Thermally Assisted Machining of Titanium

The Performance of Titanium at the Speed of Aluminum

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Motivation

- The Buy to Fly ratio of Titanium is poor, typically 11:1
- The Buy to Fly ratio of Aluminum is worse
  - Aluminum machines an order of magnitude faster
- TAM intends to bring the cost of machining titanium closer to aluminum

**Motivation**

<table>
<thead>
<tr>
<th>Sponge</th>
<th>Plate</th>
<th>Machining</th>
</tr>
</thead>
<tbody>
<tr>
<td>$50</td>
<td>$40</td>
<td>$30</td>
</tr>
</tbody>
</table>

Part (plate) Cost ($/lb) As a Function of Buy Weight

<table>
<thead>
<tr>
<th>Sponge</th>
<th>Forging</th>
<th>Machining</th>
</tr>
</thead>
<tbody>
<tr>
<td>$60</td>
<td>$50</td>
<td>$40</td>
</tr>
</tbody>
</table>

Part (forging) Cost ($/lb) As a Function of Buy Weight

- Machining of Titanium
  - 40% of the cost of part made from plate
  - 60% of the cost of a part made from a forging
Titanium 101

• Ti-6Al-4V is generally classified as “difficult to machine” because of its thermo-mechanical properties
• The primary challenge is overcoming short tool life
  – Prevents high cutting speeds
• Cutting speeds are an order of magnitude slower than aluminum
• Typical “Buy to Fly” of Titanium is poor
  – Approximately 90% of material purchased is removed during machining
• Machining of Titanium can be 40 to 50% of the cost of a titanium part for an air vehicle
• Goal to reduce cost by improving tool life and maximize Material Removal Rate (MRR)
Poor Machinability

- Titanium has low thermal conductivity
  - Impedes heat-transfer out of the cutting zone
  - Creates high cutting zone temperatures
  - Titanium shows high chemical affinity towards the Cobalt binders that are found in most cutting tool materials
  - The interface between Titanium chips and cutting tools is usually quite small, which results in high cutting-zone stresses
  - There is a strong tendency for Titanium chips to pressure-weld to cutting tools.
Why Lasers?

- Laser
- High Travel Speed + High Removal Rate + Increased Tool Life = Machining Cost Reduction

Reduces the Roughing Time by 80%
Reduces the Cutting Force by 40%
Extends the Tool Life 3X*

* Tool optimization is under way
Why it Works

- The strength of all metals decreases with temperature
- Reduces the force required to remove material
- Reduction in force allows
  - Greater tool life
  - Faster speeds
  - Smaller investment
Milled Sample with Laser Beam

- Laser beam
- Cut depth
- HAZ
- Microstructure examined
Cross Section of Laser Heated Area

4 kW @ 1.2 m/min
5 mm above focal plane

Low magnification

High magnification
Hardness Vs Depth

Hardness, HV0.1

Depth, mm

Surface
Cross Section of Milled Sample – No Laser

- Depth of cut: 1.5 mm
- Feed speed: 1 m/min
- Spindle: 3571 rpm
- Tool diameter: 25 mm
- Tool engage: 70%

Low magnification

High magnification
Cross Section of Milled Sample –
with Laser

- Depth of cut: 1.5 mm
- Feed speed: 1 m/min
- Spindle: 3571 rpm
- Tool diameter: 25 mm
- Tool engage: 70%

Laser: 1.5 kW
Tool Wear

Conventional

Volume Removed = 3.6 cm³
Cutting Speed = 200 m/min

TAM

Volume Removed = 8.4 cm³
Cutting Speed = 200 m/min

- Optimizing tools were not an objective of the pilot program
- Tools chosen for the pilot were COTS
- Trend is favorable for harder tools, similar to what is on for Al
Quantifiable Benefits #1

The target is to reduce the cycle time in roughing machining operations.

TAM achieved $6 \times \text{increase in MRR}$:
- $5 \times$ increase in cutting & spindle speed
- $6$ times increase in machining feed rate
- $80\%$ cycle time reduction for roughing operations
- $2.5 \times$ tool life increase compared to standard titanium machining using cutting inserts of the same type

The more raw material that needs to be removed - The greater the time savings
Quantifiable Benefits #2

85% Reduction in Cycle Time

<table>
<thead>
<tr>
<th>Example Component</th>
<th>Unit</th>
<th>Conventional</th>
<th>TAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of raw material</td>
<td>cm³ / (in³)</td>
<td>10,407 (635)</td>
<td></td>
</tr>
<tr>
<td>Volume of finish component</td>
<td>cm³ / (in³)</td>
<td>541 (33)</td>
<td></td>
</tr>
<tr>
<td>Material to remove</td>
<td>cm³ / (in³)</td>
<td>9,866 (602)</td>
<td></td>
</tr>
</tbody>
</table>

Roughing cycle time

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td></td>
<td>822</td>
</tr>
<tr>
<td>Roughing cycle time</td>
<td></td>
<td>130</td>
</tr>
</tbody>
</table>
Quantifiable Benefits In General

Machining time comparison of conventional machining and LMcut machining

- Minutes cycle time for conventional machining
- Minutes cycle time for LMCut machining

<table>
<thead>
<tr>
<th>Volume (cm³)</th>
<th>100 cm³</th>
<th>250 cm³</th>
<th>400 cm³</th>
<th>550 cm³</th>
<th>700 cm³</th>
<th>850 cm³</th>
<th>1000 cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>21</td>
<td>33</td>
<td>46</td>
<td>58</td>
<td>71</td>
<td>83</td>
</tr>
<tr>
<td>(in³)</td>
<td>6.1</td>
<td>15.2</td>
<td>24.4</td>
<td>33.5</td>
<td>42</td>
<td>51.8</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>9</td>
<td>11</td>
<td>13</td>
</tr>
</tbody>
</table>
Schematic Illustration of CNC Cell

1. Laser head carrier
2. Ti bar to be milled
3. Cutting tool
4. Laser head
Laser Concept
Progress Has Been Fast

- By 2011 TAM was shown to be capable of increasing MRR five times for titanium plate materials
- The laser was building too much heat in the workpiece for thicker sections
- We had a solution for equipment which utilized a rotating table (i.e. the laser was in a fixed position relative to the spindle)
- In 2012 we began to scale the solution to include a dynamic position of the laser relative to the spindle

- A solution was configured for a larger 5 axis system without the necessity of a rotating table
- A higher power diode laser was acquired which enabled closed loop control for maintaining the temperature in the workpiece
- In August, the laser system was shipped to Ferra Engineering for factory trials
- By 2013 we will be in a position to license the IP to an equipment manufacturer
Principal Advantages

• By heating the material, the force required is less
• Reduces wear on the tool
• Utilize “smaller” machine (i.e. for aluminum)
• Can be adapted to existing machines
• No re-qualification required
• No liquid coolant required
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