

Industrial Applications of Ultrasound—A Review

I. High-Power Ultrasound

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Abstract—The estimated worldwide sales of ultrasonic power equipment for industrial uses total nearly \$100 million a year. The industry had its beginnings shortly after World War II and grew steadily over the next two and a half decades.

Lower cost of ultrasonic power made possible by advances in electromechanical power conversion materials and power semiconductors has greatly contributed to the practicality of ultrasonic equipment. Yet the main reason behind the growth of power ultrasound is the ability to perform some unique jobs that save money and have become indispensable in modern manufacturing.

Not all attempts to implement ultrasonic power devices have been successful, but commercial success is a function of technological state of the art and the need for the process. Since both change with time, surprises are likely. Who would have guessed the potential of ultrasonic plastic welding, let alone that of ultrasonic "sewing"?

While stressing the more established applications, this article takes a broader look at the uses of high frequency mechanical vibratory energy, outlining the advantages and the limitations of each process.

I. GENERAL

IN CONTRAST to ultrasonic nondestructive testing, the object of a macrosonic application is to expose the workpiece to enough vibratory energy to bring about some permanent physical change. This involves a flow of mechanical power from the source to the workpiece, which, depending on the application, may range from a few watts per square inch to tens of thousands of watts per square inch. Vibratory input, during the time of exposure, is normally of the continuous wave type. Macrosonic phenomena extend well into the megahertz range, but most practical work is done at frequencies between 20 and 60 kHz, somewhat above the range of human hearing.

A basic macrosonic system consists of an electromechanical transducer and a high frequency electric power supply. The power supply converts the available electric line power into high frequency electric power which is used to drive the electromechanical transducer. The transducers are typically of a compound design, but at their heart use electrostrictive or magnetostrictive elements which change physical dimensions in response to an electric or a magnetic field. Most modern transducers use piezoelectric ceramics of lead zirconate titanate due to its superior electromechanical conversion efficiency, typically in the order of 95% or better.

Just what are the limits of practical ultrasonic power today? If the application allows stacking of sonic power sources, no particular limit to the maximum total power exists. The power available from a single half-wave transducer, however, is limited by the volume of the electromechanical conversion material that can be accommodated and varies inversely with the square of the frequency. As transducer design depends on the use, exact power limits are not possible to pin down, but 4 kW at 20 kHz could serve as a rough reference.

By definition, the mechanical power transferred from the sonic source to the load is the product of sonic source velocity at the load interface and the mechanical force resisting the source velocity [1]. The force is produced by the medium on which the sonic source is acting.

Transducer output velocity and frequency can be used as primary source parameters. The product of velocity and frequency defines acceleration, and the ratio of velocity and frequency defines the transducer output displacement. See Table I.

As a point of interest, practical ultrasonic power sources are by nature velocity or displacement generating devices, where due to high mechanical Q the motion is sinusoidal, and there are no practical ways of directly generating ultrasonic forces.

The most commonly used transducers are of extensional type where the output face of the transducer is a circular piston area vibrating sinusoidally in the direction of the transducer axis. The transducer output face can be applied directly to the load, or coupled to intermediate sonic resonators (Fig. 1). Extensional transducers impart compressional waves to the load. Transducers can also be designed to produce shear, torsional or flexural vibration, or to focus vibrational intensity in fluid media.

Contrary to the popular myth, ultrasonic treatment is normally not done by focusing sound waves on the work through the air. In most cases a direct contact with the vibratory tool is needed, or liquid is used as a vehicle. Neither is there a common mechanism responsible for all sonic effects: ultrasonic metal welding is unrelated to ultrasonic aerosol production, and plastic welding is unrelated to ultrasonic cleaning.

Yet there are some peculiarities about the basic ultrasonic parameters, as shown in the following example.

A 20 kHz transducer operating at a peak output velocity of 26 ft./sec. will have peak-to-peak displacement amplitude of 0.005 inches and peak acceleration of $10 \times 10^4 g$. To load the transducer to 1 kW the load

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TABLE I
EFFECT OF FREQUENCY ON TRANSDUCER PARAMETERS

PARAMETER	FREQUENCY	FREQUENCY $\times 2$
Length	L	L/2
Width	W	W/2
Weight	K	K/8
Output surface	S	S/4
Power	P	P/4
Power density	P	P
Displacement	D	D/2
Acceleration	A	2A
Output velocity	V	V

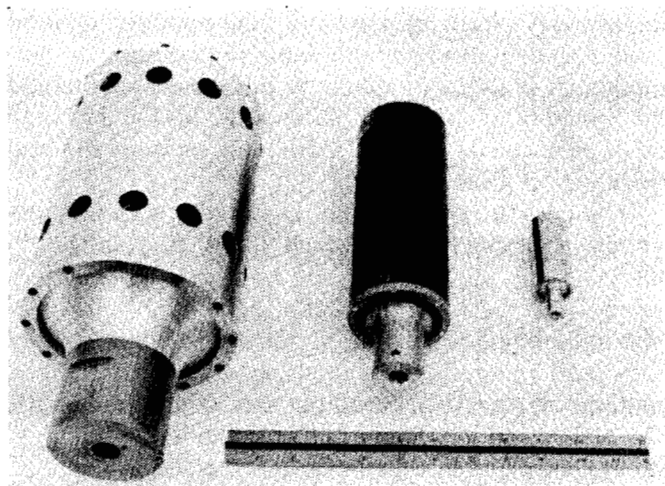


Fig. 1. Sonic and ultrasonic power transducers: 8 kW, 10 kHz; 1 kW, 20 kHz; and 40W, 40 kHz. Transducers are of piezoelectric type.

must exert on the transducer a peak force of 57 lbs. (excluding any reactive loading). The work performed by this transducer in one second is equivalent to lifting a 740 lb. load to a height of one foot. What is so unusual about these values?

First, power ultrasound is characterized by *very high repetition rates, small displacements, moderate point velocities, and very high accelerations*. Second, *large amounts of work can be done without application of high forces and large displacements*. The transducer in the example, incidentally, would weigh about 2 lbs.

Another useful characteristic is the ability to propagate through solids, liquids, and gasses and form a resonant pattern. This allows work to be done at areas away from the source and makes it possible to treat a large volume of material.

Most uses of macrosound depend on compound vibration-induced phenomena occurring in matter. These are

- 1) *cavitation and microstreaming* in liquids [2], [3]
- 2) *surface instability* occurring at liquid-liquid and liquid-gas interfaces [4],
- 3) *heating and fatiguing* in solids.

Major uses of macrosound are discussed next in order of commercial significance. Since hard facts are not available, the ranking is by necessity subjective. Sections

Sonics and Liquids and *Sonics and Solids* give an overview of macrosonic applications and highlight some of the more intriguing developments.

II. FIVE MAJOR APPLICATIONS

A. Cleaning

Ultrasonic cleaning is the oldest industrial application of power ultrasound. Present-day uses span a wide variety of industries ranging from castings to semiconductors. Ultrasonic cleaning is often combined with other pre- and post-cleaning operations such as pre-soaking or vapor rinsing and makes use of a variety of detergents and cleaning solutions. Descaling and degreasing are also done.

The main advantage of ultrasonic cleaning lies in "brushless scrubbing" due to cavitation, which in a well-designed cleaner is evenly distributed throughout the volume of the liquid and is capable of reaching normally inaccessible places. Ball bearings, carburetor parts, and vessels with complex internal cavities can be effectively cleaned.

Ultrasonic cleaning works best on relatively hard materials such as metals, glass, ceramics, and plastics, which reflect rather than absorb sound. Cleaning equipment normally operates in the range of 20–50 kHz.

The phenomenon responsible for ultrasonic cleaning is cavitation. High frequency alternating pressure in a liquid forms microscopic voids which grow to a certain size, then collapse, causing very high instantaneous temperatures and pressures. This implosion of cavitation bubbles does the rough work of loosening dirt and grease stuck to the workpiece. Oscillation of stable cavitation bubbles and the resultant microstreaming also contribute to cleaning [5].

Cavitation can be produced by other methods than ultrasonics and is common with underwater propeller blades and steam turbines. Ultrasonically induced cavitation, however, can be produced as a far field effect, away from the source, and without any gross movement of the liquid. Far field effect is achieved by resonating the total volume of the liquid in the cleaner. At frequencies of interest, the layers of maximum cavitation intensity repeat every 0.5 to 1.5 inches producing fairly uniform cleaning throughout the volume. For more uniformity the parts may be moved during exposure.

Power density of ultrasonic cleaners is relatively low, usually below 10 watts per square inch of driving area. An attempt to "overdrive" the tank results in a loss of the far field effect and causes pronounced cavitation and wear at the driving surface.

The choice of cleaner frequency is normally determined by the application. Since cavitation shock intensity is higher at lower frequencies, a 25 kHz cleaner will have more brute cleaning ability than a 40 kHz cleaner. However lower frequencies have been found damaging to some delicate parts, and for cleaning of semiconductors, for instance, 40 kHz may be preferable. 40 kHz cleaning is also quieter.



Fig. 2. Monorail automated ultrasonic cleaning system for cleaning, rinsing, and drying automotive ring and pinion gears.

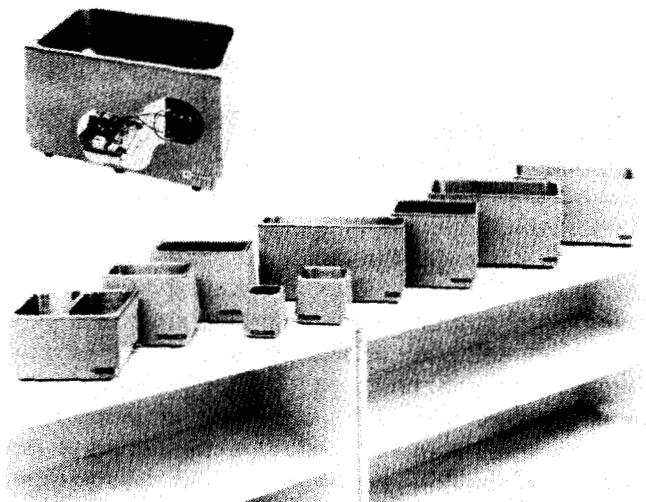


Fig. 3. Small ultrasonic cleaners with power supplies mounted in the base.

Standard industrial cleaners typically range in power from one hundred to a couple of thousand watts with corresponding tank capacities of 1-40 gallons. Multi-kilowatt special systems with tank capacities of several hundred gallons are not uncommon (Fig. 2). In recent years, low power, low cost (below \$100) cleaners have become available, which has made ultrasonic cleaning accessible to small shops and laboratories (Fig. 3).

Modern ultrasonic cleaners employ solid-state electronic power supplies with automatic tuning and do not require operator attention. A common problem to all ultrasonic cleaners is gradual deterioration of the tank due to cavitation erosion. This depends largely on the application, and well-designed systems can give years of satisfactory service.

It is hard to envision any dramatic breakthroughs in ultrasonic cleaning. Tank materials and design can probably be further improved to extend life and enhance cleaning. Since cavitation behavior is different for different solvents, and also changes with temperature,

choice of optimum cleaning parameters can be tricky and further advances in this area are likely.

B. Plastic Welding

Probably without knowing it, most people in the United States come in daily contact with ultrasonically welded plastic parts. The process was developed in the last ten years and was quickly accepted in assembly of toys, appliances, and industrial thermoplastic parts. The big break came with discovery of far field welding, which made welding of rigid thermoplastics possible and extended the technique beyond welding of plastic films practiced earlier.

Ultrasonic welding has an ideal combination of ingredients sought in modern manufacturing. The process is fast and clean, requires no consumables, does not need a skilled operator, and lends itself readily to automation. It is used extensively in the automotive industry for assembly of taillights, dashboards, heater ducts, and other components where plastics have replaced the traditional use of glass and metal.

How does the process work? Essentially, high frequency vibration produces heat which melts the plastic. Yet ultrasonically induced heat can be generated selectively, precisely at the interface of the parts being joined without indiscriminate heating of the surrounding material. Less weld energy is used, resulting in less distortion and material degradation. Since the heat is generated within the plastic and not conducted from the tool, welding can be accomplished in completely inaccessible places.

Most thermoplastics have characteristics suitable for ultrasonic welding [6]. This includes the ability to transmit and to absorb vibration, as well as low thermal conductivity to facilitate local build-up of heat.

Heating in plastic is a function of ultrasonic stress and varies roughly as the square of stress amplitude. To maximize the stress in the weld region, the contact area between the parts being joined is reduced. Static clamping force is used to keep the parts together during welding. A "hold time" of a fraction of a second is added after ultrasonic exposure to allow the plastic to solidify before unclamping. Typical welds are done in less than a second.

Compared to cleaning, ultrasonic plastic welding requires much higher power densities, typically hundreds of watts per square inch at the weld, and at the contact of the tool with the workpiece. To deliver such power densities plastic welding horns operate at amplitudes of 0.001 to 0.005 inches (over ten times higher than cleaning), and due to high energy storage exhibit very sharp mechanical resonances. Additionally, depending on the application, they must accommodate a wide variety of loads, and during the welding mechanical loading may vary. To satisfy these requirements a new breed of equipment had to be developed, raising ultrasonic power technology to a new level.

Modern ultrasonic plastic welders operate predominantly around 20 kHz at power outputs below 1000

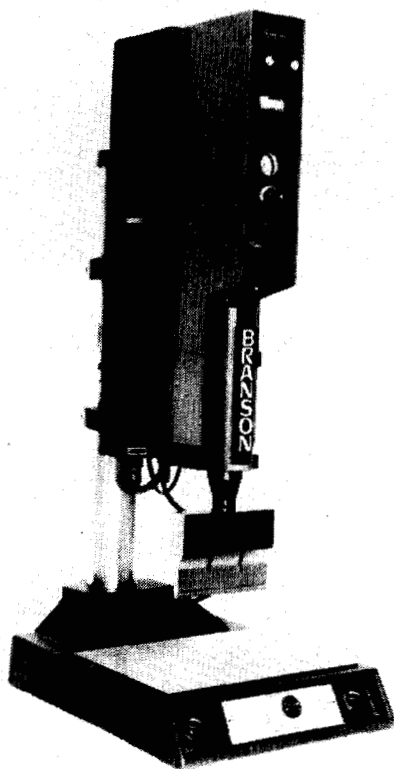


Fig. 4. 700 W, 20 kHz ultrasonic plastic welder.

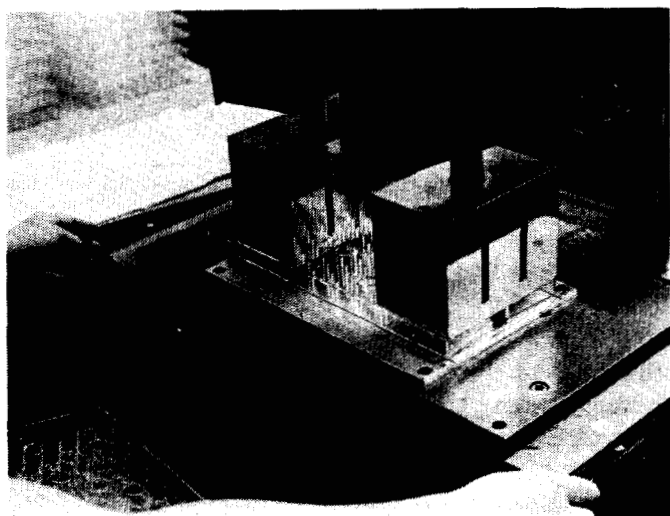


Fig. 5. Two or more horns are often used for welding larger parts. Horns are slotted to produce uniform vibration.

watts, lock automatically on the horn resonance, and hold vibrational amplitude constant for varying mechanical loads. Another useful innovation has been the use of mechanical amplitude transformers to facilitate matching of equipment to the load. Ultrasonic exposure is controlled by accurate electronic timers (Fig. 4).

The most visible progress over the years has been made in the size of plastic parts than can be ultrasonically welded, primarily helped by higher power equipment and advances in ultrasonic horn development (Figs. 5

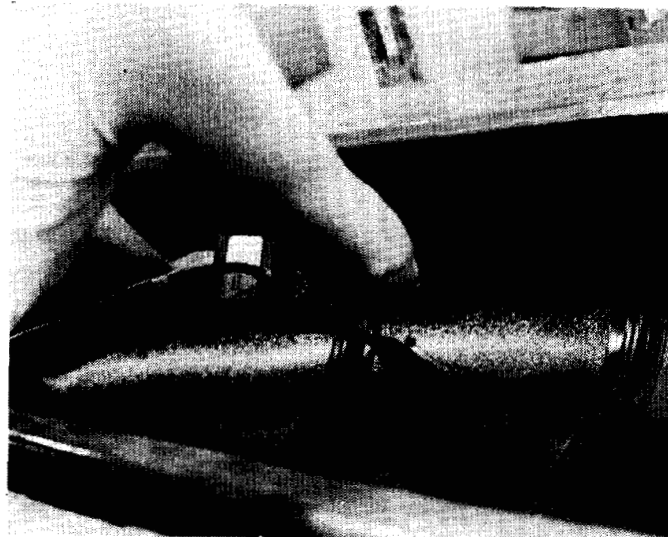


Fig. 6. Ultrasonic scan welder for assembly of large plastic panels, such as used in plastic furniture.

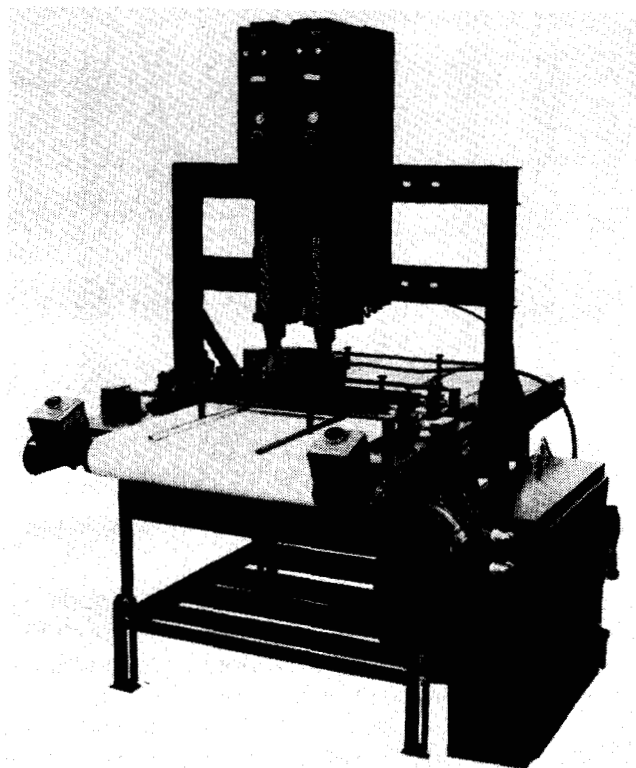


Fig. 7. Spot welding ribs onto plastic boat.

and 6). Improvements in joint design have extended ultrasonic welding to more difficult plastics and shapes.

Ramifications of ultrasonic welding process include ultrasonic staking, spot welding, and inserting of metal parts into plastic [7] (Fig. 7).

An area deserving special consideration is ultrasonic welding of woven and nonwoven fibers [8], [9]. Thermo-plastic textiles with up to 35% natural fiber content can be ultrasonically "sewn". The advantages include absence of thread and its color-matching problems, simultaneous

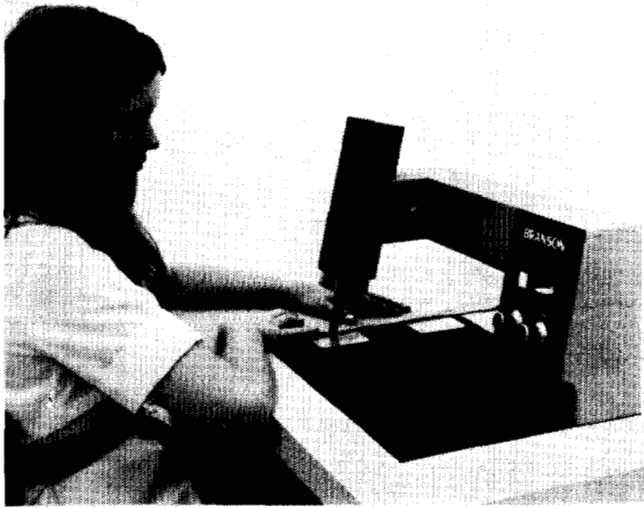


Fig. 8. Ultrasonic "sewing machine" for joining thermoplastic fabrics without needle or thread. Up to 35% natural fibre content is acceptable.

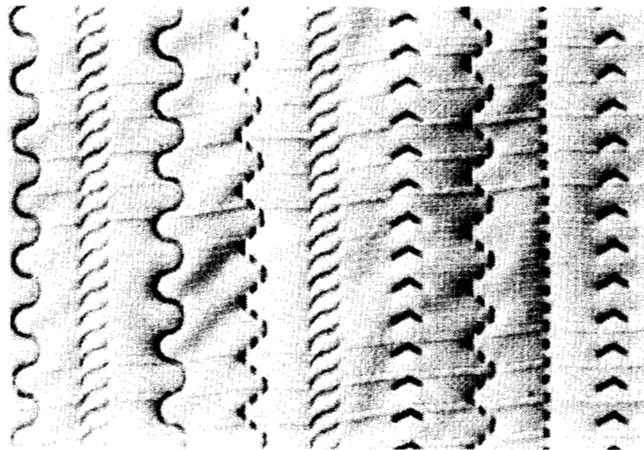


Fig. 9. Stitch patterns possible with ultrasonic sewing.

execution of several stitches, and numerous variations of simultaneous cut and seal operations (Figs. 8 and 9).

Further developments in ultrasonic plastic welding are likely to be in the area of horn improvement to expand the size and wear. Shift to lower frequencies is a possibility since many welding operations are automated and the noise can be conveniently shielded.

C. Metal Welding

Commercial equipment for ultrasonic metal welding was introduced in the late 1950's. Originally the process found acceptance in the semiconductor industry for welding of miniature conductors, known as microbonding [10]. Recent advances in equipment design and the need for better ways of joining high conductivity metals have revived the interest in ultrasonic metal welding and spurred on further improvement of the process. Standard equipment is available to weld parts up to 1/8" thick and larger, depending on the material and part configuration (Fig. 10).



Fig. 10. 1200 W, 20 kHz ultrasonic metal welder. Lap welds are produced by ultrasonic shear at the interface.

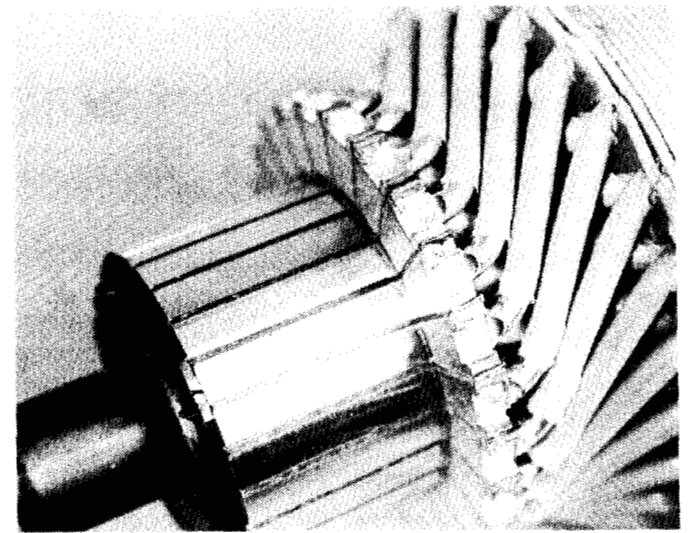


Fig. 11. Automotive starter motor armature with armature windings ultrasonically welded to commutator segments; both metals are copper (Courtesy of Ford Motor Co.).

The uniqueness of ultrasonic metal welding resides in the fact that the process is relatively "cold". While some heating occurs, the welding depends more on cleaning than on material melting. Ultrasonic shear causes mutual abrasion of the surfaces being joined, breaking up and dispersing oxides and other contamination. The exposed, plasticized, metal surfaces are brought together under pressure and solid-state bonding takes place [10]. In this respect ultrasonic welding resembles spin welding, or pressure welding, with the noted difference that there is no gross movement of parts or large displacement of material.

Ultrasonic metal welds are thus characterized by low heat and relatively low distortion. Welding temperatures are typically below the melting temperatures of the metals, which helps to avoid embrittlement and formation of high resistance intermetallic compounds in dissimilar metal welds.

Since electrical conductivity plays no role in the process, applications that are difficult, or impossible, with

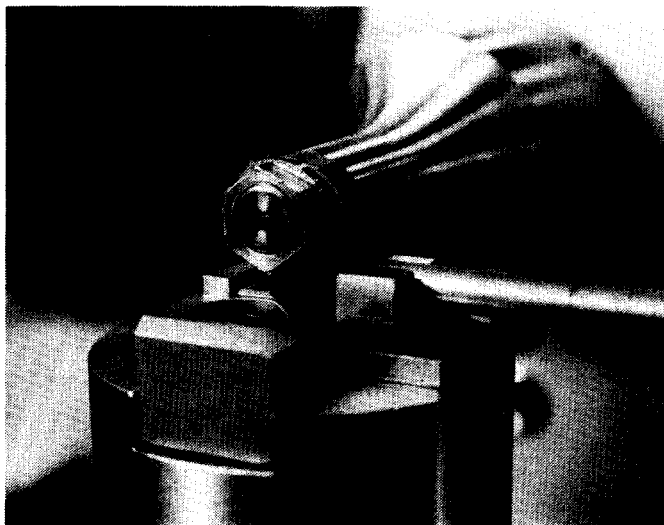


Fig. 12. Low heat of ultrasonic metal welding allows sealing liquid-filled copper tubing. Typically no pre-cleaning is needed on high conductivity metals.

resistance welding can be done ultrasonically. This includes welding of high conductivity metals, such as electric grade aluminum and copper (Fig. 11), also combinations of metals of different resistivities like copper and steel.

Welding of parts widely differing in heat capacity, such as foil to thick sections, is difficult with heat-dependent methods but can be done with ultrasound. Other uses include sealing of liquid-filled containers (Fig. 12) and packaging of heat-damageable contents and explosives.

Ultrasonic metal welding as an industrial process has the desirable characteristics of ultrasonic plastic welding but also has more competition from other metal-joining methods. Besides microbonding, its applications are mainly in electric and electronic industries in assembly of electric motors, transformers, switches, and relays. Current trend to replace copper by aluminum is helped by ultrasonic welding since there are not many reliable alternatives for joining aluminum conductors.

Since metal welding requires shear ultrasonic motion parallel to the plane of the weld, far field welding is not practical. The method is essentially suitable for producing spot welds and line welds. Continuous seaming of metal foil and sheet is also possible.

Ultrasonic power densities at the contact with the welding tip are very high, in the order of 10,000 watts per square inch. This causes tip wear and at present makes ultrasonic welding impractical for hard metals. Another limitation is compatibility of materials which due to requirement for mutual abrading ability must not be too far apart in hardness.

The equipment for ultrasonic metal welding ranges from low power microbonders operating between 40 and 60 kHz to machines of several kilowatt output capacity operating between 10 and 20 kHz, for welding of larger parts. It should be noted that on high con-

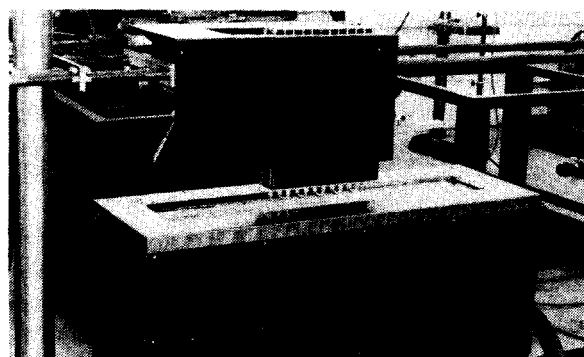


Fig. 13. Large ultrasonic tank for immersion soldering.

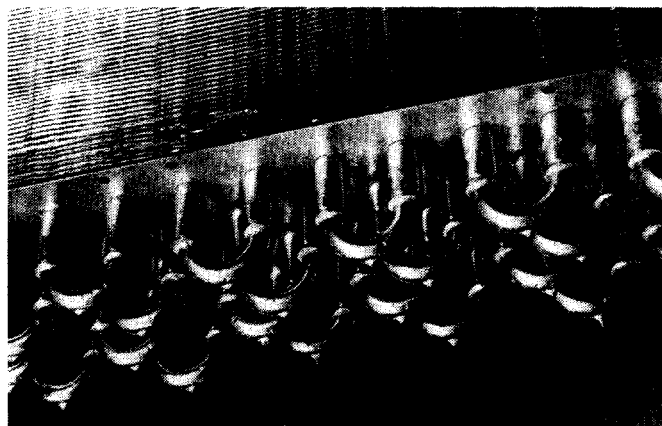


Fig. 14. Ultrasonically soldered aluminum radiator ducts. No flux was used.

ductivity materials ultrasonic welding can be over 20 times more efficient compared to resistance welding. Thus a 5 kW ultrasonic welder may be equivalent to a 100 kVA resistance welder. Automatic tuning and constant amplitude control are a must on larger ultrasonic welders.

Further acceptance of ultrasonic metal welding will largely depend on effective solutions to proper joint design and dissemination of this knowledge to potential users. To take full advantage of ultrasonic welding the parts must be designed for the process. Improvements in welding tip materials and design are also probable.

D. Soldering

Ultrasonic soldering can tin without fluxes and improves wettability under most conditions. The process is fundamentally similar to ultrasonic cleaning and has been tried with various degrees of success since the early 1950's. Growing need for fluxless soldering of aluminum and a general striving for quality have given ultrasonic soldering a new significance.

Applications of ultrasonic soldering [11] include electric and electronic components where nickel, Kovar, and other hard-to-tin metals are often used. Tinning of transformer leads, both copper and aluminum, is also effective.

Continuous soldering of printed circuits [12] and continuous wire tinning is another area of interest. Recent activity in aluminum heat exchangers with the inherent problem of trapped flux has created an opportunity for ultrasonics in the air conditioning industry and inspired development of large ultrasonic soldering tanks (Figs. 13 and 14).

Overall processing times with ultrasonic soldering can be improved because pre-cleaning and post-cleaning operations are usually eliminated. Also, the actual soldering is faster. Tinning is more uniform.

The principle of operation is simultaneous cleaning and tinning. Cavitation in molten solder erodes surface oxides and exposes clean metal to solder. Design of ultrasonic soldering equipment, however, is more involved due to high operating temperatures. Present ultrasonic soldering tanks operate at temperatures up to 850°F.

Both far field and near field soldering are done, ranging in power densities from a few watts to several hundred watts per square inch. Resistance to cavitation erosion is an important consideration in the design of equipment and is compounded by the requirement for metallurgical compatibility.

Future developments are likely to bring more efficient ways of coupling ultrasonic energy to the workpiece as well as improvements in ultrasonic tank materials. Operating temperature limits will probably be raised, which may make volume treatment of high temperature metals practical.

E. Machining

To date, ultrasonic machining has proved most effective on hard, brittle materials, like alumina, other ceramics, and glass. Two methods are currently in use.

The older method, known as ultrasonic impact grinding, makes use of abrasive slurry (usually boron carbide, silicon carbide, or aluminum oxide) fed between the non-rotating vibrating tool and the workpiece. Odd three-dimensional shapes can be reproduced, where the resulting impression is a negative of the tool. Simultaneous machining of clusters of holes is also possible. The method is inherently slow and therefore has limited possibilities in the industry.

In the more recent development, known as ultrasonic rotary machining, axial ultrasonic vibration is superimposed upon the rotary motion of the drill. Diamond impregnated or plated core drills, water-cooled through the center, are used. The tools operate typically around 5 000 rpm, and the operation is essentially high speed abrasion (Fig. 15).

Ultrasonic rotary machining substantially increases cutting rates, extends tool life, and due to the lower tool pressures used allows better dimensional control and reduces chipping. A simple explanation of the process is continuous cleaning of the tool by cavitation of the coolant, further aided by ultrasonic acceleration of the tool. The tool loads less and cuts more efficiently.

Uses for ultrasonic rotary machining [13], [14] include machining of precision ceramic components, drilling

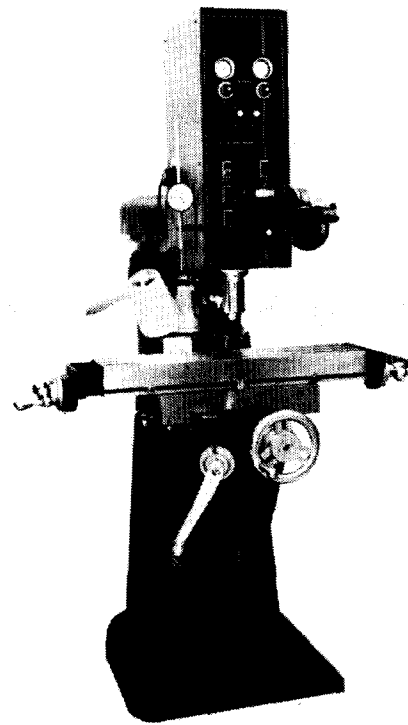


Fig. 15. Ultrasonic rotary machine for drilling, milling, and threading. Axial ultrasonic vibration is added to rotational motion of the drill.

small-diameter, deep, intersecting holes in quartz for lasers, machining nuclear reactor materials, plasma sprayed coatings and ferrite computer parts. Drilling, milling, and threading are possible. The tools are of various shapes and sizes, from 0.02 to 1.5 inches in diameter. 20 kHz frequency is used (Figs. 16 and 17).

Drilling of boron-epoxy composites laminated with steel and titanium sheet represents an interesting case and has been researched to some extent [15]. Conventional tools that cut boron fibres do not work on metal, and vice versa. Ultrasonic drilling promises a compromise.

Ultrasonic rotary machining is a useful and, in some cases, indispensable process of somewhat limited commercial potential due to the exotic nature of its applications.

III. SONICS AND LIQUIDS: OTHER APPLICATIONS

An extensive list of applications is given in Table II.

It is interesting to note that the majority of macrosonic applications involve liquids, and with few exceptions depend either on cavitation, or, like aerosol production, on surface instability. It is also interesting that to date no other liquid-related sonic application has had anything vaguely resembling the commercial success of ultrasonic cleaning.

A. Extraction

Most popular here is the use of high intensity cavitation for biological cell disruption in research and low volume processing.

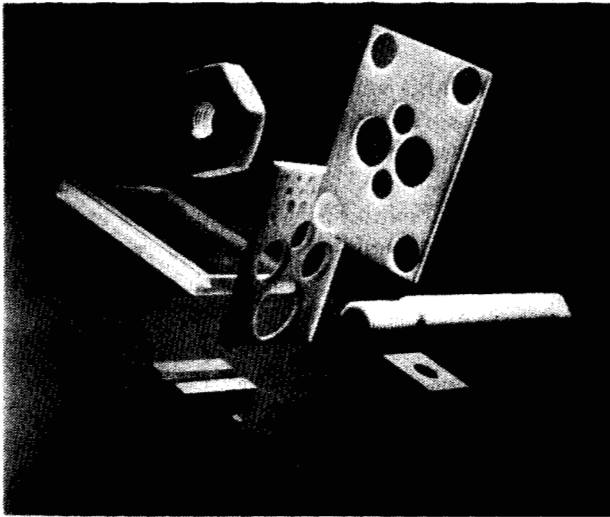


Fig. 16. Glass, aluminum oxide, and ferrite parts drilled and machined with ultrasound. Rotary method was used.

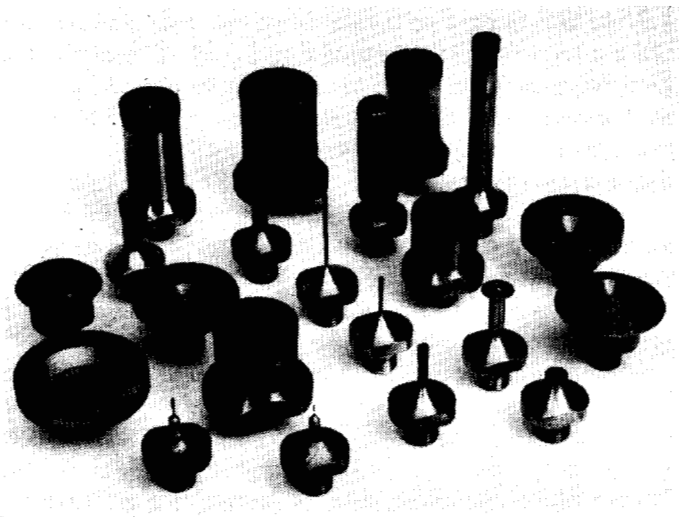


Fig. 17. Diamond impregnated and plated tools used in rotary ultrasonic machining. Most are liquid cooled through the center.

TABLE II
MACROSONIC APPLICATIONS—LIQUIDS

PROCESS	APPLICATIONS	ADVANTAGES	RANKING
CLEANING	Cleaning, degreasing, descaling industrial parts. Cleaning hospital equipment.	Saves time and manual labor. Cleans hard-to-reach areas.	A
SOLDERING	Fluxless aluminum soldering. Soldering and tinning electric and electronic components.	Eliminates flux, pre- and post-cleaning, reduces rejects.	B
EXTRACTION	Biological cell breakage for research. Antigen extraction. Extracting perfume, juices, chemicals from flowers, fruits, plants.	Simple to use. Reduces damage to contents. Speeds up extraction. Increases yields. Allows lower temperatures.	B
HOMOGENIZING	Emulsifying cosmetic toilet preparations, essential and mineral oils. Waste treatment. Dye pigment and dye dispersion. Insecticide preparation.	Emulsifies without pre-mixing. Reduces or eliminates surfactants. Fine, uniform dispersion. No flocculation.	B
ATOMIZATION	Medical inhalation, nebulizing. Fuel atomization, Metal powder production.	Small particles, controlled size. No gas used. Small particles, controlled size. More efficient burning.	B C
DRYING	Drying heat sensitive powders, food stuff, pharmaceuticals, defoaming.	Lower temperatures. Prevents damage to perishables.	C
DEGASSING	Beer and carbonated drink "fobbing". Photographic solution agitation. Degassing molten metals and glass.	Better control, safe for glass containers. Reduces porosity.	C
CHEMICAL PROCESS ENHANCEMENT	Electroplating. Aging alcoholic beverages.	Increases plating rates. Denser, more uniform deposit. Speeds up process.	C
POROUS MEDIA FLOW ENHANCEMENT	Filtering; Impregnation	Increases flow rates. Better penetration.	C
EROSION	Cavitation erosion testing. Deburring, stripping.	Convenient to use. Saves labor.	C
CRYSTALLIZATION	Metal treatment during casting and welding.	Refines grain, reduces stresses.	X
THERMAL TRANSPORT	Distillation and other chemical processes.	Speeds up heat exchange.	X
DEPOLYMERIZATION	Extruding plastics. Plastic fibre manufacturing.	Lowers viscosity.	X

A - Established large-scale process C - Some industrial use
B - Established small-scale process X - Experimental

Near field cavitation breaks down cell walls and releases cell contents into the surrounding liquid. The method is used to extract active antigens for making vaccines and as a general tool for studying cell structure. Ultrasonic extraction is simple and, if cooling is used, causes minimal degradation of contents.

The equipment is normally in the range of 100 to 500 watts, operating around 20 kHz. High amplitude horns are used, producing power densities in the order of 500 watts per square inch. Batch and continuous processing are done.

Other extraction uses include extraction of perfume from flowers, essential oils from hops, juices from fruits, and chemicals from plants [5], [16]. The potential here seems great, but application progress, at least in the United States, has been slow. A review of high intensity liquid processing is needed in view of the powerful 10 kHz equipment and other equipment improvements available today.

B. Atomization

Ultrasonic atomizers can produce small droplets of predictable size. For a given liquid, droplet size is a function of atomizer frequency and gets smaller as the frequency is increased [4].

1. *Ultrasonic nebulizers* for medical inhalation have shown best commercial progress. Medical nebulizers operate between 1 and 3 megahertz and produce droplets between 1 and 5 microns. Main advantages are small particle size, tight distribution, and the absence of gas, which makes ultrasonic nebulizers suitable for anesthetic systems [17].

2. *Fuel atomization* by ultrasound [17] has been researched to a considerable extent to improve combustion efficiency and reduce pollution. Several types of devices, both electronic and pneumatic, are in use, operating between 20 and 300 kHz. Use in oil burners as well as carburetors has been considered but due to marginal economics has never caught on in a big way.

3. *Dispersion of molten metals* for production of powders and metal spraying has been demonstrated. Spraying of molten lead, tin, zinc, bismuth, aluminum, and cadmium has been reported, but cost justification is questionable [17], [18].

There is a pattern to these applications: Greatest success has been achieved where the requirement for quality supersedes cost, and the throughput needed is low. As the product gets cheaper and the processing rates increase, ultrasonic atomization becomes less desirable.

Some of this is likely to change. Fuel, for instance, costs more today, and ultrasonic atomizers can be built for less. Molten metal dispersion with its formidable equipment problems may become practical as a result of the progress in ultrasonic soldering.

B. Crystallization

Finer grain has been produced in aluminum and other metals by insonation during the solidification stage.

Degassing and removal of residual stresses have also been reported.

In spite of a large volume of reference material on this subject [19], there is no evidence of commercial implementation. There may be some installations in eastern Europe [5].

The obvious difficulties here are the severe environment for the ultrasonic equipment and the requirement for treating a large volume. These, again, may be helped by current research in ultrasonic soldering.

C. Emulsification

The main advantage of ultrasonic emulsification is in the ability to mix some immiscible liquids without additives (surfactants). Recent publicity has called attention to the emulsification of water in heating oil for better fuel economy and less pollution [20]. Fuel saving seems uncertain, but there may be some substance to cleaner burning, and it is an interesting development to watch.

D. Heat Transfer [21]

Cavitation-induced microstirring can decrease the thermal boundary layer and improve heat transfer in a variety of systems. References date back to the early 1960's, and uses in distillation and other chemical processing have been suggested. Present concern with efficiency has made the topic once more popular.

E. Flow Enhancement

Liquid flow rates through porous media can be increased by ultrasound. Uses in filtering [22], [23] and impregnation have been suggested. The subject is intriguing because low amounts of vibratory power can be effective.

IV. SONICS AND SOLIDS: OTHER APPLICATIONS

An extensive list of applications is given in Table III.

A. Metal Forming

Over the years there has been a considerable interest in this area, heightened by the controversies about the mechanism of the process.

The benefits of vibration-assisted forming typically include lower forming forces, larger percentage deformation without tearing, and improvements in surface finish. Due to high power requirements the successful work performed to date has been limited to objects small in size or cases where the area to be affected is small.

1. *Tube drawing* with ultrasound [24] has been used in manufacturing for about ten years and is most effective on thin wall tubing having an initial diameter of about $\frac{1}{2}$ inch or less. Usually the plug is vibrated in the direction of drawing. The advantages are faster drawing rates, better size control, and ability to produce difficult shapes, such as rectangular tubing with sharp corners, or tubes with large diameter-to-wall ratios (up to 500:1). Aluminum, copper, iron, and nickel based alloy, have been drawn.

TABLE III
MACROSONIC APPLICATIONS—SOLIDS

PROCESS	APPLICATIONS	ADVANTAGES	RANKING
WELDING	PLASTICS - Welding rigid thermo-plastics. Seam welding film and fabric. Metal-in-plastic insertion. Staking.	Fast, clean, economical, good weld integrity. Welds in-accessible areas.	A
	METALS - Microbonding. Lap welding high electrical conductivity and dissimilar metals. Seam welding sheet.	Low heat, no pre-cleaning. Insensitive to electrical resistivity and heat capacity mismatch.	B
MACHINING	DENTAL - Prophylaxis teeth treatment.	Easy to use, less discomfort compared to hand scrubbing.	B
	HARD, BRITTLE MATERIALS - Vibration-assisted rotary machining.	Faster rates, longer tool life, better dimensional control.	B
	Impact grinding using abrasive slurry.	Makes multiple hole patterns, odd, three-dimensional shapes.	
FORMING	METALS - Drawing thin wall tubing of large diameter to wall ratios.	Higher drawing rates. Allows drawing difficult shapes.	C
	Drawing small diameter wire from difficult-to-form metals.	Faster drawing, less breakage, better surface.	
CUTTING	Vibration-assisted cutting of fibrous and spongy materials.	Better cutting due to blade acceleration, or melting.	C
FATIGUING	Destructive testing and quality control.	Saves testing time. Finds hidden flaws.	C
CLEAVAGE	Cleaving crystals and laminated objects.	High impact, high rate.	C
FRICTION REDUCTION	Vibrating sieves and hoppers.	Speeds up material flow.	C
	Torquing	Tighter joints	X
DENSIFICATION	Compacting powders, sintering.	Improves uniformity in complex molds. Increases density.	X

A - Established large scale process
B - Established small scale process
C - Some industrial use
X - Experimental

2. *Ultrasonic wire drawing* allows faster drawing rates, and reduces surface imperfections. Many investigations were reported in the early 1960's, with particular mention of advantages for drawing small diameter wire from hard-to-form materials like tungsten and molybdenum. There has been little commercial activity. Improved equipment is now available and may rejuvenate the interest in the process [25].

3. *Ultrasonic riveting* has been of interest to aircraft manufacturers. Experiments on aluminum and titanium rivets showed a possibility of a substantial reduction in forming force, and in some cases a larger deformation without cracking. Another set of experiments concerned aluminum leak-tight riveting. The important question here is the effect of vibratory forming on fatigue life of the rivet and is largely unanswered.

As a sobering thought on sonic metal forming, it is interesting to mention an experiment on titanium and several grades of stainless steel, designed to show the effect of sonics on volume deformation obscured in drawing operations by high surface friction.

Cylindrical slugs $\frac{3}{16}$ of an inch in diameter were flattened with and without sound. 400-600% reductions in static force were possible for equivalent deformation, but sonic power densities were over 100 000 watts per square inch

[26]. To duplicate the effect on a 3 inch diameter slug, close to one million watts of sonic power would be needed.

The use of macrosound for deformation of a large volume of metal may not be just around the corner. But small-scale applications are practical. Simultaneous metal welding and crimping, for instance, is being done.

B. Metal Drilling

Rotary ultrasonic drilling tried with conventional twist drills produced interesting but uneven results. Axial ultrasonic vibration was added to rotary motion of the drill.

Faster drilling rates and longer drill life were obtained on titanium using small-diameter cobalt drills, but no significant improvement was noticed on several other metals [26]. A number of portable drills are in use for titanium drilling in the aircraft industry. A special short ultrasonic drill adapter was developed to make the process practical (Fig. 18).

C. Dental Treatment

An interesting success story, not quite fitting into the industrial world, concerns an ultrasonic "machine tool" designed for use in prophylaxis treatment, periodontia, and other areas of operative dentistry (Fig. 19).

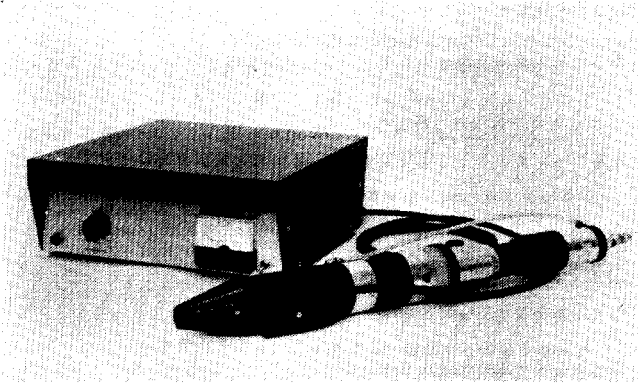


Fig. 18. Portable Quackenbush drill, used in aircraft manufacturing, equipped with ultrasonic drill adapter. Faster drilling rates and better drill life were demonstrated on titanium.

This equipment is becoming popular and is apparently liked by dentists and patients, who prefer it over the old manual scrubbing. Descaling of teeth is accomplished by a linear, or elliptical, reciprocating scrubbing at 25 kHz, aided by cavitation of the water spray. A variety of interchangeable inserts are available for various scrubbing operations.

D. Crystal Cleavage [27]

Crystal cleavage by ultrasound proved to be a valuable method of maintaining particle balance in a continuous chemical processing installation. Ultrasonically disintegrated crystals are split along cleavage planes in contrast to random breakage produced by mechanical means. While ultrasonic disintegration takes place in a super-saturated liquid, studies showed that cleavage results from direct collision of particles with ultrasonic horn and with one another [28]. It is likely that the principle would also work in a gas medium.

V. THE FUTURE

Unheralded by scientific publications, ultrasonic plastic welding has become a large-scale industrial process while the considerably researched metallurgical and metal working areas have resulted in relatively little. Equally disappointing have been "catalytic" uses of ultrasound in chemistry. The attention paid to a given ultrasonic area is largely influenced by the topic of the day, as evidenced by current interest in ultrasonic fuel treatment [20], waste treatment [29], oil well rejuvenation, etc., and is not always related to the true worth of the process.

Thus taught by experience, the author will refrain from any specific predictions save for pointing out two general factors. The cost of an acoustic watt has been declining and following the general technological trend will continue to do so in the future. This will make ultrasonic power more competitive with conventional processes. The second factor is that more ultrasonic equipment is now in use and more people are working with it. This increased exposure will undoubtedly lead to new uses.

Rather than compiling an all-inclusive list of ultrasonic applications, the author has tried to show a cross section

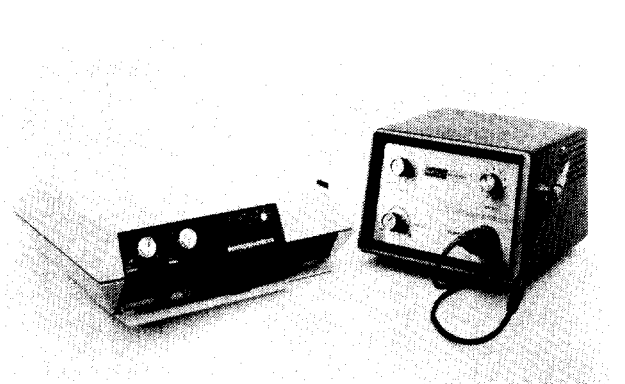


Fig. 19. Ultrasonic dental equipment for descaling teeth (prophylaxis), and other uses in operative dentistry. (Courtesy of Cavitron Ultrasonics, Inc.).

of types of things power ultrasound can do that would be representative of the present state of the art and inspire further thought on the subject.

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Industrial Applications of Ultrasound—A Review

II. Measurements, Tests, and Process Control

Using Low-Intensity Ultrasound

LAWRENCE C. LYNNWORTH

Abstract—The following applications are reviewed: ultrasonic measurement of flow, temperature, density, porosity, pressure, viscosity and other transport properties, level, position, phase, thickness, composition, anisotropy and texture, grain size, stress and strain, elastic properties, bubble, particle and leak detection, nondestructive testing, acoustic emission, imaging and holography, and combinations of these. Principles, techniques, equipment, and application data are summarized for these areas. Most of the measurements utilize approaches designed to respond primarily to sound speed, but some depend on attenuation effects. Most equipment in use involves intrusive probes, but noninvasive, externally-mounted transducers are being promoted in several areas. Both pulse and resonance techniques are widely used. Limitations due to the influence of unwanted variables are identified in some cases. A bibliography and list of vendors provide sources for further information.

INTRODUCTION

THE MAIN purpose of this review is to identify the breadth, depth, practicality, and limitations of industrial applications of small-signal ultrasound. Additionally, we will attempt to identify patterns of emerging ultrasonic technology.

In general, the scope of this review will be limited to industrial applications wherein the transduction or propagation of low-intensity ultrasound responds to the properties, state, or quality of the medium or prrt in question. By restricting the scope to "industrial" applications we choose to omit numerous interesting and important applications in research, and in medical, dental, and biological areas. "Low-intensity" avoids macrosonic and nonlinear acoustic areas such as ultrasonic

cleaning, machining, wire drawing, welding, atomizing, cavitating, emulsifying, influencing of chemical reactions, shock-wave measurements, and therapy. By limiting the scope to cases where the objective is measuring ultrasound *transduction or propagation* to indicate the value of some variable parameter, we intend to detour around devices such as quartz clocks, ultrasonic garage door openers, TV channel selectors, delay lines, filters, and signal processors despite the obvious industrial significance of such devices. In view of all these omissions, the reader may rightfully ask, "What's left?" For the answer see Table I.

This review generally makes no attempt to identify the earliest demonstration of the entries in Table I, nor to compare with competing technologies. Readers interested in the origins of acoustical measurements of sound speed, attenuation, polarization, or related quantities are referred elsewhere.¹

Standard commercial equipment, particularized for a specific application, is available for almost every item on the list. Additionally, since virtually any ultrasonic measurement can be analyzed in terms of observations related to transit time or wave amplitude, general-purpose electronic measuring equipment such as digital processing oscilloscopes, computing counters, time intervalometers, peak detectors, etc., may also be used to perform the industrial measurements or tests to be discussed below.

The items in Table I could be categorized into two major groups in terms of instrument response being associated primarily with sound speed c or attenuation coefficient

¹ R. B. Lindsay, ed., *Acoustics—Historical and Philosophical Development* (1973); *Physical Acoustics* (1973), Dowden, Hutchinson and Ross Inc., Stroudsburg, Pa. See also: D. M. Considine, ed., *Encyclopedia of Instrumentation and Control*, McGraw-Hill, New York (1971).