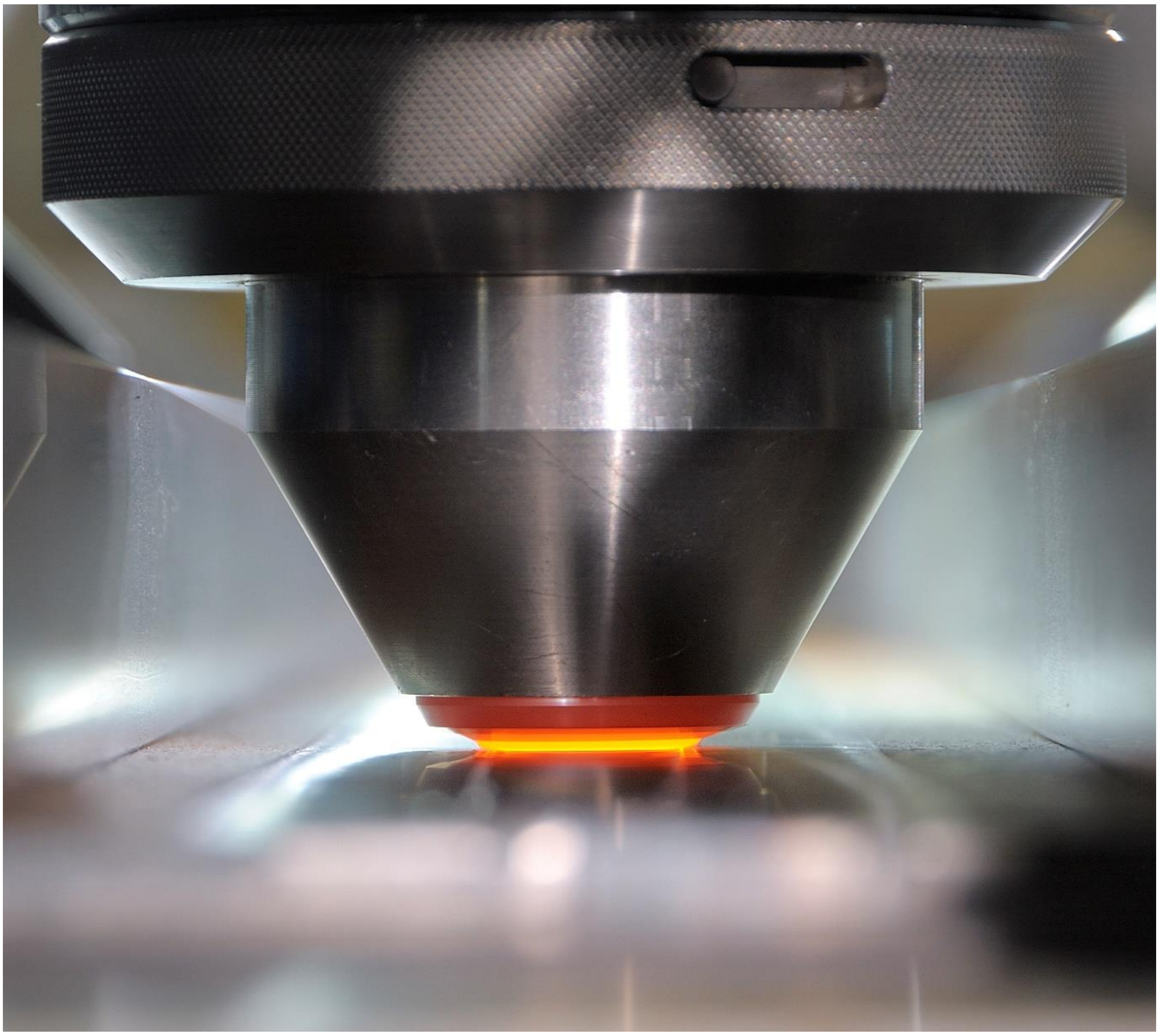

A comparison of friction stir and arc welding of carbon and stainless steels

Introduction

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 compares the emerging technology of friction stir welding in steel with the existing technology of arc welding, highlighting the advantages and disadvantages of each, and indicating where friction stir welding may offer advantages over its established competitor.

Project partners

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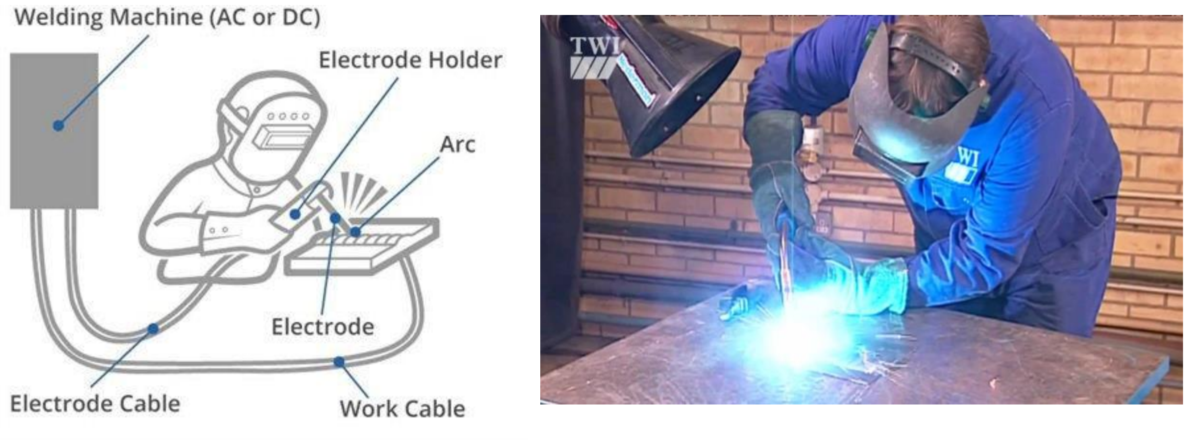
1. Overview of arc welding

Arc welding is a fusion welding process used to join metals. An electric arc from an AC or DC power source creates a gas plasma at very high temperature, which melts both the metal at the join between two work pieces as well as any additional filler metal.

Figure 1. Schematic of basic manual arc welding process, left and, right, a photo of manual arc welding.



The arc can be either manually or mechanically guided along the line of the join, while the electrode either simply carries the current or conducts the current and melts into the weld pool at the same time to supply filler metal to the join. Because the metals react chemically to oxygen and nitrogen in the air when heated to high temperatures by the arc, a protective shielding gas or slag is used to minimise the contact of the molten metal with the air. Once cooled, the molten metals solidify to form a metallurgical bond. It may be divided into two types, those methods that utilise consumable electrodes and those methods which do not use consumable electrodes. As all the techniques rely upon the melting of two workpieces at the joint line, followed by re-solidification of the molten metal to unite them, fusion welding is therefore similar to a casting process. The most common arc welding process variants are introduced briefly below.

Metal Inert/Active Gas Welding (MIG)

MIG/MAG welding uses an arc formed between the workpiece and a continuous wire electrode that is fed through the torch as well as a shielding gas to protect the base metals from contamination which may merely protect or also provide additional effects.

Shielded Metal Arc Welding (SMAW)

Also known as manual metal arc welding (MMA or MMAW), flux shielded arc welding, or stick welding, this is a process where the arc is struck between the metal rod (electrode flux coated) and the work piece, thus both the rod and work piece surface melt to form a weld pool. Simultaneous melting of the flux coating on the rod will form gas, and slag, which protects the weld pool from the surrounding atmosphere. This is a versatile process ideal for joining ferrous and non-ferrous materials with a range of material thicknesses in all positions, particularly in conditions where it is difficult to supply ancillary equipment.

Flux Cored Arc Welding (FCAW)

Created as an alternative to SMAW, FCAW uses a continuously fed consumable flux cored electrode and a constant voltage power supply, which provides a constant arc length. This process either uses a shielding gas or just the gas created by the flux to provide protection from contamination.

Submerged Arc Welding (SAW)

A frequently-used process with a continuously-fed consumable electrode and a blanket of fusible flux which becomes conductive when molten, providing a current path between the part and the electrode. The flux also helps prevent spatter and sparks while suppressing fumes and ultraviolet radiation.

Electro-Slag Welding (ESW)

A vertical process used to weld thick plates (above 25mm) in a single pass. ESW relies on an electric arc to start before a flux addition extinguishes the arc. The flux melts as the wire consumable is fed into the molten pool, which creates a molten slag on top of the pool. Heat for melting the wire and plate edges is generated through the molten slag's resistance to the passage of the electric current. Two water-cooled copper shoes follow the process progression and prevent any molten slag from running off.

1.1. Metal Inert Gas (MIG) welding

MIG welding is a welding process in which an electric arc forms between a consumable wire electrode and the work piece. This process uses inert gases or gas mixtures as the shielding gas. Argon and helium are typically used for the MIG welding of non-ferrous metals such as aluminium. The only difference between MIG and MAG is the type of shielding gas used.. These shielding gases are mixtures of carbon dioxide, argon and oxygen, for example:

- CO_2 , Ar + 2 to 5% O_2 ,
- Ar + 5 to 25% CO_2
- Ar + 10% CO_2 + 5% O_2.

The make-up of the shielding gas is important as it has a significant effect on the stability of the arc, the mode of metal transfer and the degree of spatter. The shielding gas also impacts the behaviour of the weld pool, with particular regard to the penetration and mechanical properties of the welded joint.

Advantages and disadvantages of MIG welding

MIG welding allows for the fast production of high quality welds and, due to a lack of flux being used, there is no chance of slag being trapped in the weld metal. The shielding gas protects the arc, meaning that there is little loss of alloying elements and limited weld spatter in certain metal transfer modes. MIG welding can be operated in several ways, including semi and fully automatically, and is a versatile process which can be used to join a variety of metals and alloys.

The disadvantages of MIG welding are that it cannot be performed in a vertical or overhead position without more complex welding power sources (eg pulsed current power sources), due to the high heat and fluid nature of the weld pool. Also, the equipment used by a MIG welder can be complex making it relatively bulky.

Advantages and disadvantages of MAG welding

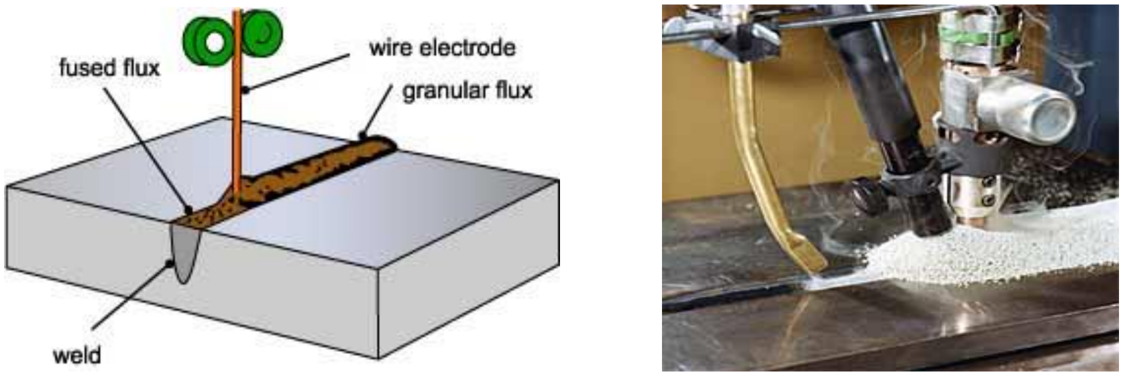
Because the weld area is protected by the shielding gas, MAG welding can work on relatively contaminated material. This is a fast welding process, which means that there is a lower heat effect on the surrounding material. MAG welding can be performed in all positions, making it one of the most widely-used welding processes, particularly in construction and general fabrication.

The disadvantages include the experience needed to perform this process correctly. MAG welding cannot easily be performed outdoors as the welding gas needs to be protected from the wind, while rust must be removed from the workpiece before welding commences. Flux cored arc welding is more suitable for outdoor applications or underwater welds, which can also be better performed using shielded metal arc welding. As with all arc processes, proper PPE must be worn and, in particular, eye protection.

1.2. Submerged Arc Welding (SAW)

Submerged-arc welding (SAW) is a common arc welding process that involves the formation of an arc between a continuously fed electrode and the workpiece. A blanket of powdered flux generates a protective gas shield and a slag (and may also be used to add alloying elements to the weld pool) which protects the weld zone. A shielding gas is not required as the arc is submerged beneath the flux blanket and is not normally visible during welding. This is a well established and extremely reliable method of welding.

Figure 2 Schematic of the SAW process, left, and, right, a photo of SAW



The electrode may be a solid or cored wire or a strip made from sheet or sintered material. The flux may be made by either fusing constituents to form a glassy slag (which is then crushed to form a powder) or by agglomerating the constituents using a binder and a corning process. The chemical nature and size distribution of the flux assists arc stability and determines the mechanical properties of the weld metal and the shape of the bead.

SAW is usually operated as a mechanised process. Welding current (typically between 300 and 1000 amperes), arc voltage and travel speed all affect bead shape, depth of penetration and chemical composition of the deposited weld metal. Since the operator cannot observe the weld pool, great reliance must be placed on parameter setting and positioning of the filler wire.

Although SAW can be operated with a single wire using either AC or DC current, there are a number of variants including the use of two or more wires, adding chopped wire to the joint prior to welding, and the use of metal powder additions. Additional productivity may be gained by feeding a small diameter non-conducting wire into leading edge of the weld pool. This can increase deposition rates by up to 20%. These variants are used in specific situations to improve productivity through increasing deposition rates and/or travel speed. Replacing the wire with a 0.5mm thick strip, typically 60mm wide, enables the process to be used for surfacing components.

SAW is ideally suited to the longitudinal and circumferential butt welds required for the manufacture of line pipe and pressure vessels. Welding is normally carried out in the flat (BS EN ISO 6947 PA) position because of the high fluidity of the weld pool and molten slag and the need to maintain a flux layer. Fillet joints may also be produced, welding in either the flat or horizontal-vertical (PB) positions.

2. Defects and problems in arc welding

Arc welding is akin to a casting process and so can exhibit virtually all the ***flaws*** and ***defects*** that can be found in a casting process. In addition, further problems can arise due to the peculiarities of the welding process itself, for example workpiece distortion, and issues arising from the arc, for example ultra-violet radiation damage, as well as the combination of metallurgies between filler metals and potentially dissimilar parent metals

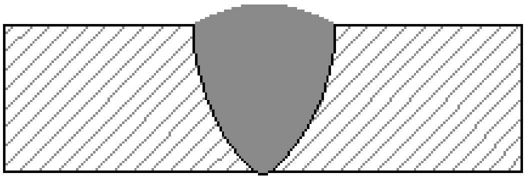
It is important to differentiate between flaws in a weld, which are imperfections that have no deleterious effect upon the weld properties, and defects, which are flaws that are deemed harmful to the weld and which are therefore unacceptable.

- A **flaw** is an unintentional imperfection in a welded structure which may or may not compromise the integrity of the structure. After a critical assessment, it could be regarded as a defect, or accepted as a tolerable flaw.

- A **defect** is an imperfection in a weld whose presence cannot be tolerated. It must be removed, or other remedial action taken.

A schematic of an ideal weld, in this case a single pass, butt or groove weld, is shown in Figure 3. The weld has been made from the upper surface in the horizontal position and is between two plates with a “V” groove preparation of their faying edges. Sufficient filler metal has been used to fill the groove without overfilling and the weld has fully penetrated the two plates. The weld is symmetrical about both sides of the joint line but asymmetrical through the plate thickness.

Figure 3 Ideal butt weld



Examples of some of the possible weld defects are discussed below. They may be divided into two broad types, internal and external.

External Welding Defects:

- Surface-breaking cracks
- Undercut
- Spatter
- Overlap
- Crater

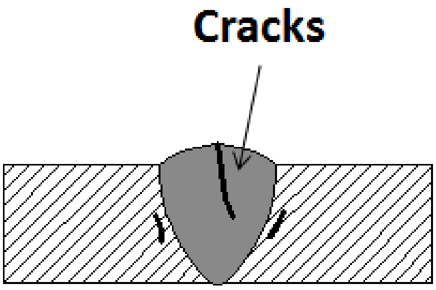
Internal Welding Defects:

- Porosity
- Slag inclusion
- Incomplete Fusion
- Internal cracking
- Incompletely filled groove or Incomplete penetration

A skilled manual welder using a properly tested and qualified procedure, or a well-designed and properly programmed automatic welding system, should be able to avoid all of these defects. However, the level of quality achieved varies from welder to welder, the environment in which the weld is taking place and the status of the welding equipment and consumables used.

2.1. Weld cracks

Figure 4. Weld cracking



Weld cracks are possibly the most undesirable of all welding defects. Welding cracks can be present at the surface, inside of the weld material or at the heat affected zones.

There are a number of different possible cracking mechanisms in welds, which depend on the material being welded. Two rough categories can be established:

Hot cracking – Is more prominent during solidification of weld joints where the temperature can change through more than 10,000 °C in a matter of seconds

Cold cracking – This type of crack occurs at the end of the welding process where the metal has solidified and the temperature is quite low. Sometimes cold cracking occurs several hours after welding or even after a few days.

Causes of weld cracking:

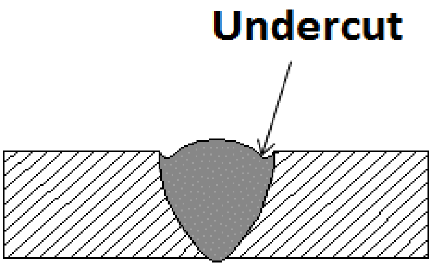
- Poor ductility of the given base metal.
- The presence of residual stress can cause a crack on the weld metal as it is pulled apart during cooling.
- The rigidity of the joint which makes it difficult to expand or contract during cooling.
- High contents of sulphur and phosphorus can cause weld cracking in sensitive materials such as austenitics.
- Contamination of hydrogen or moisture into the shielding gas while welding ferrous materials.

Remedies for weld cracking:

- Using appropriate filler materials may decrease the chances of cracking.
- Preheating the weld and reducing the cooling speed, for example by post weld heating or thermal blankets, helps in reducing cracking by removing hydgrogen
- Improve joint design to remove undesirable restraint which may lead to solidification cracking.

2.2. Undercutting

Figure 5. Weld undercutting



An undercut is formed when the parent material is melted away by the arc, and is not sufficiently fused as the the melt pool drops below the level of the surrounding parent metal and solidifies, effectively forming a notch in the surface of the weldment. This can lead to crack initiation and poor fatigue performance.

Causes of undercut:

- Arc voltage too high;
- Incorrect electrode used;
- Angle of the electrode is wrong;
- High electrode speed;
- Using a large electrode is also not advisable.

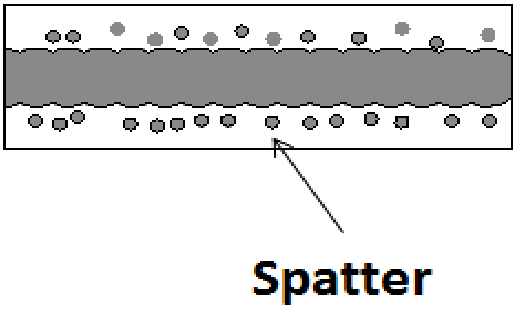
Remedies for undercut:

- Reduce the arc length;
- Reduce the arc voltage;
- Keep the electrode angle from 30 to 45 degree with the standing leg;
- The diameter of the electrode should be small;
- Reduce the travel speed of the electrode.

2.3. Spatter

When metal droplets are expelled from the weld and remain stuck to the surface, then this defect is known as spatter.

Figure 6 Weld spatter



Causes of spatter:

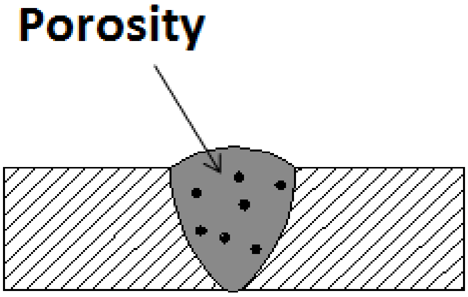
- Too high a welding current;
- Arc length too long;
- Incorrect polarity;
- Improper gas shielding.

Remedies for spatter:

- Reducing the arc length and welding current.
- Using the correct polarity;
- Increasing the plate angle and using proper gas shielding.

2.4. Porosity

Figure 7. Weld porosity



Porosity is caused by the absorption of nitrogen, oxygen and hydrogen in the molten weld pool which is then released on solidification to become trapped in the weld metal. Porosity can take several forms, including distributed bubbles, surface breaking pores, wormholes and crater pipes.

Nitrogen and oxygen absorption in the weld pool usually originates from poor gas shielding. As little as 1% air entrainment in the shielding gas will cause distributed porosity and greater than 1.5% results in gross surface breaking pores. Leaks in the gas line, too high a gas flow rate, draughts and excessive turbulence in the weld pool are frequent causes of porosity.

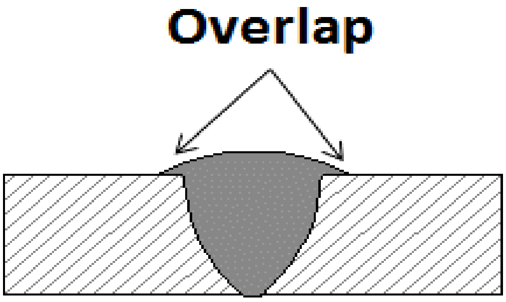
Hydrogen can originate from a number of sources including moisture from inadequately dried electrodes, fluxes or the workpiece surface. Grease and oil on the surface of the workpiece or filler wire are also common sources of hydrogen.

Surface coatings like primer paints and surface treatments such as zinc coatings, may generate copious amounts of fume during welding. The risk of trapping the evolved gas will be greater in T joints than butt joints especially when fillet welding on both sides.

2.5. Overlap

When the weld face extends beyond the weld toe, then this defect occurs. In this condition the weld metal rolls and forms an angle less than 90 degrees.

Figure 8 Overlap



Causes of Overlap:

- Improper welding technique;
- Electrodes too large;
- Welding current too high.

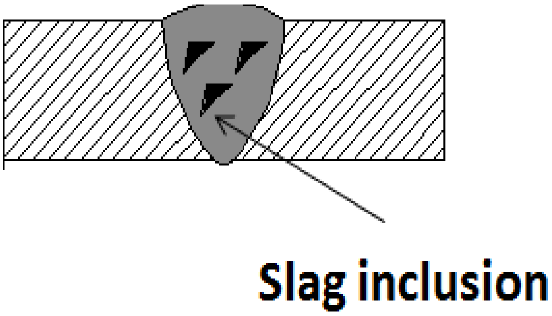
Remedies for Overlap:

- Using a proper technique for welding;
- Use small electrode;
- Less welding current.

2.6. Slag inclusions

If there is any slag in the weld, then it affects the toughness and metal weldability of the given material. Slag is formed on the surface of the weld or between the welding turns. The presence of slag decreases the structural performance of the weld material.

Figure 9 Slag inclusions



Causes of slag:

- Slag is formed if the welding current density is very small, as it does not provide the required amount of heat for melting the metal surface;
- If the welding speed is too fast then also slag may occur;
- If the edge of the weld surface is not cleaned properly then slag may form;
- Improper welding angle and travel rate of welding rod.

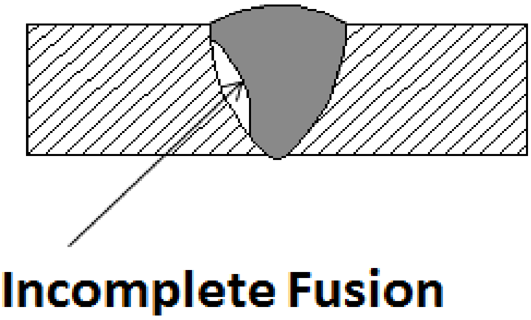
Remedies for Slag Inclusion:

- Increase the current density;
- Adjust the welding speed so that the slag and weld pool do not mix with each other;
- Clean the weld edges and remove the slags of previous weld layers;
- Have a proper electrode angle and travel rate.

2.7. Incomplete fusion

Incomplete fusion occurs when the welder does not accurately weld the material and the metal pre solidifies which leads to a gap which is not filled with the molten metal.

Figure 10 Incomplete fusion



Causes of Incomplete fusion:

- Too low heat input;
- When the weld pool is very large and runs ahead of the arc;
- When the angle of the joint is too low;
- Incorrect electrode and torch;
- Improper bead position.

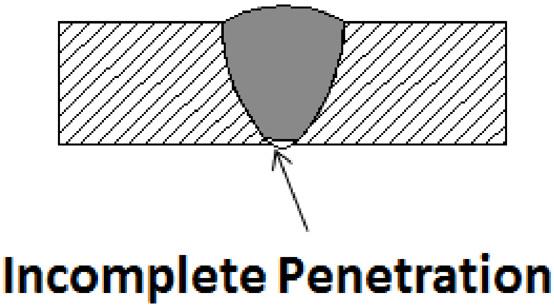
Remedies for Incomplete Fusion:

- Increasing the welding current and decreasing the travel speed helps in removing the chances of incomplete fusion;
- Reducing the deposition rate;
- Increasing the joint angle;
- Try to position the electrode and torch angle properly so that the edges of the plate melt away;
- Positioning the bead properly so that the sharp edges with other beads can be avoided.

2.8. Incomplete penetration

Incomplete root fusion is when the weld fails to fuse one side of the joint in the root. Incomplete root penetration occurs when both sides root region of the joint are unfused. Typical imperfections can arise in the following situations:

Figure 11 Incomplete penetration



- An excessively thick root face in a butt weld
- Too small a root gap
- Misplaced welds
- Failure to remove sufficient metal in cutting back to sound metal in a double sided weld
- Incomplete root fusion when using too low an arc energy (heat) input
- Too small a bevel angle,
- Too large a diameter electrode in MMA welding

Causes

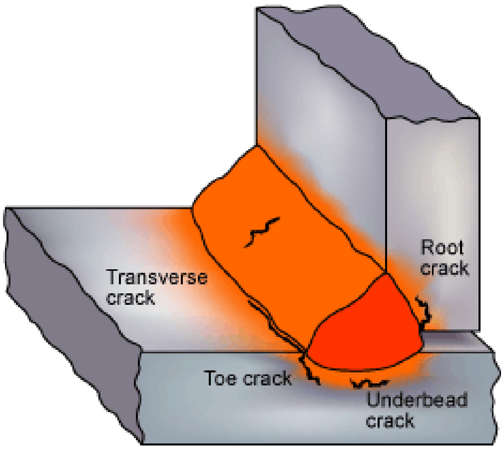
These types of imperfection are more likely in consumable electrode processes (MIG, MAG, FCAW, MMA and SAW) where the weld metal is 'automatically' deposited as the arc consumes the electrode wire or rod. The welder has limited control of weld pool penetration independent of depositing weld metal. Thus, the non -consumable electrode TIG process in which the welder controls the amount of filler material deposited independent of penetration is less prone to this type of defect.

2.9. Hydrogen cracking

Hydrogen can give rise to cold cracking and such cracks can be usually be distinguished due to the following characteristics:

- In C-Mn steels, the crack will normally originate in the heat affected zone (HAZ), but may extend into the weld metal;
- Cracks can also occur in the weld bead, normally transverse to the welding direction at an angle of 45° to the weld surface. They follow a jagged path, but may be non-branching.
- In low alloy steels, the cracks can be transverse to the weld, perpendicular to the weld surface, but are non-branching, and essentially planar.

Figure 12 Potential locations of hydrogen cracking



Typically, hydrogen dissolves into the weld pool and is then rejected into the Heat Affected Zone during solidification and transformation. Thermal stresses then arise from contraction, leading to cracking. Cracks which originate in the HAZ are usually associated with the coarse grain region. The cracks can be intergranular, transgranular or a mixture. Intergranular cracks are more likely to occur in the harder HAZ structures formed in low alloy and high carbon steels. Transgranular cracking is more often found in C-Mn steel structures. In fillet welds, cracks in the HAZ are usually associated with the weld root and parallel to the weld. In butt welds, the HAZ cracks are normally oriented parallel to the weld bead.

The principal source of hydrogen is moisture contained in the flux, i.e. the coating of MMA electrodes, the flux in cored wires and the flux used in submerged arc welding. The amount of hydrogen generated is influenced by the electrode type. Basic electrodes normally generate less hydrogen than rutile and cellulosic electrodes.

It is important to note that there can be other significant sources of hydrogen, e.g. from the material, where processing or service history has left the steel with a significant level of hydrogen or moisture from the atmosphere. Hydrogen may also be derived from the surface of the material or the consumable. Sources of hydrogen will include:

- Oil, grease and dirt;
- Rust;
- Paint and coatings;
- Cleaning fluids.

2.10. Carbon equivalent

In welding, equivalent carbon content (C.E) is used to understand how the different alloying elements affect hardness of the steel being welded. This is then directly related to hydrogen-induced cold cracking, which is the most common weld defect for steel, thus it is commonly used as a measure of weldability.

Higher concentrations of carbon and other alloying elements such as manganese, chromium, silicon, molybdenum, vanadium, copper and nickel tend to decrease weldability. Each of these elements tends to influence the hardness and weldability of the steel to different magnitudes, however, making a method of comparison necessary to judge the difference in hardness between two alloys made of different alloying elements. There are two commonly used formulas for calculating the equivalent carbon content. One is from the American Welding Society (AWS) and recommended for structural steels and the other is the formula based on the International Institute of Welding (IIW).

The AWS states that for an equivalent carbon content above 0.40% there is a potential for cracking in the heat-affected zone (HAZ) on flame cut edges and welds. However, structural engineering standards rarely use CE, but rather limit the maximum percentage of certain alloying elements. This practice started before the CE concept existed, so just continues to be used. This has led to issues because certain high strength steels are now being used that have a CE higher than 0.50% that have brittle failures.

$$CE = \%\mathrm{C} + \frac{\%\mathrm{Mn} + \%\mathrm{Si}}{6} + \frac{\%\mathrm{Cr} + \%\mathrm{Mo} + \%\mathrm{V}}{5} + \frac{\%\mathrm{Cu} + \%\mathrm{Ni}}{15}$$

The other and most popular formula is the Dearden and O'Neill formula, which was adopted by IIW in 1967. This formula has been found suitable for predicting hardenability in a large range of commonly used plain carbon and carbon-manganese steels, but not to microalloyed high-strength low-alloy steels or low-alloy Cr-Mo steels. The formula is defined as follows

$$CE = \%\mathrm{C} + \frac{\%\mathrm{Mn}}{6} + \frac{\%\mathrm{Cr} + \%\mathrm{Mo} + \%\mathrm{V}}{5} + \frac{\%\mathrm{Cu} + \%\mathrm{Ni}}{15}$$

In general, the weldability based on a range of CE values can be defined as follows:

Carbon equivalent (CE)	Weldability
Up to 0.35	Excellent
0.36–0.40	Very good
0.41–0.45	Good
0.46–0.50	Fair
Over 0.50	Poor

3. Overview of FSW

3.1. Introduction to the FSW process

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 13, 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.

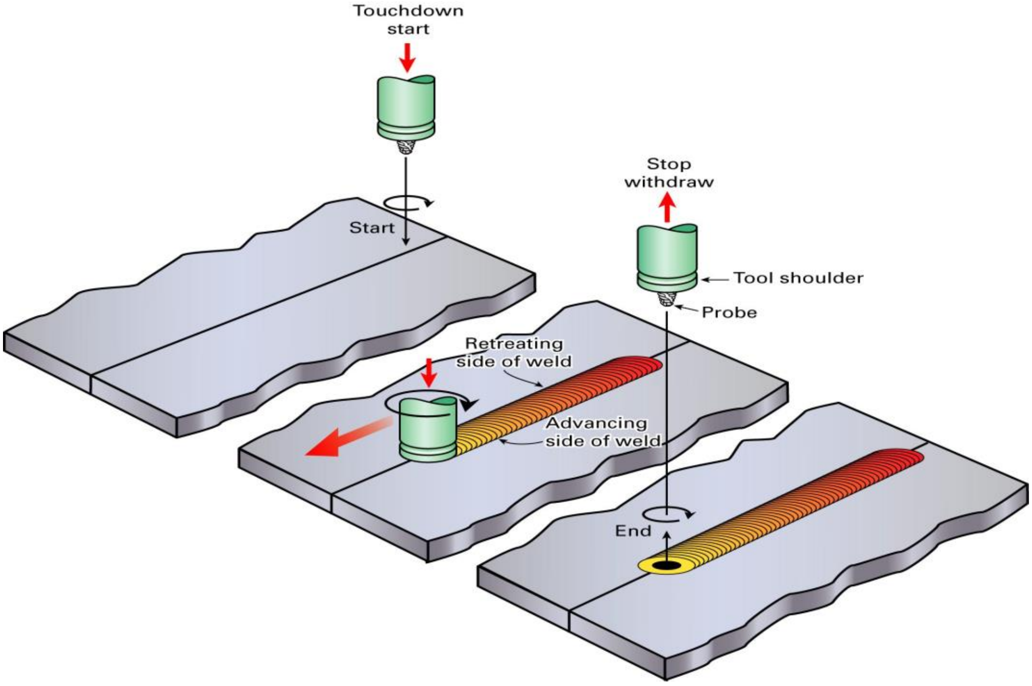


Figure 13 The basic principle of friction stir welding

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.

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.

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. In RESURGAM, these benefits are being extended to the welding of steel.

The main advantages of FSW can be summarised as follows:

- 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 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. RESURGAM now seeks to develop the friction stir welding process for the manufacture and repair of steel ships and other similar marine structures.

Figure 14. Rolled deck panel, left, and pre-fabricated hull module, right, both manufactured in aluminium by friction stir welding.

3.2. Design Implications

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 15.

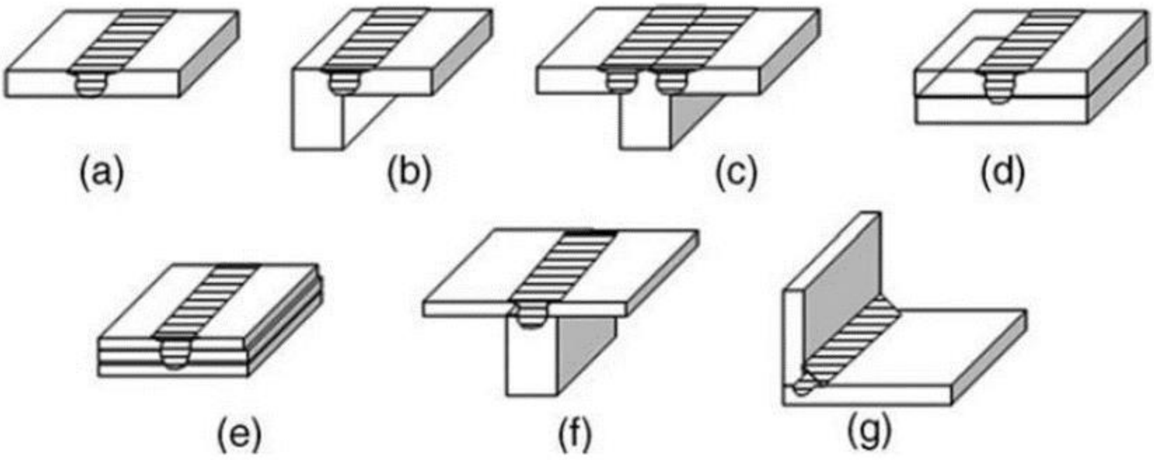


Figure 15. Weld geometries possible in friction stir welding

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.

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 16, and a small demonstration panel made by the technique is presented as Figure 17.

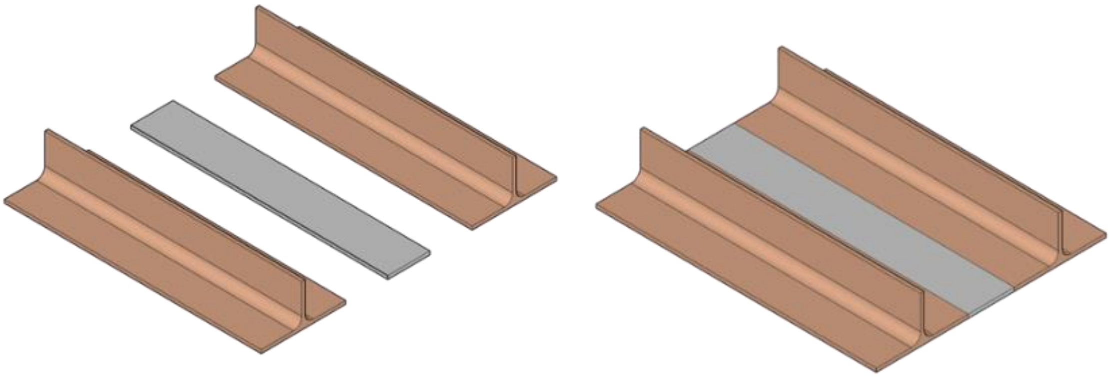


Figure 16. Concept of stiffened panel construction from rolled T sections spaced with rolled plate

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

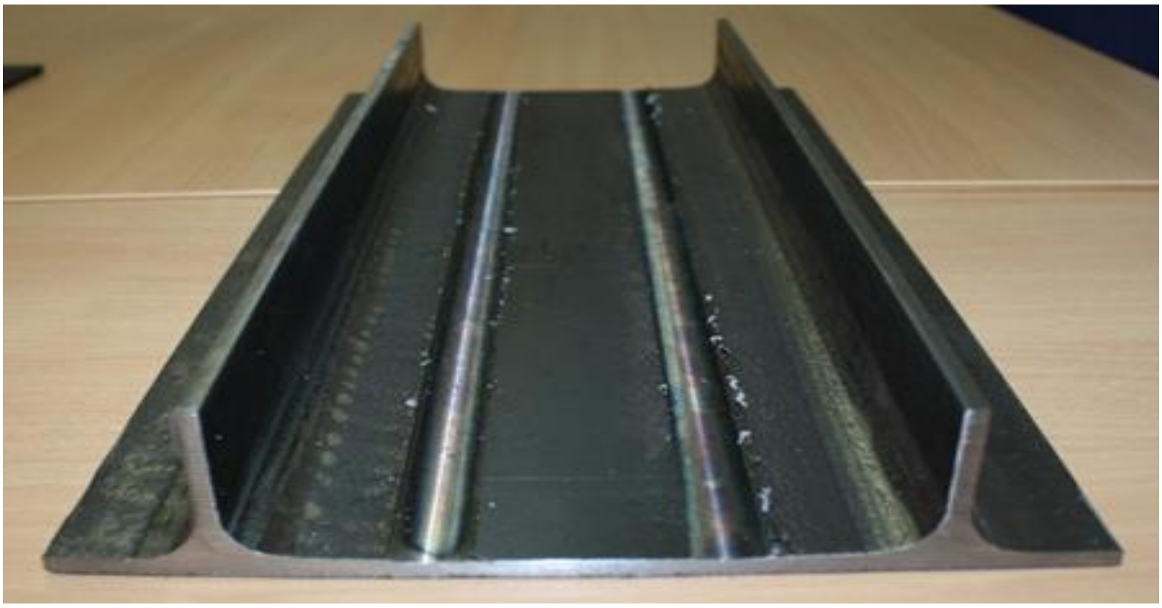


Figure 17. Integrally Stiffened Plate demonstration piece fabricated by friction stir butt welding two rolled T sections to a steel plate

3.3. 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.

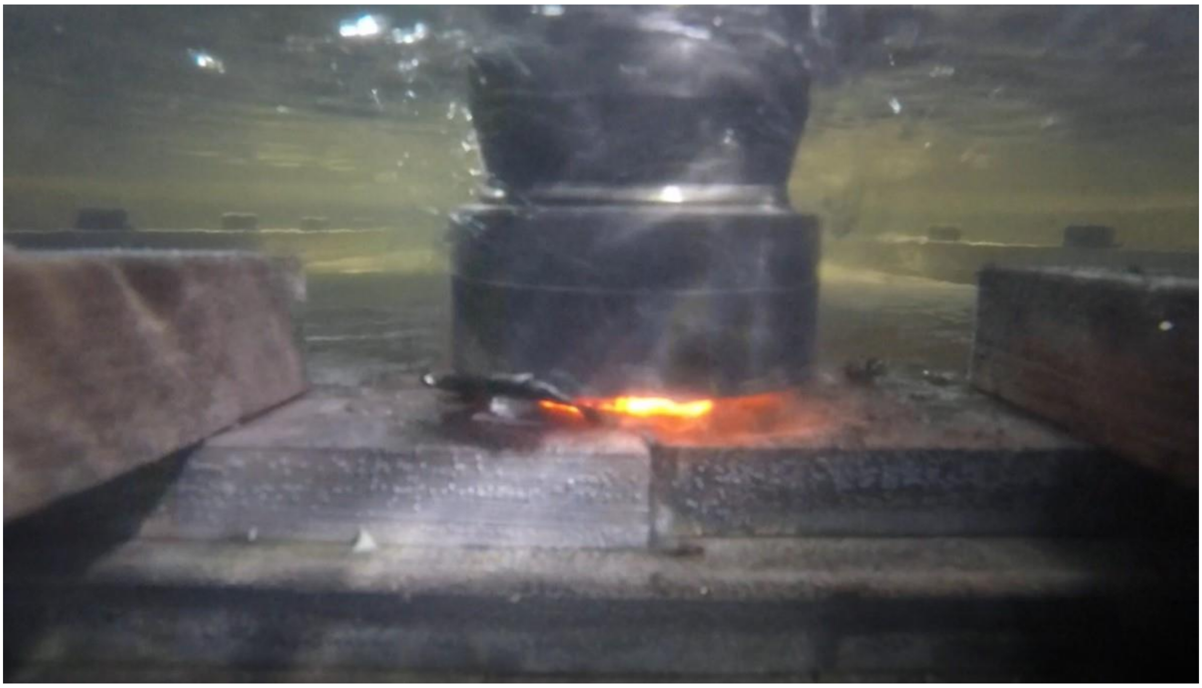


Figure 18. A friction stir butt weld being made under water to join two 12mm thick steel plates.

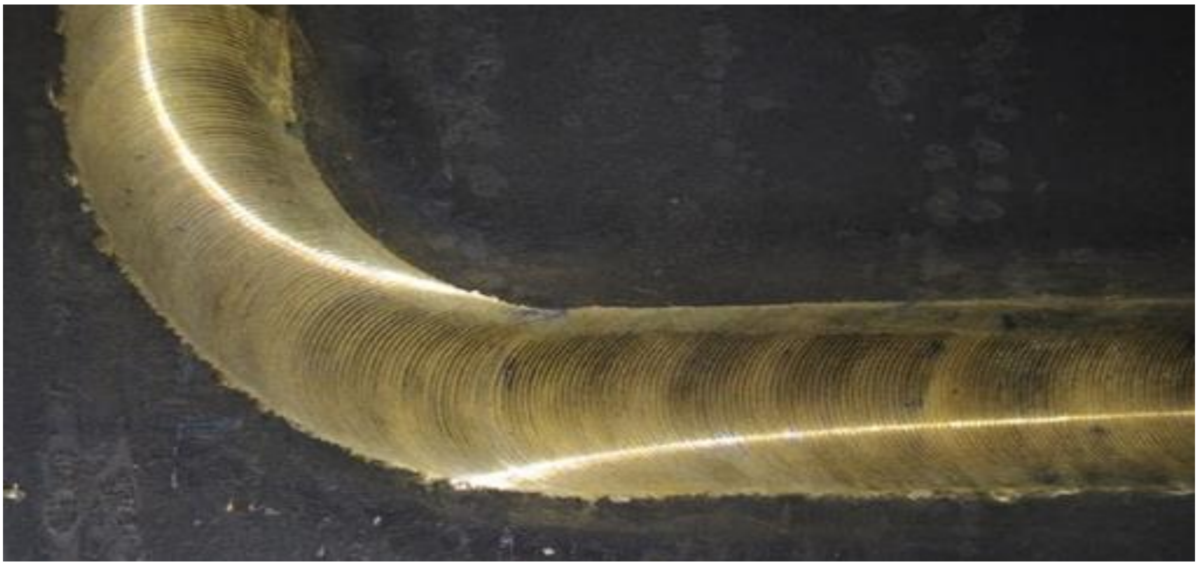


Figure 19. View of a 4mm thick plate lap welded onto a simulated damaged hull plate, under water

4. Defects in steel FSW

Though many of the casting type defects that can be encountered in arc and other fusion welding processes are not possible in friction stir welding due to the latter being a solid state process, friction stir welding can be susceptible to some other types of defects.

4.1. Lack of penetration

Friction stir welding is a mechanical process and relies on the frictional heat generated by a rotating tool to soften, plasticise and mix the metal being welded. The process was originally developed for welding aluminium, and then magnesium and copper. These metals are good conductors of heat, and are all relatively ductile, hence the plasticised zone around the tool where metal flow takes place extends beyond the region the tool physically occupies, including beneath the tip of the tool.

As a general rule of thumb for these metals, the length of tool probe is about 95% of the thickness of the component being welded as there is sufficient stirring beneath the probe tip to ensure a good bond is made at this location without the tool needing physically to pass through the metal at the weld root. The fact that the tool is a little shorter than the thickness of metal being welded also provides a safety margin in case the component being welded is not of uniform thickness. If the component is thinner than expected, for example due to rolling tolerances on wrought plate, a full length tool might well protrude through the component and weld it to the backing bar!

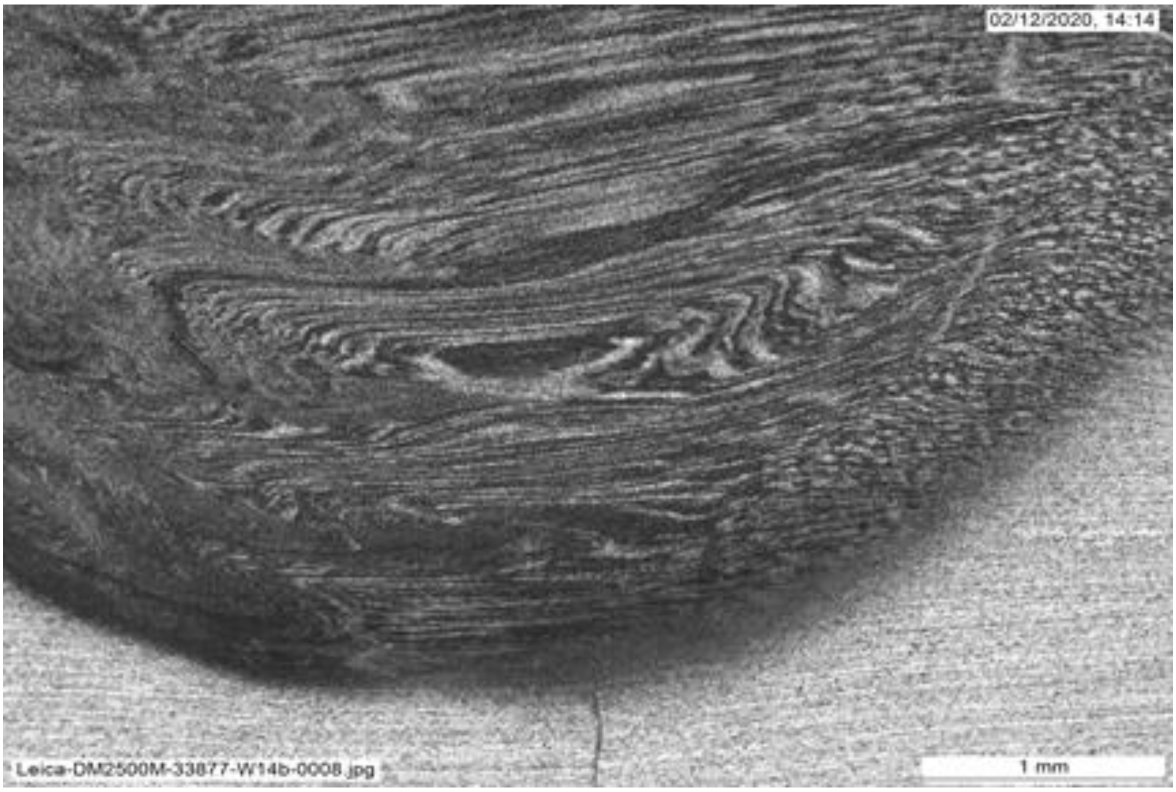


Figure 20. Lack of penetration defect at the root of a steel weld where the tool probe has not passed sufficiently close to the lower face of the plates being welded.

Steel is considerably less conductive than aluminium and so the heat generated beneath the tool shoulder does not propagate down towards the probe tip so readily as in some other metals. This, combined with steel's lower propensity to viscous flow, leads to a much smaller stir zone beneath the tool probe and so a potentially greater likelihood of there being an unbonded region at the weld root. An example of such a defect is shown in Figure 20. Here the weld zone is clearly visible, comprising a complex microstructure of stirred metal surrounded by the roll banded, elongated grain structure of the original parent metal. The original, unbonded, joint line is clearly visible beneath the stir zone.

Lack of penetration defects can be overcome by ensuring the length and position of the tool probe is carefully matched to the component thickness and geometry. Further mitigating measures could include the use of a thermally insulating back bar at the weld root or even a heated backing bar to enhance softening and metal flow at this region.

4.2. Cold lap

The low thermal conductivity of steel, around 45 W/m K compared with the 200 W/m K typical of many aluminium alloys, can also lead to cold lapping or lack of fusion type defects in the lower region of a steel weld, particularly as the thickness of the steel being welded increases. An example of such a defect is shown in Figure 21. Here, the weld on the left hand side has been made using welding parameters that did not generate sufficient heat at the lower portion of the stir zone and the metal there has not flowed adequately and fully fused to the adjacent parent metal.

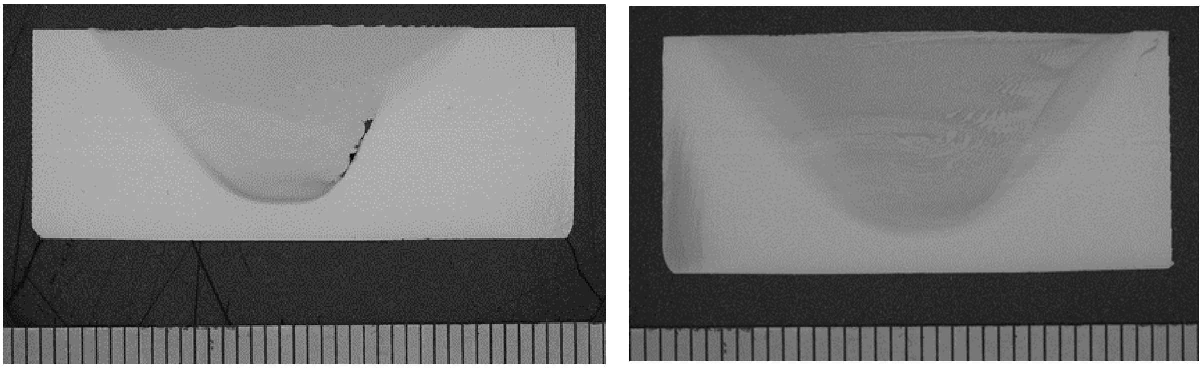


Figure 21. Examples of (left) a partial penetration friction stir weld pass in steel exhibiting a cold lap defect and, right, a similar partial penetration weld made with parameters adjusted to prevent the occurrence of such a defect.

Such behaviour is consistent with observations in steel test pieces where the upper portion of the weld fails in a ductile manner, with the fracture surface exhibiting an almost fibrous texture, but where the lower part shows a lapped, or in some cases an almost milled appearance. Such a failure surface is shown in Figure 22.

It is conjectured that in this lower region, though the steel within the weld zone is softened and physically stirred by the passage of the FSW tool through it, this stirred metal does not adequately fuse back to the colder parent metal alongside it and thus leaves lines of weakness in this region. When the weld is subjected to stress, for example in a bend or tensile stress, these weaknesses are the points which first begin to fail, leaving a characteristic surface whose features are related to the rotation rate of the tool.

In Figure 22 the lower region of the weld has a consistent, cyclic pattern that mirrors the profile of the friction stir welding tool that made it, supporting this mechanism. In addition, a micrograph through a portion of the same weld shows a defect, believed to be a crack, of a similar profile to the tool at the interface between the weld metal and the HAZ. This further suggests that there was inadequate fusion between the weld metal and HAZ at this position, and that the stresses induced by subsequent cooling were enough to initiate cracking at this point.

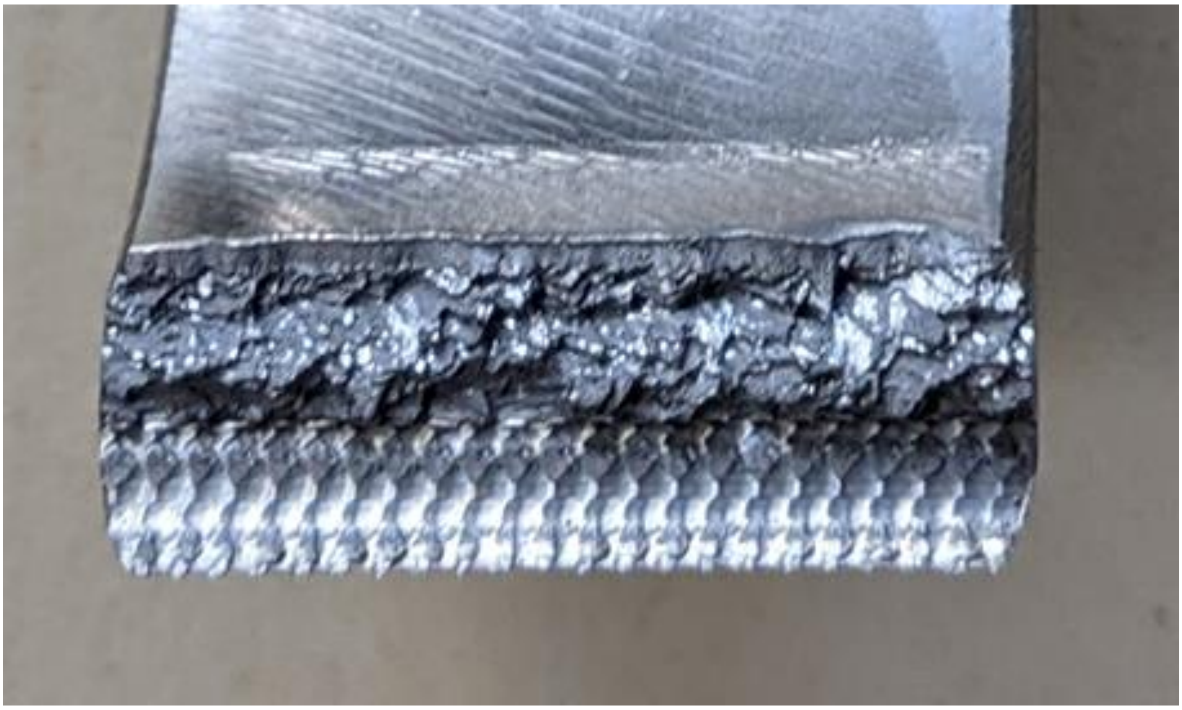


Figure 22. Failure surface of a defective friction stir weld showing cold lapping in the lower region

This type of defect can be overcome by using weld parameters that generate more heat in the lower portions of the weld, and by increasing the axial force on the tool to aid in consolidation of the plasticised metal.

4.3. Hot tearing

Hot tearing has been observed as a surface defect on friction stir welded steels, typically where high tool rotation rates have been employed. The heat generated by such parameters causes the steel to soften and lose strength, leaving it unable to support the imposed shear stresses and thus causing it to tear. This type of defect is more prevalent in the plunge and acceleration ramp region of a weld, where the localised heating is higher than in the remainder of the weld. Where this is the case, the hot tearing defect may diminish or even totally heal as the tool moves away from the plunge point and the local thermal field changes to give a cooler welding environment.

4.4. Undercutting

Where the tool plunge depth has been set too deep, usually in an effort to avoid a lack of root penetration, it is possible to generate an undercut at the surface where the shoulder compresses the plasticised metal and this then forms a weld surface that is below the adjacent parent metal surface. This type of defect can be avoided by ensuring the tool probe is of sufficient length to give a full penetration weld without the need to over plunge the tool.

4.5. Excessive flash

Where welding parameters are used that generate a lot of heat, particularly if combined with a tool using a small shoulder that is unable fully to constrain the softened metal, some of the plasticised steel can escape from beneath the shoulder and form a band of ‘flash’ alongside the weld.

5. Metallurgical evaluation of steel FSW

Friction stir welding is a solid state process and thus many of the problems regarding the weldability of steels that arise from solidification mechanisms in arc welding have not been observed. In addition, many of the thermal mechanisms that give rise to defects in arc welding of steel are absent, or far less severe, with friction stir welding due to the lower heat inputs observed.

Friction stir welding is a forging process and, in steel, is carried out with the steel heated into the transformation temperature range. FSW therefore has the potential to produce a wrought, fine-grained structure in the weld zone and some control can be exercised over the heating and cooling in order to generate particularly favourable microstructures. In many cases, it may be more informative to consider the conditions used for forging steel, for examples the temperatures, flow mechanisms and transformations possible, rather than trying to extrapolate from fusion welding practices. It also leads to the possibility that, by careful selection of the welding parameters and the composition of the steel to be welded, the microstructure and thus the properties of the weld can be tailored to a greater or lesser degree according to the needs of the application.

5.1. Microstructural comparison

Figure 22 shows a multi-pass arc weld made in 20mm thick carbon steel. The large columnar grain structure and HAZ associated with each weld pass are clearly visible, as is a shrinkage crack beneath the weld cap. The image on the right shows the effect of making a partial penetration friction stir welding pass through the upper region of the same weld. The shrinkage crack has been eliminated and the friction stir weld has generated a very fine-grained wrought microstructure akin to that of the original parent metal. The properties of this friction stir welded region are much closer to the parent metal than the properties of a conventional arc weld.

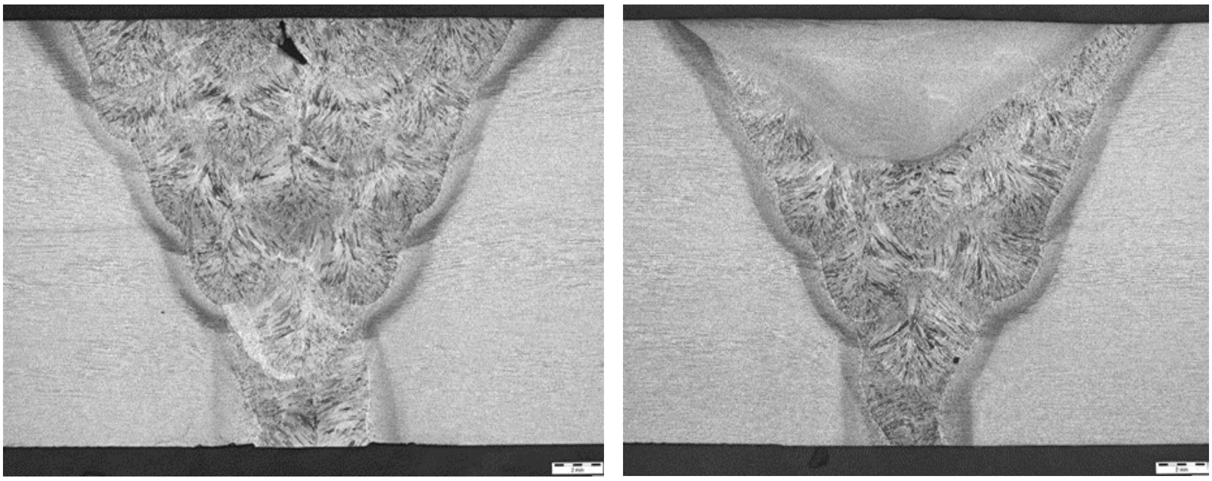


Figure 23. Left: a multi-pass fusion weld made in 20mm thick carbon steel. Right: the same weld with the cap re-processed by a friction stir welding pass.

Figure 24 shows a full penetration, square butt weld made in 8mm thick DH36 steel. It has a fine grained, wrought microstructure rather than the larger grained cast microstructure of a fusion weld. The Heat Affected Zone (HAZ) is also considerably smaller than that seen in a fusion weld.

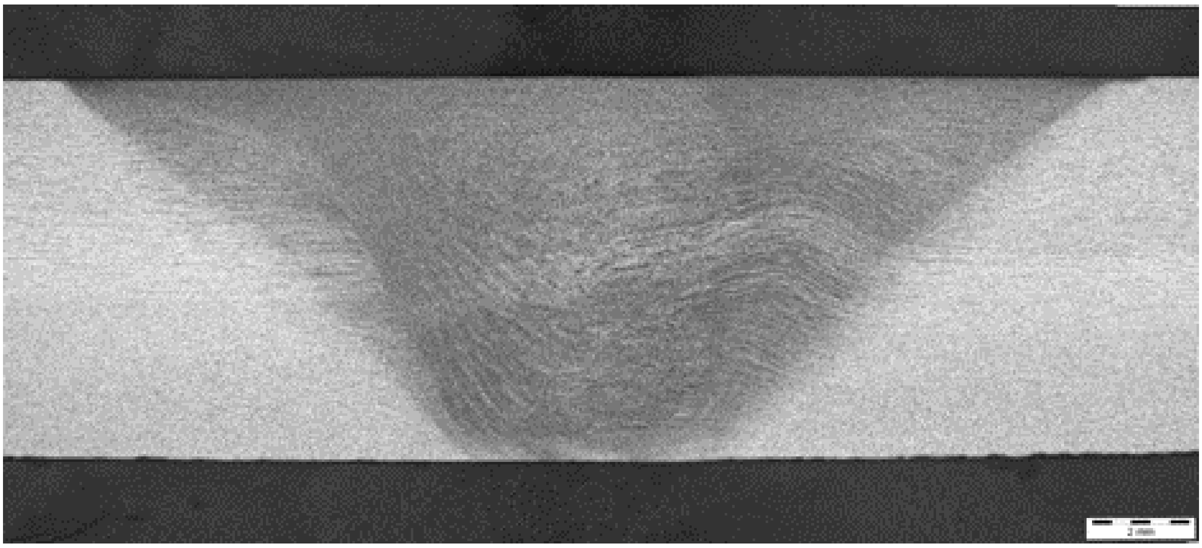


Figure 24. Friction stir butt weld made between two plates of 8mm thick DH36 steel.

That friction stir welding is a solid state process involving no melting is amply illustrated in Figure 25 which shows a friction stir butt weld made between tow very dissimilar grades of steel, one a carbon steel and the second a Duplex stainless steel. It can be seen that there has been no melting and alloying of the two grades of steel: the weld is clearly a mechanical mixing of the two. The phase balance in the welded region of the Duplex steel was reatined though the grain size of each phase was refined.

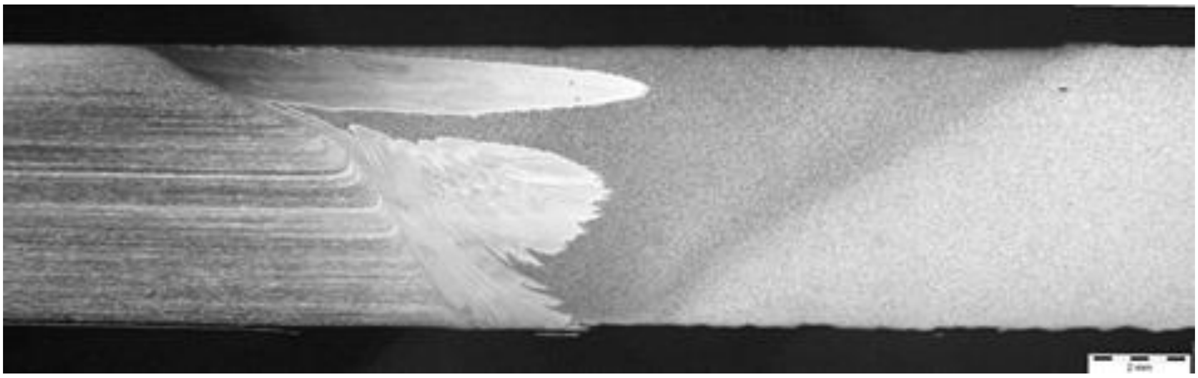


Figure 25. Macrograph of a friction stir butt weld made between Duplex stainless steel (left) and carbon steel, right.

A particular advantage of using FSW may arise from the emerging concerns regarding the release of hexavalent chromium and other heavy metals during the fusion welding of stainless steel. The risks of such releases have not been fully quantified and are thus open to challenge but, being a solid state process that produces no fume, FSW eliminates this potential source of hazard and allows welders to work unencumbered by the need to wear respiratory protection or use fume extraction systems

5.2. Weld properties

5.2.1. Strength

Early work in 12mm thick S355 and S460 steel undertaken at TWI has shown that cross weld strength in tensile test pieces was greater than that of the parent metal. Figure 26 shows a friction stir weld in 12mm thick S460 steel, made in air, which has been cut into sections and subjected to tensile testing. The position of the weld is marked in red.

All the standard, cross weld tensile test pieces (silver in colour) failed in the parent metal metal at 595 ± 7 MPa. A number of test pieces (dark coloured samples) were notched to force failure to occur in the weld metal. These failed at 760 MPa, indicating the weld metal was approximately 25% stronger than the parent metal. In both cases, consistency along the weld was excellent.

Figure 26. A friction stir weld in 12mm thick S460 steel sectioned and submitted to cross weld tensile testing.

5.2.2. Hardness

Midplate hardness distribution was tested for 6mm thick S355 or S460 FSW joints with various welding parameters at a tool shoulder diameter of 20 mm. The results are depicted in Figure 27. Welding parameters were chosen relative to some reference, referred to as ‘mid’. In all cases, hardness in the stir zone, thermo-mechanically affected zone and heat-affected zone were elevated with respect to the base material.

Peak hardness values in the weld zone range from approximately 220 HV30 to 370 HV30, depending on welding parameters. Higher welding speeds result in higher hardness values due to the heat source moving away more quickly, resulting in a higher cooling rate and possibly the formation of some bainite and martensite. However, for constant welding speed, higher rotation speed also results in higher hardness values suggesting an effect on the cooling rate as well. Some scatter is observed for welds with certain welding parameters, which is thought to occur due to the microstructure of these welds consisting of different steel phases.

Peak hardness values were observed on the advancing side for some welds and on the retreating side for others, although a slight preference seems to exist towards the advancing side. A slight dip in hardness is sometimes observed in the weld centreline. The weld cools from the outside inwards resulting in a higher cooling rate at the edges of the weld and therefore increased hardness. A drop of hardness is often observed in the transition from thermo-mechanically affected zone to heat-affected zone at the advancing side, suggesting less heat input in the heat-affected zone of the advancing side compared to the retreating side. This would also explain the increased cooling rate and thus hardness values at the advancing side compared to the retreating side.

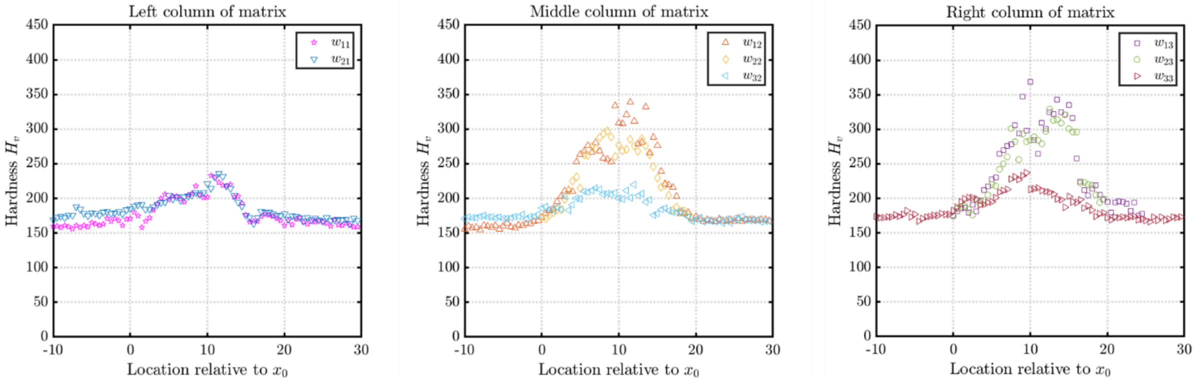


Figure 27. Hardness values measured in friction stir welded steel.

5.2.3. Toughness

Depending on the welding parameters used, the weld microstructure comprises different volumetric compositions of steel phases including ferrite, pearlite, acicular ferrite, and possibly some bainite and martensite. Usually, the presence of martensite in a weld is considered to have a negative effect on the toughness of the welds. However, with friction stir welds the very small grain and lath size of the martensite appears to counteract that effect, resulting in a weld that can be tough as well as hard and strong. This is particularly noticeable in welds that have been made with a double pass: the metal that has been stirred – effectively forged - twice can exhibit considerably enhance toughness compared with the parent metal. Figure 28 shows the results obtained from comparative impact testing of three friction stir welds and the associated parent metal.

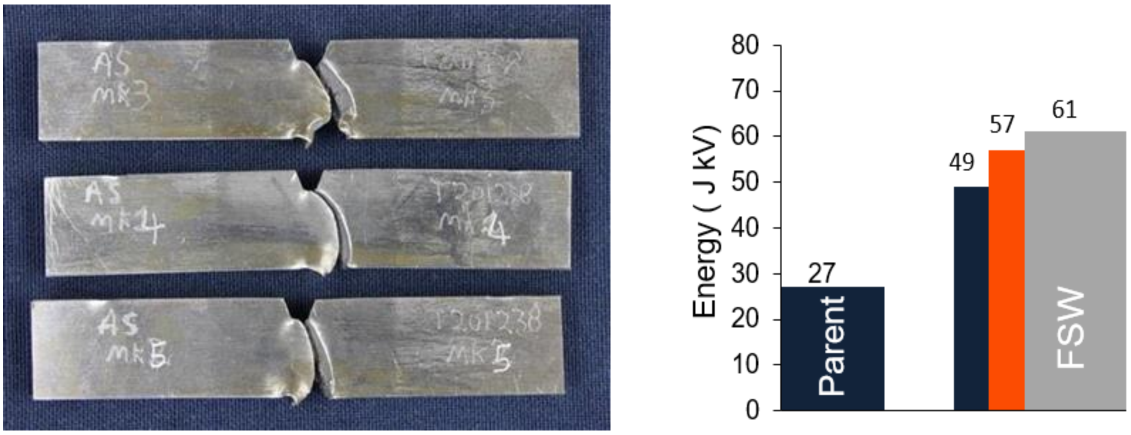


Figure 28. Charpy impact test pieces and results

5.2.4. Fatigue

Fatigue tests were undertaken for 6mm thick S355 and S460 FSW joints with various welding parameters. The results are depicted in Figure 29. Results are displayed on an SN-curve, with the nominal stress range on the y-axis and the amount of cycles to failure on the x-axis. Some tests were stopped before failure, referred to as runouts, and shown as open markers. A least-squares regression analysis excluding runouts was used to determine the slope m, fatigue strength log (C) and scatter σ. Slope m provides information about the fatigue damage mechanism, fatigue strength parameter log (C) is the x-axis intercept at that slope and σ the scatter in terms of lifetime.

The two welds with the most heat input (mid rpm, low welding speed and high rpm, mid welding speed) show similar slope and scatter, with behaviour close to that of base material. The welds with less heat input show progressively higher slopes, indicating macro plasticity, and higher scatter. Colder welds are vulnerable to a lack of sidewall fusion, resulting in a defect at the lower advancing side of the weld. This defect, which is not uniform along the length of the weld resulting in higher scatter, is the cause of the macro plasticity-induced crack growth. With the exception of the coldest weld in this series (mid rpm, high welding speed), all welds outperform the FAT80 design curve, which is the design curve for transverse arc-welded butt joints.

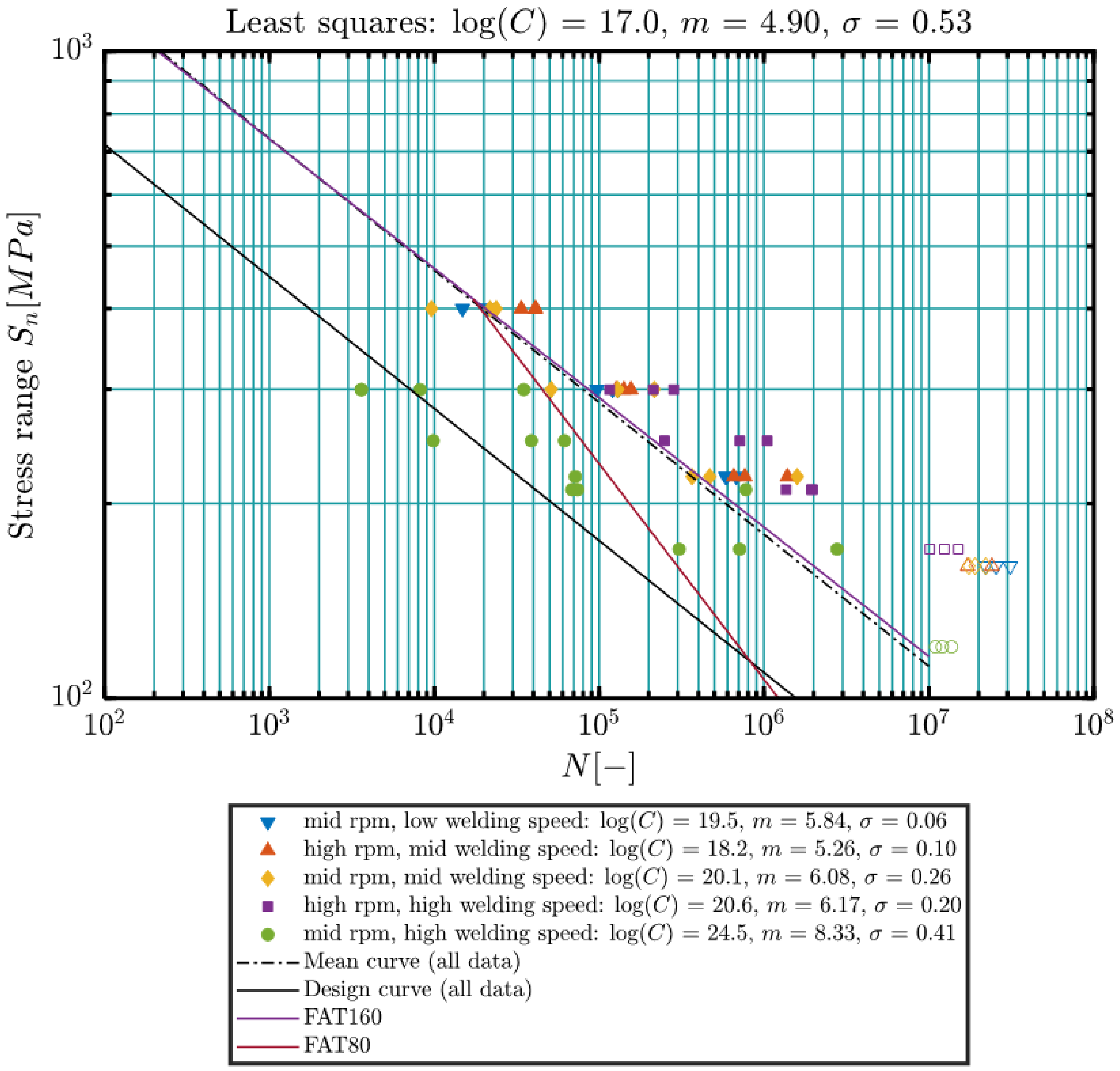


Figure 29. Fatigue test data for FSW steel

6. Further benefits of FSW in steel

The friction stir welding process has additional benefits beyond the purely technical ones of producing high quality welds across a wide range of materials. The more significant of these are summarised briefly below.

6.1. Economic

All the benefits of the 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 appears 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 fuel tank with other processes?

If one considers the true costs of welding fabrication, then an automated, mechanical process that produces high quality, tough, strong, fatigue resistant, autogenous welds 24 hours per day may already be cost competitive in many applications and, as the tooling technology matures, the friction stir welding costs are likely to reduce further.

Figure 30. Surface of an arc weld showing spatter and unevenness.

Figure 31. Surface of a friction stir weld

6.2. Health and safety

Friction stir welding has been demonstrated over many years to be a generally safe process. As it is conducted by mechanised systems and performed in the solid state the exposure of welders to liquid metal is eliminated. Further benefits include:

- Reduction of potential for thermal injuries: unlike fusion welds, friction stir welds cool rapidly due to the presence of large heat sinks (backing bar and clamping systems) and thus the potential for burns from hot metal is very much reduced;
- No arcs are struck, therefore the potential for ultra-violet burns and 'arc eye' induced blindness is eliminated;
- No radio frequency radiation is generated;
- No welding fume is generated, therefore respiratory hazards such as the inhalation of heavy metal fume is eliminated. This may become even more important in the future with increasing concerns over the release of hexavalent chrome ions when arc welding stainless steels;
- Plate edge preparation is often not a critical part of the FSW process, thus reducing the need for cutting and grinding, thereby reducing exposure of workers to both cutting and vibration induced injuries;
- FSW produces a relatively clean, spatter free weld surface, thereby further reducing the risk of grinding related injuries during post weld procedures.

Figure 32. Arc welding showing PPE needed against UV and thermal radiation

6.3. Environmental

Friction stir welding can bring a number of environmental l benefits when compared with traditional arc welding.

- No flux is used during FSW, hence no used flux is sent to landfill.
- As FSW involves only the application of localised heating rather than melting of metal, it consumes considerably less energy than arc welding.
- Plate cleaning may be much reduced over conventional fusion welding processes, thus reducing the usage of chemicals and subsequently the amount of contaminated waste.

7. Potential applications for steel FSW

7.1. Shipbuilding and repair

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 33.

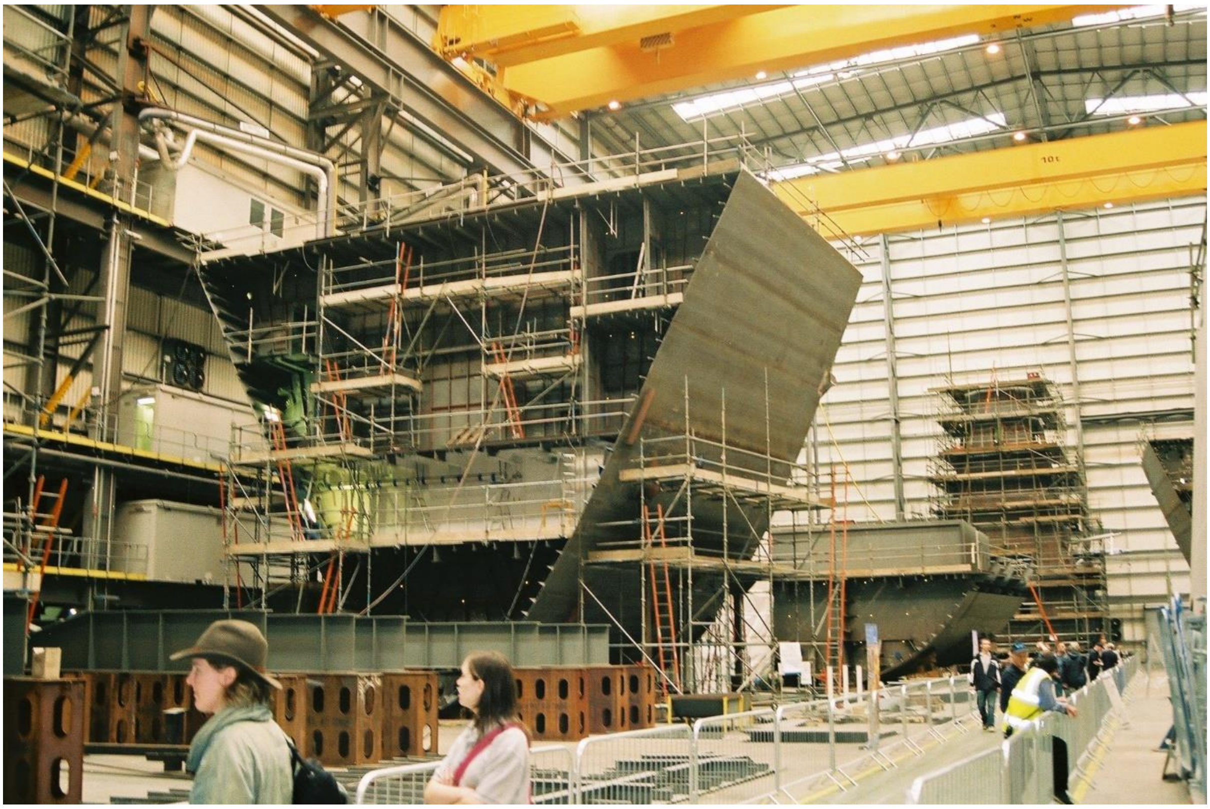


Figure 33. Modular blocks of HMS Dauntless under fabrication at HMNB Portsmouth. Image courtesy Adrian Jones.

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 16 and Figure 17.

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 cpomplexity 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.

7.2. 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.

One opportunity might be represented by the refurbishment of bridge decks. Stiffened panels manufcatured 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 34. Steel bridge decking

7.3. Nuclear engineering

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.

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.

7.4. Power generation

In an effort to enhance thermal efficiency and reduce the toxicity of combustion byproducts, much power generating plant is being run at higher temperatures, frequently requiring the use of complex alloys to withstand those temperatures. The welding of these alloys often places a limit on the upper operating temperature of the plant, and the use of some bio-mass based fuels also has implications for conventionally welded structures due to erosion-corrosion issues. FSW, with its seemingly greater tolerance to alloy complexity during welding, and autogenous nature, is potentially a means of alleviating many of thes eproblems.

7.5. Pipelines

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.

Figure 35. Conventional pipeline installation.

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.

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.

8. Summary

Arc and friction stir welding are both good techniques for fabricating metals, each with their own set of pros and cons. Arc welding is versatile, well suited to one-off fabrication and has over a hundred years' of development behind it. It can weld curved surfaces relatively easily and can make up gaps between poor fitting plates. It is also a little more forgiving than FSW of poor jigging and poor fixturing.

Conversely, friction stir welding is a relatively new technique, particularly when applied to steel, and is better suited to the automated welding of multiple, similar weld geometries. Friction stir welding is less susceptible to alloy composition, indeed it can even weld very dissimilar grades of metal together. It requires no filler metal or fluxes, thus saving on the costs of both and their associated admininstration and, in the case of flux, post-use disposal costs. Friction stir welding is a solid state process akin to forging and so produces strong, grained refined microstructures with high strength, toughness and good fatigue properties. Friction stir welding, again due to it being a solid state process, is agnostic towards position – vertical and even over-head welding being easily acchieved. Similarly, welding under liquids such as water or even oil is possible, a factor which facilitates *in situ* repair of ships and othe rmarine structures. The low heat input of friction stir welding gives the process the advantage in terms of minimal distortion.

Specifically for the shipbuilding industry, FSW might best deployed for the manufacture of the stiffened panels from which the greater tonnage of a steel ship is generally constructed rather than the curved hull plates. Stiffened panels tend to have long, linear welds and are generally fabricated in the horizontal plane. The low distortion benefits of friction stir welding would also be maximised when welding stiffened panels, offering significant savings over the current process where considerable straightening work is often required post welding. Use of the concept shown in Figure 16 for the fabrication of a stiffened panel from rolled T section and plate can potentially replaces two arc welded fillets with a single FSW butt joint, producing a fully forged structure with 50% fewer welds.

The ability to undertake simple patch repairs under water also offers great potential for ship repair, negating the need for dry docking. It may also find considerable employment in such activities as salvage, allowing damaged hulls to be made airtight without the need for deployment of divers or caissons for arc welding work, and thus allowing sunken ships to be refloated more easily. Similar benefits would also apply to the repair or installation of harbour or even riverine infrastucture such as locks.

In summary, the choice between arc and friction stir welding needs to be made based upon the application concerned, with friction stir welding being considered an additional welding technique to be deployed for fabrication where its many benefits can be deployed to best effect.

9. Project partners’ brief descriptions

www.ewf.be

EWF and its member organizations have developed an international harmonised system for education, training and qualification in the field of welding technology. It was a pioneer organization developing the first harmonized system embracing all the European countries for the qualification of personnel for a wide range of levels in welding, related technologies and inspection. EWF is the Project Coordinator for the RESURGAM project.

www.e6.com

Element Six is a global leader in the design, development and production of synthetic diamond and tungsten carbide solutions. Part of the De Beers Group, our primary manufacturing sites are located in the UK, Ireland, Germany, South Africa, and the US. We put our customers first. Since 1959, we have used our technological expertise and industrial leadership to develop innovative advanced materials that deliver competitive advantage across a wide range of industries. We don’t work for you, we work with you. Element Six are developing the high performance tools required for welding steel in the RESURGAM project.

www.esi-ltd.eu

ENGITEC Systems International provides advanced inspection services, remote condition monitoring, development of customised data acquisition systems, advanced signal processing methods, software for industrial applications, and metallurgical expertise to its customers. ESI specialises in design and analysis of composite and metallic structures for various industries. Services include design and finite element analysis of structural components and complex structures according to standards.

www.forth.uk.com

Forth is known for world-first innovations, providing solutions to complex industry challenges around the globe for more than 20 years. Dedicated to engineering excellence, FORTH works closely with industry leaders in nuclear, oil and gas, marine, and renewables. Forth partners with other specialists in innovation programmes and welcomes problem statements from any organisation. Using innovative technology, FORTH helps operators achieve what was previously considered impossible. For the RESURGAM project, Forth Engineering is developing the robotic underwater friction stir welding system that is required for performing patch repairs on ship hulls, and which also has other potential uses for the repair and fabrication of marine infrastructure.

www.ul.ie

The Centre for Robotics & Intelligent Systems (CRIS) at the University of Limerick, Ireland focuses on Marine and Field Robotics for challenging applications. Our research spans inspection, monitoring and intervention, precision navigation and control, sensor development and image referenced flight control for remote operated vehicle (ROV) and unmanned aerial vehicles (UAV). CRIS is an integral part of MaREI (Energy, Climate and Marine), CONFIRM (Smart Manufacturing) and LERO (Software) SFI Research Centers of Excellence.

www.stirweld.com

Stirweld has developed a technology allowing the use of friction stir welding (FSW) on all types of CNC machine. We support you in the optimisation of your machine park and the integration of a new know-how to offer to your customers. Our FSW head for CNC offers identical performances to a special FSW machine (effort control, quality recording.) In the RESURGAM project, Stirweld is developing a retrofit FSW system that can be added to an existing CNC machine to allow the modular fabrication of components and ship sub-assemblies.

www.gisbir.org

The Turkish Shipbuilders' Association (GISBIR) was established by shipyard owners in 1971 in Istanbul. GISBIR is one of the oldest non-governmental organizations in Turkey and representative of the Turkish ship and yacht building, repair and maintenance industry. Turkish Shipbuilders' Association (GISBIR) has almost one hundred members and represents vast majority of the industry. In project RESURGAM, GISBIR is representing the shipbuilding industry, advising the consortium on the types and thicknesses of steel of interest to the marine sector and assisting in the dissemination of project results to Industry.

www.twi-global.com

TWI is a world leading research and technology organisation. Over 800 staff give impartial technical support in welding, joining, materials science, structural integrity, NDT, surfacing and packaging. Services include generic research, confidential R&D, technical information, technology transfer, training and qualification. TWI invented the friction stir welding process in 1991 for welding aluminium. The process was subsequently developed for welding magnesium, copper, titanium and thermoplastics. In Project RESURGAM, TWI is leading the transfer of the technology into the welding of steel, both in air and under water.

www.lancaster.ac.uk

Lancaster University (J4IC) is one of the UK's leading research-intensive Universities consistently ranking no.1 in the NW of England and recently 137 in the world. Lancaster was the last of seven new UK universities conceived in the 1950s with 2014 marking its 50th Anniversary. Its 12,000 students belong to one of nine colleges, which act as interdisciplinary communities, but are taught by four academic faculties: arts and social sciences; health and medicine; management; science and technology.

www.aclunaga.es

ACLUNAGA is the only specific business association within the shipbuilding sector in Galicia, created as a dynamic tool and meeting point for all companies and agents involved in shipbuilding. Its mission is to improve the competitiveness and to promote the development of the group of companies that integrate the Galician shipbuilding sector. It currently has 130 associated companies and entities, whose products and services cover the entire value chain of the sector (from shipyards and ancillary industry to support institutions, R+D and educational environment, and support services).

www.aister.com

AISTER is a medium sized shipyard specialised in marine aluminium buildings and the construction of professional boats, marinas and maritime works. Our priorities are quality and innovation, allowing us to provide our customers with the latest advances in design and materials. AISTER is keen to expand its production to steel ship components and modules and hence will be instrumental in providing guidance an acting as an early demonstrator/adopter of the FSW technology for modular fabrication, modification and maintenance of ships.

www.ned-project.eu

NED-PROJECT Sp.zo.o. is a privately owned ship design & shipbuilding technology company. NED offers a full scope of design and engineering services for, shipowners and shipyards.

www.tudelft.nl

Delft University of Technology is consistently ranked as one of the best universities in the Netherlands and, as of 2020, it is ranked by QS World University Rankings among the top 15 engineering and technology universities in the world. With eight faculties and numerous research institutes, it has more than 19,000 students (undergraduate and postgraduate), and employs more than 2,900 scientists and 2,100 support and management staff.