Surface preparation of steels and other metals and alloys is essential prior to most finishing processes, particularly coating and vacuum coating. Otherwise, yields will suffer. Aqueous and solvent ultrasonic processes have been developed with the specific objectives of achieving the highest quality surfaces without inflicting any damage to components.

For steels, the major concern when components are to be cleaned aqueously is flash rusting, which occurs when clean active steel surfaces are exposed to water and oxygen (Fig. 1). Ironically, some halogenated (nonaqueous) solvents used to clean ferrous components have periodically, for other reasons, manifested flash rusting problems.

Aqueous ultrasonic cleaning offers excellent cleaning results. The method is preferred over solvent-based methods for well-known environmental reasons. The challenge always has been on how to clean steels aqueously without having flash rusting or worst pitting occur.

FLASH RUSTING
Flash rusting is the first phase in a corrosion process that can be visually observed on iron or iron alloy surfaces. Corrosion can be broadly defined as materials deterioration that is caused by chemical or electrochemical attack. For ferrous surfaces, water and oxygen are sufficient to initiate the electrochemical attack and to generate the surface oxide.

Corrosion processes are electron transfers, oxidation-reduction processes that can occur when the surface of a metal is in contact with a humid atmosphere. The oxidation-reduction reactions involved in the flash rusting process include generation of ferrous oxides, which is further oxidized by oxygen into ferric oxide with the familiar color, ranging from light yellow to deep brown (Fig. 1).

Examples of rustable steels include mild steels, high carbon steels, silicone core steels, iron composites, cast iron, and some ferrite stainless steels.

SURFACE CLEANING
Cleaning by general definition is freeing the surface from contaminants that are adhered chemically, physically or mechanically to that surface.

Contaminants are soils or impurities either generated during the forming process of new surfaces or deposited foreign matter from surrounding environments. Contaminants adhered to the surface under high mechanical pressure, or byproducts of chemical additives or chemical protective films are common in metal forming processes and are difficult to remove.

The degree of required cleanliness can range from practical cleaning needed in in-process operations to precision or critical cleaning required prior to coating or final assembly.

Critical or precision cleaning is defined as the complete removal of undesirable contaminants to a predetermined high standard and without introducing new contaminants in the process.

CONTAMINANTS
Contaminants may be categorized as follows:

Organic Contaminations
Examples include: lubricating oils, cutting, machining fluids and oils, fingerprints, carbon, organic vehicles in buffing and lapping compounds, waxes, silicone oils, mold release compounds, coolants, polymers, adhesives, photo resist compound, lacquers, paints, inks, antifoam additives, and residual biocides.

Inorganic Contaminants
Examples include: various metal oxides in buffing and lapping compounds, polishing compounds, inorganic salts, dust, metal fines, slivers, and other metal oxides.
Particles
Particles are insoluble individual or aggregates of micro solid contaminants, which tenaciously adhere to the surface with various physical forces. Obviously, smaller size particles are the most difficult to remove. Particles down to 10 microns can be seen under high intensity light, those down to 2 microns require dark field illumination. Particles down to 0.1 micron can be detected by laser optical scattering technique (Profilometer) or by AFM (atomic force microscopy). Particle diameters below 0.1 micron (100 nm) need scanning electron microscopy (SEM) for detection and recording.

AQUEOUS ULTRASONIC PROCESS
Aqueous cleaning is a widely acceptable alternative to the use of halogenated solvents. Decontamination of surfaces with water can be done universally, except in rare cases where the substrate itself is water sensitive or reactive or very difficult to dry.

A typical ultrasonic aqueous batch cleaning process essentially consists of four steps: ultrasonic wash, ultrasonic overflowing rinse, second ultrasonic overflowing rinse, and a drying station. The second rinse overflows to the first one and is known as reverse cascade rinsing. Spray rinsing may also be utilized to assist the removal of the cleaning chemistry. The actual number of stations, tank sizes, and process parameters are determined and verified by testing upon examining the parts, contaminants, required throughputs, cleanliness, and drying requirements. Additional mechanical assisting devices such as rotating baskets, oscillation, robotics arms, or transport mechanisms may be used. The ultrasonic cleaning system may also include external water heaters, closed loop water system for water preservation, and auxiliary process monitoring devices such as pH and resistivity meters.

CLEANING CHEMICALS AND ULTRASONIC CAVITATIONS
Cleaning chemicals are essential in removing, dispersing, or emulsifying the contaminants and then preventing contaminants from redeposition on the surfaces. Cleaning chemicals work in synergy with ultrasonically generated cavitations to provide the required levels of cleanliness. The cavitations provide the necessary scrubbing forces through continuous surface impact with the generated wave shocks and acoustic streaming. Wave micro-shock pressure can reach 5,000 psi and fluid micro-streams up to 250 mph.

The removal of contaminants may appear simple, however, it is a very complex process. Cleaning depends mainly on two concurrent steps: displacement and scrubbing. The displacement can take place through different mechanisms including wetting to lower the interfacial tension and the surface free energy followed by encapsulation, emulsification, dispersion, or solubilization. Other mechanisms involve changing the soil nature through breaking its bonds first with the surface followed by the same other steps.

Cleaning chemistry can be divided into two main categories: solvent-based and water-based. The solvent-based, known as semi-aqueous chemistries, includes pure organic nonhalogenated solvents e.g. alcohols, hexanes, heptanes, N-methyl pyrolidone, acetone, methyl ethyl ketone, esters, etc. The semi aqueous chemistries may include formulated products with bases chosen from medium-to-high flash point petroleum hydrocarbons, natural terpenes, hydrocarbons, and natural esters e.g. soy esters, cyclic alcohols, or cyclic amides. Water-based cleaning chemistry is essentially based on anionic, cationic, and nonionic surfactants and various tailored additives. Surfactants have unique properties because of their chemical structures.

In aqueous cleaning the surfactant’s first function is to interact with and wet the soiled surfaces. This is followed by one or more mechanisms, which can include displacement, dispersal, dissolution, sequestering, assisted hydrolysis, or emulsification of various soils. Disperal or suspension of soils takes place by encapsulating suspended contaminants to prevent their redeposition. The chemistry can be tailored to fit the requirement of a certain soil. The molecular structures of surfactants and additives have a significant impact on their properties and their behavior in the cleaner. Therefore, not all cleaning chemistries are equal.

The second step is rinsing with water. The water rinse steps are essential to provide surfaces free from contaminants and from cleaning chemical residues. Ultrasonic cavitations greatly assist in speeding up and completing the removal of residual surfactants. Without ultrasonics it may take longer or be incomplete. Lack of good rinsing of a detergent film or using poor quality water to rinse always results in residual detergents or salts left on surfaces. These in turn become new contaminants.

Cleaning process parameters and parts handling must be thought of as one integral process. Therefore, compatible chemistries, operating temperature, quality of rinsewater, effective removal of suspended contaminants through filtration, and the proper drying technique are all indispensable for a successful operation.
ULTRASONIC RINSING AND DRYING WITHOUT FLASH RUSTING

Rinsing of steel components with water requires that the water must be inhibited to stop any electrochemical corrosion reaction. Multiple properties must be exhibited in a good inhibitor. The inhibitor must be water soluble and active enough to protect the surfaces during the water rinse step(s) and also through the hot air drying step. Also, the inhibitor film residue must not interfere with any subsequent treatment such as vacuum coating. The inhibitor also must not affect precision or gauging measurements of clean components. A good inhibitor will not stain the surface and will be easy to remove. Most of these inhibitors are proprietary formulations. In principle they work by depleting the available oxygen or by forming a very thin organometallic protective film on the steel surface.

There are two effective approaches to rinse and air dry steel components, which are prone to rusting. The first is two ultrasonic reverse cascade rinsing where the inhibitor is injected into the second rinse station at a low rate and is overflown into the first rinse. The next step is air-drying of the components in a circulated filtered heated air dryer. HEPA filtration and nitrogen or helium injection can be utilized to dry critically cleaned components in a clean-room environment. The second process is good for the practical cleaning level (Fig. 2). Protection from flash rusting can be achieved through rinsing the components in a similar system using two individual rinse tanks. Tap water is fed into the first overflowing ultrasonic rinse and the inhibitor is added periodically to the second stationary ultrasonic rinse.

ADVANTAGES AND CHARACTERISTICS OF ULTRASONICS

Uniformity and consistency of the cleaning results are two main characteristics of cleaning with ultrasonics. An optimized ultrasonic process is characterized by selecting the appropriate frequency and the appropriate power amplitude suitable for the type of parts to be cleaned. One fact to remember is that not all industrial high-power ultrasonics are equal. The process of generating the ultrasonic waves involves specially designed PZT transducers and high-frequency power generators. For example, selecting the right materials and devising the design and dimensions for the transducer assemblies involves science and art as well. The main objective is to maximize frequency matching and lower the impedance to maximize energy transfer into the liquids. This was accomplished at Crest Ultrasonics by a new ceramic transducer design (Fig. 3). Recent developments include using two or more frequencies simultaneously in the same tank. Another important recent development is the development of wide range of rates for the sweeping frequency. Currently, sweep frequency is a standard feature in all generators. Without sweep frequency (+/- 2 kHz) the fluid in a tank will be split into active and inactive lateral zones. The new feature allows contamination control engineers to control the process and specifically determine what is the best range for their sensitive components.

Countless micron-sized vapor cavities are generated by high-power ultrasonic sound waves throughout the liquid, even in recesses, holes (blind or not), and internal cavities in the workpieces. These cavities are very short lived and they violently implode in the cleaning media (Fig. 4) giving rise to high localized temperatures (of around 20,000°F) plus the wave pressure impact (about 5,000 psi) and an acoustic streaming (250 mph) effect that causes the scrubbing action (Fig. 5).

The mechanism for producing the cavities is as follows: the alternating rarefaction and compression of the sound wave, generated during the half-cycles, stretches the liquid molecules beyond their natural bonding forces to form the micro cavities (cavitation threshold) that grow to macro cavities, proportionate to the ultrasonic energy applied and its frequen-
The instantaneous vaporization that follows to fill the cavities has a relatively shorter life compared with the very rapid violent implosions, which characterize the ultrasonic activity in liquids.

Maximum cavitation intensities can be attained at temperatures of 130 to 160°F. Lowering the surface tension of water results in faster degassing and better distribution of cavitation. The size of cavities and their number are a function of the ultrasonic frequency. Larger size cavities in a relatively smaller numbers, with intense implosion impacts, are generated at frequencies in the range of 20 to 30 kHz. Moderate-size cavities, in greater numbers and effective if more moderate implosion impact, occur at frequencies of 40 kHz. Frequencies greater than 100 kHz are utilized to generate finer implosions with fine to moderate impact. The cavitations at 132 to 192 kHz are numerous and effectively remove submicron particulates. At these frequencies the cavitations have a relatively milder impact, which makes them ideal for use in rinse stations where it is desirable for detergent films to be entirely diffused and removed into the water, without inflicting erosion damage to sensitive components. Most current commercial ultrasonic cleaning equipment operates in the range from 20 to 200 kHz.

Other cleaning process parameters are also equally important such as compatible chemistries, operating temperature, quality of rinsewater, effective removal of suspended contaminants through filtration, and the proper drying technique.

**CONCLUSION**

Selecting the proper cleaning ultrasonic equipment is equally important as selecting the appropriate cleaning chemistries and process parameters to achieve two goals when dealing with steel components. The first is to accomplish the desired cleanliness level and the second is to protect the steel components from any potential for flash rusting or corrosion. Both goals can be successfully achieved with properly designed ultrasonic aqueous process.