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Summary

The papers from the first international conference on Friction Stir Welding (FSW) have been reviewed.

Taken together the papers provide a very optimistic picture for the development and application of friction stir welding in general and to the case of the copper canister in particular. Whilst a considerable development effort is in progress the process has been industrialised for joining of aluminium sheet and it is accepted by Lloyds register for this purpose.

Development of procedures and equipments to weld thicker materials and a wider range of materials is progressing ahead of the research activity to aid the understanding of the process at this stage. Nevertheless, well-established weld assessment procedures are being applied to experimental welds with very encouraging results.

Summaries of the key papers are presented in an appendix.

Contents

1. Introduction

After many years of development effort SKB have made considerable progress towards the definition of a design and a manufacturing procedure for a canister to be used for deep geological disposal of nuclear waste.

The current reference design is a cylinder having outside dimensions 1050-mm diameter and 4.83 m long. The wall thickness is 100 mm and this is made up from a copper outer component of thickness 30–50 mm and the remainder in nodular cast iron. The copper is present as a corrosion protective layer and the iron is the load bearing structure. The inner cast component also carries an internal cast in structure to support and separate the spent fuel bundles. This design is considered by SKB to provide adequate radiation shielding against the contents of the canister together with the required durability in the disposal environment.

Whilst the materials and the dimensions of the proposed canisters have been defined, the manufacturing procedures have not. A number of manufacturing procedures are being considered and SKI need to understand the relative merits of each in terms of the effects of processing on the integrity of the product. The friction stir welding process has recently entered the list of candidate technologies.

This study examines the literature from the first international conference on friction stir welding in order to understand the process. An overview is presented in section 2 and summaries of the more relevant papers are given in appendix 1. Detailed comments on the defects which might arise if it were used in the manufacture of the copper overpack will be presented elsewhere[20].

2. Results of the Study

Friction stir welding has been described by Dawes[3] as "a new solid state process that has been applied to the joining of aluminium alloys. In principle a rotating tool is forced between two butting surfaces and results in material flowing to the rear of the tool and consolidating to give a solid joint".

The first International symposium on friction stir welding[4], which was held in California in June 1999, has added much detail to this early description. The proceedings of have been studied and the following notes have been extracted from the papers presented.

Colligen[5] reports that the steel welding tool is comprised of a shank, shoulder and pin. It is rotated along its longitudinal axis in a conventional milling machine and the workpiece is held firmly in place in a fixture. The shoulder is pressed against the surface of the metal generating frictional heat whilst containing the softened weld metal. The pin causes some additional heating and extensive plastic flow in the workpiece material on either side of the butt joint. The pin is equipped with a coarse screw thread. This thread assists in transfer of plastically deformed workpiece material around the pin resulting in a void free weld. To achieve full closure of the root it is necessary for the pin to pass very close to the backplate, since only a limited amount of deformation occurs below the pin and then only very close to the pin surface. He concludes that several aspects of material flow in friction stir welds require additional explanation. Many details of how material is deposited behind the pin are not yet known.

The design of the tool is clearly very important and Dawes[6] discusses tool design. Much but not all tool development for FSW has been concentrated at TWI under the umbrella of project 5651. Tools from this programme are referred to as 5651 technology. For material thicknesses exceeding 12 mm improved technology beyond 5651 is necessary. Aluminium of thickness 25 mm requires a tool material with improved hot shear strength. It has also been necessary to consider the tool design in conjunction with the choice of tool material.
Two tool designs, nominally the "scroll shoulder" and the Whorl™ designs are under development.

The 5651 tool technology cannot operate consistently with the tool axis normal to the work surface. To achieve good weld quality the tool is required to be inclined away from the direction of welding to ensure good compaction of the weld metal. The need to incline the tool however sometimes leads to a limitation in welding speed. Failure to control the welding speed leads to lifting of the tool from the work and formation of voids in the weld. The paper suggests that such voids may be in near surface positions. The scroll shoulder tool enables the tool to be operated with its axis normal to the surface of the workpiece. At this stage in its development the scroll shoulder tool requires very careful control to avoid local thickening of the weld and consequently possible unsoundness in the weld metal.

The development of the Whorl™ tool is aimed at welding of aluminium plate of thickness 40 mm from one side. For material of this thickness it is necessary that the proportion of the total heat input that arises from plastic deformation of material remote from the surface (compared to that which arises from friction at the shoulder) be increased. The tool is designed to achieve this end. Other tool concepts are also under consideration.

Ding[16] describes a retractable pin tool, which has been developed to enable a weld to be terminated without leaving a keyhole at the end of the run. Tests were carried out on tapered and constant thickness workpieces in aluminium alloy 2125. The system produced sound welds but mechanical property tests on specimens from the tapered test pieces and the closeout tests indicated that optimum welding parameters had not been achieved.

Hashimoto[7] studied the effects of weld parameters, tool rotation speed and forward speed on defect formation in FS welds in high strength aluminium alloys. Two defect types were observed. The first was a groove like defect on the top surface at the boundary between the stir zone and the heat-affected zone at the shearing edge. It was a running pore but the dimensions are not given. The groove is clearly visible but the underlying pore is revealed by X-ray examination. The second is a sub-surface defect. It consisted of many small voids, which appeared in the stir zone at the shear surface. The welding parameters, required for avoidance of these defects during welding of three high-strength aluminium alloys, were identified.

Dong[17] reports earlier work by Threadgill[18] to describe the microstructural variations in the weld. The cross section of the weld can be divided into three regions. They are the thermally affected zone, the thermal-mechanically-affected zone and the dynamically recrystallised zone respectively. A schematic of such a cross section is shown in figure 1 below.

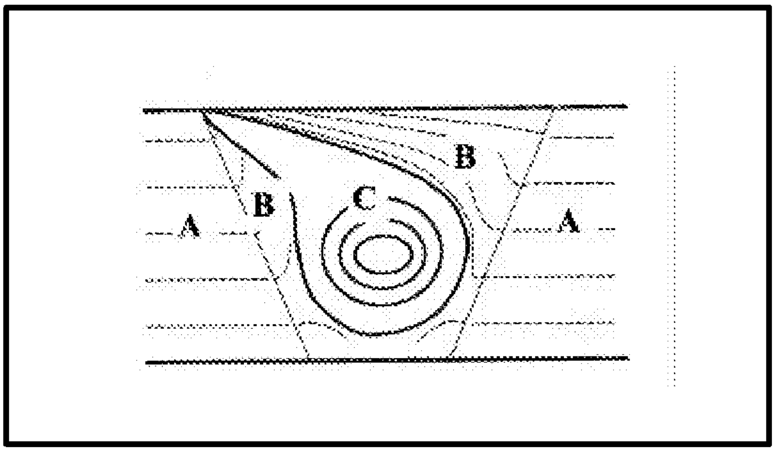

Figure1. Schematic of weld cross-section. **A** *is the thermally affected zone (*TAZ*),* **B** *is the thermo mechanically affected zone (*TMAZ*), and* **C** *is the dynamically recrystallised zone (*DRZ*).*

This description is generally accepted and Dong has used a mathematical modelling approach to understand the development of this weld structure. His conclusions included that,

1. Friction heating between the tool shoulder and the workpiece is dominant near the surface of the weld whilst plastic work induced heating dominates at the bottom. and

2. A plastic slip surface (the boundary of the TAZ) is defined by the interaction of the tool and the base material is influenced by tool design, in particular the probe.

James[8] examined residual stresses in aluminium alloys after friction stir welding using X-ray diffraction. Results indicated that within the fully recrystallised zone residual stresses are zero. Moderate stresses are present in the region between fully recrystallised material and the partially recrystallised region of the thermo-mechanically-affected zone. Residual stresses are considerably below the stresses created by fusion welding processes.

Loftus[9] and Jones[10] described the fabrication of a tubular of diameter 27.5 feet in 2195-T8-aluminium plate of thickness 0.32 inches. The assembly jig and welder position control system was adapted from a fusion welder system.
The distance from the back of the workpiece to the tip of the pin tool is important if full penetration welding is to be achieved. In this case a distance of 0.020-in was maintained by a position control system incorporating an LVDT. The relationship between pin tool depth and axial load was consistent for any particular pin tool geometry and welding parameters. This enables axial load to be used as a control parameter on pin depth. For any specific welding parameters, the weld gap has a significant effect on the

characteristics of the finished weld but no details are given. Four axes of motion are vertical travel, cross slide travel, spindle plunge and spindle rotation.

Increasing rotational speed or decreasing the plunge rate reduces the force required for the plunging operation. Axial force is used in a closed loop control system to manage rotational speed and travel speed during welding. At the end of the weld the tool is retracted at a predetermined rate and over a specified distance. An experiment was conducted to establish the sensitivity of the welding process to variations in various parameters. The range of parameter variation was ± 75 rpm for rotational speed, ± 0.75 rpm for forward traverse speed and ± 0.007 in for the penetration ligament (the distance between the tip of the weld tool and the back of the workpiece). Parameters were optimised based on maximising the tensile strength. None of the parameter variations gave statistically significant effects on tensile strength. However penetration ligament had the greatest apparent effect followed by travel speed with rotation speed having little effect. The effects of interactions between parameters were also statistically insignificant. Operational parameters were selected by comparative examination of the results of the statistical experiment.

Two tapered thickness welds were made as part of the programme. To achieve this each specimen was welded first from one side and then the other. Thus each of the first welds started at less than full thickness and proceeded until they were full thickness, The second welds in each case started in the unwelded region and proceeded to overlap the earlier full thickness weld. Both these welds were successful. A further tapered thickness weld was made using a retractable pin tool. A weld varying in thickness from 0.65 to 0.32 inches was made successfully. (This suggests that a retractable pin tool might be used for finishing a lid weld in copper canisters by continuously retracting the pin in an overlap zone at the end of the initial weld.). The authors report that further work is in hand to develop and use a retractable pin tool to weld domed ends onto the tubular.

Midling[11] discussed industrialisation of the FSW process. 110,000 m of FSW panel welds in aluminium plate has been completed to March 1999. Plate thicknesses are 3-7 mm. The appropriate maritime approval authorities approve welds, using the same criteria as those used for fusion welds. No major problems have so far been experienced in achieving the required standards.

One of the most serious defects is given as lack of bonding (“kissing bonds”, in the words of the authors). Inspection is by visual observation at the time of welding (by the operator), spot radiography on selected joints and mechanical testing of test bars. Ultrasonic inspection, which would detect “kissing bonds”, is not employed.

Midling[12] discussed the effect of tool shoulder material on achievable welding speeds. The level of heat input for any specific set of welding parameters with differing tool shoulder materials was assessed by measuring the extent of the heat affected zone on metallographic sections. A Zirconia engineering ceramic tool shoulder material was outstanding compared with other materials tested. It appeared to generate from 30% to 70% more heat than the standard tool steel. The higher rate of heat input enabled higher welding speeds before pin failure becomes a problem. Increasing welding speed requires an increase in rotational speed in order to achieve sound welds without line porosity defect.

Thomas[13] reported welding studies on other materials. He reports that FSW has been applied to lead, zinc, magnesium, aluminium alloys, copper titanium, low carbon steel, and low carbon-chromium alloy steels. FSW of the harder workpiece materials has been made possible by maintaining a suitable differential between the hot hardness and the elevated temperature properties of the tool and the workpiece material. He reveals that welds have been made on short lengths of steel at 25 mm thickness.

The feasibility of friction stir welding steel is demonstrated, and photographs indicate that weld depths of 15 mm were achieved. He reports that different hydrostatic pressures may be generated on the advancing and retreating sides of the tool when welding conditions are sub-optimal. This can lead to buried voids or a surface-breaking defect along the weld line. It can also cause the tool to veer away from the weld line but this can be avoided by the use of robust equipment.

Andersson[14] describes an exploratory programme to develop the FSW process for joining 50 mm thick copper plates. Feasibility is established, a pilot level welding machine has been designed for canister lid attachment and manufacture is in progress. A flaw that has been associated with FSW of 50 mm-copper plates is a running void on the advancing side of the weld zone. It has been linked to excessive softening of the copper, which has led to loss of clamping force. It is reported that modifications to the tool design and/or welding parameters have eliminated this defect.

Przydatec[15] presented the guidance given to Lloyds inspectors for approval of friction stir welds in shipbuilding. He points out that the welding tool is a key component and novel designs are expected to emerge as the technology develops. Inspectors are not expected to understand the intricacies of fluid flow around the tool so the manufacturer has to provide evidence of suitability. As a minimum this involves weld characteristics from mechanical and non-destructive tests. Tool wear and clogging are reported to affect weld performance. These conditions are not readily observable during processing so regular tool observations are required. No details of the problems arising from tool wear or clogging are given.

Results on aluminium sheet, plate and extrusions indicate that the process is at least as good as the equivalent fusion process.

A list of test requirements is given. These include:

(1) Visual examination	100%
(2) Radiographic or ultrasonic	100%
(3) Penetrant test	100%
(4) Macro-examination	
(5) Micro examination	
(6) Transverse tensile tests	
(7) Bend tests and	
(8) Hardness profile across the weld	

The notes attached to the above list include reference to the tool exit hole and to "herring-bone" cracking in the weld root. Visual examination of the exit hole provides guidance on the quality of the weld. With a good weld the deformed circle around the exit hole is complete. When this circle is less than 75% complete the weld quality will be low. Details of the imperfections to be expected for this case are not given but it is said later that the incomplete circle is an indication that the welding tool has been too high. When this happens cracking occurs in the weld root during bend testing. From this it might be inferred that the defect of concern is the herring bone cracking which has been observed in the weld root. This cracking causes failures in bend tests for the aluminium alloys considered. Such cracking may or may not be a problem for lid welds in copper canisters, depending on their extent.

Lloyds Register recognises the potential of FSW for weld repairs but give no further guidance. This begs the question "how are the run out and run in regions controlled?" no answer is provided at this stage.

3. Conclusion

Taken together these papers provide a very optimistic picture for the development and application of friction stir welding in general and to the case of the copper canister in particular. Whilst a considerable development effort is in progress the process has been industrialised for joining of aluminium sheet and it is accepted by Lloyds register for this purpose.

Development of procedures and equipments to weld thicker materials and a wider range of materials is progressing ahead of the research activity to aid the understanding of the process at this stage. Nevertheless, well-established weld assessment procedures are being applied to experimental welds with very encouraging results.

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14. Midling OT et al. Industrialisation of the friction stir welding technology in panel production for the maritime sector. The proceedings of the first International symposium on friction stir welding[3]. Available on CD from TWI Granta Park, Abingdon Cambridge England

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4. Appendix

Extracts from papers presented at the first International symposium on friction stir welding[3]

Loftus Z et al. Development and implementation of a load controlled friction stir welder.

A demonstration product, a 27.5-ft diameter, barrel for an external tank for NASA`s Space transportation system in 2195-T8 aluminium 0.32-in thick, was welded.
The assembly jig and welder position control system was adapted from a fusion welder system.
The distance from the back of the workpiece to the tip of the pin tool is important if full penetration welding is to be achieved. In this case a distance of 0.020-in was maintained by a position control system incorporating an LVDT. The relationship between pin tool depth and axial load was consistent for any particular pin tool geometry and welding parameters. This enables axial load to be used as a control parameter on pin depth. For any specific welding parameters, the weld gap has a significant effect on the characteristics of the finished weld but no details are given. Four axes of motion are vertical travel, cross slide travel, spindle plunge and spindle rotation.
Increasing rotational speed or decreasing the plunge rate reduces the force required for the plunging operation. Axial force is used in a closed loop control system to manage rotational speed and travel speed during welding. At the end of the weld the tool is retracted at a predetermined rate and over a specified distance.

Jones, C. et al. Assembly of a full-scale external tank barrel section using friction stir welding.

This is a companion paper to Loftus Z et al. above. An experiment was conducted to establish the sensitivity of the welding process to variations in various parameters. The range parameter variation was ± 75 rpm for rotational speed, ± 0.75 rpm for forward traverse speed and ± 0.007 in for the penetration ligament. Parameters were optimised based on maximising the tensile strength. None of the parameter variations gave significantly different effects on tensile strength. However penetration ligament had the greatest effect followed by travel speed with rotation speed having little effect. The effects of intereactions between parameters were also statistically insignificant. Operational parameters were selected by comparative examination of the results of the statistical experiment.
Two tapered thickness welds were made as part of the programme. To achieve this, each specimen was welded first from one side and then the other. Thus each of the first welds started at less than full thickness and proceeded until they were full thickness, The second welds in each case started in the unwelded region and proceeded to overlap the earlier full thickness weld. Both these welds were successful. A further tapered thickness weld was made using a retractable pin tool. A weld varying in thickness from 0.65 to 0.32 inches was made successfully. (This suggests that a retractable pin tool might be used for finishing a lid weld in copper canisters by continuously retracting the pin in an overlap zone at the end of the initial weld). The authors report that further

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J. Przydatec. A ship classification view on friction stir welding.

The main method of welding at present is to clamp the material on a flat bed and apply the tool vertically from above.
The author details guidance given to inspectors for approval of emerging novel implementations of the technology.
The welding tool is a key component and novel designs are expected to emerge as the technology develops. Inspectors are not expected to understand the intricacies of fluid flow around the tool so the manufacturer has to provide evidence of suitability. As a minimum this involves weld characteristics from mechanical and non-destructive tests.
Tool wear and clogging are reported to affect weld performance. These conditions are not readily observable during processing so regular tool observations are required. No details of the problems arising from tool wear or clogging are given.
Results on aluminium sheet, plate and extrusions indicate that the process is at least as good as the equivalent fusion process.
A list of test requirements is given. These include:

1. Visual examination 100%
2. Radiographic or ultrasonic 100%
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Concludes that several aspects of material flow in friction stir welds require additional explanation. Many details of how material is deposited behind the pin are not yet known.

James M et al. Residual stress measurements in friction stir welded aluminium alloys.

X-ray diffraction used to measure surface residual stresses in three aluminium alloys after friction stir welding. Results indicate that within the fully recrystallised zone residual stresses are zero. Moderate stresses are present in the region between fully recrystallised material and the partially recrystallised region of the thermo-mechanically-affected zone. Residual stresses are considerably below the stresses created by fusion welding processes.

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Other tool concepts are also under consideration.

Midling O T et al. Effect of tool shoulder material on heat input during friction stir welding.

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The welding parameters required for avoidance of these defects were identified, during welding of three high-strength aluminium alloys.

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Andersson C-G et al. Fabrication of containment canisters for nuclear waste by friction stir welding.

An exploratory programme to develop the FSW process for joining 50mm thick copper plates is described. Feasibility is established. A pilot level welding machine has been designed for lid attachment and manufacture is in progress. A flaw that has been associated with FSW of 50 mm-copper plates is a running void on the advancing side of the weld zone. It has been linked to excessive softening of the copper, which has led to loss of clamping force. It is reported that modifications to the tool design and/or welding parameters have eliminated this defect.