Ultrasonic Assisted Machining
Introducing Intense Vibrations to Enhance Metalworking
— Introduction to Ultrasonics
— High Power Ultrasound
— Ultrasonic Assisted Machining
— Application Examples
— Acoustech Systems
Introduction to Ultrasonics

— Intense, inaudible acoustic waves
— Field of extreme breadth
  — Low-intensity, high-frequency applications
  — High-intensity, low-frequency applications

Infrasound Acoustic Ultrasound

Low Bass Notes 20 Hz 20 kHz 2 MHz 200 MHz
Engineering Life Sciences Earth Sciences Diagnostic NDE

Infrasound Acoustic Ultrasound
Presentation Overview

— Introduction to Ultrasonics
— High Power Ultrasound
— Ultrasonic Assisted Machining
— Application Examples
— Acoustech Systems
High Power Ultrasound

- HPU is the application of intense acoustic energy to create *change* in a material or process
- Transducer is heart of system
  - Converts electrical energy to mechanical
  - Establishes resonance
A Note on Vibrations

- Longitudinal mode is single most important mode of vibration

- Expansion/contraction nature of longitudinal vibrations
- Natural frequency
- Nodes and antinodes
- Amplitude, stress distribution
- Wavelength - $\lambda$

\[ f = \frac{c}{2l}, \quad c = \sqrt{\frac{E}{\rho}} \]

Steel, Al: $c \approx 5.1 \times 10^3 \text{ m/s}$

at $20 \times 10^3 \text{ Hz (20kHz)}$

\[ l = \frac{c}{2f} = \frac{5.1 \times 10^3}{2 \times 20 \times 10^3} \]

= $0.128 \text{ m} = 12.8 \text{ cm}$

$\approx 5 \text{ in.}$
Introduction of Cutting Tools

\[ n = 1, 2, 3, \ldots \]

\[ f_n = \frac{nc}{2\ell} \]
Vibrations in Cutting Tools
Isolating Vibrations from Machine

— Node of a resonant device theoretically has no displacement
— There are no nodes in ultrasonics
  — Recall animation of simple bar
— There has to be a means of holding the system and applying force
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Ultrasonic Assisted Machining

What is Ultrasonic Machining?

Ultrasonic Vibration

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

Changing the Cutting Process

• Reducing Dynamic Friction
  • Reduces cutting forces
  • Reduces heat generated in cut

Note: UM is not .......
Ultrasonic-based Slurry Drilling Process
**Fundamental Ultrasonic System**

— **Ultrasonic Module**
  — 20kHz nominal resonant frequency
  — 5-25µm tool tip displacement
  — ER-32 collet
  — Through spindle coolant

— **Acoustech Power supply**
  — Operating bandwidth of 19,000-21,000Hz
  — Controls operating frequency
  — Maintains desired tool tip displacement
    — 2.5kW maximum output power
System Characterization

- **Amplitude**
  - Critical process variable
  - Measured as tool tip displacement in peak-to-peak micrometer values

- **Frequency**
  - Not a variable, determined by natural resonance of drill
  - Changes with tool length and geometry
  - Must be considered for every tooling application

- **Matching processes**
  - Critical velocity
A Note on Bandwidth

- Some shifting of resonant frequency can be accommodated
- Presence of other modes
- Amplitude is most critical parameter
- Loading effects
- Higher power required to maintain resonance

Strain Gauge to Measure Amplitude

Amplitude Profile During Drilling of Off-tuned System

18.2kHz
19.8kHz
21.2kHz
Applying Ultrasonics to Drilling

- **Objective is to reduce force required to make cut**
- Friction phenomena of ultrasonics reduces forces and translates to less heat generation
- Potential benefits with reduced heat
  - Better tool life, burr reduction, increased feed rates, better tolerances, improved surface finish, microstructure changes
Mechanism of UAD

3 General Methods

Thrust force and Torque in UAD

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

- **Analytical 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 conditions
Chang and Bone’s model for conventional drilling [1]

Tool wedge model offered by Merchant (1941)

The chips in this model are formed along shear plan

Merchant’s Circle

Most of the fundamental works on metal cutting use the following relations derived from his work.

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

\[
F_T = F \cdot \sin(\lambda - \gamma) = \frac{\tau_s \cdot A_C \cdot \sin(\lambda - \gamma)}{\sin \varphi \cos(\varphi + \lambda - \gamma)} = \frac{\tau_s \cdot w \cdot h \cdot \sin(\lambda - \gamma)}{\sin \varphi \cos(\varphi + \lambda - \gamma)}
\]
Two main assumptions in the current (Chang & Bone) model are:

1. **Drill bit cutting edge forces**
   - Cutting lips
   - Chisel Edge: (10-20% of total force)
   - Secondary Cutting zone
   - Indentation zone

2. **Orthogonal cutting rather than Oblique cutting**
Building Analytical Models

Evaluating the current analytical models

Total Force

Geometry of the cutting edge

Summing the force components at each element

Cutting edge divided into a number of elements

Total Thrust force

\[ F_c \text{ & } F_T \]

For each element
Analytical Models

How to calculate \( F_c \) & \( F_T \)

Cutting Force → \( F_c = F \cdot \cos(\varphi - \gamma) = \tau_s \cdot A_c \cdot \cos(\varphi + \lambda - \gamma) \)

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

Feed Force → \( F_T = F \cdot \sin(\lambda - \gamma) = \tau_s \cdot A_c \cdot \sin(\lambda - \gamma) \)

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

where
- \( \tau_s \rightarrow \) shear strength of material
- \( w \rightarrow \) width of cut
- \( h \rightarrow \) uncut chip thickness
- \( \lambda \rightarrow \) friction angle
- \( \gamma \rightarrow \) rake angle
- \( \varphi \rightarrow \) shear angle

Thrust force for each element → \( \Delta P_l = F_{l,T} \cdot \sin p \cdot \cos \eta_d + F_{l,C} \cdot \sin \eta_d + F_{pt} \)

Total Thrust force → \( \vec{F}_{Th} = \frac{1}{T} \int_0^T \vec{P}_{Total} \, dt \)
Improving the current model

Using an Oblique Cutting Model rather than using the Orthogonal Cutting Model

Orthogonal cutting (2D cutting model) vs. Oblique cutting (3D cutting model)

- Cutting edge is normal to the cutting velocity
- In order to better understand this complex process
  
Simplified

- The cutting edge is inclined by an angle \( I \) (or \( \lambda \))
- More realistic chip flow representation

Complicated
Calculating Thrust Forces

### Input
- Drill bit geometry and cutting conditions

<table>
<thead>
<tr>
<th>D (mm)</th>
<th>D’ (mm)</th>
<th>W (mm)</th>
<th>W’ (mm)</th>
<th>P</th>
<th>Beta (Degrees)</th>
<th>M</th>
<th>F (mm/rev)</th>
<th>N (RPM)</th>
<th>f (kHz)</th>
<th>A (Micron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.7</td>
<td>2.249</td>
<td>0.91</td>
<td>1.124</td>
<td>118</td>
<td>31</td>
<td>1000</td>
<td>0.114</td>
<td>1000</td>
<td>20</td>
<td>0-200</td>
</tr>
</tbody>
</table>

### Output
- Thrust Force

<table>
<thead>
<tr>
<th>Test #</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust Force (N)</td>
<td>121</td>
<td>115</td>
<td>108</td>
<td>106</td>
<td>104</td>
</tr>
</tbody>
</table>

- Test conditions:
  - Spindle speed (RPM): 1000
  - Feed rate (mm/rev): 0.114
  - A (mm): 0.040

Matlab

Output → Thrust Force
FEA of Process

FE modeling of ultrasonic assisted drilling process is in progress.
Presentation Overview

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Drilling of Titanium 6Al-4V

— System setup after characterization and tuning of tools
— Testing initiated to arrive at most significant force reduction
— Increase feed rates to obtain near original forces
— Evaluate surface finish, hole quality, burr formation, microstructure

<table>
<thead>
<tr>
<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>0%</td>
<td>995</td>
<td>13.5</td>
<td>0.0136</td>
<td>1218</td>
<td>29.38</td>
<td>1.4474</td>
</tr>
<tr>
<td>60%</td>
<td>995</td>
<td>13.5</td>
<td>0.0136</td>
<td>762.3</td>
<td>25.53</td>
<td>1.0063</td>
</tr>
<tr>
<td>60%</td>
<td>995</td>
<td>17.5</td>
<td>0.0176</td>
<td>884.5</td>
<td>37.74</td>
<td>1.3561</td>
</tr>
</tbody>
</table>

Location 1 | Location 2 | Total Average
--- | --- | ---
Baseline  | x  | y  | x  | y  | 16.0248
60% - 995RPM - 17.5IPM | 16.0172 | 16.0197 | 16.0147 | 16.0324 | 16.0210
Material Impact
### Drilling of 4340 Steel and 6061 Aluminum

#### 4340 Steel

<table>
<thead>
<tr>
<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>0%</td>
<td>2161</td>
<td>15</td>
<td>.0069</td>
<td>848</td>
<td>9.708</td>
<td>0.4415</td>
</tr>
<tr>
<td>100%</td>
<td>2161</td>
<td>15</td>
<td>.0069</td>
<td>417</td>
<td>7.165</td>
<td>0.1644</td>
</tr>
<tr>
<td>100%</td>
<td>2161</td>
<td>55</td>
<td>.0255</td>
<td>866</td>
<td>23.68</td>
<td>0.2397</td>
</tr>
</tbody>
</table>

#### 6061-T6 Alum

<table>
<thead>
<tr>
<th>Row #</th>
<th>Amplitude</th>
<th>RPM</th>
<th>IPM</th>
<th>IPR</th>
<th>IPT</th>
<th>Avg. Force (N)</th>
<th># of holes</th>
<th>Avg. Ra (µm)</th>
<th>Bore Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0%</td>
<td>1550</td>
<td>11.63</td>
<td>0.0075</td>
<td>0.0025</td>
<td>662.3</td>
<td>11</td>
<td>2.4074</td>
<td>0.4847</td>
</tr>
<tr>
<td>6</td>
<td>50%</td>
<td>1550</td>
<td>11.63</td>
<td>0.0075</td>
<td>0.0025</td>
<td>226</td>
<td>10</td>
<td>2.6251</td>
<td>0.4856</td>
</tr>
<tr>
<td>13</td>
<td>0%</td>
<td>1800</td>
<td>18</td>
<td>0.01</td>
<td>0.0033</td>
<td>848.6</td>
<td>11</td>
<td>2.4064</td>
<td>0.4825</td>
</tr>
<tr>
<td>0</td>
<td>100%</td>
<td>1800</td>
<td>18</td>
<td>0.01</td>
<td>0.0033</td>
<td>418.9</td>
<td>11</td>
<td>2.6721</td>
<td>0.4845</td>
</tr>
</tbody>
</table>

### Location 1 vs. Location 2

<table>
<thead>
<tr>
<th>Location</th>
<th>x</th>
<th>y</th>
<th>x</th>
<th>y</th>
<th>Total Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>12.5425</td>
<td>12.5349</td>
<td>12.5349</td>
<td>12.539</td>
<td>12.539</td>
</tr>
<tr>
<td>100% - 2161RPM - 15IPM</td>
<td>12.5349</td>
<td>12.5349</td>
<td>12.5298</td>
<td>12.534</td>
<td>12.534</td>
</tr>
<tr>
<td>100% - 2161RPM - 55IPM</td>
<td>12.5298</td>
<td>12.5349</td>
<td>12.5349</td>
<td>12.5298</td>
<td>12.534</td>
</tr>
</tbody>
</table>

---

![Baseline testing](image)

![Baseline with U.S.](image)

![Advanced with U.S.](image)
Micro-Drilling Titanium Post

— Application Details
  — Significant tool breakage at engagement due to spherical geometry
  — Slow processing speeds
  — Ø 0.45mm solid carbide drill

— Results
  — Increased throughput by increasing peck depth, chip load, and RPM
  — Tool life increased due to better engagement cutting on center

<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.
Drilling Hard Materials

- Powder Metallurgy – Rc 72
Milling and Drilling Tungsten

Objective to mill flat on cylinder and conduct drilling trials to evaluate tooling wear

Results

— Milling used Guhring solid carbide end mill improved surface finish (Ra 2.12µm vs. 4.34µm)
  — 4538 RPM, 47.66 IPM
— Drilling used High-Tech TSC carbide to drill 1.1” deep
  — 3600 RPM, 22.6 IPM

End mill cutting edge post milling two parts

Drill edge post drilling 12 test holes

Initial Tungsten Sample

Post Testing Sample
### Ultrasonic Assisted Reaming

#### 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 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>
</tr>
<tr>
<td>Bore Size (mm)</td>
<td>8.031</td>
</tr>
</tbody>
</table>

Utilizing ultrasonics, feed rate was increased by 150%, from 22.5IPM to 34.5IPM, and the axial force was 27% less than the baseline force.
**Ultrasonic Tapping**

- Evaluate force reductions on applied force and torque for solid carbide tap
- Stainless steel and titanium “gummy materials”
- Harder materials often rely on thread milling resulting in lower throughput

<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>
</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>
</tr>
</tbody>
</table>

Summary of Tapping Study performed on 4340 Alloy steel
US Milling Titanium

- **Peripheral Plate Milling**
  - 1,700 RPM, 0.02” DoC, 0.5” engagement, 7 IPM
  - Flood coolant
  - Guhring, Ø1/2” solid carbide, 5” OAL

- **No Ultrasonics**
- **Ra** = 198
- Climb milling
- **Taper cut** (DoC = .018-.012)

- **Ultrasonics (7µm)**
- **Ra** = 50
- Climb milling
- **No taper** (DoC = .019)
- 38% load reduction along feed axis
Titanium Milling cont.

- **Peripheral T-Plate Milling**
  - 1,700 RPM, 0.02” DoC, 0.5” engagement, 7 IPM
  - 0.25” thick rib, 5” tall, “T” section
  - Guhring, Ø1/2” solid carbide, 5” OAL

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

- Ultrasonics (7µm)
- Ra = 40 (above cut)
- Climb milling
- No taper (DoC = 0.18)
- 14% load reduction along feed axis
High Aspect Ratio Milling

Top Surface Engagement

Surface Finish Result
Understanding Tooling Affects

- Understanding acoustics with conventional cutting tools
  - “Common” drill (3d, 5d, 8d) – symmetrical and same diameter
  - Insert or carbide tip – still symmetrical
  - Indexable tool with short flute length
  - Custom grind stepped carbide
    - Note gain in amplitude due to reduction at end of tool
    - Decrease in diameters does not directly impact frequency, but mass removed from flutes does!
  - Custom form tooling
    - Note changes in flute design, diameters, and geometry
    - All three tools will tune similarly because they are roughly the same length while having different amplitude profiles
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Historical Background

Cincinnati Milacron US turning, 1960's

Grumman US Drilling, 1970's

OSU, US Cutting 1970's

Sonobond Drilling, Turning 1970's
Acoustech N-Series Module

- 1.5-in Ø straight shank mounting provision
  - 4 flats every 90°
- ER-32 collet
- Through spindle coolant
  - 3/8-NPT fitting
  - Rated for 1,500psi
- IP-65 and 68 rating
  - 65 for splash and 68 for submersion
- Lemo connector
  - IP-68 submerged for one hour
N-Series Durability

— Mechanical Design Validation

✓ — 28Mil axial cycling with no US @ 30Hz and 4kN
✓ — 28Mil shear cycling with no US @ 30Hz and 4kN
✓ — 28Mil torsional cycling with no US @ 25Hz and 25Nm
✓ — 28Mil axial cycling with US @ 30Hz and 4kN
✓ — 28Mil shear cycling with US @ 30Hz and 4kN
✗ — 20Mil torsional cycling with US @ 30Hz and 25Nm

— Test eliminated due to issues with making fixture that can be put in resonance while subjected to loading

Fig. Torsional Test Set-up
N-Series Durability cont.

Drop Testing
Machine Tool Integration

- 220VAC, 60Hz, 15A, Ø
- 120VAC, 60Hz, 4A
- Refer to manual for specifications
Rotary Turret Connector (NRT)

- Rotary slip ring to turret
- Water tight quick disconnect electrical connector
Ongoing Developments

— **R-Series Modules**
  — Design considerations
    — Electrical connection
    — Tool changers
    — Weight
    — Contamination
    — Through spindle coolant

— **Other processes**
  — Turning
  — Grinding