White Paper on Solid State Bonding and APCI's Linear Friction Welding Technology

July 2011

COMMON TYPES OF WELDING

There are multiple types of welding processes used today. Among the most common are Gas Tungsten Arc Welding (GTAW or TIG), Gas Metal Arc Welding (GMAW or MIG), LBW (Laser Beam Welding), and ERW (Electric Resistance Welding). While all of these processes have their uses, they all melt the material being welded, which causes degradation of the metal, and none produce a full interface weld. In addition, because of the melting of the material) both parent and "filler" material), these types of processes produce gases that are not friendly to the environment or to those doing the welding.

SOLID STATE BONDING (SSB), THE BETTER ALTERNATIVE

When joining two or more pieces of metal, SSB is the preferred industrial joining process especially in critical applications because it:

- Provides guaranteed repeatability
- Produces minimal material loss
- Produces minimal material degradation
- Has very little off-gassing
- Creates a full interface weld because it does not use a third party material or melt the
- parent materials.

SSB works so well because the materials being joined are plasticized and then joined using a forging process. There are four major types of SSB processes: Friction Stir Welding (FSW), Butt Welding (BW), Rotary Friction Welding (RFW), and Linear Friction Welding (LFW). There are advantages and disadvantages for each; these are discussed below.

Friction Stir Welding (FSW) is a SSB process that involves a cylindrical-shouldered tool, with a threaded or unthreaded profile probe that is rotated at a constant speed. This tool is then, under significant pressure, moved at a constant traverse rate into the joint line between two pieces of sheet or plate material, which are butted together. By combining the pressure and rotational energy of the probe the FSW machine generates friction energy in the material at the joint line which is plasticized and pushed together as a bond.

Because of the mechanics of the process, FSW is limited to joining plates. Also, due to the physics and mechanics of the process, FSW can only joint plates with very limited wall. FSW joints have a number of defects that are unique to the technology. Insufficient weld temperatures, due to low rotational speeds or high traverse speeds, for example, mean that the weld material is unable to accommodate the extensive deformation created during welding. This may result in long, tunnel-like defects running along the weld which may occur on the surface or subsurface. Low temperatures may also limit the forging action of the tool and reduce the continuity of the bond between the materials from each side of the weld.

The light contact between the materials has given rise to the name, kissing-bond. This defect is particularly worrying since it is very difficult to detect using nondestructive methods such as X-ray or ultrasonic testing. If the tool (called the "pin") is not long enough or the tool rises out of the plate, then the interface at the bottom of the weld may not be disrupted and forged by the tool, resulting in a lack-of-penetration defect. This is essentially a notch in the material which can be a potent source of fatigue cracks.

Butt Welding (BW) is a SSB process in which two ends of the material are prepared so that they butt together with good contact. They are then placed in the jaws of the machine, which presses them close together end to end. When a given pressure has been reached, a very large power source is switched on, forcing a large current to flow through the contact area. Resistance between the ends being joined brings them to welding heat. Extra pressure is then applied, and the ends are pushed into each other such that the white hot metal is welded together. As a result of the pressure and near melting of the material, BW creates an enlargement of section (budging or mushrooming of material at the joint) during the welding process.

Due to the variability in environmental conditions, cleanliness of the weld interface, precision / flatness of the weld interface, load pressures, and material composition, the BW process produces large amounts of scrap. BW is also an inefficient process as it uses a very large amount of (increasingly costly) energy, all of which makes it an undesirable bonding process.

Two of the most desirable types of SSB are Rotary Friction Welding and Linear Friction Welding. Both technologies create excellent bonds, are highly repeatable, and have the ability to weld dissimilar metals. They will be discussed and compared with each other below.

Rotary Friction Welding (RFW) is predominately the most common SSB process in use today. It involves a rigidly clamped part being contacted by a rotating part. This contact is held at a calculated pressure and rotational speed determined by the parameters of the parts to be joined. The resulting friction creates heat and then plasticizes the metals. As the bond is made all movement comes to a stop, and then the parts being joined are predefined "forge pressure" creates the weld. The rotational speed, the axial pressure, and the welding time are the key variables controlled in the process to provide the necessary combination of heat and pressure to form the weld.

The resulting joint is a Solid State Bond (SSB). Given a calculated energy input in the form of friction and forge pressure, there will be a defined upset (material loss from the two parent materials) during the final forge. Upset is one of the monitored variables during friction welding. If the upset is correct and the energy loop is completed, the quality of the joint is known.

As mentioned above, the mechanism used to generate friction is rotating one part against another under a load. RFW was the genesis of the SSB process, and was first implemented in the 1960s. It currently dominates industrial SSB applications because it is well understood, and is the simplest, lowest cost SSB solution available to date. It is for these reasons that friction welding is the most desirable joining process in several industries, such as aerospace and energy.

RFW does have limitations. First, this method of bonding is limited to shapes that can be rotated such as round material. Second, RFW creates a significant amount of upset which means it "eats up" a meaningful amount of parent material -- this creates the need for post weld machining (in most cases). Finally, the process can be relatively long, given the time needed to bring the parts up to speed, bring them together, burn off material, and machine the final part.

Globally, manufacturing industries have accepted the limitations of RFW because RFW provides the big benefits of high quality, reproducible, solid state welds produced when using conventional rotary friction welding processes. Because of the quality of RFW welds, industries have identified a need for other parts to be joined using SSB, none of which are round in nature.

Linear Friction Welding (LFW) was introduced because of the limitations of RFW. LFW is a process that shares nearly all the same characteristics as RFW, except that the mechanism of movement is different. RFW involves a rotating part contacting a stationary part; LFW involves a part the moves back and forth (reciprocating motion), contacting a stationary part, as shown in Fig 1. Therefore the rotational speed parameter is replaced by a linear movement at a specific frequency and specified amplitude.

Fig. 1

Clearly, LFW can also bond round material, meaning that an LFW machine can do everything a RFW machine can do, but the reverse is not true. While LFW is, by many measures, the best and most flexible of all SSB technologies available, it has historically had several disadvantages. Disadvantages have included high machine cost, machines that were extremely large in size and machines that created extreme maintenance issues (which, in turn, generated very high maintenance costs). It has been these disadvantages that have kept the LFW from eliminating the need for RFW.

With the recent developments by APCI, the landscape of LFW has changed. APCI has addressed each of the disadvantages associated with LFW with their latest LFW Technology. Because of its value in the industry, APCI's Patent Pending technology is still being very closely guarded by APCI. Even so, we can investigate, in the general terms, the advantages of APCI's LFW solutions.

Notice in Fig 2 below, the difference in the heat zones in RFW (left side) and LFW (right side). The RFW has more area being heated and a great heat loss in the middle of the weld. The reason for the heat loss at the middle of the weld and the large amount of heated area on the outer of the weld is because when the part is rotating, the inner most point is being rotated the least, causing the need for the part to be rotated longer, which in turn causes large amounts of heat on the outer portion of the weld. The Thermal Vision of the RFW is demonstrated in Fig 3 below.

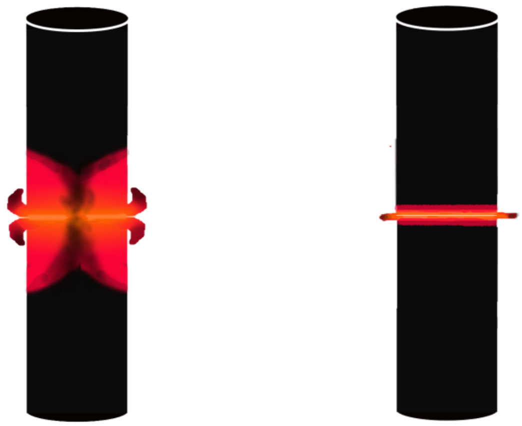


Fig. 2

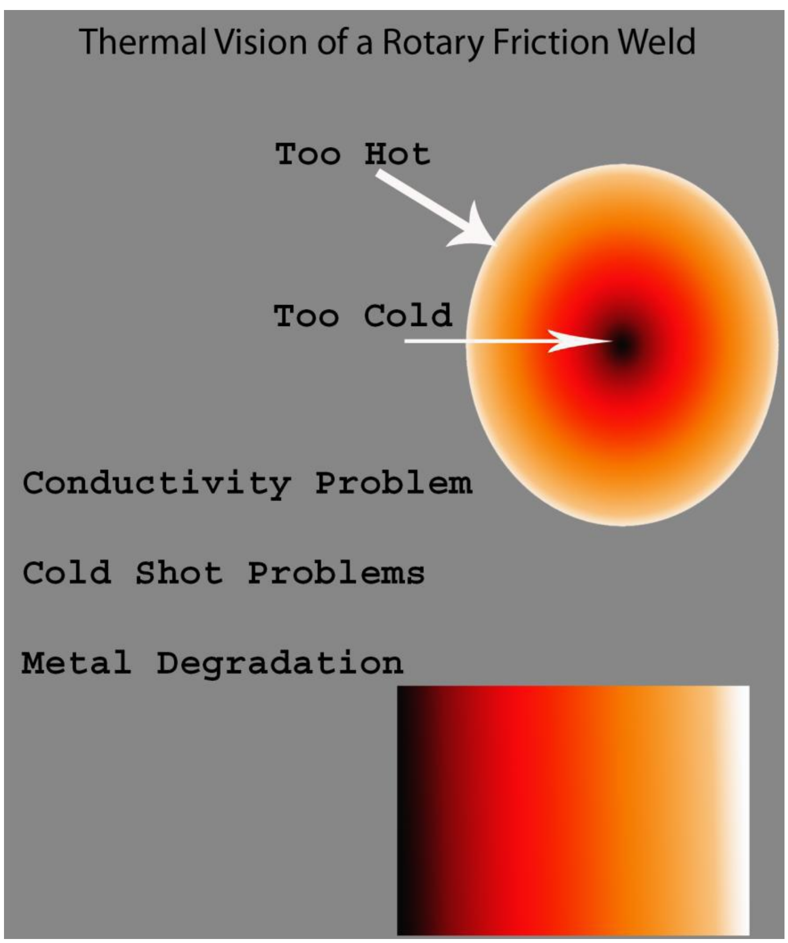
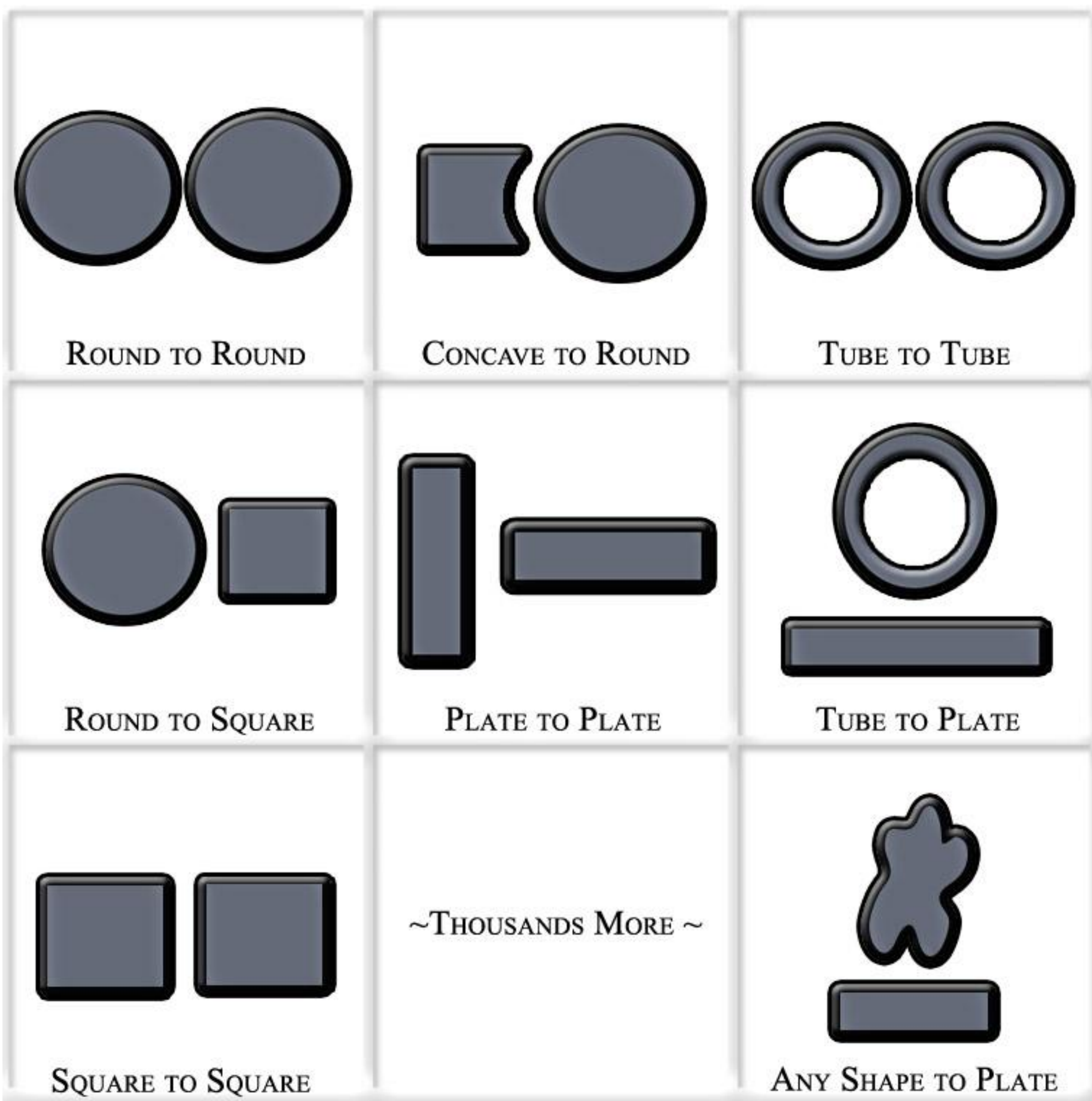

Thermal Vision of a Rotary Friction Weld
Too Hot
Too Cold
Conductivity Problem
Cold Shot Problems
Metal Degradation

Fig. 3

Other benefits of APCI's LFW Technology over the RFW and conventional LFW are that it consumes 1/10th the power, generates 1/10th the material loss, welds in 1/10th of the time, has the ability to do most types of geometry, and offers the ability to do a wider range of part types per machine. The accuracy of the repeatability rate for APCI's technology is superior to other LFW solutions and orders of magnitude superior to RFW.

Because APCI's technology allows very accurate control of all bonding parameters, APCI's systems can produce a very broad family of parts. The following picture, Fig 4, depicts some of the types of geometry that can be welded with LFW. One additional and highly advantageous aspect of LFW is the fact that it can be used to produce "near net" parts. Near net parts are parts are made up of one or more "sub" parts welded together using an SSB process to afford, with a minor amount of machining, a more complex final part. "Near Net" generates savings in time, labor, material usage, and inventory stocking costs compared to current methods (particularly, milling complex parts out of solid billets of material). This is especially valuable in operations that use materials that are expensive and/or difficult to machine, like titanium and "super alloys".



MATERIAL TYPES that can be welded using LFW include, but are not limited to the following:

ALUMINUM to

- Aluminum Alloys
- Brass
- Ceramic
- Magnesium alloys
- Nickel
- Steel - Alloys
- Steel - Carbon
- Steel - Stainless
- Titanium
- Titanium Alloys
- Tungsten Carbide -
- Cemented
- Zirconium Alloys

CARBON STEEL to

- Aluminum
- Bronze
- Carbides (Cemented)
- Cobalt
- Copper
- Copper Nickel
- Iron (Sintered)
- Monel
- Nickel
- Nickel Alloys
- Nimonic
- Steel - Alloys
- Steel - Stainless
- Steel - Maraging
- Steel - Tool
- Valve Material (Automotive)

NICKEL to

- Aluminum
- Nickel
- Steel - Alloys
- Steel - Carbon
- Steel - Stainless
- Steel – Maraging
- Steel - Tool

STAINLESS STEEL to

- Copper
- Copper Nickel
- Monel
- Nickel
- Nickel Alloys
- Nimonic
- Steel - Alloys
- Steel - Carbon
- Steel - Sintered
- Steel - Stainless
- Valve Material (Automotive)
- Aluminum Alloys
- Titanium
- Titanium Alloys
- Zirconium Alloys

TITANIUM to

- Steel Carbon (Full Strength Weld) Steel Tool (Full Strength Weld)
- Aluminum Alloys (Partial Strength Weld)

CARBIDES (Cemented) to

- Steel Carbon (Full Strength Weld) Steel Tool (Full Strength Weld)
- Aluminum Alloys (Partial Strength Weld)

OPPORTUNITIES WITH LFW

LFW presents tremendous opportunities in many industries. A few of these key industries are Aerospace, Automotive, Construction, Electrical, Energy, Heavy Equipment, Industrial, Marine, Medical, and Military.

The many thousands of items that can be friction welded in these industries include, but are certainly not limited to, the following:

- marine propellers
- aircraft engine / gas turbine blades
- automotive airbags
- automotive steering components
- square and round axles
- risers, umbilical lines, pipe couplers, and drill ends (used in oil and gas exploration and production)
- explosives
- military applications in tanks, fighter jet components, helicopters, and weapons
- precision equipment
- instruments and medical devices utilizing materials such as Titanium, Stainless Steel, 40KhNYu-VI, or various other medical materials
- sprocket to shaft, hitch pins, power splines, and power yokes in vehicle drive and steering
- robotics, production automation, and production lines in general
- pump parts
- cylinders
- copper to copper and copper to aluminum for the electrical industry
- rebar to plate, rebar to rebar, and rebar to coupler for heavy construction
- torque converter, drive shaft, engine valves, turbo charger, and air conditioner parts for
- automotive production
- engine rotors, landing gear, fuel controls, and turbine blades in the aerospace market

Overall Capabilities

- LFW is the most robust Solid State Bonding process developed for the 21st Century needs.
- LFW is up to 100 times faster than other welding techniques.
- Flexible enough to join different shapes, sizes, and materials. (Bi-Metal)
- LFW can join two 50 foot parts together.
- LFW can make 2 to 50 welds simultaneously.
- LFW can pre-heat metals during process.
- No joints preparation needed as LFW welds saw cut, machined, & sheared surfaces.
- No solidification flaws, gas porosity, separation, or slag inclusion occurs.
- No human error because the process is entirely machine controlled.

- Weld quality is not affected by operator skill or attitude.
- No special foundations or power supplies are needed.
- Materials and Geometry are pre-calculable parameters.
- The process can mathematically be scaled. Ex: small part samples can be used for large part development.
- Easily monitor process parameters and weld history.
- Any weld performed with a rotary process can be performed better and more efficient with LFW.
- 1 square inch up to 20 square inches of part inteface.

Materials

- Ability to weld different types of materials to each other
- Welds materials that are considered unweldable including titanium.
- Ability to weld powder metal components to other powder metals, castings, forgings, or wrought material.

Green Initiatives

- Produces Near Net Parts.
- Environmentally friendly. No hazardous smoke, fumes, or gases are generated that need to be exhausted.
- No consumables are required. (no flux, filler, shielding gases, etc. required)
- Few sparks are produced.
- No weld splatter.
- Uses 80% less energy per weld than conventional welding processes.

The latest Technology developed by APCI, LLC, with support from Edison Welding Institute and Purdue University, is drastically changing the landscape of Linear Friction Welding. APCI is eagerly waiting to explore all of your bonding opportunities with their Linear Friction Welding Equipment for the 21st Century.