Friction Stir and Friction Stir Spot Welding - Lean, Mean and Green
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ABSTRACT

Friction Stir Welding (FSW) is less than twelve years old and Friction Stir Spot Welding (FSSW) has just recently arrived on the scene. Up to now, most of the production applications have focused on non-automotive means of transportation such as trains, airplanes and boats. Tremendous results have been realized including dramatically improved production, quality, uptime and flexibility. Most production applications have been outside the automotive industry. This has been due to high capital investment, but the advent of lower cost FSW equipment now eliminates this impediment. It is now the automotive industries' time to really exploit this process to the fullest. The key enabler is the development of the hardware, software and process parameters which make it possible to use a standard industrial robot, such as an ABB or Kawasaki, to perform FSW or FSSW. Aluminum, aluminum alloys, and magnesium in a variety of joint types can now be successfully joined. Typical automotive components being designed for FSW and FSSW include: chassis, crush horns, body enclosures, hoods, suspension links and gas tanks. In these type applications, significant cost reductions have been realized as well as dramatic improvements in mechanical properties.

INTRODUCTION

What if someone invented a welding process that didn't need to melt the base metal to make a joint but is still stronger than conventional processes such as Gas Metal Arc or Resistance Spot Welding? What if this process was lean (L), mean (M) and green (G), having the characteristics indicated as follows.

- Improved weld quality (L)
- Reduced distortion (L)
- Low power requirements (L)
- No filler metal or shielding gas required (L)
- No unsightly soot (L)
- Adaptable to all positions (M)
- Fatigue life 2-10 times arc welding (M)
- Able to join numerous non-ferrous alloys (even those considered un-weldable) (M)
- Mechanical strength of joint equal or close to original base material (M)
- Can weld material thickness ranging from 1-50mm+ (M)
- Generates no fumes or ozone, i.e. environmentally friendly. (G)
- Quiet (G)
- No spatter (G)
- No ultraviolet light (G)
- Reduced need for cleaning of part (i.e. reduced need for chemical cleaning agents) (G)

Note: L = Lean, M = Mean, G = Green

Not possible you say? Well, there is such a welding process and it has been in production for over 7 years. It is called Friction Stir Welding (FSW) and it is making large inroads into the fabrication of trains, airplanes, automobiles, and boats, especially in Europe and Japan. FSW is being used in low and high production situations daily, lowering production costs and improving quality.
Let's look at the basics of the process and how it compares to conventional welding processes. After this, we'll review how FSW can best be exploited by discussing a case study which reviews the fabrication of a transportation component.

THE BASICS

Since it was first invented in 1991 by TWI (The Welding Institute), it was apparent that the FSW process was flexible and simple, with many potential advantages, from quality improvements, to cost savings. This was especially evident for materials, such as aluminum, that are difficult to join with traditional processes.

The FSW process is inherently simple, with few variables. The basics of the process are illustrated in Figure 1. A non-consumable, rotating FSW tool with a specific geometry is plunged into and traversed through the material. The two key components of the tool are the shoulder and the pin (probe). During welding, the pin travels in the material, while the shoulder rubs along the surface. Heat is generated by the tool shoulder rubbing on the surface and by the pin mixing the material below the shoulder. This mixing action permits the material to be transferred across the joint line, allowing a weld to be made without any melting of the material. The only variables in the process are the rotation speed, travel speed, FSW tool design, and tool orientation and position. Once the proper tool design, rotation speed, travel speed, etc. are selected, this simple process ensures high quality, repeatable welds.

Given that the FSW process uses a moving tool, the process is flexible. It can be used to weld many different joint configurations. The process can also be used to weld in any orientation (e.g. overhead), as gravity has no effect on the process. The simplicity of the process allows FSW to have significant operating cost advantages over other processes. Likewise, the lack of melting allows the process to have numerous quality advantages over other traditional fusion joining methods, such as Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), Laser Beam Welding (LBW) or Resistance Spot Welding (RSW). Cost advantages result because no consumables such as gas, wire, or fasteners) are required, less repair and rework occurs, little to no material preparation is needed, and there is a reduced need for environmental protection because there is no noise, fumes, UV light, spatter, etc. The quality related advantages of FSW include weld geometry and penetration consistency, improved yield and tensile strength, as well as improved fatigue life. Furthermore, the process avoids many of the problems with traditional processes. Typical fusion welding problems include poor weld penetration, low weld and HAZ zone mechanical properties, poor welding uptime, propensity for weld cracking and porosity, excessive distortion, etc. The quality improvements versus the traditional processes are more pronounced in harder to join materials, such as 2XXX and 7XXX series aluminum.

Other than the linear process described above, another major variation of the process is Friction Stir Spot Welding (FSSW). The FSSW process involves only the plunge and retraction of the FSW tool as shown in the diagram in Figure 2. The traverse part of the process is eliminated. The FSSW process mimics the Resistance Spot Welding (RSW) process and can be used in place of RSW, riveting, clinching or any other single point joining processes in many applications. The FSSW process has two major variants; one which uses a single sided tool which is comparable to what is known as RSW "Poke" welding and the other involving a C-Frame, which is more like traditional RSW. The main advantage of the C-Frame FSSW process is that fixturing can be reduced because there is now no need to resist any significant force on the part. The C-Frame FSSW process also makes it a lot easier to use any large robot because there is no longer the need to have precise force control. See Figure 3 showing Robotic FSSW using a C-Frame.
Resistance spot welding, toggle-lock, rivets, and self-piercing fasteners are the primary methods used today for single point joining. All of these processes have inherent disadvantages that are overcome with Friction Stir Spot Welding (FSSW). Challenges with RSW include: 1) the need to chemically clean the aluminum within 8 hours of welding, 2) excessive electrode mushrooming causing poor welds to be made 3) process variability and 4) shunting problems which require greater spacing of the welds. Challenges with the rivets include: 1) high cost for fasteners, 2) potentially higher downtime due to feeding issues and 3) need for other operations (e.g. drilling) for non self-piercing rivets. Processes such as Toggle-Lok are simple and cheap but have less strength than RSW, especially in the tensile (‘cross-tension’) direction. In addition, they experience high die wear, which can lead to further degradation of mechanical properties, unless frequent preventative maintenance is done.

FSSW is not saddled with the problems that are cited above due to the unique nature of the process. There is no consumable so this makes the process simpler. The tool has excellent life and is not mated to a die so preventative maintenance is reduced. The speed of the process is competitive with RSW but is much more consistent because FSSW is not as sensitive to changing material conditions (e.g. oxides) and surface conditions (contamination such as forming lubricants).

**Joint Configurations**

The standard FSW process is a fairly flexible process, in that it can be used in a wide variety of joint configurations. A suite of joint configurations that FSW is capable of performing is shown in Figure 4. The suite includes the butt joint (similar thickness), dissimilar thickness butt joint, lap penetration joint, lap fillet joint, and corner joint. It can be seen that the FSW process is not capable of performing welds in the T-fillet joint configuration, which is commonly used in many arc welding operations. However, one could come from the back-side on a T-fillet and join it to achieve this type of joint.

**APPLICATIONS**

There are numerous applications for both FSW and FSSW, especially in the transportation industry, employing aluminum structures. Any application that is currently riveted, toggle-locked, or spot welded (RSW) can often have FSSW substituted with little difficulty. Examples include automotive body panels, truck trailer bodies, truck chassis and suspension components, golf carts, pleasure boats, etc.

A short list of possible applications in various industries is shown in Table 1. Most of the listed applications concentrate on the joining of aluminum, as the FSW process is most advanced in this area and with other lower melting point materials. Other materials that can be joined include magnesium, copper, lead, titanium, and steel. The applications can range from 0.5 mm in thickness to over 50 mm in thickness.

**Cost**

To determine if FSW or FSSW is acceptable for use in an application, one of the first steps is to do a thorough cost analysis. The output of the cost analysis is typically a part cost or a cost per distance of weld for the product to be manufactured. The inputs of the analysis are typically limited to costs that are well defined or easy to obtain. The known cost inputs are capital equipment, labor, and consumables (FSW tools, electricity, shielding gas, weld wire, contact tips, etc). There are several other cost inputs, which can have significant impact, including maintenance, production uptime, rework, scrap and repair.
When enough experience with the new technology has been achieved, these inputs can then be included. One also needs to consider the more difficult to measure, but very real costs related to the process being more environmentally friendly. As a general rule, for medium to high volume automotive production, FSW welds cost 20% less than arc welds and FSSW costs 25% less than RSW. If indirect costs are considered (post weld operations, rework, repair, distortion) then the costs of FSW are dramatically less than GMAW.

IMPLEMENTATION EXAMPLE

Now we'll review a typical application involving the FSW of pontoon tanks. We'll look at what makes this opportunity attractive for an alternative process and then go through the cost justification.

Friction Stir Welding of Pontoon Boat Tanks

For years, pontoon boat tanks for cars and trucks have been made utilizing the GMAW process. Aluminum is by far the most popular material for these tanks due to its light weight and corrosion resistance. Aluminum is the most difficult of these materials to fabricate to the required productivity and quality requirements Figure 5 shows a typical pontoon boat and its tanks. It consists of a long seam weld and two circumferential welds. While GMAW is fairly productive with travel speeds ranging from 1-1.5 meters/minute, problems with weld quality can lead to defects (leaks, poor penetration and crater cracking) causing expensive repairs or even scrap. The main difficulty is the sensitivity of GMAW to weld seam location changes and to material that isn't perfectly clean. These problems, and the desire to make an exponential leap in productivity, make FSW an attractive alternative.

The direct replacement for the existing automatic GMAW would seem to point to doing automatic FSW. However, this is not always the best approach because the flexibility of the robot can facilitate doing both the longitudinal and circumferential seams in a work cell configuration. See Figure 6 for a view of a typical robotic FSW cell. The sources of savings going from GMAW to FSW include:
- Consumables - no wire, shielding gas, electric power
- No need for a fume exhaust system.
- Reduction in weld defects, which reduces repair and scrap costs.
- Weld speeds increased 2X over standard GMAW.

The cost of the robotic FSW system is higher than replacing the present GMAW system with a robot by about 20%. In addition, the fixturing required to resist the large FSW forces will cost 30-50% more. Both of these are onetime costs, which are quickly offset by the savings identified above

SUMMARY

FSW is a lean, mean, and green joining technology that offers numerous benefits for joining aluminum over competing processes. Advantages include reduced cost, improved quality and more flexibility. The transportation industry (automotive, trucks, boats, airplanes, trains, etc.) and the general fabrication market have numerous applications prime for exploitation of FSW and FSSW. Some applications can have FSW substituted readily while others may require design changes to take full advantage of FSW. FSW is not a magic solution, but if one truly Designs For Manufacturing (DFM), the chances for success will be much higher. Organizations exploiting FSW have found that the implementation of FSW is well worth any changes that may be required, and that costs can be dramatically reduced beyond what was originally envisioned.
The advent of industrial robotic FSW systems now allows the fabricator to realize the benefits of FSW and associated processes like Friction Stir Spot Welding and Friction Stir Processing for many more applications. Prior to the availability of robot solutions, custom-built FSW machines were required. The capital expense and lack of productivity associated with these early solutions did not allow FSW to provide an acceptable Return on Investment in many cases. This hurdle has now been overcome.

Figure 1 - Basic Principles of Friction Stir Welding
Figure 2 - FSSW Process

Figure 3 - Robotic FSSW
Figure 4 - Typical FSW Optimum Joint Types

Figure 5 - Pontoon Boat With Typical Tank
<table>
<thead>
<tr>
<th>Industry Category</th>
<th>Specific Application</th>
<th>Present Process</th>
<th>Advantages of FSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>Heat sinks-welded laminations</td>
<td>GMAW</td>
<td>Higher density of fins-better conductivity</td>
</tr>
<tr>
<td>Electrical</td>
<td>Cabinets, enclosures</td>
<td>GMAW, RSW</td>
<td>Reduced cost, Weld through corrosion coatings</td>
</tr>
<tr>
<td>Batteries</td>
<td>Leads</td>
<td>Solder</td>
<td>Higher quality</td>
</tr>
<tr>
<td>Military</td>
<td>Shipping Pallets</td>
<td>GMAW</td>
<td>Reduced cost</td>
</tr>
<tr>
<td>Extrusions</td>
<td>Customized extrusions</td>
<td>Not done today</td>
<td>Can customize, reduces need for large press</td>
</tr>
<tr>
<td>Boats</td>
<td>Keel, Tanks</td>
<td>Rivet, GMAW</td>
<td>Stronger, Less Distortion</td>
</tr>
<tr>
<td>Golf Cars, Snowmobiles</td>
<td>Chassis, Suspension</td>
<td>GMAW</td>
<td>Less distortion, Better fatigue life</td>
</tr>
<tr>
<td>Tanks, Cylinders</td>
<td>Fittings, Long &amp; Circum Seam</td>
<td>GMAW</td>
<td>Higher quality - less leaks, higher uptime</td>
</tr>
<tr>
<td>Aerospace</td>
<td>Floors, wing spars</td>
<td>Rivets</td>
<td>Higher quality, cheaper(no rivets &amp; holes)</td>
</tr>
</tbody>
</table>

Table 1 - Typical Applications for FSW