Friction Stir Welding For Ship Construction

Kevin J. Colligan
Concurent Technologies Corporation

Enables Prefabricated, Stiffened Panels with Low Distortion

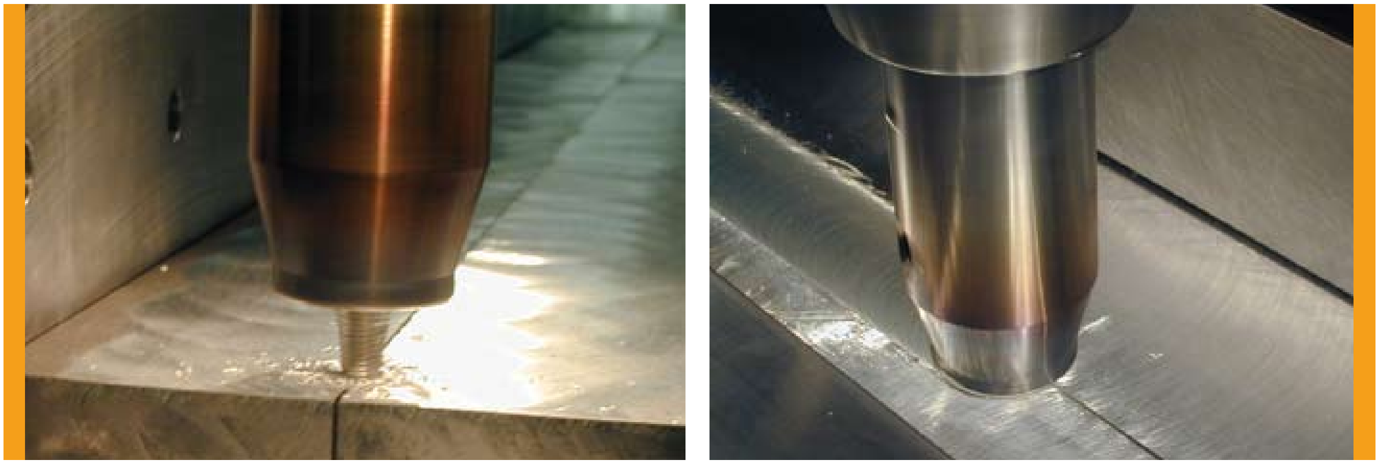

Figure 1. Welding tool plunge (left) and traverse (right).

Abstract

Aluminum alloys are relatively difficult to weld primarily due to aluminum's high thermal conductivity and the formation of defects during welding including porosity and solidification cracking. In shipyards that perform aluminum construction, much of the welding is done manually using gas metal arc welding (GMAW), otherwise known as metal inert gas (MIG) welding. Friction stir welding (FSW) is a relatively new joining process that has been demonstrated in a variety of metals, such as steel, titanium, lead, copper, and aluminum. The process is especially advantageous for joining aluminum and has been exploited commercially around the world in several industries. The unique properties of friction stir welds make possible some completely new structural designs with significant impact to ship design and construction. Improvements in construction cost, durability, and welding distortion have been demonstrated in Europe and Japan and the process is now becoming more widely accepted in the United States. However, it is up to naval architects to incorporate this new method of construction into their designs to take advantage of the benefits of FSW.

Background

Friction stir welding (FSW) is a solid-state joining process that was invented in 1991 at The Welding Institute in the United Kingdom (Thomas, 1994). The process works by plunging a rotating, non-consumable welding tool into the joint, then traversing the rotating tool along the joint, as shown in Figure 1, and schematically in Figure 2. Most remarkably, friction and plastic work provide all of the heat for the process, which is sufficient to soften the workpiece to just below the melting point, allowing the tool to "stir in" the joint surfaces. The process is especially well suited to butt and lap joints in aluminum since aluminum is difficult to weld by arc processes, but is very simple to weld by FSW. The process is carried out in aluminum without filler metal or shielding gas, and full-penetration butt welds can be made in aluminum from 0.02" thick up to as thick as 3" in a single welding pass. Different alloys of a like base metal can be welded to each other, such as 6061 aluminum to 5083 aluminum, and welds can easily be made to join wrought plate, forgings and castings to each other.

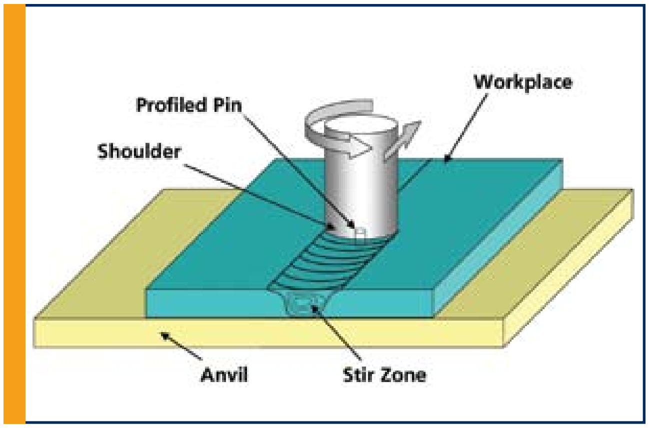

Figure 2. Schematic of the friction stir welding process.

The unique characteristics of FSW make fundamental changes in joining and processing methods possible. Since FSW operates at a much lower temperature than traditional arc processes, the residual stress and distortion are typically very low. This characteristic makes it possible to prefabricate stiffened panels that are dimensionally accurate, with implications for several industries. In addition, the FSW process produces an extremely fine grain structure, giving the stir zone unique deformation characteristics compared with other welding processes, and making it ideally suited for applications where impact damage is a concern. An extension of FSW called friction stir processing (FSP) has allowed researchers to generate desirable microstructure in specific areas of a workpiece, as opposed to using the process for joining, in order to produce localized changes in properties. These aspects of the process will be discussed below.

Friction stir welding is a fully mechanized process. The forces generated by the process are high enough that hand-held operation is not possible, except possibly for very thin materials, so the workpiece is generally constrained by a welding fixture during welding. This makes the equipment cost much higher for FSW than for most traditional fusion welding processes, but the labor cost is generally lower and the weld quality is much more consistent. Although equipment cost is certainly a barrier to widespread use of the process, the reduction in the need for skilled labor is a large selling point for the process, especially in the shipyard setting where maintaining skilled labor can be a challenge.

The high cost of FSW equipment and the relative newness of the process make it impractical for most shipyards to establish and maintain an in-house capability, but there are two FSW service providers in the United States that can construct FSW weldments and transport them to shipyards. Advanced Joining Technologies, located in southern California, and Friction Stir Link, located in Wisconsin, both specialize in welding components for various industries, including shipbuilding, as will be discussed below.

Implications of FSW for Ship Construction

The traditional method of stiffening bulkheads, decks, and hulls is to use arc welding techniques to fillet weld extruded shapes to plate materials, as shown in Figure 3. This method of construction is optimum for arc-welded construction since it reduces the number of full penetration welds, which in turn reduces labor costs and distortion. However, since FSW produces dramatically lower distortion in most welding situations, there isn't a need to avoid butt welds, and since the process is fully mechanized, labor cost is minimized. As a result, the optimum method for FSW Construction is to butt weld extruded shapes to build up stiffened panels. Since distortion is low, the welding to build up the panels does not have to be carried out on the ship as it is being built – it can be done as a pre-fabricated subassembly, then cut to fit as required for installation.

The utility of pre-fabricating integrally stiffened panels should not be underestimated. Shipyards often have difficulty maintaining staff for arc welding aluminum due to the skill required to manually make high-quality welds. If generic panels can be purchased from a subcontractor or fabricated in-house on an automated machine, there can be a significant reduction in the amount of manual welding that must be carried out. This reduces labor costs, reduces staffing requirements, and if planned correctly, reduces the time that a ship under construction is occupying floorspace. In addition, the reduced defect rate, the elimination of welding consumables and the improved panel smoothness all contribute to the case for using FSW in the fabrication of stiffened panels. Further, since less arc welding is required, fume emissions in the shipyard can be significantly reduced.

The benefit of FSW to ship construction was demonstrated relatively quickly after its invention. In Norway, Ole

Table 1. Chronology of Production Applications for FSW through 2004.

Year	Application	Company
1995	*Hollow heat exchangers	Marine Aluminum, Norway
1996	*Commercial shipbuilding	Marine Aluminum, Norway
1998	Delta II rockets	Boeing, US
1999	*Commercial shipbuilding	SAPA, Sweden
2000	*Automotive components	SAPA, Sweden
2000	Laser system housings	General Tool, US
2001	*Motor housings	Hydro Aluminum (formerly Marine Aluminum), Norway
2001	*Automotive components	Showa, Japan
2001	*Train bodies	Hitachi, Japan
2002	*Automotive components	Tower Automotive, US
2003	Aircraft structure	Eclipse, US
2003	*Commercial shipbuilding	Advanced Joining Technologies, US
2004	Space shuttle external tanks	Lockheed Martin, US
2004	Food trays	RIFTEC, Germany

*Denotes welding of extrusions

Midling of Marine Aluminum, a producer of extruded aluminum shapes, realized very early on that FSW offered the opportunity to economically join extruded shapes to make very large, integrally stiffened panels, primarily for use in shipbuilding (Midling, 1998). In fact, a look at the history of production implementation of FSW, shown in Table 1, shows that the majority of production applications have involved joining extruded shapes to make some useful product. The method has been repeated many times in Europe and Japan, and is beginning to be more accepted in the U.S. This approach has allowed some extrusion companies to expand their operations to include more value-added products, and has allowed them to compete with extruders with greater extrusion capacity.

It is also possible to FSW materials such as steel and titanium, but due to the higher melting point in these materials, welding tool life and cost is currently an issue for use in high-volume production. In spite of this current limitation, the benefits of low distortion and improved strength that have been widely documented in aluminum alloys have also been observed in titanium and steel welds. As new welding tool materials and designs are perfected for these high melting point materials, FSW of steel for shipbuilding applications will become more practical. In addition, since FSW is accomplished without the addition of filler wire, there is the potential for significant benefit in the welding of high-strength steels, where no matching filler wire materials currently exist, or where they are prohibitively expensive.

As mentioned earlier, friction stir welding generates a fine-grained microstructure in the stirred material, which when exploited for its own desirable characteristics is referred to as friction stir processing (FSP) (Mishra, 2000). For example, this has been demonstrated on a recent program funded by the Defense Advanced Research Project Agency for repairing casting defects in Navy propellers (Palko, 2003). It was found that in addition to healing large, surface-breaking porosity in nickel aluminum bronze propellers, FSP was able to approximately double the yield strength of the material while still maintaining good ductility. Friction stir processing is a relatively new area of research, and it is likely that other applications for modifying the microstructure or composition of materials will be developed as time goes on.

Implications of FSW for Ship Design

The strength of stir welded joints in aluminum compare favorably with arc welded joints. Representative values of stir welded joint properties compared to the requirements in ABS High Speed Craft Rules are shown in Table 2. For

Table 2. Base metal and GMAW strength requirements, with typical FSW tensile properties for welded aluminum materials.

Alloy	Joint Type	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (2-in gauge, %)
5456-H116	Base Metal	48, min	33, min	12, min
5456-H116	GMAW	42, min	26, min	no requirement
5456-H116	FSW (Fonda, 2004)	52.6	25.6	not reported
6061-T6	Base Metal	42, min	35, min	10, min
6061-T6	GMAW	24, min	20, min	no requirement
6061-T6	FSW (von Strombeck, 1999)	36.5	23.4	7.2

non-heat-treatable aluminum alloys, such as marine-grade 5083 and 5456, welded joints produced by arc welding and stir welding have about the same strength, with stir welded joints typically having slightly lower yield strength and slightly higher ultimate strength than arc welded joints. As a result, joint strength is not typically considered a significant advantage for stir welding in non-heat-treatable alloys. However, friction stir weld material in non-heat-treatable alloys have been shown to have very high ductility. For example, Charit (2004) reported friction stirred 5083 aluminum having elongation values in excess of 30%. This characteristic makes the process ideal for areas of a ship where structural integrity upon impact is a critical factor. For heat-treatable alloys, stir welded joints typically have higher yield and ultimate strengths, primarily due to the lower welding temperature and the fact that stir welding is carried out without the addition of filler wire. The ductility of stir welded joints in heat-treatable alloys can be significantly higher than arc welded joints, but natural aging in the stirred material can lead to strain localization, meaning that transverse ductility in heat-treatable alloys is typically lower than that observed in non-heat-treatable alloys. Based on these general trends, the improvement in joint strength can be a factor in the decision to use FSW in heat-treatable alloys and the improvement in ductility can be a performance advantage in non-heat-treatable alloys. However, in all cases FSW offers joint strength that is at least as good as arc welded joint strength in aluminum alloys.

One of the most immediately observable differences between friction stir welded panels and arc welded panels is the smoothness of the root side of friction stir welds. In conventional FSW, the side of the welded panel that is against the anvil during welding generally ends up being completely smooth after welding. After painting, it is common that the weld locations are visually undetectable on the root side of the panel. The excellent cosmetic appearance of stir welded panels makes it desirable as a method of construction where one side is exposed to view. To approach the same level of visual quality in arc welded construction, it is necessary to manually grind and polish the back side of every panel where stiffeners are attached, adding to labor costs.

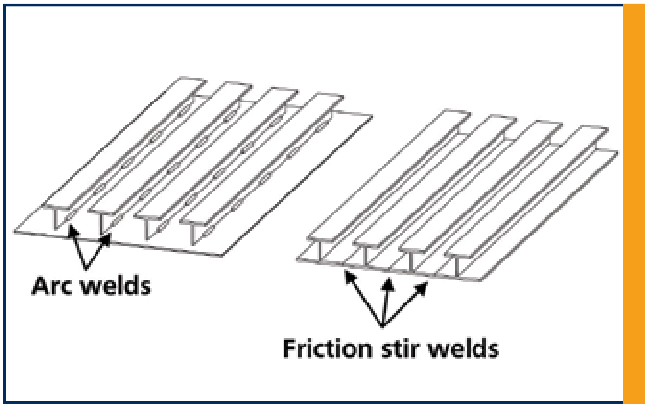

Figure 3. Sketch of arc welded construction vs. stir welded construction.

No documented studies compare the load capacity or stiffness of the two methods of construction shown in Figure 3. Since the two methods of construction locate the welds in different areas, the comparison of joint strength alone doesn't predict relative performance between the two methods. However, it is likely that the two construction methods have similar static stiffness, strength and buckling characteristics for equivalent geometry, so load carrying characteristics may not be a factor in choosing welded construction over arc welded construction, especially in non-heat-treatable alloys.

FSW is an enabling technology for the construction of low-distortion, prefabricated, stiffened panels. The process also makes practical the use of twin-wall, hollow extrusions made from 6xxx-series aluminum alloys. Due to the excellent extrudability of 6xxx alloys, very thin walled, intricate extrusions with high dimensional accuracy can be obtained from a number of domestic sources. Hollow extrusions have been used in Europe for a number of shipbuilding projects, but the only use of this type of construction in the United States so far has been on the FSF-1 "Sea Fighter." Custom designed, extruded nodes can be stir welded or arc welded to join hollow or single-wall stiffened panels, as shown in Figure 4, making new structural arrangements possible.

An alternative approach is currently under development by the Navy Metalworking Center (NMC), operated by Concurrent Technologies Corporation. A Navy ManTech Center of Excellence funded by the Office of Naval Research, NMC develops and transitions new metalworking solutions to DoD contractors for the benefit of Navy and Marine Corps weapons systems. A project was recently initiated to address the high cost of friction stir welding equipment by developing a fundamentally new type of welding system that dramatically reduces the cost of the equipment. In doing so, this new equipment will remove a barrier to the widespread use of FSW for aluminum construction, thereby making it possible to realize the cost savings and performance improvements that are possible with FSW in the shipyard environment.

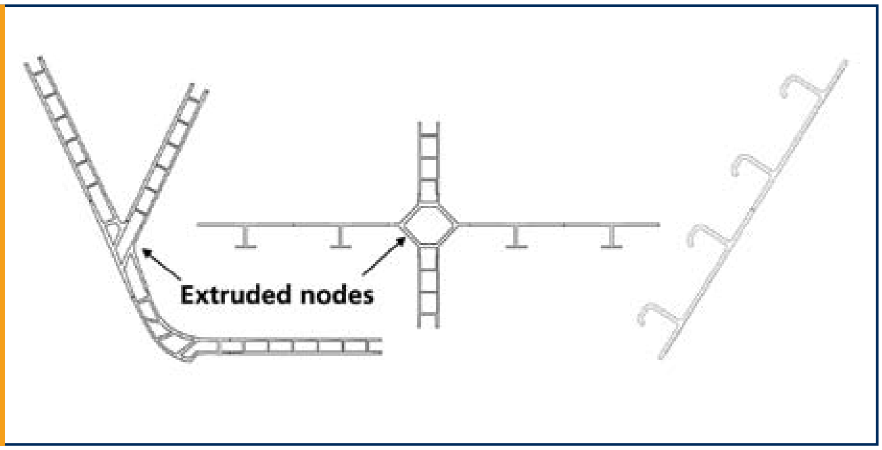

Figure 4. Examples of construction using stir welded extrusions.

FSW Use in the United States

As mentioned above, due to the cost of FSW equipment no domestic shipyards have in-house FSW equipment at the time of this publication, so projects that employ FSW have relied on the two U.S. subcontractors and suppliers in Europe to provide prefabricated stiffened panels. To date, a total of eight shipbuilding projects using stir welded panels have been completed by these two suppliers, producing over 30 miles of stir welds in 5xxx and 6xxx alloy extrusions. These projects have been completed by fabricating panels that are about 8-feet wide by 20-feet long and transporting the panels by truck to the shipyards, in some cases over long distances. Once at the shipyard, these panels are manually arc welded as the ship is assembled.

Conclusions

Friction stir welding is a relatively new method for joining metals, but it has rapidly been exploited in a number of industries. One of the most common modes for the use of FSW to date has been to take advantage of FSW's characteristically low distortion and join extrusions into dimensionally accurate assemblies for various transport structures. In the shipyard, the use of prefabricated stiffened panels made by FSW has been shown to reduce the burden of maintaining highly skilled aluminum welders. The exceptional flatness of the prefabricated panels and the extremely smooth root-side surface of the panels contribute to the superior appearance of the finished product. The unique characteristics of the process also make possible new structural arrangements, such as twin-wall construction for various applications.

The Navy Metalworking Center is initiating a project to develop very low cost FSW equipment for the purpose of joining extrusions into stiffened panels for shipbuilding or other applications. This equipment may be operated by FSW service providers or by the shipyards themselves. It is expected that the availability of low cost FSW equipment will lead to the accelerated adoption of this process for DoD and commercial products.

Acknowledgements

The author would like to acknowledge the contributions to this paper made by Mr. Douglas Waldron of Advanced Joining Technologies (3030 Red Hill Ave., Santa Ana, California 92705, 714-812-4320) and Mr. Christopher Smith of Friction Stir Link (W227 N546 Westmound Drive, Waukesha, Wisconsin 53186, 262-522-6680).

References

Charit, I., and R. S. Mishra, "Evaluation of Microstructure and Superplasticity in Friction Stir Processed 5083 Al Alloy," J. Mater. Res., Vol. 19, No. 11, Nov. 2004.

Fonda, R. W., P. S. Pao, H. N. Jones, B. J. Connolly and A. J. Davenport, "Mechanical Property and Microstructural Mapping of Friction Stir Welded Al 5456," International Journal of Offshore and Polar Engineers, 2004.

Midling, O. T., "Industrialization of the Friction Stir Welding Technology in Panel Production for the Maritime Sector," 1st International Symposium on Friction Stir Welding, June 1999.

Mishra, R. S., M. W. Mahoney, S. X. McFadden, N. A. Mara, and A. K. Mukherjee, "High Strain Rate Superplasticity in a Friction Stir Processed 7075 Al Alloy," Script Materialia, 42, 2000.

Palko, W. A., R. S. Feilder, and P. F. Young, "Investigation of the Use of Friction Stir Processing to Repair and Locally Enhance the Properties of Large Ni Al Bronze Propellers," Proceedings, Thermec 2003, Trans Tech Publications, Ltd., July 2003.

Thomas, W. M., E. D. Nicholas, J. C. Needham, M. G. Murch, P. Temple-Smith, C. J. Dawes, "Friction Welding" US Patent 5,460,317, October 25, 1995.

von Strombeck, A., J. F. Dos Santos, F. Torster, and M. Kocak, "Fracture Toughness Behavior of FSW Joints in Aluminum Alloys," 1st International Symposium on Friction Stir Welding, June 1999.

This article was prepared by the Navy Metalworking Center, operated by Concurrent Technologies Corporation (CTC), under Contract No. N0014-06-D-0048 to the Office of Naval Research as part of the Navy ManTech Program. Approved for public release; distribution is unlimited.

NMC Navy Metalworking Center

A ManTech Center of Excellence

www.nmc.ctc.com

Operated by

CTC Concurrent Technologies Corporation

For more information, contact:

NMC Information Services
Concurrent Technologies Corporation
441 Friendship Road, Suite 103
Harrisburg, PA 17111-1204
Phone: 717-565-4405 • Fax: 717-565-4420
e-mail: piastred@ctc.com

4/07