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Principles and Applications of High Power Ultrasonics

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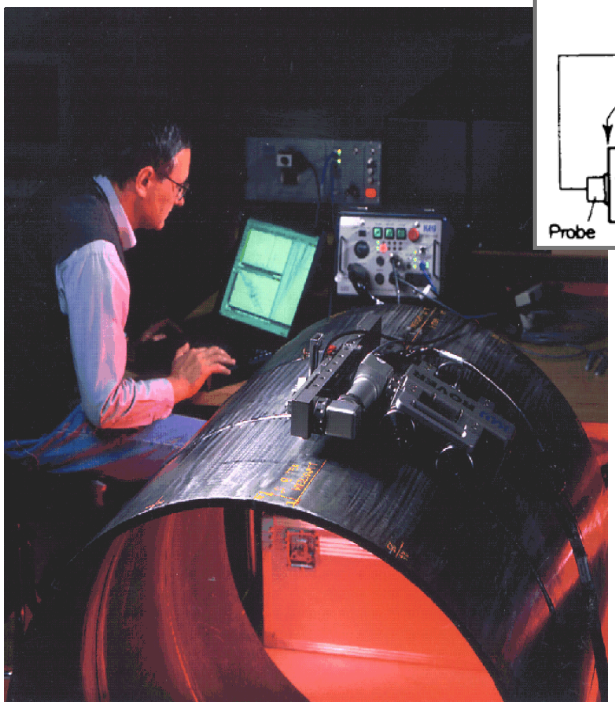
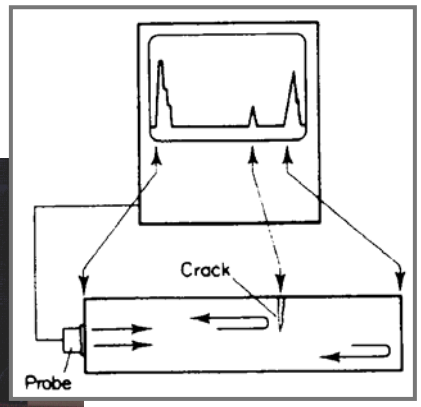
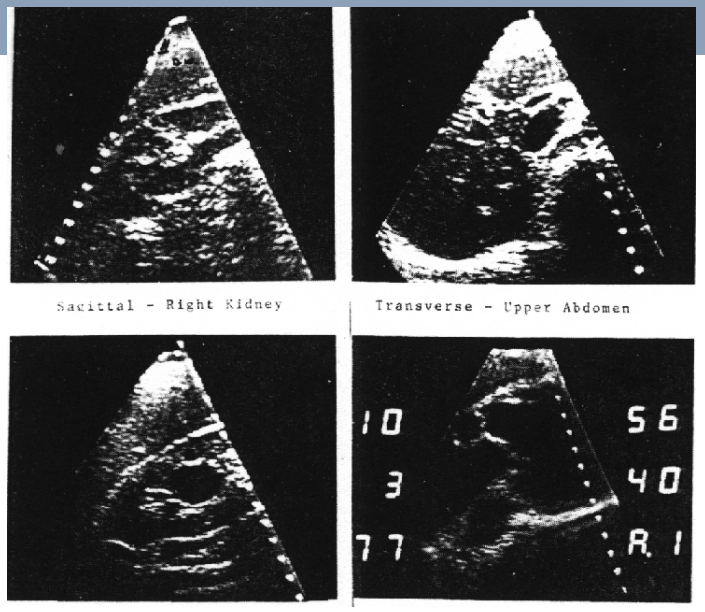
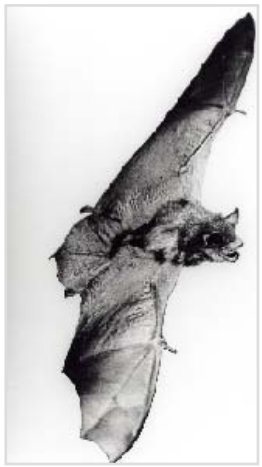
The Field of Ultrasonics

- High frequency ultrasonics
- High power ultrasonics









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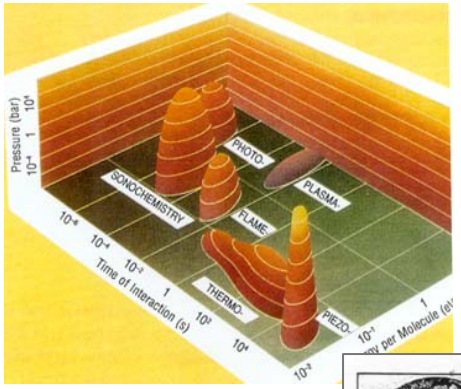
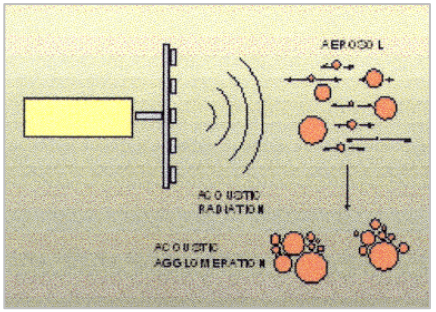
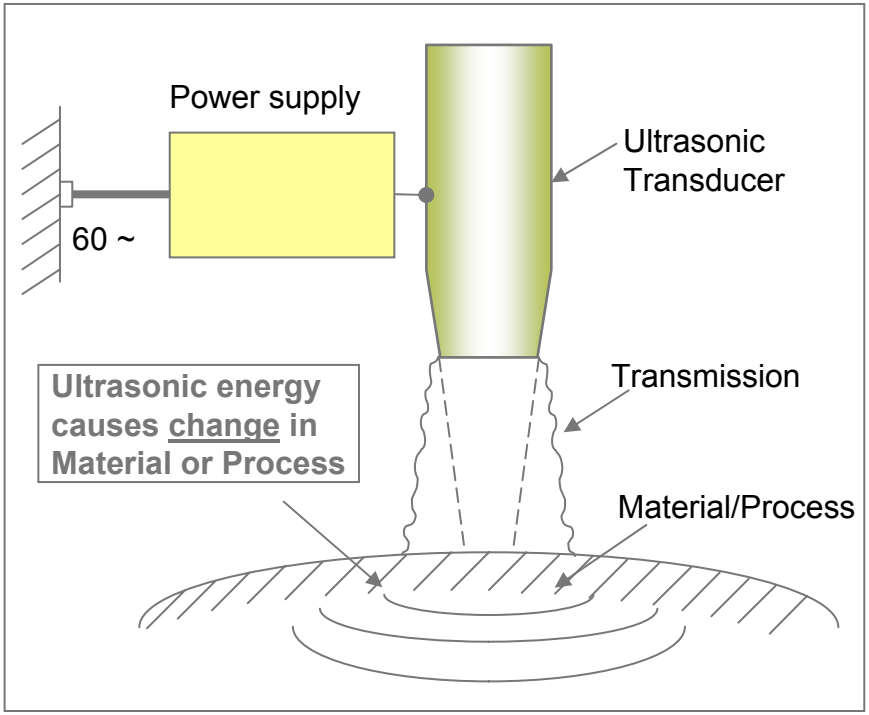
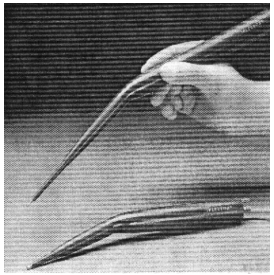
What is High-Power Ultrasonics?

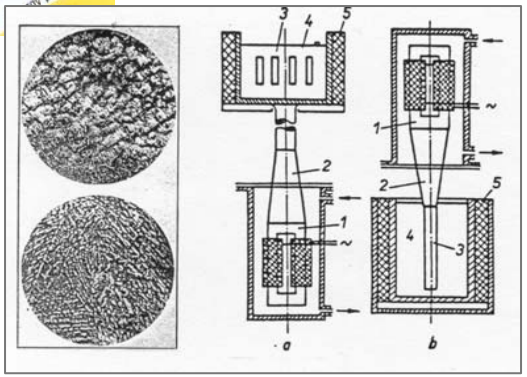
- **HPU … application of intense, high-frequency acoustic energy to *change* materials, processes.**

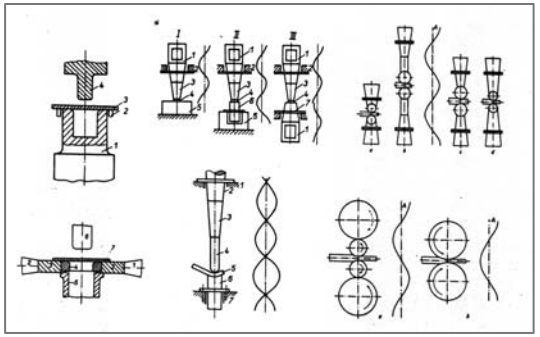












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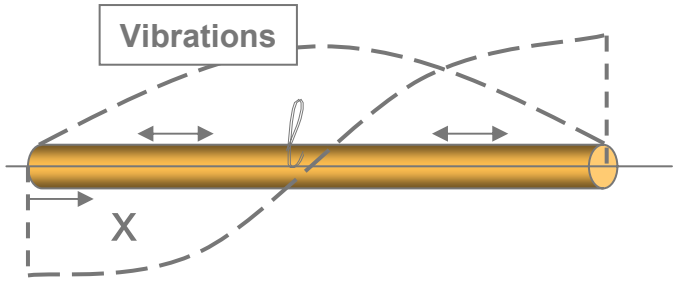
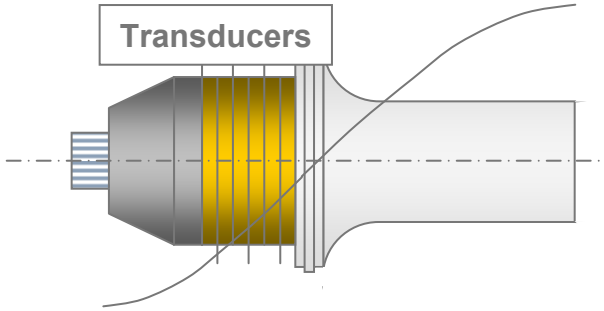
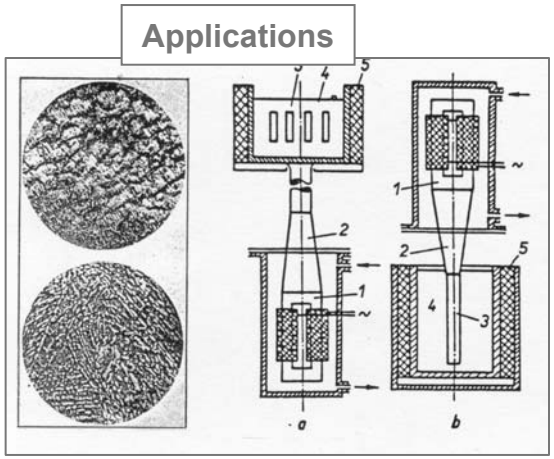
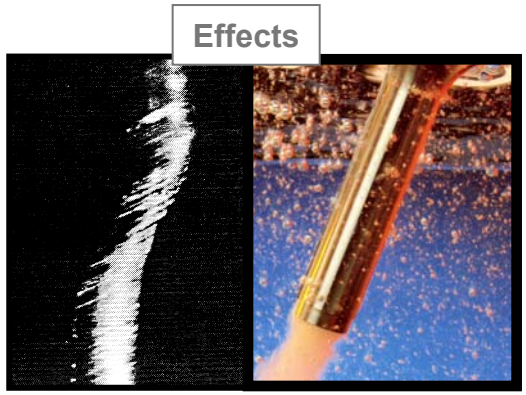
Outline …

- Ultrasonic vibrations and waves
- Transducers and systems
- Physical effects of HPU
- Applications of HPU









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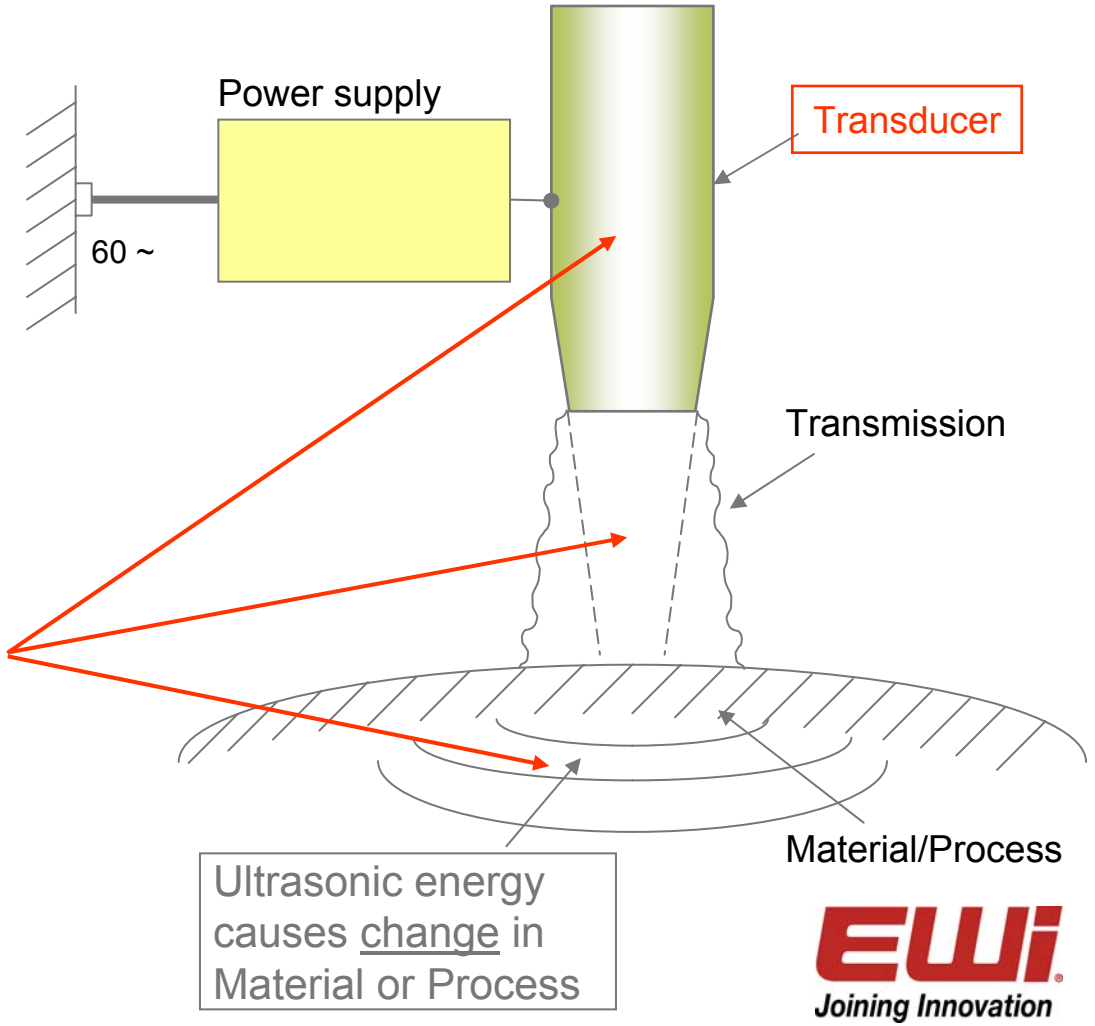
US Vibrations & Waves

- HPU … application of intense (i.e., high-power), high-frequency (i.e., ultrasonic) acoustic energy to create ***change*** in materials and processes.
- Vibrations & Waves enter at every stage of HPU



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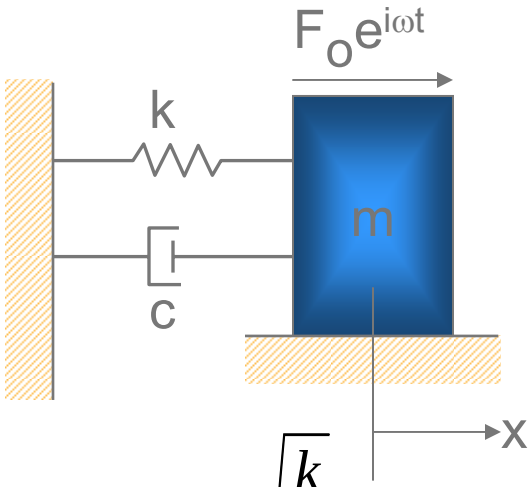
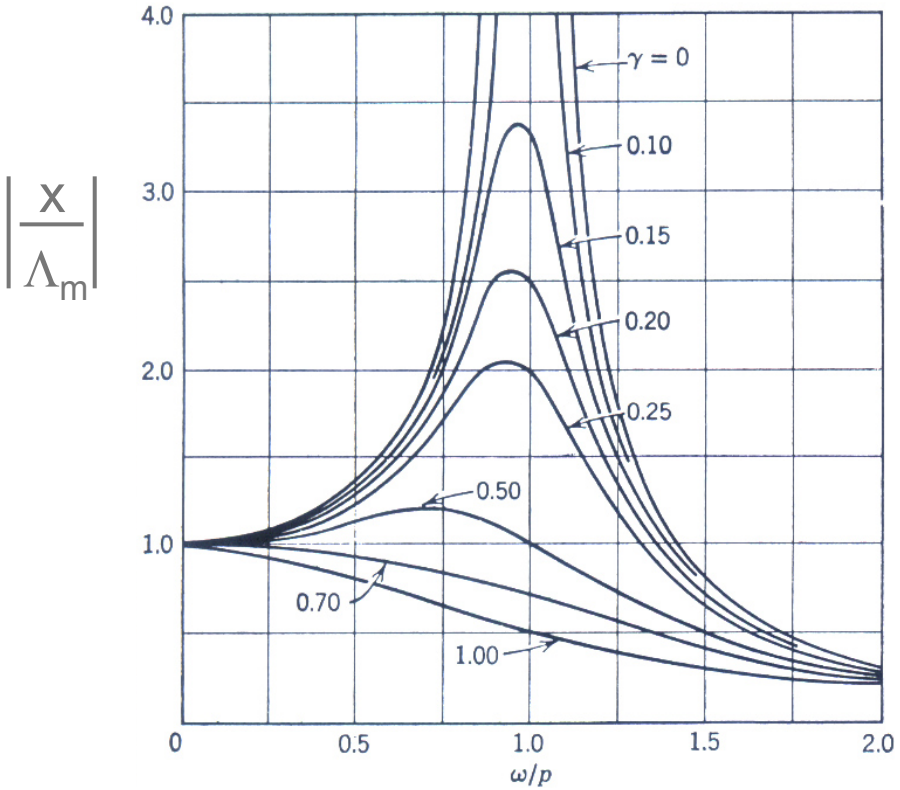
Oscillator



$$\omega_n = \sqrt{\frac{k}{m}}$$



Timoshenko, S., Young, D.H. and Weaver, W. Jr., "Vibration Problems in Engineering," Fourth Edition, John Wiley & Sons, New York, 1974, Fig. 1.33.

Teaches …

- Natural frequency
- Resonance
- High Q

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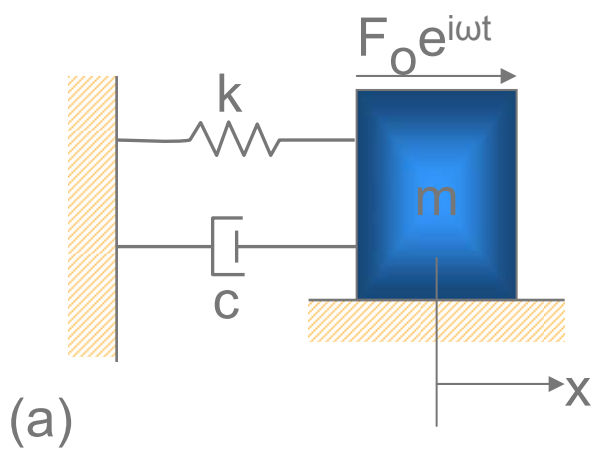
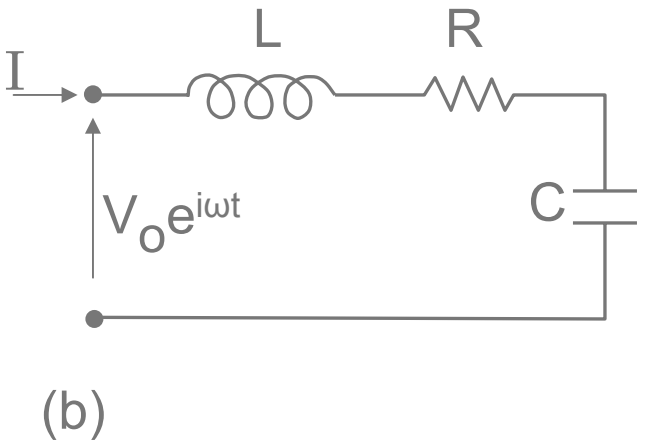
Equivalent Circuits





F - force on the mass
v - velocity of mass
k - spring stiffness
m - mass

V - voltage applied to the circuit
I - current in the circuit
L - inductance
R - resistance

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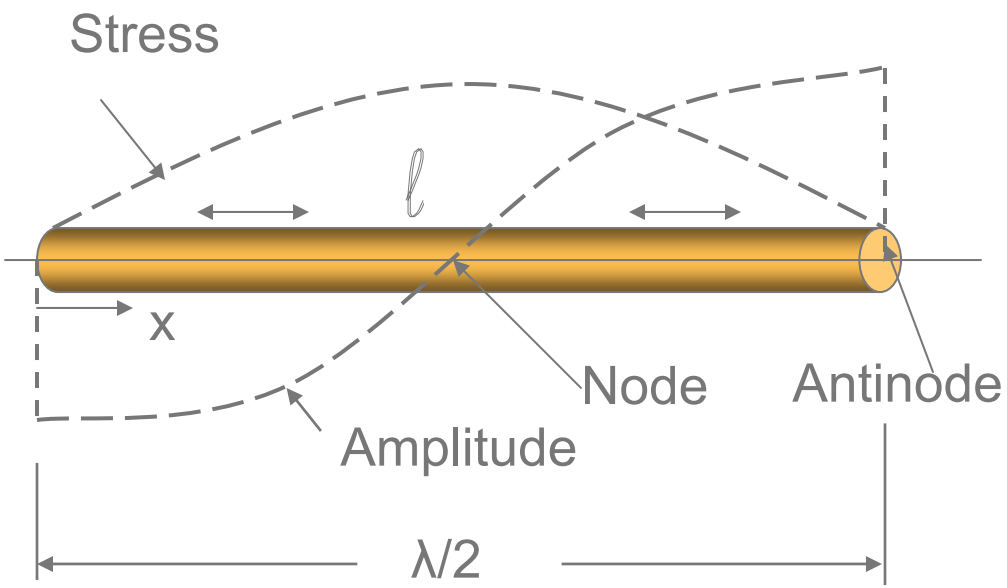
Longitudinal Vibrations

Basic Vibration Concepts



- 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 $20 \times 10^3 \text{ Hz} \quad (20 k\text{Hz})$

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

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

$$\cong 5 \text{ in.}$$

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Wave (Bar, Rod) Velocities

c ~ *Wave velocity in rod* = $(E/\rho)^{1/2}$

Material	Bar velocity	
	m s^{-1} x 10^{-3}	in. s^{-1} x 10^{-4}
Aluminum	5·23	20·6
Brass	3·43	13·5
Cadminum	2·39	9·4
Copper	3·58	14·1
Gold	2·03	8·0
Iron	5·18	20·4
Lead	1·14	4·5
Magnesium	4·90	19·3
Nickel	4·75	18·7
Silver	2·64	10·4
Steel	5·06	19·9
Tin	2·72	10·7
Tungsten	4·29	16·9
Zinc	3·81	15·0

Note: Titanium ~ steel, aluminum, magnesium

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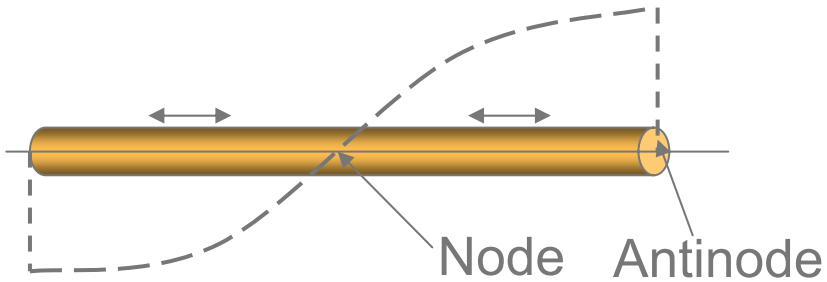
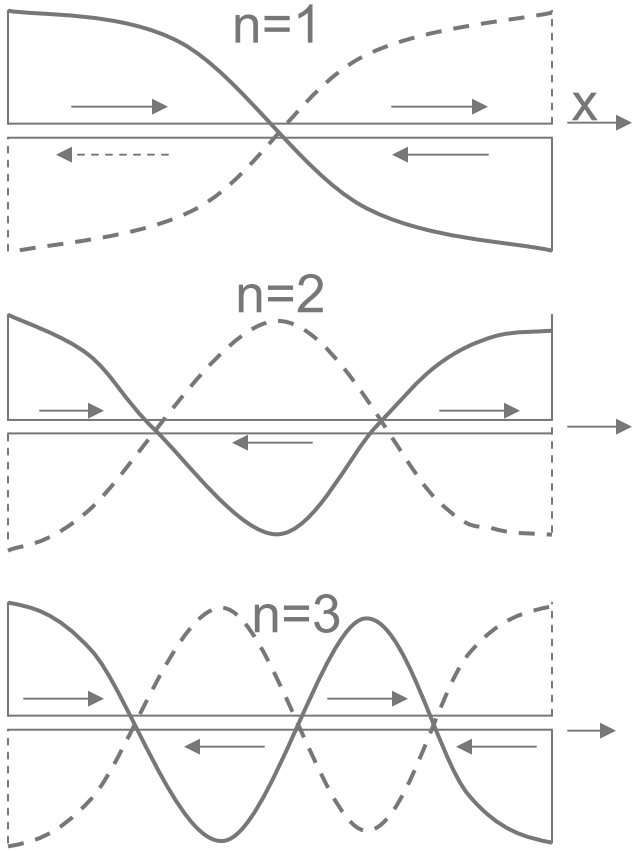
Longitudinal Vibration Modes



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

n = 1, 2, 3, …



$$f_1 = \frac{c}{2\ell}$$

$$f_2 = \frac{c}{\ell}$$

$$f_3 = \frac{3c}{2\ell}$$

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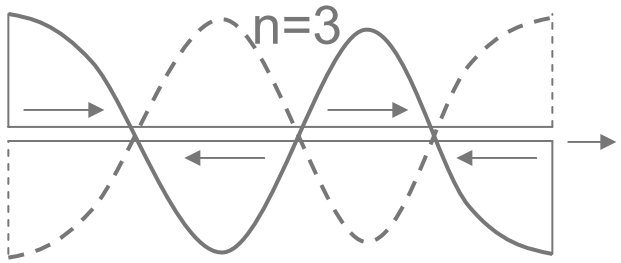
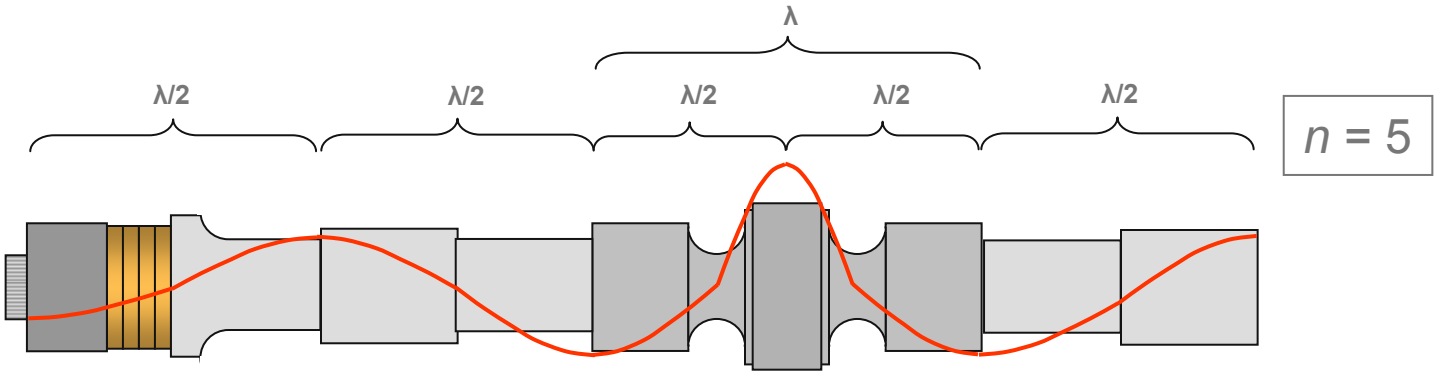
Note on “Mode Counting”

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



$$f_3 = \frac{3c}{2\ell}$$

Mode counting “with a vengeance ”



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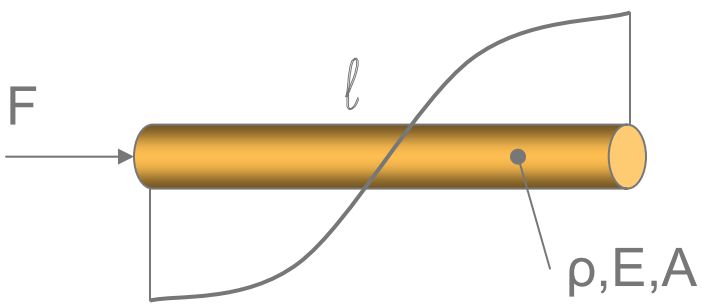
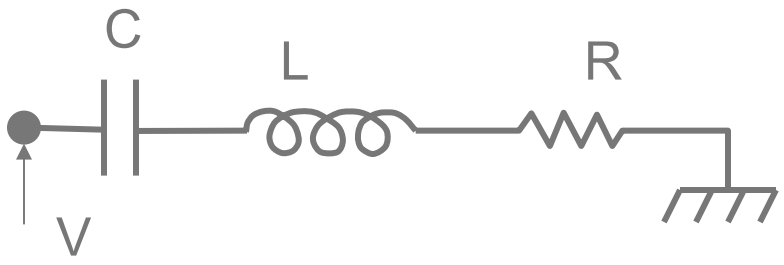
Equivalent Circuits





$$f = \frac{C_0}{2l}$$

$$1/C = \frac{\pi^2 AE}{2l}$$

$$L = \frac{\rho A l}{2}, R = \text{loss}$$

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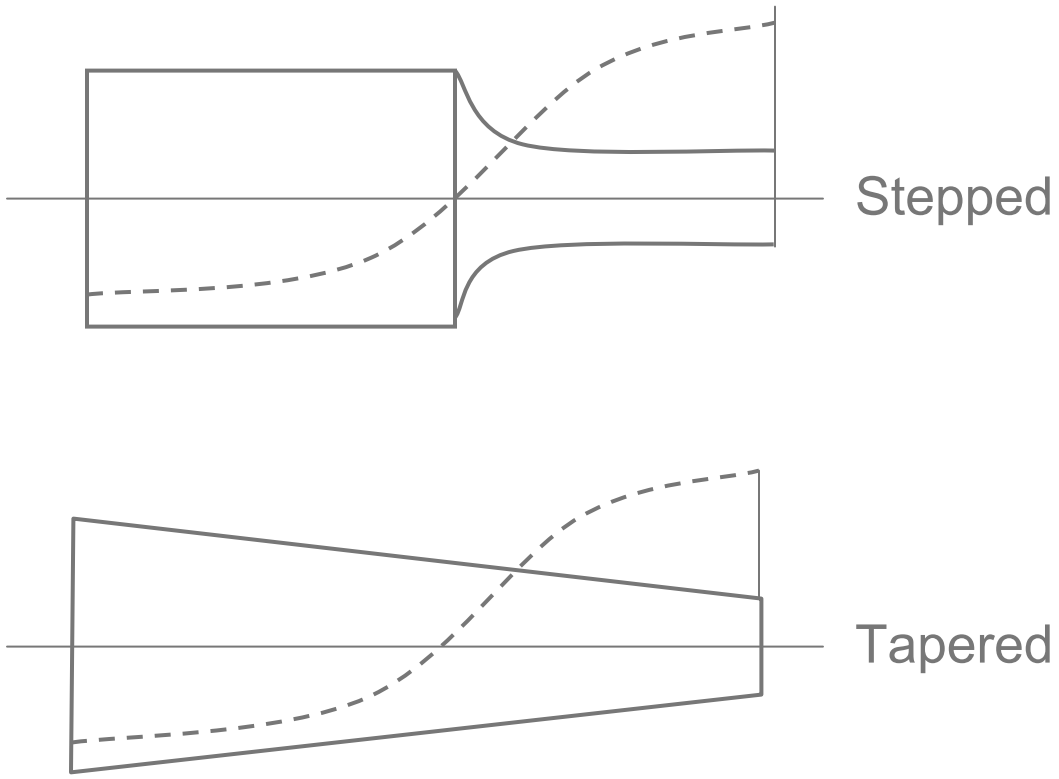
Ultrasonic Horns

$$M = \frac{U_{large}}{U_{small}}$$

Stepped :

$$M = \frac{A_{large}}{A_{small}}$$



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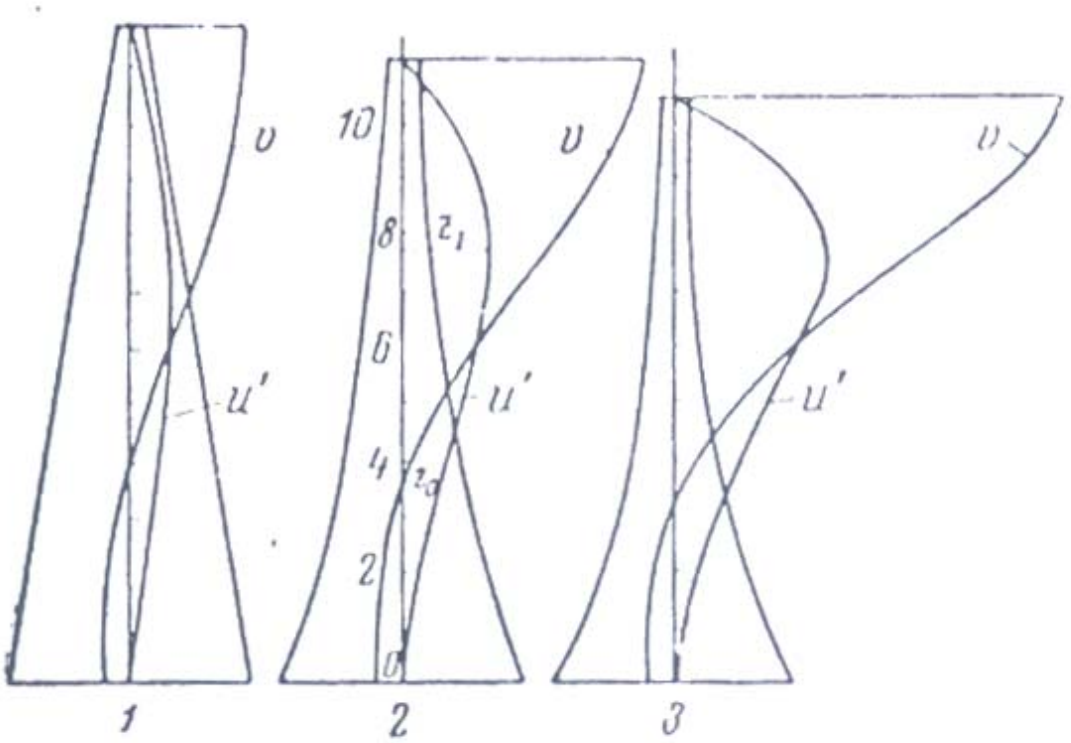
Tapered Horns



Merkulov, L.G., “Ultrasonic Concentrators,” Soviet Physics- Acoustics, v. 3, no. 6, pp. 246=255, 1957, Fig. 4.

1. Conical
2. Exponential
3. Catenoidal

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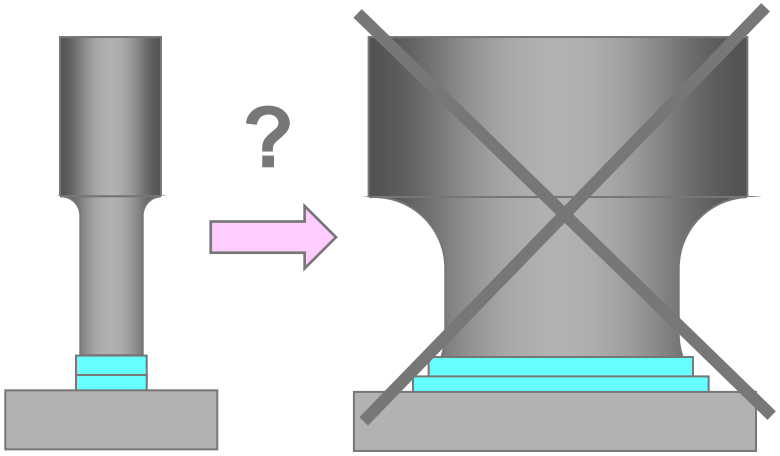
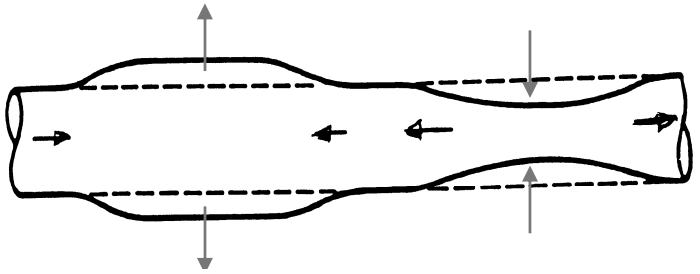
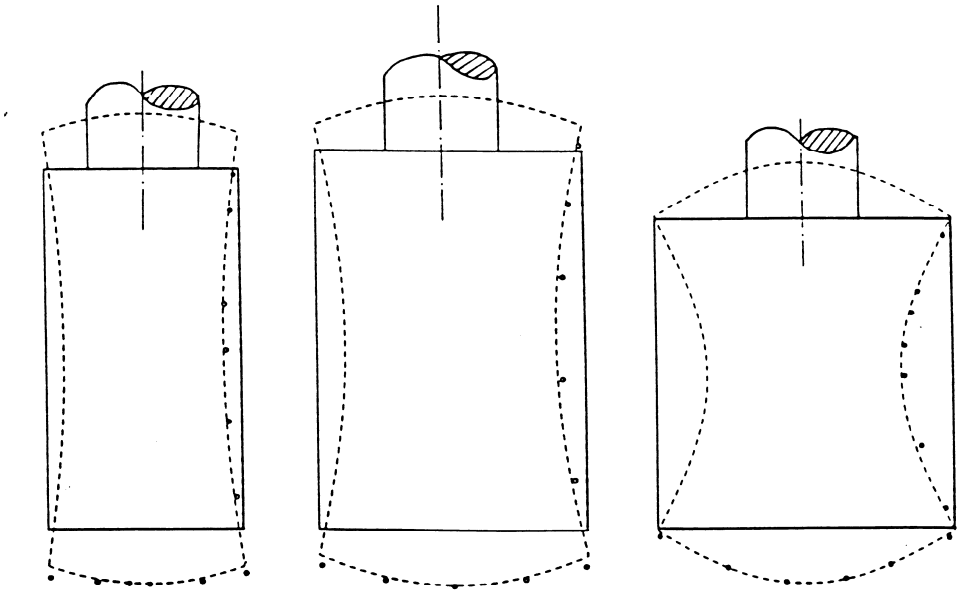
Large Horns – Lateral Strain ("Poisson" effect), etc.

- Wide parts need wide horns, but …







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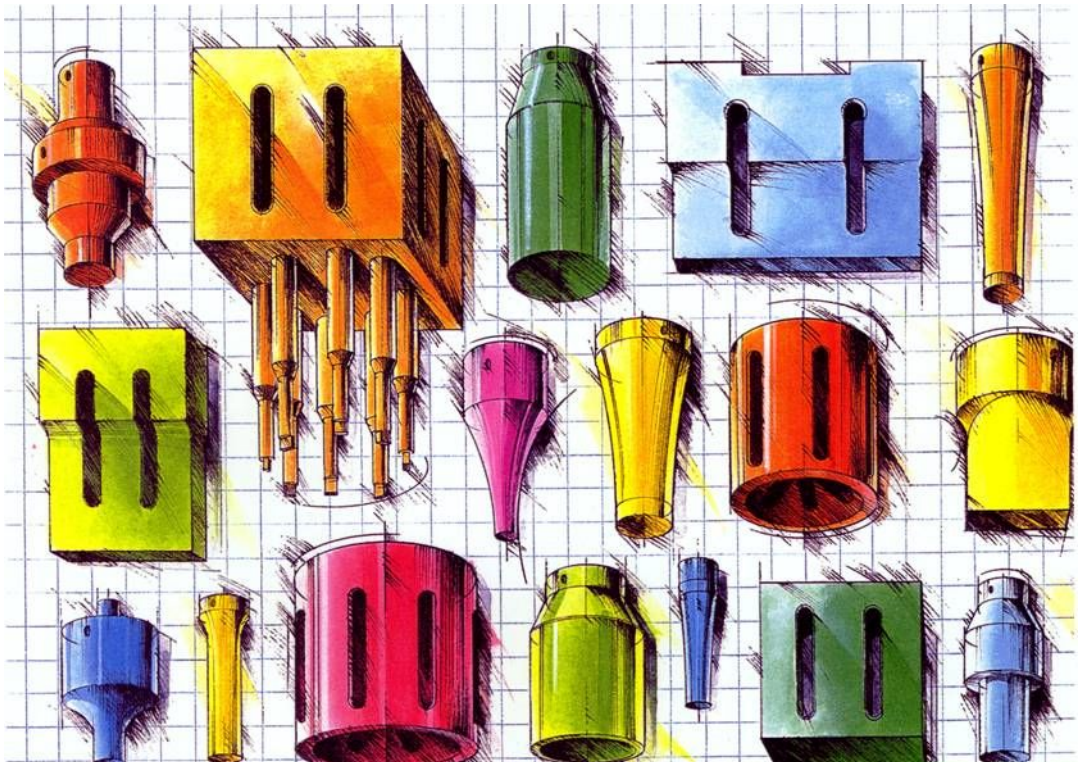
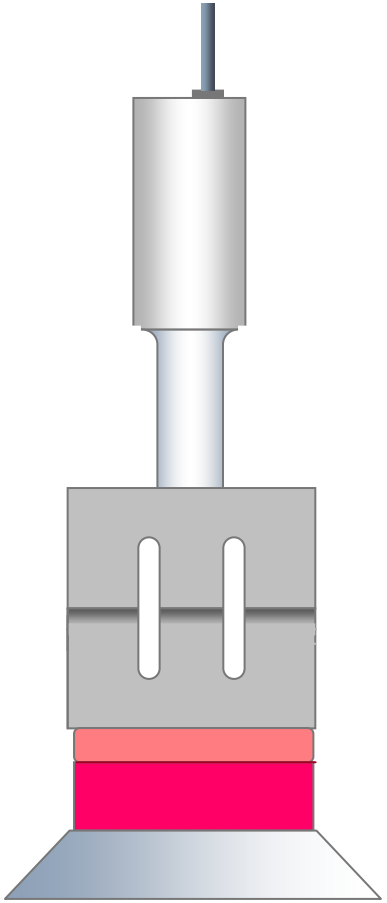
Large Horns





(From Branson product literature)

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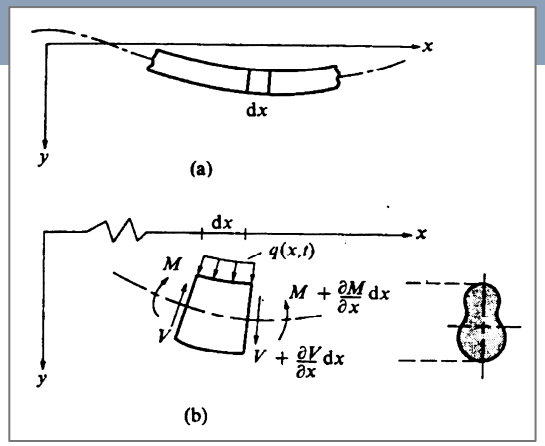
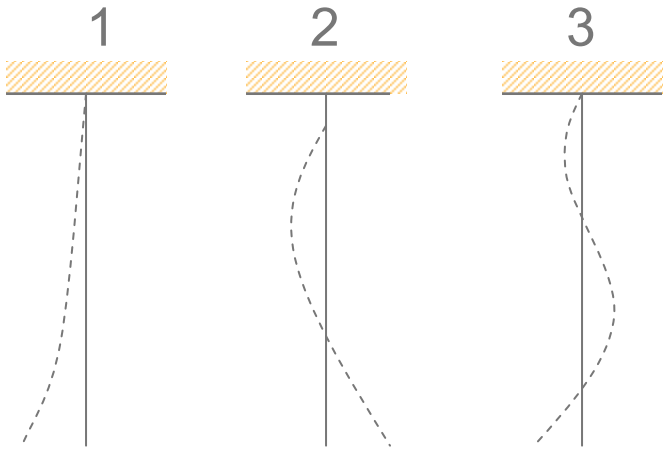
Bending Vibrations



$$f = \frac{a\beta^2}{2\pi} \qquad a^2 = \frac{Ic^2}{A}$$

A = Cross-section area
I = Moment of inertia of cross-section



β_1/=1.875
β_2/=4.694
β_3/=7.855

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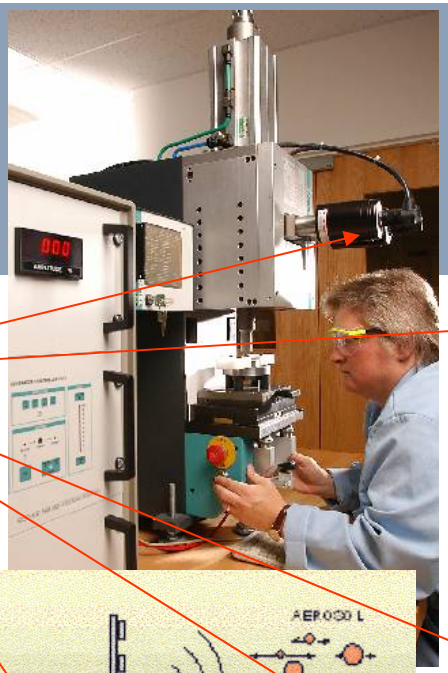
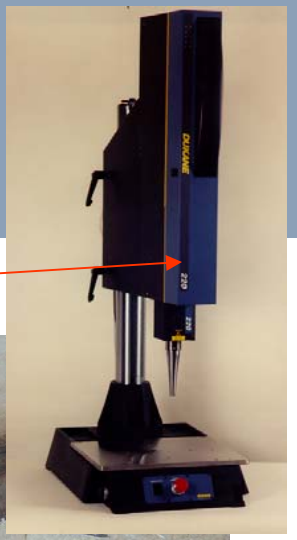
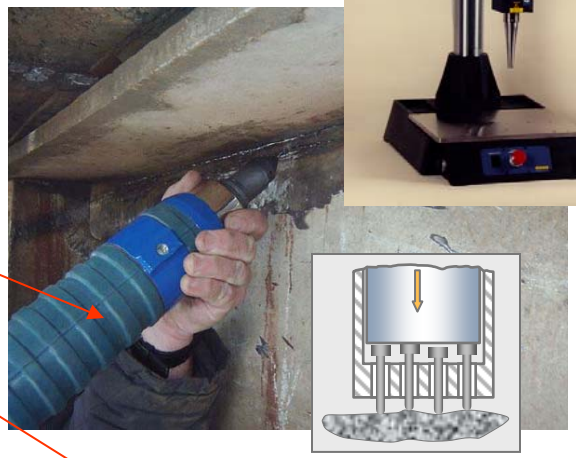
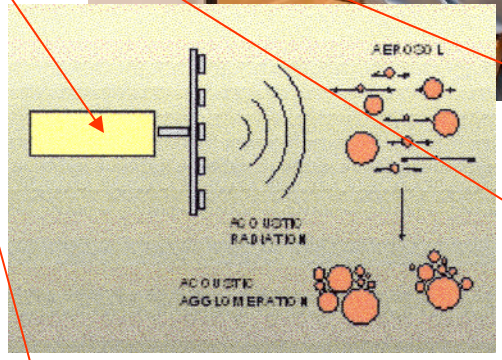
HPU Processes

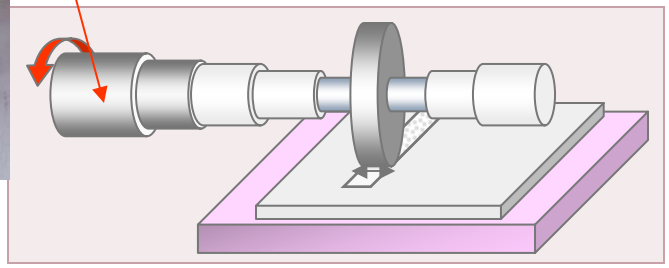
- Transducers

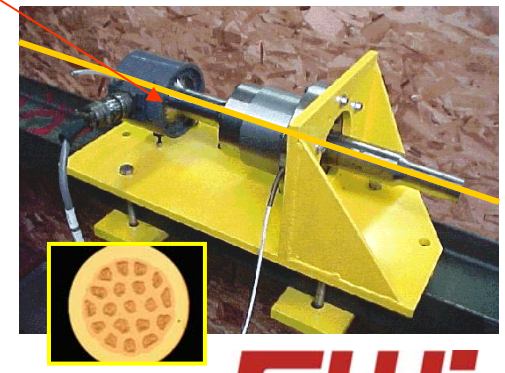












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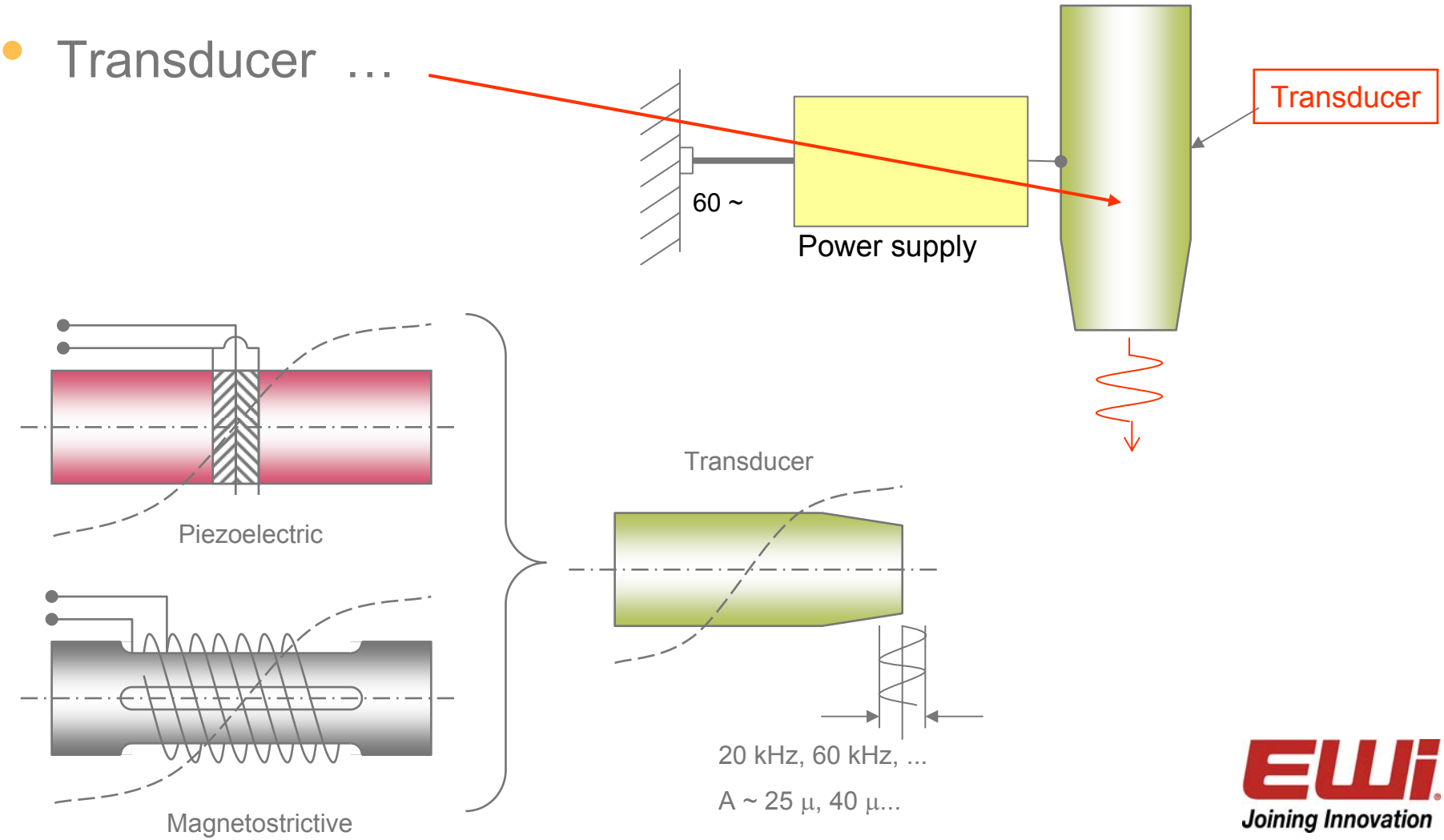
Transducers

- Transducer …



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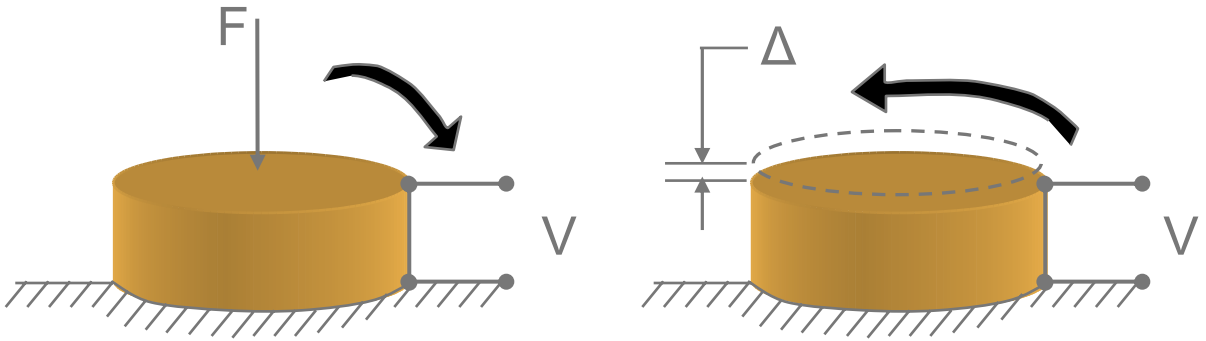
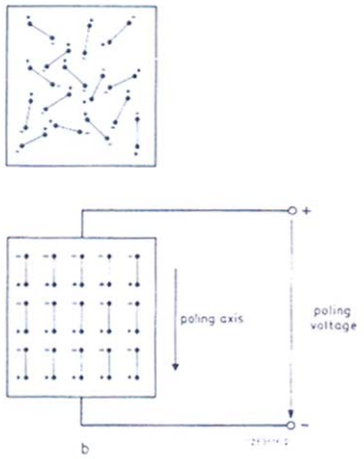
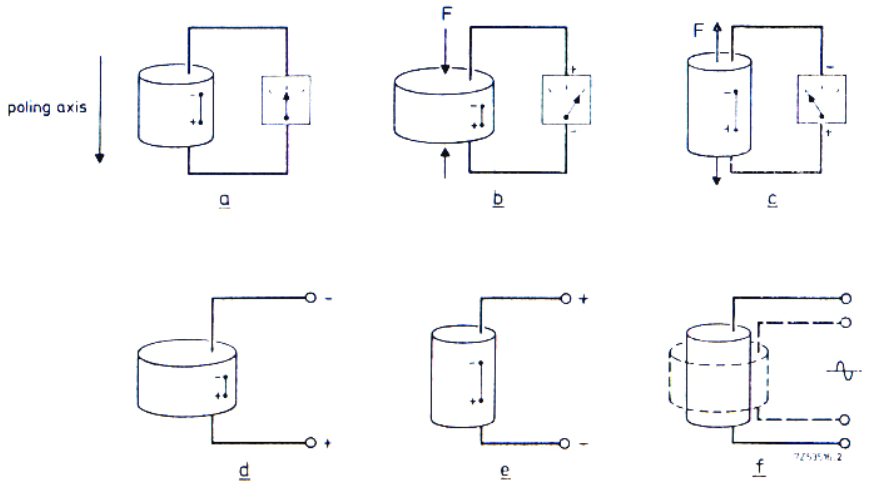
Piezoelectricity, Piezoelectric Effect





Van Randeraat, J. and Setterington, R.E., Piezoelectric Ceramics, N.V. Phillips' Gloeilampenfabrieken, Einhoven, The Netherlands, Second Edition, 1974. Fig. 2.1.



Van Randeraat, J., op. Cit., Fig. 2.2

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Piezoelectric Equations

$\sigma = c^D \varepsilon$ ~ Elastic solid

$E = \beta D$ ~ Capacitor

$$\sigma = c^D \varepsilon + hD$$
$$E = -h\varepsilon + \beta D$$

~ Piezoelectric material

σ, ε = stress, strain
E,D = electric field, displacement
c^D, β = elastic, dielectric constants
h = piezoelectric constant

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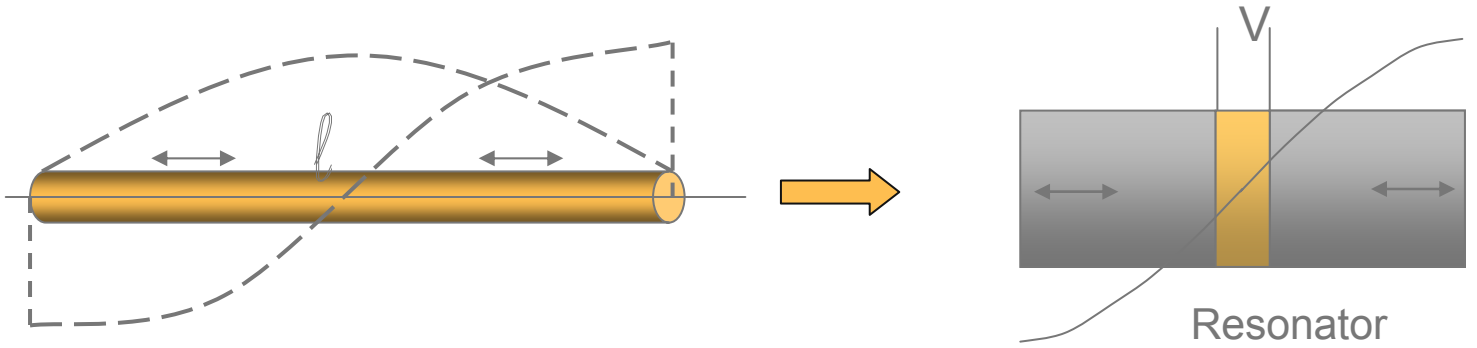
Transducer (Converter)



"Real" Transducer …

- Precompression
- Electrical safety
- Heating
- Vibration amplification
- Assembly
- Gripping/holding
- Tooling attachment

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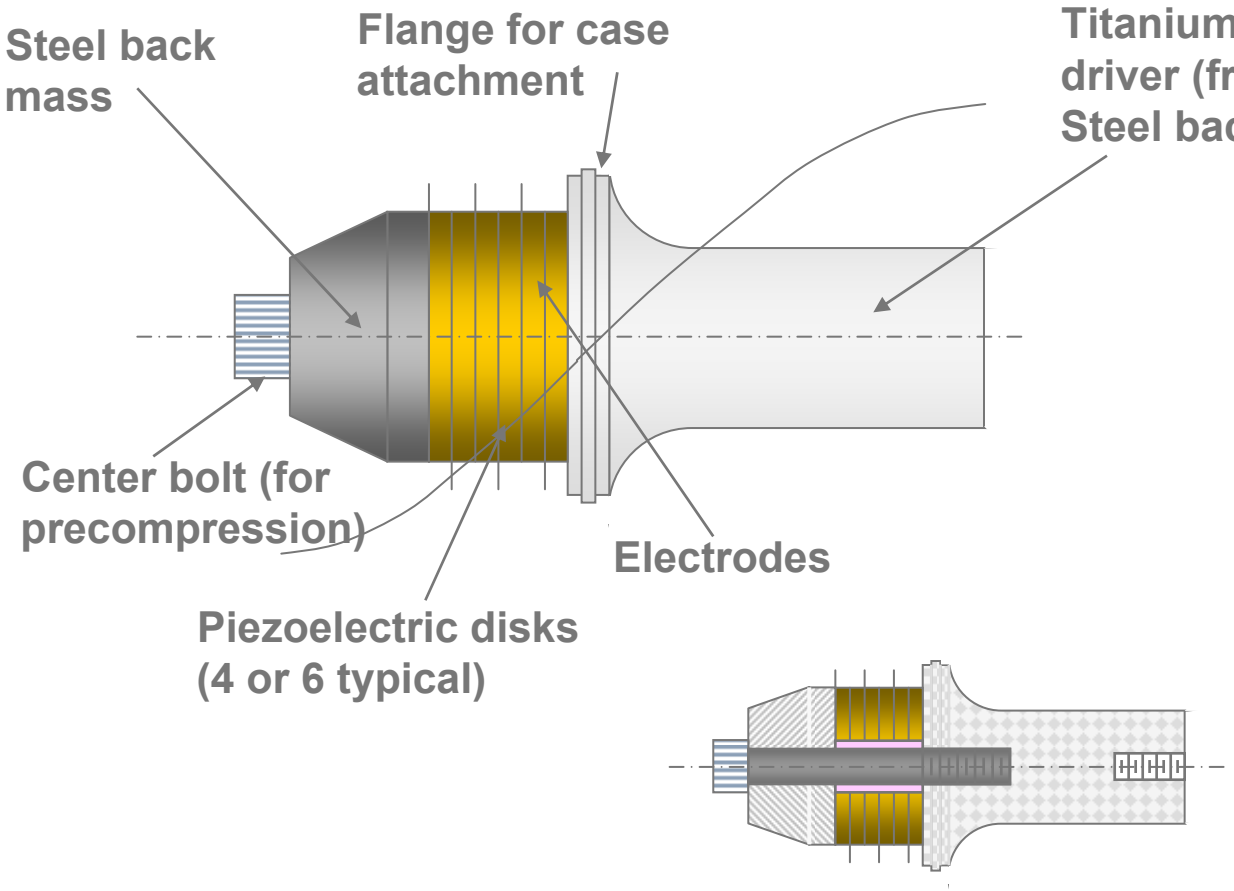
HPU Piezoelectric Transducer



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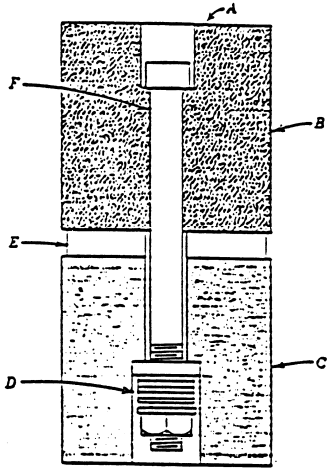
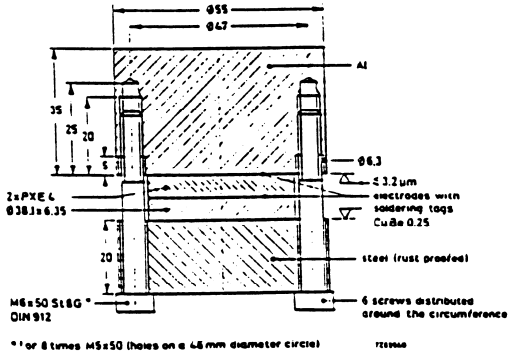
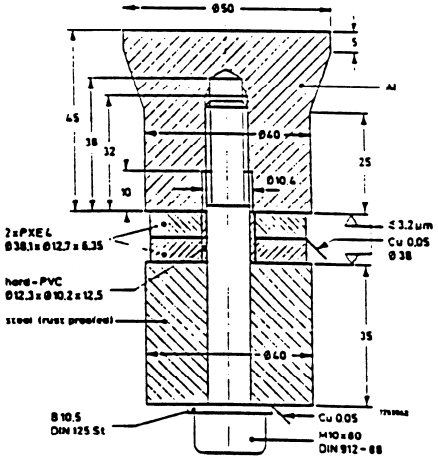
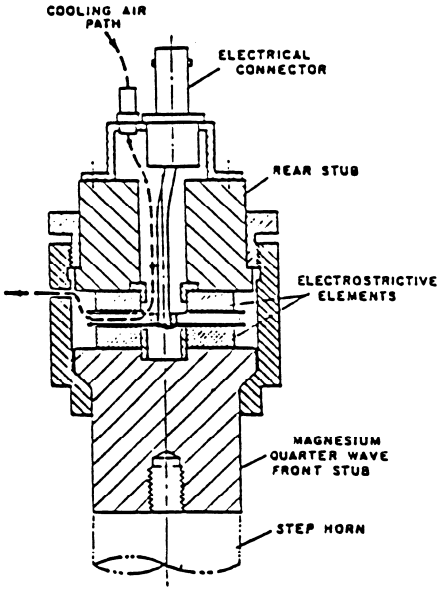
Transducer Designs



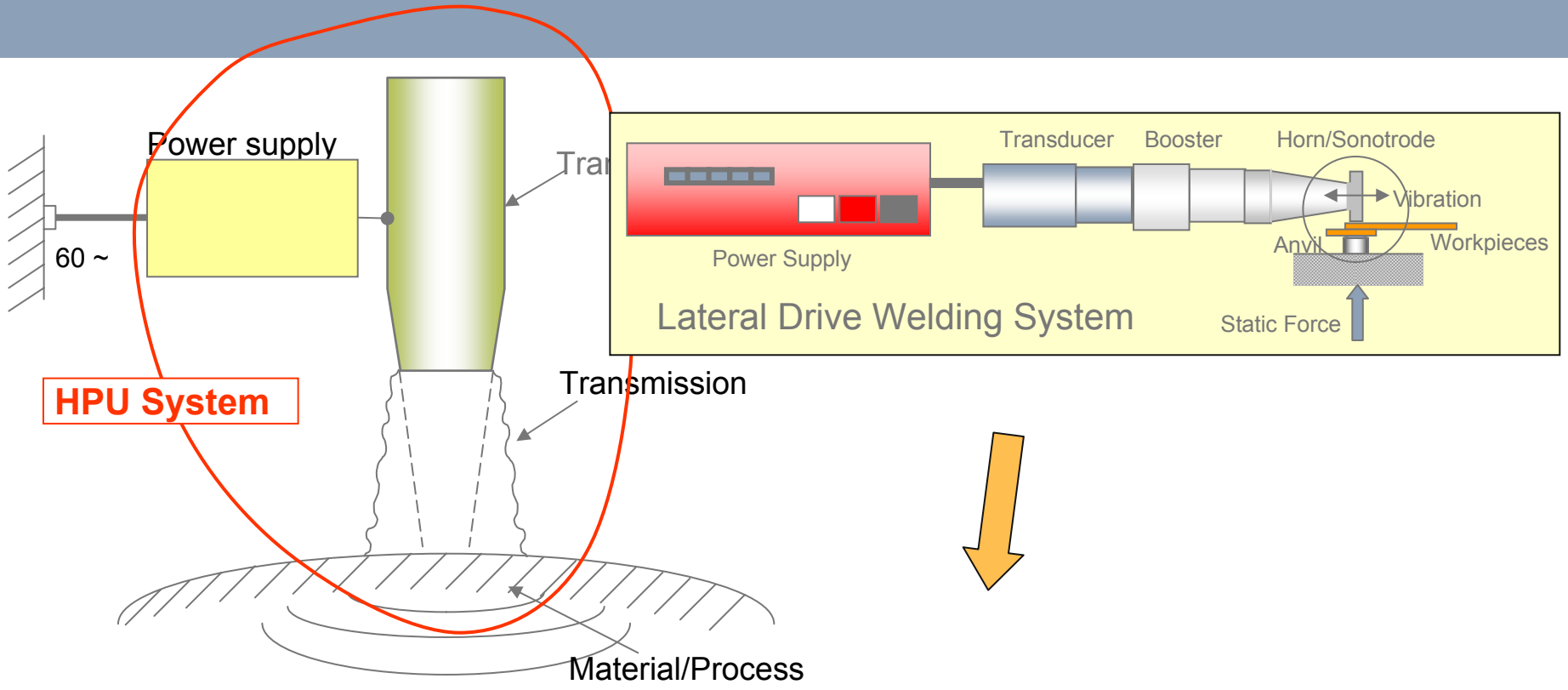


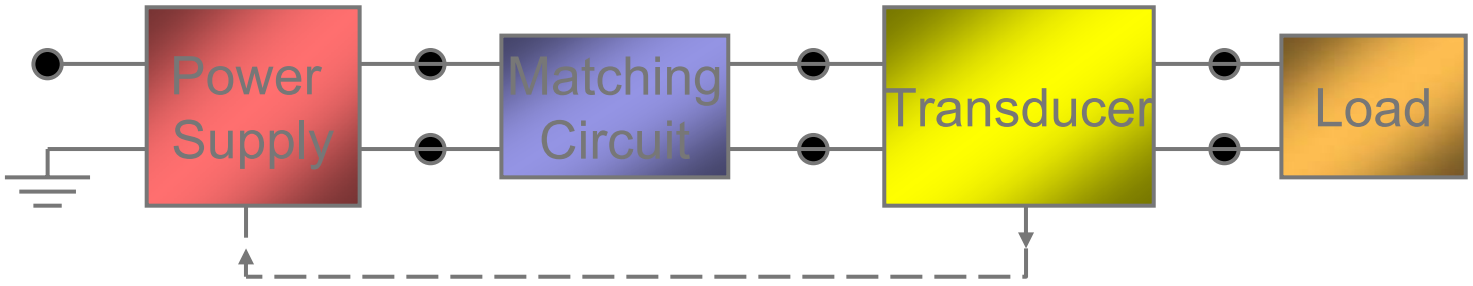




EWI
Joining Innovation

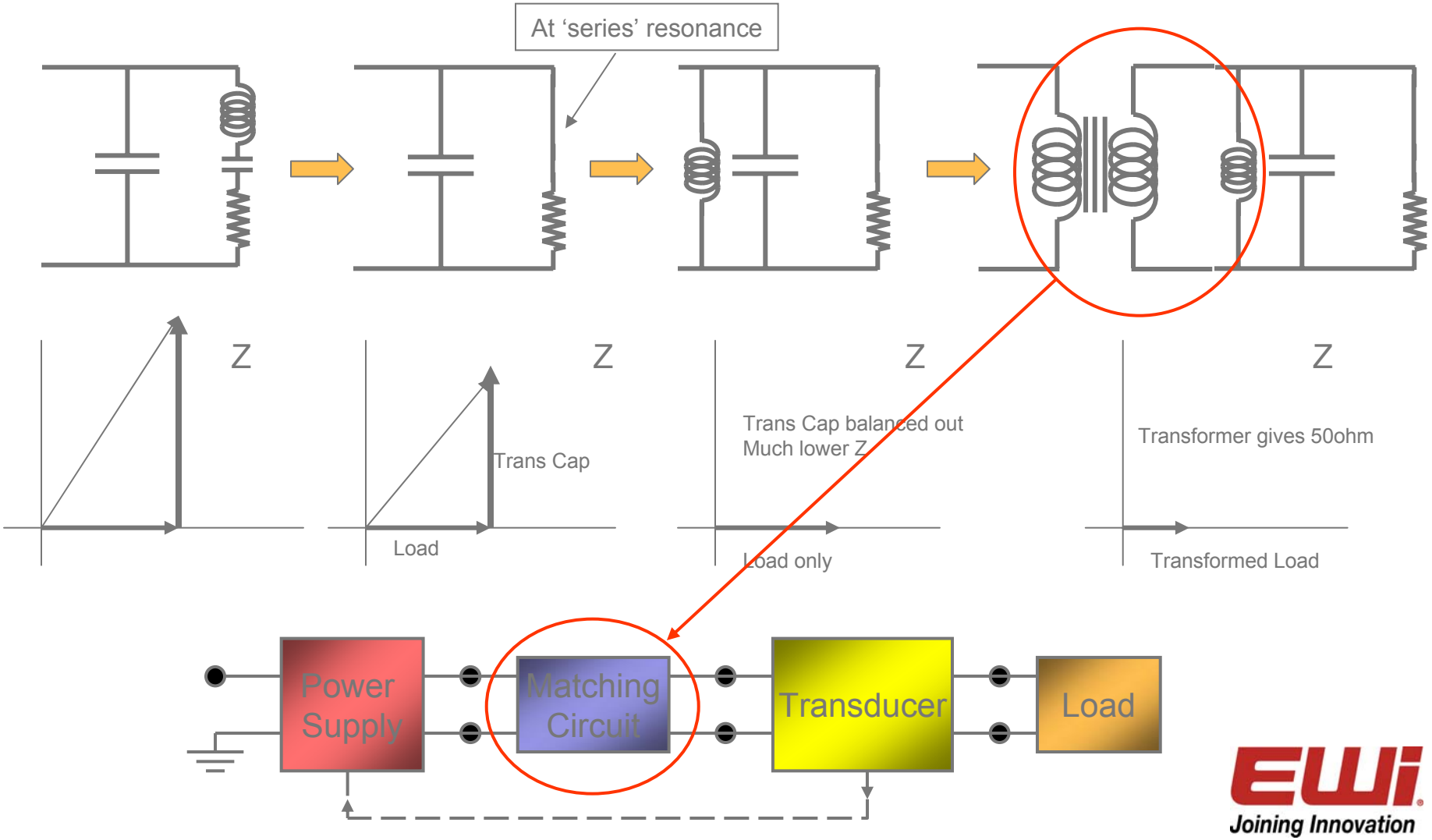
High-Power Ultrasonic System





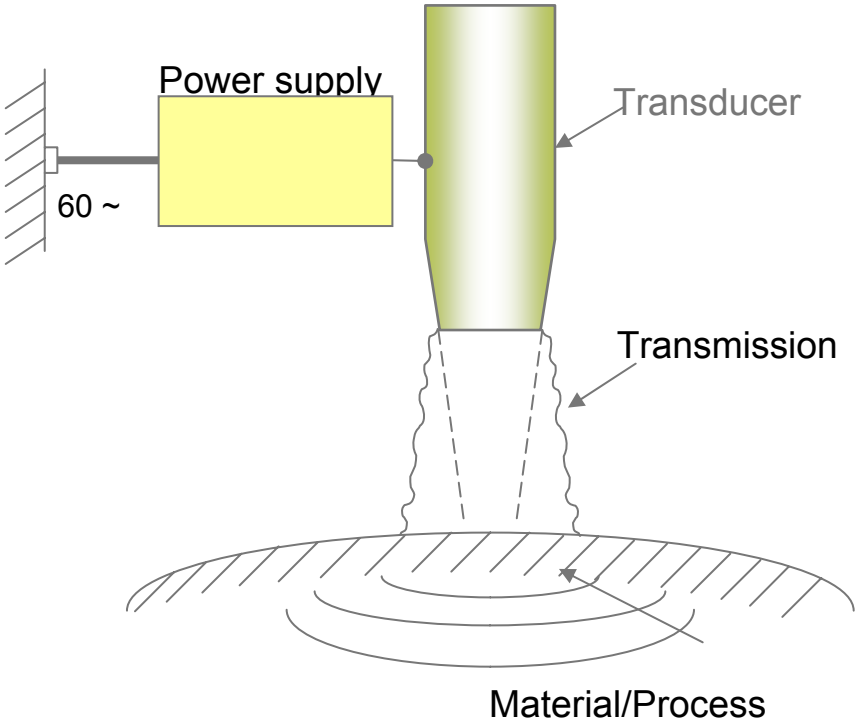
Joining Innovation

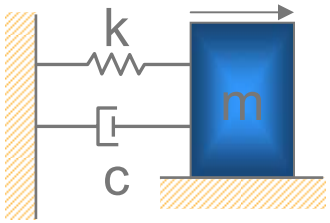
Impedance matching

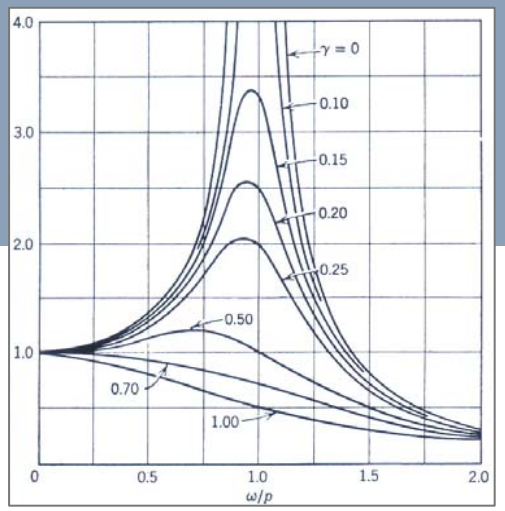


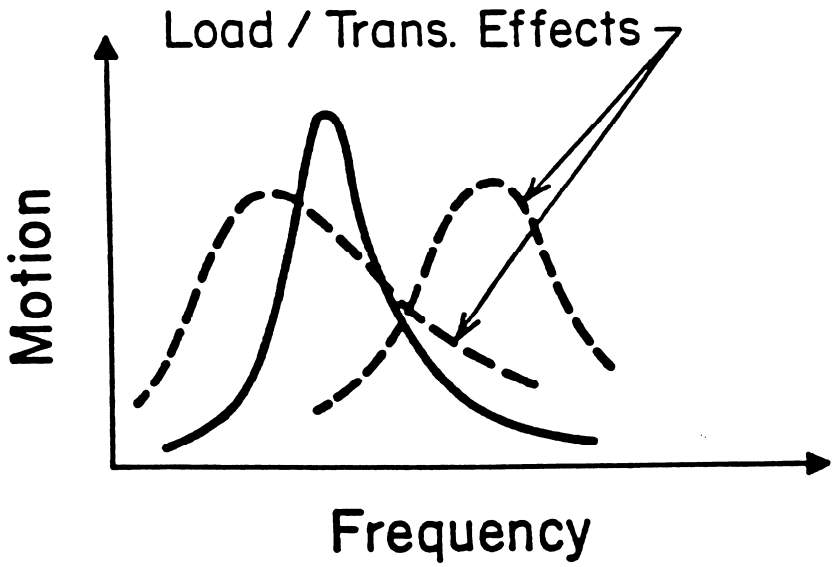
Joining Innovation

Feedback Control





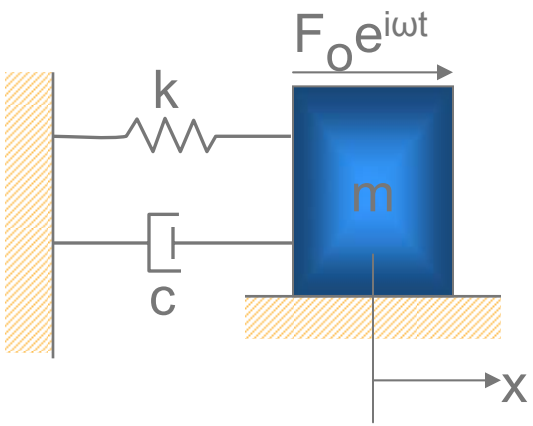


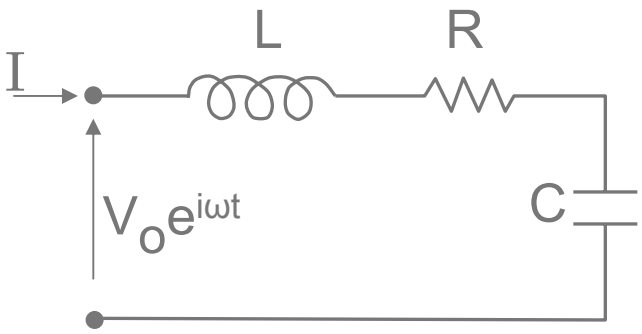


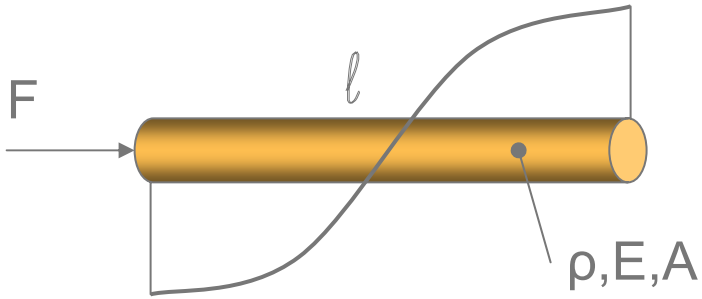
System Frequency Variation

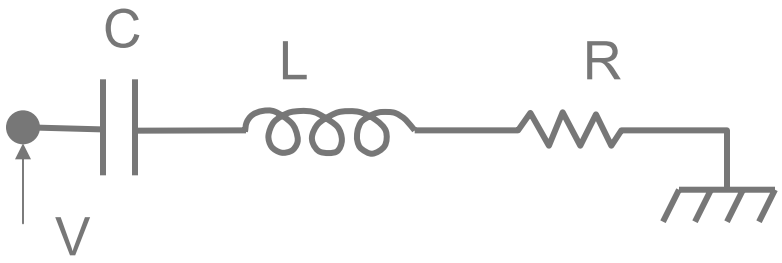
Joining Innovation

Recall … Equivalent Circuits



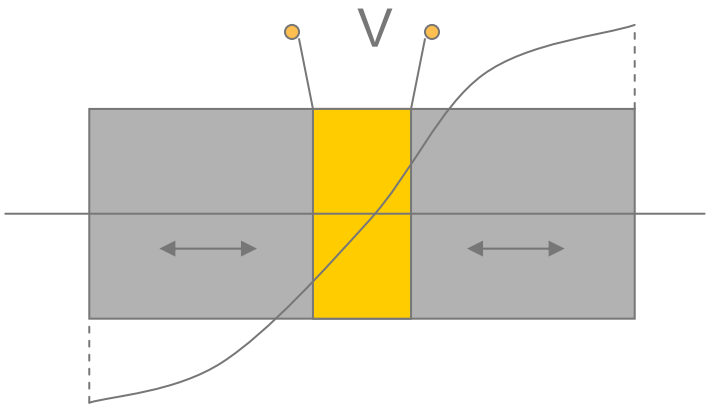


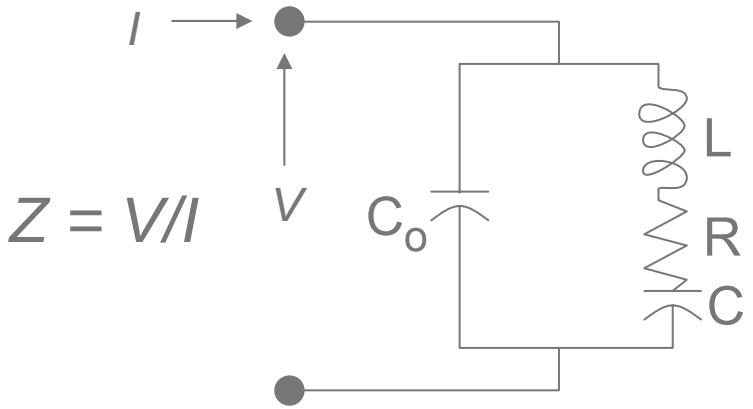


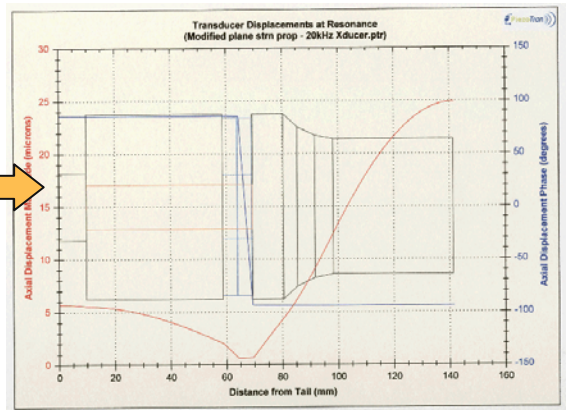


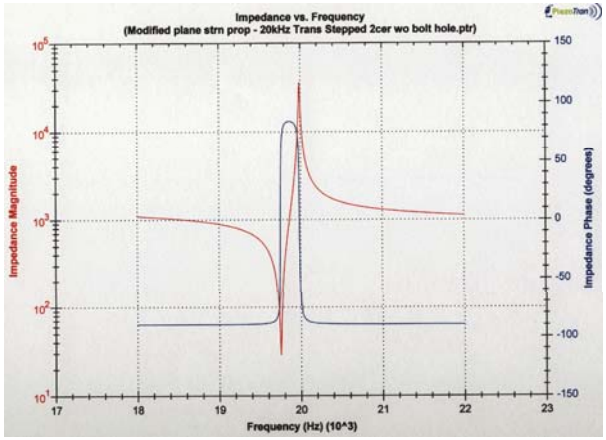
Joining Innovation

Transducer Equivalent Circuit



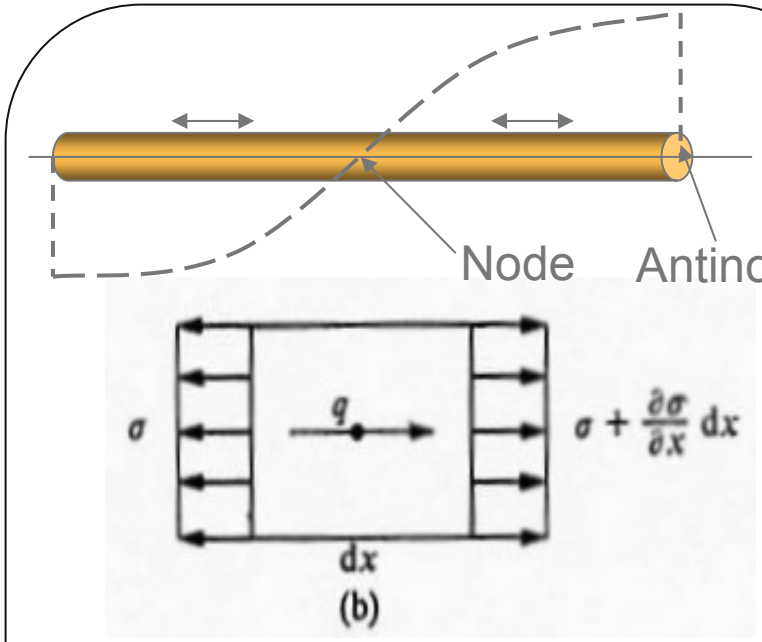






EWI
Joining Innovation

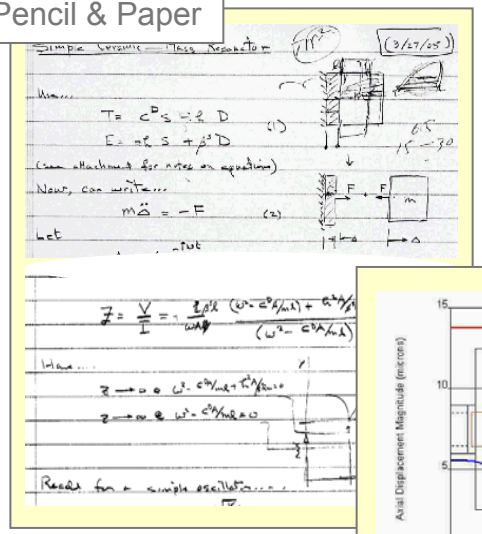
Transducer Modeling – 1D



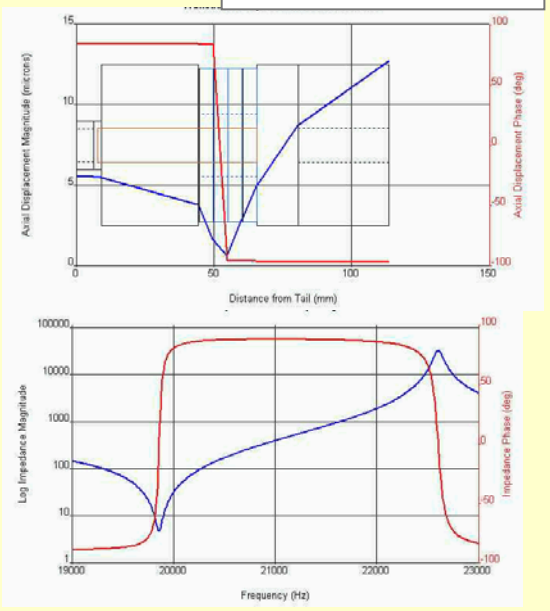
$\partial^2 u/\partial x^2 = (1/c_o^2)\partial^2 u/\partial t^2$

$c_0 = (E/\rho)^{1/2}$

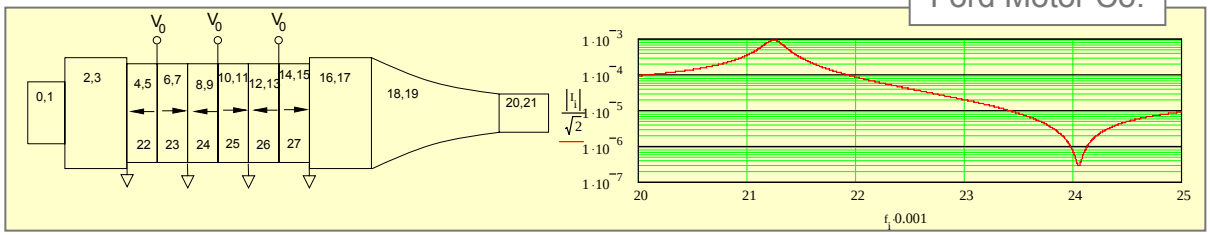
Pencil & Paper



PiezoTran (British Navy sonar expert)



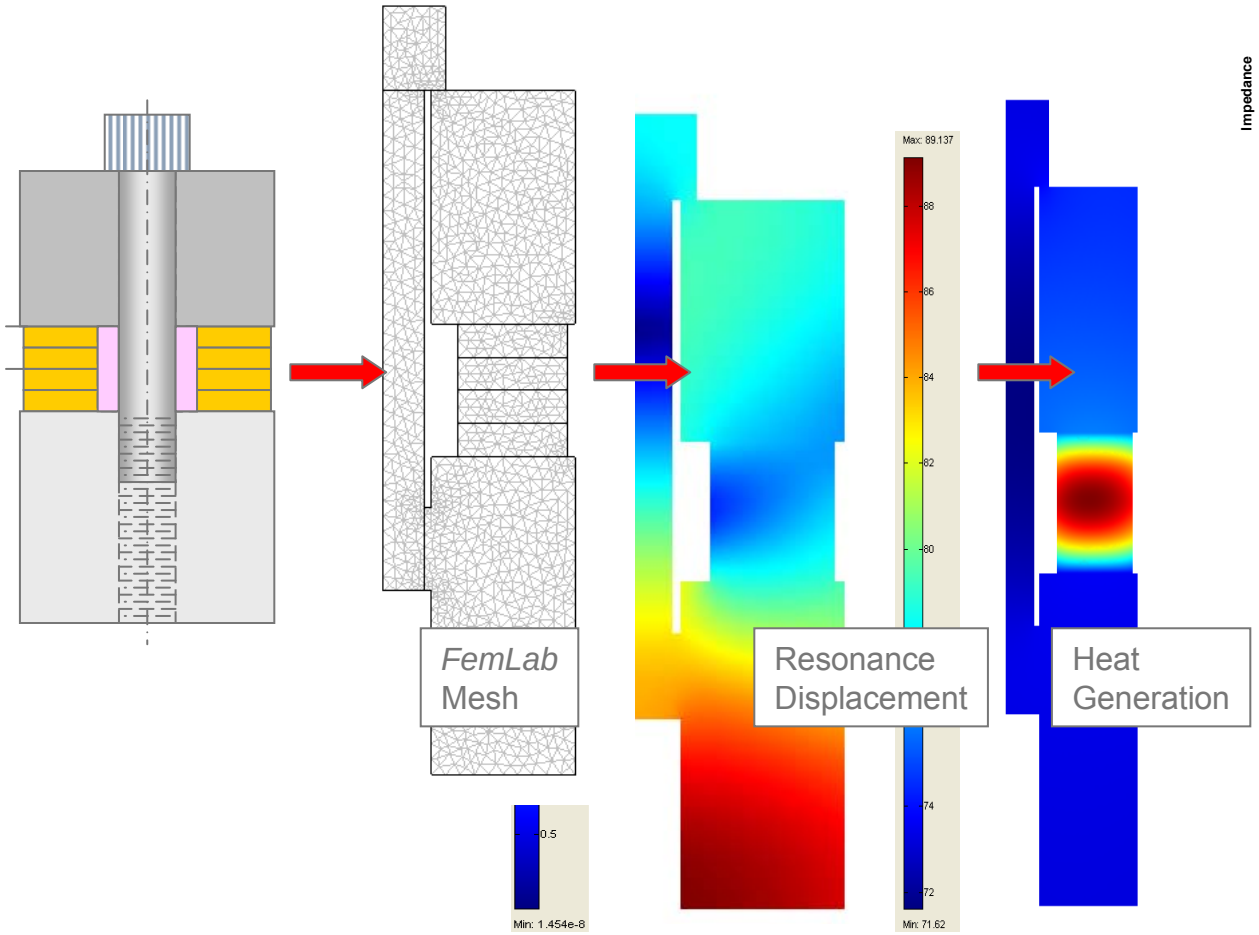
Ford Motor Co.

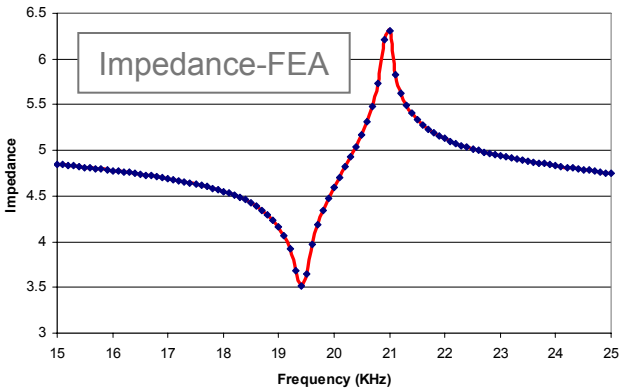


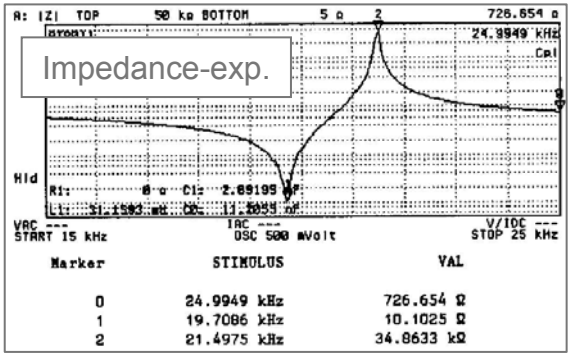
Joining Innovation

Modeling the Transducer

- Use of advanced FEA







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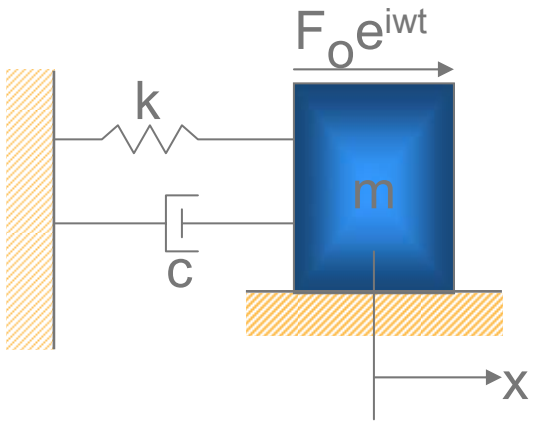
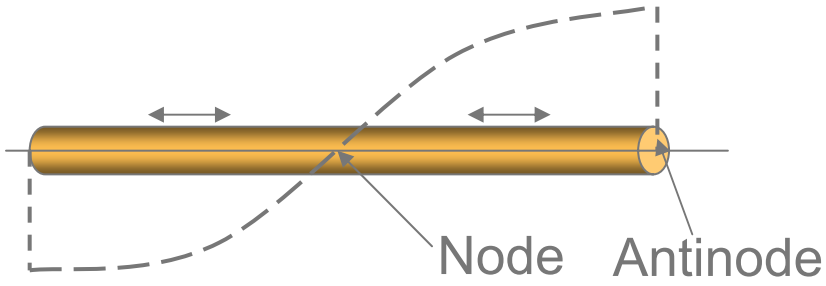
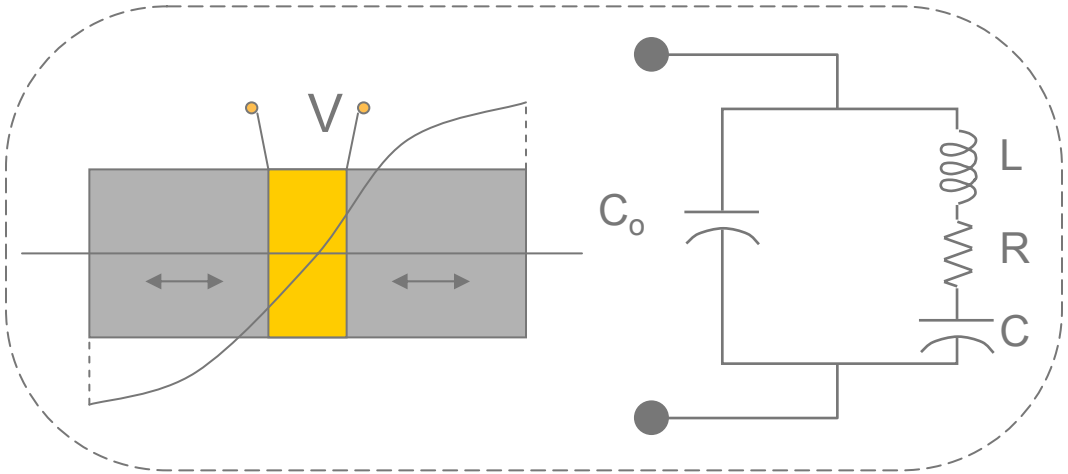
Joining Innovation

“Three (or four) Things”



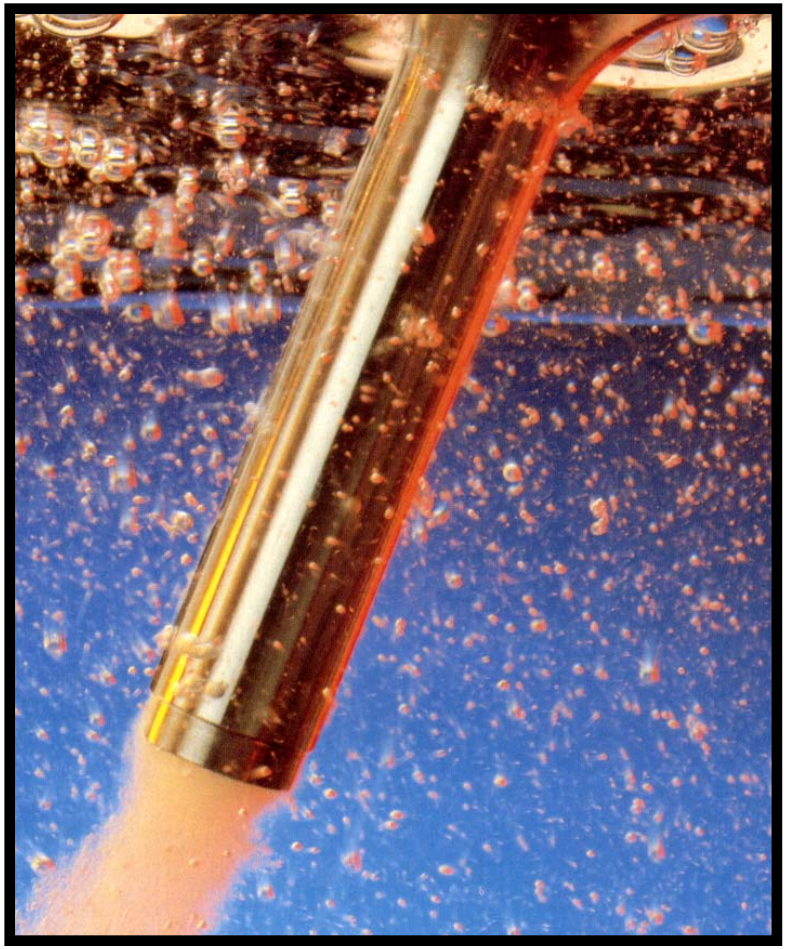




Joining Innovation

Physical Effects of HPU

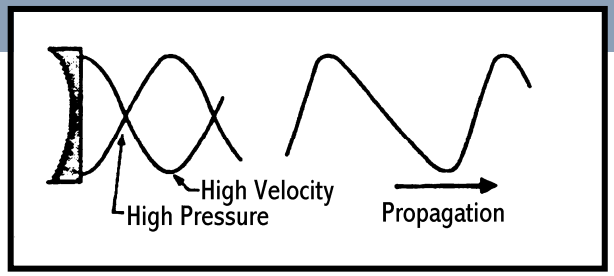
- In fluids (gases, liquids)
- In solids

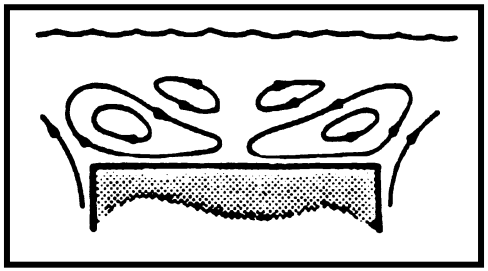


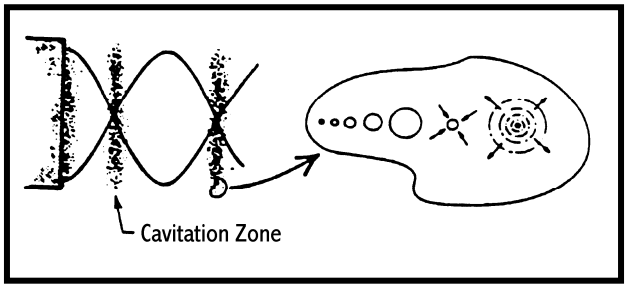
Joining Innovation

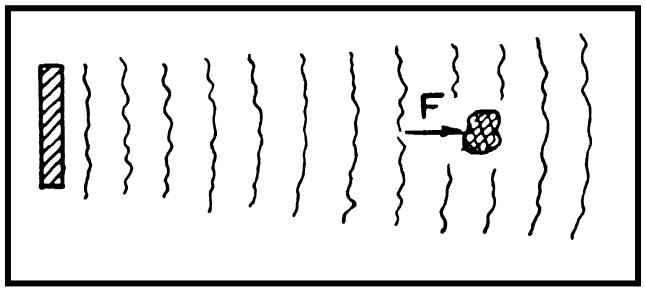
HPU Effects in Fluids

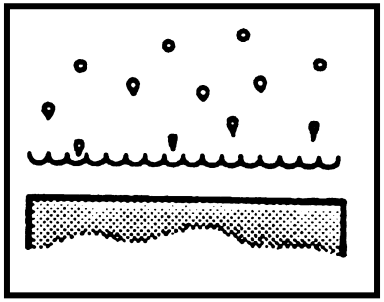
- Absorption/attenuation
- Nonlinear waves
- Radiation pressure
- Acoustic streaming
- Atomization
- Cavitation







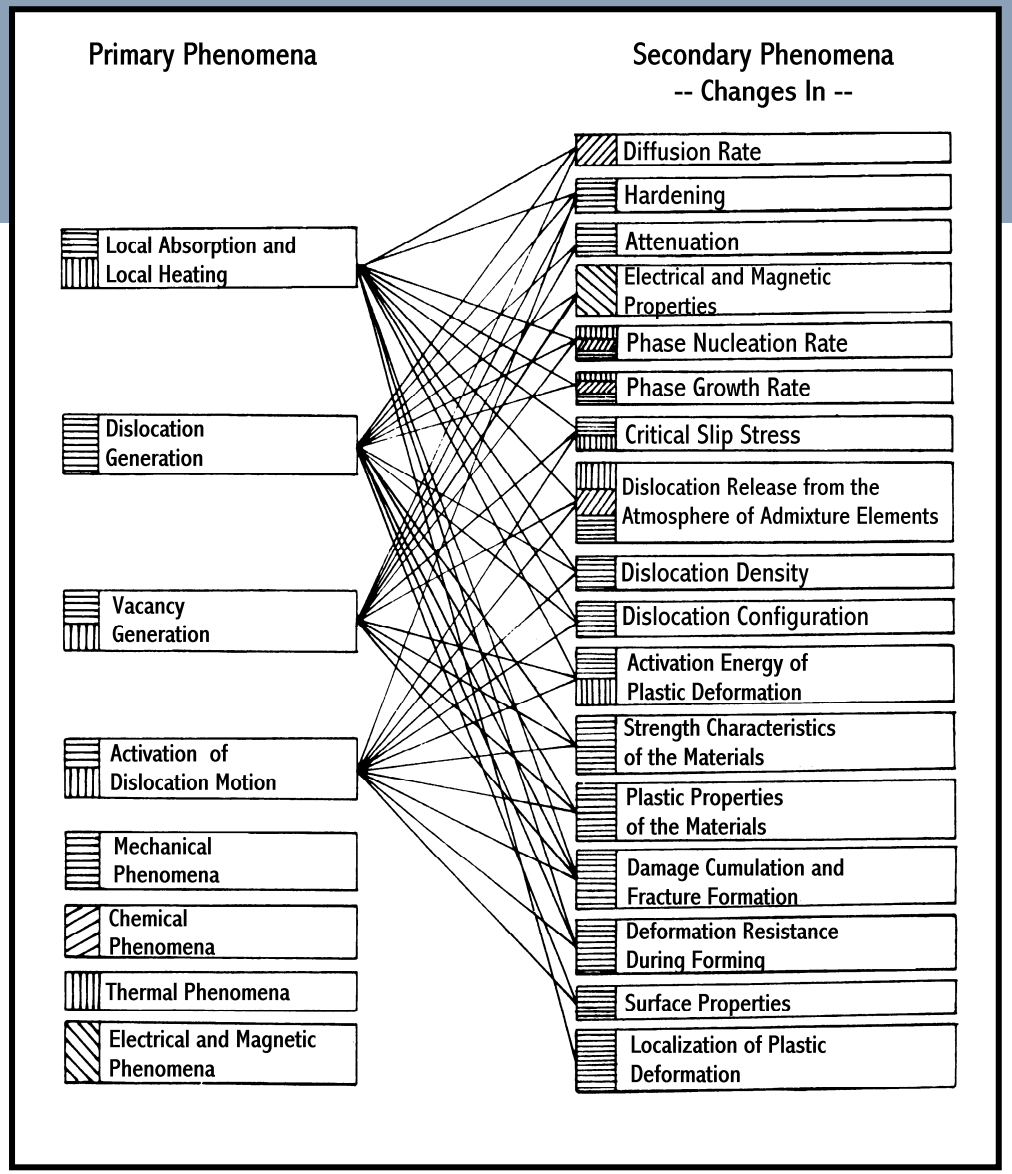




Joining Innovation

HPU Effects in Solids

- Anelasticity, absorption/heating
- Fatigue
- Deformation
- Surface effects

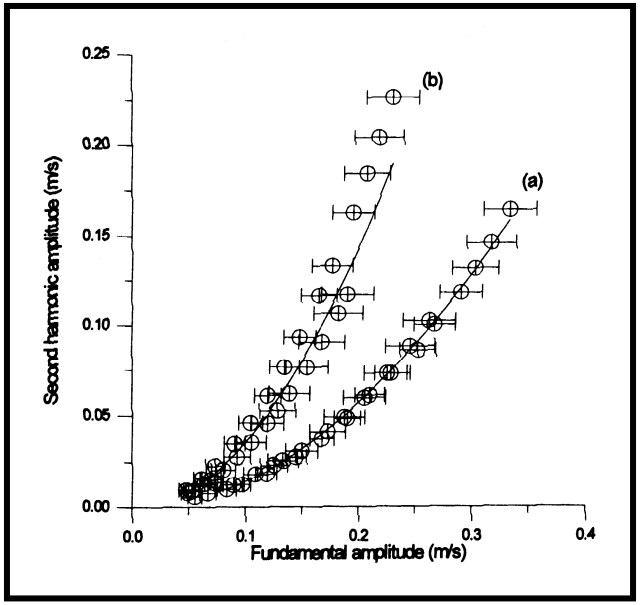


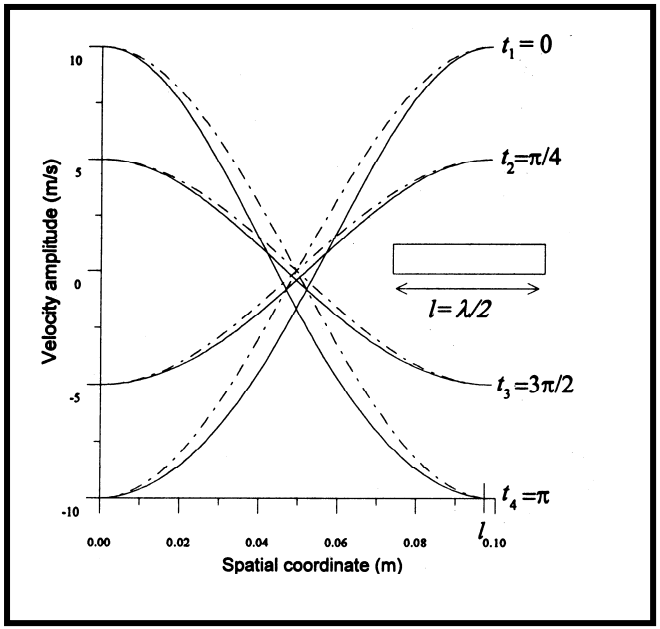
EWI
Joining Innovation

Anelasticity

- Higher order “constants”
- Leads to harmonics
- Affects horns, transmission lines

$$T = C_1\varepsilon + C_n\varepsilon^2$$

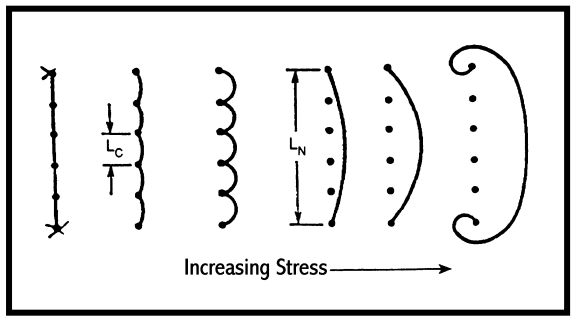




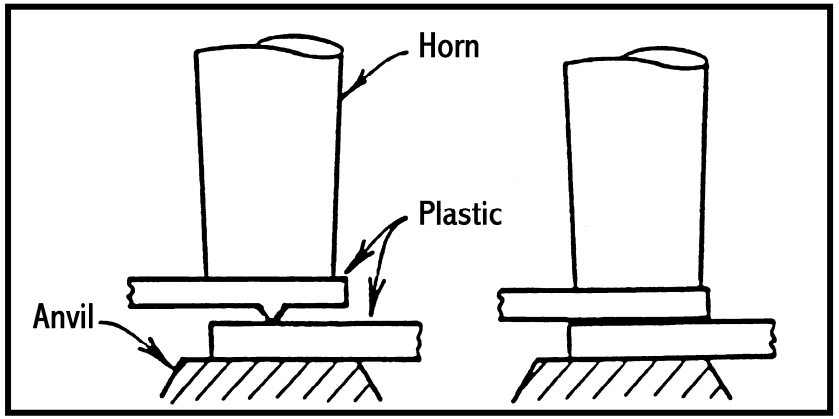
Joining Innovation

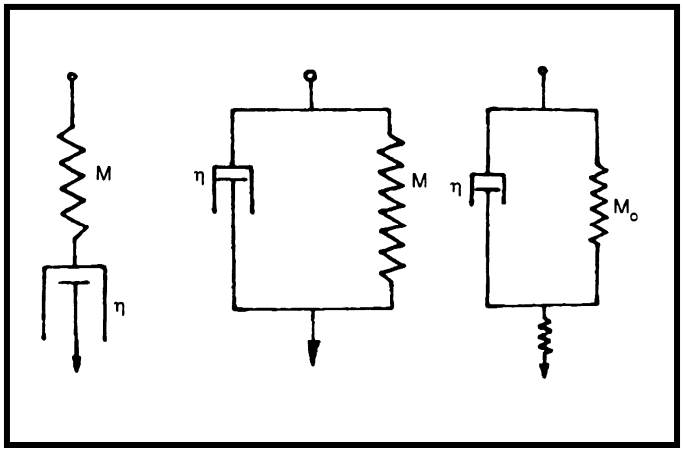
Absorption/Heating

- Metals - grain structure
  Polymers - long chains
- "Macro description"" - loss moduli, viscous moduli
- Uses: Polymers - welding, processing; metals - usually a problem



$$E^* = E' + iE''$$

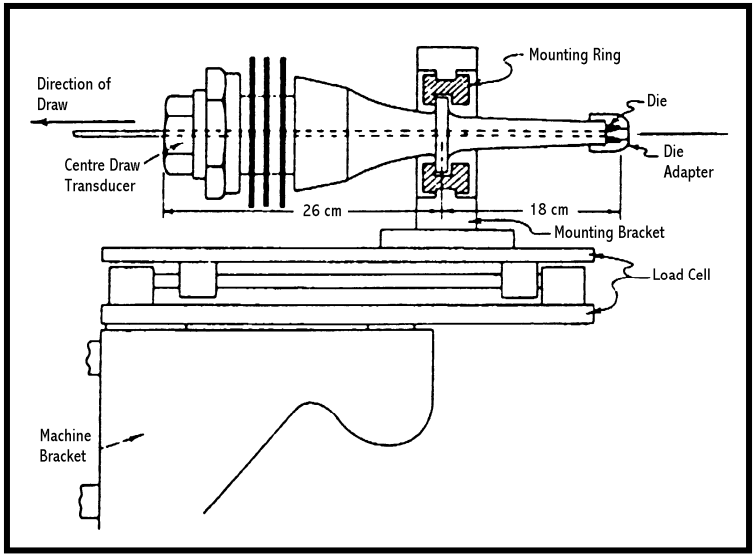


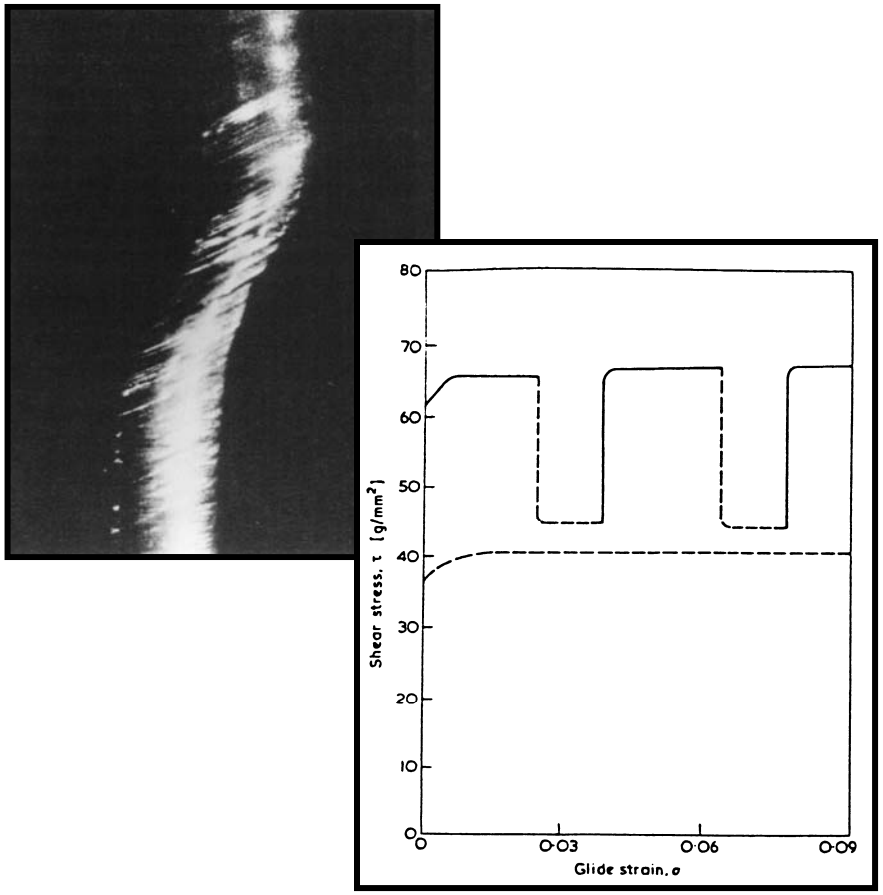


EWI
Joining Innovation

Deformation

- Mechanism unclear (acoustic softening or superposition)
- Uses: Many potential

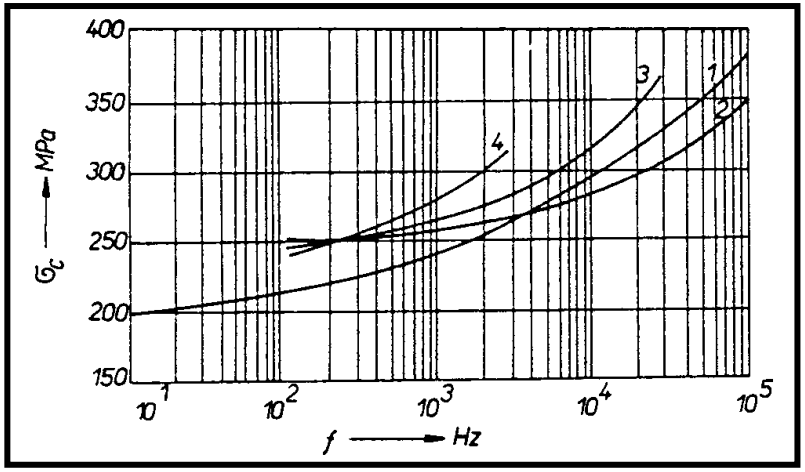


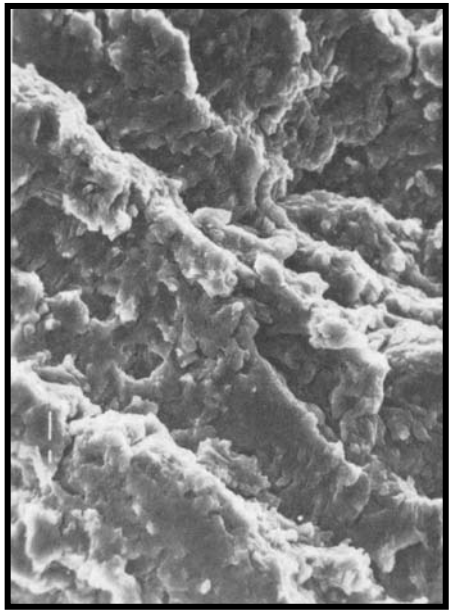


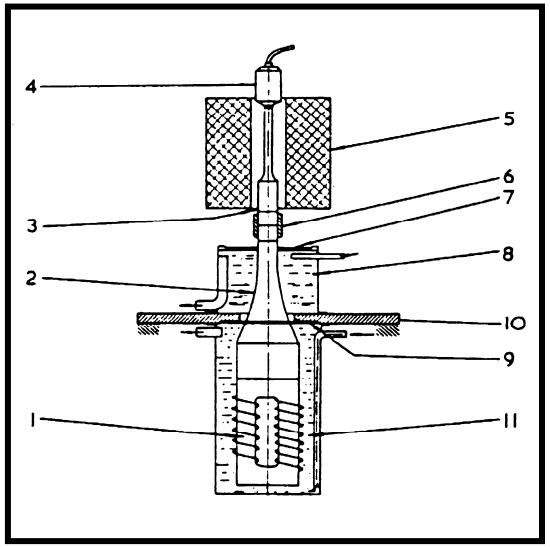
Joining Innovation

Fatigue

- Not necessarily just “Fast” low-frequency fatigue
- Testing
- Usually a problem



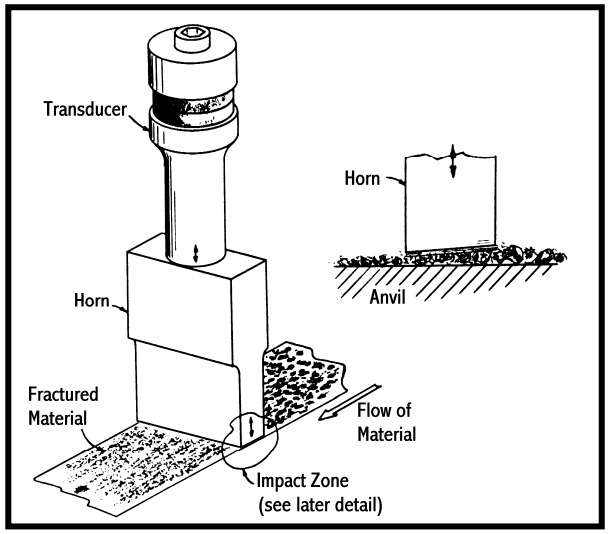


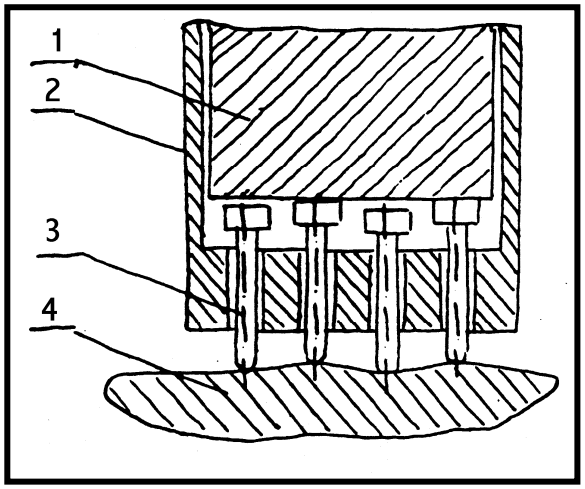


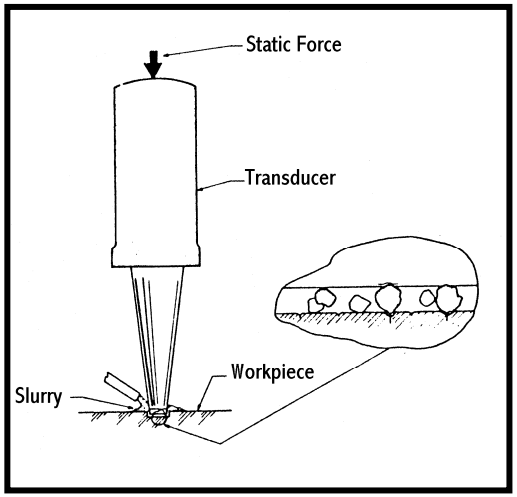
Joining Innovation

Mechanical Impact

- "Hammer" action of US tool
- Uses: US machining, comminution, surface treatment, . . .



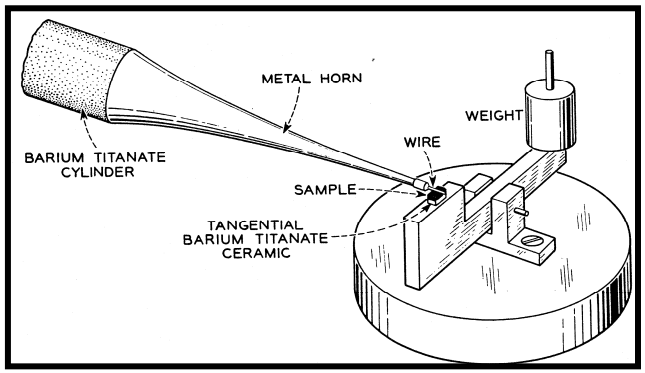


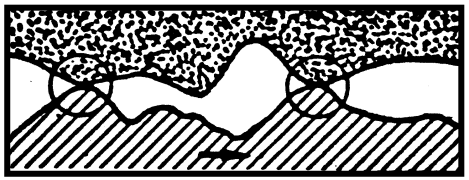


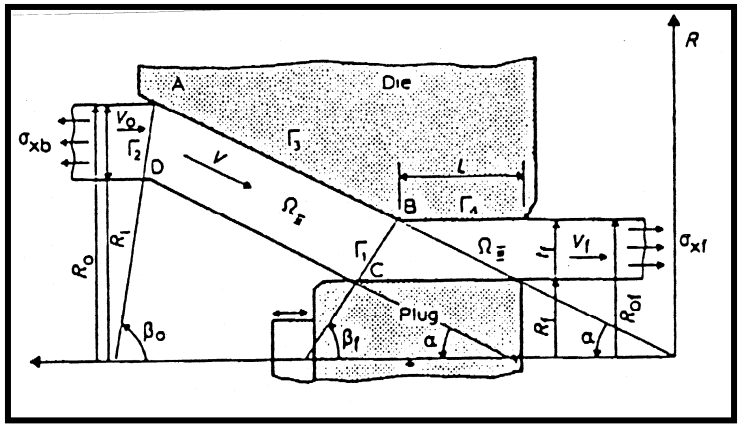
Joining Innovation

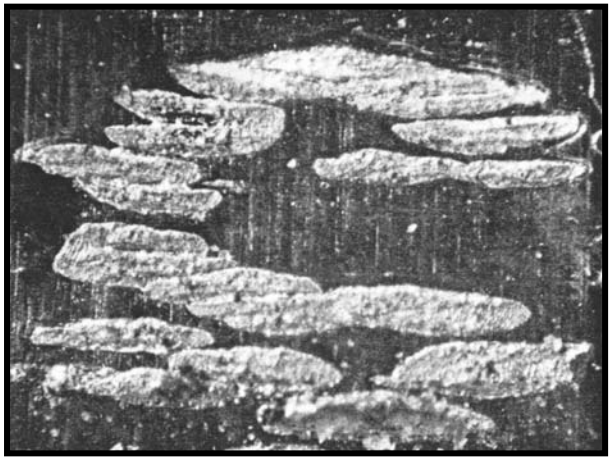
Surface Effects

- Friction
- Effects on forming, flow, welding processes





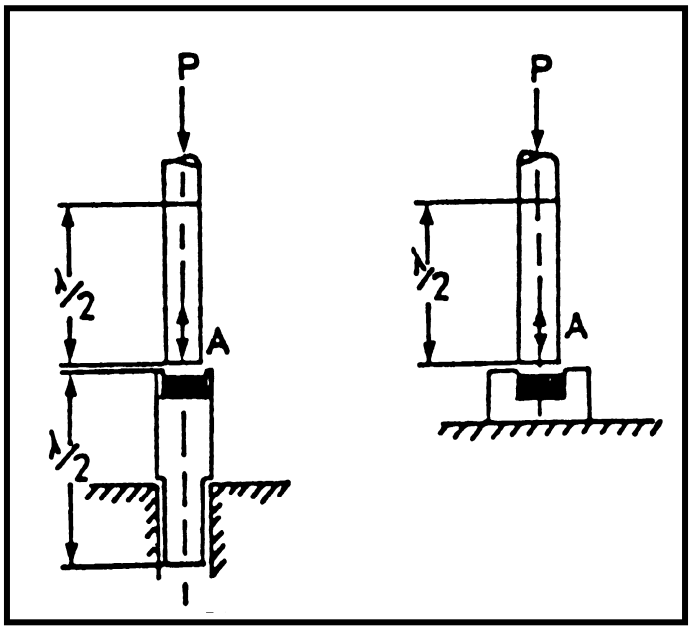


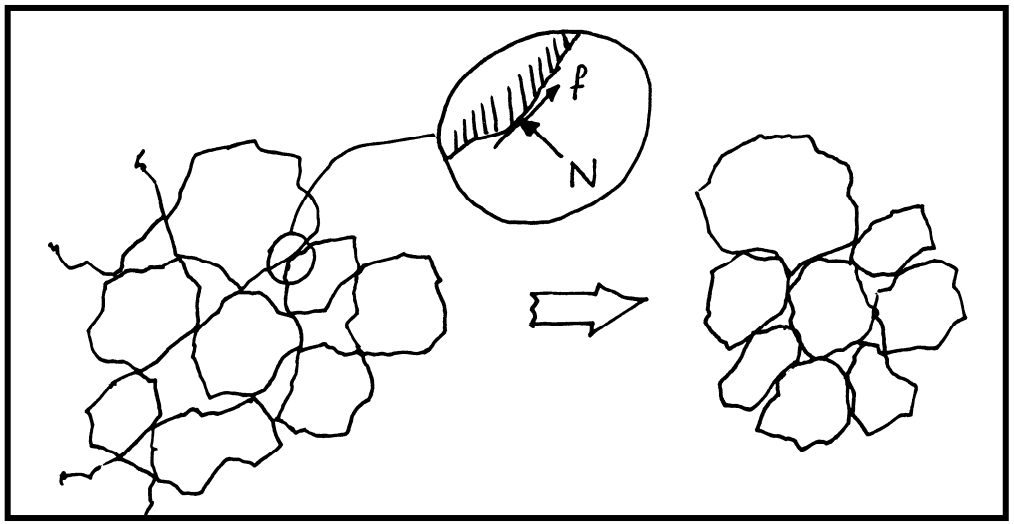


Joining Innovation

Friction and Shear Reduction

- US vibrations disrupt friction forces
- Uses: Compaction, sieving, flow enhancement

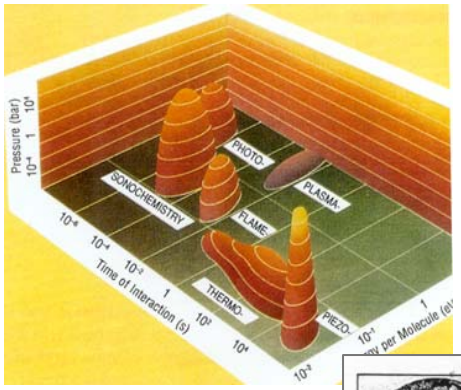


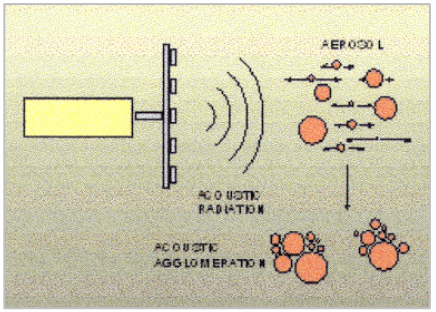


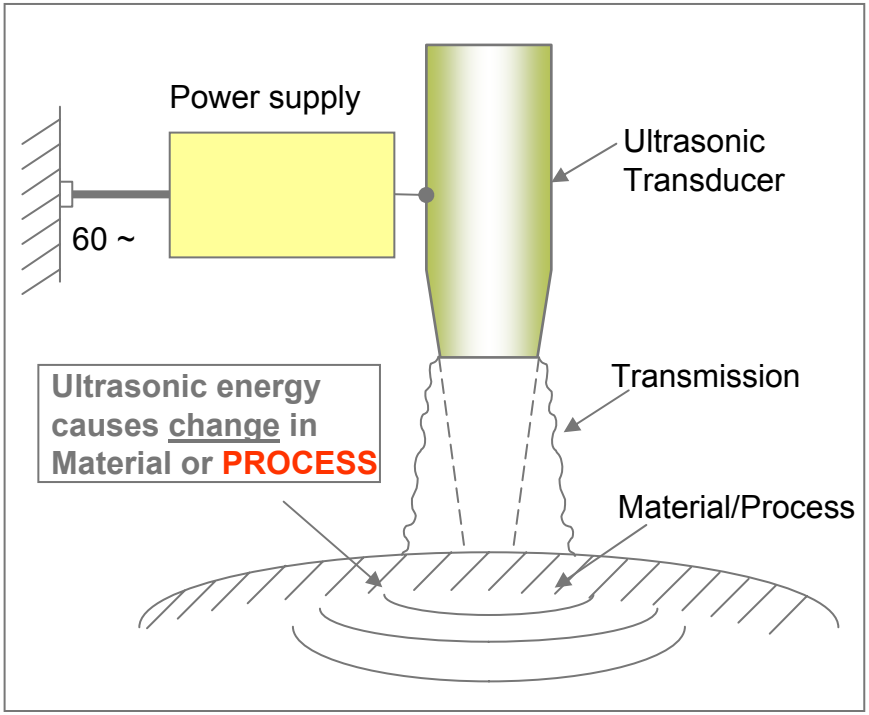
EWI
Joining Innovation

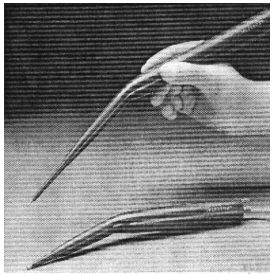
HPU Applications – A Reminder

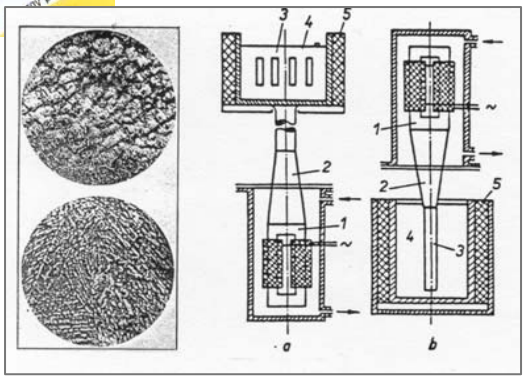
- **HPU … *application* of intense, high-frequency acoustic energy to change materials, processes.**

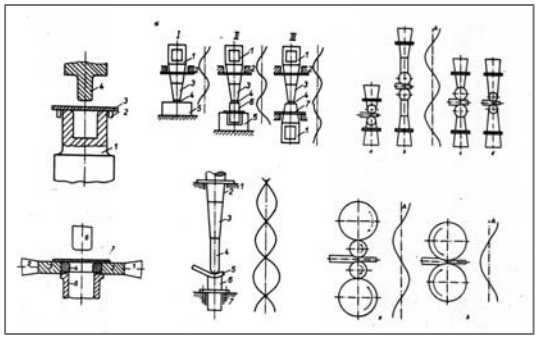












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Joining Innovation

Some Applications of HPU

- Agglomeration, coagulation of particulates
- Atomization – combustion, humidification
- Biological – cell disruption, …
- Casting (see metal processing, molten)
- Chemical/sonochemical processing
- Cleaning
- Comminution
- Compaction, consolidation
- Cutting, drilling, machining
- Defoaming
- Drying
- Emulsification/dispersion
- Filtering, sieving, separation, flow enhancement
- Food processing – cutting, drying, …
- Forming of materials (see also metals)
- Joining-welding, soldering
- Liquid processing (non chemical)
- Medical – surgical, therapeutic
- Metal processing – molten metals
  - Melt degassing
  - Solidification
  - Crystal growth
  - Composites
  - Atomization (powdered metals)
- Metal processing – solid metals
  - Forming
  - Heat treatment, annealing
  - Surface hardening
- Mineral processing
  - Flotation, emulsification
  - Disintegration of minerals, surface films
  - Defrothing, dehydration of ores
  - Hydrometallurgy
- Mixing
- Motors, ultrasonic
- Stress relief
- Surface treatment, cladding, plating
- Testing – erosion, fatigue, hardness
- Transport/positioning – uses of levitation

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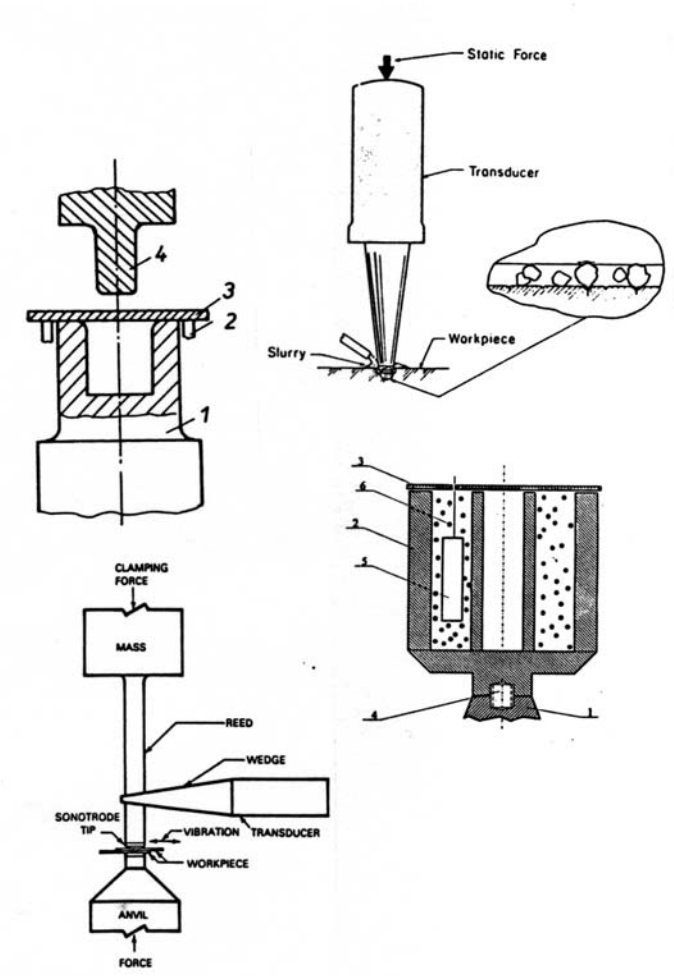
Joining Innovation

Manufacturing Applications

- Molten metal
- Metal deformation
- Machining
- Materials joining
- Cleaning/compaction
- Airborne US
- Liquid processing

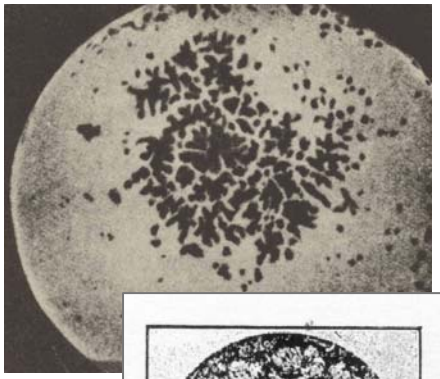


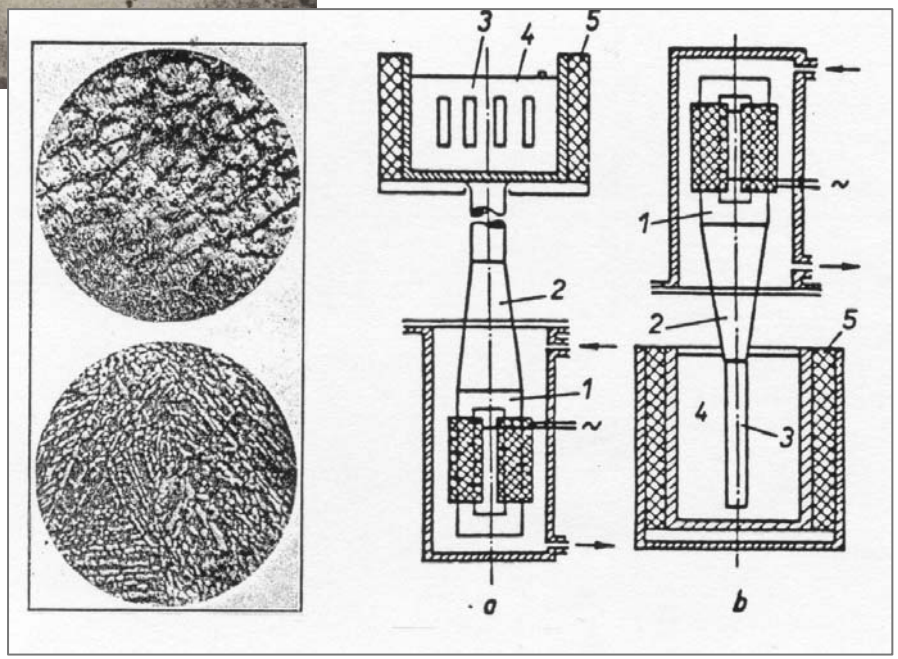
Joining Innovation

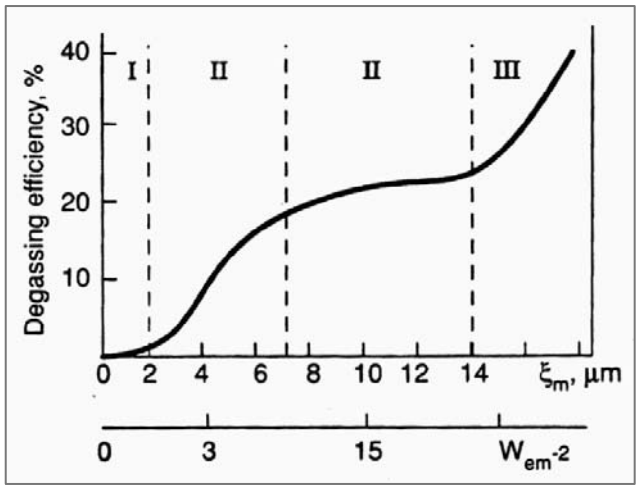
HPU in Molten Metals

Key Effects …

- Degassing
- Reduce grain size
- Control columnar structure
- Vary phase distribution
- Improve homogeneity
- Disperse inclusions







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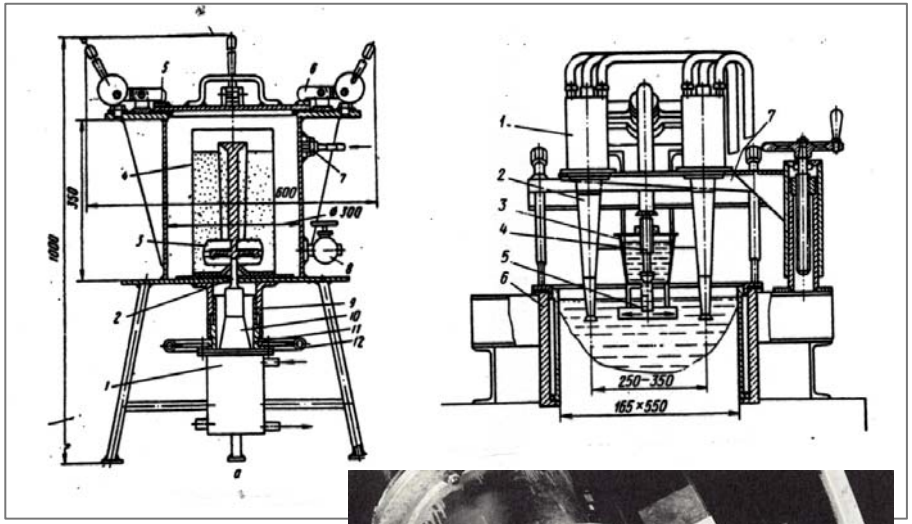
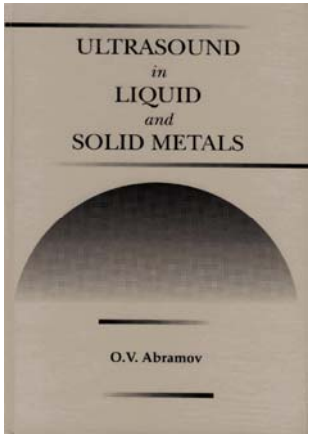
Joining Innovation

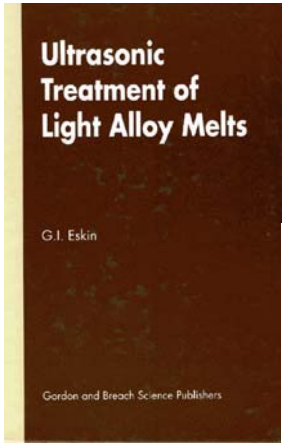
Extensive Work in This Field

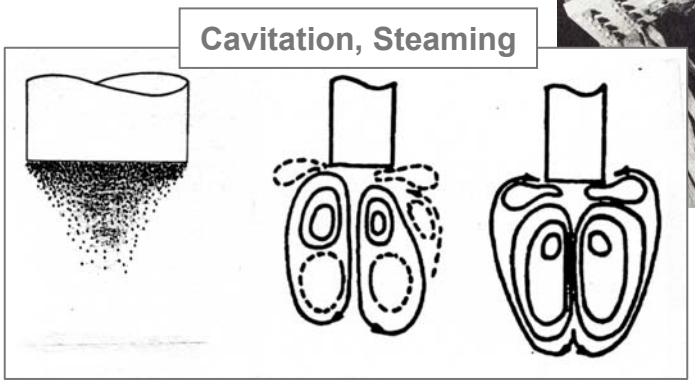
Metals Treated with US …

- Pure metals (Fe, Al, Co, Zn, Sn, Bi)
- Low Melting (Bi-Pb-Sn-Cd, Bi-Cd, …)
- Aluminum, magnesium alloys
- Copper, silver
- Steels, cast irons
- Nickel-based superalloys









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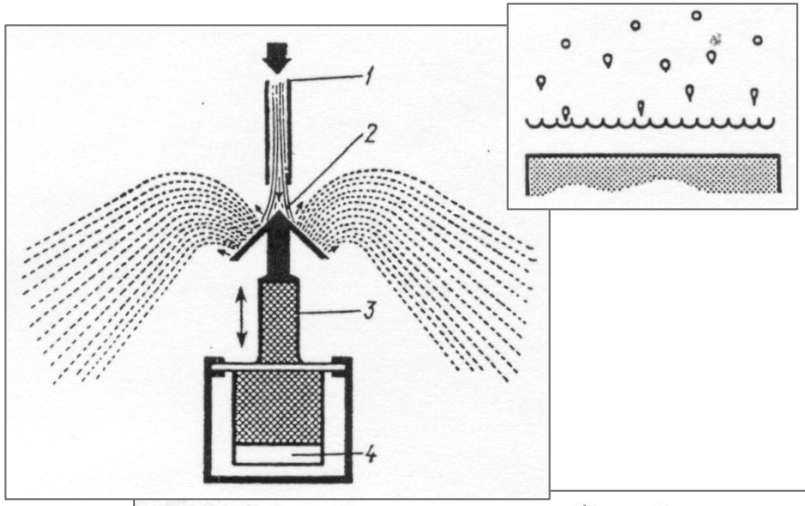
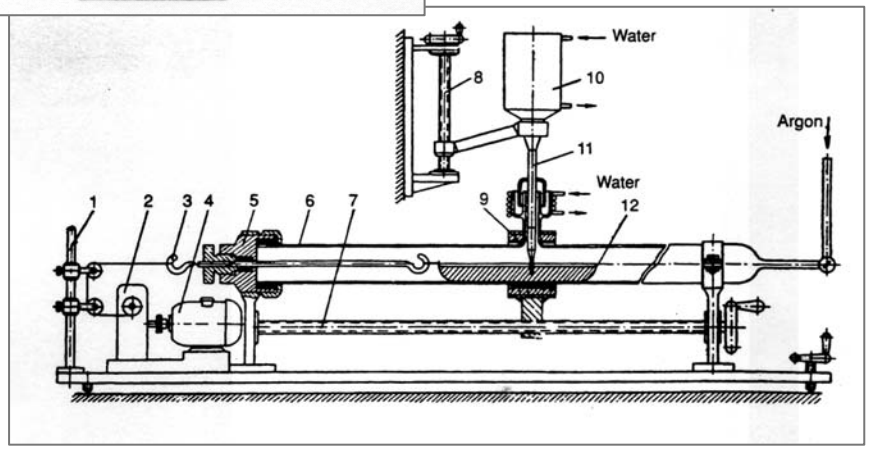
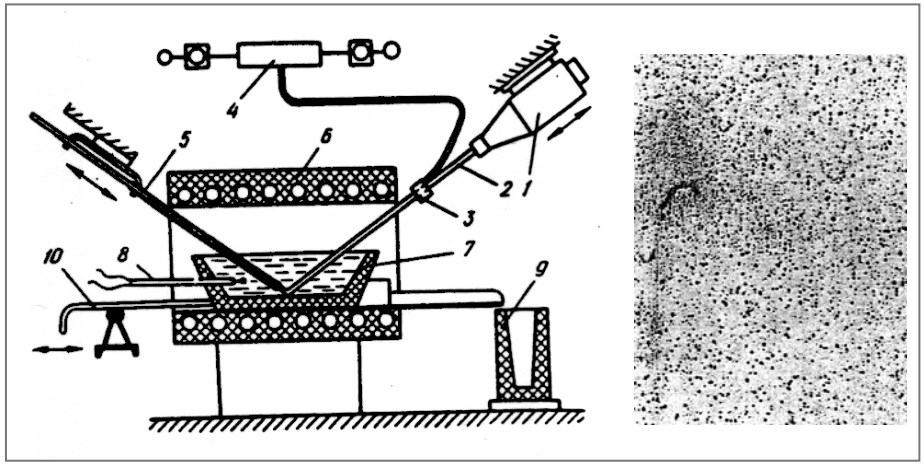
Allied Processes

- US-assisted crystal growth
- Plating
- Powder metallurgy – atomization
- Composites



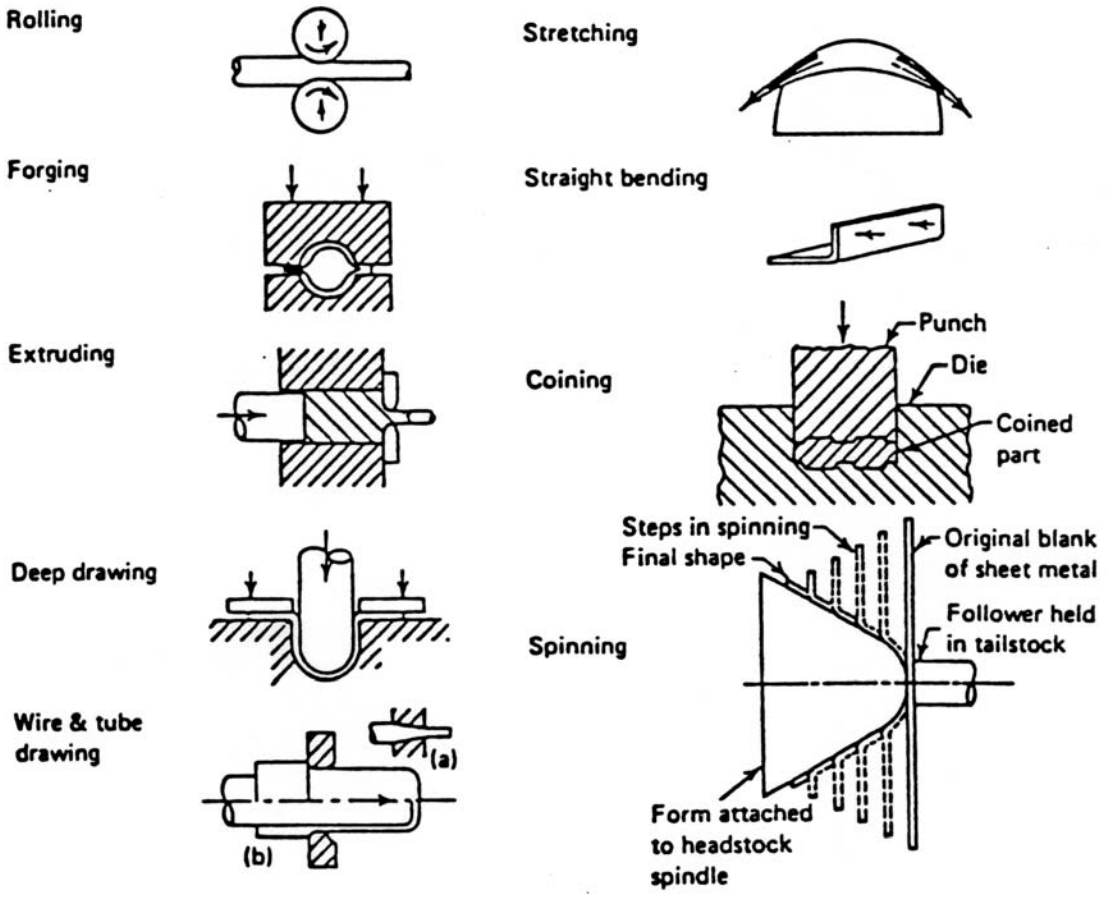




Joining Innovation

Metal Deformation Processes

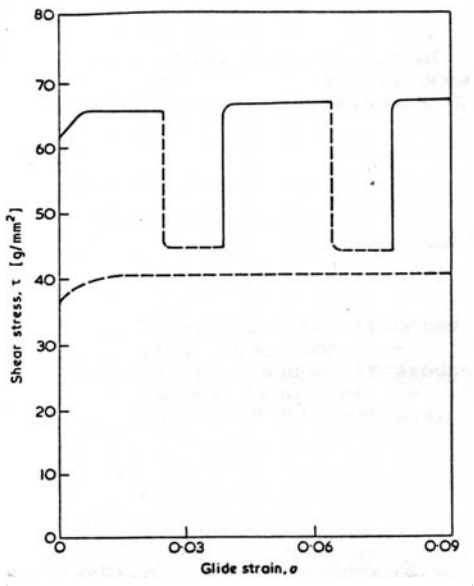
Traditional Forming Processes



Joining Innovation

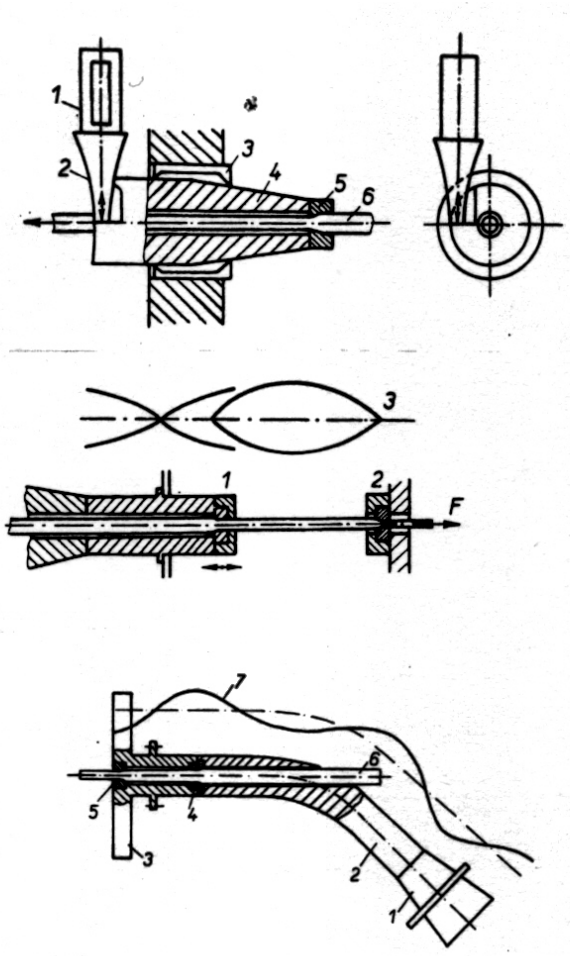
Historical Note on US Forming

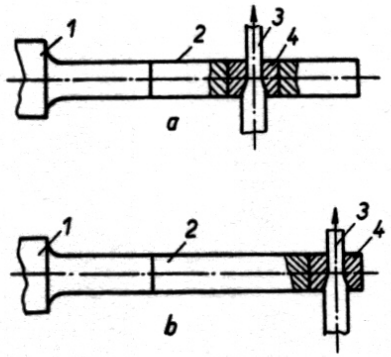
- Blaha/Langenecker (1955) introduced concept of ‘acoustic softening’ - launched extensive research in metal forming
- Question of ‘acoustic softening’ vs. ‘stress superposition’ not conclusively resolved – latter most supported
- US forming continues as active field – recent search shows 65 citations since ‘85

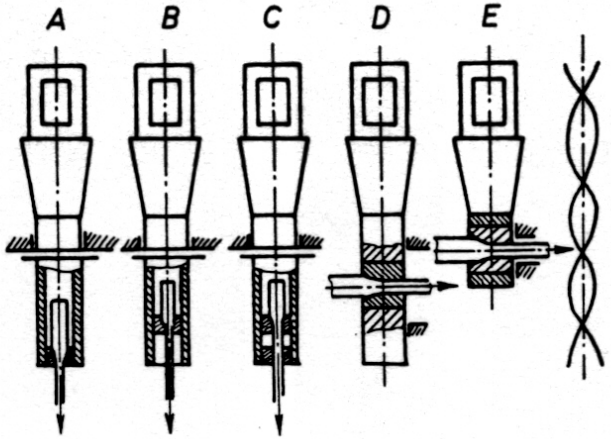


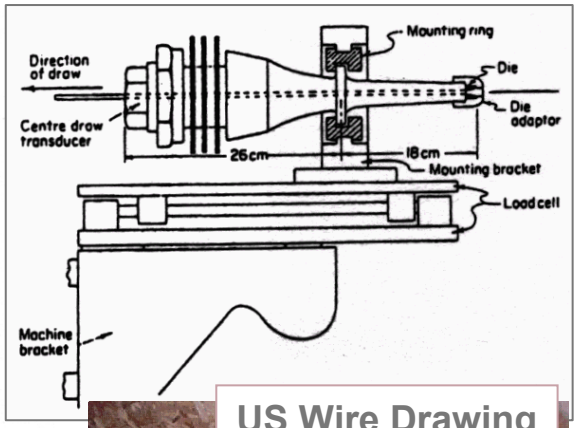
Joining Innovation

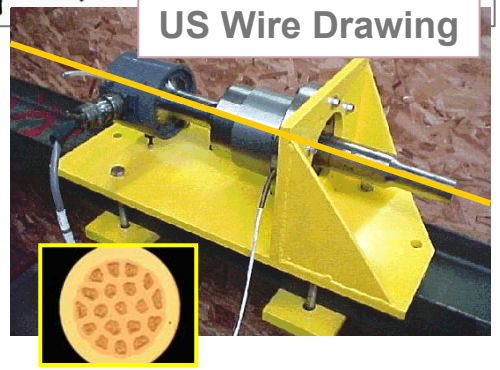
US Wire and Tube Drawing





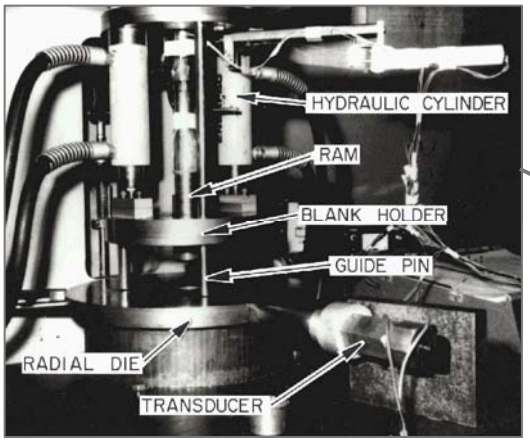


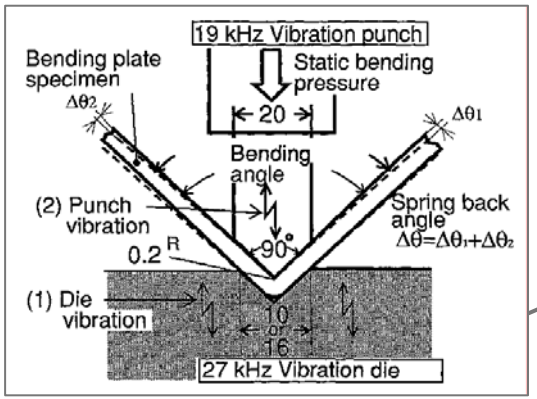


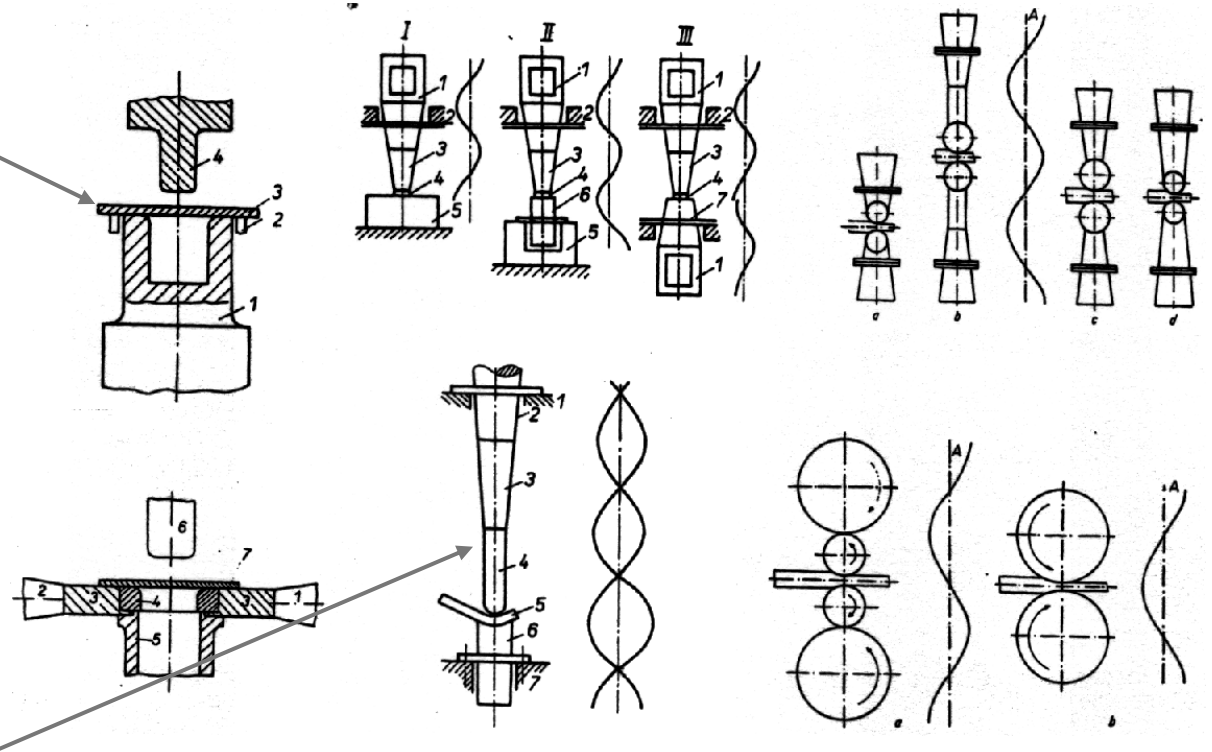


Joining Innovation

US Forming Operations



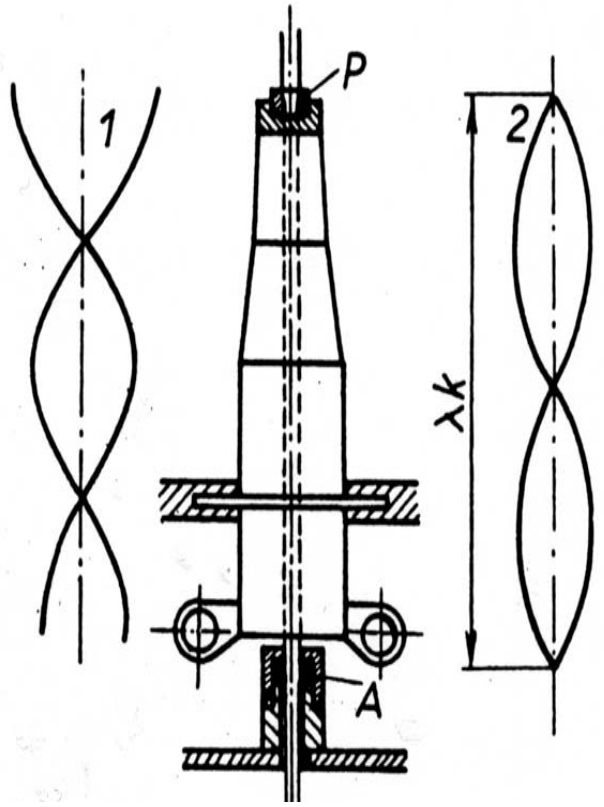




Joining Innovation

Benefits of US Forming

- Increased draw speed
- Improved surface finish
- Reduced draw force
- Greater area reduction
- Longer tool life



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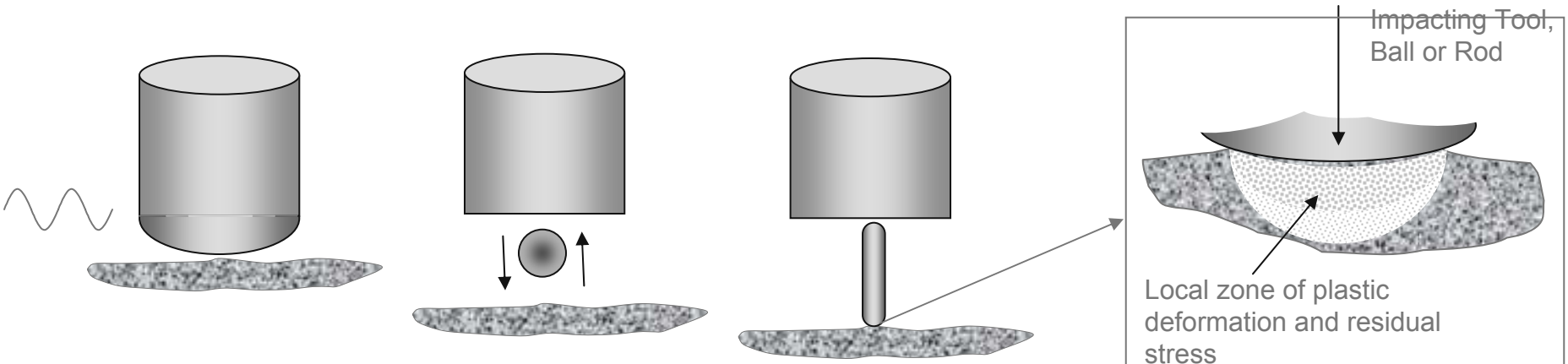
US Impact Treatment (UIT)

- UIT – means of creating US “impact” against metal surface – and resulting local plastic deformation and residual stresses in the metal.
- Three primary means of creating US impact …



Direct intermittent “hammering” impact of US tool against metal surface

Intermittent impacts of metal ball between US tool and metal surface

Intermittent impact of US tool against rod with transmission of stress pulse into metal surface

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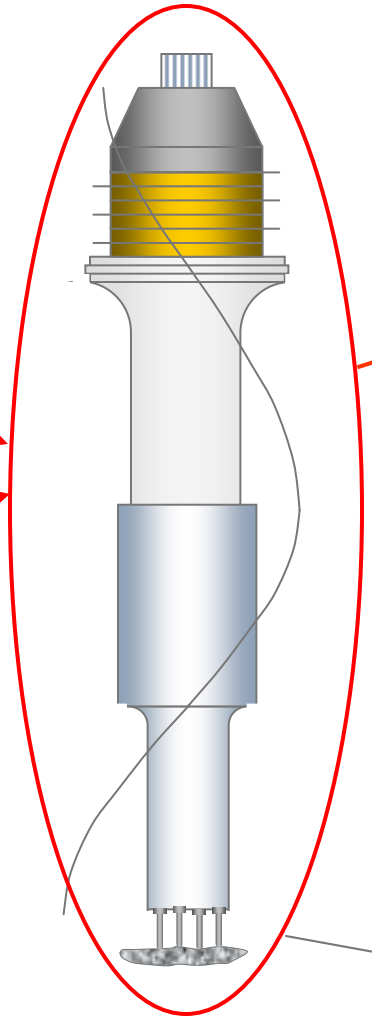
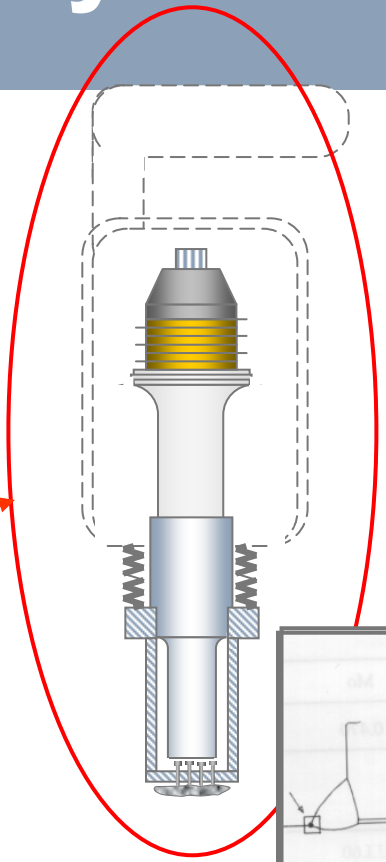
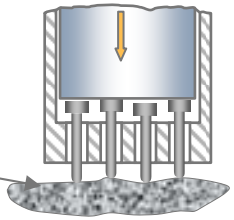
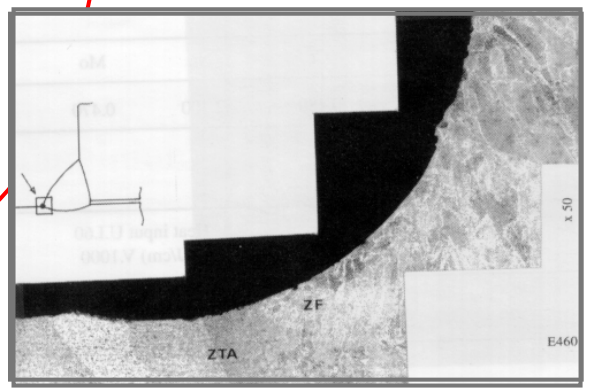
Features of UIP System

ITL System









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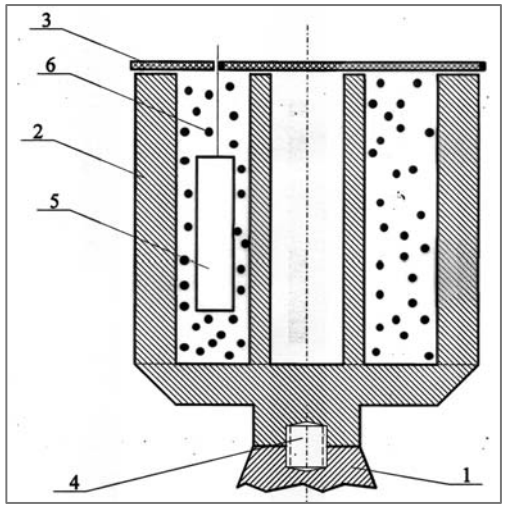
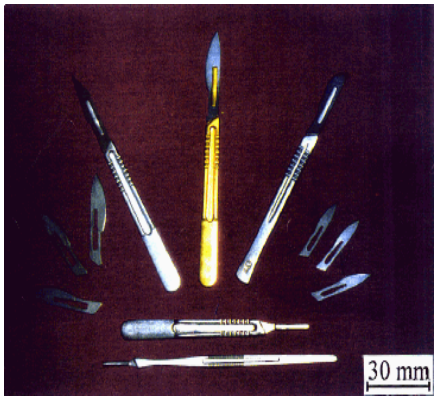
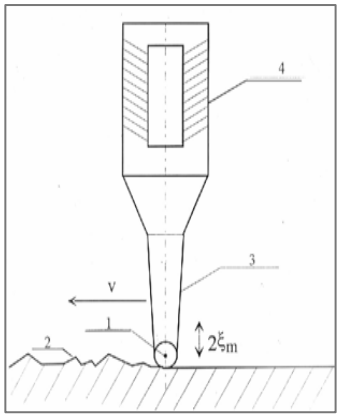
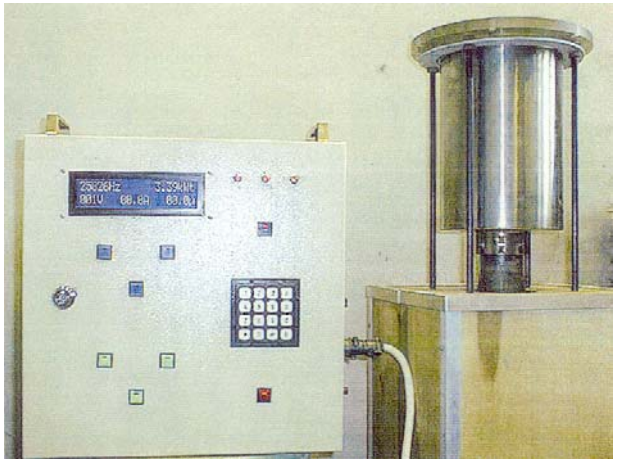
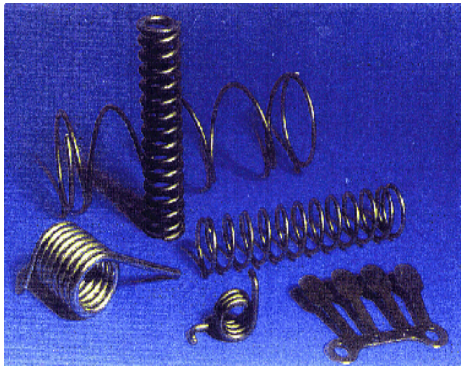
Other US Impact Technology - Surface Hardening, Microalloying

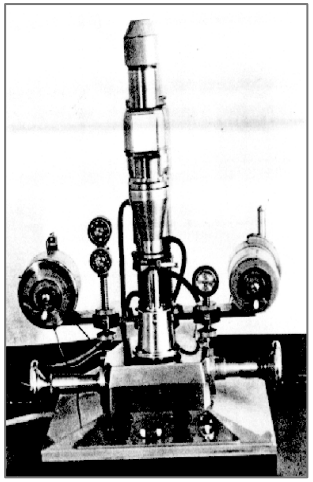








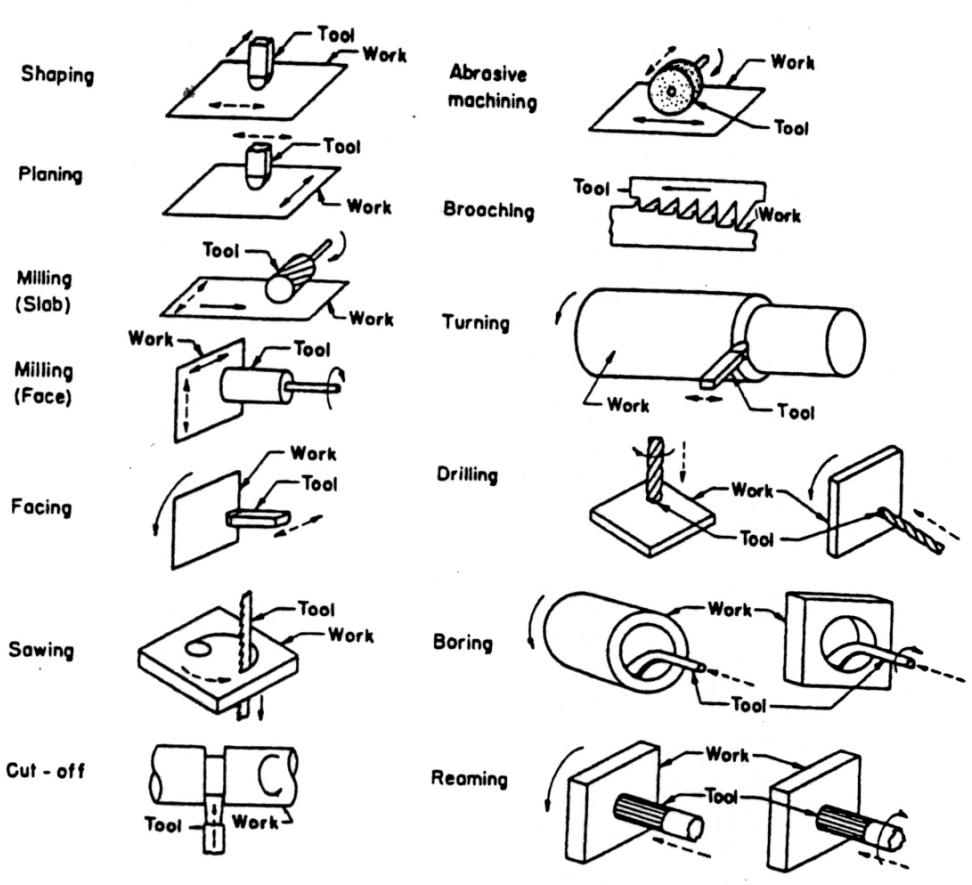




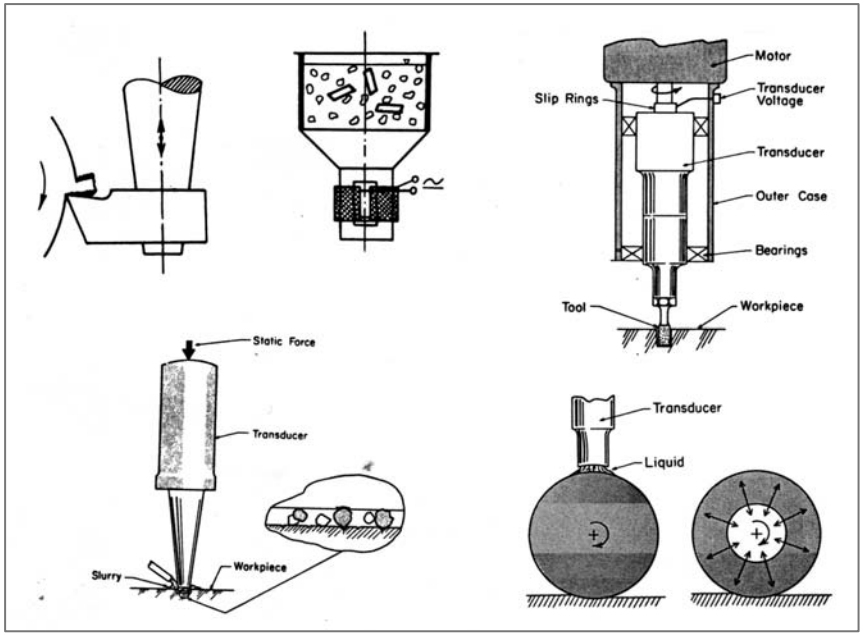
Joining Innovation

Machining Processes

Traditional Machining Processes



US Machining Processes



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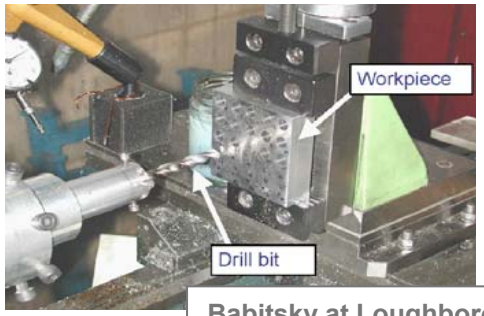
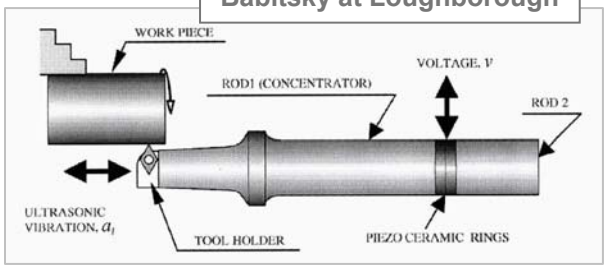
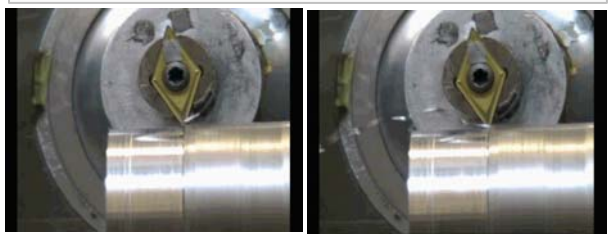
US Machining Applications

- Extensive work over 50+ years
- Re-emergence in 1990's to present – issues of materials, productivity as in 60', 70's

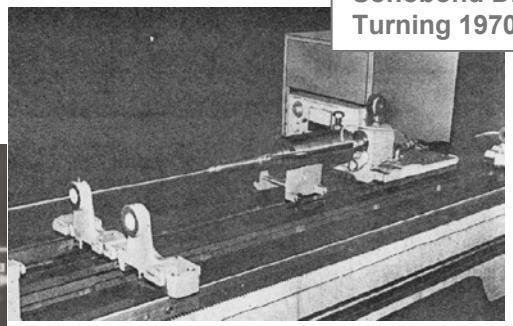


Babitsky at Loughborough

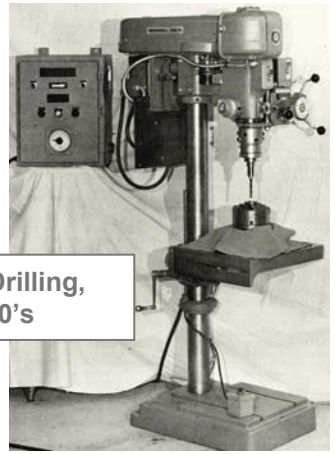


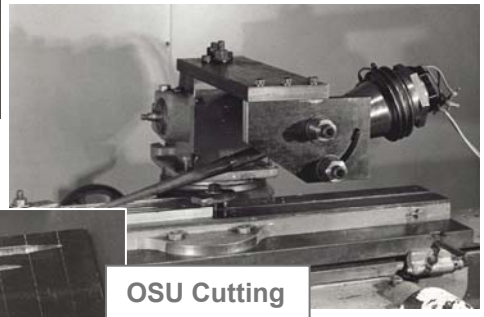


Cincinnati Milacron US turning, 1960's

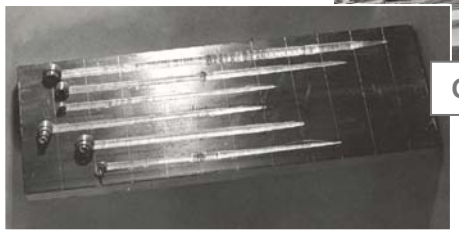


Sonobond Drilling, Turning 1970's

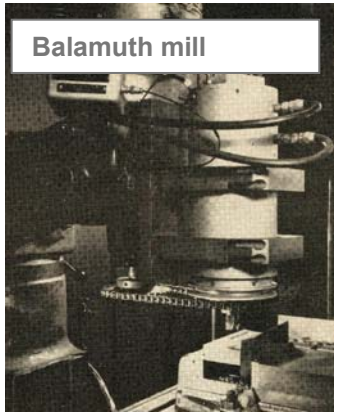




OSU Cutting



Balamuth mill



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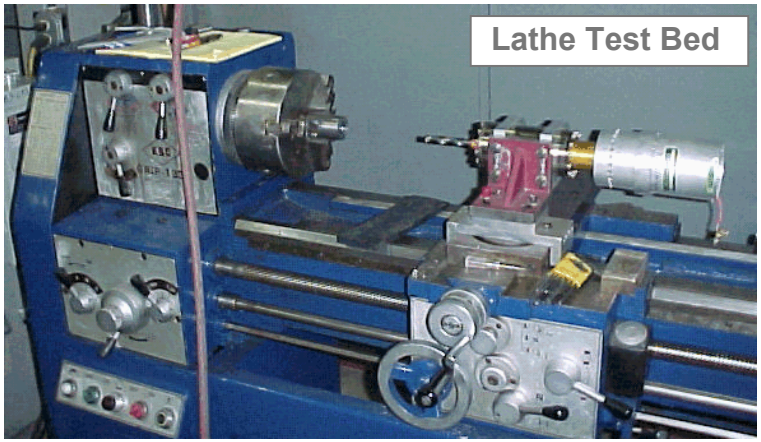
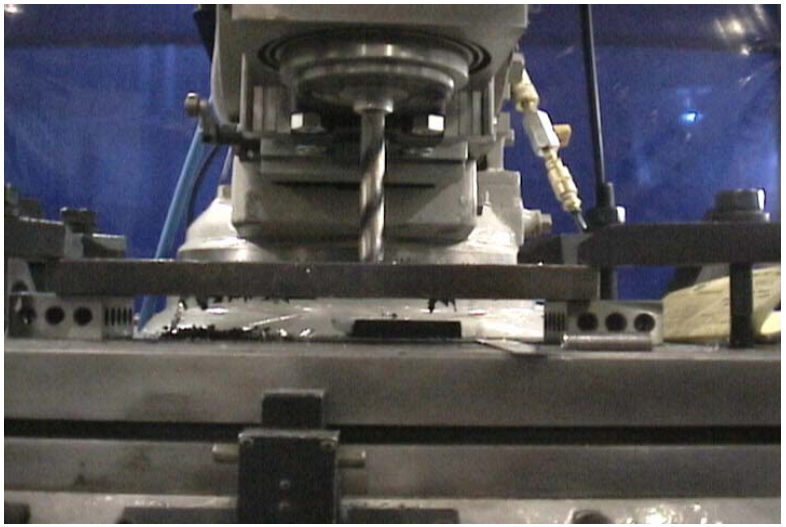
Recent Work





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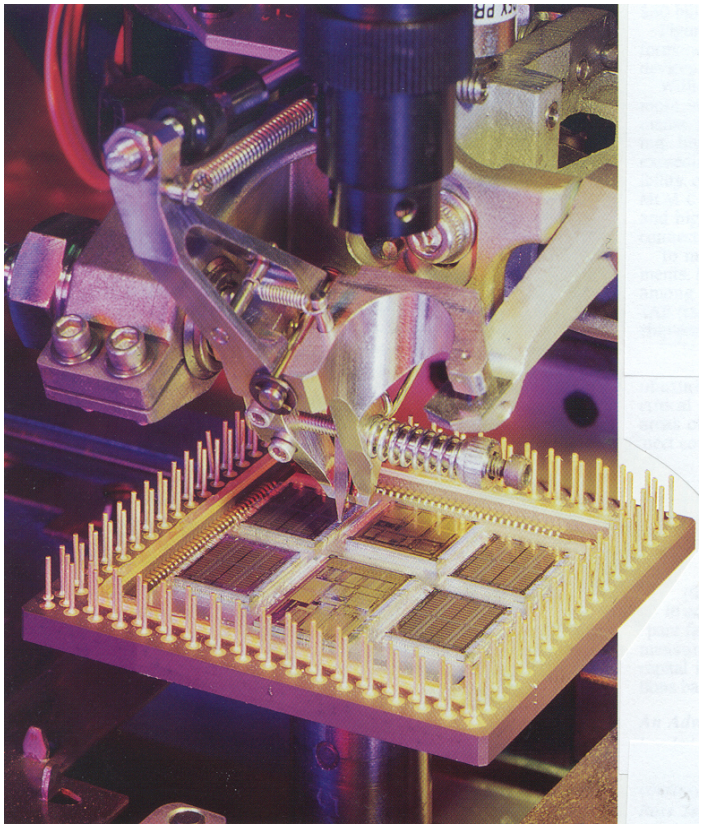
Joining Innovation

US Materials Joining

- Metal welding
- Plastic welding
- Wirebonding
- Soldering
- Adhesives
- Fusion welding



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US Metal Welding (UMW)

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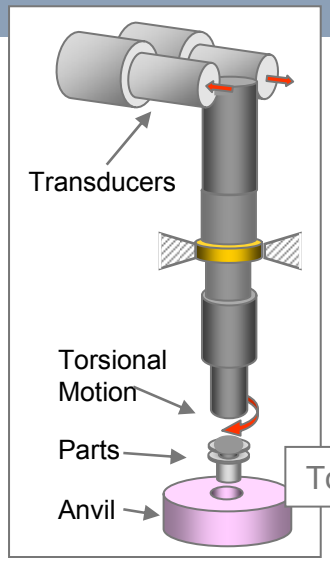
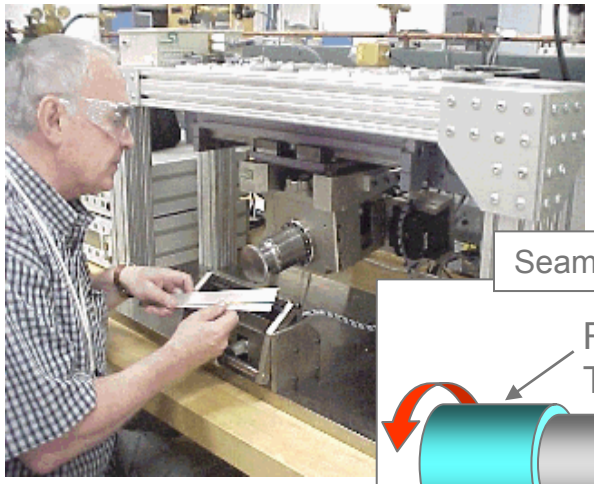
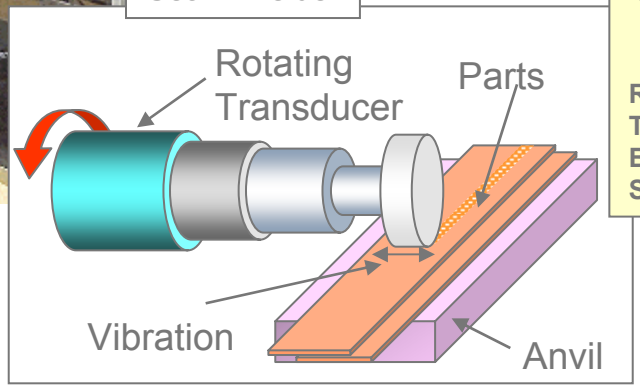
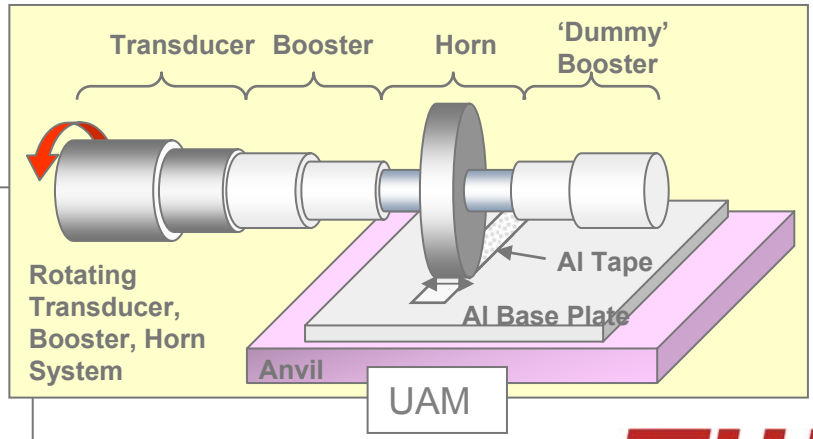
Additional UMW Processes



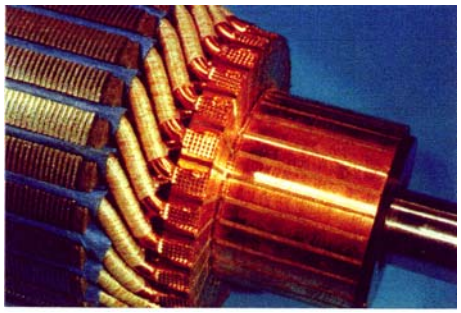


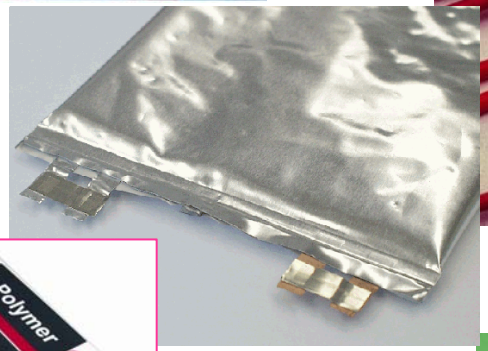


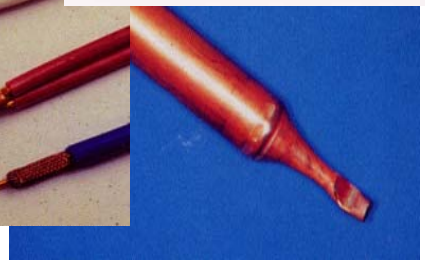


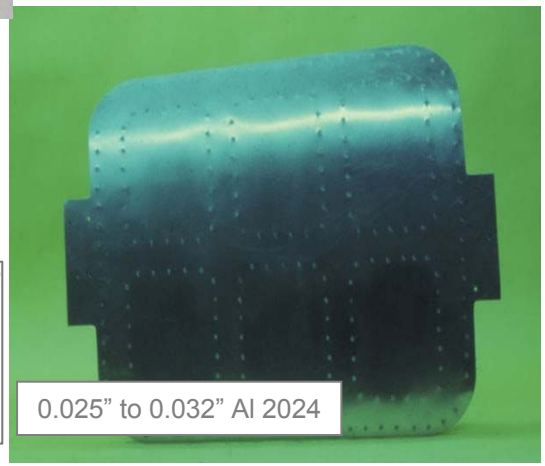
Joining Innovation

Applications









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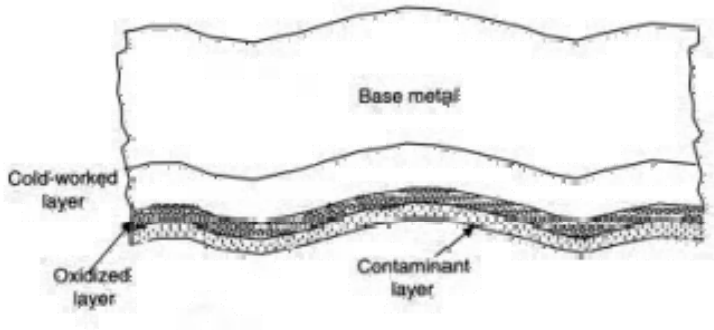
Advantages/ Disadvantages

- High conductivity materials
- Solid state bond, low heat input
- Weld through oxides, contaminants
- Thick-thin material combinations
- Dissimilar materials
- No filler materials, special atmospheres
- Low power requirements
- Easily automated



- Lap joints
- Joint thicknesses
- Restricted materials
- Deformation
- Noise, parts resonance
- Unfamiliarity
- Tool wear

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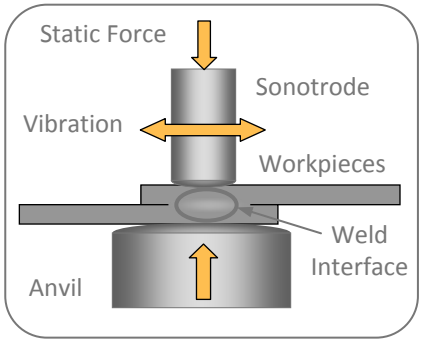
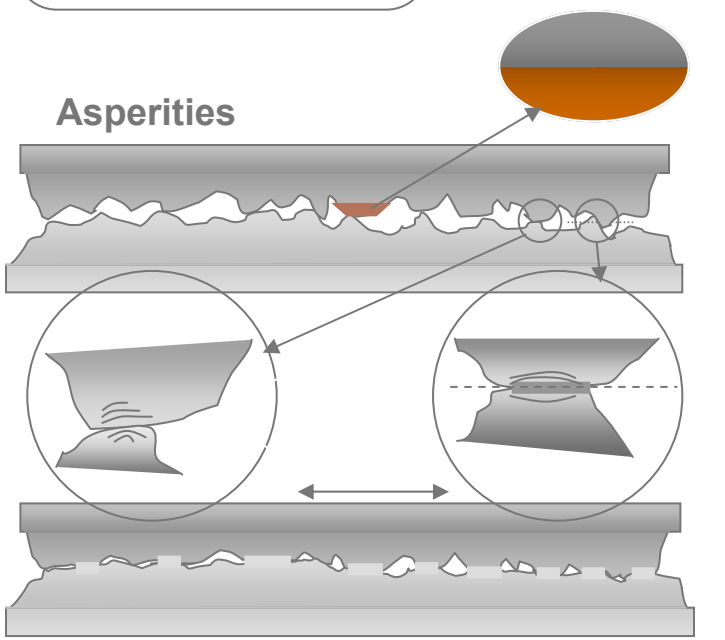
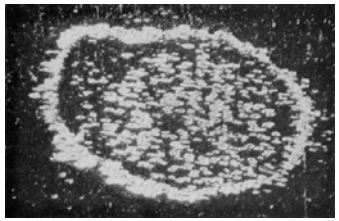
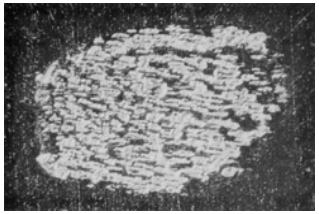
Bonding Mechanism

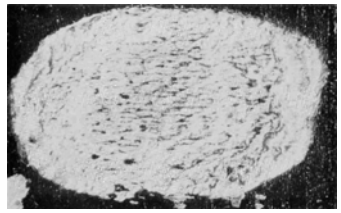




- Transverse friction-like action
- Pressure, deformation and temperature
- Surface asperities sheared and collapsed
- Oxides, surface contaminates are dispersed, or fragmented – permits intimate contact, metallic bond
- Crystallographic matching across boundary must occur
- Local bond line stresses relieved by thermal energy







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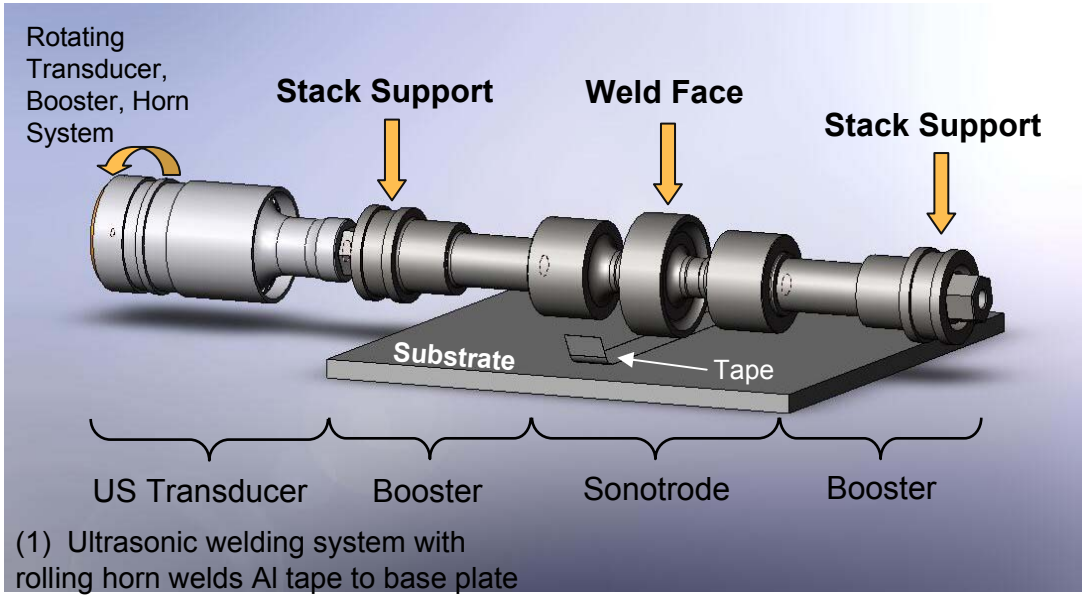
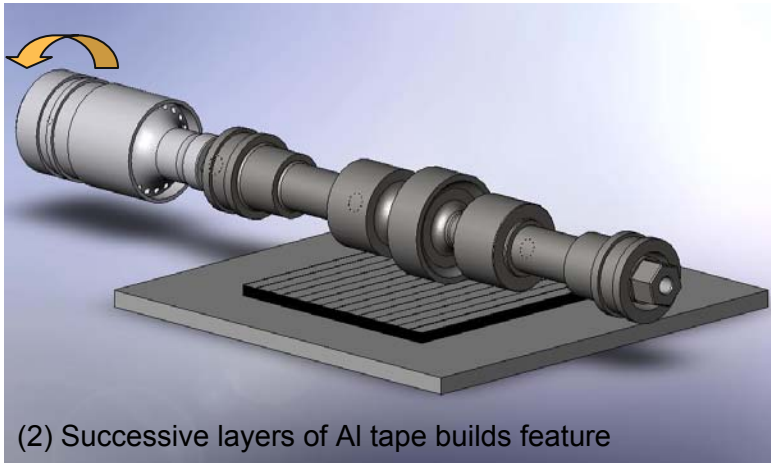
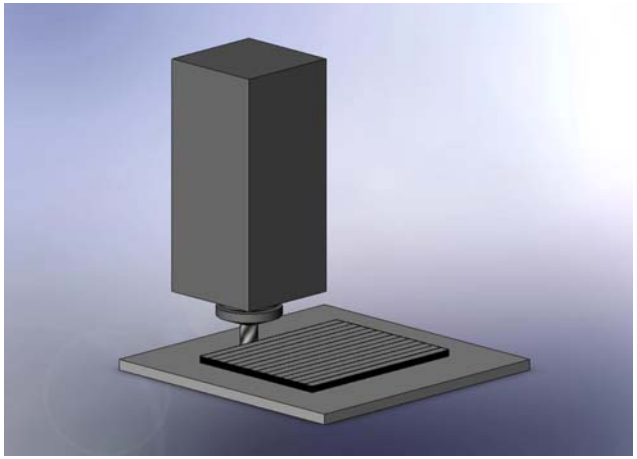
US Additive Manufacturing (UAM)

- UMW basis for UAM
- Sequence of bonding and shaping to produce solid metal parts



(1) Ultrasonic welding system with rolling horn welds Al tape to base plate


(2) Successive layers of Al tape builds feature


(3) Periodic machining operations to shape feature and maintain uniform welding surface

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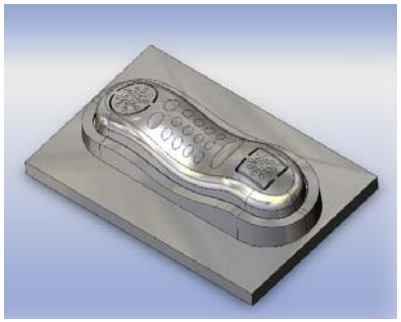
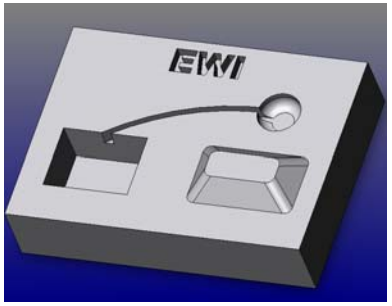
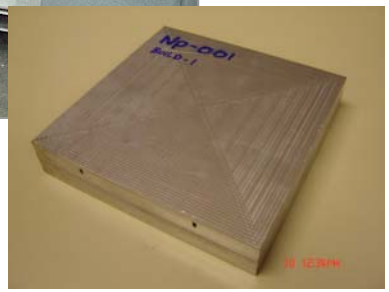
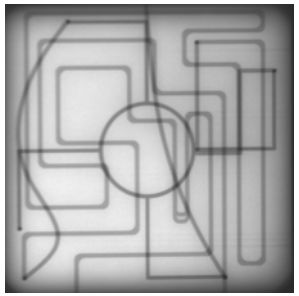
Results …

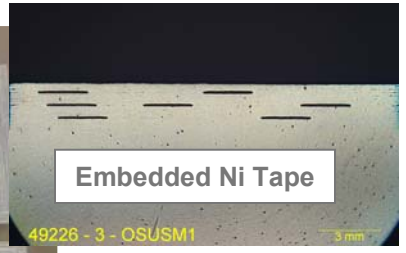








- Many <u>emerging</u> applications … rapid prototyping, low volume tooling, direct parts manufacture, tailored materials, MMC, embedded fibers, smart materials, sensors, cladding, armor, thermal management



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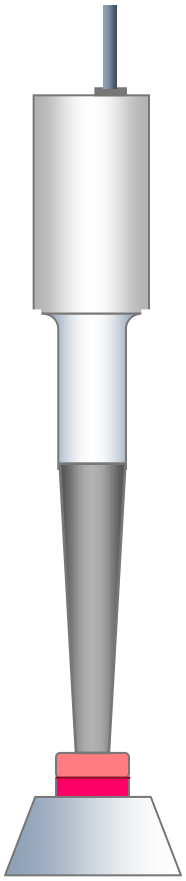
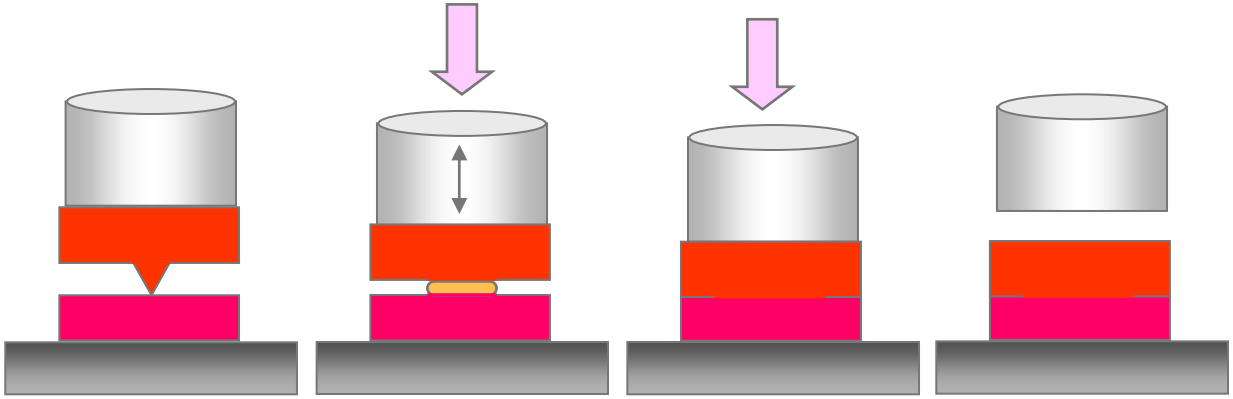
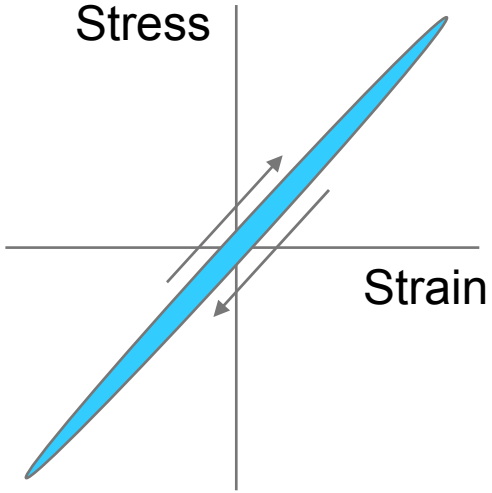
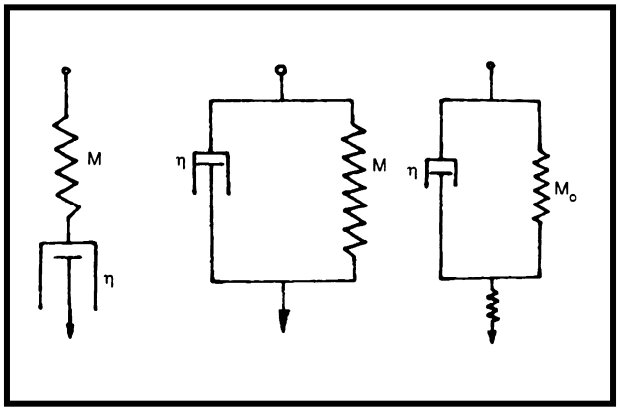
US Plastic Welding









Joining Innovation

Things Welded with US

- Wide variety of materials, thicknesses and shapes demands varied systems and tooling

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Weldability of Thermoplastics

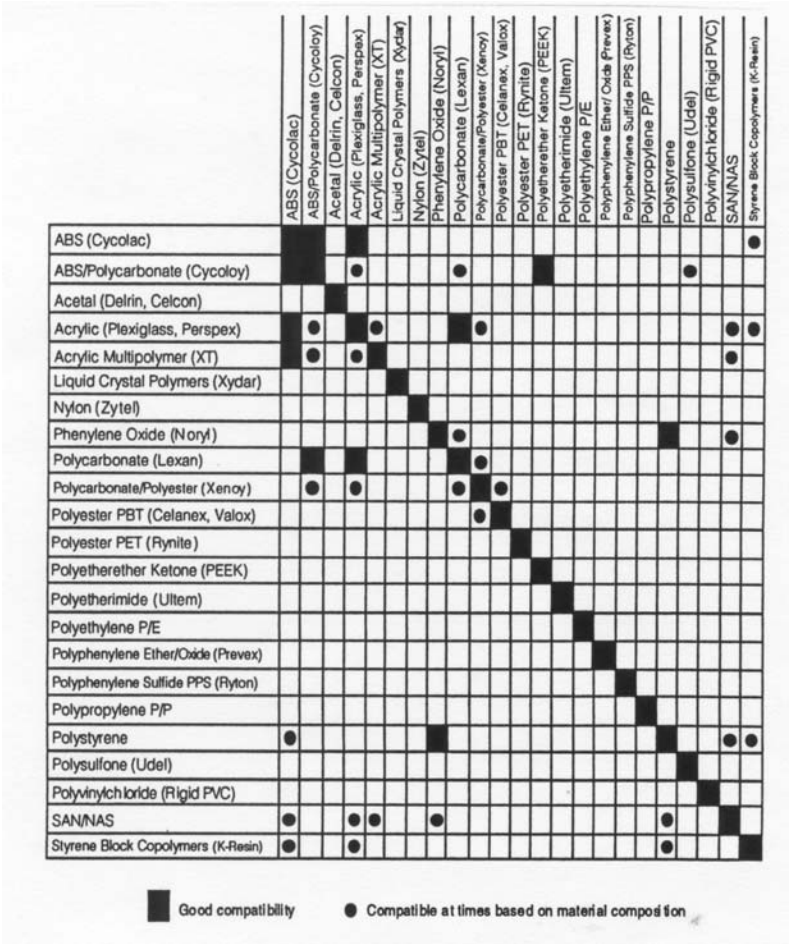
- Commonly welded thermoplastics

  Polystyrene

  ABS

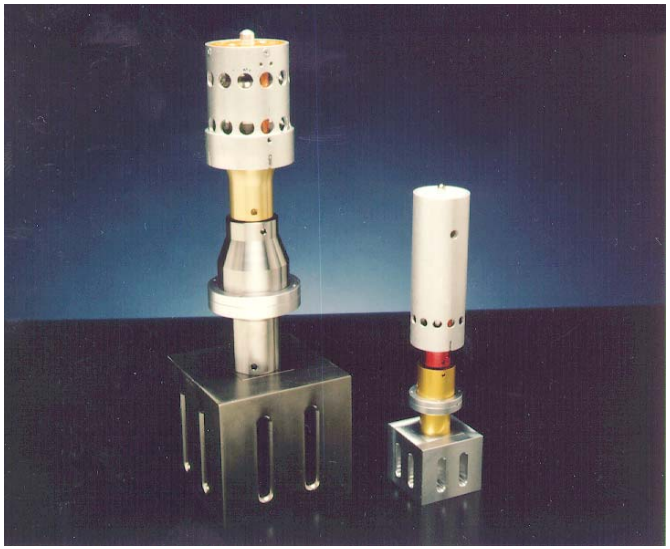
  Polycarbonate

  Nylon, etc.

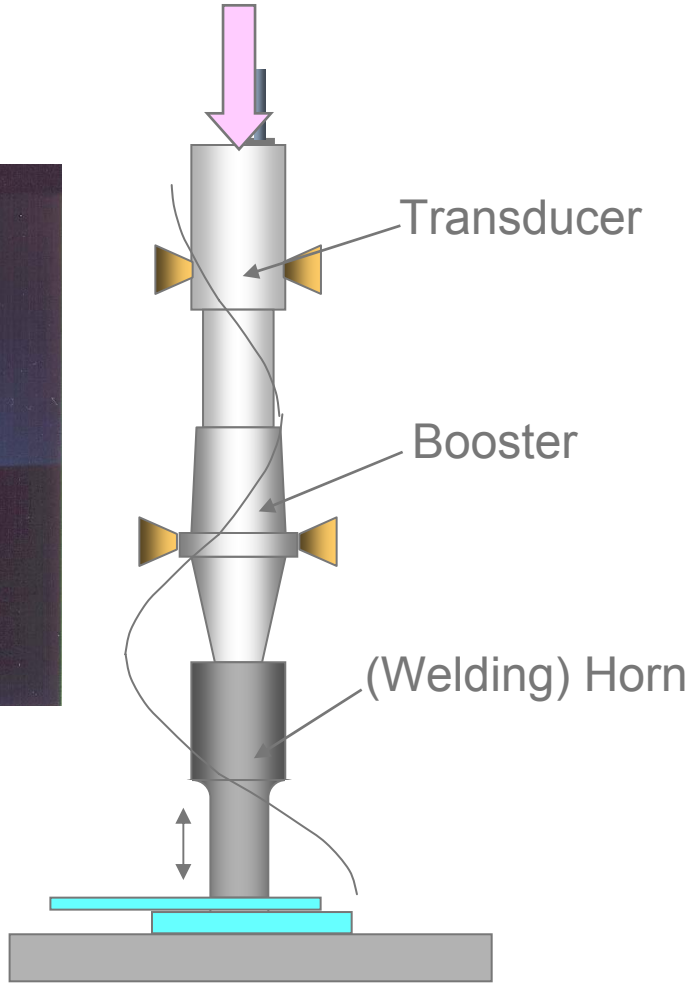


Joining Innovation

US ‘Stack’ and Press



20 kHz, 40 kHz stacks



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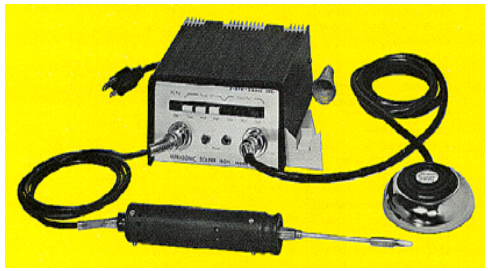
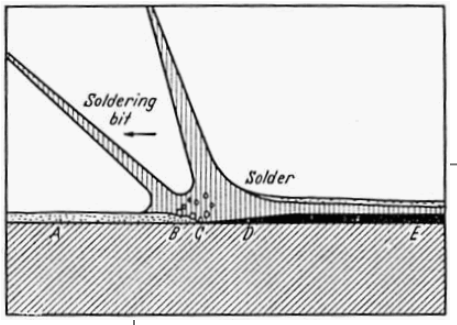
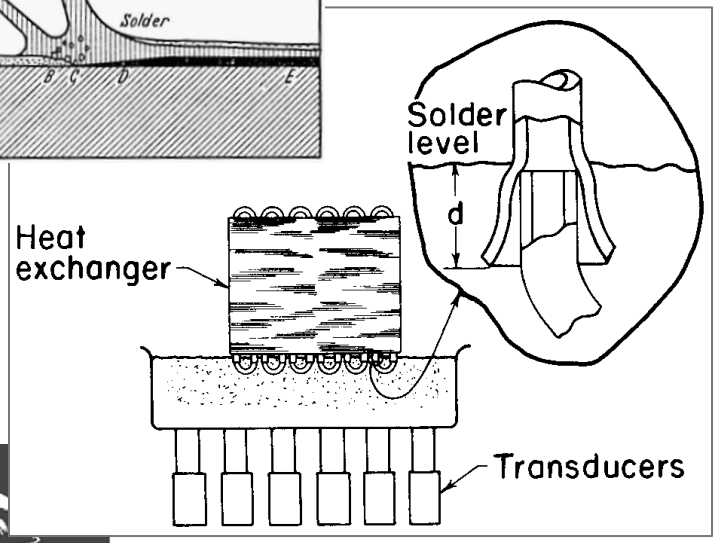
US Soldering

- Process of pretinning surface using US vibrations to remove oxides – instead of flux



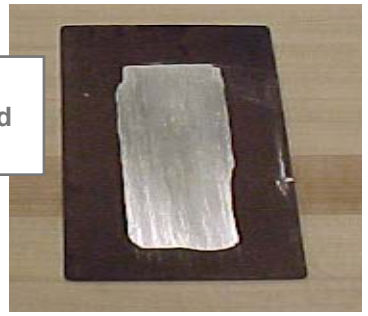




Joining Innovation

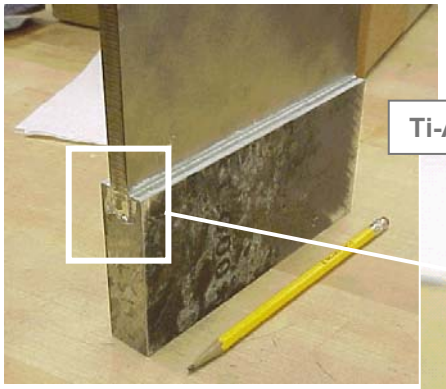
Special Ultrasonic Solder

- EWI patented Sn-based (lead free) soldering alloy* for difficult-to-wet materials
  - Ti, Ni, Au, Ag, Pt, Al, Cu, SS, Fe, etc.
  - Al_2O_3, SiC, WC, BC, nitrides, etc.
  - Heavily oxidized or anodized metals
  - Glass, Carbon Foams, Exotic Materials

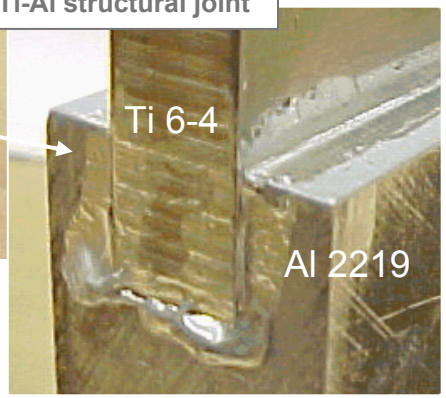


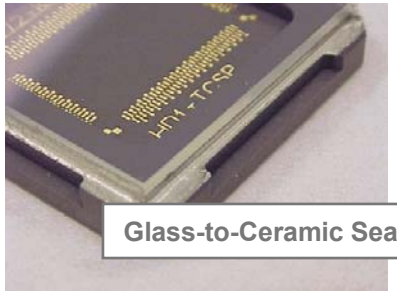
Heavily Oxidized Metals

Glass-to-Metal Joint



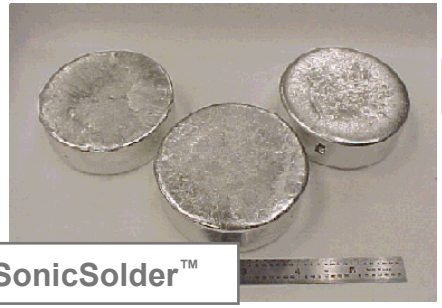
Ti-Al structural joint





Glass-to-Ceramic Seal

25 mm SiC to Ti-6-4 or Al



* EWI SonicSolder™

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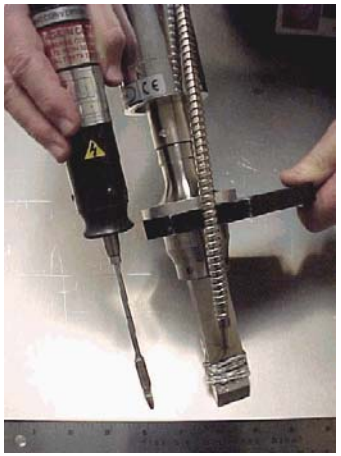
Scale-up

- Wide blade horns
- Large area horns
- Arrays



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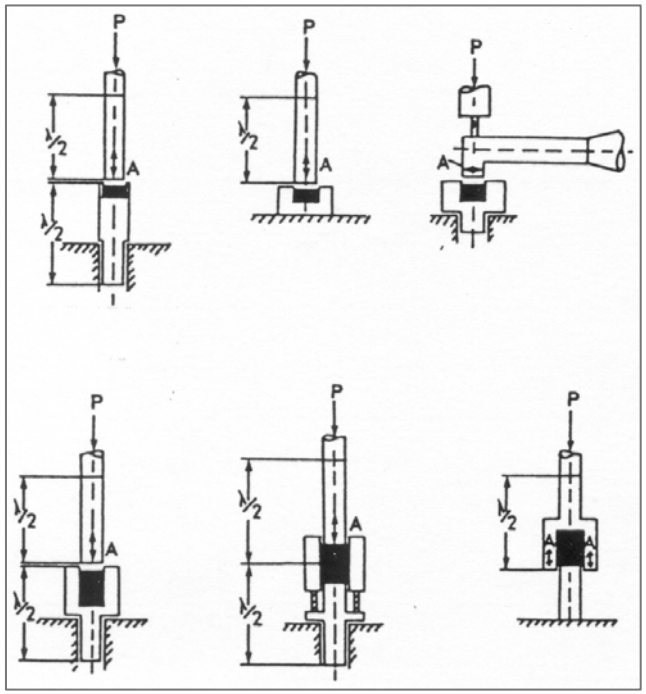
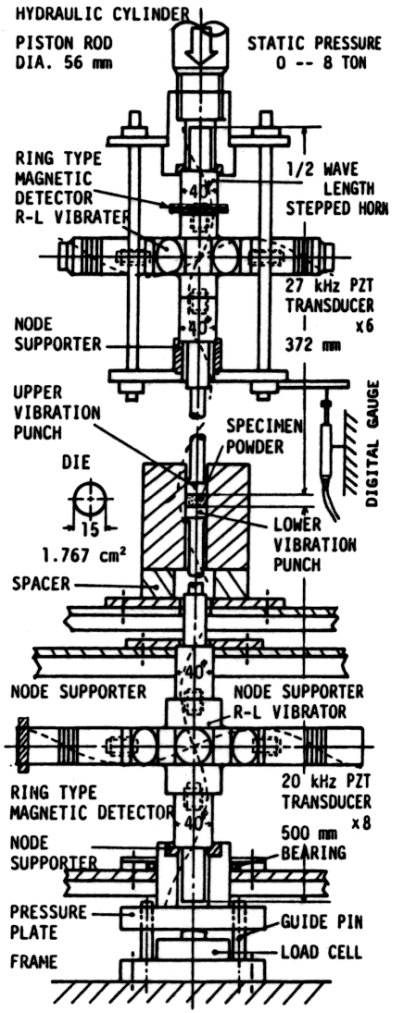
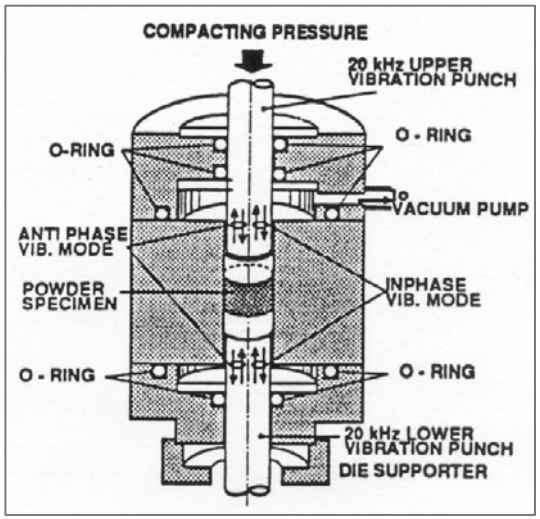
US Compaction







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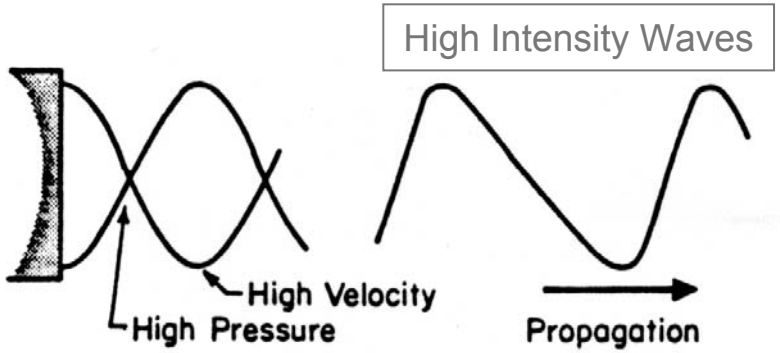
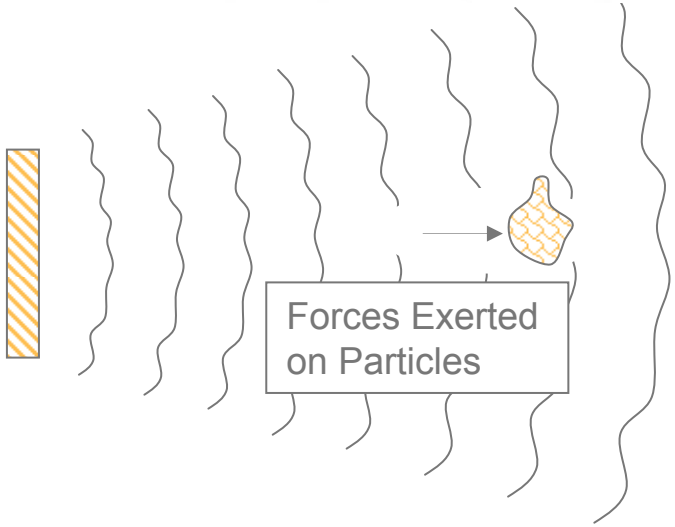
Airborne US Applications

Applications of US in Air (and other gases)

- Filtering/separation
- Agglomeration
- Defoaming/drying
- Levitation

Typically, SPL's > 150dB required to produce useful effects





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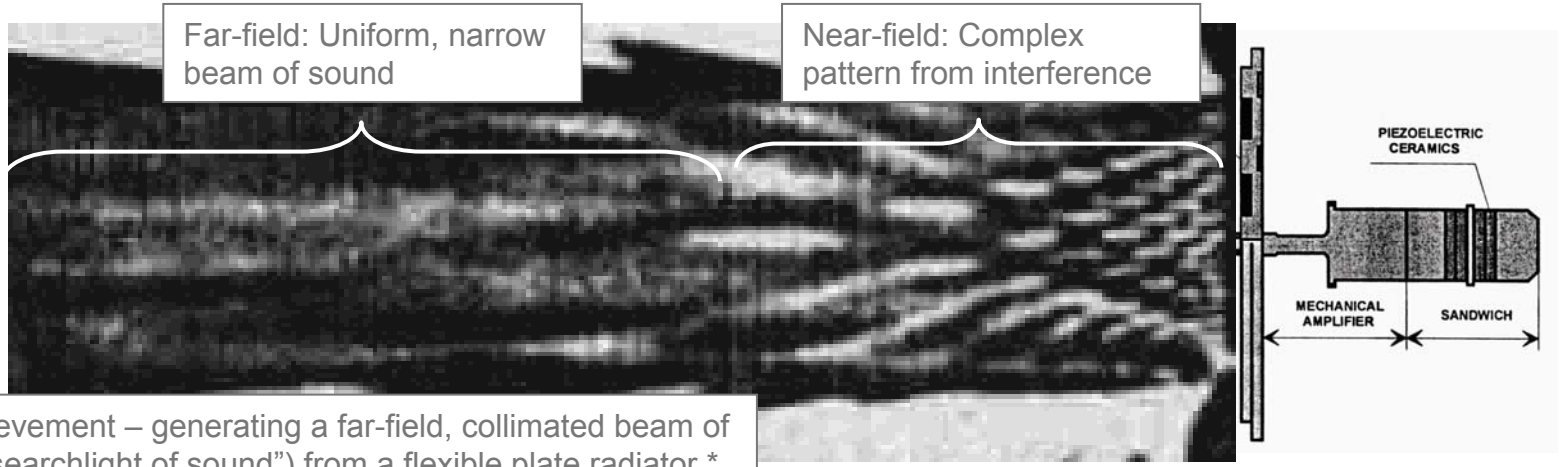
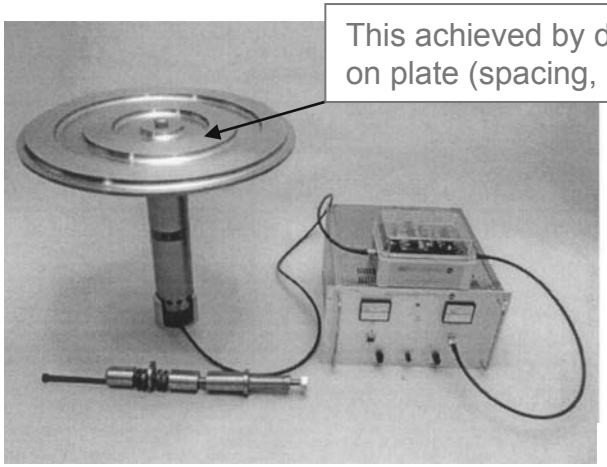
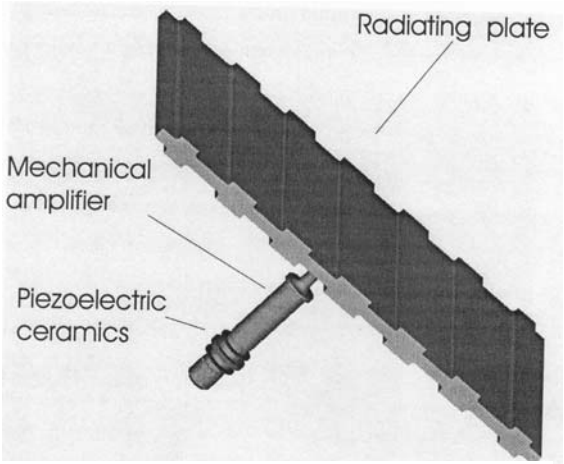
Generating Intense Airborne US – Gallego-Juarez



Key achievement – generating a far-field, collimated beam of sound ("searchlight of sound") from a flexible plate radiator *





* General illustration of acoustic field from piston radiator

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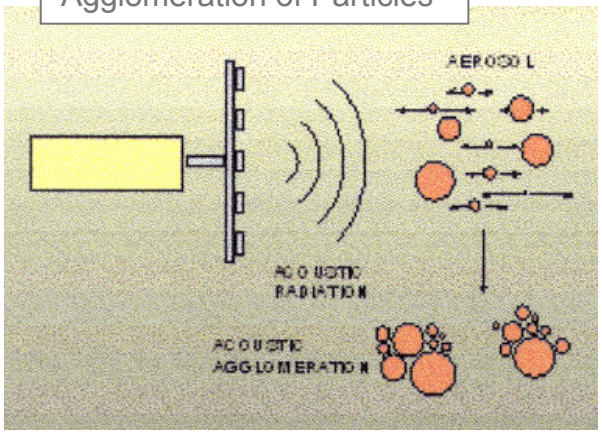
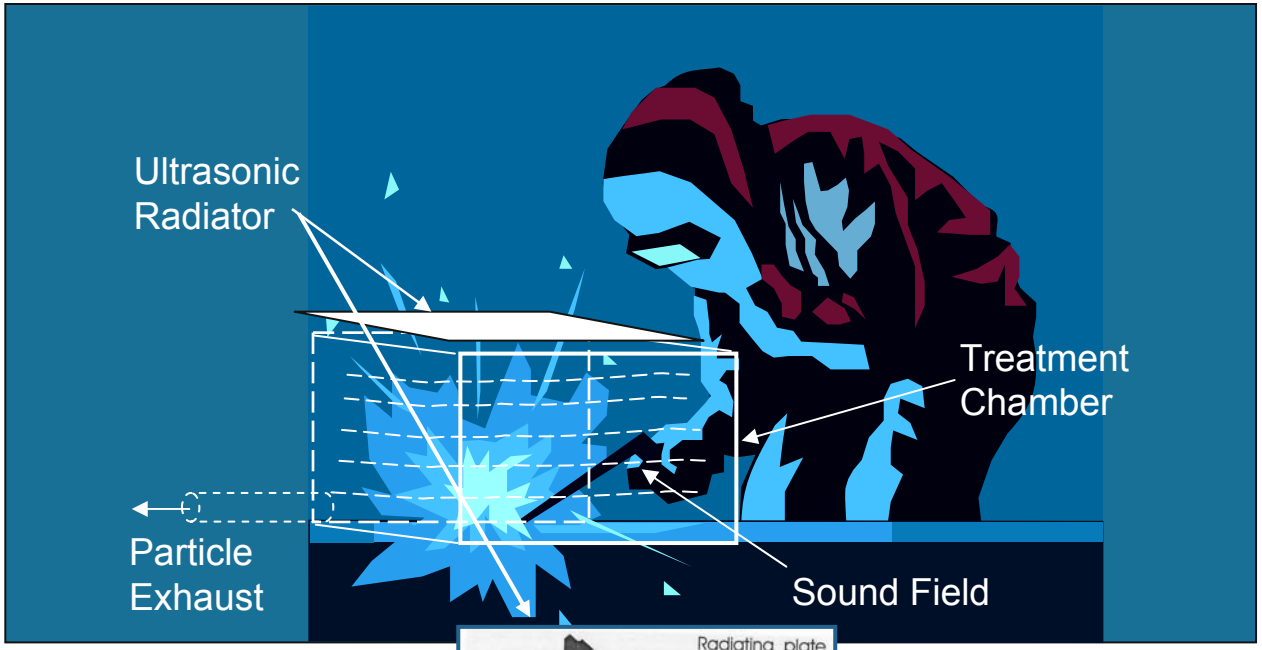
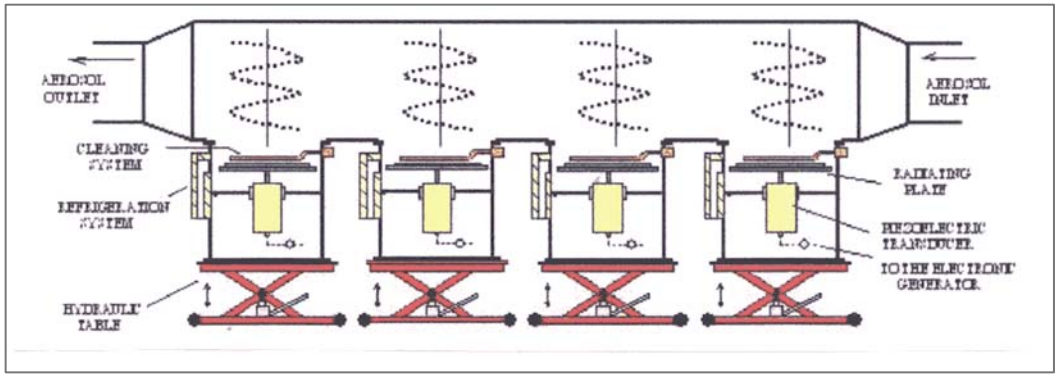
Particulate Removal

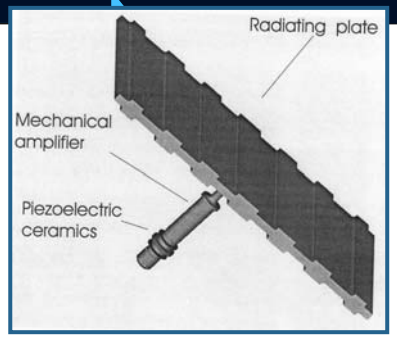
Agglomeration of Particles





Power Plant Emissions





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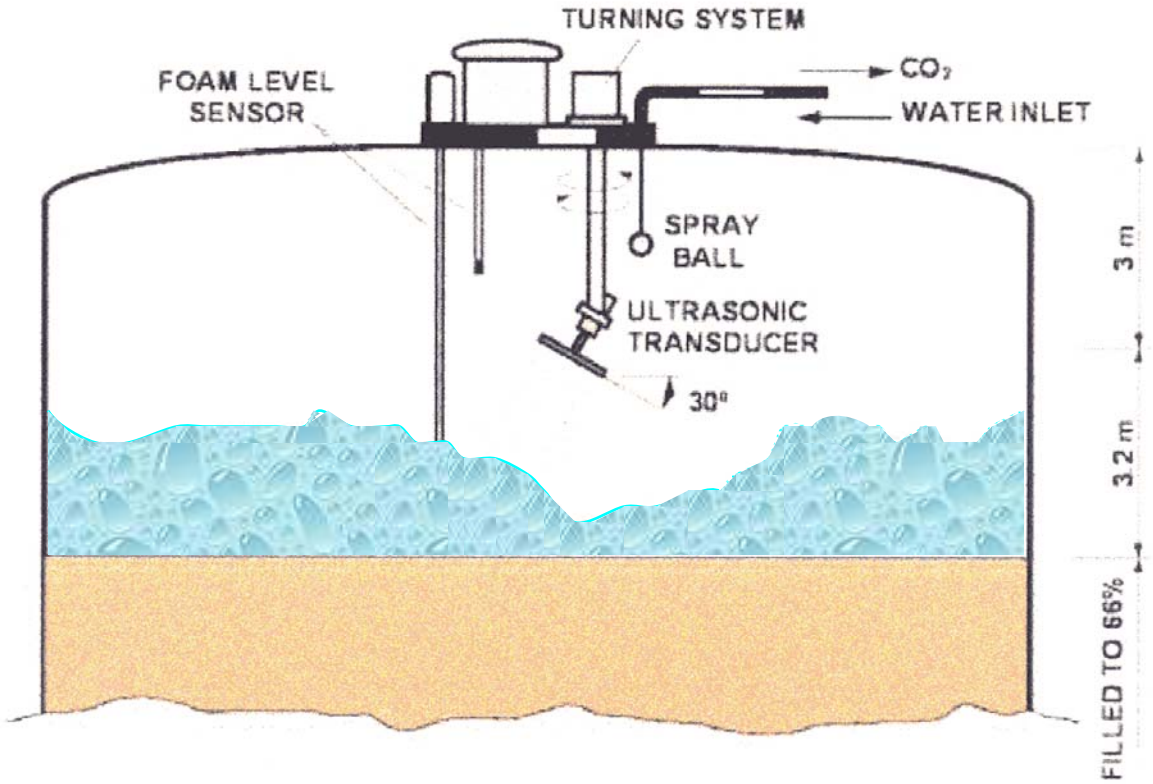
Defoaming



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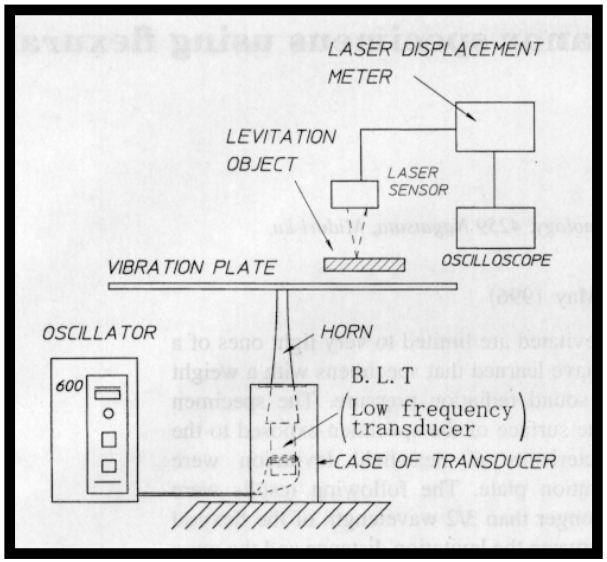
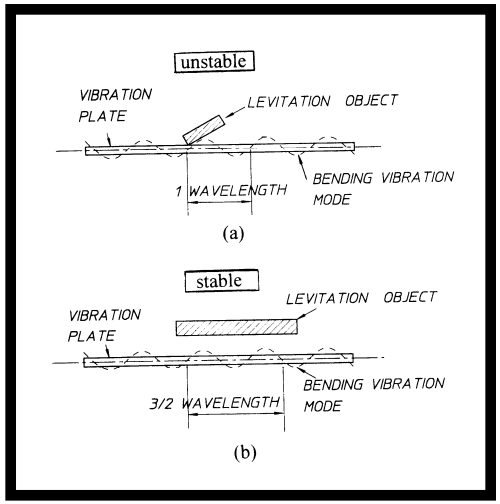
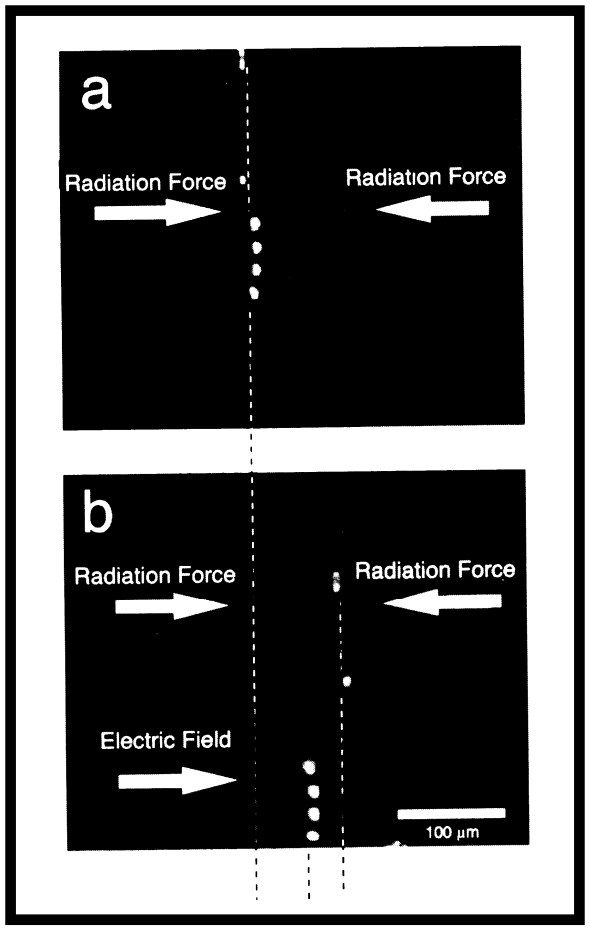
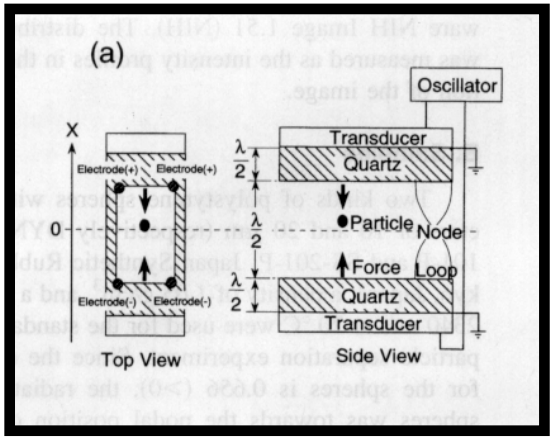
Levitation, Particle Separation









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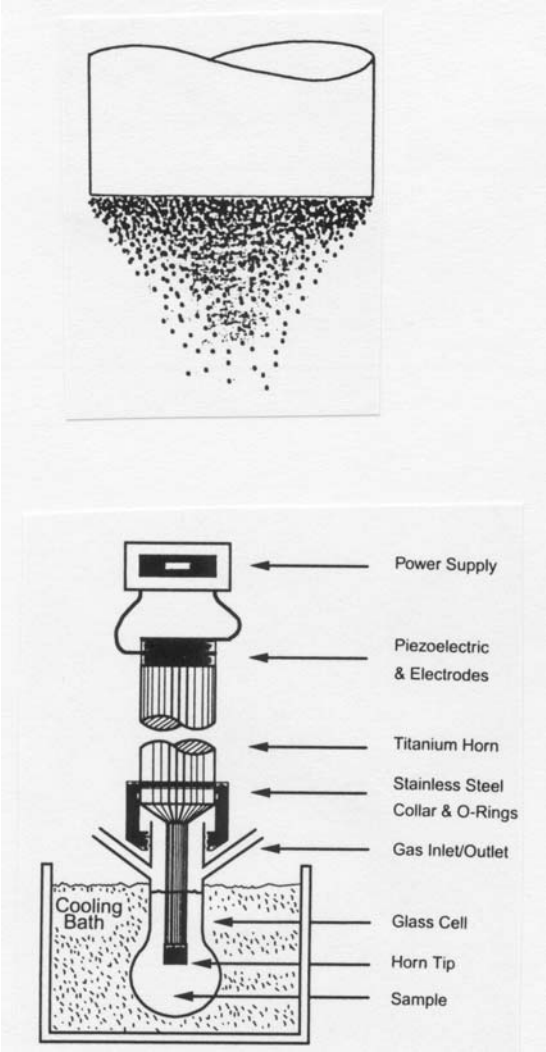
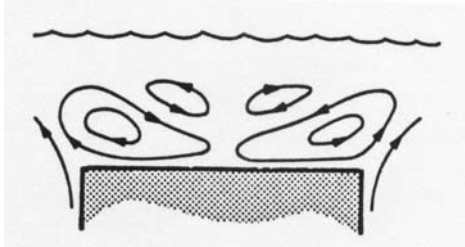
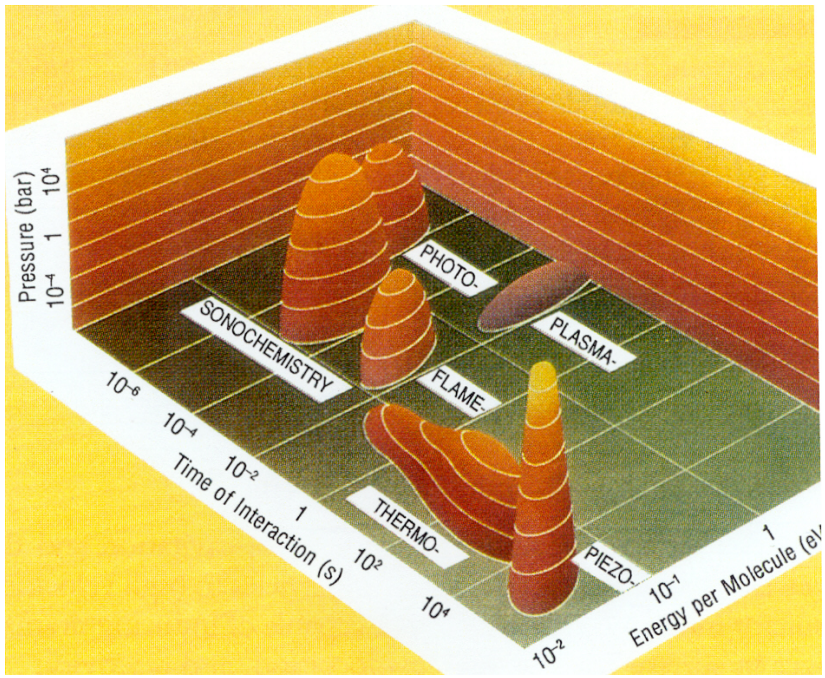
US Liquid Processing, Sonochemistry

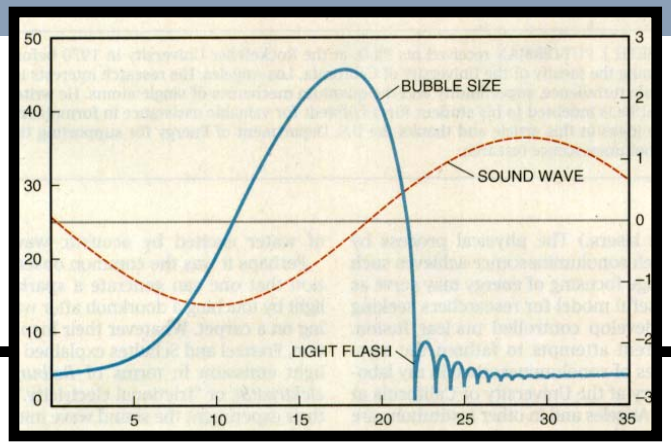


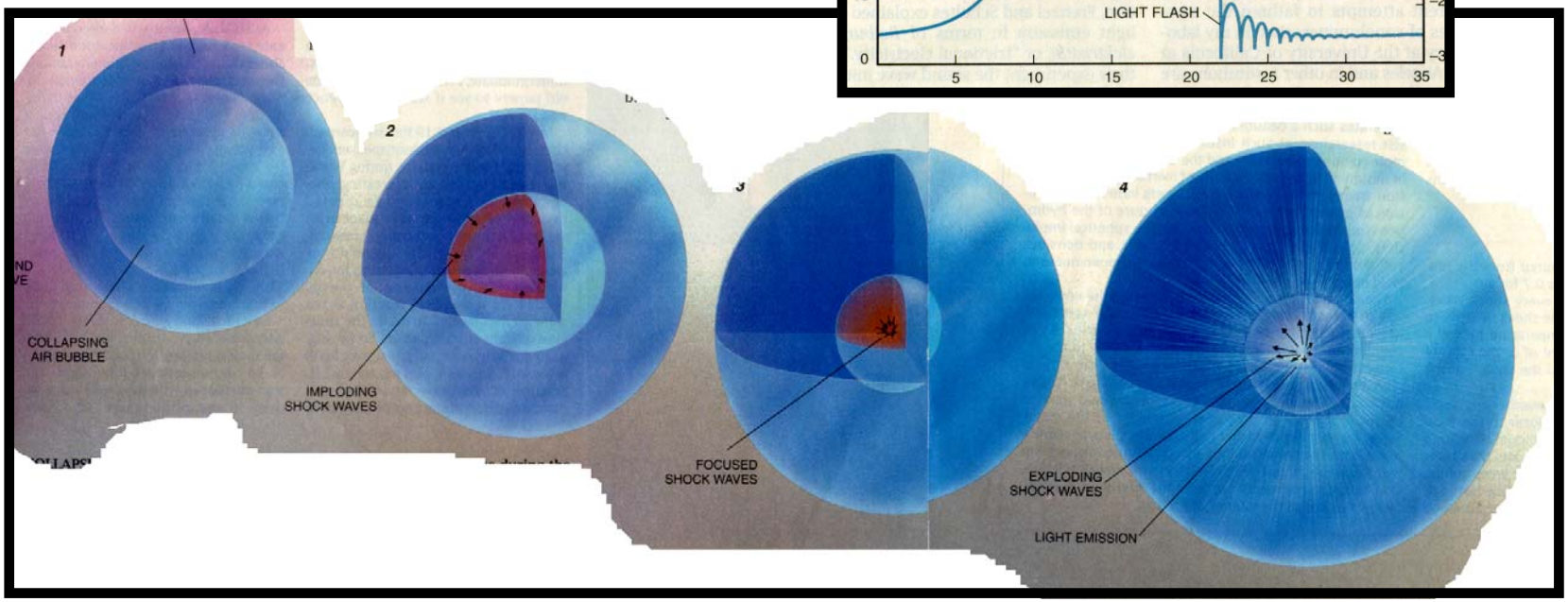




Joining Innovation

Sonoluminescence





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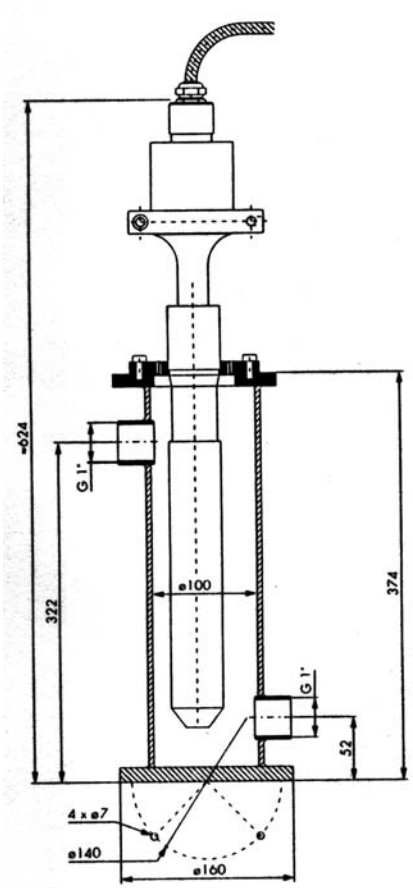
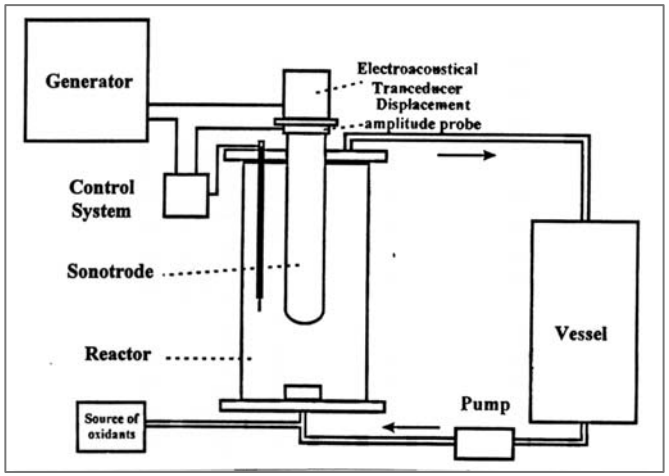
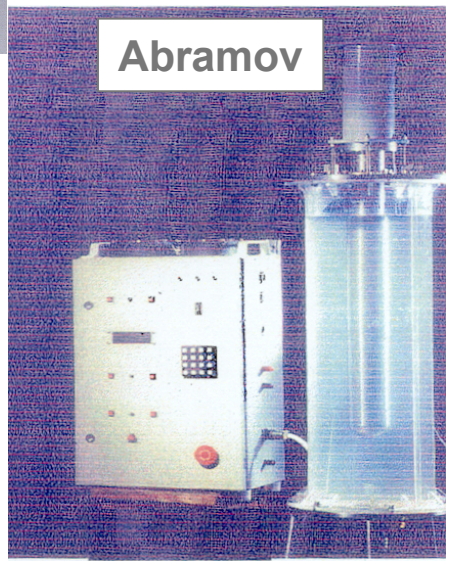
Sonochemical Reactors



Telsonic





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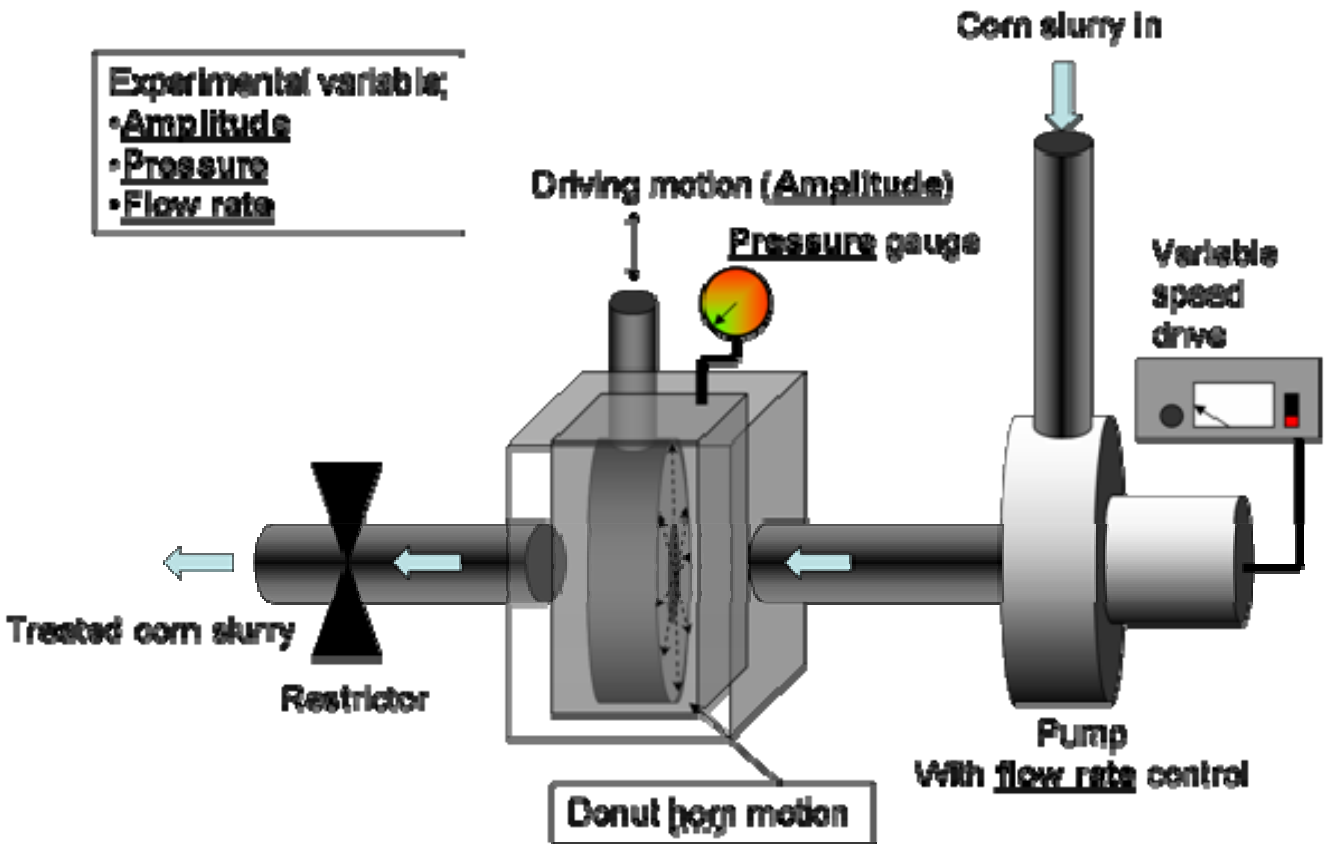
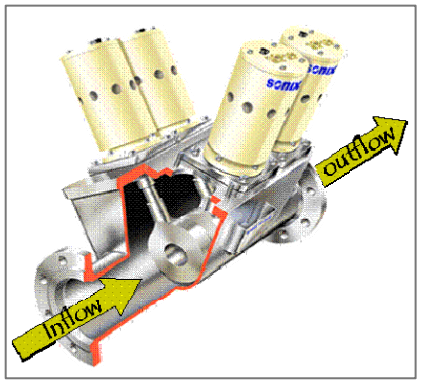
US in Ethanol Processing*





* From … "Bioenergy and Value-added Bioproducts from Agro-based Feedstocks: Application of Ultrasound Technology," Samir Kumar Khanal , Ph.D., P.E., Iowa State University, Feb., 2007

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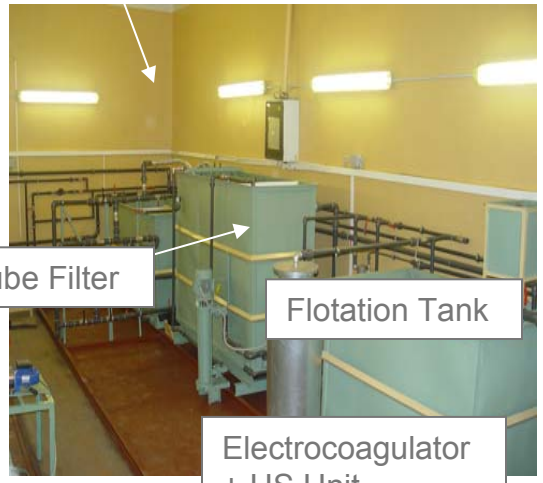
Pilot Plant System – 2m^3/hr

Settling Tank

Centrifuge

US Unit



Tube Filter

Flotation Tank

Electrocoagulator
+ US Unit

Separator

Pilot System >>> Typical “Test Tube” Demonstrations of Liquid Processing

From Professor Abramov

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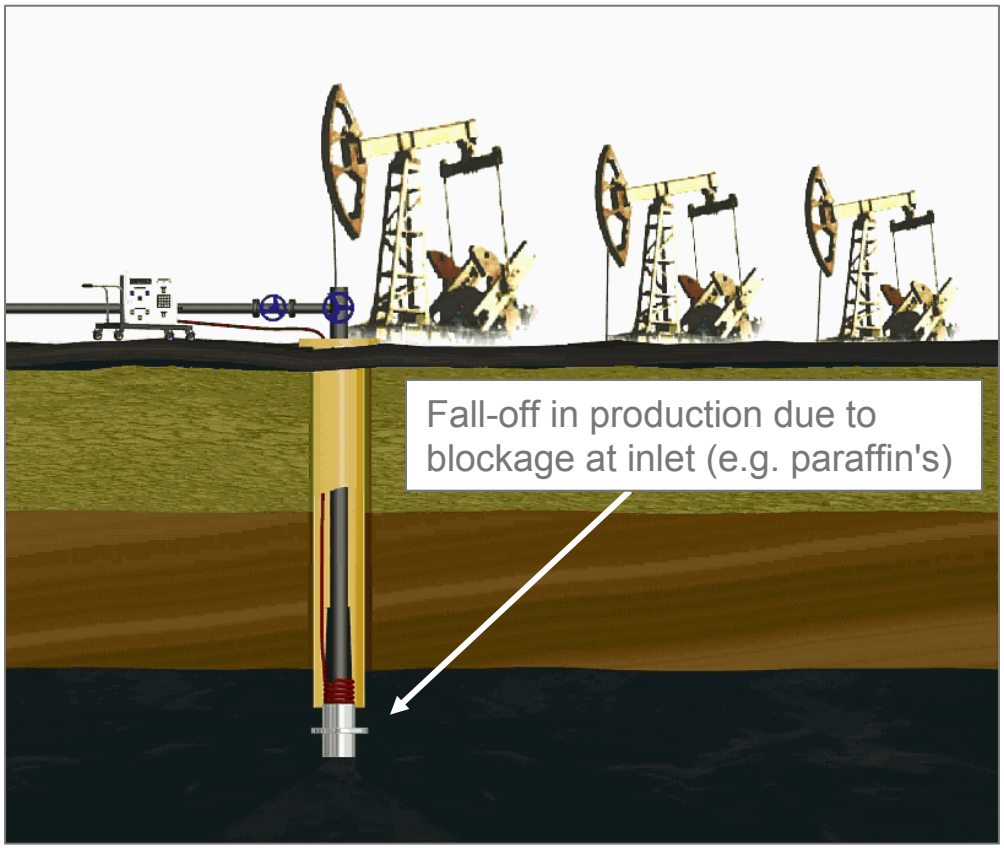
Oil Extraction

From Professor Abramov



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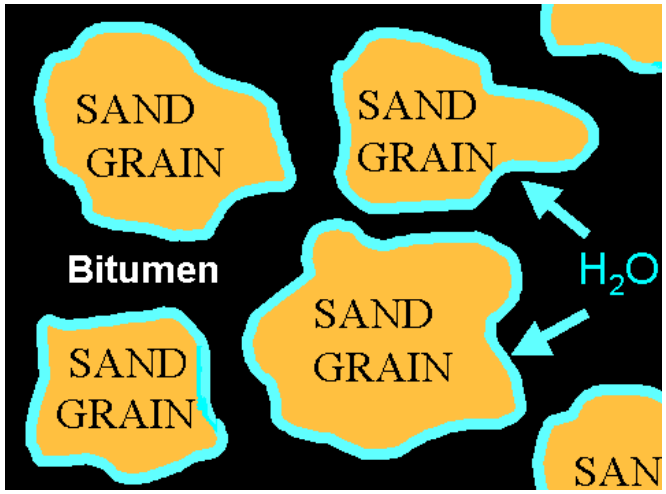
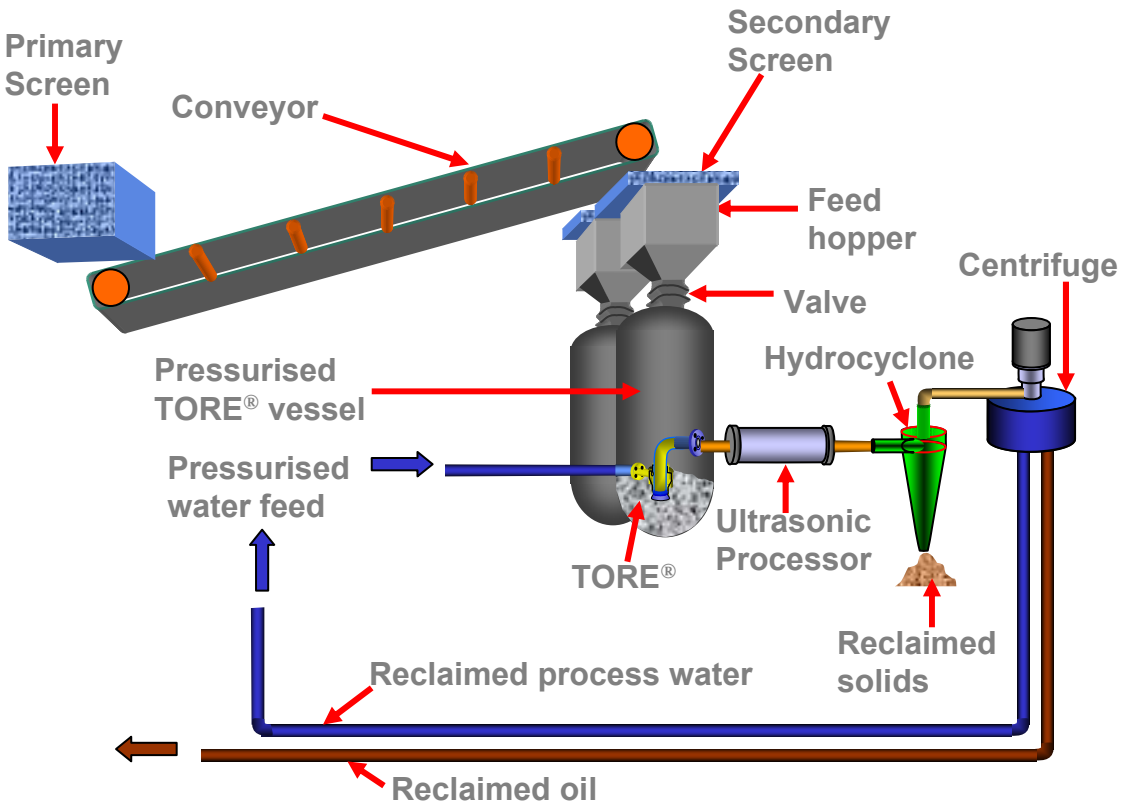
Treatment of Tar Sands





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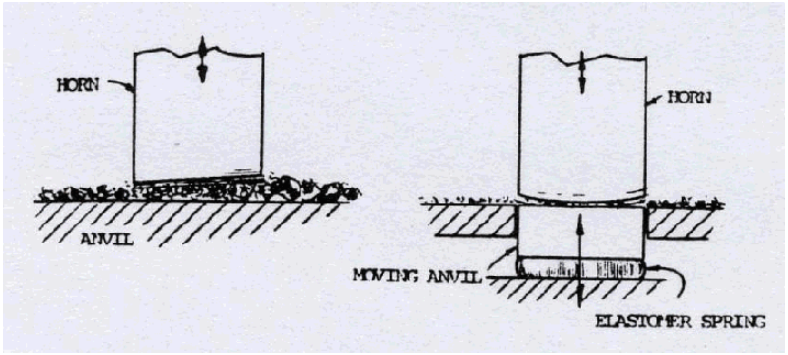
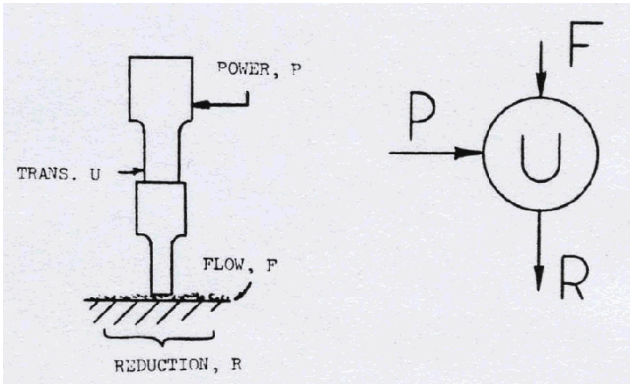
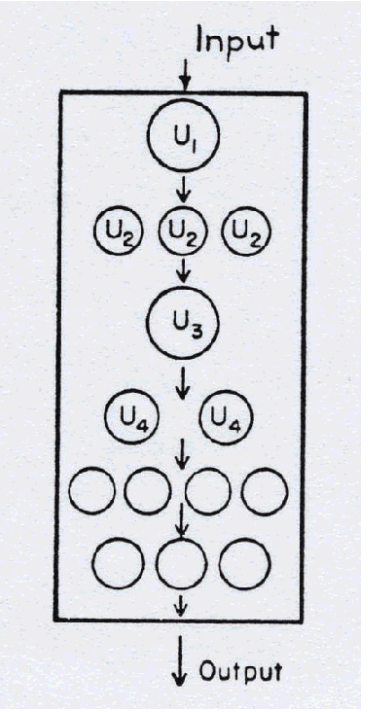
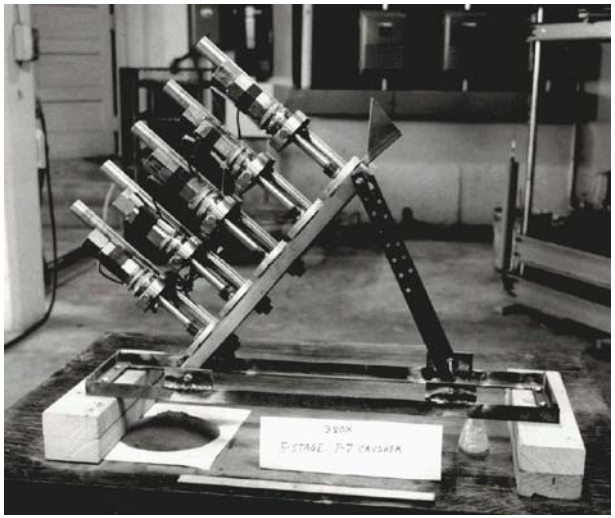
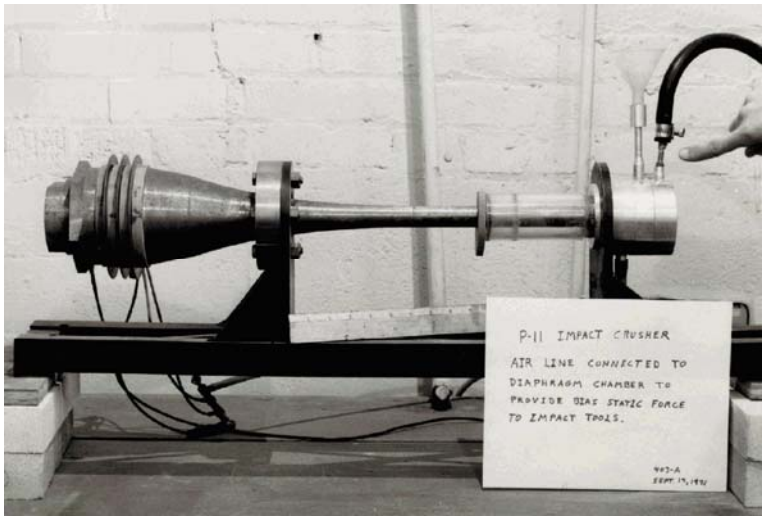
Comminution (Grinding)











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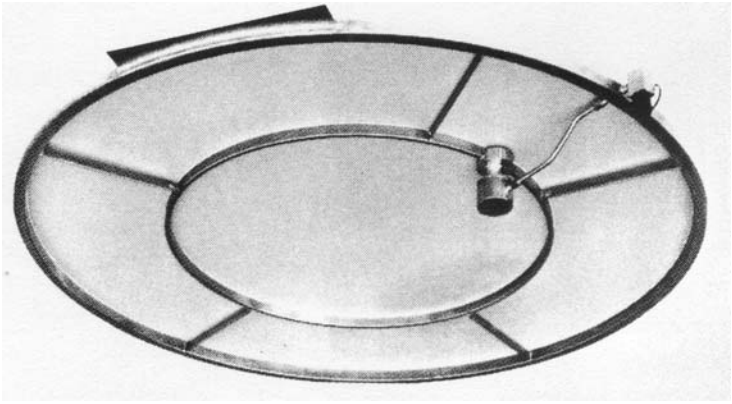
US Sieving



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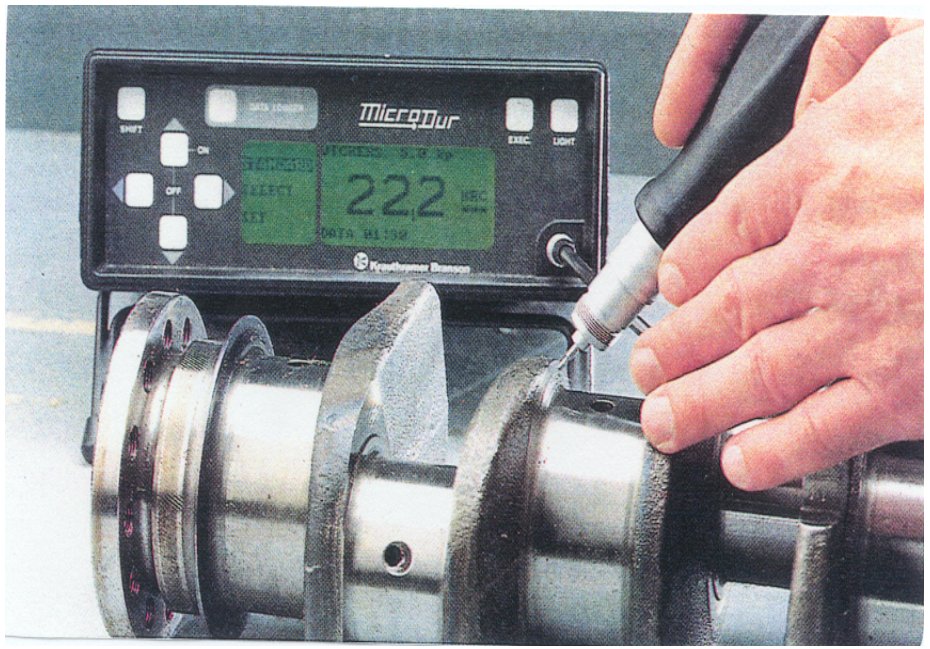
HPU for Testing

- Hardness, fatigue
- Internal friction
- Fluid/thermal coefficients
- Cavitation erosion
- Suspensions



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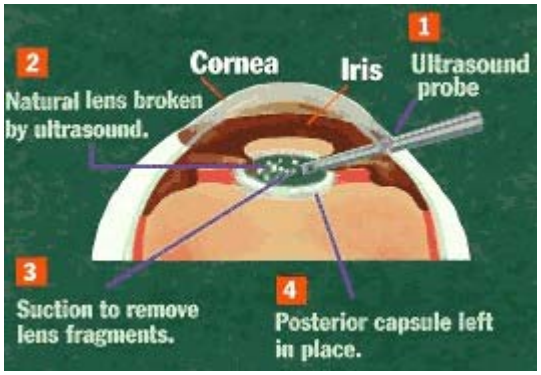
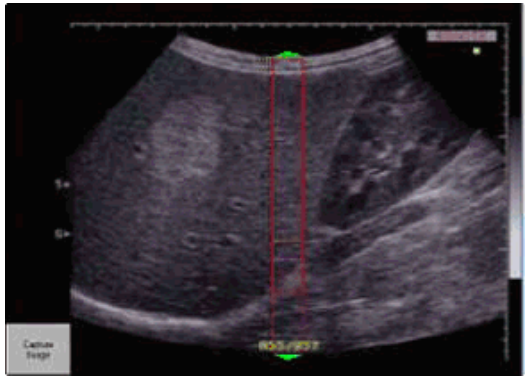
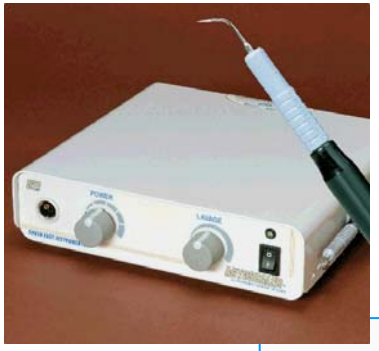
HPUS in ‘Everyday Life’







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Questions

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