Plunge Tool

Sweep Tool
Cornering Operation

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Plunge Corner

Sweep to clean Cusps
## Cornering Cycle Times

**Boeing Technology | Phantom Works**  
Advanced Manufacturing Research & Development

**Cycle Times for Corner Reduction**

<table>
<thead>
<tr>
<th>Corner Diameter (in)</th>
<th>Corner Height (in)</th>
<th>Side Milling Time (min)</th>
<th>Plunging Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>5.500</td>
<td>4.700</td>
<td>1.800</td>
</tr>
<tr>
<td>0.750</td>
<td>4.125</td>
<td>10.400</td>
<td>4.300</td>
</tr>
<tr>
<td>0.625</td>
<td>3.438</td>
<td>19.250</td>
<td>5.600</td>
</tr>
<tr>
<td>0.500</td>
<td>2.750</td>
<td>14.700</td>
<td>4.150</td>
</tr>
<tr>
<td>0.375</td>
<td>2.063</td>
<td>18.800</td>
<td>4.700</td>
</tr>
</tbody>
</table>

Plunging is 2-4x faster
Roughing

- Crest Kut Milling
- High Feed Milling
- High Feed Plunging
- Center Cutting Plungers
Crest-Kut Roughing

1.25” (31.75mm) & 2” (51mm) Diameter

60SFM (18M/min)

1.25” (31.75mm) Axial Depth Of Cut in a full slot

.004” (.1mm) Feed Per Tooth

60-90 minutes life
Roughing Strategies

Recommend drilling starter holes in pockets to eliminate time consuming ramping as well as premature cutting tool failure.
High Feed Milling

- Highly Productive Roughing Tool
- Performs Well With Up To 8 Inches Of Reach
- Insert Geometry Puts Forces In The Z Direction
- Capable Of End Milling And Z Axis Plunging
- 150 Surface Feet, .020”-.030” Chip Load
- 33-36 IPM
- 4+ Cubic Inches Per Min
Mouse Hole Features Machined With a .787 Diameter Button Style HFM With a 4.75 Inch Reach
• Match your surface feet to the radial depth of cut being made
  
  - .3 radial immersion, 200sfm, .004ipt, 764rpm, 15ipm
  - 4.5 Cubic Inches Per minute
  - No cutting in corners
  - Cutting tool lasts for 90 min

5 Flute Solid Carbide
Plunge Roughing

- 2" (50.8mm) diameter center cutting plunger
- Drill 2" dia starter hole
- Plunge Using 1.8" Step overs (this will leave stars)
- To remove stars, center plunger over star and double feed and speed
How Long Should A Tool Run?

Roughing

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OVERHEAD INPUTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine Hourly Rate ($/hr)</td>
<td>$100.00</td>
<td>$100.00</td>
<td>$100.00</td>
</tr>
<tr>
<td>Tool change time (min)</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Tool Change hourly Rate ($/hr)</td>
<td>$50.00</td>
<td>$50.00</td>
<td>$50.00</td>
</tr>
<tr>
<td><strong>PROCESS INPUTS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool Cost ($)</td>
<td>$200.00</td>
<td>$200.00</td>
<td>$200.00</td>
</tr>
<tr>
<td>MRR(in^3/min)</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Tool Life (min)</td>
<td>300</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td><strong>OUTPUT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost/in^3</td>
<td>$2.38</td>
<td>$1.74</td>
<td>$3.17</td>
</tr>
</tbody>
</table>

**NOTES:**

1. Long cutter life might be a waste of machine time
2. Every machine is different, ex. $1,000,000 machine vs. $500,000 machine, will have different hourly rates
3. In this example, decreasing cutter life by 5 times will decrease cost per cube by 57%
• Solid carbide high feed mills
• Glued on tabs for clamping of titanium parts
• Titanium machining on light duty machines
• 20 Flute 1 inch diameter cutters
• 92 Inch per minute feed rate
• 2 inch diameter carbide hollow mills
• 103 inch per minute feed rate
Solid Carbide High Feed Milling

- High performance web finishing capability
- Capable of a .030 inch (.76mm) chip load
- Potential to finish webs at 100 ipm (2540mm/min)
- Web finishing with long reaches
Glued On Tabs

- Excellent Holding Power
- Used to Manufacture Hot Stretch Formed Side Frame
• Preliminary tests on a CAT 40 machining center produced very good results providing the capability to rough titanium in excess of 4.5 cubic inches per minute using high feed mills

• High performance finishing works very well also using 10 flute 1 inch diameter solid carbide cutting tools

• Machining of a section of an Edge Frame is underway
Advancements In Carbide Finishing

20 Flute Finishing

- 400sfm (122M/min), .003ipt (.08mm), 1528rpm, 92ipm (2337mm/min)
- 1" (25.4mm) adoc, .03" (.76mm) rdoc
- Major finishing time reduction potential
2 Inch Diameter Carbide Hollow Mills

• Made From Molded Carbide
• 400sfm (122M/min), .003ipt (.08mm),
• .035" (.89 mm) rdoc, 1" (25.4mm) adoc
• Productive tool for finishing parts up to 8" deep
• Plug style tool fits into long reach heat shrink holder
• High performance finishing solution in 2" diameter
• Cost effective solution for 2 inch diameter carbide
QUESTIONS AND DISCUSSION