Ultrasonic Assisted Machining

Introducing Intense Vibrations to Enhance Metalworking

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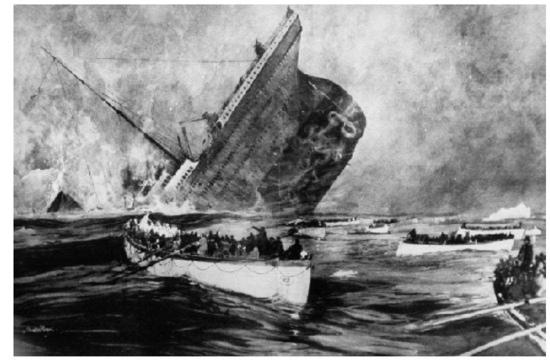
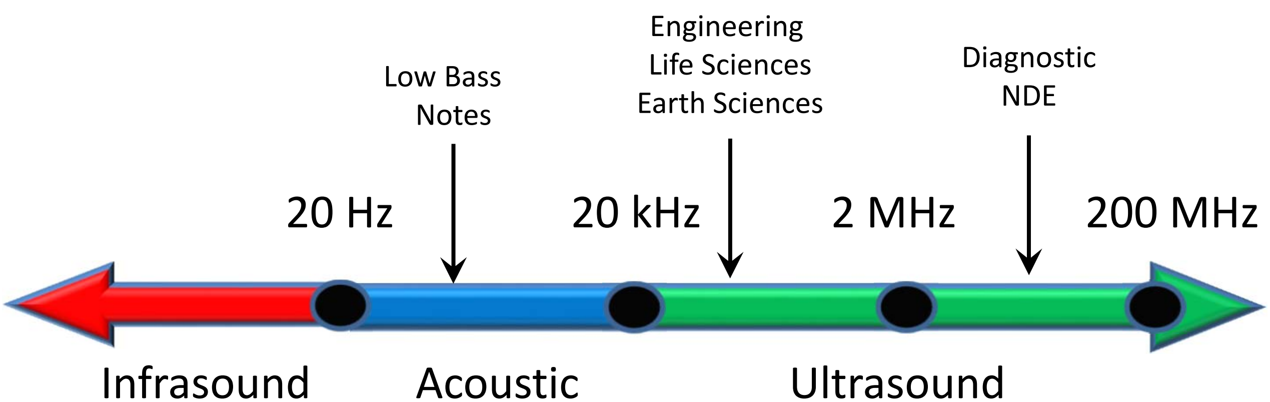
Presentation Overview

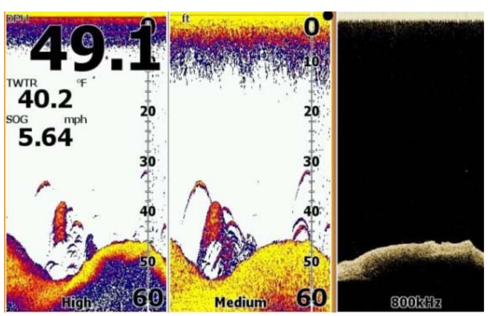
- Introduction to Ultrasonics
- High Power Ultrasound
- Ultrasonic Assisted Machining
- Application Examples
- Acoustech Systems

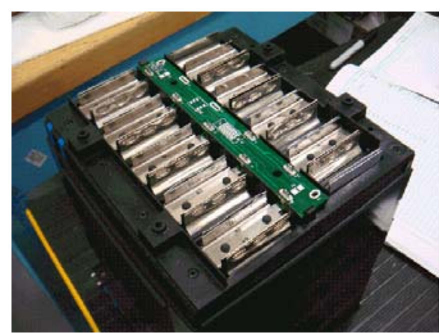
Introduction to Ultrasonics

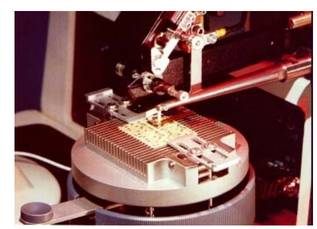
- Intense, inaudible acoustic waves
- Field of extreme breadth
  - Low-intensity, high-frequency applications
  - High-intensity, low-frequency applications











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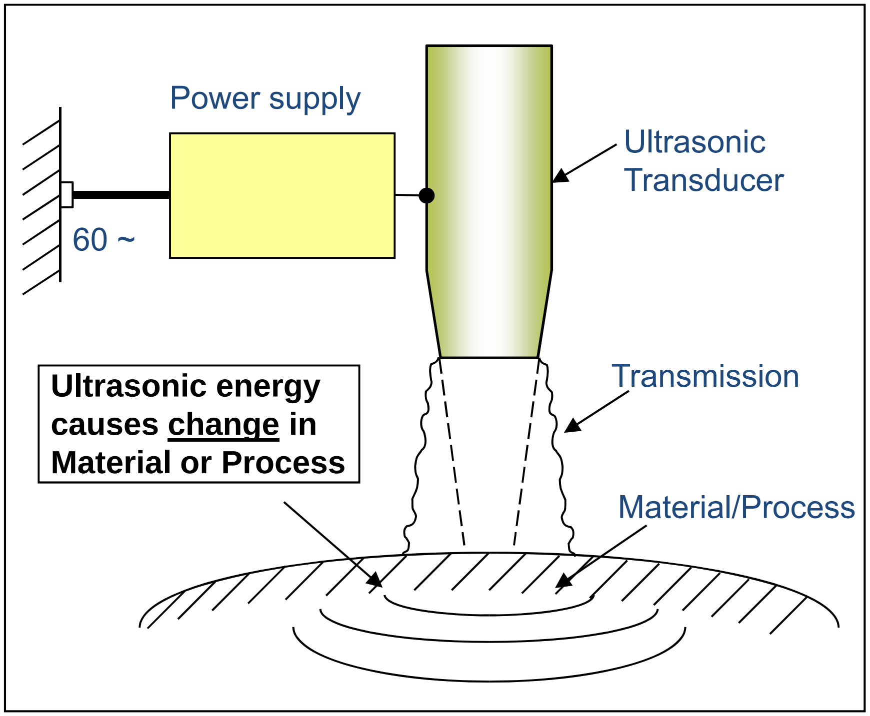
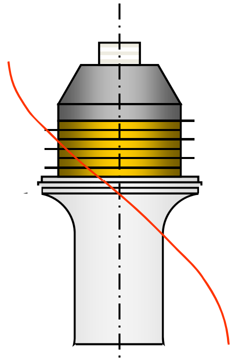
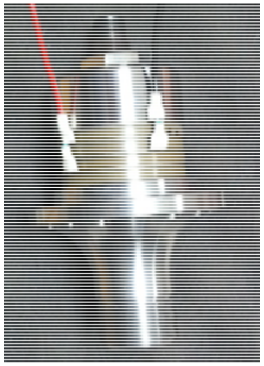
High Power Ultrasound

- **HPU is the application of intense acoustic energy to create *<u>change</u>* in a material or process**
- **Transducer is heart of system**
  - Converts electrical energy to mechanical
  - Establishes resonance





Classic Transducer



US Machining Transducer

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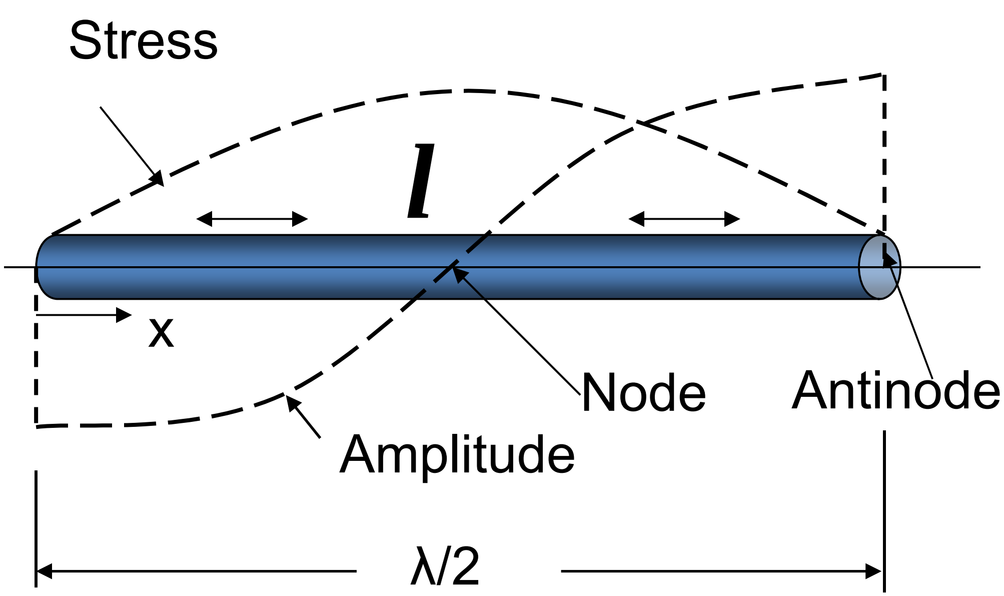
A Note on Vibrations

— **Longitudinal mode is single most important mode of vibration**

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



$$f = \frac{c}{2l}, \; c = \sqrt{\frac{E}{\rho}}$$

cylinder-20khz.avi
(1 MB)

Steel, Al: $c \cong 5.1 \times 10^3$ m/s

at 20×10^3 Hz (20kHz)

$$\rightarrow l = \frac{c}{2f} = \frac{5.1 \times 10^3}{2 \times 20 \times 10^3}$$

$= 0.128$ m $= 12.8$ cm

$\cong 5$ in.

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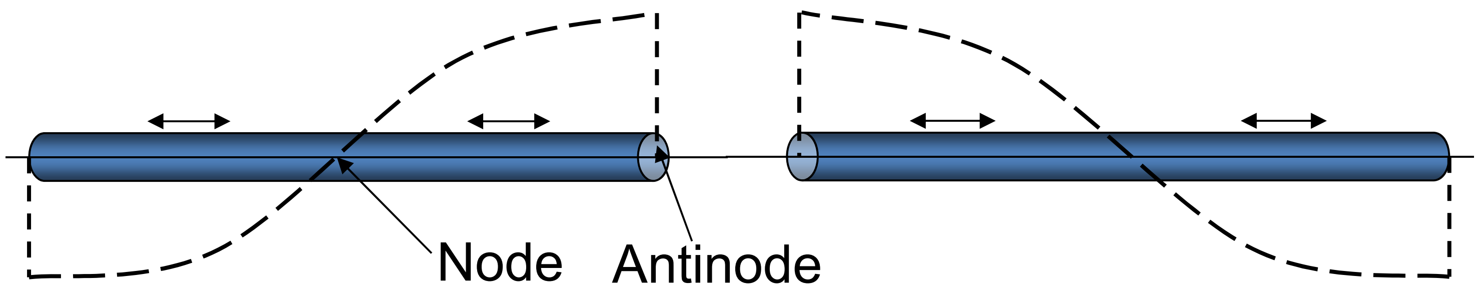
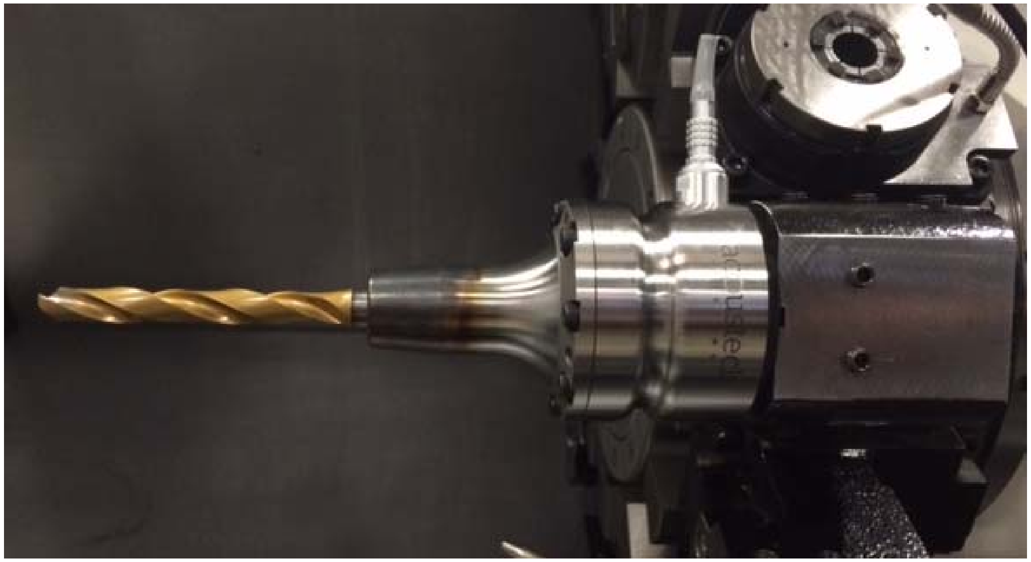
Introduction of Cutting Tools





$$f_n = \frac{nc}{2\ell}$$

n = 1, 2, 3, …

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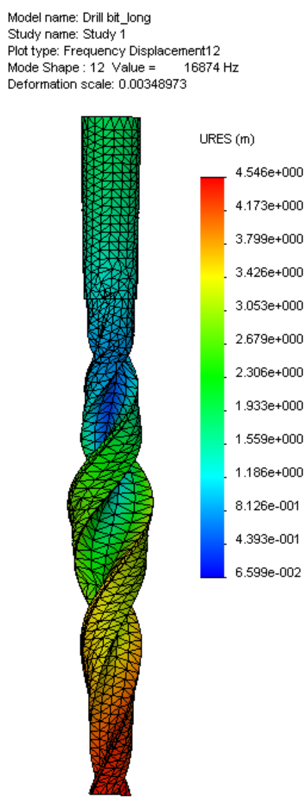
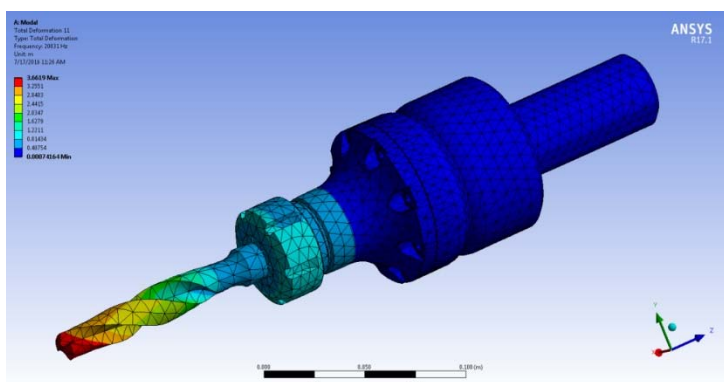
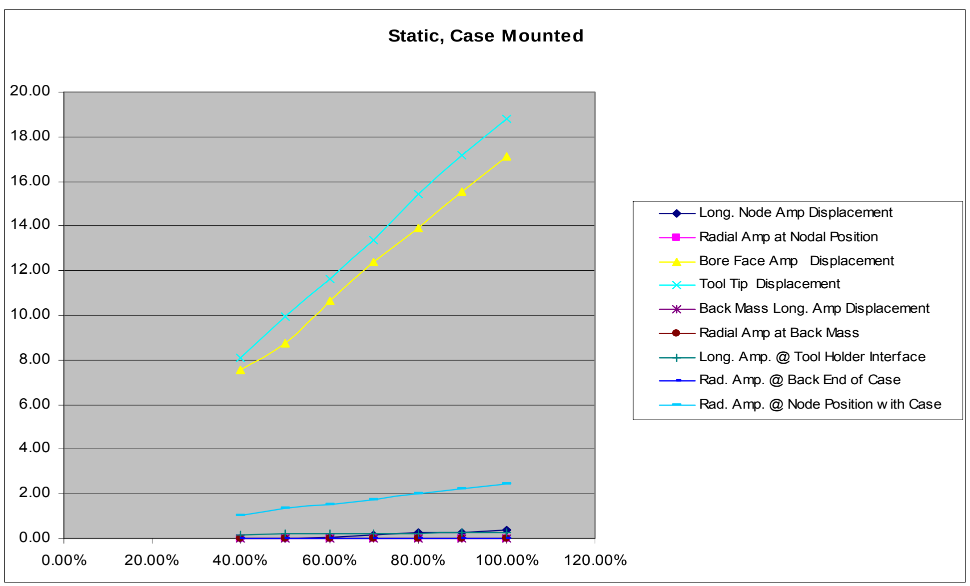
Vibrations in Cutting Tools

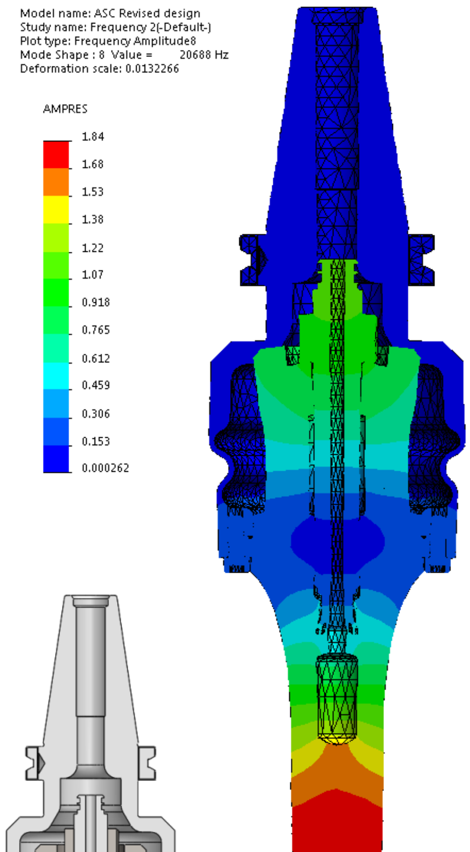


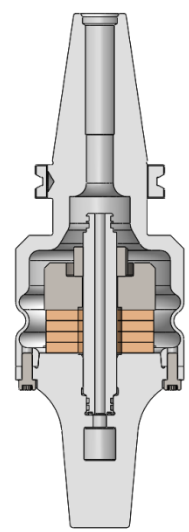


Isolating Vibrations from Machine

- 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?

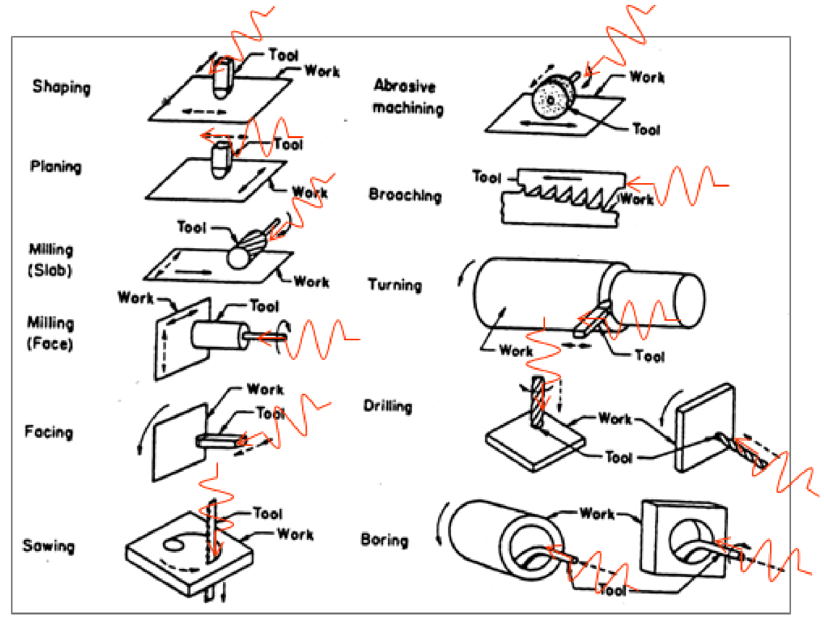
Ultrasonic Vibration

+

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

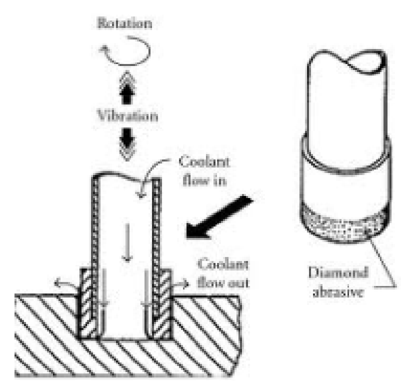
Changing the Cutting Process

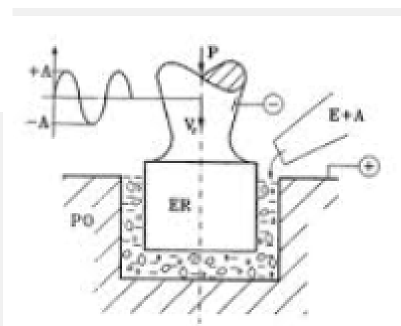
- Reducing Dynamic Friction
  - Reduces cutting forces
  - Reduces heat generated in cut



Note: UM is not ……..

Ultrasonic-based Slurry Drilling Process





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Fundamental Ultrasonic System

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

Ultrasonic Assisted Machining Module

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

Ultrasonic Generator

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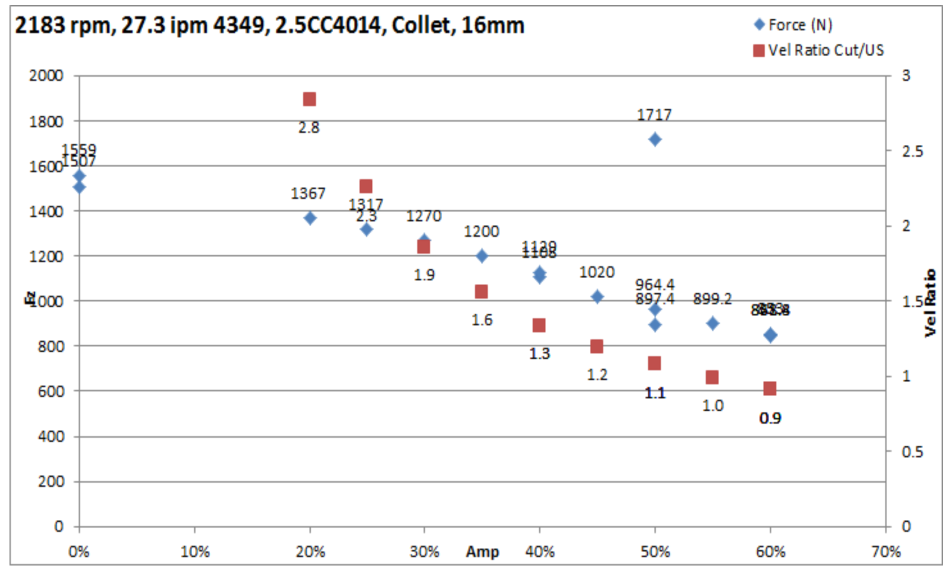
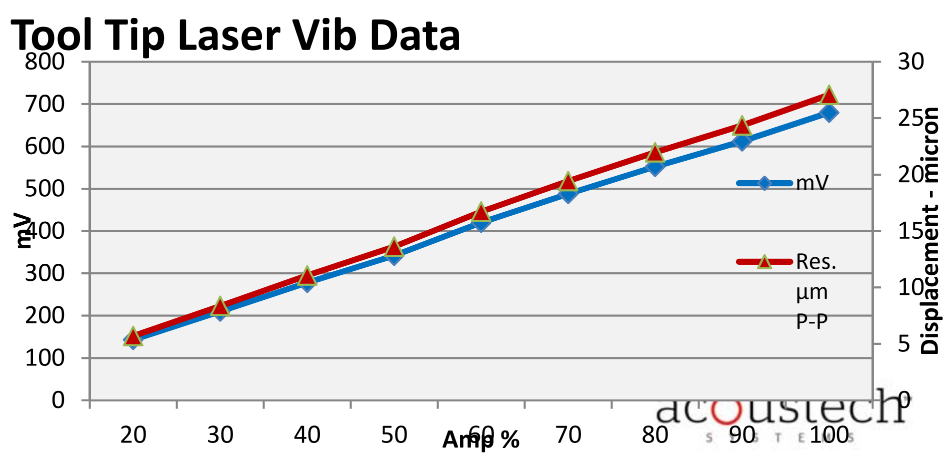
System Characterization

- **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

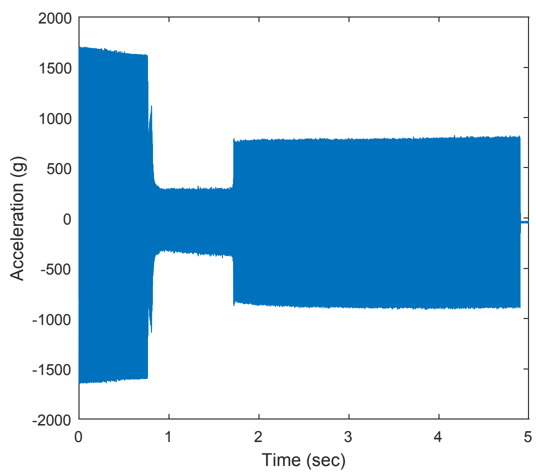




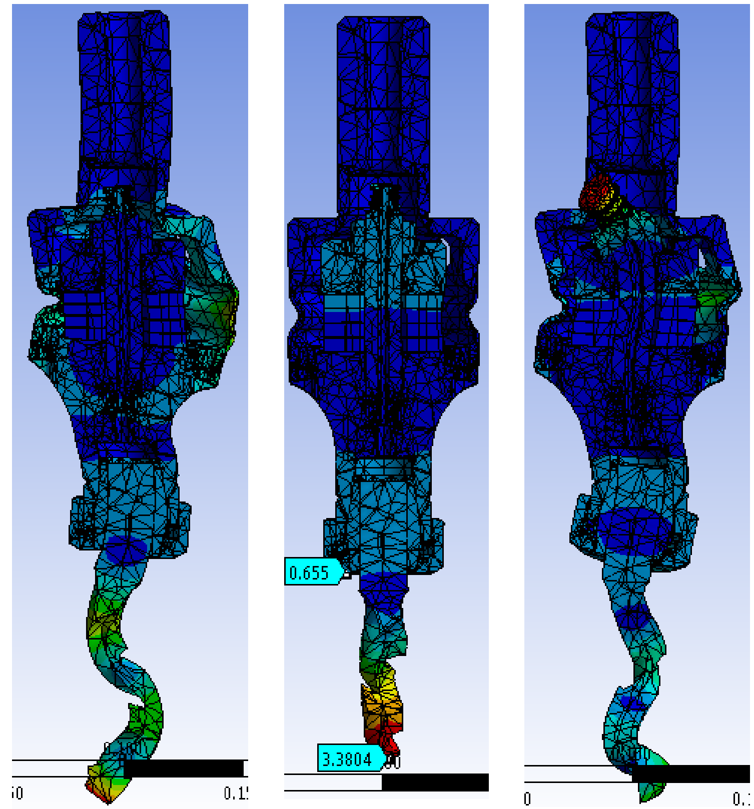
A Note on Bandwidth

- **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

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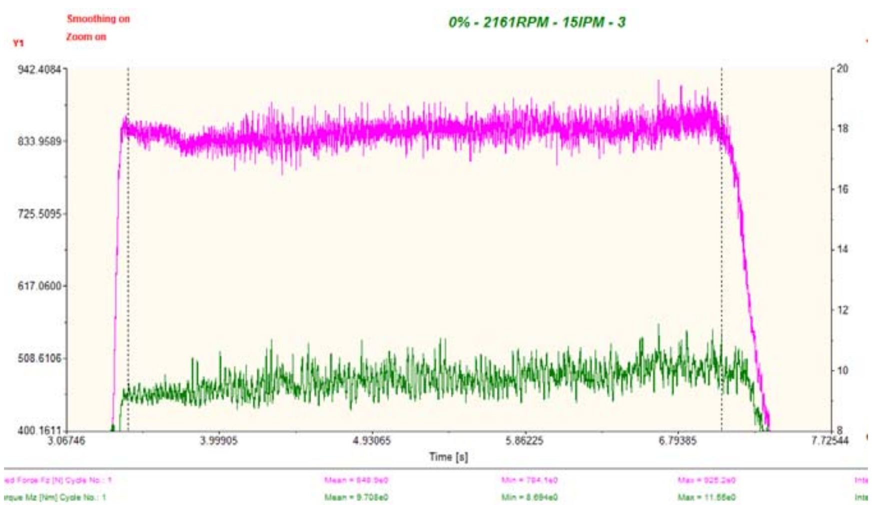
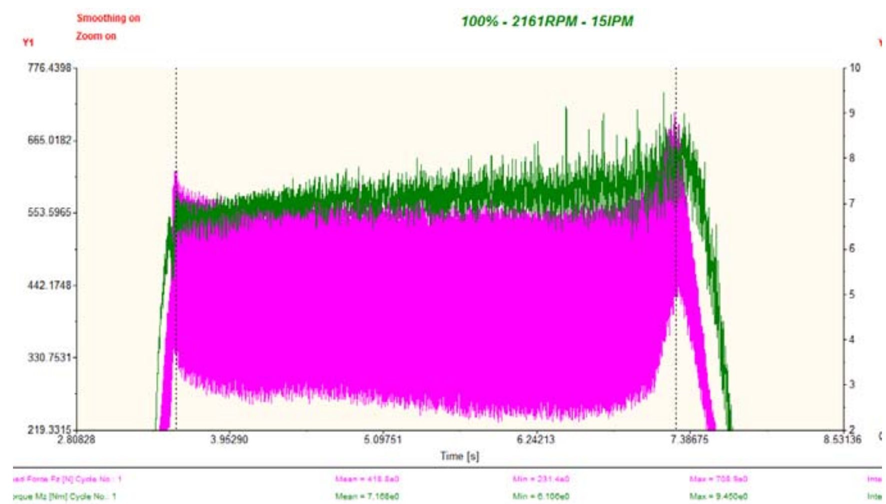
Applying Ultrasonics to Drilling

- **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





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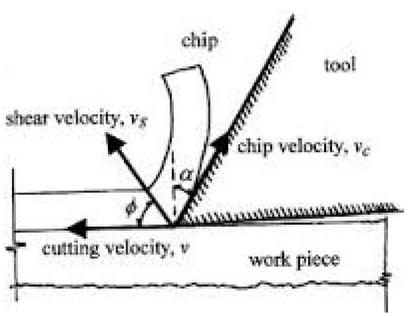
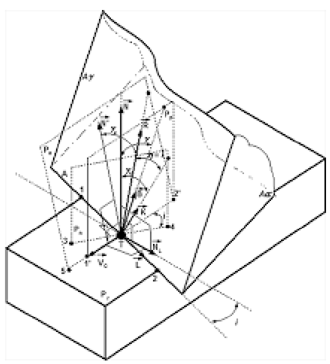
Mechanism of UAD

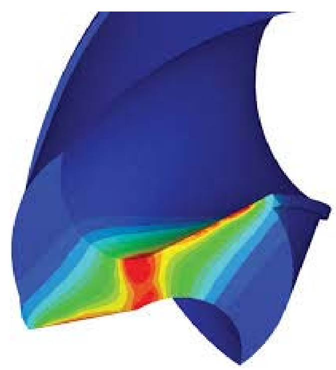
3 General Methods

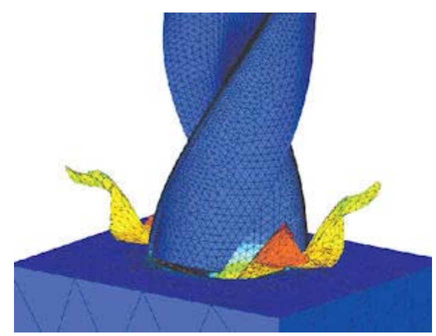
Thrust force and Torque in UAD

- **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









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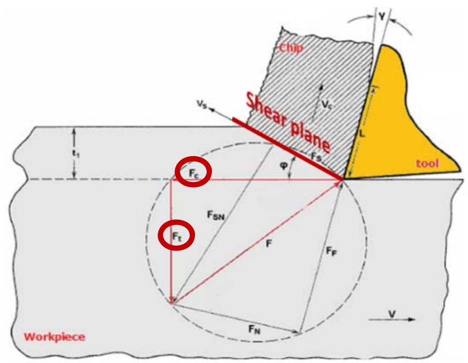
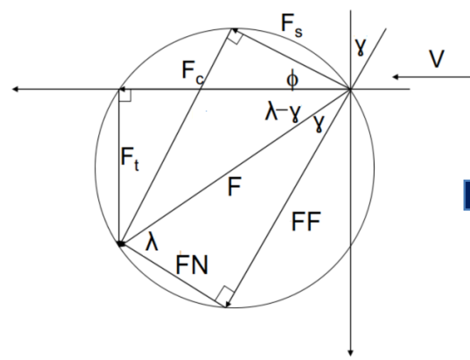
Research Approaches

Chang and Bone's model for conventional drilling [1]

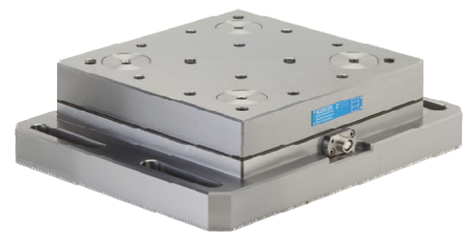
Tool wedge model offered by Merchant (1941)

The chips in this model are formed along shear plan





Merchant's Circle



F_c and F_T

Measurable by dynamometer

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

$$F_c = F * \cos(\lambda - \gamma) = \frac{\tau_s * A_c * \cos(\lambda - \gamma)}{\sin\varphi \cos(\varphi + \lambda - \gamma)} = \frac{\tau_s * w * h * \cos(\lambda - \gamma)}{\sin\varphi \cos(\varphi + \lambda - \gamma)}$$

$$F_T = F * \sin(\lambda - \gamma) = \frac{\tau_s * A_c * \sin(\lambda - \gamma)}{\sin\varphi \cos(\varphi + \lambda - \gamma)} = \frac{\tau_s * w * h * \sin(\lambda - \gamma)}{\sin\varphi \cos(\varphi + \lambda - \gamma)}$$

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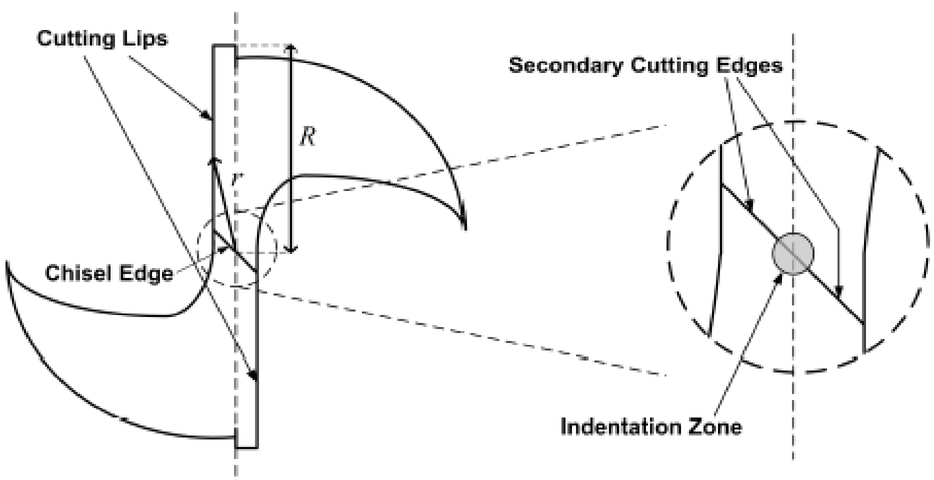
Assumptions

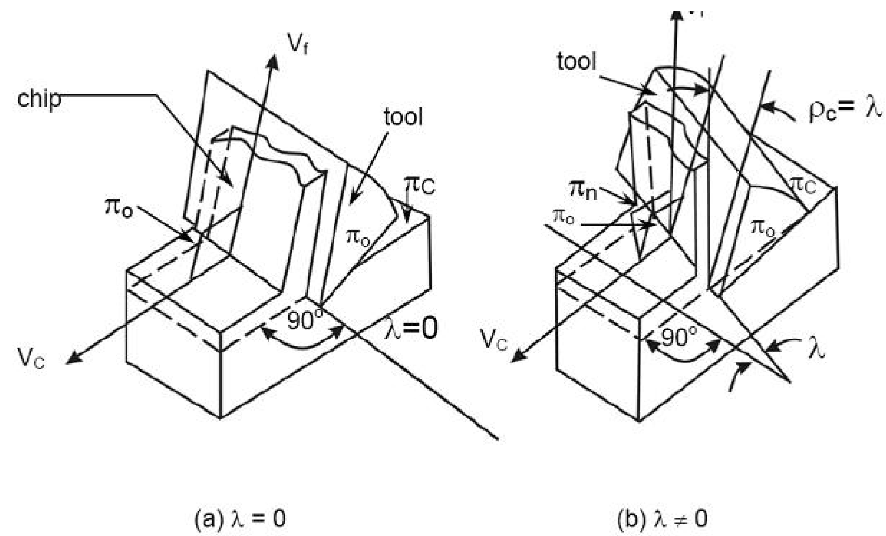
Two main assumptions in the current (Chang & Bone) model are:

(1) Drill bit cutting edge forces

- Cutting lips ✓
- Chisel Edge (10-20%of total force) ✗
  - Secondary Cutting zone
  - Indentation zone



Twist Drill Cutting Sections



Orthogonal Vs. Oblique

(2) Orthogonal cutting rather than Oblique cutting

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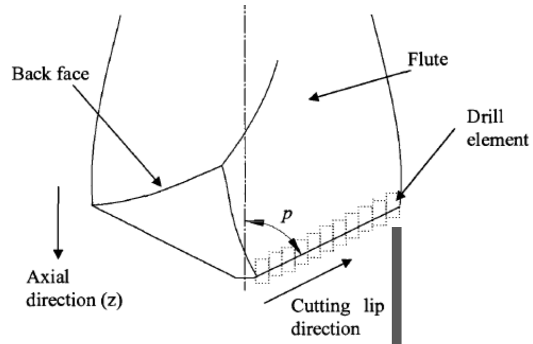
Building Analytical Models

Evaluating the current analytical models

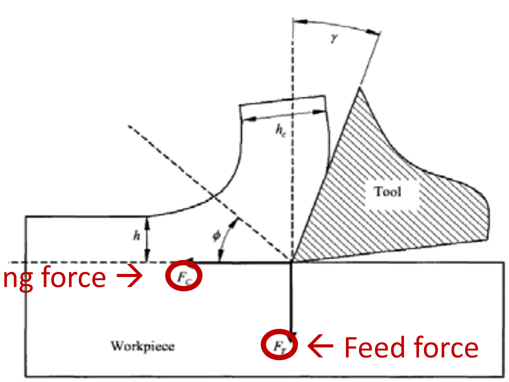
Total Force

Geometry of the cutting edge

Summing the force components at each element



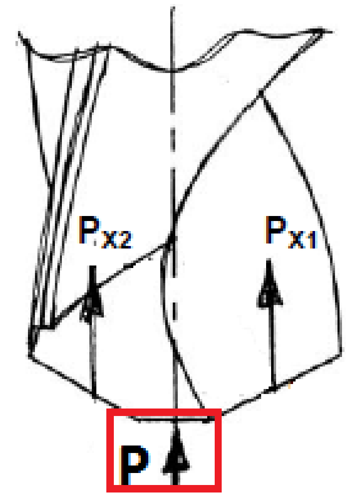
Cutting edge divided into a number of elements



F_C & F_T
For each element

Σ

Total Thrust force



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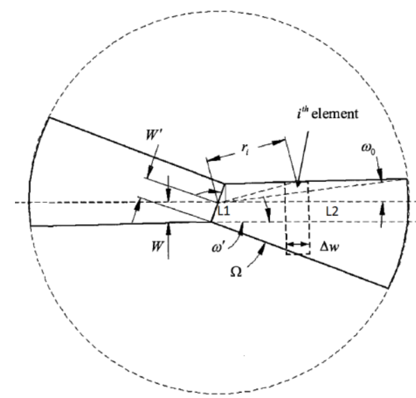
Analytical Models

How to calculate F_c & F_T

$$\text{Cutting Force} \rightarrow F_c = F * \cos(\lambda - \gamma) = \frac{\tau_s * A_c * \cos(\lambda - \gamma)}{\sin\varphi \cos(\varphi + \lambda - \gamma)} = \frac{\tau_s * w * h * \cos(\lambda - \gamma)}{\sin\varphi \cos(\varphi + \lambda - \gamma)}$$

$$\text{Feed Force} \rightarrow F_T = F * \sin(\lambda - \gamma) = \frac{\tau_s * A_c * \sin(\lambda - \gamma)}{\sin\varphi \cos(\varphi + \lambda - \gamma)} = \frac{\tau_s * w * h * \sin(\lambda - \gamma)}{\sin\varphi \cos(\varphi + \lambda - \gamma)}$$



where

- τ_s → shear strength of material
- w → width of cut
- h → uncut chip thickness
- λ → friction angle
- γ → rake angle
- φ → shear angle

$$\text{Thrust force for each element} \rightarrow \Delta P_l = F_{l,T} * \sin p * \cos\eta_d + F_{l,C} * \sin\eta_d + F_{pt}$$

$$\text{Total Thrust force} \rightarrow \bar{F}_{Th} = \frac{1}{T}\int_0^T P_{Total}\,dt$$

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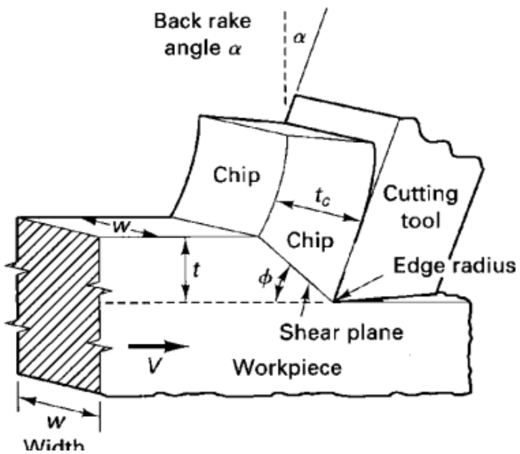
Notes on Modeling

Improving the current model

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



Orthogonal cutting (2D cutting model)

{ F_T, F_C }

↓

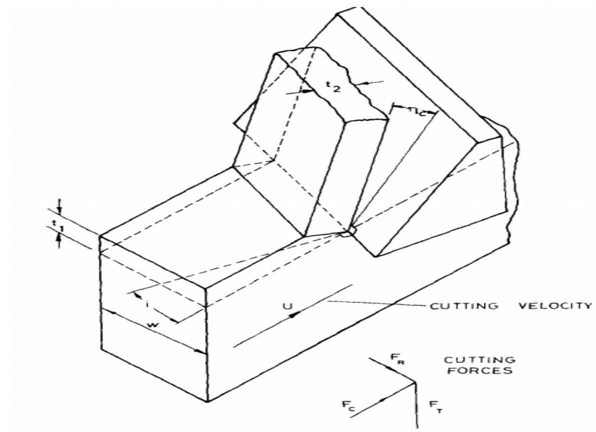
Cutting edge is normal to the cutting velocity

↓

In order to better understand this complex process

↓

Simplified



Oblique cutting (3D cutting model)

{ F_T, F_C, F_R }

↓

The cutting edge is inclined by an angle I (or λ)

↓

More realistic chip flow representation

↓

Complicated

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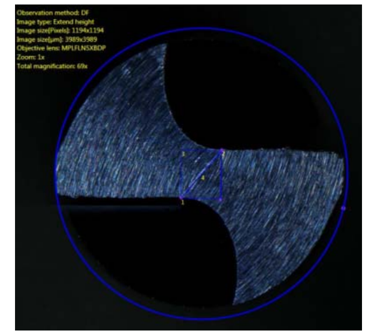
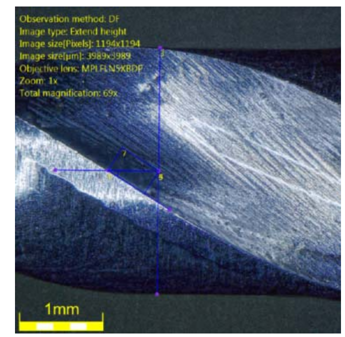
Calculating Thrust Forces

Input

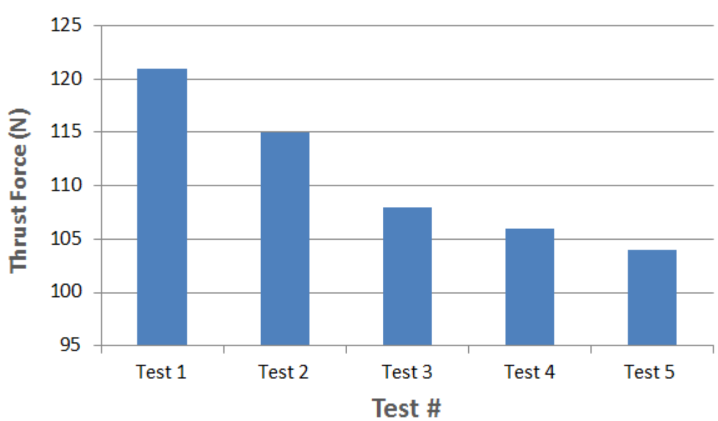
Drill bit geometry and cutting conditions

D	D'	W	W'	P	Beta	M	F	N	f	A
Diameter (mm)	Chisel edge Diameter (mm)	Web thickness (mm)	Chisel edge thickness (mm)	Drill point angle (Degrees)	Helix angle (Degrees)	Number of elements	Feed (mm/rev)	Speed (RPM)	Frequency (kHz)	Amplitude (Micron)
12.7	2.249	0.91	1.124	118	31	1000	0.114	1000	20	0-200





MATLAB



	Test 1	Test 2	Test 3	Test 4	Test 5
Spindle speed (RPM)	1000				
Feed rate (mm/rev)	0.114	0.114	0.114	0.114	0.114
A (mm)	0.040	0.080	0.120	0.160	0.200
Average thrust force (N)	**121**	**115**	**108**	**106**	**104**

Output → Thrust Force

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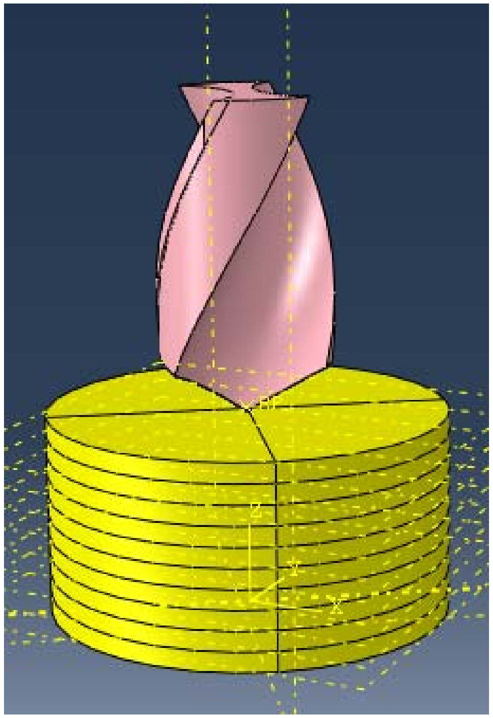
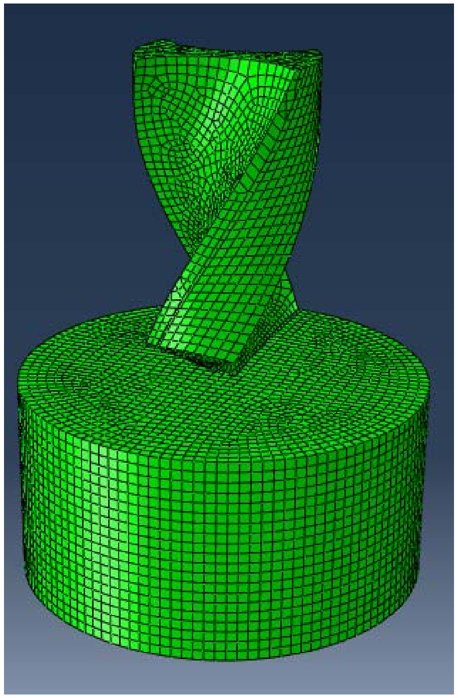
FEA of Process

FE modeling of ultrasonic assisted drilling process is in progress





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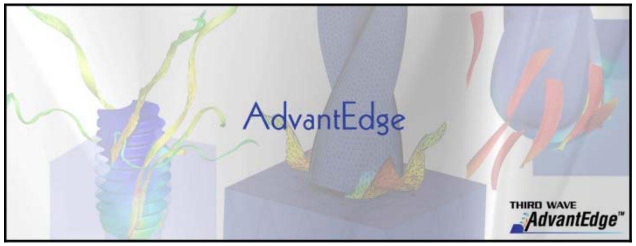
DEFORM™

Design Environment for FORMing



ABAQUS

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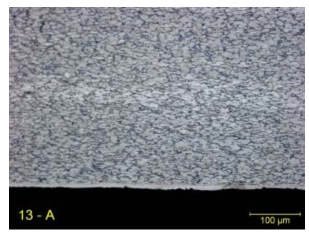
Drilling of Titanium 6Al-4V

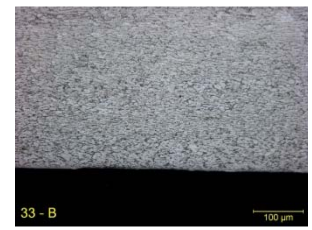
- System setup after characterization and tuning of tools
- Testing initiated to arrive at most significant force reduction
- Increase feed rates to obtain near original forces
- Evaluate surface finish, hole quality, burr formation, microstructure

Amplitude	RPM	IPM	IPR	Force (N)	Torque (Nm)	Ra (µm)
0%	995	13.5	0.0136	1218	29.38	1.4474
60%	995	13.5	0.0136	762.3	25.53	1.0063
60%	995	17.5	0.0176	884.5	37.74	1.3561



Baseline testing

Baseline with U.S.



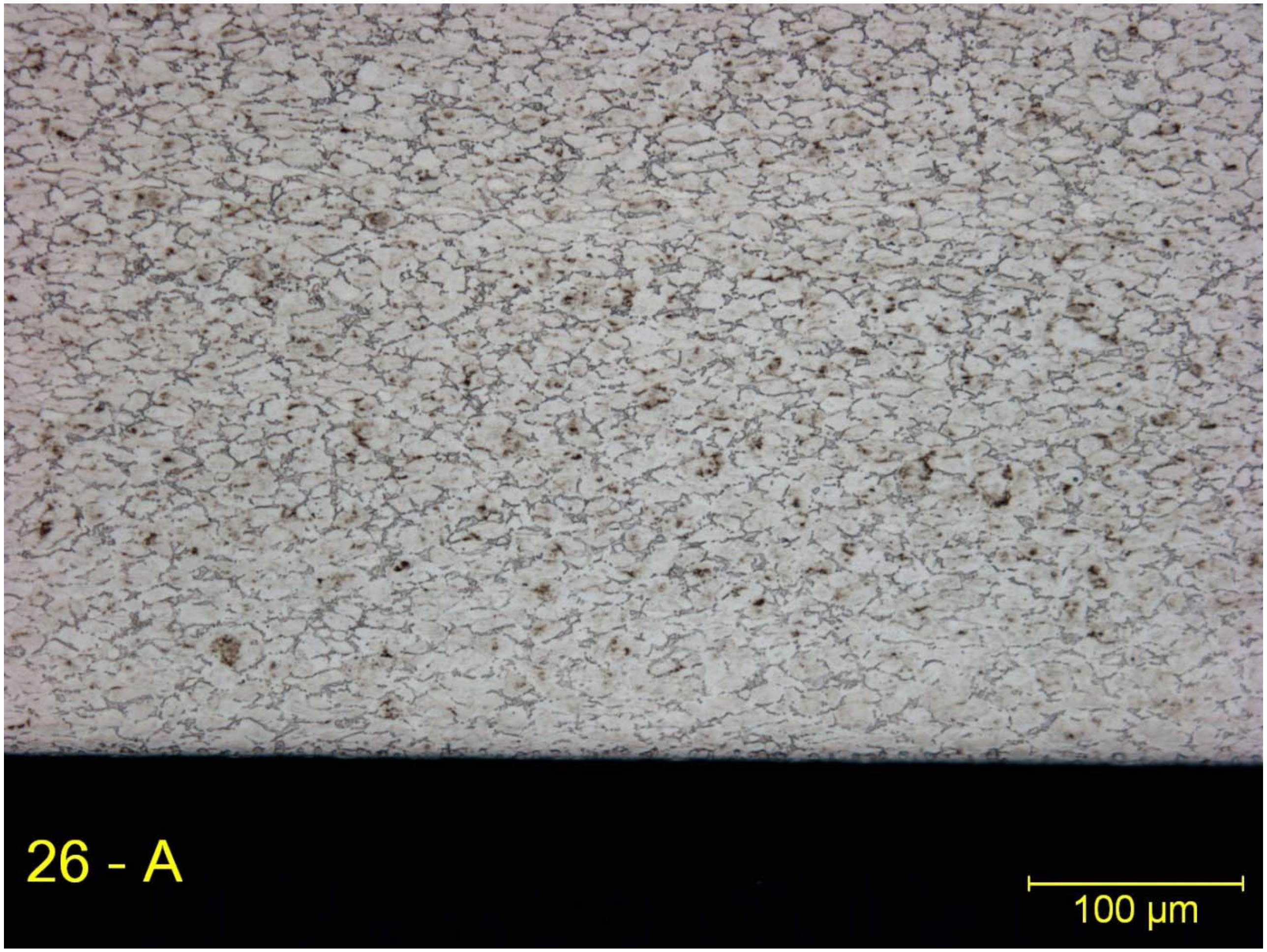
Advanced with U.S.

	Location 1		Location 2		
	x	y	x	y	Total Average
Baseline	16.0096	16.0197	16.0477	16.0223	16.0248
60% - 995RPM - 13.5IPM	16.0147	16.0426	16.0375	16.0426	16.0343
60% - 995RPM - 17.5IPM	16.0172	16.0197	16.0147	16.0324	16.0210

Measuring surface roughness


Measuring hole diameter

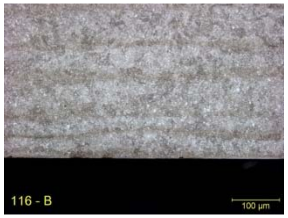
Material Impact



Drilling of 4340 Steel and 6061 Aluminum

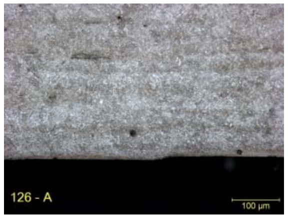
4340 Steel

Amplitude	RPM	IPM	IPR	Force (N)	Torque (Nm)	Ra (µm)
0%	2161	15	.0069	848	9.708	0.4415
100%	2161	15	.0069	417	7.165	0.1644
100%	2161	55	.0255	866	23.68	0.2397



Baseline testing

Baseline with U.S.

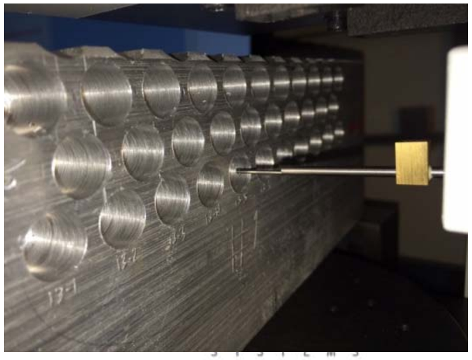


Advanced with U.S.

	Location 1		Location 2		
	x	y	x	y	Total Average
Baseline	12.54252	12.5349	12.5374	12.5399	12.539
100% - 2161RPM - 15IPM	12.53744	12.5349	12.5349	12.5298	12.534
100% - 2161RPM - 55IPM	12.52982	12.5349	12.5399	12.5298	12.534

6061-T6 Alum

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


Aluminum Test Sample

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

Trial	Amplitude	RPM	IPM	IPR	Peck Depth (in)	DoC (in)	Cycle Time
1	0%	3538	1.37	.00039	.005	.02	3:55
2	30%	4500	2.25	.0005	.027	.2	0:52

Figure 1: Fixture and tooling setup.

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Drilling Hard Materials

— **Powder Metallurgy – Rc 72**

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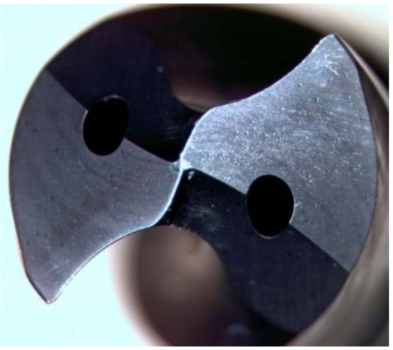
Milling and Drilling Tungsten

- 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

Initial Tungsten Sample

Post Testing Sample

End mill cutting edge post milling two parts



Drill edge post drilling 12 test holes

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Ultrasonic Assisted Reaming

Baseline Results	
Force (N)	169.0
Torque (Nm)	2.141
Surface Finish (Ra µm)	0.2648
Bore Size (mm)	8.014

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

Ultrasonic Results	
Force (N)	108.0
Torque (Nm)	0.9525
Surface Finish (Ra µm)	0.6153
Bore Size (mm)	8.024

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

Ultrasonics Applied at 150% of baseline feed rate	
Force (N)	123.9
Torque (Nm)	1.816
Surface Finish (Ra µm)	0.2839
Bore Size (mm)	8.031

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

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

Summary of Tapping Study performed on 4340 Alloy steel

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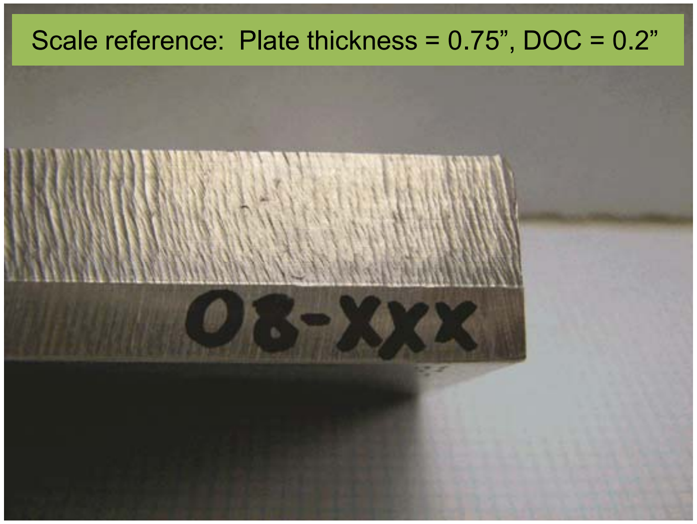
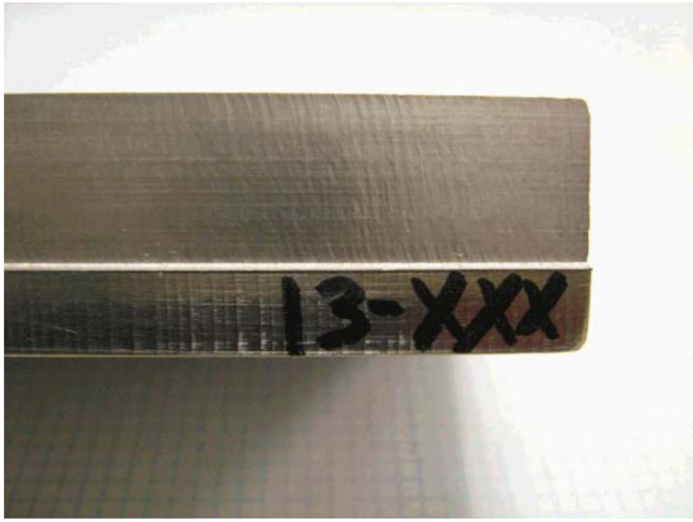
US Milling Titanium

- **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**

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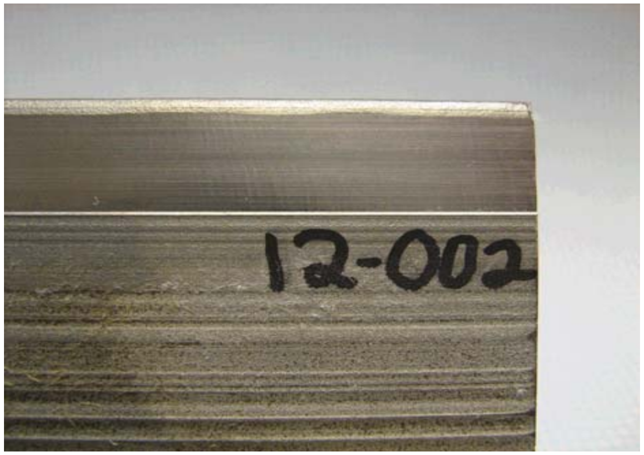
Titanium Milling cont.

- **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**

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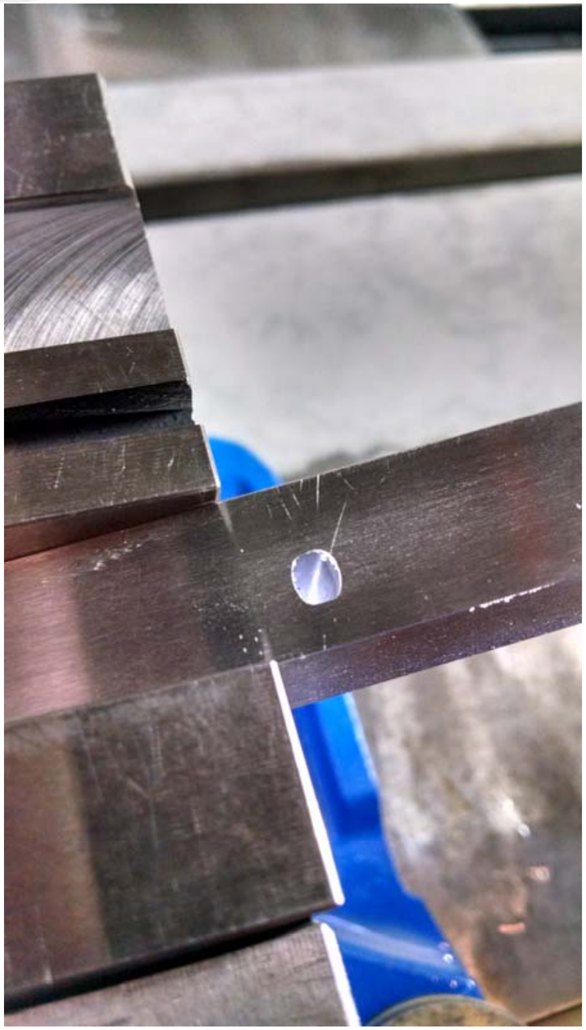
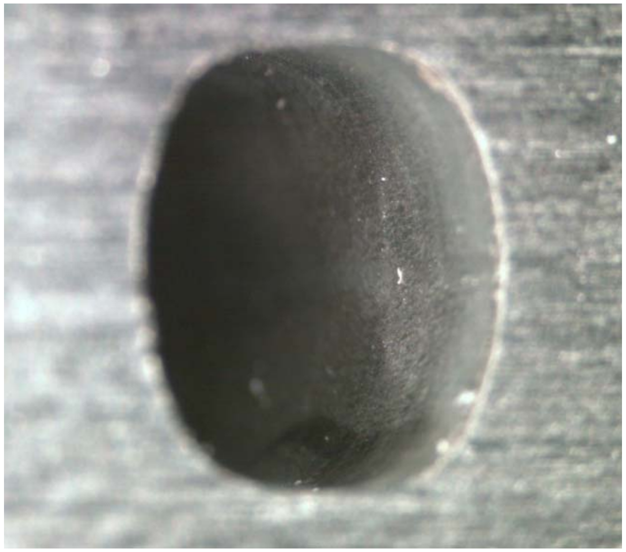
High Aspect Ratio Milling





Surface Finish Result

Top Surface Engagement

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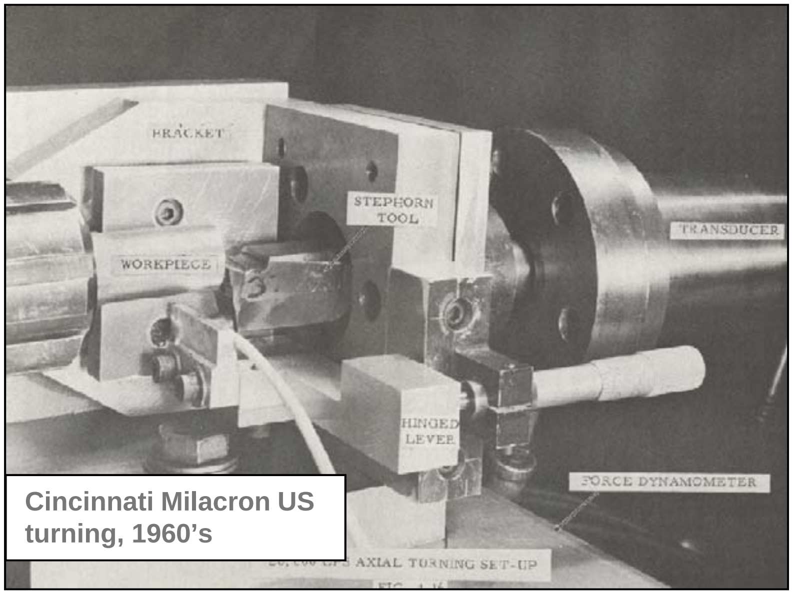
Understanding Tooling Affects

- **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

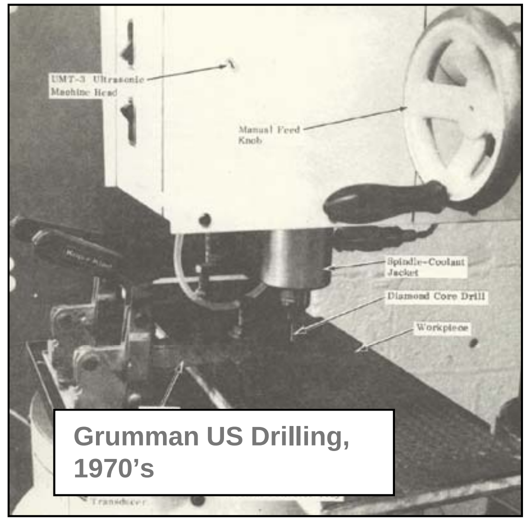
Presentation Overview

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

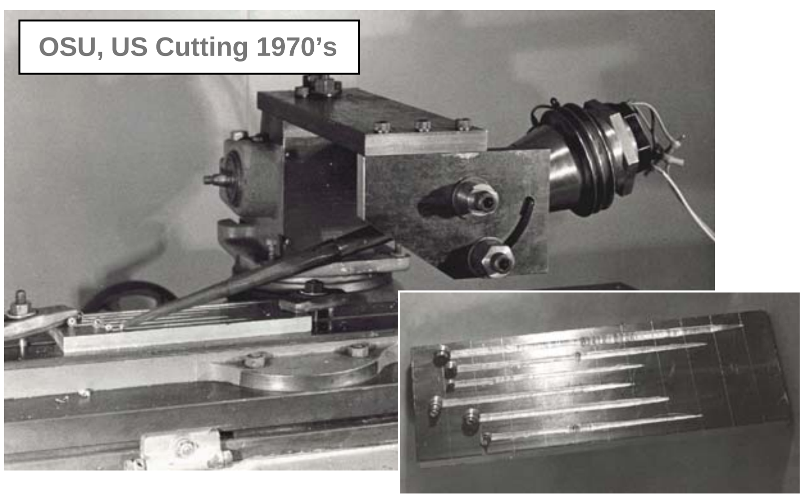
Historical Background



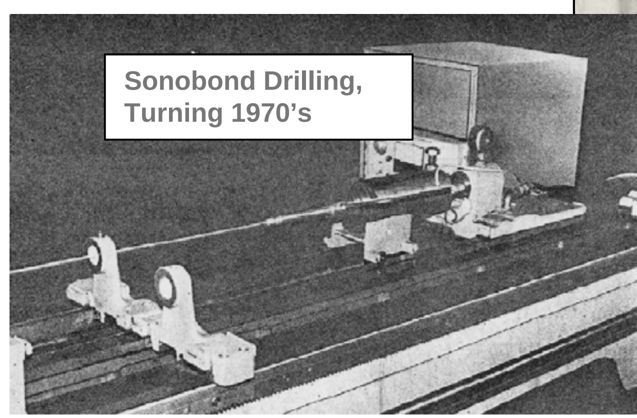
Cincinnati Milacron US turning, 1960's



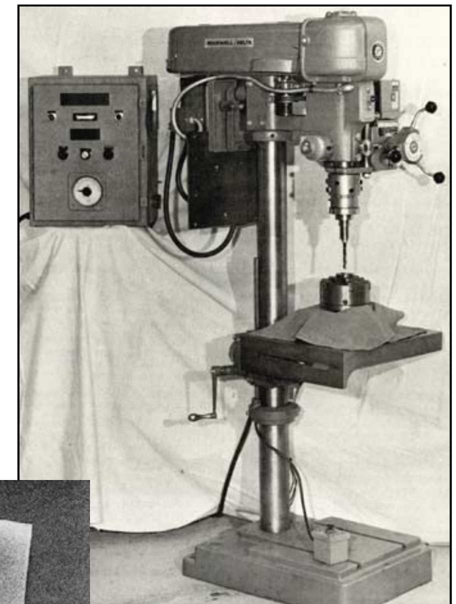
Grumman US Drilling, 1970's



OSU, US Cutting 1970's



Sonobond Drilling, Turning 1970's



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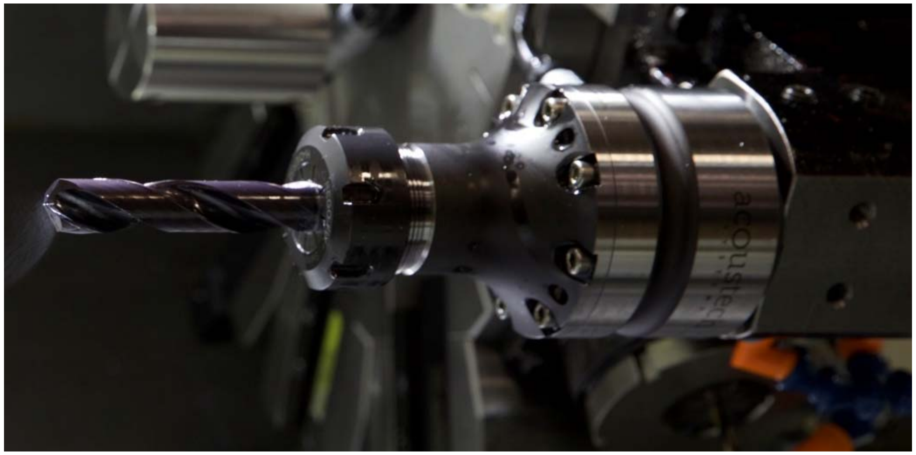
Acoustech N-Series Module

- **1.5-in Ø straight shank mounting provision**
  - 4 flats every 90º
- **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

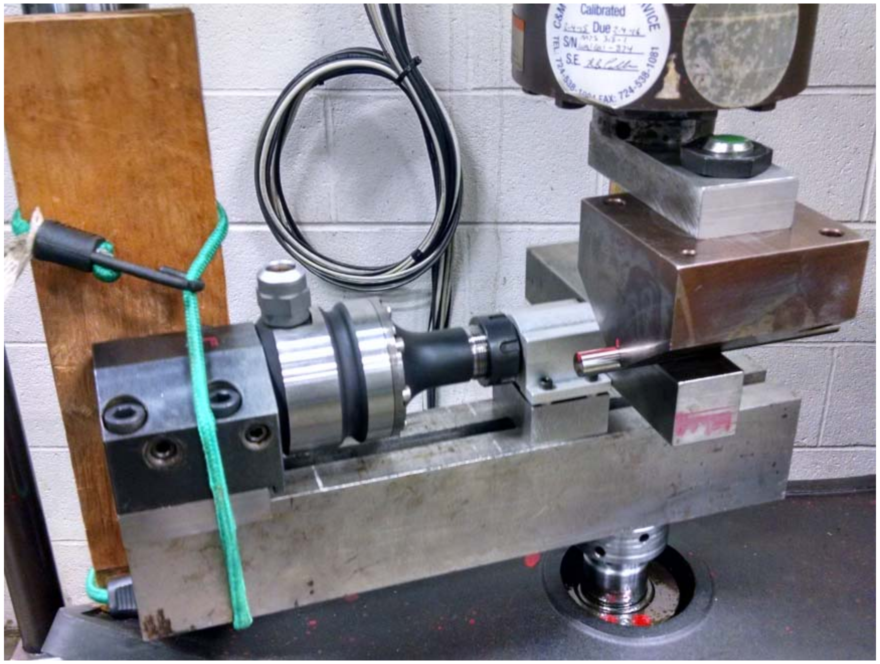


Fig. Torsional Test Set-up

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N-Series Durability cont.

Drop Testing

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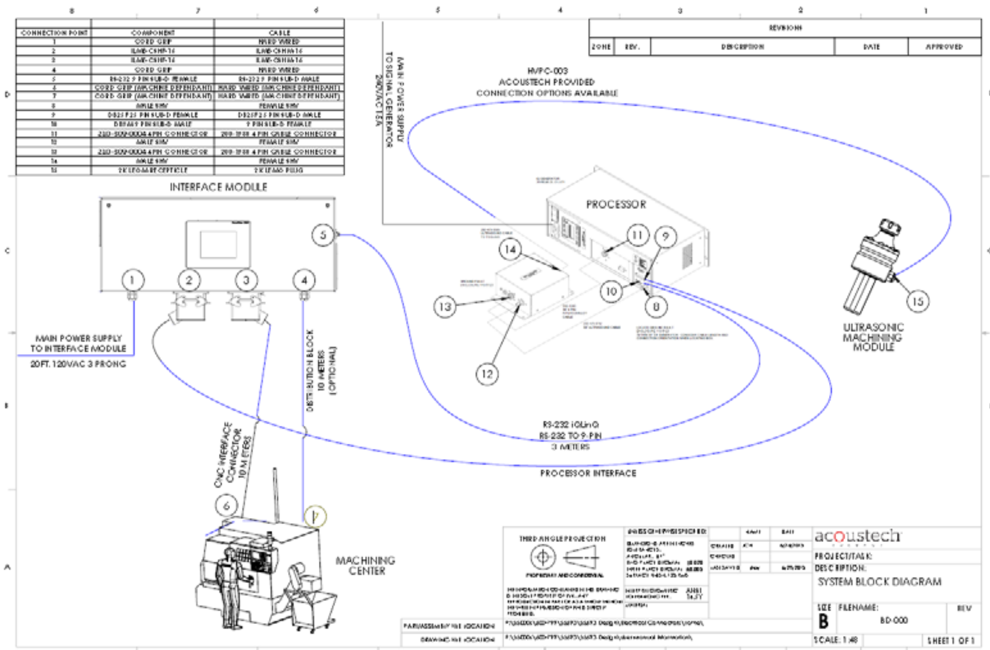
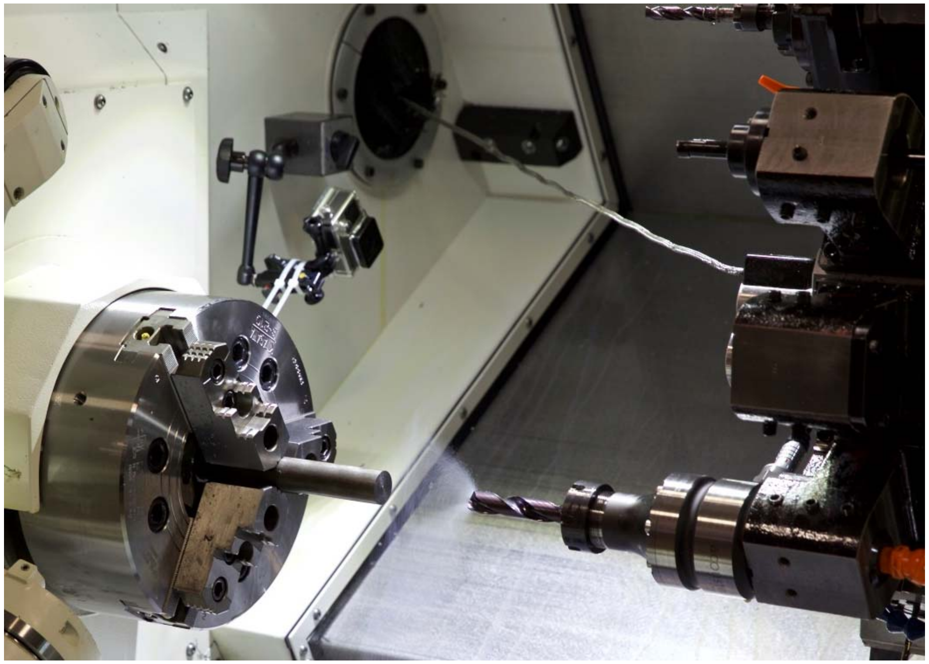
Machine Tool Integration



- 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



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Ongoing Developments

- **R-Series Modules**
  - Design considerations
    - Electrical connection
    - Tool changers
    - Weight
    - Contamination
    - Through spindle coolant
- **Other processes**
  - Turning
  - Grinding

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