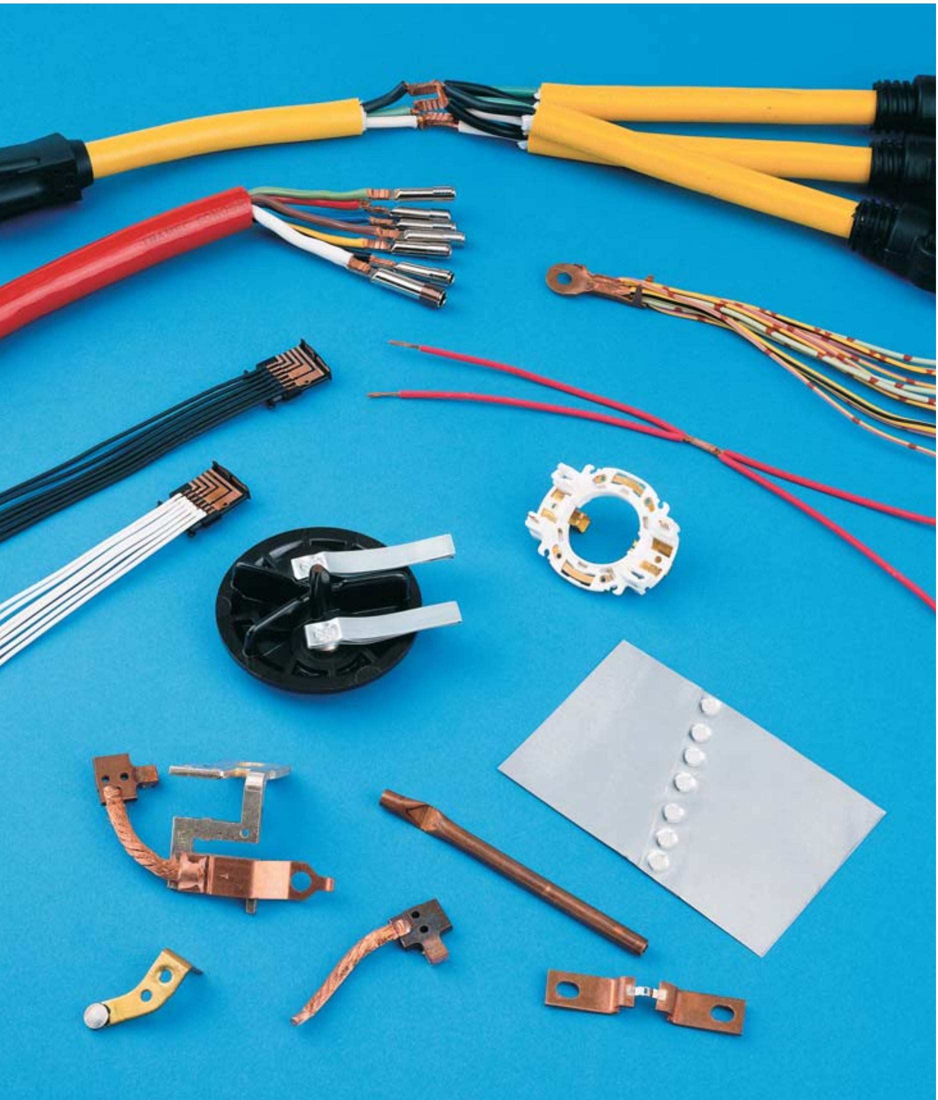
Ultrasonic Metal Welding



A Primer

Stranded Wire Ultrasonically Bonded to a Terminal

Ultrasonic welding is a solid-state process which produces a weld by the introduction of high-frequency vibration while the weldment is held under moderately high clamping forces. The weld is produced without significant melting of the base materials.

The advantages of ultrasonic welding include the following:

- permits joining thin to thick materials
- permits dissimilar metal joints
- provides joints with good thermal and electrical conductivity
- joins metals without the heat of fusion
- provides efficient energy use
- requires no filler materials, fluxes, or special atmosphere
- usually requires no special cleaning processes
- welds through most oxides

Applications

Commercially successful applications generally fall into the following categories:

- joints must be lap joints, not butt joints
- thin sections are required adjacent to the welding tip
- better results are obtained with nonferrous alloys

Production uses include fabricating electrical wire harnesses for the appliance and automotive industry, bus bars, fuses, circuit breakers, contacts, ignition modules, starter motors, aluminum and copper foils, battery foils, capacitors, encapsulation of explosives, microelectronic wires, HVAC tubing and many others.

Equipment

The components of an ultrasonic welding system include:

- a power supply which converts line power to the high frequency and high voltage needed by the transducer
- a transducer which transforms high frequency electrical energy to vibratory energy and is incorporated in the welding head
- the welding head which also provides the means - either pneumatic, hydraulic, or mechanical - to clamp the workpieces
- the components or waveguides to transmit the energy to the desired weld area

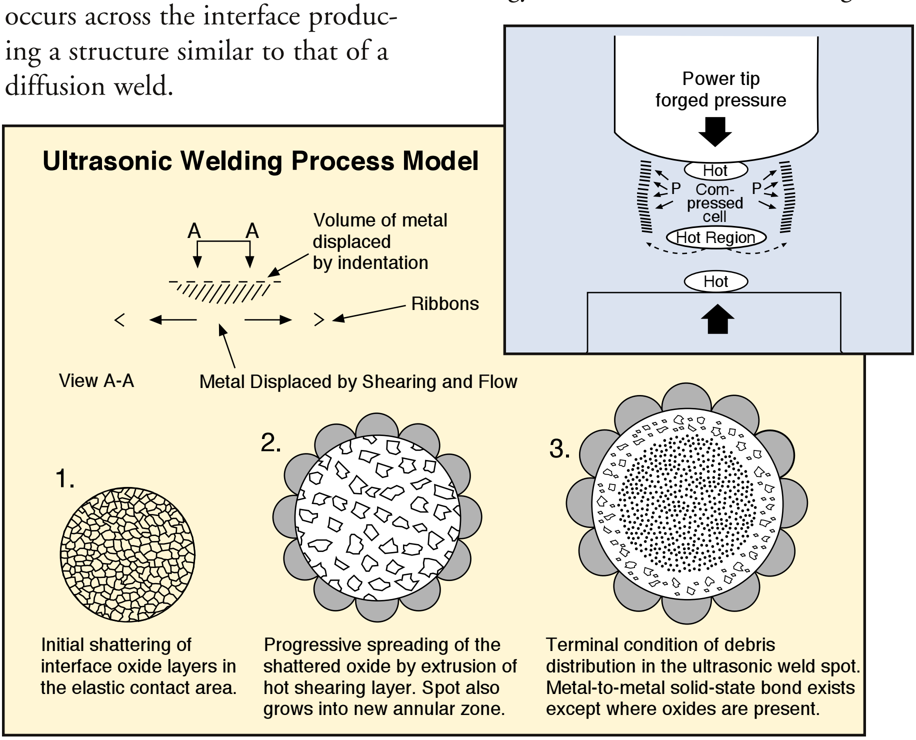
Principles of Operation

Ultrasonic welding occurs by the introduction of oscillating shear forces at the interface between two metals while they are held together under moderate clamping force. The resulting internal stresses cause elastoplastic deformation at the interface.

Highly localized interfacial slip at the interface tends to break up oxides and surface films, permitting metal-to-metal contact at many points. Continued oscillation breaks down the points, the contact area grows and diffusion occurs across the interface producing a structure similar to that of a diffusion weld.

Ultrasonic welding produces a localized temperature rise from the combined effects of elastic hysteresis, interfacial slip, and plastic deformation. The welding process is completed without having fully melted metal at the interface when the force, power, and time are set correctly.

Interface temperature rise is greater for metals with low thermal conductivity, such as steel, than for metals of high conductivity, such as aluminum or copper. Ultrasonic welding of such high conductivity materials requires substantially less energy than does resistance welding.



Ultrasonic Welding Process Model

1. Initial shattering of interface oxide layers in the elastic contact area.

2. Progressive spreading of the shattered oxide by extrusion of hot shearing layer. Spot also grows into new annular zone.

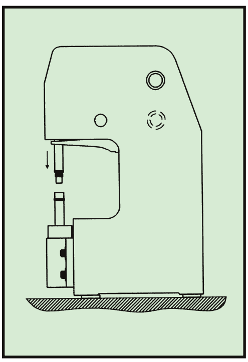
3. Terminal condition of debris distribution in the ultrasonic weld spot. Metal-to-metal solid-state bond exists except where oxides are present.

Weld Variations and Limitations

Variations of the process provide different weld geometries - spot, line, continuous seam, and ring welds.

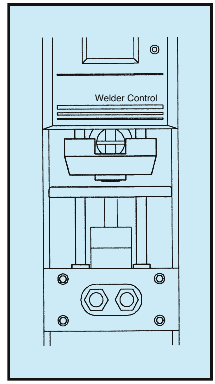
Spot Welding

Spot welds may be circular, elliptical or rectangular, solid or ring-like in geometry. They are formed when the material is clamped between a shaped tip (sometimes called a sonotrode) and an anvil. The tip vibrates as ultrasonic energy is momentarily introduced in a plane parallel to the interface and perpendicular to the clamping force. Weld time varies according to the thickness and composition of the material to be joined and the power of the welding machine, but most spot welds can be accomplished in less than 1.5 seconds.



Welds can be made adjacent or overlapping previous welds to form a continuous weld joint.

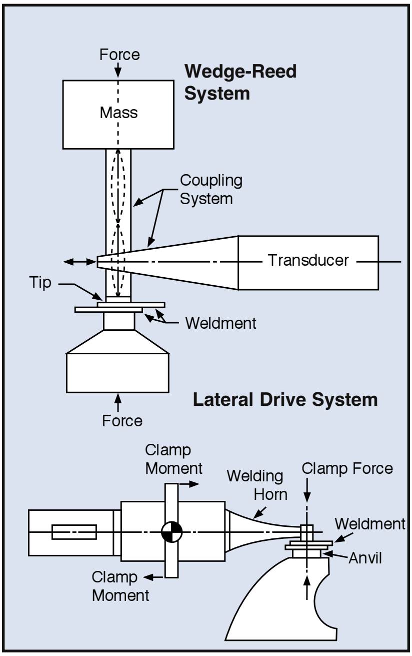
A product clamp may be necessary to prevent the dispersion of ultrasonic energy into adjacent areas of the workpiece. The product clamp is usually concentric with the welding tip and has a slightly larger diameter than the tip.



There are two distinct designs for the ultrasonic (or acoustic) system; these are the Wedge-Reed and Lateral Drive systems.

The Wedge-Reed produces low amplitude vibration combined with high clamp force. This permits high energy transfer, particularly useful where stranded wire or larger area bonds are required, because electrical characteristics improve as bond area increases.

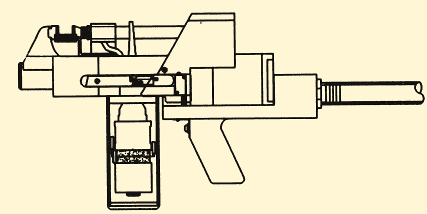
High amplitude and low clamp force characterize the Lateral Drive system which is useful for etched foil, fine wires and thin sheets. Suitability of this technique is limited due to the bending stresses at high clamp force, which cause



early fatigue failure in certain applications. These systems will sometimes stall at high force levels.

Line Welding

Line welding is a variation of spot welding in which the weld geometry is elongated by using a linear sonotrode tip and/or anvil. Custom multiple transducer heads have been used to produce line welds several inches long but most commercially available equipment is limited to lines of 1 1/2 inches (38mm) or less in length. Adjacent welds can produce a longer line. Usually, the longer welds are attainable only in thin



Tube Sealing Welder

materials, typically 0.010 inch (2.5mm) or less. Single line welds of up to 2 inches (50mm) in length have been made in joining expanded nickel foil to solid foil for a lithium battery application.

Line welding is also used to seal copper tubes in HVAC applications. This technique can replace sealing by crimping and brazing.

Continuous Seam Welding

Continuous seam welds are produced when a disk-shaped ultrasonically vibrating roller is rotated and traversed over a workpiece that is supported on a fixed anvil. Typical uses include joining foil ends in aluminum and copper foil mills. Commercial equipment is available to weld sheet thicknesses up to about 0.006 inch (0.15mm). High-frequency systems (typically 50 kHz), permit excellent welds in even the thinnest of foils, such as 0.00017 inch (0.004mm) without tearing or puckering. This technique is also used to join 0.0015 inch (0.004mm) aluminum interconnects to foil in photovoltaic panels.

Ring Welding

A circular tip used on a spot welder may be used to form a ring weld. The diameter is limited to about 3/8 inch. The shape can be circular, oval or elliptical.

Microelectronic Welding

Fine wire bonding represents the earliest widely used application for ultrasonic metal welding and still accounts for a large volume of industrial activity. Millions of wire bonds are performed daily.

Wire diameters range from less than 0.001 inch (0.025mm) to .020 inch (0.5mm) with the highest volume occurring in the 0.001 to 0.002 inch (0.025 to 0.050mm) diameter range.

Operation Procedures

Operation of the ultrasonic equipment requires no elaborate or extensive training. Once the process parameters have been determined, usually by a process engineer, the operator is required only to load the parts into a nest or supporting/locating anvil assembly, press palm buttons or other starting device and then unload the finished part.

In-process monitoring may be performed electronically by use of a microprocessor or visually by the operator. Visual observation by the operator usually involves occasionally looking at a power indication gage.

The process engineer needs to work closely with the equipment manufacturer for guidance regarding tooling design and selection of process parameters.

There is no arc, spark or molten filler material associated with ultrasonic welding and no electrical current passes through the weldment. Since the welder is usually configured in a press form with moderately high forces, the normal precautions need to be observed for operator safety - that is, the use of anti tie-down palm buttons or similar provision to protect hands.

Another common consideration involves the high-frequency noise level produced by the ultrasonic vibration. In some instances, especially with the higher power level equipment, the noise exceeds the OSHA approved levels and provision must be made for sound-reducing barriers or enclosures.

The ultrasonic welding process requires overlapping of the materials to be welded. In general, the materials need only be presented to the welder in proper orientation and this is usually achieved by use of a nest or anvil fixture which supports the parts while they are welded. When joining stranded wires to other solid or stranded wires or to a terminal, it is necessary to use a “gathering” fixture to pull the wires together and to exert a slight pressure while welding so the wires do not escape from the intended weld area. This type of fixture is usually supplied by the manufacturer with machines intended for use with wires and is adjustable to accommodate a wide range of sizes and combinations.

Weldable Alloys

Aluminum

All combinations of aluminum alloys are ultrasonically weldable. Photomicrographs show the significant diffusion typical of ultrasonic welds in aluminum. In general, the hardness of work-hardenable aluminum should be 1/4 to 1/2 hard. Annealed materials exhibit high deformation. Some aluminum alloys, particularly the 1100 series and 2036 alloy, tend to stick to the welding tip. Tip-sticking can sometimes be overcome by using high power and a short weld time. Hardened tool steel tips exhibit the most satisfactory results. Other solutions have included the use of a mechanical stripper where light sticking occurs or the placing of a thin gage steel shim between the vibrating tip and the weldment. Various tip geometries and surface finishes may be used, including circular radiused tips, flat cross-hatched, bulls-eye, and serrated. Tips may be circular, rectangular, line-shaped, etc., as suits the end purpose. The aluminum adjacent to the tip should be less than 0.1 inch (2.5mm) thick for the highest strength results, but the material to which it is welded needs no thickness limitation. Wires up to about 0.125 inch (3mm) diameter solid, or stranded wires up to 0.25 inch (6mm) diameter can be welded.

Commercial applications include:

- seam welding of light gage foils
- stranded wire to terminals
- joining multiple layers of aluminum foil to a capacitor terminal
- joining aluminum frame to an aluminum grille for a heating duct
- aircraft panel welding for the A-10 aircraft
- aluminum interconnect welding on photovoltaic panels

Copper Alloys

The greatest industrial use of ultrasonic welding is in the joining of copper and brass materials. Copper alloys may be joined together or to other materials such as aluminum with great success. Various tip geometries and surface finishes may be used.

Copper sheet up to 0.08 inch (2mm) thick produces excellent joint strength. Stranded wires for wire harnesses represent one common use. Bundles having a cross-sectional area up to 30 square mm are readily bondable. The high thermal conductivity of copper is not a deterrent to ultrasonic welding as it is with fusion welding.

Applications include:

- stranded wire to stranded wire for automotive, truck and appliance harnesses
- stranded wires to terminals for automotive and other electrical harnesses
- stranded wires to solid wires
- solid wire to solid wire to commutator for starter motors
- copper strip to copper strip for electrical grounding gridwork
- flat wire to flat wire for starters and coils
- flat copper slug to aluminum plate for ignition module
- enameled wire to steel housing for solenoid coil ground
- copper tube closure for HVAC industry
- brass “U” shaped section to a brass plate for a brush holder
- copper/steel laminate to itself for a communications cable sheathing

Dissimilar Metal Combinations

Perhaps one of the most useful characteristics of ultrasonic welding is its ability to weld dissimilar metal combinations. Primarily used to join copper and aluminum alloys, this technique combines the advantages of aluminum as a backing plate with the solderability of copper for attaching circuitry. For instance, copper slugs are ultrasonically welded to an aluminum backing plate for ignition modules and for ABS brake sensors. The copper is more suitable for soldering the circuitry and a better match to the expansion coefficient of the chip carrier, which is important if the stress of thermal cycling is encountered.

A lithium battery application requires the joining of thin aluminum, copper and nickel sheet to expanded nickel mesh. Ultrasonics provides strong, electrically and thermally sound welds.

Copper wires are bonded to copper-flashed steel plate to make a carbon brush holder for a locomotive. The ultrasonic assembly replaces a lengthy process which involves riveting and forming the "bridge" for the brush.

Copper wires are welded to copper-plated steel for an automobile seat switch. Copper wires to stainless steel are welded as part of a photovoltaic assembly. Copper wires and strips can also be welded to silver-plated terminals.

Precious Metals

Most of the precious metals, such as gold, silver, platinum, and their alloys, are weldable ultrasonically. Materials plated with such metals are also ultrasonically bondable.

Nickel Alloys

Many nickel alloys and nickel-plated materials are bondable with ultrasonics.

Surface Condition

Most of the readily weldable materials, such as aluminum, copper, or brass, can be welded in the mill condition or may require degreasing with a common solvent or detergent to remove surface lubricants. Oxide coatings, unless very thick, will disperse during the process.

Heavy surface scale should be removed by mechanical abrading or chemical etching before welding. The time lapse between cleaning and welding is generally not critical unless the atmosphere is corrosive.

Some types of coatings and insulations, such as low temperature magnet wire coating, may be penetrated while welding, but some must be mechanically removed.

It is important that fairly consistent surface cleanliness and quality be maintained if production weld quality is to be consistently uniform.

Use of an Interlayer

A useful technique in improving the weld quality of some weldments involves the placement of a thin foil, usually aluminum or copper, between the metals to be bonded. This is particularly useful when materials of disparate hardnesses are to be bonded. The use of an interleaf is sometimes more convenient than plating the materials with a more weldable material, such as copper or gold.

In a technique known as weld bonding, a layer of adhesive is placed between the panels to be ultrasonically welded. This technique not only provides a watertight seal, but increases the weld strength beyond that achieved by separate adhesive bonding or ultrasonic welding. Ultrasonic weld bonding can be achieved through either a paste adhesive or a fabric-supported adhesive.

Control of Parts Resonance

Complex workpieces, especially those with multiple parts or thin wall sections, may be induced to vibrate by the ultrasonic welding system. This may cause fracture in the part, in previously made welds, or inconsistent weld quality. This resonance may be eliminated or dampened by applying pressure to the vibrating section.

For instance, in ultrasonic welding of aluminum foil layers to the studs in capacitor caps, it is necessary to clamp the stud quite tightly; otherwise the vibration not only prevents welding but can even melt the plastic cap surrounding the stud.

Sometimes the vibrating part can be clamped to a comparatively large fixture or anvil. Significant pressure may be required and some machines come equipped with a product clamp for this purpose. Resonance in the tooling may also be encountered and, for this reason, fixtures should be rugged and not contain multiple small devices, such as springs and pins. It is best to avoid light materials, such as aluminum for parts fixturing, anvils, and supports; steel is preferred for these components.

Tooling, Tips and Anvils

The welding tip (or sonotrode) which contacts the weldment is best made of high-quality, heat-treated tool steel. The fit between the tip and the waveguides must be of the highest quality if efficient transmission of vibratory energy is to be achieved. A locking (Morse) taper is frequently used and the fit should cover 75% of the contacting surface area between the tip and its matching receptacle. In lower power systems, the tip and the waveguide (horn) may be integral and sometimes have several surfaces for welding. Rotation of the horn provides a new welding surface.

A welding tip with a taper lock fit is less expensive to replace and more amenable to resurfacing when necessary than an integral horn-tip combination.

Certain alloys may stick to the tip when welded, especially the very soft aluminum alloys. A mechanical stripper may be needed to pull the part free or sometimes a low-power, ultrasonic pulse may be sufficient to remove the stuck part from the tip. If a nugget remains on the tip, a weld pulse with the tip clamped against a thick piece of brass may remove the stuck nugget better than mechanical abrasion.

Some exotic alloys can be used for tips to prevent particularly tenacious sticking, with limited success. A steel shim with an oxided surface is found to be particularly effective in preventing both sticking and deformation in bonding high-strength aluminum and titanium alloys of interest to the aircraft industry.

The anvil tip is subject to the same problems of wear and tip sticking as the sonotrode tip and the same high-strength, heat-treated tool steel, typically M2, heat-treated to RC 58 to 60 is recommended.

Welding tip and anvil tip surfaces with serrated or cross-hatched patterns are useful in preventing slip between the tip and the weldment which sometimes cause the welding to occur between the metal and the tools instead of at the required interface. A typical cross-hatched pattern would be 0.02

inch (0.5mm) peak-to-peak and about 0.008 inch (0.2mm) deep. When welding wire to a terminal for instance, a grooved tip may be preferred.

Weld Quality

Influencing Factors

The quality of ultrasonic welds is affected by the materials and geometry of the weldment, the hardness and the cleanliness of the weldment, the selection of welding conditions, such as power, clamping force, weld time, and the ability of the tooling to properly support and clamp the parts to prevent unwanted vibration.

Surfaces at which welding is required should be reasonably flat and parallel. This is more critical for ring welding where a high degree of hermeticity is required. Some materials may be weldable in the as-received condition, however, a change in lubricants or other surface conditions may require an adjustment in machine settings to maintain quality. For this reason, it is sometimes advisable to degrease or abrade surfaces before welding so that a certain level of consistency is maintained.

Surface Appearance and Deformation

Depending on the material and tip geometry, the surface of an ultrasonic weld may leave a slight scuffing mark or a significant depression. The thickness deformation is greater in soft, ductile materials, such as soft aluminum. The actual weld interface is usually smaller than the surface impression.

A tip surface having serrations or a cross-hatched pattern will duplicate this pattern in the surface of the weldment. A spherical radius on the tip will generally produce a deeper, bowl-shaped depression than a flat tip of the same diameter.

Harder materials generally have a shallower and smaller surface depression than soft, ductile materials.

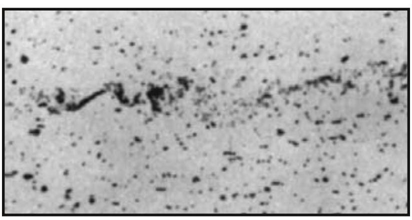
Stranded or braided wires may be welded to form a solid cross section, if so desired. Slightly lower power, time, or force can give a compressed, but not solid cross section.

Judicious radiussing and angling of tools are recommended to avoid sharp transitions in areas which may lead to early failure of an assembly.

Metallographic Examination

The metallographic examination of ultrasonic welds in a wide variety of metals reveals phenomena occurring in the microstructure which include surface film and oxide disruption, plastic flow and extrusion, recrystallization, phase transformation, and diffusion.

A heat-affected zone is seen in certain alloys, such as aluminum and nickel. Phase transformation, recrystallization and precipitation may occur.



1100 H14 Aluminum Weld

Diffusion across the interface is usually shallow because of the short weld times although significant penetration across the interface is sometimes exhibited. Alloying may occur in welding certain dissimilar metals.

Mechanical Properties

Tensile shear tests performed on single weld lap joints often fail in the base metal or tear-out of the weld nugget rather than through the weld itself. Consistency is generally good with one standard deviation typically less than 5% of the average strength value.

Welds tested after thermal cycling, exposure to salt baths and other corrosive environments maintain a good tensile strength level.

Fatigue strength of ultrasonically welded metals often exceeds that of fusion-welded materials, probably because the ultrasonic bonding does not leave the cast nugget structure typical of melted and resolidified metal.

For fairly thin foils, the ductility of the ultrasonic bond permits reforming the parts after welding without cracking the welded joint.

Prepared by

SONOBOND ULTRASONICS

The First Name in Ultrasonics for Metals

1191 McDermott Drive, West Chester, PA 19380
800-323-1269 • 610-696-4710 • Fax 610-692-0674
Web: www.SonobondUltrasonics.com
E-mail: Sales@SonobondUltrasonics.com