Ultrasonic Assisted Machining

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Agenda

• Technical Overview
• Vision for Industry
• Drilling Data
• Demonstrations
• Additional Metalworking Processes
• Current State
• Conclusion
Technical Overview

- Within broad field of High Power Ultrasound
- HPU … application of intense, high-frequency acoustic energy to change materials, processes.

Ultrasonic energy causes change in Material or Process

Power supply

Ultrasonic Transducer

Transmission

Material/Process
What is Ultrasonic Machining?

Ultrasonic Vibration + Conventional Machining (Drilling, Reaming, Turning, Milling,..)

Improved Performance

• Higher productivity (faster feed)
• Better tool life
• Better surface finish
• Increased dimensional accuracy

Note: UM is not ........

Ultrasonic-based Slurry Drilling Process
Ultrasonic Assisted Drilling

**Acoustech Machining**
- Application of intense acoustical vibrations to conventional cutting tools
  - 20kHz
  - Up to 5kW power
  - Longitudinal vibrations

**Benefits**
- Lower operating forces
- Increased feed rates
- Improved chip extraction
- Lower tool temperatures
- Improved surface finish
- Reduced burr formation
- Machining of hard materials
Extensive Survey of Prior Work

Cincinnati Milacron US turning, 1960’s

Grumman US Drilling, 1970’s

OSU, US Cutting 1970’s

Sonobond Drilling, Turning 1970’s
Vision for development ...

- Development of machining center compatible US tools* seen as critical to expanding US machining technology.
Ultrasonic Assisted Drilling Module

◆ **Critical Design Requirements**
  – Minimal addition to tool stick-out
  – Robustness for varying load conditions
  – Ease of installation
  – Through spindle coolant
  – Easily repaired
  – Maximum tool run-out of 0.0001-in
  – Leak proof
  – 20-kHz nominal frequency

◆ **Improvements**
  – IP-68 rated
  – Static resonance under 30-Watts
  – Run-out held to 0.00008-in
  – Under 3.5lbs
Critical measurement is longitudinal displacement at tool holder interface.

Laser vibrometer data proves that all vibrations are isolated out of the tool holder, therefore, spindle.
Titanium 6Al-4V Drilling

Drilling Data

<table>
<thead>
<tr>
<th>Trial</th>
<th>Amplitude</th>
<th>RPM</th>
<th>IPM</th>
<th>IPR</th>
<th>Force (N)</th>
<th>Torque (Nm)</th>
<th>Ra (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0%</td>
<td>1500</td>
<td>10</td>
<td>.0067</td>
<td>803.2</td>
<td>13.15</td>
<td>2.09</td>
</tr>
<tr>
<td>2</td>
<td>70%</td>
<td>1500</td>
<td>10</td>
<td>.0067</td>
<td>482.5</td>
<td>13.68</td>
<td>1.05</td>
</tr>
<tr>
<td>3</td>
<td>70%</td>
<td>1500</td>
<td>16</td>
<td>.011</td>
<td>650</td>
<td>18.86</td>
<td>1.66</td>
</tr>
</tbody>
</table>

100% Amplitude + Baseline test parameters → 40% Force Drop
100% Amplitude + 2x Feed → Same force as baseline with US
The same or even better surface quality

Measuring surface roughness
Measuring hole diameter

<table>
<thead>
<tr>
<th>Location 1</th>
<th>Location 2</th>
<th>Total Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>x</td>
</tr>
<tr>
<td>12.54582</td>
<td>12.51966</td>
<td>12.56284</td>
</tr>
<tr>
<td>12.54252</td>
<td>12.51966</td>
<td>12.56284</td>
</tr>
</tbody>
</table>

*All measurements shown in mm
Material Improvements

26 - A

100 μm
## Summary of data

### Summery of drilling data for Al 6061, Stainless steel, Alloy steel 4340 and Ti

<table>
<thead>
<tr>
<th>Material</th>
<th>Trial</th>
<th>Amplitude</th>
<th>RPM</th>
<th>IPM</th>
<th>Force (N)</th>
<th>Torque (Nm)</th>
<th>Ra (µm)</th>
<th>Dia. Average (mm)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Al 6061</strong></td>
<td>1</td>
<td>0%</td>
<td>1392</td>
<td>29</td>
<td>712.3</td>
<td>10.34</td>
<td>1.5007</td>
<td>12.564</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>100%</td>
<td>1392</td>
<td>29</td>
<td>197.6</td>
<td>6.607</td>
<td>1.2701</td>
<td>12.576</td>
<td>72% Force drop</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>100%</td>
<td>1392</td>
<td>69</td>
<td>671.4</td>
<td>17.6</td>
<td>1.4088</td>
<td>12.588</td>
<td>3 x Baseline Feed</td>
</tr>
<tr>
<td><strong>Stainless Steel</strong></td>
<td>1</td>
<td>0%</td>
<td>910</td>
<td>7.28</td>
<td>1065</td>
<td>17.25</td>
<td>2.6488</td>
<td>16.059</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>72%</td>
<td>910</td>
<td>7.28</td>
<td>708.9</td>
<td>17.04</td>
<td>2.4272</td>
<td>16.052</td>
<td>34% Force drop</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>72%</td>
<td>910</td>
<td>14.56</td>
<td>934</td>
<td>25.85</td>
<td>2.3164</td>
<td>16.045</td>
<td>2 x Feed + 12% Force drop</td>
</tr>
<tr>
<td><strong>Alloy steel 4340</strong></td>
<td>1</td>
<td>0%</td>
<td>2161</td>
<td>15</td>
<td>848.9</td>
<td>9.708</td>
<td>0.44145</td>
<td>12.539</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>100%</td>
<td>2161</td>
<td>15</td>
<td>417.8</td>
<td>7.165</td>
<td>0.16445</td>
<td>12.534</td>
<td>51% Force drop + 62% Ra improvement</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>100%</td>
<td>2161</td>
<td>55</td>
<td>866.9</td>
<td>23.68</td>
<td>1.2897</td>
<td>12.534</td>
<td>3.7 x Baseline Feed</td>
</tr>
<tr>
<td><strong>Titanium</strong></td>
<td>1</td>
<td>0%</td>
<td>1500</td>
<td>10</td>
<td>803.2</td>
<td>13.15</td>
<td>1.0553</td>
<td>12.548</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>70%</td>
<td>1500</td>
<td>10</td>
<td>482.5</td>
<td>13.68</td>
<td>2.0943</td>
<td>12.536</td>
<td>40% Force drop</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>70%</td>
<td>1500</td>
<td>15</td>
<td>562.3</td>
<td>18.86</td>
<td>1.6676</td>
<td>12.539</td>
<td>1.5 x Feed + 30% Force drop</td>
</tr>
</tbody>
</table>
Micro-drilling of Titanium

- Drilling of Ti nozzles
  - Significant tool breakage
  - Slow drilling rates
  - Kyocera carbide (Ø 0.45mm)

- Objective
  - Increase productivity
  - Achieve repeatable tool life

<table>
<thead>
<tr>
<th>Trial</th>
<th>Amplitude</th>
<th>RPM</th>
<th>IPM</th>
<th>IPR</th>
<th>Peck Depth (in)</th>
<th>DoC (in)</th>
<th>Cycle Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0%</td>
<td>3538</td>
<td>1.37</td>
<td>.00039</td>
<td>.005</td>
<td>.02</td>
<td>3:55</td>
</tr>
<tr>
<td>2</td>
<td>30%</td>
<td>4500</td>
<td>2.25</td>
<td>.0005</td>
<td>.027</td>
<td>.2</td>
<td>0:52</td>
</tr>
</tbody>
</table>

Figure 1: Fixture and tooling setup.
Titanium Milling

- Peripheral Plate Milling
  - 1700-RPM, 0.02-DoC, 0.5-in. cut, 7-IPM
  - Flood Coolant

Scale reference: Plate thickness = 0.75”, DOC = 0.2”

- No Ultrasonics
- $R_a = 198$
- Climb milling
- Taper cut (DoC = 0.018-0.012)

- Ultrasonics (7µm)
- $R_a = 50$
- Climb milling
- No taper (DoC = 0.019)
- 38% load reduction along feed axis

Guhring, Solid Carbide, ½-in diameter, 5-in OAL
Titanium Milling cont.

- Peripheral T-Plate Milling
  - 1700-RPM, 0.02-DoC, 0.5-in cut, 7-IPM
  - 0.25-in. thick rib, 5-in. tall
  - Flood Coolant

No Ultrasonics
$R_a = 130$
Climb milling
Taper cut (DoC = .017-.011)

Ultrasonics (7µm)
$R_a = 40$ (above cut)
Climb milling
No taper (DoC = 0.18)
14% load reduction along feed axis

Guhring, Solid Carbide, ½-in diameter, 5-in OAL
Drilling Hardened Materials
Material Comparisons

SEE THE DIFFERENCE
Ultrasonic Assisted Reaming

Application Details:
- 8-mm TSC Carbide Reamer
- Powder Metallurgy – HRc72
- Pressed to NNS – ream to size
### Baseline Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force (N)</td>
<td>169.0</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>2.141</td>
</tr>
<tr>
<td>Surface Finish (Ra µm)</td>
<td>0.2648</td>
</tr>
<tr>
<td>Bore Size (mm)</td>
<td>8.014</td>
</tr>
</tbody>
</table>

At baseline settings (1406RPM – 22.5IPM), an axial feed force of 169N was achieved.

### Ultrasonic Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force (N)</td>
<td>108.0</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>0.9525</td>
</tr>
<tr>
<td>Surface Finish (Ra µm)</td>
<td>0.6153</td>
</tr>
<tr>
<td>Bore Size (mm)</td>
<td>8.024</td>
</tr>
</tbody>
</table>

At the same baseline settings as above, this time adding ultrasonic energy, the feed force was dropped by **36%**.

### Ultrasonics Applied at 150% of baseline feed rate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force (N)</td>
<td>123.9</td>
</tr>
<tr>
<td>Torque (Nm)</td>
<td>1.816</td>
</tr>
<tr>
<td>Surface Finish (Ra µm)</td>
<td>0.2839</td>
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<tr>
<td>Bore Size (mm)</td>
<td>8.031</td>
</tr>
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</table>

Utilizing the benefits of the ultrasonic energy, the feed rate was increased by **150%**, from 22.5IPM to 34.5IPM, and the axial force was still **27%** less than the baseline force generated.
Ultrasonic Assisted Tapping

Application Details
- Applying ultrasonics to 4340-HRc48
- Extend tool life and increase quality of threads

Hub Design

ER-32 collet with Guhring solid carbide Tap.
Tapping Trials Summary

- Objective is to reduce torque applied to tap generally causing breakage
- Difficult materials to tap (Stainless Steel, Inconel, Titanium, hardened alloys) rapidly wear cutting faces producing interference in thread clearance or undercut thread

<table>
<thead>
<tr>
<th>Ultrasonic Amplitude</th>
<th>Power Supply</th>
<th>RPM</th>
<th>IPM</th>
<th>IPR</th>
<th>Axial Force (N)</th>
<th>Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>L.D.</td>
<td>809</td>
<td>47.8119</td>
<td>0.059</td>
<td>172</td>
<td>6.234</td>
</tr>
<tr>
<td>20%</td>
<td>L.D.</td>
<td>809</td>
<td>47.8119</td>
<td>0.059</td>
<td>168</td>
<td>5.495</td>
</tr>
<tr>
<td>30%</td>
<td>L.D.</td>
<td>809</td>
<td>47.8119</td>
<td>0.059</td>
<td>162</td>
<td>5.975</td>
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<tr>
<td>...</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>100%</td>
<td>L.D.</td>
<td>809</td>
<td>47.8119</td>
<td>0.059</td>
<td>147</td>
<td>5.511</td>
</tr>
<tr>
<td>20%</td>
<td>Std.</td>
<td>809</td>
<td>47.8119</td>
<td>0.059</td>
<td>145</td>
<td>5.485</td>
</tr>
<tr>
<td>30%</td>
<td>Std.</td>
<td>809</td>
<td>47.8119</td>
<td>0.059</td>
<td>138</td>
<td>6.272</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>80%</td>
<td>Std.</td>
<td>809</td>
<td>47.8119</td>
<td>0.059</td>
<td>93</td>
<td>4.601</td>
</tr>
<tr>
<td>90%</td>
<td>Std.</td>
<td>809</td>
<td>47.8119</td>
<td>0.059</td>
<td>52</td>
<td>3.713</td>
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<tr>
<td>100%</td>
<td>Std.</td>
<td>809</td>
<td>47.8119</td>
<td>0.059</td>
<td>Overloaded</td>
<td></td>
</tr>
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</table>

Summary of Tapping Study performed on 4340 Alloy steel
Current State
Acoustech Power Consumption Assessment

- **Total Power Assessment**
  - Conventional
    - 1,350N force (white)
    - 6.5Nm torque (blue)
  - Acoustech
    - 600N force (white)
    - 4Nm torque (blue)

- **Monthly Power Consumption**
  - Conventional Machine consumes 1,872-kWh
  - Acoustech Machining consumes 1,288-kWh

- **Production Environment Utilizing 20 Machining Centers Monthly**
  - Conventional Machining consumes 37,440-kWh
  - Acoustech Machining consumes 25,760-kWh

<table>
<thead>
<tr>
<th>Machine Condition</th>
<th>Power Consumption (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Idle</td>
<td>0.2699</td>
</tr>
<tr>
<td>Machine Idle with Ultrasonics On</td>
<td>0.3412</td>
</tr>
<tr>
<td>Spindle Running – 2500RPM</td>
<td>1.6667</td>
</tr>
<tr>
<td>Cutting Trial with Coolant, No US</td>
<td>4.0103</td>
</tr>
<tr>
<td>Cutting Trial with Coolant and US</td>
<td>2.7560</td>
</tr>
</tbody>
</table>

Acoustech Drilling Trial on 6061-Al
Conclusion

- EWI has continued the development of UAD for new or existing machining centers
- Technology has advanced our ability to control heat generation
- Ultrasonic system successfully integrated with very stringent metalworking systems and practices

- Acoustech Systems
  - Spin-out company taking product to market
  - Provides sales, service, installation, training
Since the early 1980s, EWI has helped manufacturers in the energy, defense, transportation, heavy manufacturing, and consumer goods industries improve their productivity, time to market, and profitability through innovative materials joining and allied technologies. Today, we operate a variety of centers and consortia to advance U.S. manufacturing through public private cooperation.