Friction Stir Cutting for Decommissioning – 16130

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ABSTRACT
Safe and cost effective decommissioning of redundant nuclear plant is a primary consideration to countries and companies with aging nuclear facilities. The wider media coverage of nuclear issues and strong public feeling is ensuring decommissioning options are also considered prior to development of new nuclear facilities. A project has been undertaken to demonstrate the feasibility of applying friction stir cutting, a non-fusion, non-machining, method of separating materials for size reduction of redundant metallic nuclear plant, specifically as a flexible low cost tool for plant dismantling.

The research program was designed to provide a fast and effective approach to the assessment of process feasibility in stainless steels. Friction stir cutting may begin by traversing the rotating tool into the edge of the plate, or alternatively, by piercing the plate with a suitably profiled rotating friction stir cutting tool. Plate piercing trials were conducted to determine the downforce required to pierce the plate and to identify the appropriate tool tip profile for efficient piercing.

The friction stir cutting process has been successfully demonstrated in 3mm and 6mm thick stainless steel plate. Provided sufficient torque is available, the friction stir cutting process is suitable for robotic application. The process is suitable for submerged applications such as the removal of pond furniture. Special attention was given towards any fume generation or particulate emissions during cutting. Friction stir cutting of bare steel plate does not generate fume, results in a relatively smooth edge profile and produces minimal loose debris.

INTRODUCTION
The friction stir cutting (FSC) process involves traversing a rotating non-consumable tool through the plate to be cut. Friction stir cutting may begin by traversing the rotating tool into the edge of the plate, or alternatively, by piercing the plate with a suitably profiled rotating FSC tool. Frictional heat is generated by the action of the rotating tool on the stationary workpiece. Provided the heat generated is sufficient to adequately soften the plate material, the FSC tool is able to reliably provide a solid phase cut as the tool processes through the material. Features on the tool assist softened material flow and ensure that a clean, clear cut is made.

The FSC process can operate in one of two control modes. Under position control the tool is maintained at a given vertical position through automatic variation of the applied vertical force (downforce). Under force control the applied vertical force is constant and the vertical position of the tool varies. Force control may be implemented to cut flat or profiled plate, position control is only suitable for cutting flat plate.

The research program was based on TWI's experience of friction stir process development and was designed to provide a fast and effective approach to the assessment of process feasibility in this case. This work provides baseline process data and indicative information on the following aspects of the process:

- Process capability.
- Equipment requirements.
- Cut edge morphology.
- Tool performance and lifetime indications.

EXPERIMENTAL APPROACH

The experimental set-up used in this feasibility study was not designed to replicate an actual decommissioning situation, but to enable accurate assessment and measurement of the process. A simple fixture was manufactured to clamp 150mm wide steel plates onto the workstation of a FSW machine, with the plate locally unsupported in the middle for approximately 70mm width. The fixture enabled the machine head to have clear access to the plate surface, allowing a cutting tool to be started from an edge, or alternatively enabling the plate to be pierced from the top surface (Figure 1).

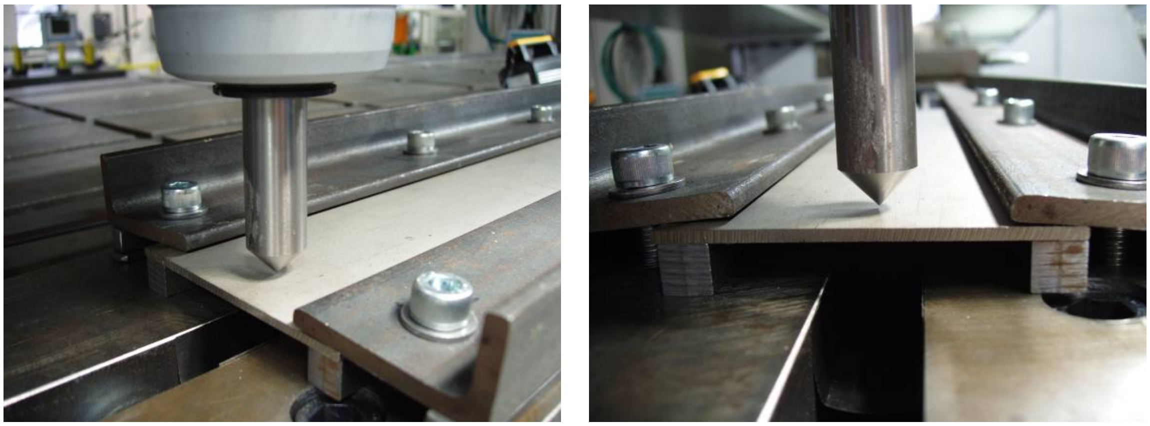

Fig.1. Experimental work holding fixture

A range of plate materials and thickness were selected to provide a representative set of candidate materials: 3, 6, & 10mm 304L austenitic stainless steel, 6mm 316L austenitic stainless steel & 10.0mm 316L austenitic stainless steel and C-Mn steel.

All results of the FSC trials were assessed visually, and by metallographic sectioning/assessment of the cut edges as required. Machine records were analysed to provide information on the in-process forces and torque measurements. Special attention was given to any fume generation or particulate emissions during cutting. Temperature measurements were implemented in selected trials for additional analysis of the tool and plate material performance during processing.

RESULTS

Tool Design

The FSC tool developed in these trials has three functional sections, the tip, the profiled groove and a larger diameter tool shoulder as shown in Figure 2. The profiled tungsten tip facilitates plate piercing. The tool used for FSC must be of a suitable profile to pierce the plate material without damage to the tool and conical profiles are used for this purpose in many engineering applications. A 110° cone angle and rounded tip profile was selected for use on the cutting tool as it resulted in the lowest measured torque of the geometrics studied. The profiled groove encourages the softened materials to fold back during FSC to leave a reasonably smooth cut edge profile (Figure 3). The larger diameter tool shoulder provides some frictional heating during the cutting process.

For FSC to be generally applicable to the nuclear decommissioning environment it is important that the process is fully automated and can be controlled remotely. It is envisaged that a working system could comprise a remotely operated vehicle (ROV) fitted with a robotic FSC arm/head. For robotic application the vertical force required to push the rotating tool through the plate (downforce) should be below 10kN. Piercing trials were conducted using the preferred 110° tip profile under applied loads of 2kN, 4kN, 6kN, 7kN, 8kN and 9kN. A maximum piercing time of 3 minutes was arbitrarily selected as the piercing criteria. Piercing was successful using an applied downforce of 7kN and above, piercing at 7kN took 2 minutes 9 seconds.

Fig.2. Friction stir cutting tool for 3mm thickness material.

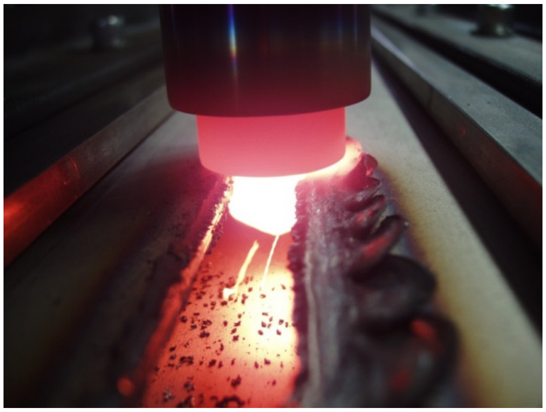

Fig.3. Friction stir cutting of 3mm thickness 304L stainless steel.

Friction Stir Cutting Trials

3mm plate cutting trials

The plate piercing trials had already demonstrated that the tool tip generated sufficient frictional heat to soften the plate material. Therefore, a rapid transition between the piercing phase and the cutting phase of the process was desirable to prevent over softening of the plate which, if operating under force control, would result in the tool over penetrating the workpiece.

Trials were conducted using tool rotation speeds of 350-800rpm at traverse speeds of 20-100mm/min. All parameter combinations resulted in satisfactory FSC of the steel plate. Analysis of the force and torque data recorded during cutting did not highlight major differences between individual cuts. From research into torque in friction stir welding, it is known that torque is dominated by shoulder contact and approximately constant provided the material to be welded is sufficiently soft to flow readily. As anticipated, torque values were essentially uniform for cuts made under position control. Lateral and traverse forces were also essentially constant, indicating that the parameter combinations investigated resulted in similar material softening effects in the material adjacent to the tool. Figure 4 shows the appearance of the cut edge produced.

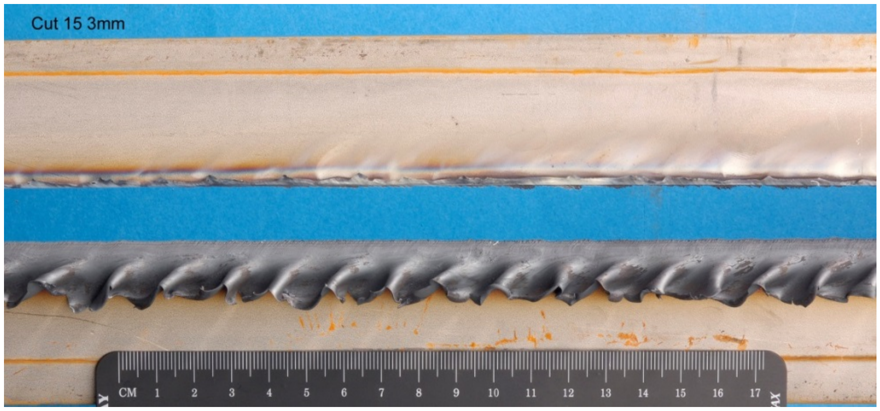

Fig.4. Photograph showing appearance of cut edge of 3mm thickness 304L stainless steel.

Optical examination of friction cut samples revealed microstructural features that can be related to the processing temperature. Much of the highly plasticised material produced when cutting in air is lost as flash (Figure 5) The Heat-affected-zone (HAZ) partly recrystallised grains in the air cut sample are only ~30% smaller than the diameter of the parent material. This level of grain growth is consistent with operating temperatures of ~1090°C. The width of the HAZ that extends from the junction where the highly plasticised material became detached into the plate varies from 0.8 - 1.0mm in width. The operating temperatures that the results of this examination suggest, almost certainly mean that the immediate surface of the cutting tools is very much hotter than 1000°C. Also the rapid wear of friction cutting tools used for cutting 10mm plate in air suggest that softening of the tungsten alloy is occurring, and that the temperature is in excess of 1500°C.

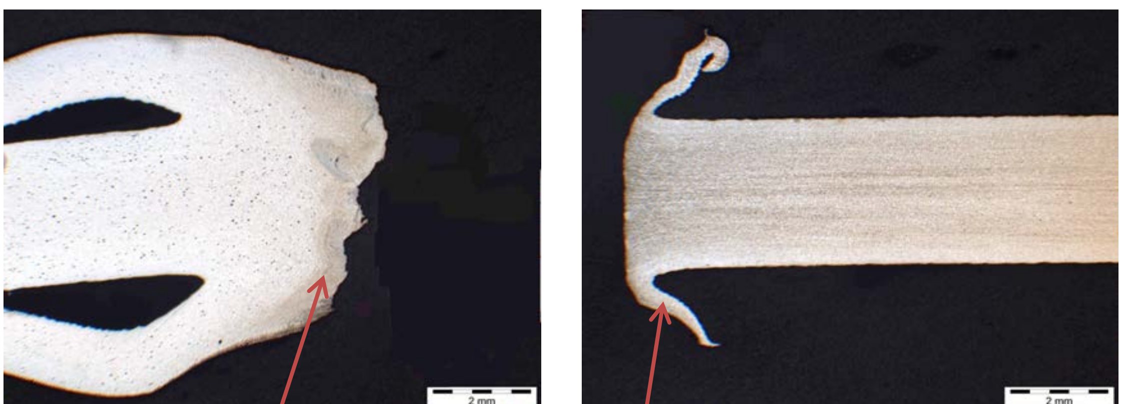

Fig.5. Cut edge morphology

<u>6mm plate cutting trials</u>

A further assessment of process capability was conducted using 6mm thickness 304L and 316L stainless steels. Adapting the FSC process for different material thicknesses requires assessment of both plate piercing and cutting parameters. The cutting tool was of the same general design and dimensions as that used for the 3mm trials. The single change was an increase in profiled groove height to accommodate the increased plate thickness. A single plate piercing trial confirmed that the parameters developed for 3mm 304L stainless steel could be successfully applied to 6mm thickness plate. Preliminary cutting trials were similarly successful, a clean cut was produced (Figure 6), indicating adequate heat input by the FSC tool during the cutting process.

Examination of records revealed that the process torque was comparable to levels recorded for FSC of 3mm thick plate. This is largely to be expected as torque is dominated by the shoulder contact and the same shoulder diameter was used for both 3mm and 6mm FSC tools. Traverse forces for 3mm and 6mm plate are also comparable, indicating that the reduction in cutting speed from 100mmm/min to 40mm/min has compensated for the increase in plate thickness. Applying these parameters to 316L stainless steel also produced a good quality friction stir cut. The change in material composition and properties had no significant impact on process forces and torque.

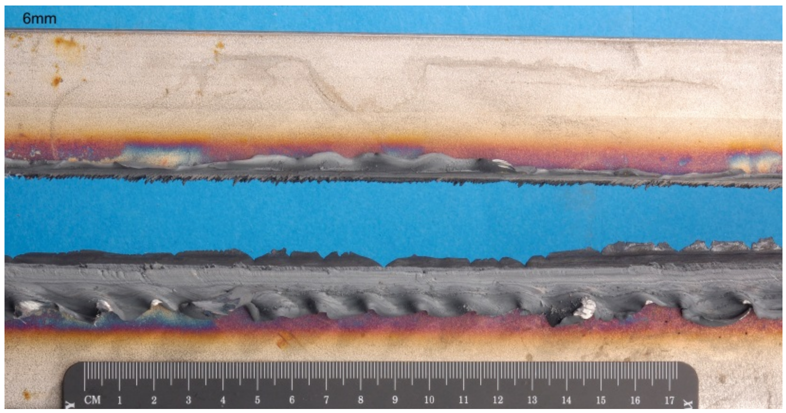

Fig.6. Appearance of FSC in 6mm plate.

<u>10mm plate cutting trials</u>

Cutting 10mm steel plate is an extremely challenging application of the FSC process. Increased process force requirements were anticipated for FSC of 10mm thickness steel plate. A piercing time of 6 minutes was recorded for piercing 316L stainless steel plate using a tool rotation speed of 800rpm and an applied vertical force of 9kN. It was noticed that the tool moved vertically through the plate in a series of steps rather than the smooth downward motion witnessed during piercing of 3 and 6mm thickness stainless steel. However, the maximum recorded vertical force for this piercing trial was 14.1kN, exceeding the maximum of 9kN set to allow robotic application of the process. The plunge rate was reduced to 3mm/min resulting in a 10 minute plunge phase although the vertical force remained in excess of 9kN at 11.8kN.

A stronger cylindrical tool was used to cut both 10mm thick 316L stainless steel and 50D C-Mn steel (Figure 7). Significant heat is generated during the prolonged piercing phase which may be detrimental to tool life. The increase in tool diameter resulted in an increase in applied vertical force as pressure was applied over a greater area during the piercing phase, this also resulted in increased torque. Cutting 10mm thick plate also results in appreciable tool wear, the tool profile after making a 525mm cut in 316L stainless steel and a 675mm cut in 50D C-Mn steel, is shown in Figure 7. Clearly this level of tool wear is unacceptable. Possible solutions may include the use of tool coatings, the selection of different cutting parameters or the implementation of tool cooling.

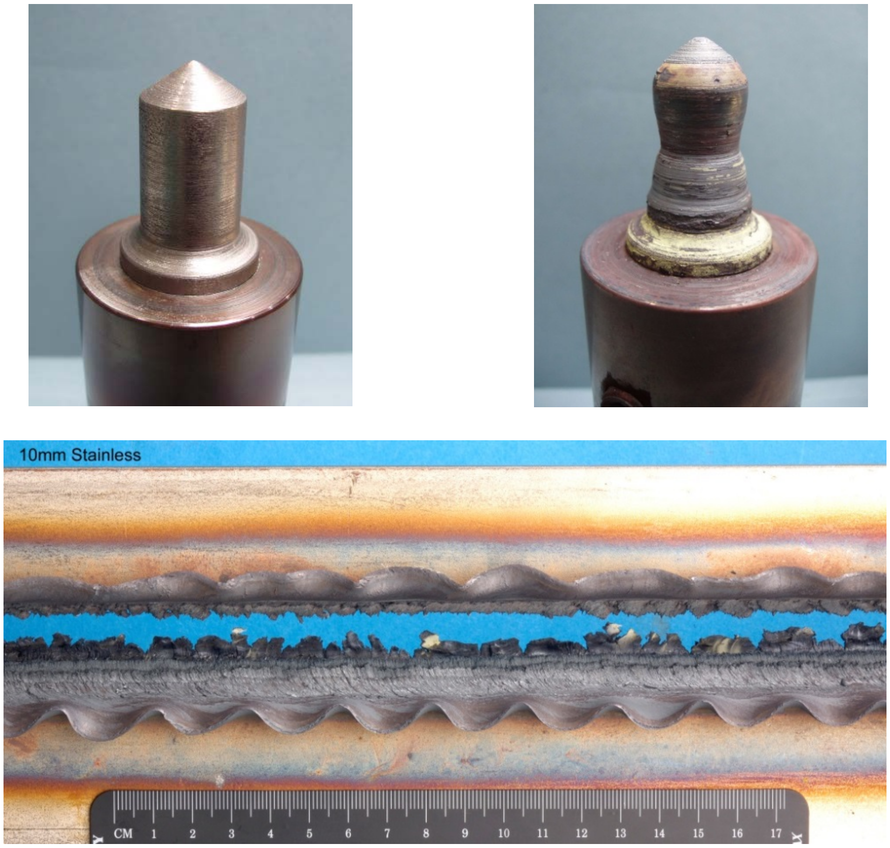

Fig.7. FSC of 10mm 316L stainless steel showing illustrating tool wear after cutting 1200mm and the appearance of the resulting cut edge.

Debris Assessment

The base of the workpiece jig was lined to enable collection and assessment of debris produced during a 975mm long x 13.23mm wide cut in 6mm thick 304L stainless steel plate. 4.65g of debris was collected. The debris was analysed by EDX to identify the chemical elements present in the sample. The resulting spectrum is shown in Figure 8. The presence of tungsten (W) in the spectrum is indicative of tool wear. The remaining debris elements (Fe, C, Cr, Mn, Ni) are consistent with the chemical composition of 304L stainless steel. Analysis of the debris by ICP showed 18% of this debris was from the cutting tool, the remaining 82% stainless steel.

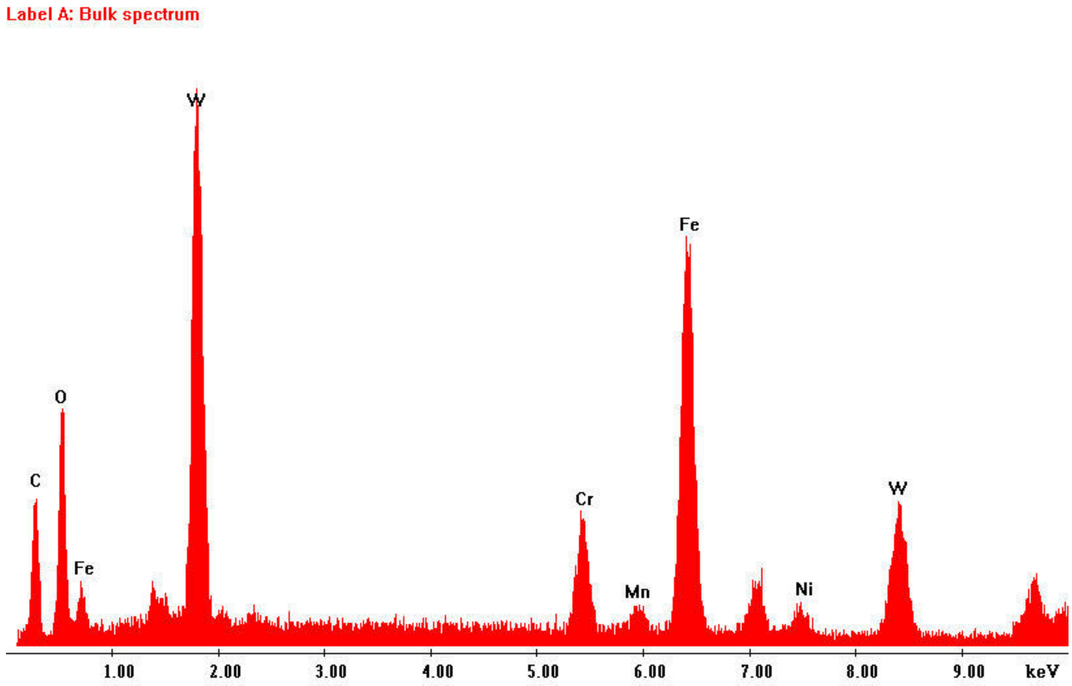

Fig 8 EDX spectrum of debris collected from cut in 6mm 304L stainless steel.

Submerged friction stir cutting

A limited number of trials were conducted to demonstrate submerged FSC in 3.0mm thickness 304L stainless steel. For this demonstration the material to be cut was secured in a waterbath and sufficient water added to cover the plate to a depth of approximately 25mm. The water was not cooled during the cutting trials. It was found to be necessary to increase the tool rotation speed during the piercing phase to compensate for the cooling effect of the water. Adopting the rapid phase transition used for the in-air cutting trials resulted in a rapid loss of heat in both the tool (as deduced from tool colour) and the plate, with no cut produced.

An alternative approach was necessary to achieve the transition between piercing and cutting phases to ensure maintenance of heat input during the transition. The introduction of an intermediate step was developed as illustrated in Figure 9.The plate piercing phase was halted when the tip of the tool was 6mm below the upper surface of the plate. A composite motion was programmed such that the tool pierced the plate by a further 8mm while traversing forward 20mm at a nominal traverse rate ramp of 0-5mm/min. The cutting phase then commenced at the set traverse rate.

Analysis of the weld records showed that the vertical and traverse forces experienced by the tool in the final submerged trial were comparable to those recorded for a similar trial in-air. However, the torque developed in the submerged FSC more than doubled from 27Nm to 59Nm. Such an increase is obviously undesirable from machine specification standpoint. It is possible that a program of tool design and parameter optimisation may reduce the torque required in submerged FSC to the levels recorded for similar trials conducted in air.

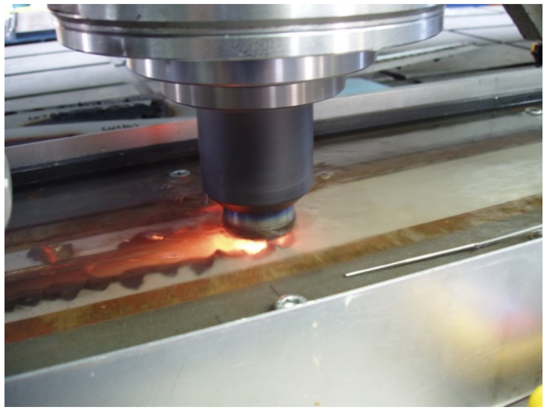

Fig.9. Submerged FSC of 3mm thickness 304L stainless steel showing reduced heat input during cutting (from tool colour) and appearance of the cut edge.

In the submerged FSC trials much of the highly plasticised material produced has been retained, rather than lost as flash (Figure 10). The HAZ was very narrow, ~0.2-0.3mm compared with 0.8-1.0mm for samples cut in-air. The grain size in this region was very small and barely resolvable. A feature of the highly plasticised region was a fine grain size in combination with parallel bands of fine dark etching particles. The etching response of these particles was consistent with carbide precipitation that can occur between 425-900°C. Thus the fine HAZ grain size and the combination of fine grain and carbide precipitation in the highly plasticised region suggested that a temperature of 900°C had not been exceeded.

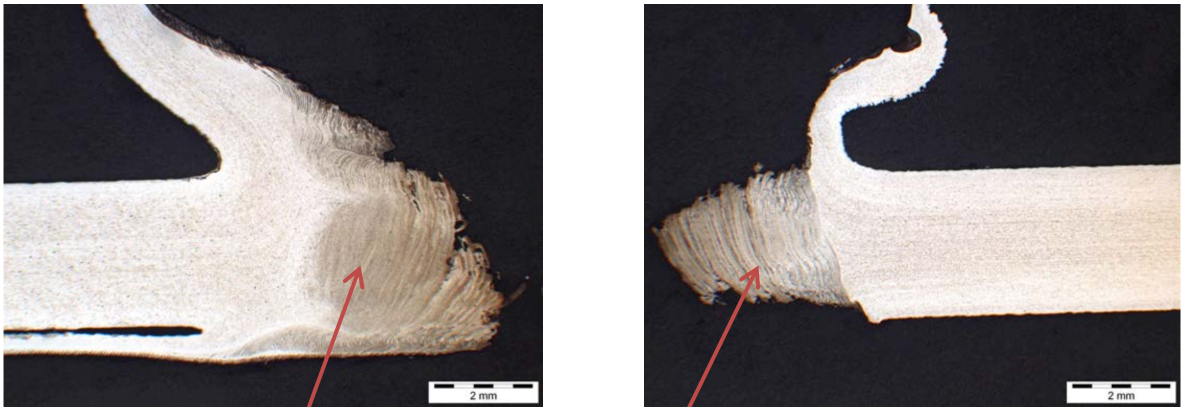

Fig.10. Cut edge morphology for submerged FSC

DISCUSSION

Process capability

The FSC process has been successfully demonstrated in 3mm and 6mm thick stainless steel plate. While it has been possible to demonstrate FSC of 10mm thick 316L stainless steel and 50D/S355 carbon-manganese steel plate, significant challenges in terms of tool life and process forces must be overcome before consideration for industrial application for this plate thickness. The profiled groove in the FSC tool provides consolidation of the cut material at the processed edge, resulting in a relatively smooth edge profile and minimal swarf or debris, which forms problematic secondary waste in an irradiated environment. The process developed in this study generated 4.65g of fine debris during a 975mm long by 13.23mm wide cut in 6mm thick plate; 3.81g stainless steel 0.84g tool material. This equates to a stainless steel debris volume of 0.48cm^3 compared to a displaced volume of 77.4cm^3. It may be possible to reduce the secondary waste still further through the adjustment of the tool design. Alternatively, it may be desirable to incorporate an integral debris collection system in any FSC equipment developed. The friction stir welding process, and by analogy the FSC process does not result in fume [1] or airborne particulate generation as process temperatures are not sufficient to cause material melting. FSC has minimum predicted impact on ventilation systems.

The FSC process compares favourably to other available cutting processes, which generate debris over the full width of the cut (termed the kerf width). TWI has experience in the application of a range of commercial cutting processes, data for kerf widths for 6mm 316L stainless steel is summarised in Table I. While laser cutting techniques give small kerf widths, the associated safety considerations, equipment size and cost are prohibitive for many applications. The debris collected during FSC is equivalent to a cut width of less than 0.1mm, a 90% reduction in width, and therefore debris, compared to conventional oxy-fuel cutting.

It has been demonstrated that the FSC process is stable and repeatable in the materials and plate thicknesses investigated in this study. The process evaluation in 3mm thick plate demonstrated effective FSC over a range of process parameters, including the cutting of submerged plate where plate temperatures were relatively low. Further parameter development is required to improve frictional heating of submerged plate. It is envisaged that parameter optimisation will have a positive impact on process forces and torque, reducing values in-line with those recorded for FSC in air.

TABLE I. Kerf width for 6mm thick 316L stainless steel plate.

Cutting technique	Kerf width, mm	Secondary Waste	Remote Operation
Oxy-fuel	2.2	H	M
Plasma	2.76	H	M
High tolerance plasma are (HTPAC)	2.4	H	M
Nd:YAG laser	0.35	M	H
Saw cut	2.0	L	L
Friction stir cutting (FSC)	0.1	L	M

Tool performance

The FSC tool design and material have proved robust for cutting 3-6mm thick stainless steel plate, withstanding FSC over a range of processing parameters including submerged cutting, where the water rapidly removed friction heat generated by the cutting tool, significantly reduced the temperature of the plate, increased the torque experienced by the tool due to reduced material softening. A tool life in excess of 12 linear metres has been demonstrated for 3mm thick 304L stainless steel. The design of the cutting tool requires refinement to prevent tool failure on the tool shank. Further cutting trials will be required to make accurate tool life predictions once the shortcomings in tool holding have been rectified.

Equipment requirements

The current piece of work has demonstrated that the approach can be effectively applied to 3-6mm thickness stainless steels and it is anticipated that FSC of carbon-manganese steels would be equally successful. This level of capability suggests that FSC could be applied to the dismantling of a wide range of metallic plant such as:

- Ventilation ducting
- Gloveboxes
- Waste containers
- Pond furniture

It is envisaged that any equipment used in an irradiated environment would be remotely operated, attached either to a robot or forming part of a remotely operated vehicle (ROV). The principal process control will stem from control and monitoring of process parameters. A video system should be fitted to permit visual monitoring of the process. A debris and/or fume extraction system may also be required depending on application. A substantial heat shield is necessary to manage heat transfer from the cutting tool to the rest of the system. Commercial ROV equipment is available and deployed in the Oil & Gas sector for underwater friction stud welding [2].

In-process monitoring of the forces and torque developed during the FSC process has enabled equipment requirements to be assessed for 3-10mm thick carbon-manganese and stainless steels. The FSC parameters used in this study and the resulting process forces and torque are summarised in Table II below. The FSC parameters used in this study have not been fully optimised and any modifications to parameters or operating environment may impact on equipment requirements.

TABLE II. Equipment requirements

	3mm 304L	**3mm 304L, Submerged**	**6mm 304L/316L**	**10mm C-Mn steel**	**10mm 304L**
Tool rotation speed, rpm	800-1000				
Cutting speed, mm/min	15-100				
Applied vertical force - piercing, kN	9kN max	9kN max	9kN max	22.0	14.1
Applied vertical force - cutting, kN	2.2	Position control cut			
Traverse force, kN	6.9	6.2	304L 5.6 316L 6.4	14	7.5
Torque, Nm	27	59	304L 43 316L 38	47	47

CONCLUSIONS

The following conclusions may be drawn from this research study.

- The FSC process has been successfully demonstrated in 3mm and 6mm thick stainless steel plate.
- The friction stir cutting process is suitable for robotic application provided sufficient torque is available. Rapid piercing of 3mm and 6mm stainless steel plate was achieved using a maximum vertical force of 9kN.
- Friction stir cutting is suitable for submerged applications such as the removal of pond furniture
- Friction stir cutting results in a relatively smooth edge profile and minimal loose debris.

ACKNOWLEDGEMENTS

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REFERENCES

1. R.S. Mishra, P.S. De and N. Kumar, *Friction Stir Welding and Processing*, pp119 Springer, New York (2014)
2. Proserv webpage http://www.proserv.com/MARINE/Friction-Welding, accessed 09/12/2015
3. NDA Tender ref CJ0000050 July 2006