Understanding Process and Material Improvements through Ultrasonic Assisted Machining

April 20th, 2015

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Overview

• At UIA 2010
• Drill Module
• Drilling Data
• Modeling Trust Force
• Future Developments
• Summary
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
At UIA 2010

Previous work reviewed

Titanium Trials with Ultrasonics

Tool wear studies
Vision for development ...

- Development of machining center compatible US tools* seen as critical to expanding US machining technology

*US tools: USA-made tools that are compatible with US-made machining centers.
US Module Development

Compression Collet – FEA Results

Note: Transducer/collet tuned low — brought to 20kHz with drill

15,694 Hz
US Module Development

Compression Collet with drill

2\textsuperscript{nd} Mode @ 20149 Hz
3.16" drill ‘stick-out’

Shrink fit collet with 18mm drill shank

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**2.5kW Module Tool Length Study**

- **Short Tool**: 21.87 Hz
- **Target Length**: 19.63 Hz
- **Mid-length Tool**: 19.33 Hz
- **Standard Length Tool**: 18.75 Hz

Note:
1. Shank Insert Depth = 1.25-inch
2. 14mm shank test tool

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Imped Frequency @ PS

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Generator Operating Limits

Tool Stick-out Available Length

29.53 kHz No Tool Inserted

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Long Tool

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We Manufacture Innovation
Transducer Power Testing

Drive Voltage
Drive Current
Input Power
Displacement 1
FM Temperature 1
BM Temperature 1

Driven Voltage
Driven Current
Output Power
Displacement 2
FM Temperature 2
BM Temperature 2
2.5kW and 5-kW Acoustech Modules

- 20-kHz, 2.5kW @ 35µm
- 20-kHz, 4.5kW @ 28µm
- 2.5kW @ 4lbs, 2.75”OD x 6” L
- 4.5kW @ 7-lbs, 3.75” OD x 7” L
- Both use CAT, HSK or BT tool holders.
- Both can have Hydraulic, Compression or Shrink-fit collets and use conventional tools (drills, mill, taps, reamers)
Critical Requirements of Design
- Minimal addition to tool stick-out
- Robustness for varying load conditions
- Ease of installation
- Through spindle coolant within transducer
- 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
Acoustech Machining Module

- System Demonstrations
Drilling Data

Drilling tests on:

- Aluminum 6061 → Rep. of soft material
- Stainless Steel 316
- Alloy Steel 4340
- Titanium → Rep. of harder material

Results:

- Force
- Torque
- Tool life
- Surface roughness
- Dimensional error
- Microstructure of the hole

Three types of Collet:

- Shrink Fit Module
- Compression Collet Module
- Hydraulic Module
## Aluminum Drilling

### Drilling Data for Aluminum 6061

<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>1392</td>
<td>29</td>
<td>0.0208</td>
<td>712.3</td>
<td>10.34</td>
<td>1.5007</td>
</tr>
<tr>
<td>2</td>
<td>100%</td>
<td>1392</td>
<td>29</td>
<td>0.0208</td>
<td>197.6</td>
<td>6.607</td>
<td>1.2701</td>
</tr>
<tr>
<td>3</td>
<td>100%</td>
<td>1392</td>
<td>69</td>
<td>0.0496</td>
<td>671.4</td>
<td>17.6</td>
<td>1.4088</td>
</tr>
</tbody>
</table>

100% Amplitude + Baseline test parameters → 72% Force Drop

100% Amplitude + 3x Feed → Same force as baseline with US

The same or even better surface quality

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**Baseline testing**

No U.S. - 1392RPM – 29IPM

712.3N, 10.34Nm, 1.5007Ra(µm)

200x Magnification

**Baseline Parameters with U.S.**

U.S. 100% - 1392RPM – 29IPM

197.6N, 6.607Nm, 1.2701Ra(µm)

200x Magnification

**Advanced Parameters with U.S.**

U.S. 100% - 1392RPM – 69IPM

671.4N, 17.6Nm, 1.4088Ra(µm)

200x Magnification

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**No Effect on dimensional accuracy**

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<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>Baseline</td>
<td>12.56284</td>
<td>12.55014</td>
</tr>
<tr>
<td>100% - 1392RPM 29 IPM</td>
<td>12.53998</td>
<td>12.6365</td>
</tr>
<tr>
<td>100% - 1392RPM 69 IPM</td>
<td>12.5857</td>
<td>12.6365</td>
</tr>
</tbody>
</table>

*All measurements shown in mm*
**Summary 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>
Mechanism of US Drilling

3 General Methods

Thrust force and Torque in US Drilling

- **Empirical Models**
  - Time consuming and Expensive
  - Use Regression analysis to fit the equations

- **Mechanistic Models**
  - More precise model than the Empirical model
  - Require study of cutting process in depth

- **Finite Element Models**
  - Cheaper model and faster analysis
  - Use to optimize the drill bit geometry and cutting condition
Mechanistic Models

Step 1: Evaluating the current mechanistic models

Geometry of the cutting edge

Total Force

Summing the force components at each element

\[ F_c = F \cos(\lambda - \gamma) = \frac{\tau_S \cdot A_c \cdot \cos(\lambda - \gamma)}{\sin \varphi \cos(\varphi + \lambda - \gamma)} \]

\[ F_T = F \sin(\lambda - \gamma) = \frac{\tau_S \cdot w \cdot h \cdot \cos(\lambda - \gamma)}{\sin \varphi \cos(\varphi + \lambda - \gamma)} \]

\[ \Delta P_l = F_{l,T} \sin p \cos \eta_d + F_{l,C} \sin \eta_d + F_{pt} \]

\[ \bar{F}_{Th} = \frac{1}{T} \int_0^T P_{Total} \, dt \]
Next steps in modeling

Step 2: Validating the current mechanistic model

1. Use math software (e.g. MATLAB) to calculate thrust force, drilling parameters for a specific material – Al

2. Conduct experiments to calibrate the model for above conditions

3. Use the calibrated model to predict thrust force for other cutting and US conditions

4. Conduct experiments to determine if predicted forces are accurate

Step 3: Improving the mechanistic models

- If the model shows promise, work to increase accuracy
- If not, develop a new force model
Future Developments

Mazak CNC Turning Center
Ultrasonic Assisted Reaming

Application Details:
• 8-mm TSC Carbide Reamer
• Powder Metallurgy Valve Guide – HRc72
• Pressed to NNS – ream to size
### Summary of Reaming Trials

#### Baseline Results

<table>
<thead>
<tr>
<th>Metric</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 provided by Federal Mogul (1406RPM – 22.5IPM), an axial feed force of 169N was achieved.

#### Ultrasonic Results

<table>
<thead>
<tr>
<th>Metric</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>Metric</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>
</tr>
<tr>
<td>Bore Size (mm)</td>
<td>8.031</td>
</tr>
</tbody>
</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 hub
- Extend tool life and increase quality of threads

ER-32 collet with Guhring solid carbide Tap.

Hub Design 2
### 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 slop 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>
</tr>
<tr>
<td>...</td>
<td></td>
<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>
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<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>
</tbody>
</table>

Summary of Tapping Study performed on 4340 Alloy steel.
Summary

- EWI has continued the development of UAD for new or existing machining centers
- Technology has advanced to a point where we can control heat
- Ultrasonic system successfully integrated with very stringent metalworking systems and practices
- Drilling mechanisms being studied
  - Other processes to follow including turning operations

- 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.