RESURGAM Technical Bulletin

Friction stir welding of steel: Key findings & potential applications

RESURGAM

Robotic Survey, Repair & Agile Manufacture

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1. Executive Summary

Project RESURGAM, part funded by the EU and led by the European Welding Federation, aims to deliver a decisive break-through with Friction Stir Welding (FSW) as a high integrity, low distortion, environmentally benign, welding technique to be developed in steel,

- In air, to facilitate the modular construction of ships across multiple yards with final assembly at one master yard;
- Under water, using robotic systems to allow repairs to be carried out on marine structures without needing to bring ships or platforms ashore to a dry dock.

This booklet identifies the advantages and benefits of the emerging technology of friction stir welding in aluminium and presents the RESURGAM project developments of FSW for steel, highlighting key findings, underwater welding, design and cost implications. A forward perspective in the form of a tool development roadmap is given and a few applications for several sectors of activity identified, namely shipbuilding and repair, civil engineering, defence, nuclear, Off-highway, quarrying and construction applications and pipeline.

2. Introduction to friction stir welding

Friction stir welding (FSW) is a solid-state welding process invented by TWI in 1991 and subsequently widely used for the fabrication of structures requiring high strength, lightweight, fatigue resistant joints. The process was originally developed for joining aluminium, as this is considered a difficult material to weld, and was subsequently developed for other hard to weld metals such as magnesium and copper. The process of friction stir welding, illustrated schematically in Figure 1, is very simple:

- A rotating tool is used to generate frictional heating which softens the material to be welded;
- The tool is then traversed along the joint line, mechanically stirring the two components together.

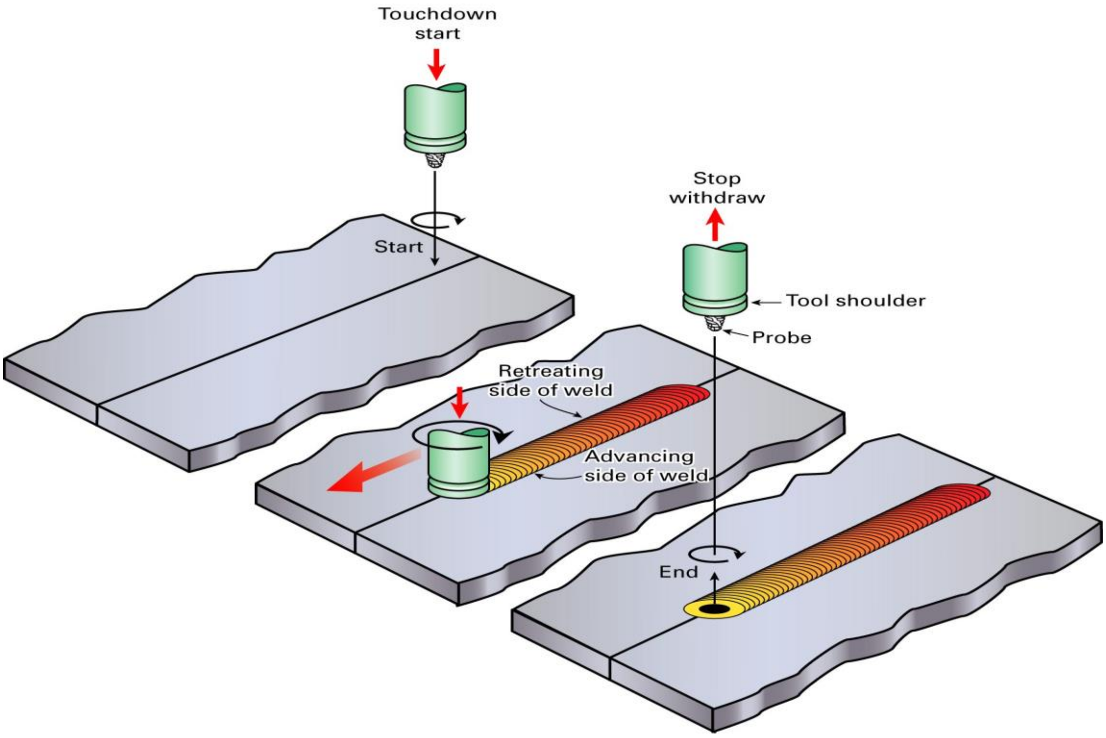


Figure 1 The basic principle of friction stir welding

Friction stir welding can be thought of as a process of constrained extrusion under the action of the tool. The frictional heating causes a softened zone of material to form around the probe. This softened material cannot escape as it is constrained by the tool shoulder. As the tool is traversed along the joint line, material is swept around the tool probe between the retreating side of the tool (where the local motion due to rotation opposes the forward motion) and the surrounding undeformed material. The extruded material is deposited to form a solid phase joint behind the tool. The process is by definition asymmetrical, as most of the deformed material is extruded past the retreating side of the tool. The process generates very high strains and strain rates, substantially higher than found in other solid state metalworking processes, for example extrusion, rolling and forging.

The advantages of the FSW process result from the fact that welding takes place in the solid phase below the melting point of the materials to be joined. The benefits include the ability to join materials that are difficult to fusion weld, for example, 2xxx and 7xxx series aluminium alloys, magnesium and copper.

2.1. Proven advantages and benefits of FSW in aluminium

Friction stir welding has been shown to have many benefits and advantages when compared with more traditional welding processes.

- As a solid state process, it can be applied to all the major alloys and avoids problems of hot cracking, porosity, element loss etc. common to fusion welding processes;
- As a mechanised process, FSW does not rely on specialised welding skills; indeed manual intervention is seldom required;
- No filler wire is required;
- The absence of fusion removes much of the thermal contraction associated with solidification and cooling, leading to significant reductions in distortion;
- FSW is very flexible, being applied to joining in one, two and three dimensions, being applicable to butt, lap and spot weld geometries; welding can be conducted in any position;
- Excellent mechanical properties, competing strongly with welds made by other processes.
- Workplace friendly: there are no ultraviolet or electromagnetic radiation hazards as the absence of an arc removes these hazards from the process; the process is no noisier than a milling machine of similar power, and generates virtually zero spatter, fume and other pollutants.
- High welding speeds and joint completion rates: in single pass welds in thinner materials (down to 0.5 mm thickness), FSW competes on reasonable terms with fusion processes in terms of welding speed; in thicker materials, FSW can often be accomplished in a single pass, whereas other processes need multiple passes. This leads to higher joint completion rates for FSW, even though the welding speeds may be lower. Thick plates can also be joined by FSW on either side.
- Various mechanical and thermal tensioning strategies can be applied during welding to engineer the state of residual stress in the weld.

Friction stir welding was originally developed for welding aluminium and quickly gained acceptance as a means of construction in the maritime sector for aluminium ships.

The process has already been used for the following applications in aluminium:

- Panels for decks, sides, bulkheads and floors;
- Hulls and superstructures;
- Helicopter landing platforms;
- Masts and booms, e.g. for sailing boats;
- Refrigeration plant.

An advantage of friction stir welding for fabricating marine components is the ability to manufacture deck or panel modules indoors at specialist suppliers, away from the dockyard, thus freeing up slipways and yard space. The pre-fabricated modules are then brought together at the building yard for final assembly. Batch production by FSW further reduces the welding workload in shipyards. Shipbuilding changes from manual fieldwork to standardised production lines. Production efficiency of shipbuilding is therefore greatly improved.

3. Project RESURGAM – developing FSW for steel

Project RESURGAM is a three year, EU funded, multi-national research initiative to develop the equipment, processes and qualification routes needed for fabricating ships and conducting underwater repairs of steel structures using FSW.

3.1. Key findings of RESURGAM

RESURGAM has shown that steel can be friction stir welded using a range of specialist tools developed by Element Six, and that these tools consistently produce defect free, strong, tough welds with low distortion and good fatigue resistance.

- The tools have been shown to have a life of 60m of weld in 6mm thick steel and a life of 30m in 12mm thick steel.
- Welds have been made in air and under water.
- Welds have been made in square butt and lap geometries.
- A range of carbon steels have been welded, including S355, S460 and S690.
- Stainless steel grades 304 and 316 have been welded.
- Stainless steel (316) has been welded to carbon steel (S355)

Figure 2 shows a metallographic section through a friction stir weld in carbon steel. The weld was made as a single pass joint between two square edged plates and is free from defects such as voids, cracking or lack of penetration. The weld metal has a fine grained, equiaxed microstructure very different from the large columnar grained microstructure typical of an arc weld. The Heat Affected Zone (HAZ) is small. The small grain size and absence of defects are the key to the process producing welds in steel that are typically stronger and tougher than the original parent metal.

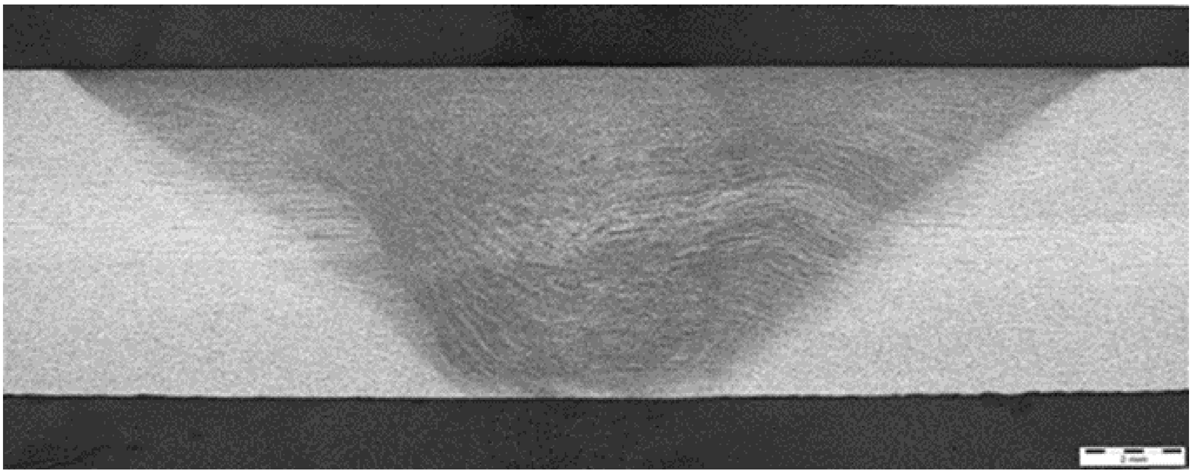


Figure 2. Metallographic section through a single pass, square butt, friction stir weld in carbon steel

Figure 3 shows a number of test samples of friction stir welded carbon steel. The tensile test pieces (left) show that the weld has failed in a ductile manner in the parent metal quite some distance from the weld and outside of the HAZ. The ductility of the weld and its freedom from defects is shown by the face and root bend test pieces (right), which have been bent through 180 degrees with no sign of splitting or breaking. Centre are several impact test pieces, notched in the centre of the weld: these showed greater toughness than the original parent steel. Data for these tests are presented below as Figure 4 and comparisons of the parent metal and weld metal microstructures are shown as Figure 5.

Figure 3. Tensile, Charpy impact and bend test samples of friction stir welded steel.

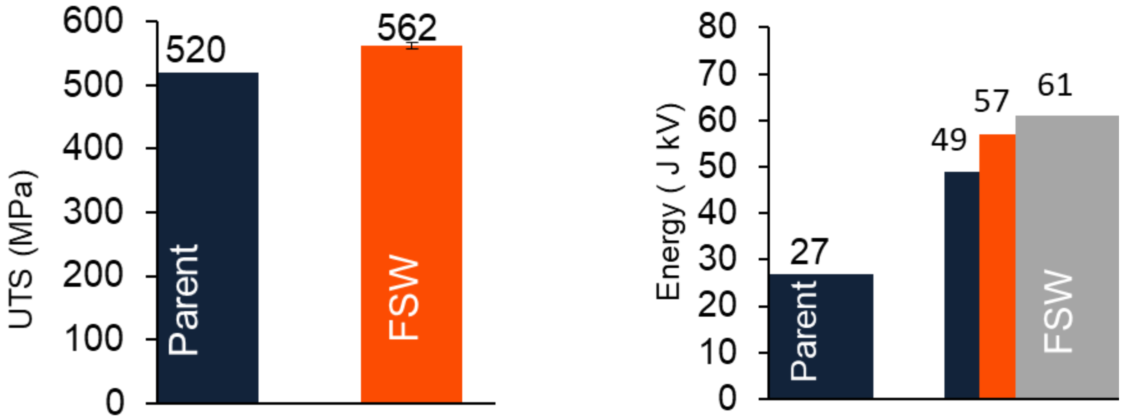


Figure 4. Tensile test (left) and Charpy impact toughness test (right) results for friction stir welded steel.

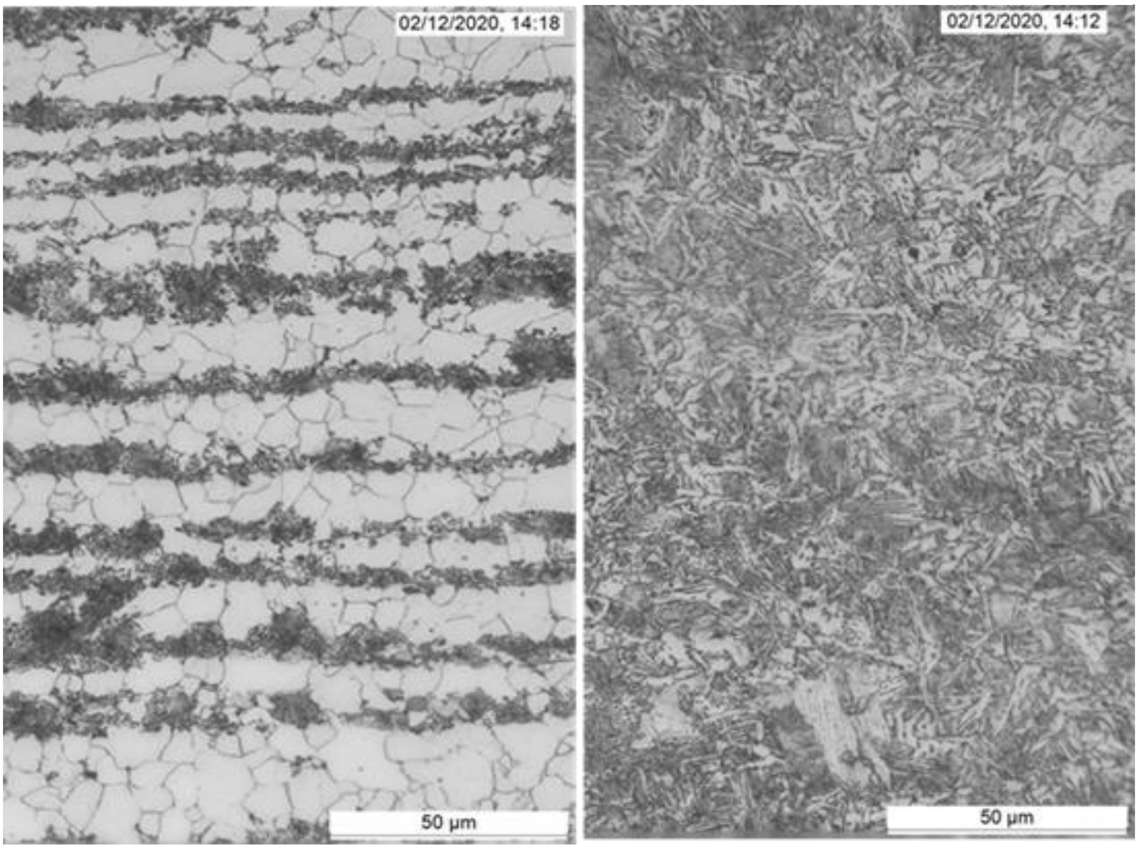


Figure 5. Microstructures of the parent metal (left) and weld metal (right) of friction stir welded carbon steel.

3.2. Underwater welding

As friction stir welding is a solid state process it can be performed under water, and has even been performed under oil to demonstrate its suitability for the repair of a live oil pipeline. It is capable of operating at any depth and does not require the use of cofferdams or hyperbaric chambers. Part of the RESURGAM project will develop a marinised robotic friction stir welding system capable of welding a steel patch over a damaged hull to enable at sea or in harbour repairs without the need to dry dock the vessel. The same technology could, of course, be applied to the repair of other marine infrastructure such as oil rigs, wind turbine tower and harbour or riverine facilities.

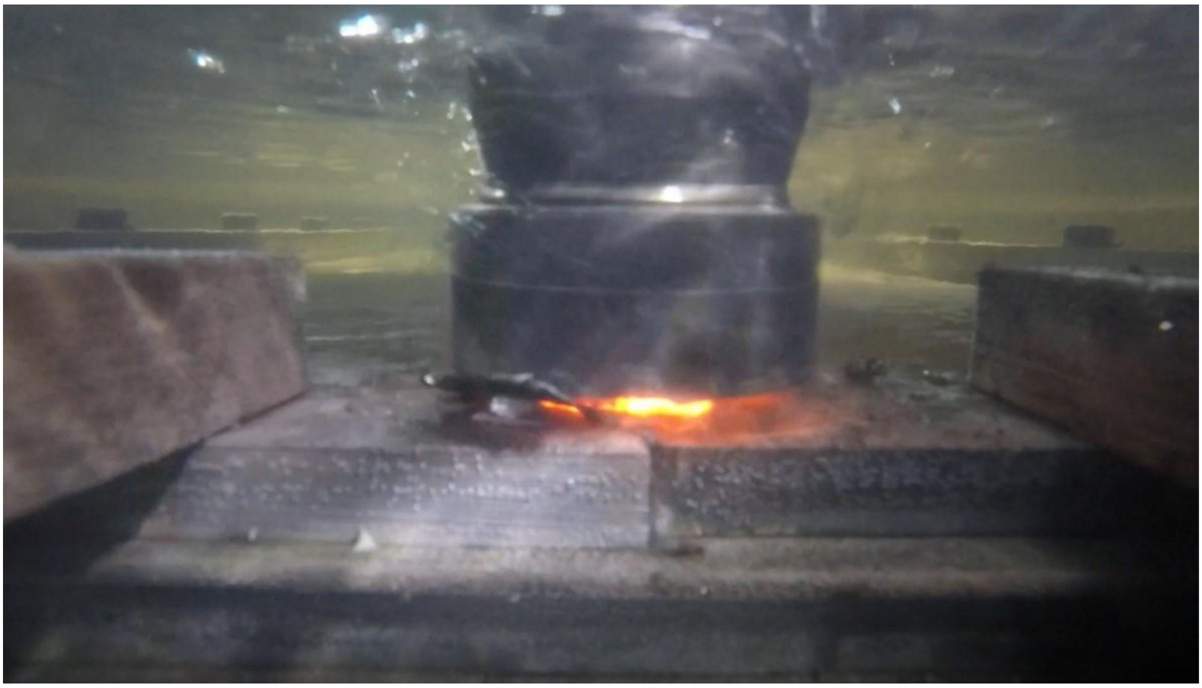


Figure 6. A friction stir butt weld being made under water to join two 12mm thick steel plates.

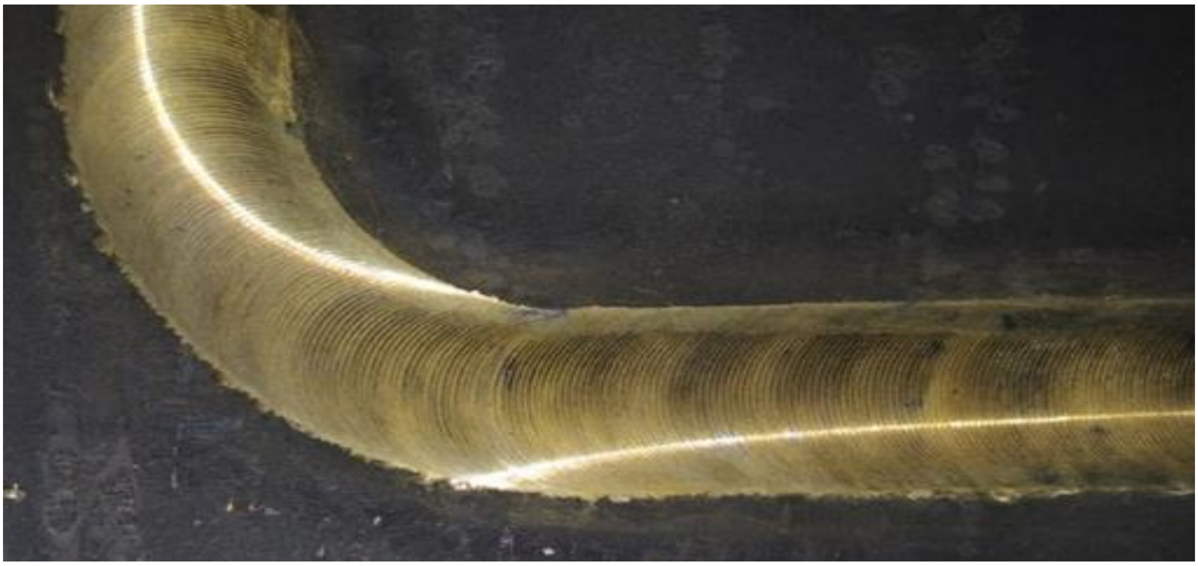


Figure 7. View of a 4mm thick plate lap welded onto a simulated damaged hull plate, under water

3.3. Design Implications of steel FSW

Designing for friction stir welding is different from, but not necessarily more difficult than, designing for conventional welding. Thought must be given to the need to utilise a backing bar during friction stir welding though this is also frequently used in arc welding process too. Additionally, it may also be necessary to consider the implications of the asymmetry of friction stir welds in some applications and the management of the hole left behind at the end of a weld. None of these represent insurmountable issues.

Friction stir welding can make welds in most recognised weld geometries, for example, butt, lap and T. Most weld geometries that are possible in conventional fusion welding are equally achievable in FSW and some of them are actually easier. For example, as FSW does not cause any melting of the metal it is equally as easily performed vertically, upside down and even under water. Typical joint configurations already demonstrated to possible in friction stir welding of aluminium are shown as Figure 8.

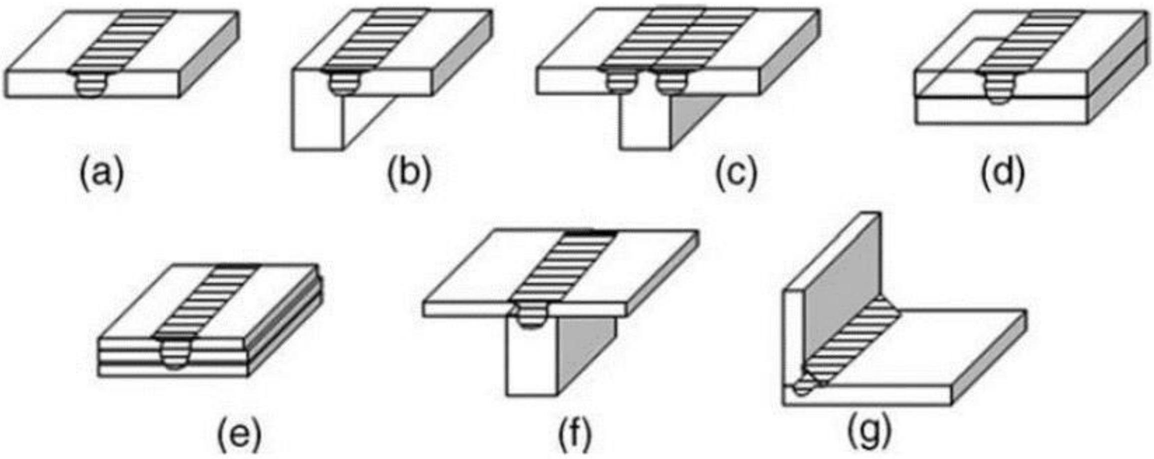


Figure 8. Weld geometries possible in friction stir welding

The introduction of friction stir welding also presents an opportunity to adopt new fabrication techniques and potentially make improvements of existing practices. For example, many ships (and civil engineering structures) are built in a modular fashion from assemblies of stiffened panels. Traditionally, these stiffened panels are made by welding ribs onto a flat steel plate, usually by making a fillet weld along both sides of the rib. Complex welding procedures are necessary to minimise distortion arising from the heat input to the weld zone and so allow good fit up of the panels produced.

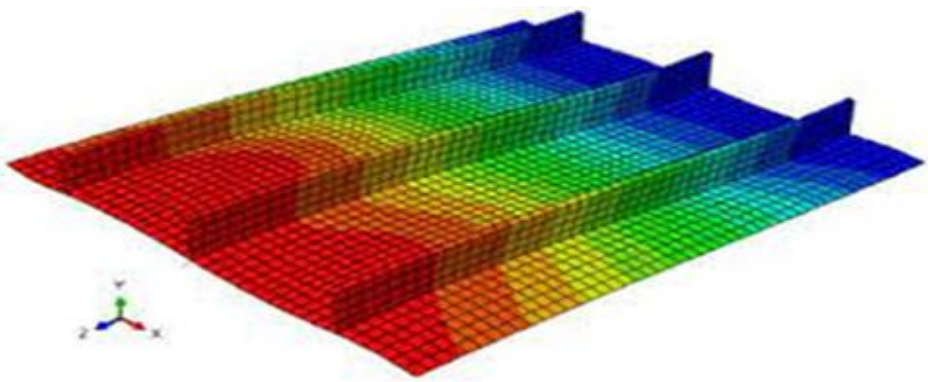


Figure 9. Simulation of welding distortion in an arc welded stiffened panel

An alternative technique, maximising the benefits of friction stir welding, replaces the two fillet welds with a single butt weld to join a wrought plate spacer to a rolled T section. This Integrally Stiffened Panel (ISP) concept is shown as Figure 10, and a small demonstration panel made by the technique is presented as Figure 11.

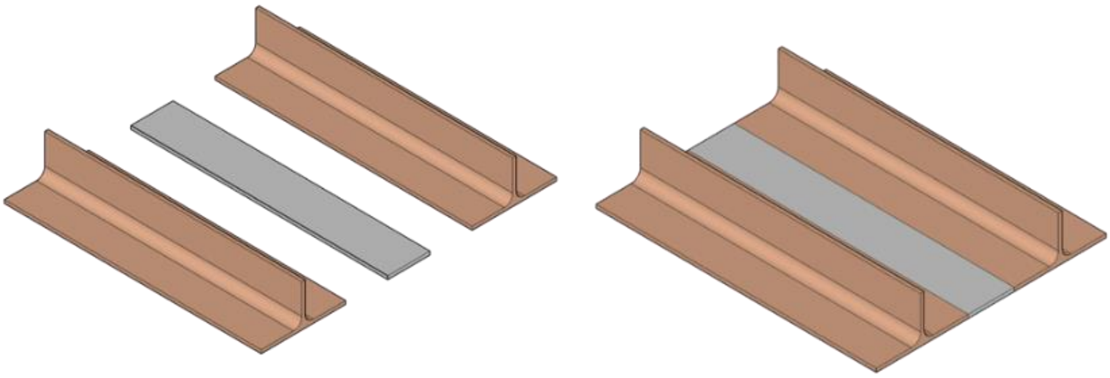


Figure 10. Concept of stiffened panel construction from rolled T sections spaced with rolled plate

The friction stir welded,ISP results in a fully forged structure that is potentially stronger, more fatigue resistant and less distorted than an arc welded equivalent. In summary, the ISP:

- Replaces two arc fillet welds with one FSW butt weld;
- Gives a fully forged structure;
- Uses commodity items;
- Permits easier inspection;
- Reduces distortion;

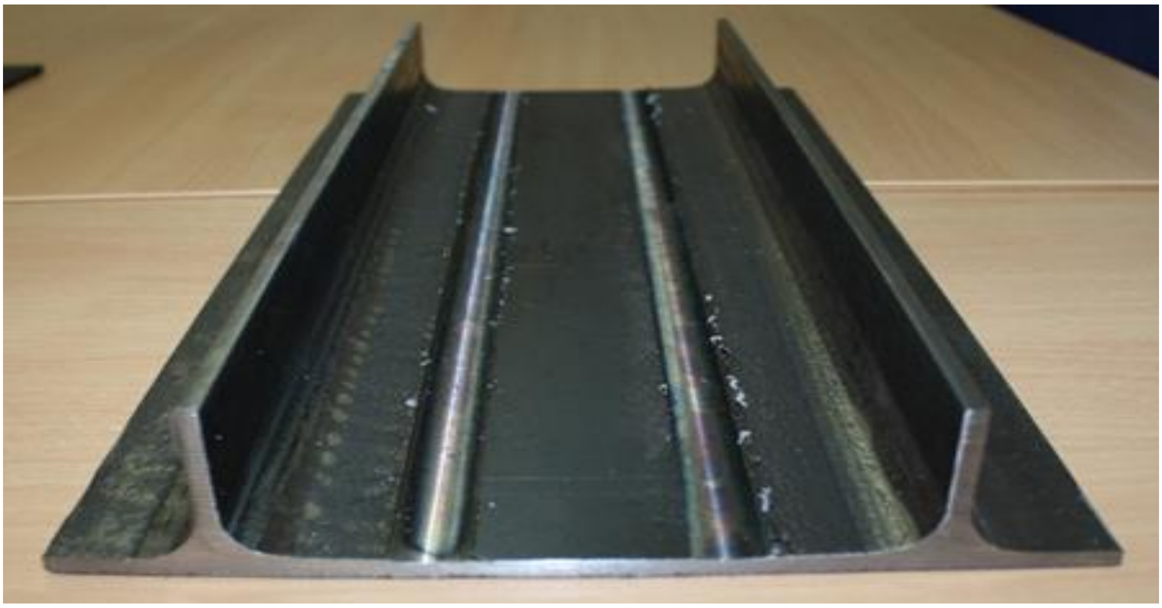


Figure 11. Integrally Stiffened Plate demonstration piece fabricated by friction stir butt welding two rolled T sections to a steel plate

3.4. Cost implications of steel FSW

RESURGAM has shown that all the benefits of the FSW process already proven in aluminium apply to steel, producing strong, tough welds in a wide range of steels – including dissimilar grades and those traditionally considered difficult to weld by other processes. However, whereas in aluminium friction stir welding is usually lower cost than other processes, in steel the process is generally considered to be more expensive than existing techniques due to the higher cost of tools for steel FSW.

But is it really?

- How much is spent on pre-weld preparation and post-weld clean up with existing processes?
- How much is spent on purchasing, storing and controlling filler wires in existing processes?
- How much is spent on distortion control and rectification during arc welding?
- How much is spent on NDT, QC and rectification during other welding processes?
- How much is spent on purchasing, storing, controlling and disposal of flux in arcs processes?
- How much is spent on welder training and qualification with other welding processes?
- How costly does it become to weld under water with other processes? Is it even possible?
- Would you weld inside a live oil pipe or fuel tank with other processes?

If one considers the true costs of welding fabrication, then FSW, an automated, mechanical process that produces high quality, tough, strong, fatigue resistant, autogenous welds 24 hours per day may be cost competitive in many applications.

FSW reduces or even eliminates many of the costs identified above. Consider just a few of these.

Weld preparation and cleaning

Friction stir welding is typically performed as a simple square butt weld, eliminating the need to machine specialist edge preparations such as V or J groves. A finished friction stir weld typically has a smooth, spatter free surface, reducing or eliminating the need for post weld grinding and cleaning in many applications.

Elimination of filler wire.

The obvious cost saving associated with the elimination of filler wire is the cost of the wire itself. However, it is often forgotten, or not even realised, that the major cost of the filler wire lies in its storage and administration. The wire should be kept in humidity controlled storage to mitigate against problems with moisture absorption and potential hydrogen embrittlement of the welds made. Filler wire also incurs significant administrate costs too when it is dispensed at the start of each shift, and taken back into storage after each shift, to ensure that the correct wire is used for each job.

Distortion control

The low temperatures and lack of melting associated with friction stir welding reduce the heat input to the weld zone, frequently resulting in fabrications with minimal distortion and so eliminating the need for subsequent straightening operations.

Underwater welding

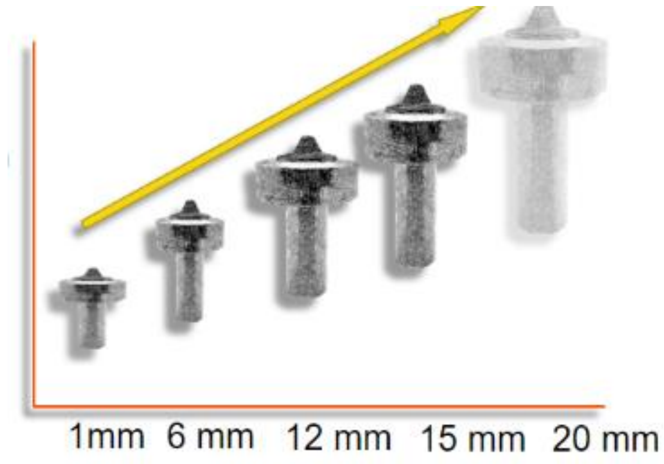
Conventional arc welding processes become costly, less effective and potentially hazardous when employed under water. At shallow depths divers can be employed, with all their associated cost and safety implications, and at greater depths it is necessary to use robotic welding systems or hyperbaric chambers. Friction stir welding can be performed at any depth using virtually the same equipment as is used for welding in air, and with far fewer problems such as hydrogen embrittlement arising from ingress of moisture into the weld zone as this is sealed off from the water by the embedded tool.

4. FSW tools for steel – development road map

The development of tools sufficiently strong to stir steel, and to be chemically inert to the steel itself at the high temperatures required to soften it, means that introducing FSW to steel is a challenging undertaking. Steel does not soften and flow sufficiently for friction stir welding until almost twice the temperatures experienced with aluminium, typically around 900 to 1,000°C. Few materials retain adequate strength, toughness and abrasion resistance to stir steel at such temperatures and of those that do, the problems of steel's high chemical reactivity results in rapid tool wear as the hot steel effectively alloys with and dissolves the tool.

Consortium member Element Six is a world leader in the development of materials for use in extreme environments, particularly at high temperatures and under extremely abrasive conditions. Using that expertise, Element Six developed a Polycrystalline Cubic Boron Nitride (PCBN) based tool for welding steel of 6mm and 12mm thickness. An example of such a tool is shown below.

Figure 12. FSW tool for steel. Image courtesy of Element Six



Work is ongoing to refine the design of the tools and the materials used to manufacture them, the intent being to enhance tool life, reduce tool cost and Increase the thickness of steel that can be welded.

5. Shipbuilding and repair applications

The RESURGAM project has specifically investigated the use of friction stir welding in steel for two applications, the modular construction of ships and the repair of ships at sea. Many larger ships are built in a modular fashion from stiffened panels, these then being built up into blocks which are in turn built up to form the majority of the inner structure of the ship. An example of such construction is shown in Figure 13.

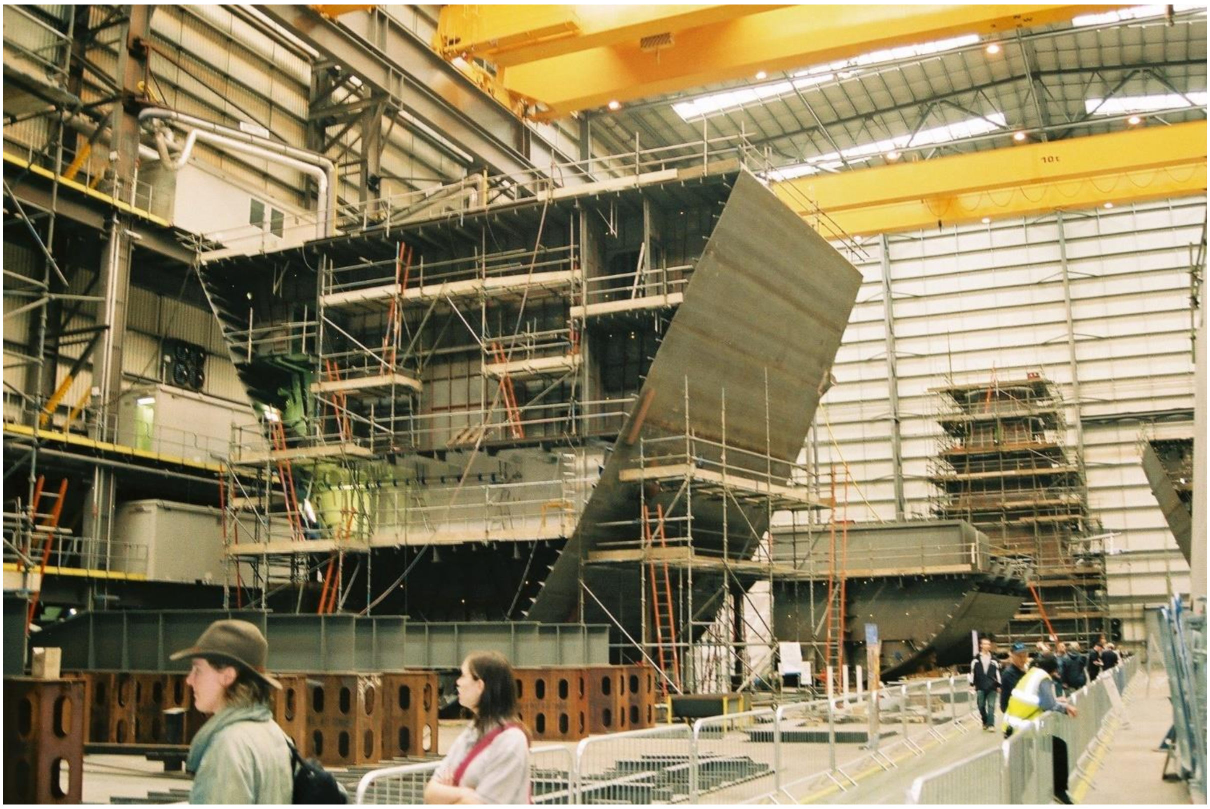


Figure 13. Modular blocks of HMS Dauntless under fabrication at HMNB Portsmouth. Image courtesy Adrian Jones.

Friction stir welding is an ideal process for the manufacture of stiffened panels, particularly if the designers elect to maximise the benefits of friction stir welding by moving to the Integrally Stiffened Panel concept illustrated earlier in Figure 10 and Figure 11.

RESURGAM also investigated the repair aspects of FSW, particularly the capability to weld underwater which will allow watertight patches to be placed over damaged ship hulls withoiut the need for dry docking them. Welding a plate over a small hole by arc welding may of itself be a relatively straightforward and low cost task, but the cost, complexity and dangers involved in the process increase dramatically if the task has to be undertaken by divers. If the repair is of sufficient size or complexity that it has to be done in a dry dock, then the costs increases yet further: not only must a dry dock be sourced and hired and the repair performed, but the ship is out odf service and earning no revenue whilst it travels to the dry dock and the repair id performed.

Resurgam looks to eliminate those costs by developing a small robot that can be deployed over the side of a ship whilst it is in harbour loading or unloading routine cargo, and manouevred into place if required by a commercially available ROV to carry out an in situ friction stir weld patch repair.

6. Civil engineering applications

Many applications in civil engineering utilise stiffened panels or very similar fabrications, for example bridge decks, floors for multi-storey steel framed buildings and supporting or reinforcing structures for concrete fabrications. In many cases, these would be ideal candidates for manufacture by friction stir.

One opportunity might be represented by the refurbishment of bridge decks. Stiffened panels manufactured in higher strength steels than are typically used could be manufactured off-site and brought to the bridge for installation. The weight saving presented by the use of high strength steel would allow the bridge's load bearing capacity to be increased to cope with the typically higher traffic volumes most bridges have to contend with – often well beyond their original design intent.

Figure 14. Steel bridge decking

Storage tanks, for fuel, oil, water or grain are all structures that might benefit from friction stir welding, particularly for the repair of liquid filled tanks whilst they still contain products, thus saving the need to drain them and the hazards associated with arc welding in a fume filled environment.

Figure 15. Large storage tanks

7. Defence applications

Many applications in the defence sector use complex alloy steels that are far from easy to weld by conventional arc welding techniques, frequently requiring pre- and post-weld heat treatment and the use of specialist fillers and shielding gases. Friction stir welding is less susceptible to problems caused by alloy composition, thus reducing or eliminating many such issues, and has already been utilised for aluminium armoured vehicles. In addition, friction stir welding's ability to generate very strong, tough microstructures, and now to do so in hard materials such as steel, offers considerable promise for enhanced performance in applications where ballistic impact and blast loading may be a concern.

Figure 16. Friction stir welded AFV hull in aluminium. (Concurrent Technologies Corp)

Bridging applications may also benefit from friction stir welding, allowing traditionally difficult to weld high strength steels to be used to make bridges that are either longer, or have greater load carrying cappacity than existing bridges.

Figure 17. Dry gap crossing with an Armoured Vehicle Launched Bridge (AVLB) (US Army)

8. Nuclear engineering applications

The nuclear sector provides a number of potential applications for FSW of steel. The sealing of copper canisters for radioactive waste by FSW has already been approved by the Swedish nuclear authorities and the use of the process to seal cheaper stainless or mild steel canisters is under investigation in the USA, Sweden, Switzerland and Canada.

Other potential applications include:

- The welding of ODS steels for the fabrication of next generation of reactors;
- The repair of existing stainless steel pipe work and fuel ponds.

Oxide dispersion strengthened (ODS) alloys, including steels, have been developed for applications where good mechanical properties are required at elevated temperatures, for example in steam plant, nuclear plant and gas turbines. ODS alloys typically consist of a high temperature metal matrix (such as iron aluminide, iron chromium, iron-chromium-aluminium, nickel chromium or nickel aluminide) with small (5-50nm) oxide particles of alumina or yttria dispersed within it. Iron-based and nickel-based oxide dispersion strengthened alloys exhibit good corrosion resistance and mechanical properties at elevated temperatures. These alloys also show excellent creep resistance, which stems partly from the dispersion of oxide and other particles. Fusion welding of these alloys, however, is detrimental to their properties and thus there is limited scope to fabricate large components from ODS materials. Friction stir welding, being a solid state process, offers an opportunity to overcome this difficulty.

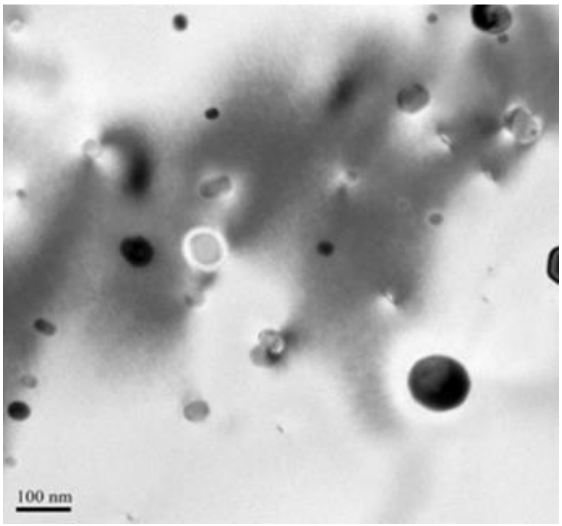


Figure 18. Electron micrograph of friction stir welded ODS steel showing the presence of the particulates after welding

Stainless steels, often 304L and 316, are widely used in the nuclear industry. Friction stir welding has the ability to produce high integrity welds in these steels and, being a solid state process, is far less susceptible to problems associated with hydrogen entering and embrittling the weld metal than conventional fusion processes. Hydrogen embrittlement is a very significant issue in the nuclear industry, especially in areas subjected to irradiation. Alpha particle irradiation of trapped hydrogen results in the formation of helium and consequent stress cracking in the weld, hence welding processes that reduce this are highly desirable. Feng *et alia* demonstrated that, even with no attempt to optimise the FSW process, the maximum helium bubble size in a friction stir weld is only about 27% of a gas tungsten arc weld of comparable size.

9. Off-highway, quarrying and construction applications

Friction stir welding has potential applications in the off highway, construction, quarrying, mining and wider yellow goods sectors. FSW can be used to construct beam structures with minimum or no distortion from higher strength steels than arcs based techniques, thus allowing cranes and excavators to have longer reach, or lift greater payloads. Alternatively, for the same reach on an excavator, a lighter boom enabled by FSW of high strength steel would allow a smaller motor to be specified, improving fuel and thus emissions efficiency.

Figure 19. Gantry and portal cranes could benefit from FSW, having potentially greater spans and / or lifting capacity.

Figure 20. Excavators could have greater reach through the use of higher strength steels to save boom weight

10. Pipeline applications

Construction

Pipelines continue to represent one of the most efficient ways of transporting bulk fluids over long distances, both on land and sub-sea. Many pipelines are still fabricated by hand welding, or the use of semi-automated systems. Replacing these techniques with an automated friction stir welding solution would potentuially bring considerable benefits, both technical and in terms of Health and Safety where pipelines are being constructed in inhospitable environments. Orbital FSW systems could make single pass girth welds in thin walled pipes (up to 12mm wall thickness), and pipes of wall thickness up to 25mm could be welded by using a simultaneous internal and external welding system, each reacting its tool forces against the other system. The welding head could use interchangeable milling and friction stir welding tools in order to prepare the pipes mating ends for welding, and then cleaning them up afterwards.

Figure 21. Conventional pipeline installation.

Internal repair

Technologies such as the robotic FSWBOT system can be deployed to carry out internal repairs on pipelines, even when they are live. FSWBOT has shown that it is possible to weld under oil, thus avoiding penalties for non-delivery of oil whilst a pipeline is having a corroded area repaired. A similar consideration may apply to public utility pipelines such as water or district heating, it potentially being possible to repair these without closing them down or digging up the road network to access them.

Pipeline refurbishment and re-purposing

A second area where FSW of steel has attracted interest is for the refurbishment of existing pipelines for the transport of new products for example CO_2 in sequestration schemes, or the transport of hydrogen (sometimes in the formof ammonia) as part of the drive towards a hydrogen economy. Both these applications require weld joints that are tough at low temperatures and which, ideally do not have a large columnar grain structure that can provide a rapid diffusion path for small gas molecules. A robotic FSW sytem could travel through old pipelines to refurbish the welds, generating a tough, fine grained microstructure at the existing girth welds in order to improve their fitness for purpose and allow existing infrastruture to be re-used for new products.

Welding of coated or clad pipes.

As friction stir welding is a solid state process, i.e. one in which no melting takes place, it is also suited for the welding of coated or clad pipes. Careful choice of tool design and process paramters will allow a weld to be made without the coating or cladding being melted and dissolved into the underlying steel, thus maintaining the integrity and preserving the protective function of the added layer.