Technical Bulletin No. 1

Friction stir welding of steel for shipbuilding and marine applications

RESURGAM

Robotic Survey, Repair & Agile Manufacture

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Table of Contents

1. Executive Summary

Friction stir welding is a solid state joining process invented by TWI and originally used for making strong, lightweight, fatigue resistant, aluminium fabrications. Its success in that application has spurred demand for the process to be developed for joining steel, particularly for the European shipbuilding industry, and project RESURGAM was set up to achieve that. RESURGAM is a three year, EU funded, multi-national research initiative managed by the European Welding Federation (EWF) to develop the equipment, processes and qualification routes needed for fabricating ships and conducting underwater repairs of steel structures using FSW. This Technical Bulletin summarises progress made during the first six months of the project, specifically regarding the technical achievements in developing the FSW tools and welding techniques that provide the underlying process technology.

The objectives of the process development that forms Work Package 1 of the RESURGAM project are to:

1. Develop FSW tools suitable for welding marine grade steels in air and liquids;
2. Establish the performance (longevity and reliability) of FSW tools for steel used in air and water;
3. Establish the FSW process envelope for specific tool sizes in air and water;
4. Determine the weld properties of marine grade steels welded by FSW in air and water;
5. Develop a route map that will enable guidelines to be drawn up to allow the use of steel FSW for marine applications.

Work performed on the fundamental friction stir welding technology that underpins RESURGAM during the first six months of the project has shown that:

1. Steel up to 12mm thick can be friction stir welded by the tools developed by Element Six;
2. Butt welds in the grades of steel being targeted can be made whose strength is at least equal to that of the parent metal;
3. 2 dimensional lap welds suitable for making fully sealed patch repairs can be made through 6mm thick steel plate;
4. An integrally stiffened panel (ISP) can be made from rolled T sections and flat plate, reducing the number of welds required by half when compared with conventional welding techniques.

2. Introduction and the need for steel FSW

Friction stir welding 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.

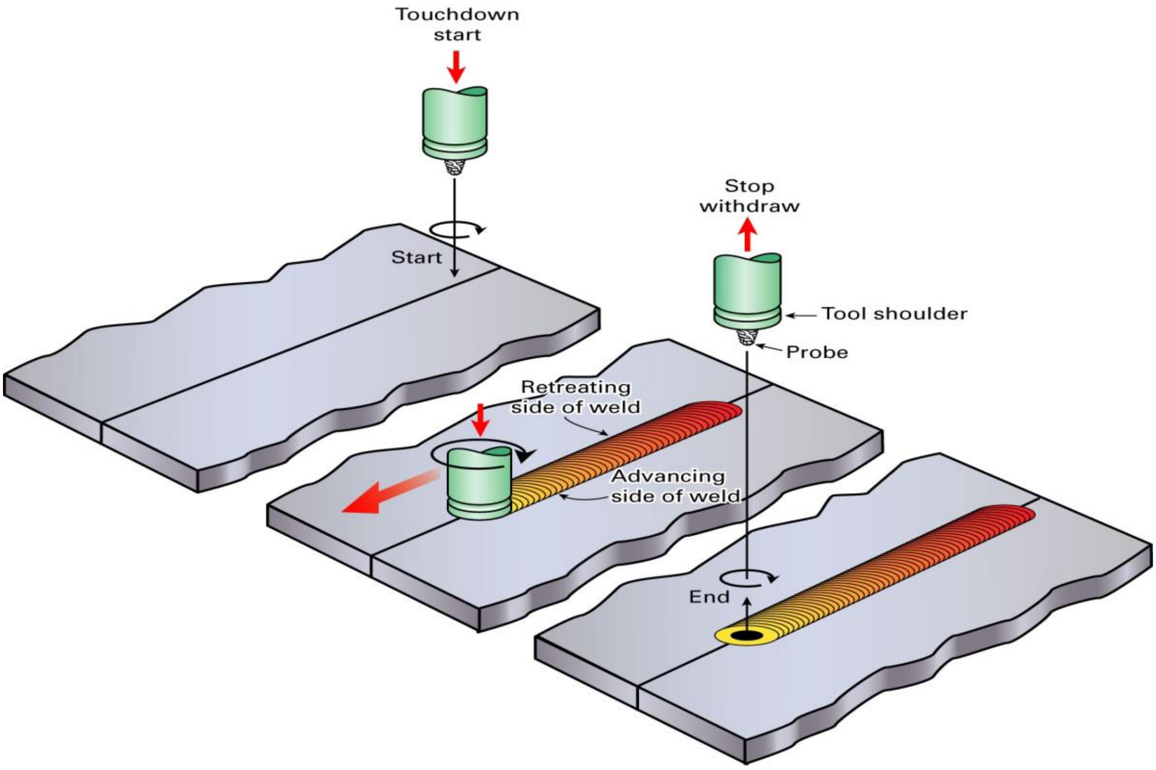

Figure 1 The basic principle of friction stir welding

FSW was quickly adopted as a fabrication technique for spacecraft, trains, shipping and automotive components, as well as electronics assemblies and consumer goods, all applications where aluminium joints needed to be made that were strong, tough, fatigue resistant and lightweight. Once the good mechanical properties of FSW joints were recognised, along with the benefits of the potentially low cost and automated means of creating them, users began to request that the process be developed for steel too.

An area where FSW in steel is likely to see early use is in shipbuilding and ship repair, for which the technology is being developed as part of the RESURGAM project. This 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. 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. 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. Examples of the tools are shown as Figure 2.

Figure 2. Element Six FSW tools for welding 6mm and 12mm thick steel.

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;
- Increase the thickness of steel that can be welded.

4. Process development for steel FSW

4.1. Preliminary tool evaluation

The prototype tools developed by Element Six for welding 6mm thick steel have been tested at TWI and shown to be consistent from batch to batch, and capable of producing defect free welds in carbon steel under several different testing conditions. These test conditions were:

Regimen 1: Multiple 2m welds

- Multiple tool plunges into cold, hard steel;
- Tool operating several minutes at elevated temperatures;
- Typical of pipeline welding, repair welds, assembly work.

Regimen 2: Multiple 5m welds

- Fewer tool plunges into cold, hard steel;
- Tool operating typically 20 minutes at elevated temperature;
- Typical of modular construction, pressure vessels.

Regimen 3: Fewer, but longer, 20m welds

- Two or three tool plunges into cold, hard steel;
- Tool operating at elevated temperature for an hour or more;
- Typical of panel production for ships.

The welds were made at a welding speed of 300mm/min in S355J2+N steel. Under all service conditions, the tools were capable of producing consistent, defect free welds. All tools tested reached an accumulated weld length of 40m, with no failures experienced during the trials. Testing is still ongoing to determine the ultimate longevity of the tools.

4.2. FSW objectives in project RESURGAM

A second series of tools, designed for welding steel 12mm thick, was then developed by Element Six and provided for further development of the FSW process at TWI. The objectives of the process development that forms Work Package 1 of the RESURGAM project are to:

1. Develop FSW tools suitable for welding marine grade steels in air and liquids;
2. Establish the performance (longevity and reliability) of FSW tools for steel used in air and water;
3. Establish the FSW process envelope for specific tool sizes in air and water;
4. Determine the weld properties of marine grade steels welded by FSW in air and water;
5. Develop a route map that will enable guidelines to be developed to allow the use of steel FSW for marine applications.

4.3. FSW parameter and process envelope development

As part of RESURGAM, process control parameters will be developed for steel that will allow good welds to be made in S355, S460 and DH36 steel, in both air and water, in thicknesses up to 12mm. These parameters will need to be suitable for the two application cases being considered under RESURGAM:

1. The fabrication of modular assemblies, e.g. stiffened panels, using a converted milling machine, for dockyard construction;
2. The welding of a repair patch, under water, to a representative section of damaged ship's hull.

4.3.1. Primary and secondary process control parameters

Parameters exist that, by varying them, allow control to be exerted over the FSW process. These may be termed Primary or Control parameters and include:

- Tool rotation speed
- Welding speed
- Tool plunge depth
- Tool tilt angle
- Tool down force (FZ)

During the weld, other parameters can be measured to give some degree of feedback as to how the FSW operation is proceeding. These are the Secondary parameters and include:

- Spindle torque
- Traverse force (FX)
- Lateral force (FY)
- Tool temperature
- Workpiece temperature

4.4. Operational constraints

Different constraints will apply to the two applications cases. It is envisaged that the force and torque requirements in particular will place limitations upon the thickness of steel that can be friction stir welded by a retro-fit head on a converted milling machine. Previous experience has shown that it is possible to friction stir weld 6mm thick carbon steels at industrially useful speeds (around 300mm/min) using axial forces of around 60 kN, and it is the aim within RESURGAM to try and develop tool designs and process parameters that will bring this force requirement down to around 40 kN for similar thicknesses of steel. Consideration will also be given to devveloping paramters that minimise heat transfer into the welding machine.

The FSW machine that is required to work under water will need to be marinised, and be capable of remote operation. These particular attributes will be addressed by consortium partner Forth Engineering, who have considerable experience in this type of work. It is likely that the machine will need to be hydraulically rather than electrically actuated, and the marine environment may present problems with control systems that rely on vision. The machine can probably be reasonably large, thus space is not likely to be a constraint, and cooling of the tool holder may not be a critical factor either as the marine environment will provide a large and effective heat sink.

5. Proof of concept demonstrations

5.1. Butt welds

The simplest weld geometry is a square butt weld where the two plates to be joined are laid edge to edge and joined by making a single pass with the FSW tool along the joint line. This has been demonstrated for DH36, S355 and S460 steel in two thicknesses, 6mm and 12mm. Figure 3 shows just such a weld made between two plates of 12mm thick S460 steel.

To represent a real world rather than a laboratory welding scenario, the plates to be welded were not cleaned and degreased, nor were the mating edges prepared. Despite being made through a layer of surface rust, the weld was smooth and regular with no toe flash or surface imperfections.

A macro-section through the weld showed there to be no internal defects and, under tensile testing, the cross weld test piece failed in a ductile manner in the parent metal outside the weld and heat affected zone. Test pieces cut from the weld at the weld start, middle and end all passed face and root bend tests.

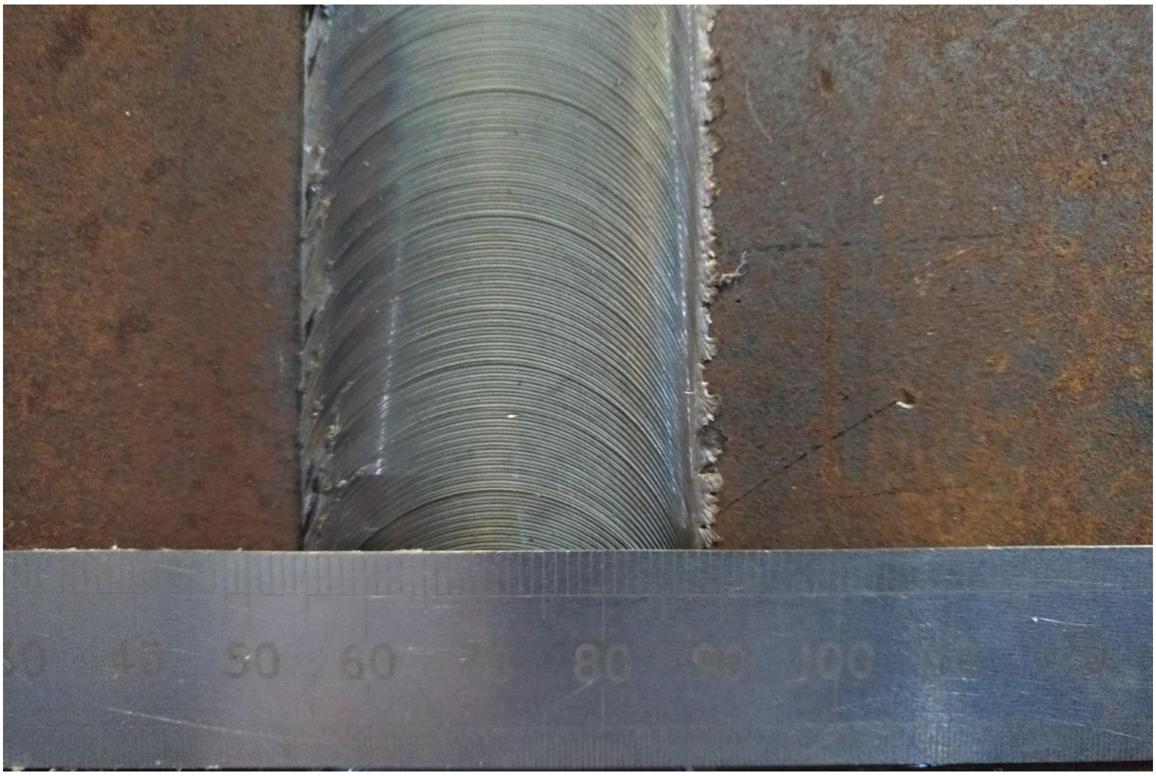

Figure 3. Surface detail of a friction stir weld in 12mm thick S460 steel.

More detailed mechanical testing of the welds, including hardness, toughness and fatigue testing will be undertaken by consortium member TUD (Technical University of Delft) at a later stage in project RESURGAM.

5.2. Lap welds

A second application of friction stir welding being developed in RESURGAM makes use of the ability of FSW to make good welds under water – or even other fluids such as oil. Consortium member Forth Engineering Ltd is developing a robotic system that will be capable of being deployed underwater to weld a repair patch over a damaged structure, such as a ship's hull, to effect a temporary or even permanent repair without the need for either dry docking the vessel or using a hyperbaric welding chamber and conventional welding techniques.

Such a weld is most easily achieved by making a lap weld through a steel patch placed over the damaged region of the ship's hull, and the feasibility of this has been demonstrated at TWI. Figure 4 shows a 4mm thick DH36 steel patch lap welded to a 12mm thick S460 steel hull plate using a 2D weld. The weld was made using a 12mm tool, so penetrating 8mm into the hull plate to provide a watertight seal. The weld was made through the primer coat of the patch, and the underlying hull plate was not cleaned or degreased prior to welding.

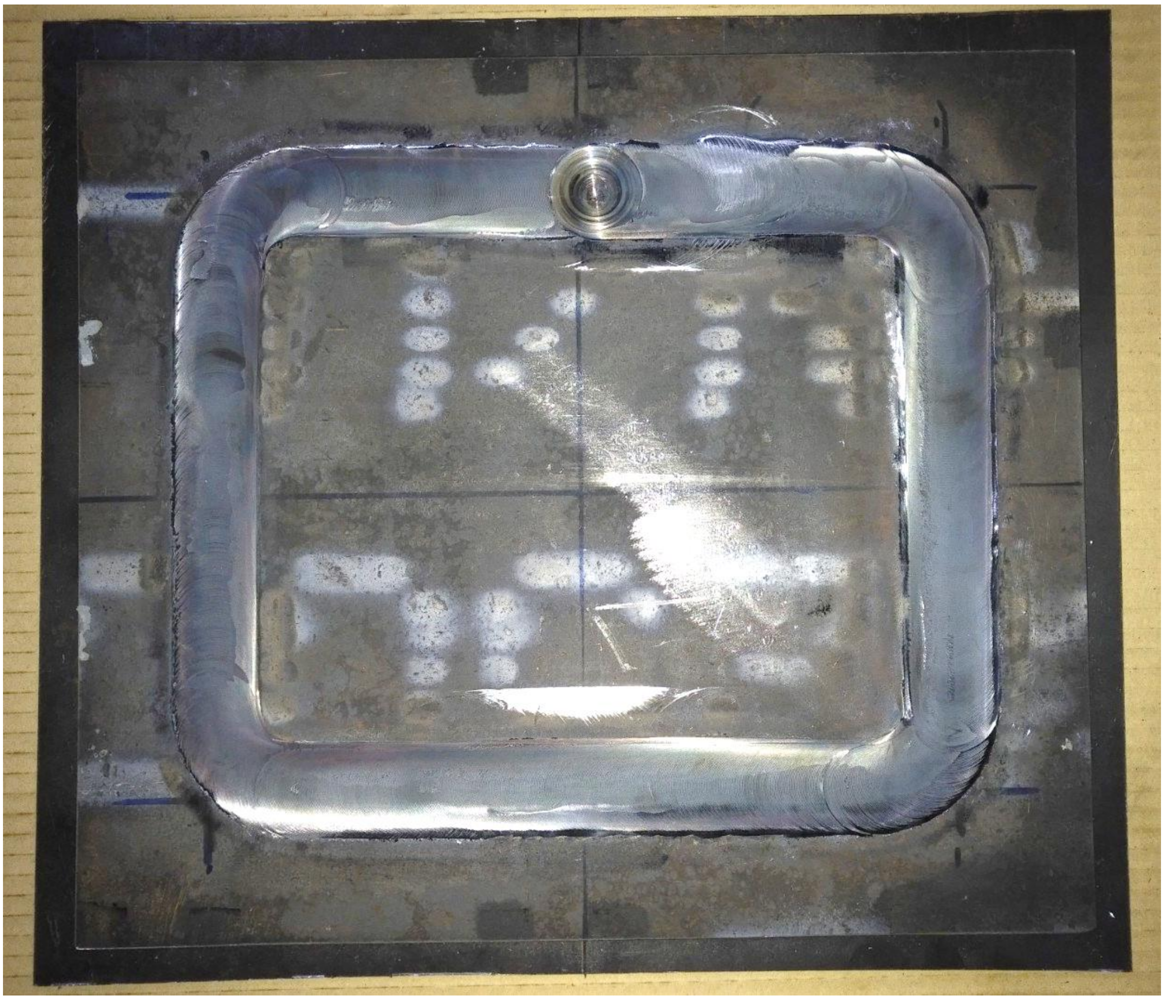

Figure 4. Image of a DH36 steel 'patch' lap welded to a 12mm thick S460 'hull' plate.

5.3. Integrally stiffened panels

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. 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 results in a fully forged structure that is potentially stronger, more fatigue resistant and less distorted than an arc welded equivalent.

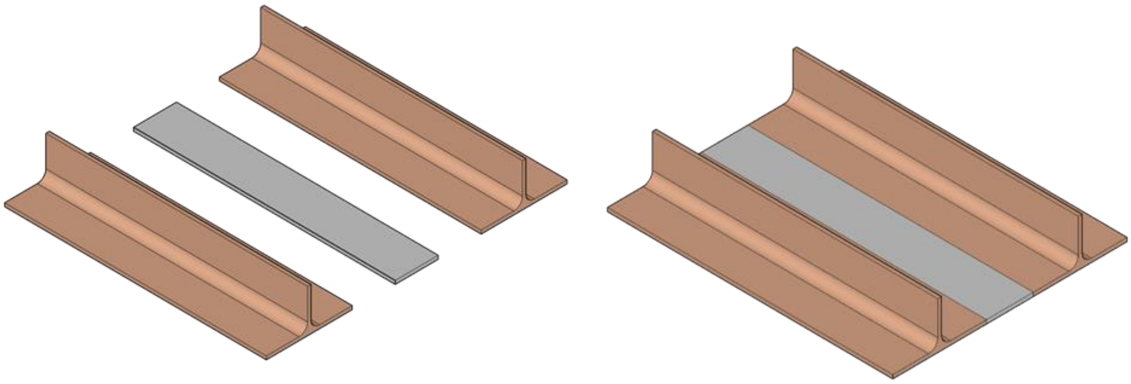

Figure 5. Concept of stiffened panel construction from rolled T sections spaced apart with rolled plate.

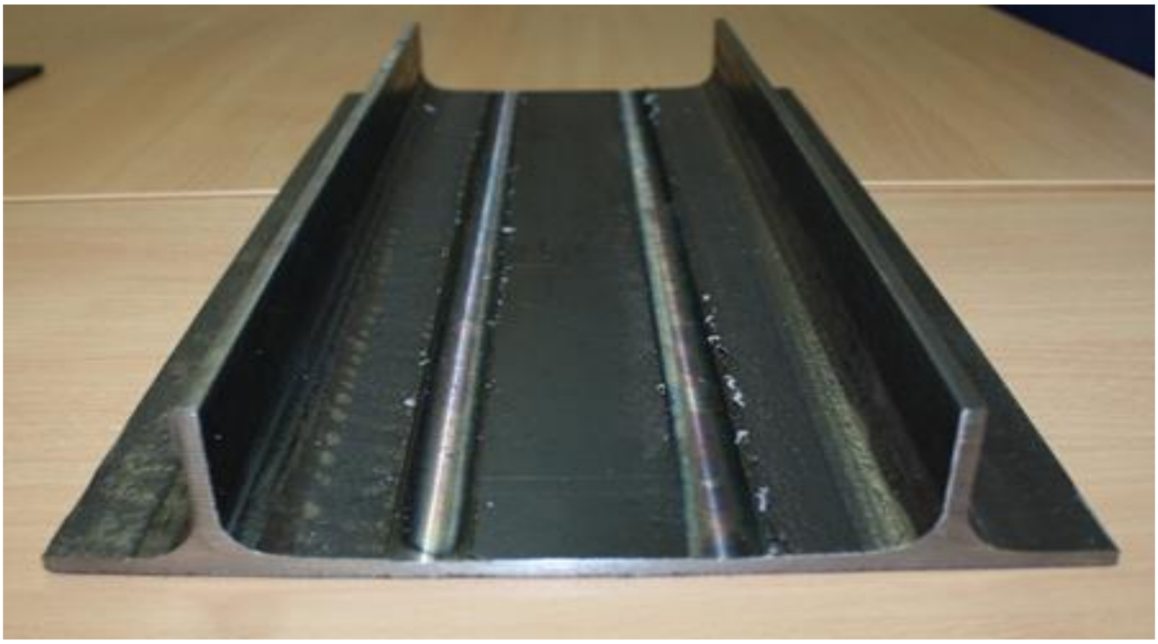

Figure 6. Integrally Stiffened Plate demonstration piece fabricated by friction stir butt welding two rolled T sections to a steel plate.

6. Metallurgical considerations

The fine grained microstructure seen in friction stir welds generally provides them with tensile strength properties closer to the parent metal than is typically the case with conventional fusion welding. With steel, this benefit is further enhanced by the fact that welding takes place in the transformation temperature range and careful selection of the welding parameters can exert a useful degree of control over the phase transformations that take place during the welding process. It is possible, for example to make welds optimised for strength or for toughness, or a combination of both, depending upon the service requirement. It is generally the case that friction stir welds in steel are found to be stronger than the parent metal in which they were made. Where friction stir welds are made between dissimilar grades of steel, for example a carbon steel and a stainless steel, the failure tends to occur in the weaker of the two parent metals and away from the weld zone.

During RESURGAM, TUD will investigate the microstructures generated in steel FSW and assess how they influence the mechanical properties of the welds made.

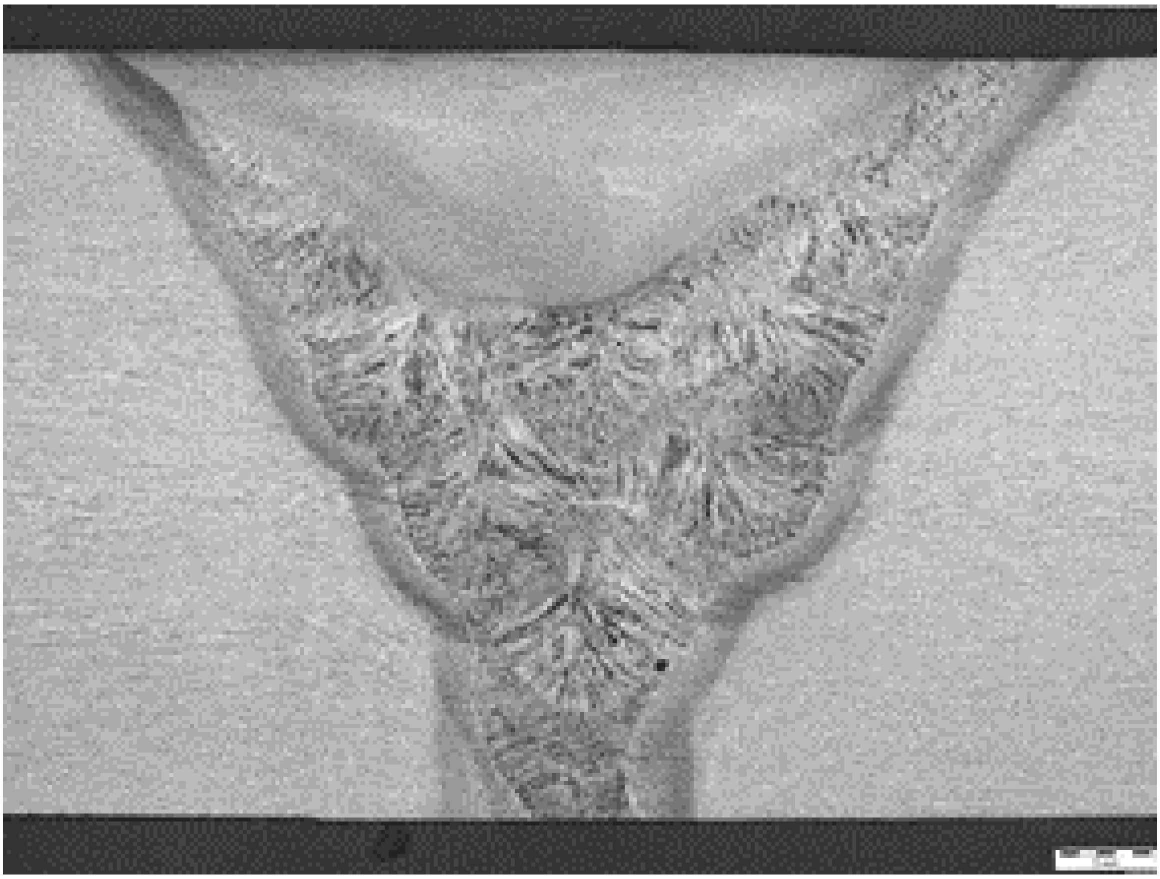

Figure 7. A metallographic section through a multi-pass arc weld in 20mm thick carbon steel, with the weld cap re-processed by FSW to show the difference in weld microstructure. The FSW has a fine microstructure close to that of the parent metal, whereas the arc weld has a coarse, cast microstructure.

7. Conclusions

Work performed on the fundamental friction stir welding technology that underpins RESURGAM during the first six months of the project has shown that:

1. Steel up to 12mm thick can be friction stir welded by the tools developed by Element Six;
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