

FRICTION STIR WELDING – OVERVIEW AND PERSPECTIVES

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Abstract. *This paper presents a new joining process known as Friction Stir Welding (FSW). The process description, and some aplication possibilities are shown, including several possible joint designs. An overview of development research status of several materials has been shown. The state of the art of FSW at present makes the welding of aluminium alloys its main application. Other materials have been successfully welded in laboratory and are either in, or nearing production. Several applications have been found at shipbuilding industry, followed by space industry and train industry too, and a lot of applications are in research at aircraft, automotive, and other industrial sectors.*

Keywords. *Friction Stir Welding , Applications , FSW , Aluminum Alloys*

1. Introduction

Friction Stir Welding (FSW) is a promising solid state joining process particularly suited to Al-alloys. As this process is performed on solid state, it is not associated with major weldability problems such as porosity formation or solidification cracking observed in precipitation hardening aluminum alloys such as 2XXX and 7XXX series.

The process FSW was invented by TWI, and the first patent application was filled in the United Kingdom in December 1991 (Thomas, 91). Initially the process was regarded as a laboratory curiosity, but it soon became clear that the process had much to offer in the fabrication of aluminum alloy components. As it is a solid-state process, it was found that alloys such as 2xxx and 7xxx series, which are difficult to be welded by fusion process, could be quite easily welded by FSW. Other materials suitable for joining by this process were soon identified and successfully welded.

2. Process Description

Friction Stir Welding (FSW) is a continuous, fully mechanical, solid state joining process. In principle, two parts to be welded are brought into contact, placed on a backing device and securely clamped. A specially designed cylindrical tool, consisting of a shoulder and a profiled pin is inserted into the joint line by a rotational movement. During welding, rotation of the shoulder (which is in intimate contact with the upper surface of the workpiece) and the pin produces frictional heat, bringing the material to a high temperature and to a plasticised state, without reaching its solidus temperature, and allows the tool to be traversed along the joint line. As the tool translates along the joint line, plasticised material is stirred and forged behind the trailing face of the pin, where it consolidates and cools down to form a solid phase bond between the two pieces. A schematic FSW principle can be seen at Fig. (1) and (2).

The process can be regarded as a solid phase keyhole welding technique since a hole to accommodate the probe is generated, then filled during the welding sequence.

In contrast to fusion welding processes, solid-state FSW results in a lower distortion and residual stresses weld due to the low heat input characteristic of the process. Moreover, filler material is not required.

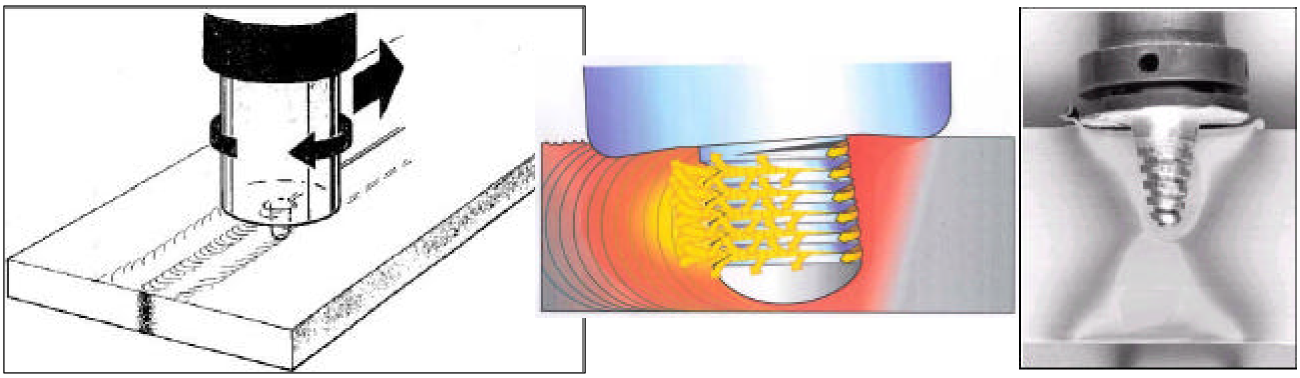

Figure 1. Schematic Friction Stir Welding Principle (adapted from Threadgill , 2002; and Kalle, 2002)

As FSW operates below the solidus temperature of the workpiece, it is possible to weld not only all aluminum alloys, but it is also possible to weld dissimilar aluminum alloys such as 5XXX to 6XXX series or even 2XXX to 7XXX series, joints with weldability issues when welded by fusion processes. No shielding gas or filler metal is required for welding. There has already been developed FSW for aluminum alloys in the thickness range from 0.8mm to 75mm.

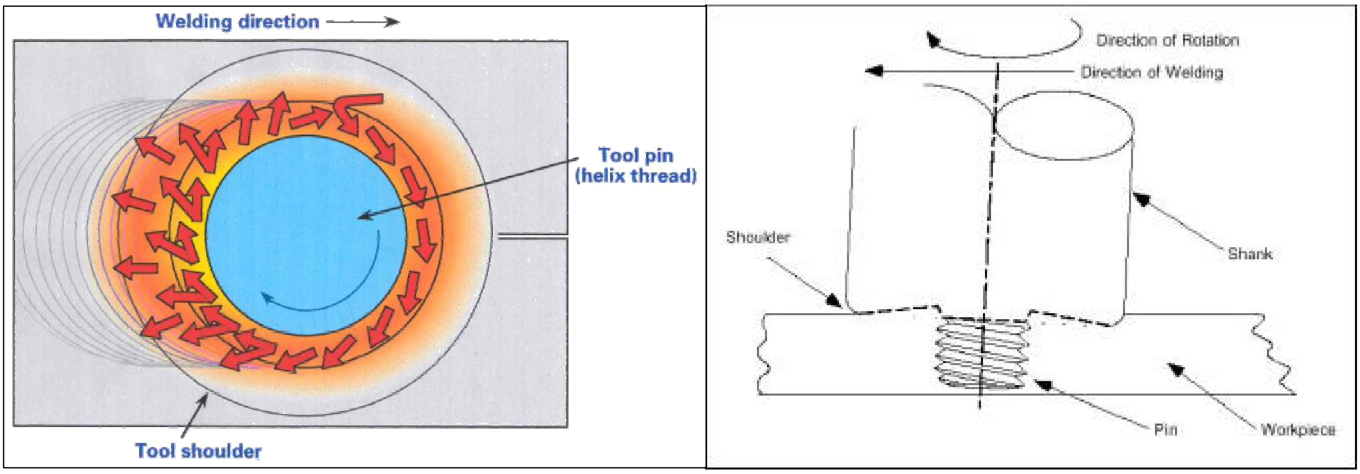

Figure 2. Schematic Friction Stir Welding Principle (adapted from Threadgill, 2002; and Reynolds, 2000)

A series of specially profiled FSW tools has been designed and tested (Threadgill, 2002). The tool related know-how about welding parameters has been developed to support nowadays and future industrial demands. The stirring effect of the tool is clearly visible in transverse macro sections if different processing types of materials have been welded such as extruded parts to wrought sheets, or wrought aluminum sheets to cast aluminum parts (Kallee, 1998). The onion ring like structure of the nugget is typical of high quality stir welds in which no porosity or other internal discontinuities took place.

The process can also be applied to copper, titanium, magnesium, zinc, and lead. Even pilot trials on steel sheets and plates have been done with considerable success. Preliminary trials have also yielded encouraging results when FSW was used to join aluminum based metal matrix composites (MMCs), and when the process was applied to join dissimilar materials such as cast magnesium alloy to extruded aluminum alloy (Threadgill, 1999).

Macrographies of sound welds of aluminum alloys show a well-developed nugget at the weld centerline, as schematically shown in Fig. (3). Outside the nugget there is a thermomechanically affected zone (TMAZ), which has been plastically deformed and shows some areas of recovering and recrystalisation (Threadgill, 1997). A heat affected zone (HAZ) could be seen between thermomecanically affected zone and parent metal in the same way that occurs on conventional fusion processes.

The overall shape of the nugget is very variable, depending on the alloy used and process conditions. The transverse dimension of the nugget is typically slightly greater than the pin diameter, and significantly smaller than the shoulder diameter.

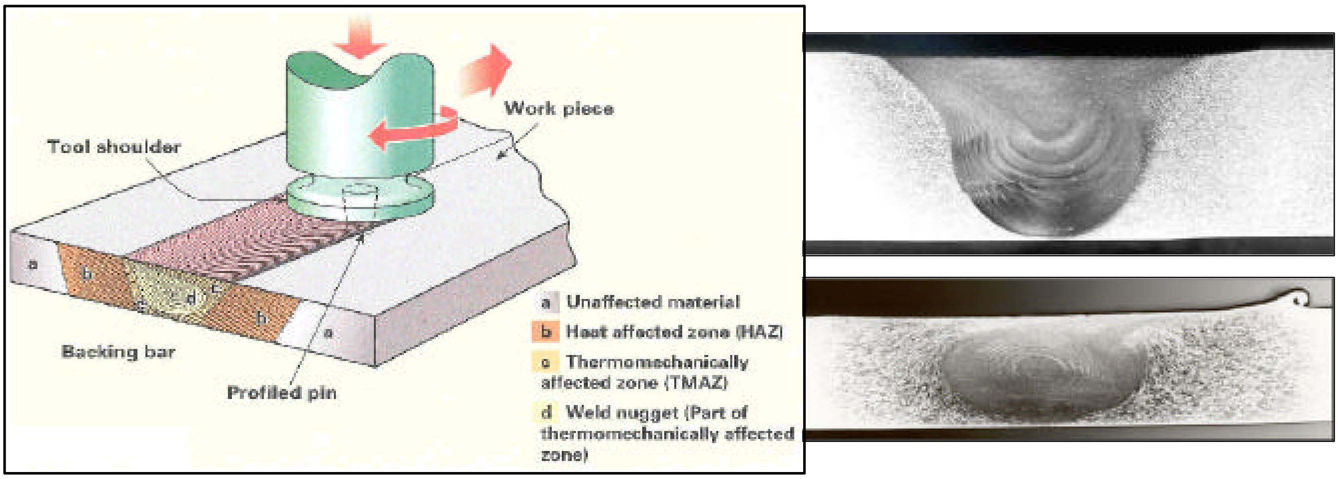

Figure 3. FSW Transverse macrosection (adapted from Threadgill, 2002)

3. Materials

The suitability of FSW for joining a wide variety of materials has been assessed by many organizations, and this work continues. A resume of the State-of-the-Art for this process development for Aluminum and non-aluminum alloys is presented at Tab. (1) and (2), respectively (adapted from Threadgill, 2002).

In addition, as the process is performed on a solid-state many dissimilar alloy combinations can be welded, as previously mentioned. For example, welding dissimilar aluminum alloys and carbon steels, an operation that in general can be done without difficulty. Other combinations, such as aluminum alloys to magnesium alloys and to copper have all been investigated, but these are generally much more challenging due to formation of intermetallic phases in the weld region. This is an area of considerable interest for further research.

Table 1. FSW Development Stage for Aluminum Alloys (adapted from Threadgill, 2002).

Aluminum Alloy type and thickness	Demonstrated	Active Research	Pre-Production Development	Industrial Production
1xxx	x			
2xxx; (< 25mm)				x
2xxx ; (25-50mm)		x		
3xxx; (< 5mm)	x			
4xxx; (< 5mm)	x			
5xxx; (< 25mm)				x
6xxx; (< 25mm)				x
6xxx (25-50mm)			x	
7xxx (< 25mm)				x
7xxx; (25-50mm)		x		
8xxx	x			
Al-Si Castings		x		
Al-Mg Castings		x		
Al MMCs	x			
Al-Be alloys	x			

Table 2. FSW Development Stage for Other Materials (Non-Aluminum) (adapted from Threadgill, 2002).

Material	Demonstrated	Active Research	Pre-Production Development	Industrial Production
Pure Copper				x
Pure Cu thick section			x	
Cu Alloys			x	
Brasses & Bronzes			x	
Magnesium - Die Castings			x	
Mg - Castings		x		
Mg - Wrought Alloys		x		
Titanium Ti-6Al-4V		x		
Titanium beta Alloys		x		
CP Ti		x		
Gamma-Ti-Al		x		
C-Mn steel - various		x		
Austenitic Stainless 309, 316L, 304L		x		
Martensitic Stainless 3Cr12		x		
Pure Nickel	x			
Pure Lead	x			
Pure Zinc	x			
Thermoplastics PP, ABS, PVC, PMMA, Nylon 6	x			

An important information is related to welded joint performance. This can be evaluated by different parameters. One of then is the joint efficiency, calculated by the ratio between ultimate tensile strength (UTS) of welded joint and UTS of base metal. Values closer to 1.0 means that base metal and weld joint have the same mechanical behavior. Table (3) presents some results of FSW joint efficiency.

Table 3. FSW joint efficiency (adapted from Nicholas, 2000)

Material	Joint efficiency
5083-O	1.00
5083-H321	0.91
6082-T6	0.83
6084-T4	0.93
7108-T79	0.86

As one can note from Tab. (3), FSW presented a good joint efficiency, which is close to joint efficiency observed on fusion joining processes with very high-quality weld.

4. Joint Designs

Although the Friction Stir Welding process is ideally suited to the manufacture of long straight welds, it is in fact remarkably flexible, and a variety of joints of 1 , 2 and 3 dimensions have been demonstrated. Some typical joint designs are shown in Fig. (4). The restriction on joint design is that no filler is added, and so conventional fillet welds can be made in a different way. A proposed solution is presented in figures 3(j), 3(k) and 3(l). In the case of 3(l) joint geometry a solution has been proposed in which the fillet is pre-extruded onto the workpieces, but the industrial feasibility of this has not been demonstrated. This solution would only be applicable to extrudable alloys where the need of a fillet weld might be easily overcome by redesign of the structure. This point emphasizes that FSW is an additional member of the family of mainstream welding processes. Although it may have many advantages over other processes for certain joint geometries, there are many cases where other processes are, and will continue to be, more appropriately used.

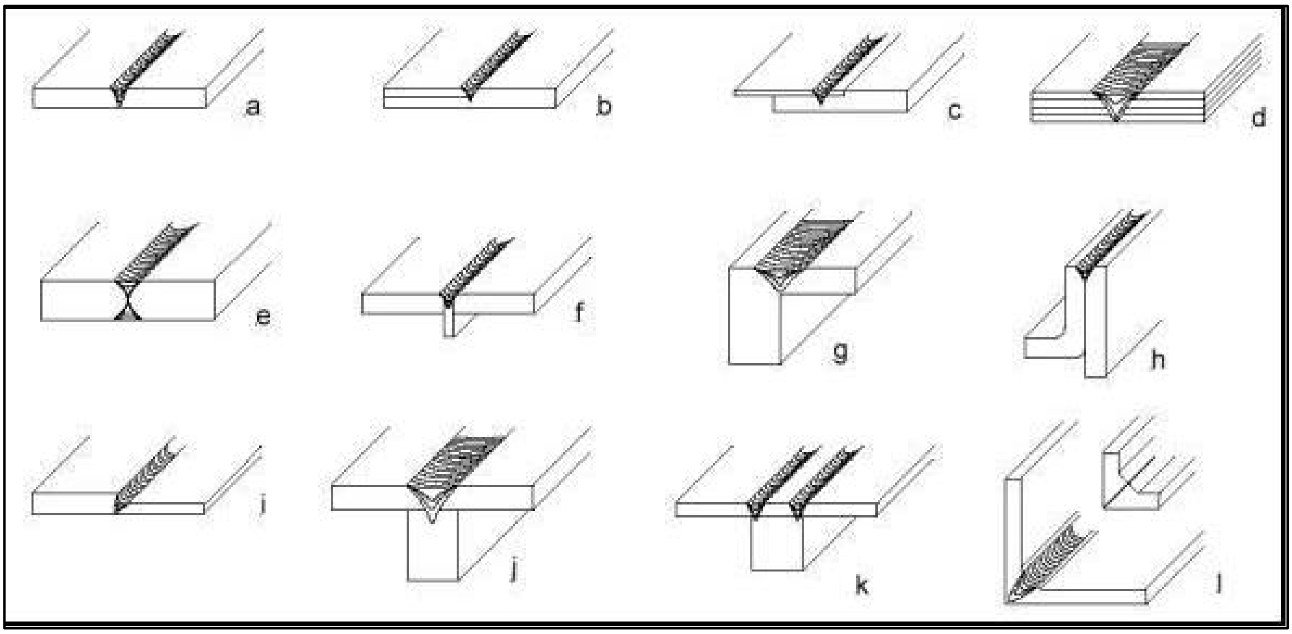

Figure 4. Typical Joint Designs for Friction Stir Welding (adapted from Threadgill, 2002).

5. Application Overview

Today, development of the process is underway in many companies, research institutes and universities throughout the world, and there are a lot of evidences that the activity level is still growing. Applications have been reported for several industry sectors (Midling, 1999). Some application examples are presented here.

The shipbuilding and marine application industries, Fig. (5), were the first industrial sectors to implement the process for commercial use, and a lot of applications for FSW were found, such as => Deck panels, => Floors, => Refrigeration plants, => Aluminum extrusions, => Helicopter landing platforms, => Transport structures, etc.

Figure 5. Prefabricated FSW Panel for Naval Applications (Midling, 1999)

Space Industries had found important applications for FSW. Longitudinal butt welds and circumferential lap welds of Al alloy fuel tanks for space vehicles have been FSWed and successfully tested. An increasing number of fuel tanks for spacecraft are now being produced from difficult-to-weld aluminum. Boeing has applied FSW to the Interstage Modules of Delta II rockets, and the first of these was launched successfully on 17 August 1999 (Boeing website). This rocket contained a friction stir welded intertank, a critical, but not pressurized, application. First Delta II rocket with pressurized friction stir welded fuel tanks flew at Mars Odyssey on 7th April 2001. These were longitudinal welds, circumferential FSW were still being introduced. After Delta II positive results, FSW application were extended to Delta IV rockets, with first launch at 20th November 2002, Fig. (6). The fuel and LOx (Liquid Oxigen) tanks were designed for friction stir welding, allowing the use of thinner parts with valuable weight savings. Applying FSW to the Delta IV tanks instead of VPPA welding increased the joint strength by 30 to 50% (Boeing website).

The key milestones in Boeing's FSW activities were the successful production and testing of a subscale prototype FSW tank at TWI and then the delivery of the first ESAB production machines. From then to now, 2100m long 'free of defect' welds have been produced for Delta II rockets, and 1200m for the larger Delta IV rocket. The FSW specific design achieved 60% cost saving, and reduced the manufacturing time from 23 to 6 days.

Figure 6. Delta IV Rocket and its FSW Tank Manufacturing (Boeing website)

The aeronautical industry has recognized the technical advantages of FSW and has begun to embrace the process, although stringent certification tests must be carried out for most applications. Prototype parts have been FSWed, and are undergoing certification tests. The first aircraft with a significant number of structural FSWed parts was the 6-pax executive jet “Eclipse 500”, Fig. (7). It made its first prototype flight in the USA in August 2002 and its certification process is still running. Opportunities exist to replace riveting and machining from rolled plates by FSW, therefore reducing manufacturing costs and providing weight savings with obvious benefits to the industry. The process could also be used to increase the size of commercially available sheets by welding them prior to forming.

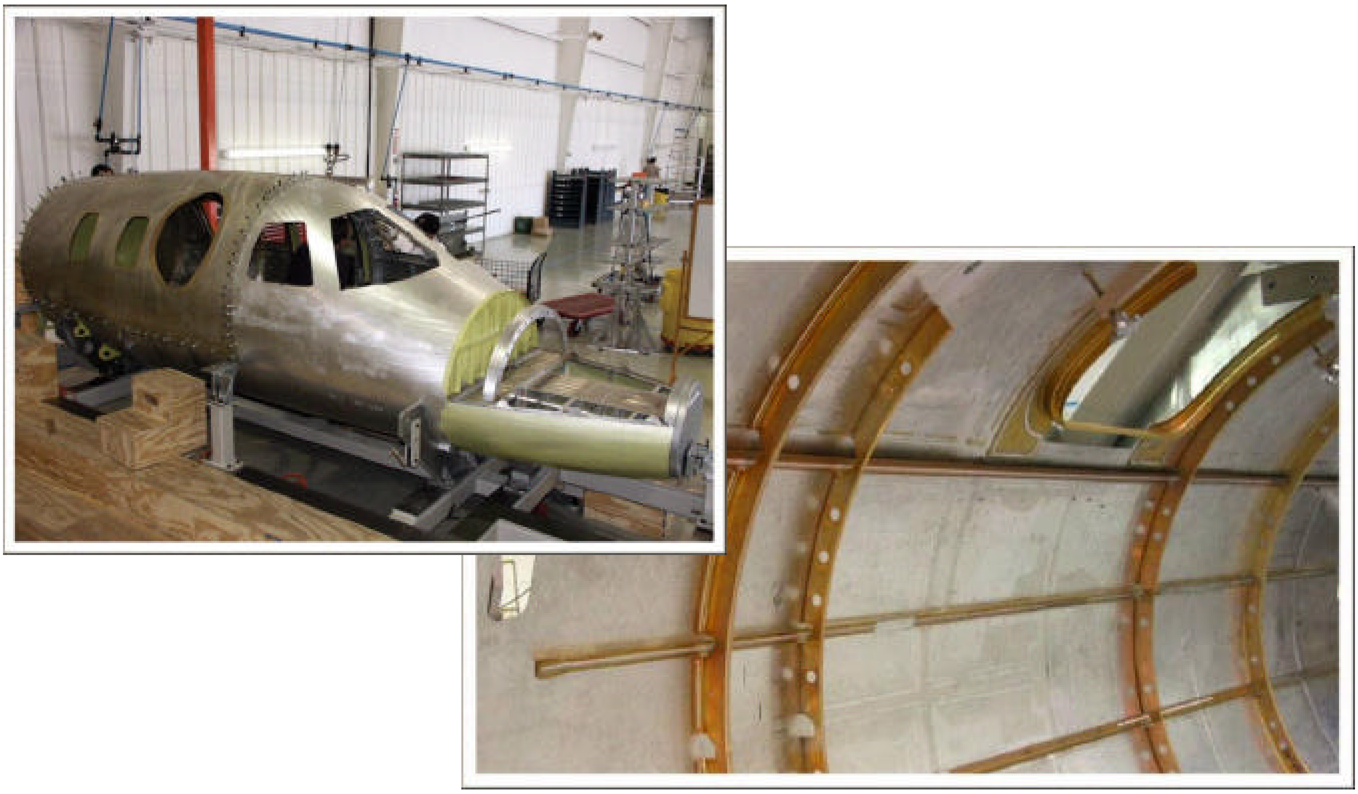

Figure 7. Eclipse 500 Final Assembly and Entirely FSW Panel (Velocci, 2000)

The commercial production of high-speed trains made from aluminum extrusions joined by FSW, has also been implemented. Modern passenger rail cars are increasingly produced from longitudinal aluminum extrusions with integrated stiffeners. Using this concept the whole body shell can be made from either single wall or hollow double skin extrusion. This design approach can enhance the crashworthiness of vehicles due to the absence of transverse welds and the high buckling strength of the panels under longitudinal compression (Davenport, 2001). Large aluminum extrusions with complicated shapes joined by FSW are available and are being used in the manufacture of single and double deck trains. The special joint design used by Hitachi in manufacturing of Series 885 Tilting EMU for JR-Kyushu can be seen at Fig. (8). Material used was Aluminum 6xxx extrusion with overall width about 40mm (Takai, 2001).

Figure 8. Series 885 Tilting EMU for JR-Kyushu and Assembly Possibilities (Takai, 2001)

Several automotive companies and suppliers of this industrial sector are currently experimentally assessing the FSW process. New “designed-for-manufacture” joints are under development for automotive lightweight structures. The concept of spaceframe for automotive bodies was developed by Audi in Germany for manufacturing of aluminum cars using extruded profiles welded to hydroformed parts by FSW and laser beam processes.

Portable FSW equipment that can be carried and positioned by two people to make on-site welding possible is under development for the construction industry.

The electrical industry has shown increasing interest on use of FSW , in particular for joining pure copper conductors.

The state of the art of FSW at present makes the welding of aluminum alloys its main application. Other materials have been successfully welded and in some cases are either in, or nearing production (Kallee, 2002).

6. Conclusion

Friction Stir Welding is a very promising process for joining metals, particularly for precipitation hardening aluminum alloys that couldn’t be welded by conventional processes.

Dissimilar alloys can surely be joined by FSW.

Joint efficiency is higher than achieved on conventional fusion joining process.

FSW enabled thinner wall structures reaching a lighter weight structure overall.

The FSW technique has found commercial application in a range of industries around the world and several machine manufacturers can provide suitable welding machines.

The market for FSW of aluminum is growing strongly, and this growth is expected to continue.

Further research and development work is necessary to experimentally assess new joint designs for critical structures, to establish mechanical and corrosion data, to determine acceptance criteria and to develop welding procedures and qualification criteria for friction stir welding.

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