FSW Stirs Up Welding Process Competition

Friction stir welding is making fabricators take a closer look at welding costs and quality relative to traditional welding processes.

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A relatively new process called friction stir welding (FSW) is making inroads in manufacturing, especially in Europe and Japan, to reduce production costs and improve quality. We will first look at process basics and how they compare to conventional welding, then, see how FSW is being used in fabricating a structural component for the Panoz Esperante.

FSW BASICS

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

FSW is inherently simple, with few variables. A non-consumable, rotating FSW tool with a specific geometry is plunged into, and traversed through, the material (Figure 1). The tool's key components are the shoulder and pin (probe). During welding, the pin travels in the material, while the shoulder runs 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

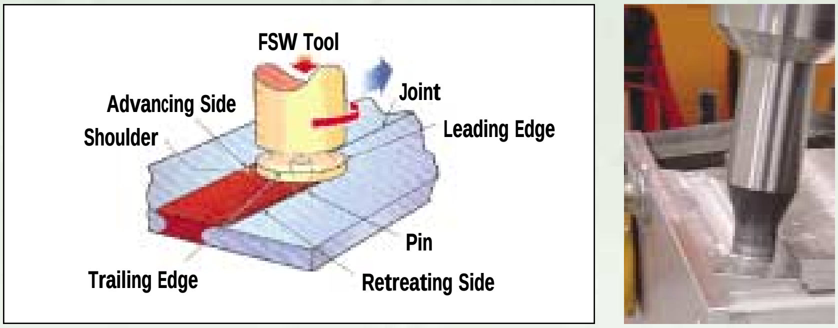

Figure 1. The diagram on the left details the FSW process. A weld being made is shown on the right.

material to be transferred across the joint line. Process variables are rotation and travel speeds, and tool design, orientation, and position. Once these parameters are selected, this simple process makes high-quality, repeatable welds.

Given that the process uses a moving tool, the process is flexible. It can be used to weld many different joint configurations. It also welds in any orientation, e.g. flat, vertical, three o'clock, and overhead, because gravity has no effect on the process. Process simplicity provides operating cost advantages. Because the process does not generate high temperatures that cause extensive melting and metal flow, it offers quality advantages over traditional fusion joining methods.

Cost advantages occur because consumables (gas, wire, or fasteners) are not required; there is less repair and rework; little-to-no material preparation; and no need for environmental protection because there are no fumes or spatter. Quality-related advantages include weld geometry and penetration consistency, improved yield and tensile strength, and improved fatigue life. This process also avoids many of the problems associated with traditional processes. Typical fusion welding problems include poor weld penetration, low weld-zone mechanical properties, poor welding uptime, propensity for weld cracking, and excessive distortion. Quality improvements are more obvious in harder to join materials, such as 2XXX- and 7XXX-series aluminum.

Other than the linear process described above, there is one major process variant that is very effective in many applications. This is friction stir spot welding (FSSW). FSSW involves only plunging and retracting the FSW tool. The traverse part of the process is eliminated. Some friction stir spot welds are shown in Figure 2. FSSW mimics resistance spot welding (RSW) and can, in many applications, replace RSW, riveting, or other single-point joining processes.

Figure 2. A sample of FSW spot welds

Resistance spot welding, toggle-lock, rivets, and self-piercing fasteners are the primary methods used today for single-point joining. RSW issues include: 1) the need to chemically clean the aluminum within eight hours of welding, 2) excessive electrode alloying resulting in poor welds, and 3) long cycle time because extra weld cycles are needed to compensate for process variability. Issues when riveting include: 1) fastener costs, 2) potentially higher downtime due to feeding issues, and 3) need for other operations (e.g. drilling) for rivets that are not self-piercing. Processes in which metal is joined by expanding material from one piece into the next are simple and cheap, but have less strength than RSW, especially in the tensile direction. In addition, they experience high die wear, which can lead to further degradation of mechanical properties, unless frequent preventative maintenance is performed.

In FSSW there are no consumables. The tool has excellent life and is not mated to a die, so preventative maintenance is not as difficult. Process speed is competitive with RSW but more consistent because FSSW is not as sensitive to changing material conditions, e.g. oxides, and surface conditions, contamination.

FSW can be used in a variety of joint configurations (Figure 3), but is not capable of performing welds in the T-fillet joint configuration commonly used in many arc welding operations.

APPLYING FSW

There are many applications for FSW, especially in the aluminum fabrication industry. Any application that is currently riveted, toggle-locked, or spot welded by RSW can often be replaced by FSSW.

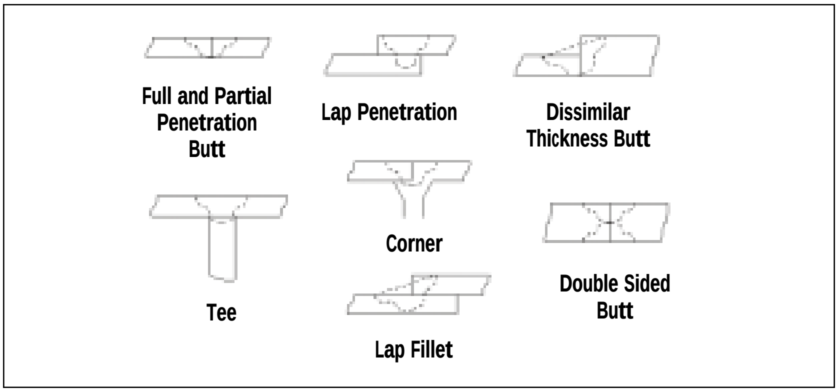

Figure 3. Weld joints possible with FSW

Many gas metal arc-welded (GMAW) products can also be friction stir welded. However, high force requirements, the need to support the part, and common use of T-fillet joint configurations often require design changes to take advantage of FSW. Before implementing it into operations, industries using FSW are performing design for manufacturing (DFM).

Many FSW applications are in joining aluminum, but other materials can also be joined including, but not limited to, magnesium, copper, lead, titanium, and steel. Material thickness can range from 0.5 to more than 50 mm.

An aluminum automotive structural part was redesigned to permit FSW and avoid the issues associated with traditional joining processes. It involved fabricating a chassis part for the Panoz Esperante front and rear ends. FSW replaced the existing arc welding process, which was not as cost effective or consistent as desired.

The existing aluminum arc-welded structure is shown in the lead

Figure 4. The chassis part used to test the FSW process

photo. During initial testing of a GMAW-welded joint, welds failed prematurely. In order for the component to meet strength requirements, steel reinforcements had to be added and the welding process changed to GTAW. This added more labor and processing, including riveting and adhesives, to join the steel reinforcements to the aluminum structure.

To overcome these problems, a project was initiated to replace the arc-welded structure with a friction stir-welded structure. It was believed the structure could be redesigned to eliminate reinforcements and reduce overall cost. One goal was to minimize number of parts, weight, and cost. To help minimize cost, further goals were to use only extrusions or other available material, and minimize the need for machining. The part was also designed for FSW, with the following considerations:

- FSW joint configurations are different: Use lap penetration or lap fillet joint configurations versus the T-fillet joint configuration
- FSW requires significant forces: Parts and fixturing must be designed to accommodate these forces, in one of two ways: (1) design parts and weld joints to allow access for supporting (backup) fixturing, and (2) if parts could not be designed for backup fixturing, they were designed to be self-supporting.

Following these considerations, the part was redesigned (Figure 4). At the part's right side are two angled extrusions. Extrusions replaced a flat plate. The two angled extrusions are joined via a lap penetration weld through the flange to the extruded tube and a partial penetration butt weld between the extrusion's corner and end of the tube. Support for high forces during friction stir welding is accomplished via a simple expandable mandrel in the end of the tube.

There is another extrusion on the left side. Because of bolt-hole location, the concept used on the right side could not be used on the left. An extrusion had to be designed to cover the end of the tube. This made for a more challenging joining condition, as it blocked access for the supporting fixture. To overcome this, the extrusion was designed so there is a supporting rib that extends into the tube to provide support for lap penetration welds on the flanges.

A fourth extrusion (angle) was designed to reinforce the other two sides at the right end. This was required because the part's right end experiences more severe loading than the left. This reinforcement was designed to distribute loads through to the end plate more effectively. To determine the redesigned part's effectiveness, it was tested for strength in the same test apparatus as the arc-welded version. Final results showed:

- The first friction stir-welded component reached a failure load of 2.5 times the GMAW component without reinforcements.
- The initial friction stir-welded component attained a strength that was 20% less than the arc-welded version with all the reinforcements. However, the friction stir-welded version did not have steel reinforcements and the failure was in the parent material, not in the welds.
- The final friction stir-welded component attained failure strength at least 20% greater than the arc-welded, steel-reinforced component. Actual failure strength is unknown, because the test fixture yielded before the friction stir-welded component.

IMPLEMENTING FSW

Implementing FSW can be accomplished by several means. Until recently, due to the forces required for the FSW process, custom-built FSW machines could be considered only for production solutions. However, with the advent of industrial robots with higher force capabilities, industrial robot use is now possible. For custom-built machines, different solutions could be considered—a single- or a multi-axis machine. For robot solutions, a large payload robot is required. Industrial robots allow for capital cost reductions, productivity improvements, and flexibility required to justify FSW in many applications.

This particular application has 10 welds in a relatively small area, with welds on surfaces with four different orientations. Based on these characteristics, this application would favor equipment that can weld in different orientations and positions. This would suggest using a multi-axis machine. A single-axis machine would require 10 different setups, requiring undesirable, non-value added, operator intervention between each weld. This would reduce productivity and add significantly to the part's cost.

Comparing a custom-built, multi-axis FSW machine and an industrial robot solution, both provide similar flexibility and productivity capabilities. However, the industrial robot solution is more cost effective, but the robot is limited in the material thickness range it can weld. For this particular application, material thickness is in the less-than ¼″ (6 mm) range. Thus, a robot could be used for this application, making a custom-built machine an unnecessary capital expense. Before proceeding further, a cost study is performed to see if FSW is more cost effective compared to GMAW.

COMPARING COSTS

To determine if FSW is acceptable in an application, one of the most important decision points is the result of a cost analysis. Cost analysis output is typically part cost or weld cost per distance. Initially, analysis inputs are limited to costs that are well defined or easy to obtain. Known cost inputs are capital equipment and labor costs, and consumables, including FSW tools, electricity, shielding gas, weld wire, and contact tips. Several other cost inputs can have significant impact, including maintenance, production uptime, rework, scrap, and repair.

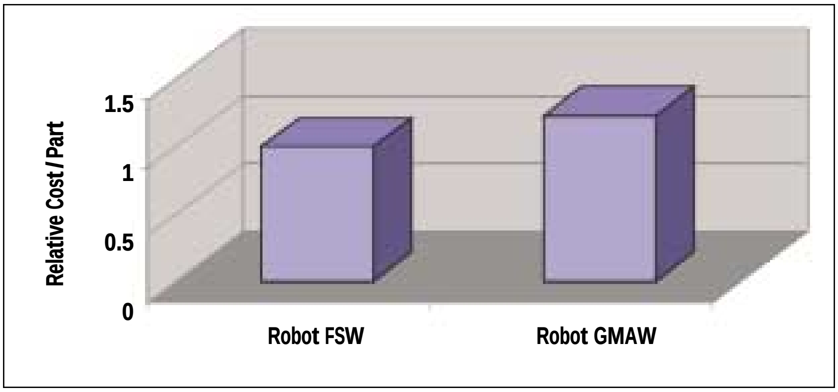

Figure 5. Comparison of FSW and GMAW costs

However, since these costs are application dependent and require significant production experience, they are initially assumed to be the same as the competing technology. Once enough experience with the new technology has been achieved, these inputs can be included.

To do the cost analysis, the friction stir-welded component will be compared to the GMAW component. The cost of welding the redesigned part with GMAW will be compared with FSW costs of the redesigned part, keeping in mind that reinforcement costs make the comparison favor FSW. For the purposes of this study, the application is assumed to have the following characteristics:

- Three fixtures to make 10 welds (one sub-assembly, two final assemblies)
- Cycle time about 2.5 minutes
- Two-shift operation
- Seven-year model cycle
- 80% uptime
- Productive time of 87.5% (one hour out of eight-hour shift is for breaks)

In the analysis, the following capital equipment is assumed: FSW robot system (industrial robot), and GMAW robot system (industrial robot).

In general, capital equipment cost for a FSW robot system is about the same as a GMAW robot system, though individual component costs may differ. For FSW, the robot and fixturing have a cost penalty because a larger robot is required. These costs are offset by the need for ventilation equipment, more safety equipment, and more positioners when welding aluminum with robotic GMAW. Welding equipment cost is about equal in both processes. Individual welding equipment components (wire feeder, power supply, regulators, torch cleaners, etc.) for GMAW typically cost less than those components for FSW (spindle and power supply), but GMAW requires significantly more pieces of equipment.

For the cost analysis, these additional assumptions are made:

- A cellular type solution is assumed, with one operator to load and unload parts.
- For the robot systems, it will be assumed a turntable positioner will be used, where welding can be performed in one set of fixtures, while parts are being loaded and unloaded in another set of fixtures to optimize productivity.
- There are three fixtures on each side of the turntable (not all welds can be reached with one fixture setup)
- FSW weld starts require more time than GMAW starts, but FSW ends require less time than a GMAW end. Weld start and stop times for both processes are assumed to be approximately equivalent.
- Weld travel speed is 40 ipm (1 m/min).

Using these inputs, welding cost per part is calculated. The bar chart (Figure 5) shows welding cost per part, with relative results of each particular solution. Costs are normalized to FSW cost, where FSW cost is set to 1.0. FSW is a more cost-effective solution if the industrial robot is used. FSW provides a 20% reduction in cost over GMAW. Although the capital expense associated with GMAW and FSW robotic solutions is about equivalent, the FSW robotic solution achieves a lower welding cost due to significant reduction in FSW consumables costs.

Of course, this is just one scenario, and several of the inputs can significantly affect the cost for any particular application. The most significant application characteristics that may affect the actual cost of the application are:

Duty cycle: Higher duty cycles will favor FSW, due to consumable cost difference. Applications with longer welds favor FSW; many short welds, GMAW.

Cost of repair and rework: Although assumed to be zero for this cost analysis, repair and rework costs may dramatically affect cost analysis results and highly favor FSW due to process robustness.

Downtime: Cost due to higher downtime or lower costs due to improved downtime may also significantly affect cost. This will favor FSW in most applications.

Fixturing: Cost of fixturing can be significantly higher for FSW, since FSW requires significant forces that fixturing must support. This is especially true if FSW is used for final assembly. FSW is more suited to sub-assembly type operations, where fixturing size and costs can be controlled.

CONCLUSIONS

The advent of industrial robotic FSW systems now allows fabricators to realize the benefits of FSW in many more applications. Prior to the availability of robots, custom-built FSW machines would have been required. The capital expense and/or lack of productivity associated with these early solutions would not allow FSW to provide cost reductions required to justify the use of the process.

Some applications can have FSW substituted, e.g. applications currently using RSW and riveting, 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 and considers FSW characteristics, the chances for success will be much higher. ❐

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