conference preview

FRICTION STIR WELDING

An emerging alternative to fusion welding for steel.

BY ANDREA SUROVEK, P.E., PH.D., AND BHARAT K. JASTHI, PH.D.

IMAGINE WELDING TOGETHER two plates of similar or even dissimilar metals with no electrode, no flux and no melting of the materials. The resulting weld strength meets or exceeds the strength of the base metals and has no defects. It's not an impossible scenario; it's friction stir welding (FSW).

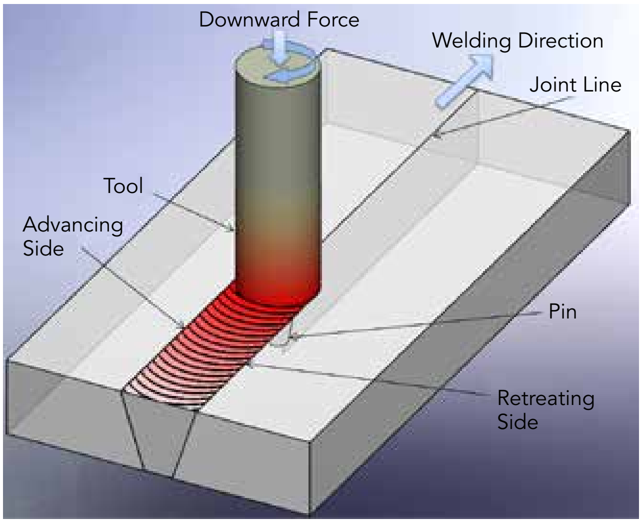
In 1995, the U.S. National Critical Technologies Report called FSW one of the most significant advances in joining technology in the last 50 years. The technique was developed by The Welding Institute (TWI) in the U.K. in the early 1990s to address difficulties in welding aluminum, and the results have allowed for welding of alloys that could previously only be achieved through mechanical means, such as rivets. While most early research focused on low- to medium-temperature softening materials such as aluminum and zinc, the feasibility of FSW of steels was established in the late 1990s and research has continued to advance the capabilities and industrial applications of steel FSW.

What is FSW?

FSW is a solid-state joining process. A rotating tool moves along the joint; this tool is a combination of a pin that penetrates the material and a shoulder that travels over the surface as the "pin tool" traverses along the joint. The underlying principle is the conversion from mechanical energy to thermal energy; the mechanical energy is provided by a rotating, non-consumable pin tool plunged into the abutted edges of the plates to be welded. During this process, heat is generated within the material from both friction between the pin tool and weld material and severe plastic deformation of the material being welded. Temperature may approach, but is unlikely to reach, the melting point of the material. As the pin probe rotates and proceeds in the direction of the weld, the plasticized material is extruded to the back of the tool where it is forged and consolidated under hydrostatic pressure. The intense plastic deformation in this process creates a fully recrystallized, equiaxed and fine-grained microstructure in the weld nugget.

Rather than being a true welding process, FSW is actually a localized extrusion and forging process; however, the resulting weld zone, like fusion welding, does typically form a heat-affected-zone (HAZ). Unlike fusion welding, however, there is also a thermo-mechanically affected zone, which is a partially deformed transition zone between fully reworked and recrystallized material within the weld nugget and heat-affected material surrounding the weld zone.

Also unlike the fusion welding processes, where there are numerous essential variables, FSW requires only three variables for a specific pin tool design: spindle rotational speed,



Schematic of a typical butt joint being created by friction stir welding.

Andrea E. Surovek is an associate professor of civil and environmental engineering at the South Dakota School of Mines and Technology in Rapid City, S.D. She currently chairs the ASCE/SEI Technical Administrative Committee on Metals. You can reach her at **surovek@sdsmt.edu**. **Bharat K. Jasthi** is a research scientist with the Advanced Materials Processing (AMP) Center and is also an adjunct faculty member with the Department of Materials and Metallurgical Engineering at the South Dakota School of Mines and Technology. You can reach him at **bharat.jasthi@sdsmt.edu**.

travel speed and penetration depth of the tool into the material. Penetration depth can be monitored either through load control or displacement control.

It's useful to note that at a prototype level, FSW has been used to manufacture butt welds, overlap welds, T-sections, fillet welds and corner welds in aluminum. The FSW process can also cope with circumferential, annular, non-linear and three-dimensional welds.

Weld setup and pin tool during the FSW process.

Advantages of FSW

Since mild steels used in steel construction, such as A36 and A992, are generally considered to be easily weldable materials, why consider FSW as an alternative? While FSW of steel is still a developing technology, there are a number of advantages of FSW over tradition fusion welding including:

- Improved weld quality
- Application to previously "unweldable" materials and/or dissimilar metals
- Lower cost
- Significantly lower environmental impact

Improved weld quality. FSW has shown simpler processing, higher strength, higher toughness, diminished weld defect formation, more predictable microstructure, lower residual stresses, equivalent corrosion resistance and less distortion as compared to the traditional fusion welding methods. For longer welds and/or in thinner material, where residual stresses are more likely to manifest as significant distortion, this can be particularly advantageous. The primary reasons for the improvement in properties is that FSW produces wrought microstructure, rather than cast (no re-solidified liquid weld pool), with very fine grain size (typically between 1–5 um), significantly less heat input and no liquid-to-solid phase transformations.

Currently, steel welds up to ½ in. are possible with studies showing failures occurring outside the weld nugget region. Defect-free FSW is even possible under water or in the presence of liquid contaminants because the high forging pressures in the weld zone expel any liquids as the tool advances preventing entrapment of contaminants in the weld zone.

Applicability to "unweldable" materials. Dissimilar metals with vast differences in properties, chemical composition and melting temperatures can be successfully joined using the friction stir process. Conventional fusion welding of dissimilar metals leads to detrimental reactions at the joint interface and results in inferior mechanical properties. Since FSW is a solid-state joining process, all the problems associated with fusion welding can be avoided. Aluminum, magnesium and copper can successfully be friction stir welded to steel with bond strengths close to base metals. Similarly, ultra-fine grained steels can be successfully joined using friction stir welding. Fusion welding of these materials leads to grain growth in the nugget region and thus results in inferior mechanical properties.

One example where FSW has been successfully implemented is FSW of oxide dispersion strengthened (ODS) steels. ODS steels are a special class of high-strength alloys that contain fine dispersion of oxide particles. A major challenge when joining ODS alloys is retention of dispersoids and nanofeatures that provide the creep resistance. During conventional fusion welding of these ODS alloys, the fine dispersoids will segregate and rise to the surface of the weld pool and decrease the creep resistance in the weld area. Since fiction stir welding is a solid-state joining technique, the problem of dispersoid segregation seen in fusion welding can be avoided. The primary advantage of friction stir welding compared to other fusion welding technique is the lower heat input and avoidance of problems arising from hydrogen embrittlement and gas entrapment.

Lower cost. A compelling argument for greater development and application of FSW of steels lies in the potential economic and environmental impacts. In 2007, William Arbegast reported (in *Friction Stir Welding and Processing*) that U.S. industry could see a benefit of nearly $5 billion dollars due to the improved weld properties, reliability and environmental benefits of FSW. In the original 1999 study on the feasibility of FSW in steel ("Friction Stir Welding of Ferrous Materials: A Feasibility Study" by W.M. Thomas, which appeared in *Science and Technology of Welding and Joining*) a cost analysis was performed that included both cost of labor and consumables; it determined that a savings factor of three or greater could be achieved with FSW over traditional fusion welding. It should be noted that problems with tool wear have slowed more rapid implementation of FSW in steel, and the cost of tools may prove to limit the cost effectiveness of FSW of steels. As with any developing technology, it is anticipated that the cost of the tools will reduce as the research advances and the technology matures.

Lower environmental impact. Another report by Arbegast ("Friction Stir Welding—After a Decade of Development," which appeared in the *Welding Journal* in 2006), indicated that if 10% of the U.S. joining market were replaced by FSW, there could be a 1.28×10^{13} Btu/yr. energy savings and a 500 million lb/yr reduction in greenhouse gasses. Another advantage is the reduction of hazardous fumes currently produced by arc welding. Carl Sorensen and Tracy Nelson reported (also in *Friction Stir Welding and Processing*) on a side-by-side comparison of arc welding and FSW to determine the hazardous fumes produced by each process. The FSW process produced both hexavalent chromium and manganese well below detectable levels, and in the case of manganese three orders of magnitude below the arc welding process.

Potential for Industrial Applications

Perhaps the most promising application of FSW in steel lies in the potential for joining high-strength or specialty steels, since high-strength steels are being used more and more frequently in structural engineering applications. Significant cost savings have been achieved using higher-strength steels, such as ASTM A913 Grade 65, in numerous building and bridge projects in the U.S, and ultra-high strength steels, such as H-SA 70 (F_y = 700 MPa), are being used in seismic and high-rise construction in Japan. Other common applications include off-shore oil platforms and long-span building structures. While mild carbon steels (e.g., ASTM A36 and A992) are considered easy to weld using conventional arc welding techniques, difficulties in high-strength steel welding remain an issue in construction. Recently, Nucor Corporation has developed a high-strength, low-alloy steel for structural applications. Preliminary studies at the Advanced Materials Processing (AMP) Laboratory at South Dakota School of Mines and Technology suggested that FSW can be used to both retain the microstructure and improve the mechanical properties of these alloys.

Currently, FSW is having an impact on the steel pipe industry. Portable FSW equipment developed specifically to produce orbital welds can now be used for field welding of steel pipe. The reported savings in energy for using FSW is over 80%.

The Future of FSW

While FSW of steel is still a developing technology, its impact on the aluminum industry provides a compelling case for greater development and application with steel. With the development of new materials, the continued application of higher-strength steels, the potential for significant savings in energy and a reduction in hazardous fumes, FSW has the potential to make a major impact on steel construction in the foreseeable future. MSC

This article serves as a preview of Session N45 at NASCC: The Steel Conference, taking place April 17-19 in St. Louis. Learn more about the conference at ***www.aisc.org/nascc****.*