Ultrasonic Cleaning

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Introduction

ULTRASONIC CLEANING involves the use of high-frequency sound waves (above the upper range of human hearing, or about 18 kHz) to remove a variety of contaminants from parts immersed in aqueous media. The contaminants can be dirt, oil, grease, buffing/polishing compounds, and mold release agents, just to name a few. Materials that can be cleaned include metals, glass, ceramics, and so on. Ultrasonic agitation can be used with a variety of cleaning agents: detailed information about these agents is available in the other articles on surface cleaning in this Section of the Handbook.

Typical applications found in the metals industry are removing chips and cutting oils from cutting and machining operations, removing buffing and polishing compounds prior to plating operations, and cleaning greases and sludge from rebuilt components for automotive and aircraft applications.

Ultrasonic cleaning is powerful enough to remove tough contaminants, yet gentle enough not to damage the substrate. It provides excellent penetration and cleaning in the smallest crevices and between tightly spaced parts in a cleaning tank.

The use of ultrasonics in cleaning has become increasingly popular due to the restrictions on the use of chlorofluorocarbons such as 1,1,1-trichloroethane. Because of these restrictions, many manufacturers and surface treaters are now using immersion cleaning technologies rather than solvent-based vapor degreasing. The use of ultrasonics enables the cleaning of intricately shaped parts with an effectiveness that corresponds to that achieved by vapor degreasing. Additional information about the regulation of surface cleaning chemicals is contained in the article "Environmental Regulation of Surface Engineering" in this Volume. The article "Vapor Degreasing Alternatives" in this Volume includes descriptions of cleaning systems (some using ultrasonics) that have been designed to meet regulatory requirements while at the same time providing effective surface cleaning.

Process Description

In a process termed cavitation, micron-size bubbles form and grow due to alternating positive and negative pressure waves in a solution. The bubbles subjected to these alternating pressure waves continue to grow until they reach resonant size. Just prior to the bubble implosion (Fig. 1), there is a tremendous amount of energy stored inside the bubble itself.

Figure 1

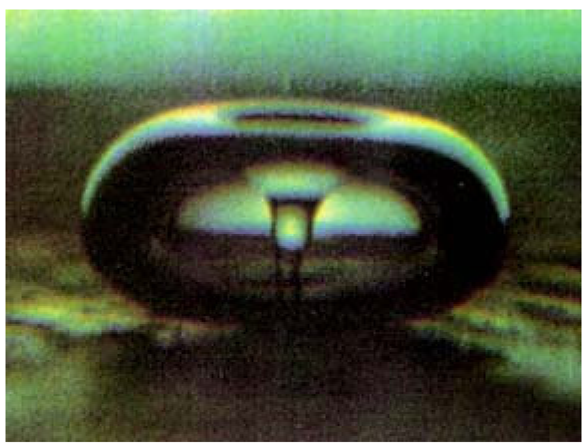

Fig. 1- Imploding cavity in a liquid irradiated with ultrasound captured in a high-speed flash photomicrograph. Courtesy of National Center for Physical Acoustics, University of Mississippi.

Temperature inside a cavitating bubble can be extremely high, with pressures up to 500 atm. The implosion event, when it occurs near a hard surface, changes the bubble into a jet about one-tenth the bubble size, which travels at speeds up to 400 km/hr toward the hard surface. With the combination of pressure, temperature, and velocity, the jet frees contaminants from their bonds with the substrate. Because of the inherently small size of the jet and the relatively large energy, ultrasonic cleaning has the ability to reach into small crevices and remove entrapped soils very effectively.

An excellent demonstration of this phenomenon is to take two flat glass microscope slides, put lipstick on a side of one, place the other slide over top, and wrap the slides with a rubber band. When the slides are placed into an ultrasonic bath with nothing more than a mild detergent and hot water, within a few minutes the process of cavitation will work the lipstick out from between the slide assembly. It is the powerful scrubbing action and the extremely small size of the jet action that enable this to happen.

Ultrasound Generation. In order to produce the positive and negative pressure waves in the aqueous medium, a mechanical vibrating device is required. Ultrasonic manufacturers make use of a diaphragm attached to high-frequency transducers. The transducers, which vibrate at their resonant frequency due to a high-frequency electronic generator source, induce amplified vibration of the diaphragm. This amplified vibration is the source of positive and negative pressure waves that propagate through the solution in the tank. The operation is similar to the operation of a loudspeaker except that it occurs at higher frequencies. When transmitted through water, these pressure waves create the cavitation processes.

The resonant frequency of the transducer determines the size and magnitude of the resonant bubbles. Typically, ultrasonic transducers used in the cleaning industry range in frequency from 20 to 80 kHz. The lower frequencies create larger bubbles with more energy, as can be seen by dipping a piece of heavy-duty aluminum foil in a tank. The lower-frequency cleaners will tend to form larger dents, whereas higher-frequency cleaners form much smaller dents.

Equipment

The basic components of an ultrasonic cleaning system include a bank of ultrasonic transducers mounted to a radiating diaphragm, an electrical generator, and a tank filled with aqueous solution. A key component is the transducer that generates the high-frequency mechanical energy. There are two types of ultrasonic transducers used in the industry, piezoelectric and magnetostrictive. Both have the same functional objective, but the two types have dramatically different performance characteristics.

Piezoelectric transducers are made up of several components. The ceramic (usually lead zirconate) crystal is sandwiched between two strips of tin. When voltage is applied across the strips it creates a displacement in the crystal, known as the piezoelectric effect. When these transducers are mounted to a diaphragm (wall or bottom of the tank), the displacement in the crystal causes a movement of the diaphragm, which in turn causes a pressure wave to be transmitted through the aqueous solution in the tank. Because the mass of the crystal is not well matched to the mass of the stainless steel diaphragm, an intermediate aluminum block is used to improve impedance matching for more efficient transmission of vibratory energy to the diaphragm. The assembly is inexpensive to manufacture due to low material and labor costs. This low cost makes piezoelectric technology desirable for ultrasonic cleaning. For industrial cleaning, however, piezoelectric transducers have several shortcomings.

The most common problem is that the performance of a piezoelectric unit deteriorates over time. This can occur for several reasons. The crystal tends to depolarize itself over time and with use, which causes a substantial reduction in the strain characteristics of the crystal. As the crystal itself expands less, it cannot displace the diaphragm as much. Less vibratory energy is produced, and a decrease in cavitation is noticed in the tank. Additionally, piezoelectric transducers are often mounted to the tank with an epoxy adhesive, which is subject to fatigue at the high frequencies and high heat generated by the transducer and solution. The epoxy bond eventually loosens, rendering the transducer useless. The capacitance of the crystal also changes over time and with use, affecting the resonant frequency and causing the generator to be out of tune with the crystal resonant circuit.

Energy transfer of a piezoelectric transducer is another factor. Because the energy is absorbed by the parts that are immersed in an ultrasonic bath, there must be a substantial amount of energy in the tank to support cavitation. If this is not the case, the tank will be "load-sensitive" and cavitation will be limited, degrading cleaning performance. Although the piezoelectric transducers utilize an aluminum insert to improve impedance matching (and therefore energy transfer into the radiating diaphragm), they still have relatively low mass. This low mass limits the amount of energy transfer into the tank (as can be seen from the basic equation for kinetic energy, mv_2). Due to the low mass of the piezoelectric transducers, manufacturers must use thin diaphragms in their tanks. A thick plate simply will not flex (and therefore cause a pressure wave) given the relatively low energy output of the piezoelectric transducer. However, there are several problems with using a thin diaphragm. A thin diaphragm driven at a certain frequency tends to oscillate at the upper harmonic frequencies as well, which creates smaller implosions. Another problem is that cavitation erosion, a common occurrence in ultrasonic cleaners, can wear through a thin-wall diaphragm. Once the diaphragm is penetrated, the solution will damage the transducers and wiring, leaving the unit useless and requiring major repair expense.

Magnetostrictive Transducers are known for their ruggedness and durability in industrial applications. Zero-space magnetostrictive transducers consist of nickel laminations attached tightly together with an electrical coil placed over the nickel stack. When current flows through the coil it creates a magnetic field. This is analogous to deformation of a piezoelectric crystal when it is subjected to voltage. When an alternating current is sent through the magnetostrictive coil, the stack vibrates at the frequency of the current.

The nickel stack of the magnetostrictive transducer is silver brazed directly to the resonating diaphragm. This has several advantages over an epoxy bond. The silver braze creates a solid metallic joint between the transducer and the diaphragm that will never loosen. The silver braze also efficiently couples the transducer and the diaphragm together, eliminating the damping effect that an epoxy bond creates. The use of nickel in the transducers means there will be no degradation of the transducers over time; nickel maintains its magnetostrictive properties on a constant level throughout the lifetime of the unit. Magnetostrictive transducers also provide more mass, which is a major factor in the transmission of energy into the solution in the ultrasonic tank. Zero-space magnetostrictive transducers have more mass than piezoelectric transducers, so they drive more power into the tank, and this makes them less load-sensitive than piezoelectric systems.

A radiating diaphragm that uses zero-space magnetostrictive transducers is usually 5 mm (3/16 in.) or greater in thickness, eliminating any chance for cavitation erosion wearthrough. Heavy nickel stacks can drive a plate of this thickness and still get excellent pressure wave transmission into the aqueous solution.

In summary, the advantages of zero-space magnetostrictive transducers are:

- They are silver brazed for permanent bonding with no damping effect
- They provide consistent performance throughout the life of the unit with no degradation of transducers
- Their high mass results in high energy in the tank and less load sensitivity
- Their thick diaphragm prevents erosion wear-through

The magnetostrictive transducer is not as efficient as a piezoelectric transducer. That is, for a given voltage or current displacement, the piezoelectric transducer will exhibit more deflection than the magnetostrictive transducer. This is a valid observation; however, it has offsetting disadvantages. The efficiency of concern should be that of the entire transducing system, including not only the transducer but also the elements that make up the transducer, as well as the diaphragm. It is the inferior mounting and impedance matching of a piezoelectric-driven diaphragm that reduces its overall transducing efficiency relative to that of a magnetostrictive transducer.

The **ultrasonic generator** converts a standard electrical frequency of 60 Hz into the high frequencies required in ultrasonic transmission, generally in the range of 20 to 80 kHz. Many of the better generators today use advanced technologies such as sweep frequency and autofollow circuitry. Frequency sweep circuitry drives the transducers between a bandwidth slightly greater and slightly less than the center frequency. For example, a transducer designed to run at 30 kHz will be driven by a generator that sweeps between 29 and 31 kHz. This technology eliminates the standing waves and hot spots in the tank that are characteristic of older, fixed-frequency generators. Autofollow circuitry is designed to maintain the center frequency when the ultrasonic tank is subjected to varying load conditions. When parts are placed in the tank or when the water level changes, the load on the generator changes. With autofollow circuitry, the generator matches electrically with the mechanical load, providing optimum output at all times to the ultrasonic tank.

Ultrasonic tanks are generally rectangular and can be manufactured in just about any size. Transducers are usually placed in the bottom or on the sides, or sometimes both when watt density (watts per gallon) is a concern. The transducers can be welded directly into the tank, or watertight immersible units can be placed directly into the aqueous solution. In some instances the immersibles may be mounted at the top of the tank, facing down. For applications such as strip cleaning, one immersible is placed on top and one on the bottom, with minimal distance between them. The strip is then run through the very high energy field. A tank should be sturdy in construction, ranging from 11 to 14 gauge in thickness. Larger, heavy-duty industrial tanks should be 11 to 12 gauge and should contain the proper stiffeners for support due to the weight of the solution.

Solution

The solution used in ultrasonic cleaning is a very important consideration. Solvents such as 1,1,1-trichloroethane and freon have been used effectively for many years, with and without ultrasonics. However, with the advent of the Montreal protocol, which calls for elimination of key ozone-depleting substances by 1996, companies are searching for more environmentally friendly methods to clean their parts. Chemical formulators are developing products that meet the demands of cleaning operations, yet are compatible with the health and well-being of society.

Whenever possible, it is best to use a water-based detergent in the ultrasonic cleaning process. Water is an excellent solvent, nontoxic, nonflammable, and environmentally friendly. However, it can be difficult and expensive to dispose of soiled water. Rinsing and drying can also be difficult without detergents. High surface tension exists in solutions without detergents, thus making rinsing difficult in hard-to-reach areas. Detergents can therefore be added to lower the surface tension and provide the necessary wetting action to loosen the bond of a contaminant to a substrate. As an added bonus, the cavitation energy in a water-based solution is more intense than in an organic solvent.

Table 1 is a guide for selection of appropriate cleaning agents for use with ultrasonic cleaning. Additional information about many of these agents is available in the other articles in this Section of the Handbook.

Solution temperature has a profound effect on ultrasonic cleaning effectiveness. In general, higher temperatures will result in higher cavitation intensity and better cleaning. However, if the temperature too closely approaches the boiling point of the solution, the liquid will boil in the negative pressure areas of the sound waves, reducing or eliminating cavitation. Water cavitates most effectively at about 70ºC (160ºF); a caustic/water solution, on the other hand, cleans most effectively at about 82ºC (180ºF) because of the increased effectiveness of the chemicals at the higher temperature. Solvents should be used at temperatures at least 6ºC (10ºF) below their boiling points (Ref 2).

Table 1

Solutions Used With Ultrasonic Cleaning Of Various Parts (Source: Ref. 1)

Material of construction	Types of parts	Contaminants	Suitable cleaning agent
Iron, Steel, Stainless steel	Castings, stamping, machined parts, drawn wire, diesel fuel injectors	Chips, lubricants, light oxides	High caustic with chelating agents
Iron, Steel, Stainless steel	Oil-quenched, used automotive parts; fine mesh and sintered filters	Carbonized oil grease, carbon smut, heavy grime deposits	High caustic, silicated
Iron, Steel, Stainless steel	Bearing rings, pump parts, knife blades, drill taps, valves	Chips; grinding, lapping and honing compounds; oils; waxes and abrasives	Moderately alkaline
Iron, Steel, Stainless steel	Roller bearings, electronic components that are affected by water or pose dryer problems, knife blades, sintered filters	Buffing and polishing compounds; miscellaneous machining, shop and other soils	Chlorinated-solvent degreaser (inhibited trichloroethylene, for example)
Aluminum and zinc	Castings, open-mesh air filters, used automotive carburetor parts, valves, switch components, drawn wire	Chips, lubricants and general grime	Moderately alkaline, specially inhibited to prevent etching of metal, or neutral synthetic (usually in liquid form)
Copper and brass (also silver, gold, tin, lead, and solder)	Printed circuit boards, waveguides, switch components, instrument connector pins, jewelry (before and after plating), ring bearings	Chips, shop dirt, lubricants, light oxides, fingerprints, flux residues, buffing and lapping compounds	Moderately alkaline, silicated, or neutral synthetic (possibly with ammonium hydroxide for copper oxide removal)
Magnesium	Castings, machined parts	Chips, lubricants, shop dirt	High caustic with chelating agents
Various metals	Heat treated tools, used automotive parts, copper-clad printed circuit boards, used fine-mesh filters	Oxide coatings	Moderately to strong inhibited proprietary acid mixtures specific for the oxide and base metal of the part to be cleaned (except magnesium)
Glass and ceramics	Television tubes, electronic tubes, laboratory apparatus, coated and uncoated photographic and optical lenses	Chips, fingerprints, lint, shop dirt	Moderately alkaline or neutral synthetic
Plastics	Lenses, tubing, plates, switch components	Chips, fingerprints, lint, shop dirt	Moderately alkaline or neutral synthetic
Various metals, plastics (nylon, Teflon, epoxy, etc.)	Precision gears, bearings, switches, printed circuit boards, miniature servomotors	Lint, other particulate matter, and other light oils	Trichlorotrifluoroethane (fluorocarbon solvent), sonic-vapor degreaser

System Design

Considerations in the design of any cleaning system include the contaminants on the part(s), the required cleanliness level, the geometry and material of the part(s), the quantity to be processed, and the previous system design and layout (if applicable). The part geometry, production rate, and cleaning time required will determine the size of the cleaning system, once the overall process has been decided. Typical tanks range from 20 to 400 L (5 to 1000 gal), and some are even larger.

Industrial, heavy-duty applications require industrial, heavy-duty ultrasonic equipment. Other factors that need to be considered are cleaning solutions and temperatures, rinsing (with or without ultrasonics), drying, automation, and load requirements. Most manufacturers of ultrasonic cleaning systems will assist in these decisions and will offer laboratory services and technical expertise. A typical system is shown in Fig. 2.

Figure 2

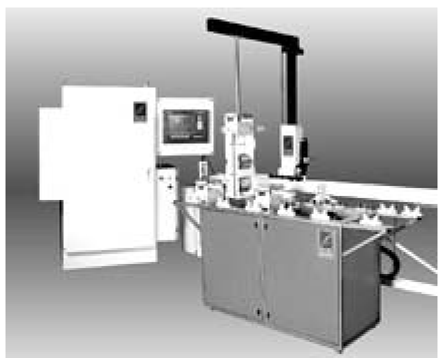

Fig. 2- Automated ultrasonic cleaning system. This system is designed to clean intricate metal hearing-aid components using a neutral-pH solution at 60ºC (140ºF) and three rinse stages at 70ºC (160ºF). Basket rotation (1 to 3 rpm) is used during each stage to ensure adequate cleaning and rinsing. The system computer controls all functions, including the hoist, and allows for storage of different process parameters for different types of parts. Courtesy of Blue Wave Ultrasonics.

Cleanliness Considerations. In a typical aqueous ultrasonic cleaning system, it is the cleaning stage(s) that will remove or loosen the contaminants. The following rinse stage(s) remove any remaining loosened soils and residual detergent, and a dryer removes any remaining rinse water. The overall process of the system is usually determined experimentally. Most reputable industrial cleaning equipment manufacturers have an applications lab where, through a process of experience, trial, and error, a properly designed cleaning process can be determined to meet the cleanliness levels specified.

There are a variety of ways to check for cleanliness. Some are as simple as a water break test on the part to see if most oil has been removed. Others are as elaborate as surface quality monitoring that uses optically stimulated electron emission technology to measure thin films of contaminants down to the Angstrom level.

Changing Existing Systems. If a current system exists, such as a vapor degreaser or soak tank, several things need to be considered. It may be practical, and possibly most economical, to retrofit the existing unit from one that uses solvent an organic solvent to one that uses an aqueous cleaner. Ultrasonic transducers can be added to an existing tank by cutting a hole in the tank and welding the transducer(s) in, or by simply dropping a watertight immersible unit into the tank. The latter method will take up some room in the tank, but it requires less labor. Additional work may have to be done to the tank, such as removing the cooling coils from the vapor degreaser, adding additional fittings for a filtration system, and so on.

In some existing systems, there is a large inventory of stainless steel baskets for handling the parts throughout the cleaning system. If possible, it is best to use these baskets due to the relatively high cost of replacement. In ultrasonic cleaning, the mesh size or hole configuration of the basket is very important. Some mesh sizes will inhibit the cavitation process inside the basket, thereby affecting the overall cleaning capability. Mesh sizes greater than 200 mesh or less than 10 mesh work best. An interesting note is that ultrasonic activity will pass through a variety of media. For example, solution A placed in a Pyrex beaker will cavitate if placed in solution B, which is cavitating in an ultrasonic tank.

Additional information on adapting vapor degreasing systems for ultrasonic immersion cleaning is provided in the article "Vapor Degreasing Alternatives" in this volume.

Part Handling. The geometry of the parts must be carefully analyzed to determine how they will be placed in the cleaning tank. Large parts, such as engine blocks, can be suspended directly from a hoist, whereas smaller parts will usually be placed in a basket. The most important factor in parts placement is to be sure that air is not trapped anywhere inside the part. If an air pocket is allowed to form, such as in a blind hole that would be facing downward toward the bottom of the tank, the cleaning solution and effects of cavitation will not be able to reach this particular area. The part will have to be rotated somehow in the tank during the cleaning process to allow the cleaning solution to reach the area where air was previously trapped. This can be accomplished either manually, by the attending operator, or by a rotating arm on an automated lift mechanism.

It is best if small parts can be physically separated when placed in a basket. An example would be to place machined valve bodies in a basket with some type of divider or locator for each one. Many times, however, in high output lines it is not possible to separate parts physically, such as in the manufacture of electrical connector pins where thousands of parts may need to be cleaned at one time because of the high production output and the small size. Ultrasonic agitation will be able to reach between these parts and allow the solution's scrubbing power to remove the contaminants, even if the parts are stacked on top of one another. On the other hand, rinse water may not remove all of the residual detergent , and a dryer has a very hard time removing moisture from embedded parts. The problem is easily solved by having an automated hoist with a constant rotating fixture on the arm that allows the basket to tumble at 1 to 3 rpm. This rotation allows the parts to tumble slowly and exposes the embedded pieces for proper rinsing and drying.

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