FRICTION STIR WELDING OF STEEL CONNECTIONS

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ABSTRACT

Friction Stir Welding (FSW) is a relatively recent addition to joining technology, having been developed in the early 1990's by The Welding Institute (TWI) in the UK. FSW is a solid state process that has been shown to have many benefits over traditional arc welding, particularly in the areas of joint quality and environmental impacts. While the technology readiness level of FSW of aluminum has reached a stage where it has been employed by multiple industries, most notably in shipbuilding, transportation, and aerospace industries, FSW of steel has not achieved the same level of industrial readiness. FSW remains relatively unknown in the area of civil engineering structures.

This paper will provide an overview of the FSW process with a particular emphasis on current advancements in the area of steel FSW. Examples of joint configurations, materials welded, and resulting microstructures and properties will be provided from the literature and ongoing investigations at the Arbegast Materials Processing and Joining Laboratory, a member of the Center for Friction Stir Processing (CFSP), an NSF Industry/University Cooperative Research Center (I/UCRC), founded by the South Dakota School of Mines and Technology. In addition, the paper will provide potential applications for FSW in the civil engineering / structural arena.

1. INTRODUCTION

Structural steel connections are traditionally comprised of a combination of bolted and/or welded elements. The mild steels used in structural applications are considered to be reasonably easy to weld, whether in the shop or in the field. However, for steel to remain competitive among rapid advances in other materials, including composites, advances in other joining technologies can be examined to establish when special processes may offer an advantage over traditional arc welding.

A workshop on innovations in steel design was held on March 28, 2012 to develop a list of potential innovations and research needs to advance steel design in the new millennium (Surovek and Liu 2012). Example questions that were asked of the participants included:

- What do you see as the most important near future advances in steel design?
- What basic knowledge do we need to advance steel design to the next level of innovation?

- What technologies would help improve steel design?

From the workshop emerged six overarching themes, one of which was the development of novel and/or improved joining methods. Included in the ideas generated on joining methods were new welding methods and reduced requirements for weld inspection. Because weld inspection compromises a large time and labour requirement in construction a method that produces defect free welds could provide significant cost and time saving in construction.

One potential avenue for such advances in steel fabrication and joining technology is friction stir welding (FSW), a solid state welding process originally developed by the Welding Institute for welding aluminum (Thomas et. al. 1991). Early research in FSW focused on metals with low to moderate melting temperatures with an emphasis on aluminum welding. Based on this research and applications of FSW in industry, FSW has been shown to have a number of advantages over traditional arc welding (Arbegast 2006). Friction stir welding is revolutionizing the welding of aluminum in industry (Thomas et. al. 2002), due to allowing welding of alloys that could previously only be joined by mechanical means such as rivets (Dracup and Arbegast 1999).

Research on FSW of steel has primarily been centered on industry driven applications with an emphasis on specialized steel alloys and stainless steels. As the technology becomes more commercially viable, knowledge of its application to traditional structural steels has the potential for application in steel construction; for example, FSW of steel could broaden the potential grades and combinations of steels used in structural applications, because FSW is particularly suitable to join highly dissimilar materials. By expanding options for fabrication of steel members with the potential for increased fatigue strength and a reduction in residual stresses, FSW could provide new avenues for steel construction.

It is also worth noting that one of the four identified discussion areas at the innovations workshop was sustainability. Sustainability and green construction continue to gain ground as being considered necessary advancements in steel construction, so knowledge on construction techniques such as FSW that have reduced environmental impact will be beneficial to the industry as a whole.

2. FRICTION STIR WELDING

The South Dakota School of Mines and Technology (SDSM&T) is home to the Arbegast Materials Processing and Joining Laboratory, a world leader for research and development in the emerging FSW and friction stir processing (FSP) technologies. As one of the founding members of the National Science Foundation (NSF) sponsored Industry/ University Collaborative Research Center (I/UCRC) on FSP, SDSM&T is focused on developing large scale structural applications for FSW as well as design guidelines for structural members fabricated using FSW. The focus of the center to date has been on FSW of both ferrous and non-ferrous alloys and built-up shapes based on industry driven desires and potential military applications. SDSM&T is home to one of the most versatile and capable friction stir weld systems in any academic institution (see Figure 1).

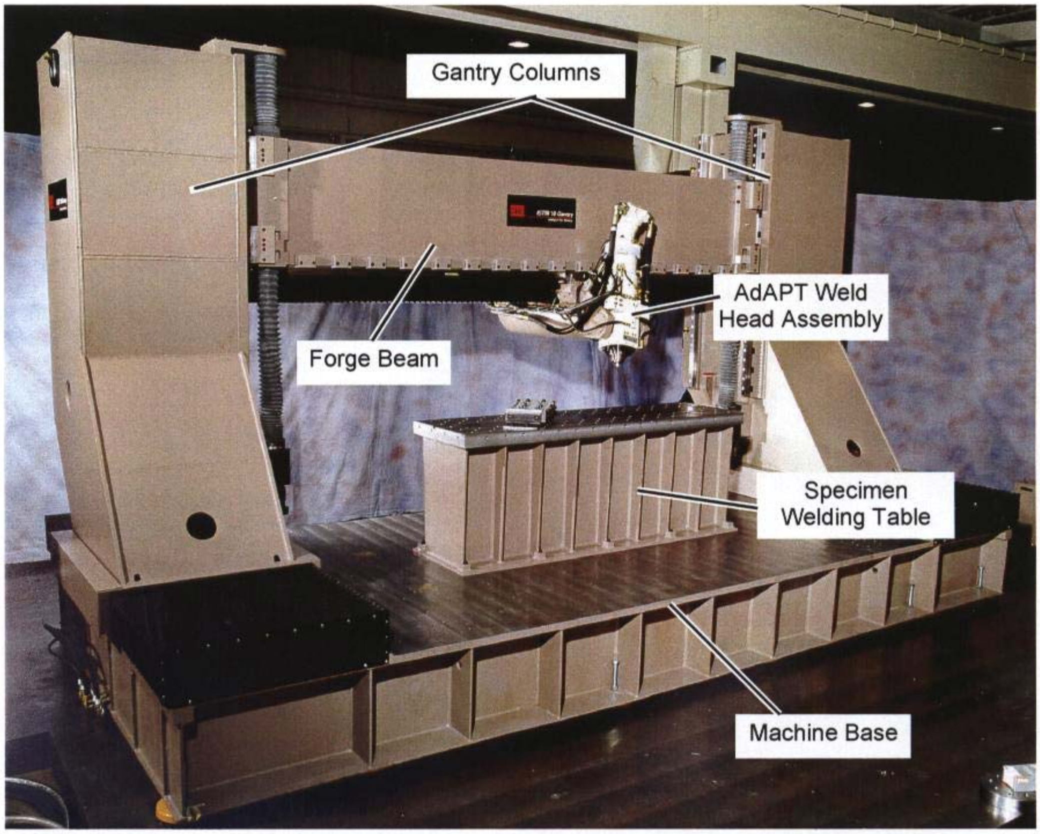

Figure 1. SDSM&T Friction Stir Welding Tool

FSW is a solid state joining process that has been described as one of the most significant advances in joining technology in last fifty years (OSTP 1995). This process uses a rotating tool with a combination of a pin which penetrates the material and a shoulder that travels over the surface as the “pin tool” traverses along a weld joint or simply through the material using modified milling equipment, firm fixturing tooling, and backside supports (weld anvil). The material around the pin tool is frictionally heated, plasticized and extruded/forged to the back of the pin tool where it consolidates and cools under hydrostatic pressure conditions. Since it is a solid-state process, there is no liquid to solid phase change, and all of the defects that are associated with the melting and re-solidification of conventional welding (e.g. hot cracking and porosity) are not present. Creation of a typical butt joint using the friction stir process is shown in Figure 2. A longitudinal diagram of the FSW process showing the metal working steps that the material experiences as tool advances was developed by Arbegast in 2003, and is shown in Figure 3. The figure shows that, rather being a true welding process, FSW is really a localized extrusion and forging process; however, the resulting weld zone, like fusion welding, does typically form a heat-affected-zone, or HAZ, as shown in Figure 4. Unlike fusion welding, though, 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.

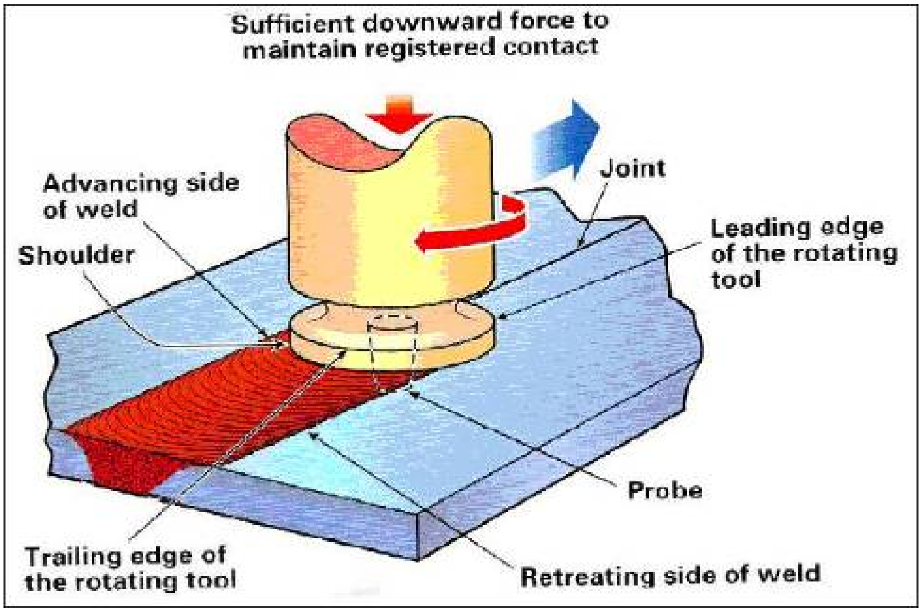

Figure 2. Typical butt joint being created by friction stir welding.

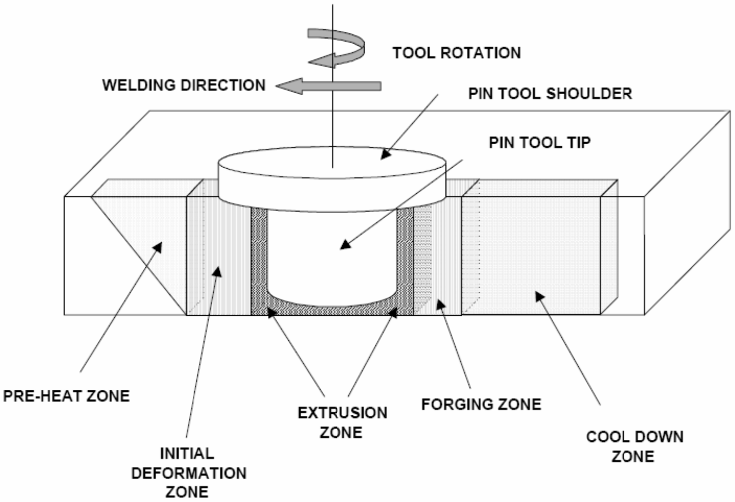

Figure 3. Longitudinal diagram of the FSW process showing the five principle steps in the process (Arbegast 2003).

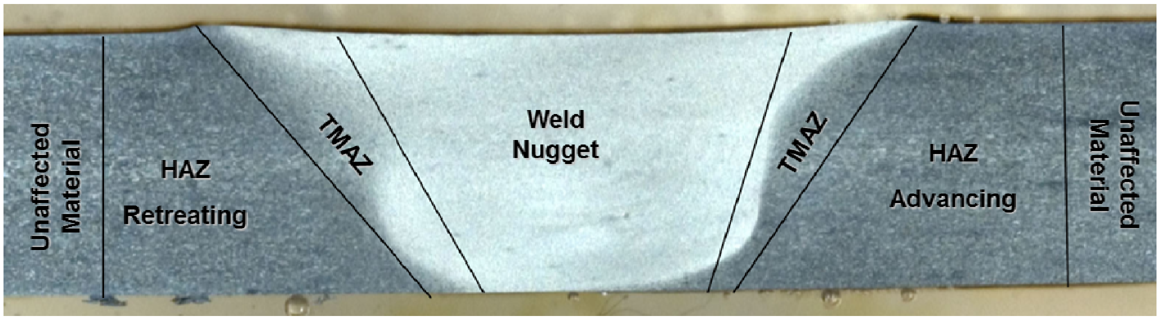

Figure 4. Typical friction stir weld nugget indicating weld zones (shown in aluminum).

At a prototype level, FSW has been used to manufacture butt welds, overlap welds, T-sections, fillet, and corner welds in aluminum (see Fig. 5). The FSW process can also cope with circumferential, annular, non-linear, and three-dimensional welds. Since gravity has no influence on the solid-phase welding process, it has been successfully demonstrated for use in all positions including horizontal, vertical, overhead and orbital. The potential to develop complex structural shapes can be seen in Figure 6, in which the stiffened shape has been fabricated with friction stir welds on three sides and in multiple orientations. 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.

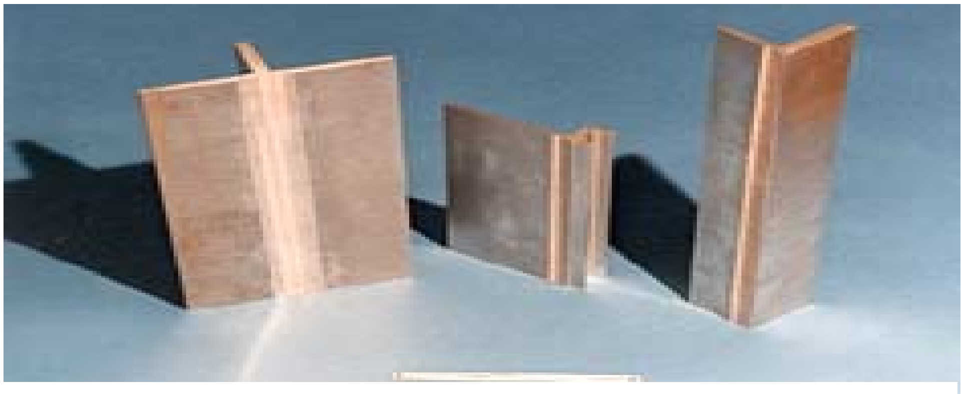

Figure 5. Typical Friction Stir Weld Joints in Aluminum

FSW has shown simpler processing, higher strength, higher toughness, fewer weld defects, more predictable microstructure, lower residual stresses, and less distortion as compared to the traditional methods (Arbegast and Hartley 1998). 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 changes. It has become an accepted replacement technology for fusion welding (VPPA, GTAW, GMAW) of aluminum alloys because the process allows the welding of previously un-weldable aluminum alloys, like 2XXX and 7XXX series alloys, and even dissimilar alloy welding. Traditionally, these alloys have found use only in mechanically joined structures (Dracup and Arbegast 1999). Friction stir welding is considered to be revolutionizing the welding of aluminum in industry (Thomas et. al 2002). FSW can weld aluminum alloys, as well as welding combinations of wrought, extruded and cast alloys that have not previously been possible.

The impact of FSW on the aluminum industry presents a strong argument for greater development of FSW of steel. Basic research and applications research has reached the point in Aluminum FSW that it is being actively used in industrial applications. Examples of industries currently using FSW of aluminum include aerospace, civil aviation, shipbuilding, railroad, bridges, automotive, and architectural.

Figure 6: Front, side and rear views of a fabricated shape using multiple orientations of friction stir lap welds (location of welds indicated by arrows).

3. FRICTION STIR WELDING RESEARCH ON MILD STEELS

The earliest research in FSW was focused on low to medium softening temperature metals, such as aluminium, lead, magnesium and zinc. Thomas (1999) first demonstrated the feasibility of friction stir welding of steels, a high softening temperature material, and much of the research since the initial feasibility studies has focused on development of appropriate pin tools and the effect of FSW on steel microstructure (e.g. Jashti et. al 2005 Ramasubramanian et. al 2005, Leinert et al 2003 and Steel et al 2005.)

In Thomas' original study, defect free welds of equal strength to the base material were made on 12mm thick sheets of low carbon, 12% chromium alloy steel using a two pass approach. Failure of the joint occurred in the parent metal and not in the heat affected zone of the weld. The primary difficulty encountered is that the pin tools, an essential part of the FSW process, had to be replaced after approximately four metres of weld length. Ozekcin et. al (2004) performed a microstructural examination of welds made in X80 and L80 API-grade steels, which have significantly different chemical make-up, and found that both could be successful friction stir welded with no defects. They also determined that properties of the weld such as hardness could be modified based on the process parameters used when welding the materials. Studies on welding of T-joints in ASTM A36 steel (Steel et al 2005) produced fully consolidated welds, but NDT detected a defect in the form of a ligament on the interfaces of the vertical and horizontal members. With changes in the weld parameters, including rotational speed of the tool, defects were reduced in the weld. The researchers anticipated that the defects could be eliminated with additional work on optimizing process parameters and joint configuration.

Of particular importance in the development of FSW of steel has been the research on tool materials and process improvements. Important tool material qualities include elevated temperature strength and stability, wear resistance, tool reactivity, fracture toughness and thermal expansion. Tungsten and tungsten-rhenium tools were initially studied, but durability of the pin tool proved to be a problem. Subsequent research into tool materials for high melting temperature alloys has developed polycrystalline cubic boron (PCBN) tools, and Tungsten and Molybdenum based metal matrix composite alloys for pin tools. Current development of these tools has allowed for welds up to 12mm thick and for weld lengths that are sufficient for commercial development (Fuller 2007).

4. POTENTIAL APPLICATIONS AND IMPACT

Perhaps the most promising application of FSW in steel lies in the potential for joining high strength steels, since high strength steels are being used more and more frequently in civil engineering applications. Significant cost savings have been achieved using higher strength steels, such as ASTM A913 Gr 65, in numerous building and bridge projects in the US (Axmann 2003), and ultra high strength steels, such as H-SA 70 (F_y = 700 MPa) are be 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 have been reported. For example, Lawlor (2000) discussed the difficulties and careful consideration required in joining high strength steel (EN10210, Fy = 460 MPa) as well as joining 460MPa to 350 MPa steel. Special attention to preheating and heat input during the process was required. In that project, high strength steels were necessary for a long span retractable roof to lower the weight of the support structure and to facilitate retraction of the roof. The offshore industry is making significant use of high strength steels, and it has been estimated that over 50% of the expense of building a platform lies in the cost of forming and welding (Billingham et al 2003). Another potential advantage of FSW over arc welding, even in mild carbon steels, is a reduction in weld distortion as compared to traditional fusion welds. For longer welds and especially in thinner material, where residual stress is more likely to manifest as significant distortion, this can be particularly advantageous.

Currently, FSW is impacting the steel pipe industry (Defalco and Steel 2009). 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%. Defalco and Steel enumerate a number of advantages for FSW in steel pipe welding including (but not limited to) time savings due to the use of single-pass full-penetration welds with no root pass required, significantly lower costs, elimination of the need for skilled welders, low distortion, adaptability to external environmental conditions, and reduction in defects. With reported challenges in welding of hollow steel sections (HSS) (Packer and McFadden 2012) FSW could be considered for welding HSS given its ability to produce low distortion, single pass welds of up to and beyond 13mm (½ inch) in thickness.

A compelling argument for greater development and application of FSW of steels lies in the potential economic and environmental impacts. Arbegast (2007) reports two sets of data that provide a compelling argument for the increased development of FSW. First, the US industry could see a benefit of nearly $5 billion dollars due to the improved weld properties, reliability and environmental benefits of FSW. Second, FSW could provide a reduction of 500 million pounds per year of greenhouse gas emissions over traditional joining methods if FSW were used for only 10% of the US market. In the original study on feasibility of FSW in steel, Thomas (1999) performed a cost analysis that included both cost of labor and consumables and determined a savings of a factor of 3 or greater could be achieved with FSW over traditional fusion welding. However, problems with tool wear have slowed more rapid implementation of FSW in steel. Currently there are two primary weld tool materials choices for steel, ceramic tools like polycrystalline cubic boron nitride (PCBN), and refractory tool materials like tungsten-25% rhenium alloy tools. PCBN tools are known to have excellent wear resistance but at a high cost with poor fracture resistance. Refractory tool materials on the other hand, have higher fracture resistance, but with less wear resistance; however, where PCBN tools must be scrapped when they break, refractory tools can be re-machined. As reported in Rai et. al (2011), the cost of tools like PCBN may prove to limit the cost effectiveness of FSW of steels until the tool cost can be reduced. As with any developing technology, it is anticipated that the cost of the tools will reduce as the research advances and the technology matures.

In addition to the previously mentioned positive environmental impact of replacing arc welding with FSW, another advantage is the reduction of hazardous fumes currently produced by arc welding. Sorensen and Nelson (2007) report on a study at Rockwell that did a side-by-side comparison of arc welding and FSW to determine the hazardous fumes produced by each process. This is significant considering anticipated changes in OSHA regulations regarding hexavalent chromium emissions. The FSW process produced both hexavalent chromium and manganese well below detectable levels and in the case of manganese, 3 orders of magnitude below the arc welding process.

5. CONCLUSIONS AND GENERAL RECOMMENDATIONS

FSW represents a significant advancement in joining technology and has the potential to replace traditional arc welding for many applications. It has been shown to produce welds of higher quality with no defects, reduced cost and lower environmental impact when compared to traditional fusion welding of steels. Current applications in pipe and offshore industries and studies on high strength steels provide evidence of potential for civil engineering applications. While additional advances are required in processes and pin tools to ensure economic viability in industrial applications, FSW could prove to fulfil one of the predicted needs for innovation in steel design and construction.

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