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Advances in Steel FSW for Transport Applications

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Abstract. Friction stir welding (FSW) is a solid-state joining process that gives welds with excellent mechanical properties. The drive towards electrification has seen FSW adopted by the automotive sector for the fabrication of lightweight aluminium car bodies and battery assemblies. Element Six utilised their expertise in high performance, abrasion and temperature resistant materials to develop a FSW tool for steel and this was trialled at TWI where welding techniques were developed to allow welds to be made both in air and under water. A rigorous, independent assessment of weld quality was undertaken by the Technical University of Delft (TUD) and publications and dissemination resulting from this work has identified a number of potential other applications across the wider transport sector.

Keywords: Friction Stir Welding · inland waterways · rail · hydrogen transport · cryogenic service

1 Introduction

Friction stir welding (FSW) was invented and developed for fabricating difficult to weld metals such as aluminium in the 1990's by The Welding Institute (TWI). FSW is a solid-state joining process that gives high strength, tough, fatigue resistant welds with minimal distortion and so was quickly adopted by the aerospace, rail and shipbuilding sectors for building aircraft, fast ferries and high-speed railway locomotives and carriages. More latterly, the drive towards electrification has seen FSW adopted by the automotive sector too for the fabrication of lightweight aluminium car bodies and battery assemblies. Transferring the technology to the fabrication of steel was always seen as desirable but was frustrated for almost three decades by the difficulty in developing a FSW tool that can withstand the higher temperatures and forces associated with welding steel.

In 2013 the EU Project HILDA (High Integrity Low Distortion Assembly) identified a viable steel FSW tool as a key technology that would be required to maintain the competitiveness of the EU shipbuilding sector. Project RESURGAM, led by the European Welding Federation (EWF) and with partners representing the EU shipbuilding sector, developed in response to that challenge.

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2 Friction Stir Welding

Friction stir welding is a solid-state welding process and as such has a number of technical advantages over more tradition welding techniques that rely first on melting and then on resolidifying the metal of components to be joined. The process of friction stir welding 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.

3 Tool Development

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. Few materials retain adequate strength, toughness and abrasion resistance to stir steel at the required temperature (around 900 to 1,000 °C) 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 6 mm and 12 mm thickness. 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 too cost and increase the thickness of steel that can be welded.

Historically, other materials like refractory metal tools made from tungsten (W) or (W-Re) and Polycrystalline Cubic Boron Nitride (PCBN) have been successful in welding steel. However, low tool life and high cost in combination with lack of consistency in performance makes commercial application difficult. As part of RESURGAM project Element Six has developed and produced advanced PCBN tools to address some of the challenges that were seen before. PCBN is produced through a High-Pressure High Temperature sintering technique, where CBN is mixed with carefully designed binder containing high temperature refractory materials. The mix was sintered under a pressure between 4–6 GPa and temperature between 1200–1600 °C. Tools were scaled up through design modification and keeping synthesis conditions similar to produce tools with similar thermal and mechanical properties and consistent properties helped achieving reproducible results in welding different thicknesses.

4 Weld Properties

Friction stir welds in steel are performed over the transformation temperature range of steel and so, with careful choice of the welding parameters, the scope exists to tailor the microstructure and thus properties of the welds made towards particular service conditions such as high strength, toughness, cryogenic service or fatigue resistance.

The resulting weld has a fine grained, forged microstructure rather than the large, columnar grained, cast microstructure typical of a traditional fusion weld and thus has excellent mechanical properties (strength, toughness, ductility) along with good resistance to fatigue and corrosion. The process is automated and also has considerable Health and Safety benefits.

Hardness testing has shown that the hardness of the welded material exceeds that of the parent metal, reaching values as high as 350HV2. The main driver behind the increased hardness is the reduced grain size. However, for certain combinations of welding parameters, the thermal profile in time and space results in the formation of harder steel phases. These results are confirmed by tensile tests which fail outside the welded material when no large defects are present in the weld. Tensile test pieces that were notched to force the failure to take place in the weld rather than the parent metal were failing at about 750 MPa, thus giving a measure of the weld metal strength. The welds have impact toughness between 80 and 120 J, depending on the welding parameters. The impact toughness is significantly increased compared to the base metal value of approximately 25 J, even when the welded material was much harder.

Fatigue performance of defect free welds have fatigue strength exceeding that of base material at FAT170, with similar slope of $m = 5$. Cracks initiate at the weld toe and grow perpendicular to the loading through the HAZ and base material. Fatigue strength of welds that contain defects is lower at FAT120, however, still higher than the design FAT class of FAT90. Rather than decreasing, which is typical for welds with defects, the slope increases reaching values as high as $m = 9$, meaning that fatigue performance at higher stresses is poor.

5 Process Economics

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?

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.

An 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.

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.

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.

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 h 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.

- 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?

6 The Route to Industrialisation

A key feature of the RESURGAM project has been the aim to develop an industrialisation strategy alongside the technical innovations needed to bring about the transfer of FSW technology from aluminium to steel. This was initially targeted on two specific applications in the shipbuilding sector, the modular fabrication of new ships and the at sea repair of existing ships. In addition, the consortium was also keen to explore the possibility of expanding the technique into other sectors. In parallel with this, effort has also been put into the regulatory requirements that will need to be satisfied if steel FSW is to become a widely used technique, with TWI leading discussions with classification societies such as Lloyd’s Register in order to facilitate the approval of the process for shipbuilding, and the creation of an ISO Working Group to develop an ISO standard for FSW of steel for more general use.

6.1 Modular Manufacture

Many ships are now 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 alternative technique for the manufacture of stiffened panels, maximising the benefits of friction stir welding, is by moving to the Integrally Stiffened Panel concept developed as part of Resurgam. The ISP 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 and a small demonstration panel made by the technique is presented in Fig. 1. 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.

In order to make the adoption of FSW easier, consortium member Stirweld has developed a friction stir welding head that can be retrofitted to an existing CNC milling machine. This is a much lower cost approach than buying a bespoke friction stir welding machine. Stirweld was created in 2017, based on a simple purpose: Make FSW accessible to any company already equipped with a CNC milling machine. Stirweld created an FSW head that can reach forging forces up to 25 kN. A Stirweld FSW head turns the position control of the CNC into a force control, and therefore protects the spindle of the CNC, and ensures a very high-quality weld. Of course, one of the top advantages of using an FSW head instead of buying a specific machine is the way much lower investment needed at first. And, furthermore, you can easily unmount the head, and use the regular functions of your CNC.

R & D is always ongoing at Stirweld, so many add-ons have been developed, such as temperature measurement system, milling add-on, automatic head drop off…etc. Based on this, Stirweld has designed and manufactured an FSW head, made to weld steel and meant to be used on huge CNC machines such as in drydock shipyards. Its forging force goes up to 50 kN, and its cooling system has been entirely re-designed to deal with high temperature reached during steel welding.

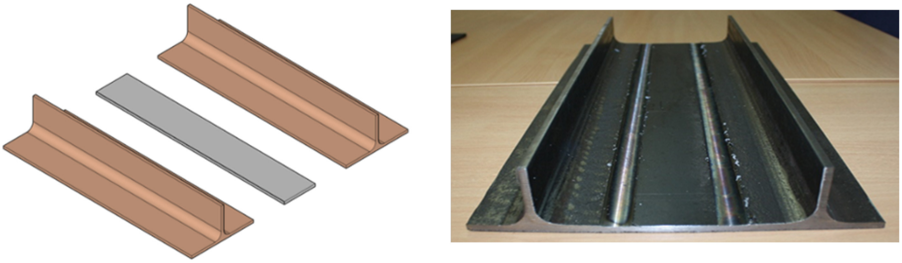

Fig. 1. Integrally Stiffened Plate demonstration fabricated by friction stir butt welding two rolled T sections to a steel plate. Source: Authors.

6.2 At Sea Repair

Resurgam looks to eliminate the costs and dangers associated with underwater repair 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. The weld repair robot, design and manufactured by Forth Engineering, operates using the validated weld parameters confirmed by TWI at their test facility. To which it exerts a 4000 kg plunge force, 246 Nm torque at 200 RPM (Ramped down from 800 RPM), driven at a linear speed of 260 mm/min, found to be a strong combination of output parameters when looking to install a mild steel repair patch of 4mm thickness, using a 6 m FSW tool supplied by Element 6.

The robot enacts its operational requirements by utilising a modular design, consisting of a compact FSW Head, linear drive track and tied together with a robust support body. Using 2 hydraulic motors to transmit the respective required welding spindle and linear drive speeds and 2 hydraulic cylinders to provide the requisite plunge force. As well as retractable rare earth magnet clamping assemblies, to locate itself onto the site of any prospective ship. All of which are connected through and remotely controlled by an intelligent hydraulic valve chest, programmed to drive the robot at the exact specified set points. The robot prototype has now been fully manufactured and has entered its testing phase, which will conduct numerous dry welds and subsequent wet weld tests. To not only confirm the suitability of the design's integrity, but also checks the designed equipment can also in fact delivery the required weld operational outputs, and ultimately create a Friction Stir Weld of acceptable quality that could be used in real life applications. And finally, develop a plan of residual work required to take this robot from a prototype, to a commercialised product that can start to be used in the field and realising its benefits (Fig. 2).

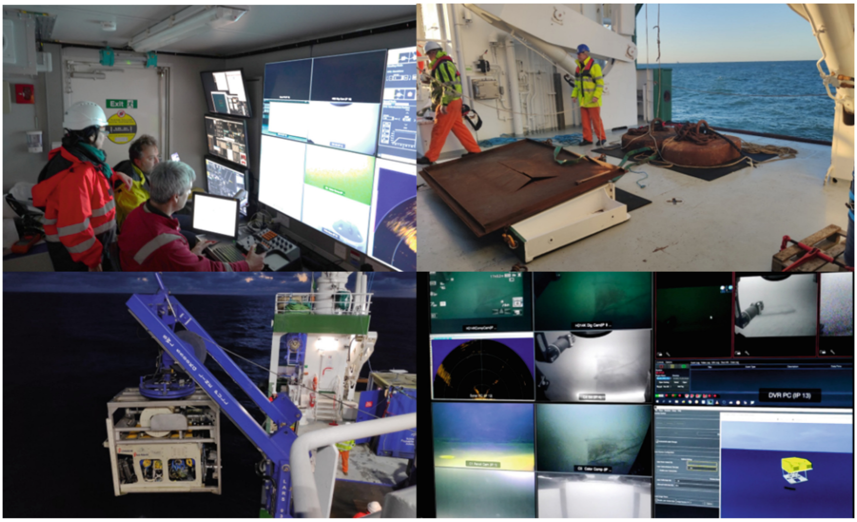

Fig. 2. Use of an ROV at sea to undertake scanning of an area of a ship to be repaired. Source: Authors.

6.3 Other Sector Applications

During the course of the RESURGAM project, particularly as the dissemination efforts began to report on the achievements being made, enquiries were received about friction stir welding of steel from other sectors, all interested in discovering if the advances being made in the shipbuilding application could be applied in their market sectors. These are briefly outlined below.

Civil Engineering: 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.

Defence: 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.

Nuclear: 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.

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. 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.

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. 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.

Pipeline Construction and Repair: Pipelines continue to represent one of the most efficient ways of transporting bulk fluids over long distances, both on land and subsea. 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 potentially 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 12 mm wall thickness), and pipes of wall thickness up to 25 mm could be welded by using a simultaneous internal and external welding system, each reacting its tool forces against the other system.

Steel FSW, in combination with 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 further area where FSW of steel has attracted interest is for the refurbishment of existing pipelines for the transport of new products for example CO2 in sequestration schemes, or the transport of hydrogen (sometimes in the form of 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 system 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 infrastructure 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 parameters 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 layer.

7 Conclusions

In summary, it can be stated that 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 a life of 60 m of weld in 6mm thick steel and a life of 30 m in 12 mm thick steel. Welds have been made in air and under water, 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, and stainless steels (316 and Duplex 2205) have been welded to carbon steel (S355).

Resurgam has therefore successfully demonstrated that not only can the technique of friction stir welding and all its benefits be transferred from aluminium to steel, but has also developed the tools and proof of concept equipment that will be required for the industrial adoption of the process. The objectives of achieving this for the transport sector have been met, and the process is now seeing widespread interest from many other markets, providing Europe with potentially world leading opportunities to enhance its manufacturing capabilities.