Technical Report

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Friction stir welding – an alternative method for sealing nuclear waste storage canisters

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Executive summary

Background

In Sweden, spent nuclear fuel will be housed in purpose built cylindrical canisters and stored in a deep underground repository. The major requirements of the canisters are: very long term corrosion resistance, and sufficient strength to resist the pressure loads in the deep repository. To satisfy these requirements a copper tube ~1.0 m diameter × ~5.0 m long with 50 mm thick walls, sealed at either end will be used. The pressure resistance is provided by a cast iron insert containing the spent fuel, inside the copper tube (1). The canister is completely sealed by welding a bottom and lid to either end.

When welding 50 mm thick copper a very high heat input is required to combat the high thermal diffusivity and only the Electron Beam Welding (EBW) process had this capability when this copper canister concept was conceived. Collaborative SKB/TWI work has involved an EBW development programme that continues in the SKB Canister Laboratory.

Despite the encouraging results achieved using EBW with thick section copper, SKB felt that it would be prudent to assess other joining methods. This assessment concluded that friction welding, a solid phase welding process, could also provide very high quality welds to satisfy the service life requirements of the SKB canister design. A friction welding variant called Friction Stir Welding (FSW) was shown to have the capability of welding 3 mm thick copper sheet with excellent integrity and reproducibility. This later provided sufficient encouragement for SKB to consider the potential of FSW as a method for joining thick section copper, using relatively simple machine tool based technology. It was thought that FSW might provide an alternative or complementary method for welding lids, or bases to canisters. In 1997 an FSW development programme started at TWI, focussed on the feasibility of welding 10 mm thick copper plate.

Once this task was successfully completed, work continued to demonstrate that progressively thicker plate, up to 50 mm thick, could be joined. At this stage, with process viability established, a full size experimental FSW canister machine was designed and built. Work with this machine finished in January 2003, when it had been shown that FSW could definitely be used to weld lids to full size canisters.

This report summarises the TWI development of FSW for SKB from 1997 to January 2003. It also highlights the important aspects of the process and the project milestones that will help to ensure that SKB has a welding technology that can be used with confidence for production fabrication of copper waste storage canisters in the future.

Objectives

This report describes the rapid development of FSW for thick section copper from 1997 to January 2003. Throughout that time each phase of the work programme had a series of focussed objectives. The overall objective of the entire work programme was to demonstrate, without doubt, that the FSW process could be used to produce full size copper lid to canister welds in a production environment.

To achieve this, work programmes with a duration of one year were broken down into a series of objectives, which were directly aligned to a number of tasks. Many of the tasks needed to be undertaken in parallel to achieve the necessary timescales.

Project progress and the feasibility of the results achieved were regularly reviewed by SKB staff. This ensured that if insurmountable technical difficulties were encountered the financial risk to SKB was minimised, but fortunately it was never found necessary to use this option.

The work programme progressed from 1997–2003 and was linked to the more focussed objectives as listed below:

a) 1997 – To determine the feasibility of FSW copper plate up to 10 mm thick.

b) 1998 – To determine the feasibility of FSW copper plate up to 50 mm thick.
   - Welding machine requirements such as strength, transmission power and forces.
   - FSW tool development.
   - Identification of commercial equipment with the capability of producing 3 m long welds in 50 mm thick copper plate.
   - Produce the operating specification for a prototype FSW machine capable of producing 3 m long circumferential welds.

c) 1999 – Design and build an experimental FSW canister welding machine.
   - Optimise FSW tool probe profiles and materials.
   - Commission and carry out welding trials with the experimental FSW machine. A lid simulation to be used with segments cut from canisters, for economic reasons.

d) 2000 – Develop the FSW procedure for welding lids to canisters.
   - Welding trials with 1 m long canister segments.
   - Establish welding conditions.
   - Mechanical and physical property assessment.

e) 2001 – Produce a complete circumferential weld.
   - Produce full penetration welds on a routine basis.
   - Minimise tool probe failures.
   - Develop a working specification for an SKB FSW pre-production machine.
   - Assist in production of an Invitation to Tender document to FSW machine manufacturers.
   - Assist in the selection procedure for an FSW machine.
   - Assist in the identification of the site requirements and facilities for an SKB FSW machine.

f) 2002–January 2003 – To ensure that good quality complete circumferential lid/base to canister welds can be made on a routine basis, with no FSW tool probe failures, evidence of wear, or contamination of the weld zone
   - To introduce the latest, relevant project information to the SKB FSW machine design and build in at an early stage to avoid post manufacture modifications.

Work carried out

The first major task was to demonstrate that 10 mm thick copper plate could be joined successfully using the FSW technique. The work was undertaken using an existing FSW machine in combination with FSW tools (probe and shoulder), which were similar in design to those that had been used to weld aluminium alloys. However, as the copper plate thickness increased it became clear that a more powerful dedicated FSW machine was necessary for the work programme to move forward. Also, FSW tools were needed that could operate at between 800–900°C and, more importantly, withstand the increased force and torque regime resulting from thicker plate.

In 1999 a full size experimental FSW canister welding machine was designed and built, in parallel a study was undertaken to generate new concepts for FSW tool geometries. In particular an extensive survey of potential probe material, that had adequate strength at welding temperatures, was undertaken which created the next generation of FSW tool probes.

Initially, for economic reasons, a lid simulation was used in combination with segments cut from canisters. The lid simulation could be separated from the welded interface and thus used numerous times. This set up enabled rapid development of FSW procedure and FSW tools that could produce 1 m long welds in 50 mm thick copper, which was a project milestone.

The results of the mechanical and physical property assessment led to the manufacture of complete circumferential 3.3 m long welds in 2001. Following this, in 2002 full penetration (52 mm) complete circumferential welds could be produced on a routine basis, with no FSW tool probe failure providing the recommended welding temperature was maintained.

The ultimate project goal was achieved in January 2003 when it was demonstrated that good quality lid to canister welds could be produced. The development programme was focussed on the optimisation of FSW weld parameters and procedures and required a wide range of disciplines, which were required to undertake the following:

- FSW tool probe and shoulder material selection and assessment.
- Development of an operating specification for an experimental FSW canister machine.
- Development of FSW process control methods suitable for production welding.
- Development of an operating specification for a production FSW machine for operation in the SKB Canister Laboratory.

Conclusions

The overall conclusion to this FSW development is that there is no doubt that the FSW process could be used to produce full size copper lid to canister sealing welds in a production environment. However, more focussed conclusions directly associated with a series of project objectives are listed below:

- It is feasible to FSW 10 mm thick copper plate.
- It is feasible to FSW 50 mm thick copper plate.
- A fully operational experimental FSW canister welding machine was designed and built.
- Procedures for FSW of lids to canisters were successfully developed.
- Complete circumferential, full penetration lid/base to canister welds could be made, with no FSW tool probe failures, evidence of wear or contamination of the weld zone.

Recommendations

The overall recommendation is that the FSW development should be continued at the SKB Canister Laboratory to a stage where it can be used reliably in the production. It is also recommended that SKB consider keeping TWI personnel involved in the FSW development programme in a similar manner to the EBW development. A benefit of this continued collaboration would be that relevant TWI FSW developments in FSW tools, materials, process control methods and procedures could be rapidly assimilated into the

SKB development programme. TWI now have a large, powerful, thick section FSW machine at the TWI Sheffield facility, which has the capability of welding full size copper canisters. The sophisticated operating specification could greatly help in the development of the FSW machine, which will eventually be used in the Encapsulation Plant.

Contents

1 Introduction

1.1 Method for storing nuclear waste

In Sweden, spent nuclear fuel will be housed in purpose built canisters and stored in a deep underground repository. The major requirements of the canister are very long-term corrosion resistance, and sufficient strength to resist the pressure loads in the deep repository. To satisfy these requirements, a copper tube ~1.0 m diameter × ~5.0 m long × 50 mm wall thickness, sealed at either end will be used. The pressure resistance is provided by a cast iron insert, containing the spent fuel, inside the copper tube (1). The canister is completely sealed by welding a bottom and lid to either end.

In order for this type of canister to achieve the expected service life, the sealing welds must be of the highest integrity, to avoid preferential corrosion, and the life cycle stresses. An additional complication associated with this canister concept is the high thermal diffusivity of copper, which is 10–100 times greater than that of many steels and nickel based alloys. Therefore when welding 50 mm thick copper a very high heat input is required to combat the high thermal diffusivity. When the SKB canister concept was first considered, there was only one welding process with this capability, which was Electron Beam Welding (EBW).

1.2 EBW for sealing copper canisters

In 1986 TWI were commissioned to investigate the feasibility of sealing copper canisters using the EBW technique. EBW is a fusion welding process in which a joint between two components is made in the liquid phase, with the result that the narrow weld zone has a cast microstructure.

High heat input to the weld is achieved using a high power density heat source, which permits thick section welding without the need for preheating. High heating rates keep the weld cycle time short and help to reduce the heat losses into the surrounding material.

A work programme to develop a dedicated EBW gun system and to optimise welding parameters has been carried out by TWI. EBW equipment installed at SKB's Canister Laboratory has been successfully used to continually develop the technique, and good quality welds have been produced. However work continues to optimise machine operation and weld parameters, with the aim of producing good quality circumferential canister to lid, or base welds on a routine basis.

1.3 Solid phase welding

Despite the encouraging results achieved using EBW in thick section copper, SKB felt that it would be prudent to assess other candidate joining methods. This assessment concluded that friction welding, a solid phase welding process, could also provide very high quality welds to satisfy the service life requirements of the SKB canister design.

Solid phase joining techniques, such as forge welding have been used for centuries, and simply require control of the three interrelated factors, time, temperature and welding pressure. Welds are produced below the material melting point and usually have a fine-grained weld zone microstructure due to the forging action, which causes severe plastic deformation.

One variant of the forge welding process known as friction welding is an established production technique, with a reputation for producing high quality reproducible welds.

1.4 Friction welding

Friction welding is a relatively simple machine tool based technology, and in-process monitoring can be used to confirm if the welding conditions are being accurately maintained on a real time basis.

These attractive features of the friction welding process encouraged SKB to consider the possibility of using the process as an alternative and/or complementary canister fabrication route, in particular for making the circumferential base to canister weld. Welding trials demonstrated that it was feasible to use friction welding to join copper tubes of 200 mm outside diameter × 15 mm wall thickness and achieve high integrity welds with a weld cycle time of approximately 20 seconds, see Figure 1-1.

This weld was made by holding one of the copper tubes in the rotating chuck of a friction-welding machine, and the other tube in a non-rotating chuck mounted on the same axis. The non-rotating tube is moved towards the rotating tube under an axial force. Once the faces of each tube touch, the rubbing motion rapidly removes any surface oxidation and generates frictional heating. Very rapidly the interface becomes hot and softened, and a solid phase joint is initiated. After a suitable time period, the rotating tube is stopped to terminate heating, but the axial force is maintained. This so-called forging action consolidates the weld, and the result is a narrow heat affected zone, with a fine hot forged microstructure.

Figure 1-1. *Friction welded copper tube.*

Due to the excellent weld integrity achieved, the practicality of using friction welding to manufacture full size canister to lids, was explored. When the friction welding conditions were scaled up for welding full size copper canisters the projected welding force required was up to 24,000 kN. A TWI survey showed that no available commercial friction welding machines existed with that force capability. Additionally, SKB concluded that the costs (£2–3M) to develop a dedicated friction welding machine for canister base welding were prohibitive and the risk too great.

Although this conclusion was initially disappointing, it was fortunate that a new friction-welding variant called Friction Stir Welding (FSW) had been invented [2]. FSW had the ability to produce high quality solid phase welds, but with a reduced force requirement, and thus lower welding machine costs. In 1997 most FSW work had focussed on joining aluminium alloys, and excellent weld integrity and reproducibility had been achieved. Additionally in 1992, 3 mm thick copper sheet had been successfully friction stir welded, but not developed further.

This latter information provided sufficient encouragement for SKB to consider the potential of FSW as a method for joining thick section copper, using relatively simple machine tool based technology. It was thought that FSW might provide an alternative or complementary method for welding lids, or bases to canisters.

Therefore in 1997 an FSW development programme started at TWI, focussed on the feasibility of welding 10 mm thick copper plate.

Once this task was successfully completed, work continued to demonstrate that progressively thicker plate up to 50 mm thick could be joined. At this stage, with process viability established, a full size experimented FSW canister machine was designed and built. Work with this machine finished in January 2003, when it had been shown that FSW could definitely be used to weld lids to full size canisters.

These development programmes were always undertaken in a step-wise manner, so that in the event of insurmountable technical problems, the project work could be terminated. This approach minimised the financial risk to SKB Ltd.

This report summarises the TWI development of FSW for SKB from 1997 to January 2003. It also highlights the important aspects of the process and the project milestones. It is intended that the information included will provide SKB with benchmark welding conditions, FSW tools and production welding machine procedures to assist with the further development of FSW for producing lid to waste storage canister sealing welds.

The results of this project were recorded in internal Progress Reports that were issued at either 2 or 4 month intervals or alternatively when significant progress had been made. Issue of these reports usually coincided with SKB/TWI project review meetings where project direction or continuation was discussed.

2 Friction stir welding (FSW)

2.1 The principles of FSW

Friction welding was described in Section 1.4 where it was shown that by using a combination of rotation (movement) and applied force, two copper tubes could be joined in the solid state. The geometry of components that can be friction welded in production is confined to round, square or rectangular sections. Before 1991 it was not possible to use friction techniques to butt weld plates longer than 100 mm together. However, in that year, FSW was invented, and has gone on to be remarkably successful for butt-welding a wide range of aluminium alloys.

The FSW technique was readily adopted by the aircraft, aerospace and transport industries involved in the fabrication of aluminium alloy components, due to the reproducible production of high integrity welds, in contrast with some conventional welding methods.

Instead of rubbing the contact faces of two plates together to generate frictional heating, a different approach is taken in FSW. The heat is generated by using a rotating tool, which does not deteriorate in any way during the welding process. This rotating tool is forced into the interface between the two plates, which are clamped tightly together. The rubbing action of the tool generates sufficient heat to soften the plate material adjacent to the interface. Once a suitable temperature has been reached, the tool is translated along the length of the interface to join the plates together. A sketch of FSW in action is shown in Figure 2-1.

The FSW tool consists of the shoulder, which generates most of the heat, and the probe. As this tool progresses along the weld interface, softened copper is extruded through a profile machined on to the probe body, from the leading face of the probe to the back. The downward or welding force applied to the FSW tool consolidates the softened extruded copper, and as a result of this combination of time, temperature and pressure a solid phase joint is formed.

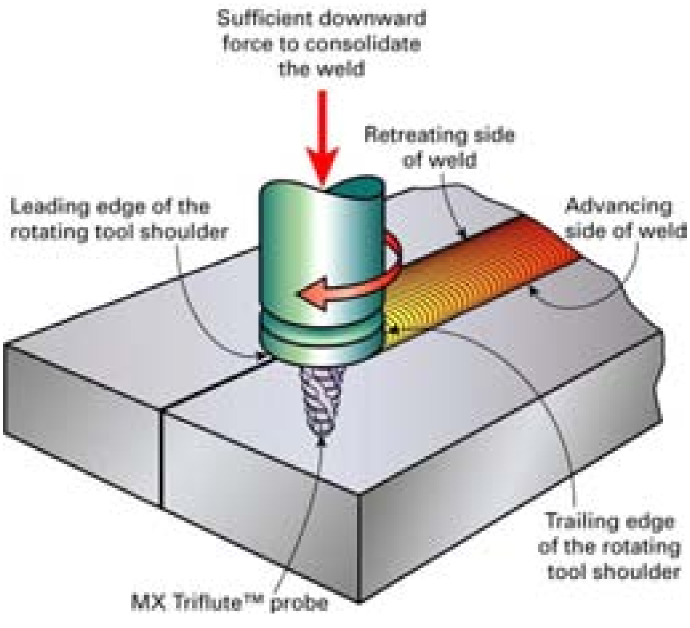


Figure 2-1. *The principle of FSW.*

The weld zone consists of hot forged material usually with a smaller grain size than that of the parent material, under optimised operating conditions, no macro melting occurs.

2.2 The advantages of using FSW

When SKB decided to explore the potential of FSW for copper, a number of process advantages were carefully considered and compared with the capabilities of fusion welding techniques. These advantages can be grouped as follows:

a) FSW is a relatively simple mechanical and energy efficient process for the reasons listed below:
   - FSW is based on existing or readily available machine tool technology.
   - No filler material or shielding gas is required.
   - Environmentally friendly (no fume, no light emission).
   - Suitable for automation.

b) FSW is a solid state process with no base metal melting, giving rise to the following:
   - Low residual stress and distortion.
   - No solidification cracking.
   - A fine hot worked microstructure.

c) Improved mechanical properties as follows:
   - Higher joint strength.
   - Increased weld ductility.
   - Improved fatigue life.
   - Higher fracture toughness.

3 Objectives

This report describes the rapid development of FSW for thick section copper from 1997 to January 2003. Throughout that time each phase of the work programme had a series of focussed objectives. However, the overall objective of the entire work programme was to demonstrate without doubt that the FSW process could be used to produce full size copper lid to canister sealing welds in a production environment.

To achieve this overall objective, work programmes with a duration of one year were broken down into a series of tasks, which were directly aligned, to a number of technical objectives. Many of the tasks needed to be undertaken in parallel to achieve the necessary timescales.

Project progress and the results achieved were regularly reviewed by SKB staff. This ensured that if insurmountable technical difficulties were encountered then the financial risk to SKB was minimised, but fortunately no difficulties of this magnitude were encountered.

The work programme progressed from 1997–2003 and was linked to the focussed objectives as listed below:

a) 1997 – To determine the feasibility of FSW copper plate up to 10 mm thick.

b) 1998 – To determine the feasibility of FSW copper plate up to 50 mm thick.
   - Welding machine requirements such as strength, transmission power and forces.
   - FSW tool development.
   - Identification of commercial equipment with the capability of producing 3 m long welds in 50 mm thick copper plate.
   - Produce the operating specification for a prototype FSW machine capable of producing 3 m long circumferential welds.

c) 1999 – Design and build an experimental FSW canister-welding machine.
   - Optimise FSW tool probe profiles and materials.
   - Commission and carry out welding trials with the experimental FSW machine. A lid simulation to be used with segments cut from canisters, for economic reasons.

d) 2000 – Develop the FSW procedure for welding lids to canisters.
   - Welding trials with 1 m long canister segments.
   - Establish welding conditions.
   - Mechanical and physical property assessment.

e) 2001 – Produce a complete circumferential weld.
   - Produce full penetration welds on a routine basis.
   - Minimise tool probe failures.
   - Develop a working specification for an SKB FSW pre-production machine.
   - Assist in production of an Invitation to Tender document to FSW machine manufacturers.
   - Assist in the selection procedure for an FSW machine.
   - Assist in the identification of the site requirements and facilities for an SKB FSW machine.

f) 2002–January 2003 – To ensure that good quality complete circumferential lid/base to canister welds can be made on a routine basis, with no FSW tool probe failures, evidence of wear, or contamination of the weld zone.
   - To introduce the latest, relevant project information related to the SKB FSW machine design and build at an early stage, thus avoiding post manufacture modifications.

4 FSW of plates 10–50 mm thick

4.1 10–20 mm thick plate

When the FSW of copper programme started, TWI's experience was limited to a short study aimed at joining 3 mm thick copper plate. The results of this work did not reveal any major technical difficulties that could prevent 50 mm thick copper from being joined by FSW. The fact that copper is a soft, ductile metal and can be readily deformed by cold, or hot working generated additional confidence in the potential for application of the FSW technology. However, even at this early stage it was clear that a considerable amount of effort would be required to develop FSW tools that would operate reliably at considerably higher temperatures than those used to weld aluminium alloys. To a large extent, this requirement dictated the step-wise approach to the whole FSW development programme. The first task was to prove that 10 mm thick copper plate could be joined, and then welding of progressively thicker sheet was attempted. At any stage of the development when technical difficulties were encountered, they were reported and discussed to determine a route forward that could be accomplished within reasonable timescales and costs.

4.1.1 The FSW machine

The majority of the FSW projects at the time were concerned with joining 2–5 mm thick aluminium alloy plate, using modified milling machines. Transmission power requirements and the welding forces recorded when welding aluminium alloys were comfortably within the working capability of these machines. However, from the results of the 3 mm thick copper plate study, it was clear that welding of 10 mm copper plate would place greater requirements on the machine. Therefore a large modified milling machine with a rigid 'C' frame which had been used successfully to weld up to 75 mm thick 7000 series aluminium alloy was selected for undertaking the SKB development of FSW for 10 mm thick copper.

Although this machine was of an outdated design, it was considered to be ideal for FSW trials due to its massive cast construction. This machine is shown in Figure 4-1.

An essential feature of this milling machine, when friction stir welding, is the rotating spindle onto which the FSW tooling is clamped. This spindle is driven by a 22 kW electric motor through a robust gearbox, which provided sufficient torque for welding copper. A range of spindle rotation speeds varying from 40–1270 rev/min are available.

The large rigid work table, which can be traversed in either the x or y directions underneath the rotating FSW tool, is an equally important FSW machine feature, with a welding speed capability of between 30–900 mm/min.

It had been demonstrated throughout the development studies on aluminium plate, that it was important to incline the rotating spindle at an angle of 1–3° away from the vertical position, so that the leading edge of the rotating FSW tool shoulder does not become buried under the softened surface layers of copper, which could cause FSW tool damage. This angle of inclination is known as the "tool tilt angle".

The welding force, or z downward force generates frictional heating and is applied via a sturdy rack and pinion drive system, which is simply manually adjusted throughout a weld cycle. When welding the 10 mm thick copper plate, it was not possible to measure the z

Figure 4-1. *TWI's large milling machine modified for FSW.*

force. However, as the project progressed towards welding thicker plates, the value of the z force was needed to assist in quantifying the heat input. Measurement of the z force was accomplished by embedding a peizo-electric transducer into the 'C' frame of the large milling machine. Flexure of the 'C' frame was measured and translated into applied force.

Throughout the 10 mm thick plate welding trials, it was only possible to record the spindle rotation speed and the welding speed. However, to be able to diagnose the influence of the various weld parameters on weld quality and tool life when welding thicker plate, it was necessary to improve the monitoring system. These additions are explained later in the text.

4.1.2 Making friction stir welds in 10–20 mm thick plate

As described in Section 1.3, friction stir welding is accomplished by a suitable combination of time, temperature and pressure. Pressure is applied at the interface between two plates when the rotating FSW tool probe is forced into the joint. This would normally cause the two plates to separate if they were not tightly clamped together throughout the weld cycle. To prevent this movement, a suitable steel clamping fixture was designed and built to hold two copper plates, each 10 mm thick × 50 mm wide × 510 mm long, as shown in Figure 4-2.

The base plate of the clamping fixture was water cooled to simulate the rate at which heat would naturally be conducted away from the weld zone in a full size lid to canister weld. When this facility was not used, the copper plates became severely overheated.

Before clamping the plates into the clamping fixtures the first step in making a weld was to clean the faces of the plates to be welded together using either Scotchbrite™ pads or stainless steel wire brushes. The abrasive action assisted the removal of any oxide or debris before degreasing.

Figure 4-2. *Water-cooled clamping fixture for 10–25 mm plate.*

Normally when joining aluminium alloys of thicknesses 3–12 mm, the first stage of a FSW welding cycle is to plunge the probe of the rotating friction stir welding tool into the interface between the two plates to generate sufficient frictional heating to locally soften the material surrounding the probe. Once adequate softening has been achieved, the stir tool is traversed along the joint. However, as the forging temperature range of copper is higher (between 590 and 930ºC) than that of aluminium alloys (between 340 and 480ºC), this plunge procedure could not be used because the stir tool probes experienced high torque during the plunge and this resulted in tool breakage.

In order to assist stir tool probe penetration into the copper plate, and to minimise the high torque reactions generated, a pilot hole was drilled at the start of the weld. The diameter of this pilot hole was normally slightly smaller than that of the probe diameter to enable sufficient frictional heat to be developed. During the trials, tool probe geometry was modified from a standard parallel profile to more complex shapes; the dimensions and geometry of the pilot hole were altered accordingly. The tool probe and shoulder development is described separately in Section 7.

The pilot hole was drilled using the rotating spindle of the friction stir welding machine in order to match the tilt angle of the stir welding tool. Friction stir welds in the copper plate were made by feeding the rotating stir welding tool slowly into the pilot hole to locally heat the plates, until the tool shoulder just touched the plate surface. When welding the 10 mm plate, the trailing edge of the tool shoulder was held at a constant depth below the plate surface by constantly adjusting the rack and pinion system. However, when the 20 mm thick plate welding trials started, a z force measuring facility was added to the machine. The z force generated during the plunging was measured and recorded by a load cell and the plunge depth (or depth the stir tool shoulder penetrated below the top surface of the copper plate) was measured using a digital height gauge. A certain dwell time was then allowed for the temperature adjacent to the tool probe to reach 400ºC. At this temperature the traverse mechanism was started at a low welding speed of 15 mm/min. The welding speed was then progressively increased to a steady state value, which was maintained to weld completion. Minor adjustments were made manually to the height of the rotating tool shoulder throughout the weld cycle to maintain the downward z welding force. These adjustments were necessary due to thermal expansion and movement of the copper plates.

A series of welding trials was undertaken where the major weld parameters, and the FSW tool size and shape were varied until good quality welds were achieved. A friction stir weld is shown being made in Figure 4-3 and a completed weld in Figure 4-4.

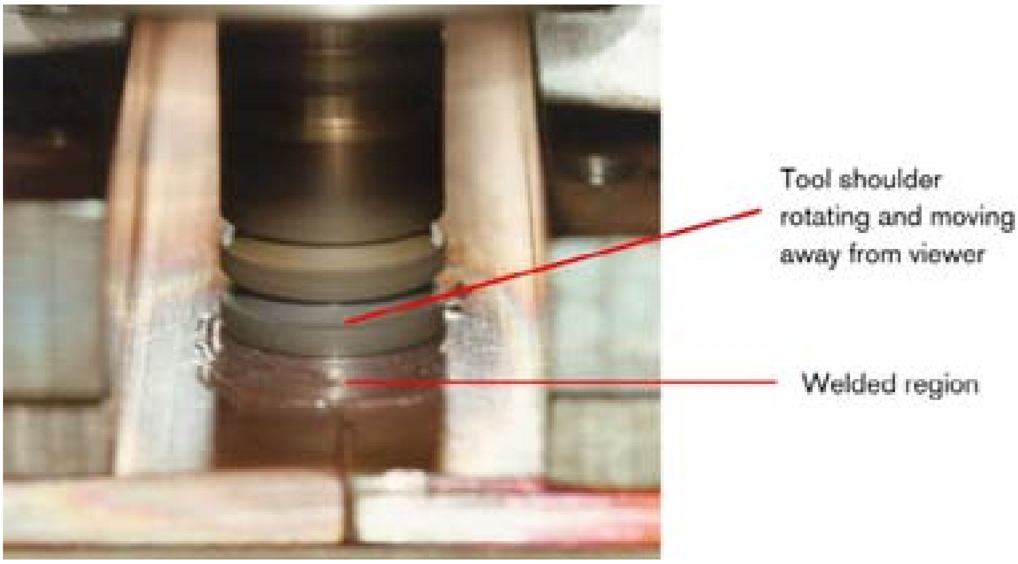


Figure 4-3. *FSW 10 mm copper plate.*

Figure 4-4. *Completed FSW in copper plate 10 mm thick.*

The welding conditions used were as shown in Table 4-1 below:

Table 4-1. The welding conditions used to join 10 mm thick copper plate.

Welding variables	Conditions Used
Pilot hole	No. 6 centre drill (60° included angle) × 7.5 mm deep.
Welding tool rotation speed	213 rev/min.
Tool plunge depth	Initially 0.8 mm below the surface, and then 0.2 mm when steady state conditions were reached.
Welding speed	Start speed 15 mm/min. Steady state speed 60 mm/min.

The first project major milestone was achieved when it was demonstrated that FSW could be used to join 10 mm thick copper plates. Evidence of the excellent weld integrity achieved when welding 10 mm copper plate is demonstrated by the transverse metallurgical section cut through a region at which the steady state welding speed was 56 mm/min shown in Figure 4-5.

The weld zone is free from root or face flaws and the microstructure consists of indistinctly etching, fine re-crystallised grains within the central weld nugget. Larger grains that had been subjected to some plastic deformation were present in the thermo-mechanically affected zone (TMAZ) adjacent to the nugget. In the heat affected zone (HAZ), equiaxed grains larger that the parent metal grain size were present.

Further evidence of excellent weld quality was substantiated by bend test results. 180º root and face bend angles were achieved without failure, as shown in Figure 4-6. These three point bend tests were made using a 3t (or 30 mm diameter) former where t = the thickness of the copper plate.

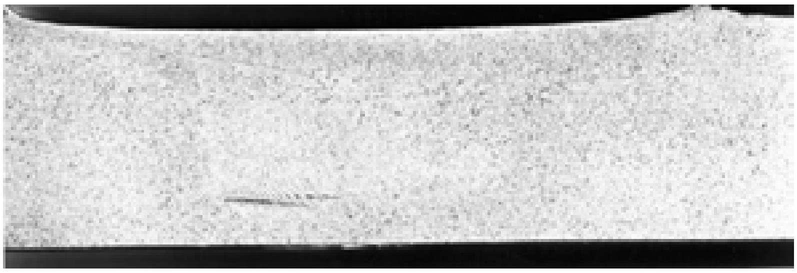


Figure 4-5. *Transverse metallurgical section cut through an FSW in 10 mm copper plate.*

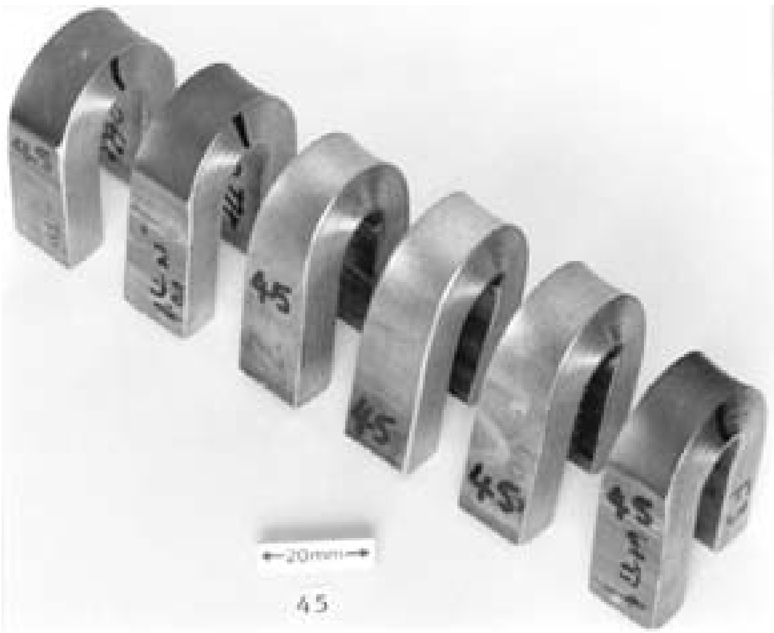


Figure 4-6. *Root and face bend test specimens.*

Tensile test samples cut from the start, middle and end of a series of welds gave very uniform tensile strengths with final fracture occurring at random locations along the gauge length of the test samples with no point of weakness identified that could be associated with the fracture. Tensile strengths of between 216 and 218 N/mm^2 were recorded compared with a patent material tensile strength of 280 N/mm^2.

The results provided sufficient confidence for SKB to initiate a follow-on work programme. The overall objective was to determine the maximum thickness of copper between 10–50 mm that could be joined by FSW. It proved to be relatively easy to weld 20 mm thick plate using small weld parameter changes, and by increasing the length of the FSW tool probe. However, when welding 30 mm thick plate it was not possible to maintain the welding speed at the set constant value. Variation in speed generated an undesirable cyclic loading on the leading edge of the FSW tool probe causing probe fracture. The welding speed variations were due to the traverse table mechanism operating at the upper limit of the machine's transmission power capability.

At this point in the development, it was concluded that increased transmission power was needed to drive the milling machine's traversing work table.

4.2 Welding 30–50 mm plate

4.2.1 Modifications to the FSW machine

The 30–50 mm thick plate work programme continued using the same large milling machine as used in the 10–20 mm programme, but in modified form. As it was not practical in terms of time and cost to increase the transmission power to the traversing work table, an independent powerful, linear traversing table was designed and built. This table was attached directly on top of the original work table, and proved to have more than adequate power for welding 50 mm thick copper. A sketch of the general arrangement of this system is shown in Figure 4-7.

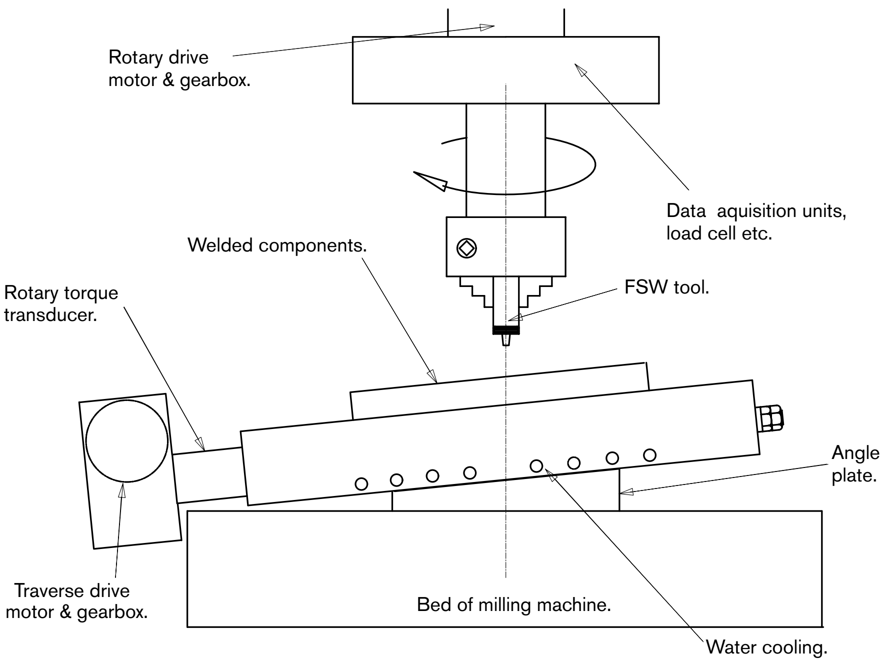


***Figure 4-7.** General arrangement of the linear traverse unit.*

The new table was driven by a variable speed AC, 0.55 kW motor through a gearbox with a large reduction ratio of 142:1, which was connected to an 80 mm diameter re-circulating ball, deep groove screw and nut system. This is shown in Figure 4-8. This facility enabled welding speeds of 1–220 mm/min to be achieved.

Experience of welding aluminium alloys indicated that the FSW machine design could be simplified if an FSW tool tilt angle was not used. When used for welding certain aluminium alloys, a reduction in FSW tool tilt angle from 2–3º to 1º and 0º also resulted in faster welding speeds. Therefore welding trials were undertaken to establish if reduced tool tilt angle yielded similar benefits for copper. However, it was practically difficult to change the tool tilt angle on the large milling machine. A solution to this problem was devised consisting of a series of angle plates that allowed tilt angles of between 1º and 3º to be set, but without moving the rotating spindle from the vertical position. These plates and the main features are identified in Figure 4-8.

Two copper plates ready for welding are shown with the combined dimensions of 300 mm × 500 mm held in the fixture using hydraulic clamps. Additionally, top clamps could be bolted into position to prevent the plates from being pulled upwards. The copper pipes running around the side of the traversing table supply cooling water to the steel base of the table. This cooling water protected the large screw from excessive heating and also cooled the copper plates.

In contrast to the limited weld parameter monitoring carried out when welding 10–20 mm thick copper plate, additional instrumentation was interfaced with the large milling machine and the new traversing table. The weld parameter input values were:

- FSW tool rotation speed.
- Welding force (z).
- Welding speed.
- Location of the FSW welding tool relative to the surface of the plate.

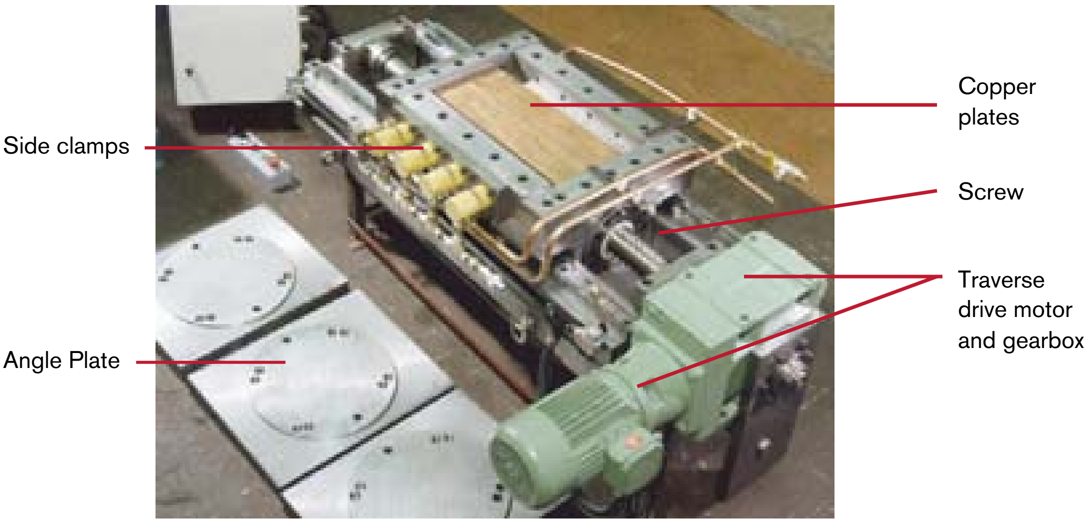


Figure 4-8. *The purpose-built linear traversing table.*

The improved monitoring system allowed measurement of weld condition indicators such as:

- Torque on the lead screw.
- Traverse (x) force acting on the leading edge of the stir tool probe.
- Total weld length with accurate location of any position.
- Temperature of various locations along the weld.

The weld records helped to create the working specification for future dedicated FSW equipment.

4.2.2 Making friction stir welds in 30–50 mm thick plate

Welding trials with progressively thicker plates were continued in much the same way as described in Section 4.1.2 for 10 mm thick plate. The second major milestone of this project was achieved when it was demonstrated that, without doubt, 50 mm thick copper plates could be joined. Importantly there was adequate spindle rotation transmission power available to drive the FSW tool, and more than enough transmission power to drive the new linear traverse unit. The information was added to the growing list of working specification requirements for a full size canister welding machine.

It was found that subtle weld parameter changes needed to be made for each thickness of plate, to compensate for the increased volume of copper. Over a period of 40 years, basic guidelines have been established for generating optimum friction welding conditions but it was discovered that these guidelines were not applicable to FSW of thick section copper. For example, when using conventional friction welding to join solid round bars of increasing diameter, the rotational speed is decreased in order to maintain a constant peripheral velocity. However, this did not apply to FSW as it was found that as the FSW tool probe diameter was increased, it was not necessary to maintain the same peripheral velocity as used for smaller diameter probes. The volume of thicker copper plate resulted in rapid conduction of heat away from the weld zone. To compensate for this rapid heat loss by increasing the energy input, the FSW tool rotation speed had to be progressively increased to 500 rev/min, from the ~200 rev/min used to weld 10 mm thick plate, and the welding force increased from 20 kN to 80 kN.

As the welding trials progressed, it became clear that the force clamping the two plates together was also a very important FSW parameter. A triangular shaped flaw ~3 × 3 × 3 mm was generated in the advancing side of a weld. The exact location of the weld advancing side is identified in the sketch in Figure 4-9, and a typical triangular flaw is shown in Figure 4-10.

It proved possible to prevent the formation of this type of flaw by increasing the plate side clamping force such that it exceeded the force generated by the passage of the rotating FSW tool probe along the weld interface. The plate clamping force had not been considered as a weld parameter before this study, but was used later in the work programme to predict the force required to hold a full size lid against a canister. Examples of good quality welds in both 40 and 50 mm thick copper plate are shown in Figures 4-11 and 4-12.

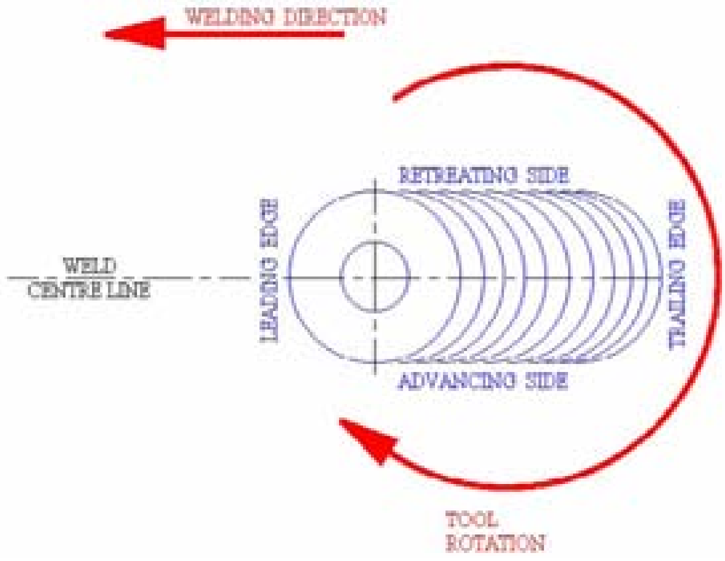


Figure 4-9. *The major features of a friction stir weld.*

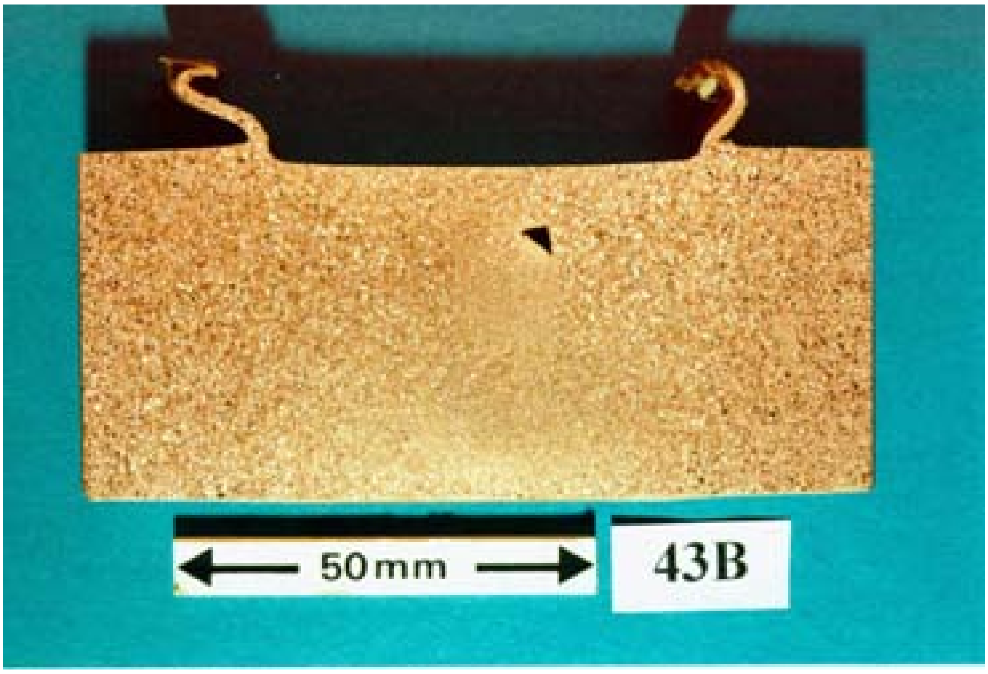


Figure 4-10. *Transverse metallurgical section cut through 40 mm thick weld No. 43B showing triangular shaped flaw on the advancing side.*

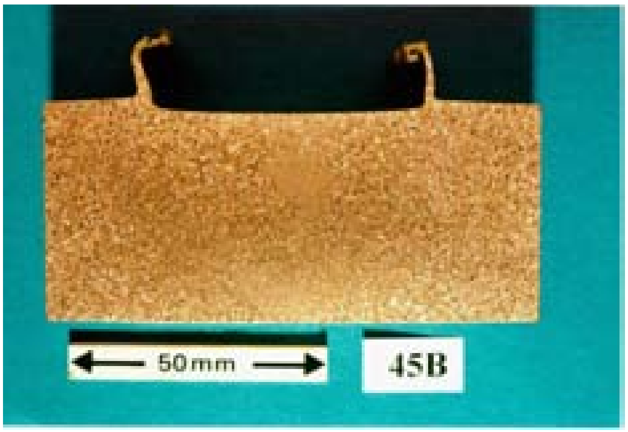


Figure 4-11. *A transverse metallurgical section cut through weld No. 45B where increased side clamping force was used to eliminate advancing side flaws.*

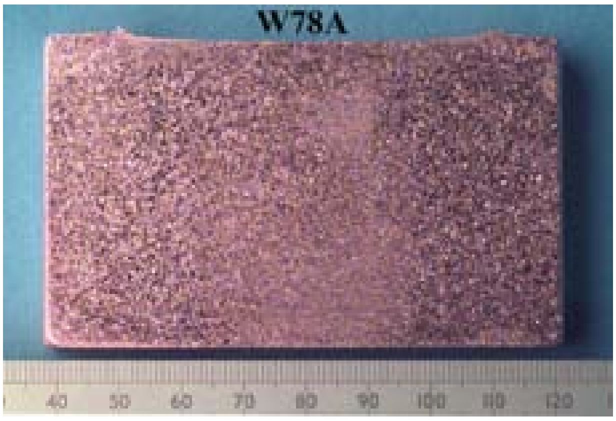


Figure 4-12. *A transverse metallurgical section cut through weld No. 78A which is free from any major flaws.*

4.2.3 Summary of the results when welding plate

Although being able to weld 50 mm copper plate by FSW was regarded as an important achievement, the development of a method to do so routinely was required. The results from the work programme suggested that it was important to control heat input to the weld with greater precision than had previously been considered necessary when welding aluminium alloys. Heat input could be monitored by temperature, or rotating spindle torque measurements. Of these two, weld zone temperature was judged to be the more reliable weld condition indicator. Additionally it was not considered cost effective to purchase and fit a spindle torque transducer to the large milling machine.

Temperature measurement was selected because it was easy to attach thermocouples very close to the path of the rotating FSW tool shoulder. Although this method did not provide the absolute temperature at the weld interface, it did provide an indicator of the temperature distribution during welding.

The peak temperature recorded by a sacrificial thermocouple located at the weld interface was above 800ºC before failure, but only 200–300ºC was measured by a thermocouple positioned just 90 mm away from the weld interface. The location of the thermocouples and the resulting temperature measurements are shown in Figure 4-13a and 4-13b respectively.

Temperature measurement provided a valuable insight into the weld energy input requirements. The first stage of the weld known as "weld start" is very important. If excess energy is used to start a weld, overheating occurs, and it is then very difficult to lower the welding temperature and control it at a constant value. Conversely insufficient energy input makes welding impossible.

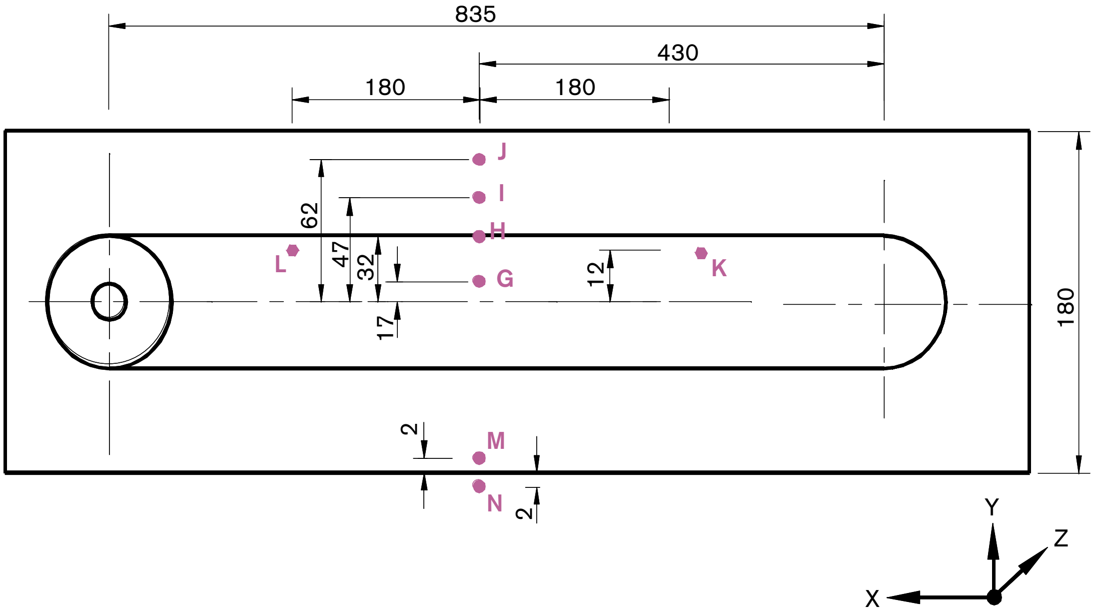


Figure 4-13a. *Positioning of thermocouples in thermal field measurement tests, not to scale, all dimensions in mm.*

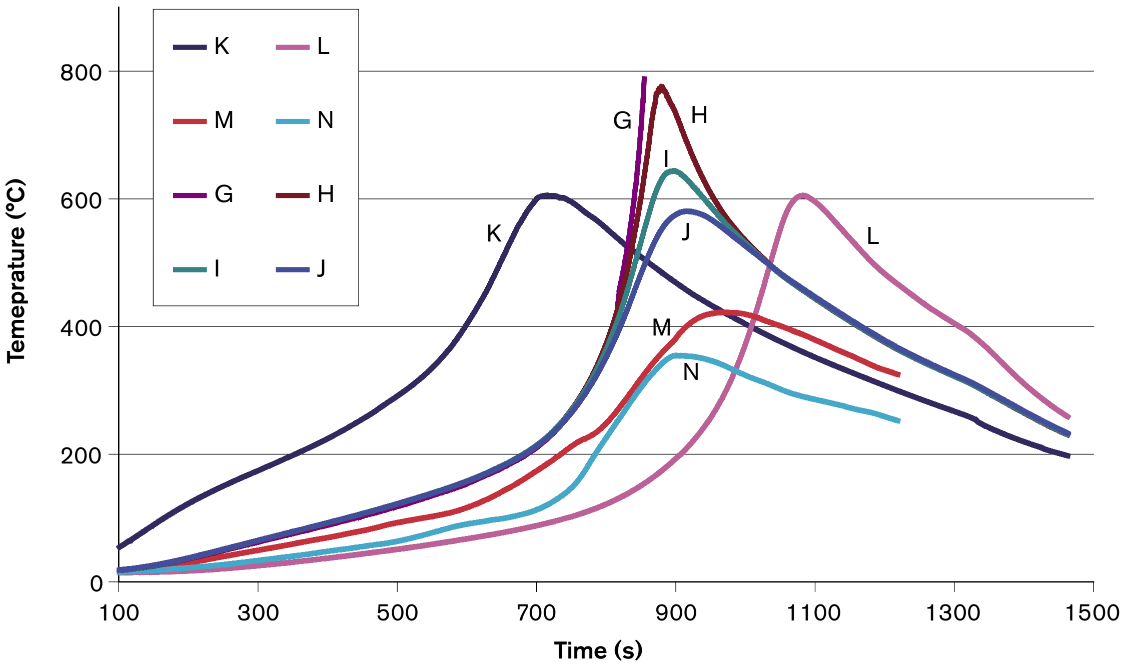


Figure 4-13b. *Thermal field data obtained for FSW sample shown above.*

Energy input into a weld was closely related to the following:

- Size and shape of the pilot hole.
- Size and shape of the FSW tool probe and shoulder.
- Magnitude of the z force and the rate at which it is applied.
- The rate at which the welding speed is increased.
- The rate at which heat could be extracted from the weld zone using a cooling system.

If all these weld parameters are applied correctly, and a balanced heat input achieved, then it is possible to maintain a constant welding condition and a steady state temperature.

When welding 30–50 mm thick copper, the improved monitoring instrumentation provided guidelines for the choice of welding conditions that would produce high integrity welds. The welding conditions used are listed below in Table 4-2. Excluded from the table are the pilot hole details, described in Section 6 and the FSW tool probe details, which are described in Section 7.

At this stage in the development, a maximum welding speed of 20 mm/min was achieved welding 50 mm thick plate. This restriction was imposed by the high temperature strength properties of the FSW tool probe material, and the tool shape/dimensions used at that time. Practically this welding speed was far too slow, as it would take 2.75 hours to produce a complete 3.3 m circumferential weld. Additionally the FSW tool probe materials used at the time would not withstand exposure to the welding temperature and forces for that length of time. Therefore, further work was required to identify superior tool probe materials and shapes to reduce the welding time and this development is described in Section 7.

A simple inert gas shroud was fabricated to enclose the rotating friction stir welding tool and to shield an area of 50 mm × 150 mm long. Argon gas ensured that the weld surface remained bright and oxide free. The shroud was built in case it became necessary to prevent surface oxidation in future work.

The results of this work provided not only a work programme milestone, but also a pivotal point in the development. A decision was required on the direction of continued work, as described in the following sections.

Table 4-2. The welding conditions used to join copper plate between 25 and 50 mm thick.

Welding conditions		Plate thickness (mm)			
		25	30	40	50
FSW tool rotation speed	rev/min	213	265	518	400
Welding force (*z*)	kN	20–30	30–40	30–50	50–70
Welding speed	mm/min	50	50	20	20
Force at the leading edge of the FSW tool probe (*x*)	kN	Not measured	Not measured	15	15–20
FSW tool tilt angle	º	2–3	2–3	2–3	3
Weld start temperature	ºC	400	430	430	430

5 The development of the experimental FSW machine for welding lids or bases to canisters

5.1 The original FSW work programme goals

As described in Section 4, it had been demonstrated that high integrity welds in 50 mm thick × 500 mm long copper plates could be produced using a large milling machine. In order to produce longer welds, which matched the 3.3 m, long weld required to seal a lid to a canister, a much larger machine was needed.

Originally it had been planned that a machining centre available for hire should be located. The machine would be modified to operate in the FSW mode. If such a machine was not available, then it was planned that dedicated prototype equipment would be designed and built at TWI. This equipment would produce 3.3 m long linear welds. It was proposed that TWI carry out welding trials to generate weld quality acceptable to SKB. At this stage the machine would be transferred to the SKB Canister Laboratory at Oskarshamn, and then modified to produce circumferential welds. This scenario was originally seen as the best method for transferring the FSW technology, and allowing SKB staff time to gain operational experience.

However, the cost and logistics of hiring a large machining centre, either in the UK or Sweden, was prohibitive, and in excess of the funding available for the FSW development. In addition, the logic of providing a facility which could only produce 3.3 m long linear welds, when the lid to canister joint was circumferential was considered. As a result, a concept of an experimental canister welding machine was developed and costed. The costs of a full size experimental canister FSW machine to be built at TWI were compared with the alternative linear weld solutions and a decision was made to go ahead with the experimental canister machine option.

5.2 Design and build of the TWI experimental machine

The experimental machine was designed and built in 1999. A drawing showing the main features of the experimental machine is shown in Figure 5-1.

SKB requested that the welding machine should be designed with the canister held in the vertical position as shown in Figure 5-1. Also it was essential that the canister could be presented to the welding machine via SKB's jacking frame system. The TWI design was purposely flexible to permit exploration of two routes for making circumferential lid to canister welds as follows:

- The canister held stationary during the welding cycle with the welding head rotating around the circumference of the canister.
- The welding head held stationary during welding with the canister is rotating.

For operation at TWI, the second option was selected, it overcame the problem of needing to supply rotating hydraulic connections to the welding head and the lid clamping fixture, to prevent twisting of hoses.

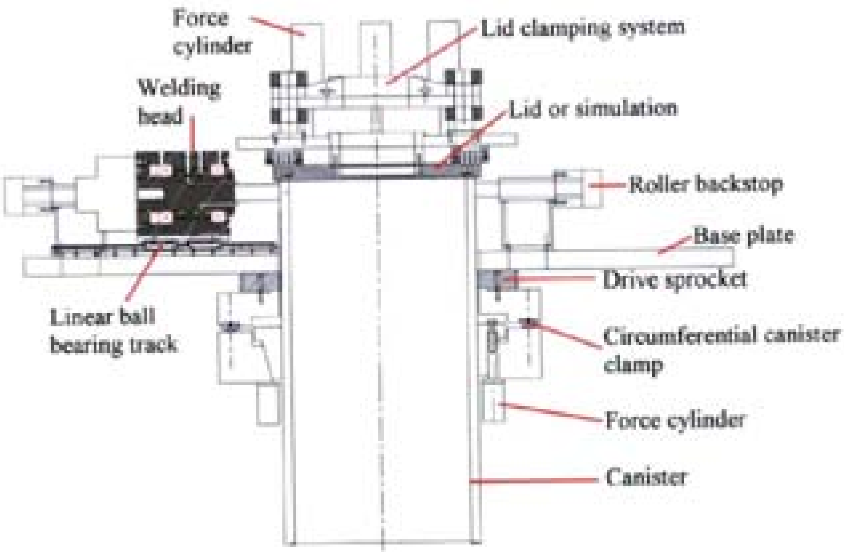


Figure 5-1. *Section through the experimental base welding machine.*

The experimental machine operating specification had been generated by extrapolation of the results of the feasibility trials described in Section 4. Of prime importance for a FSW machine, is that it has sufficient strength and stiffness to react all the process forces without excessive flexure. If machine frame flexure does occur, it could cause an unacceptable reduction of the welding force, and possible major component misalignment resulting in weld integrity problems. In order to satisfy this requirement, all the resultant forces were retained in a rectangular force frame, and within the circumferential canister clamping system, which prevented damage or deformation of the canister.

The main features of the experimental canister lid welding machine are described below:

a) Canister circumferential clamping system.

   The circumferential canister clamping system consists of four radial retracting clamps housed within a large steel cylinder. A maximum clamp opening diameter allows for excessive flash formation of up to 10 mm depending on the welding conditions used. The canister clamp can be seen in Figure 5-2 to 5-5.

   The four clamps are operated by four pairs of hydraulic cylinders, with each cylinder capable of applying a maximum force of 200 kN, providing a total of 1600 kN. Using a series of wedges, this force can be increased to a maximum of 4000 kN, which provides a maximum clamping pressure of 6.0 N/mm^2.

b) Canister or welding head rotation mechanism

   The canister clamping system is rotated using a small 0.37 kW electric motor driving through a large reduction ratio gearbox with an input/output ratio of 15,300:1. The gearbox output shaft drives a toothed sprocket, which drives, via a 50 mm pitch chain, a large sprocket that is attached to the body of the canister clamping system. It is possible to rotate the canister at welding speeds up to 150 mm/min. This drive system is shown in Figure 5-2 to 5-3.

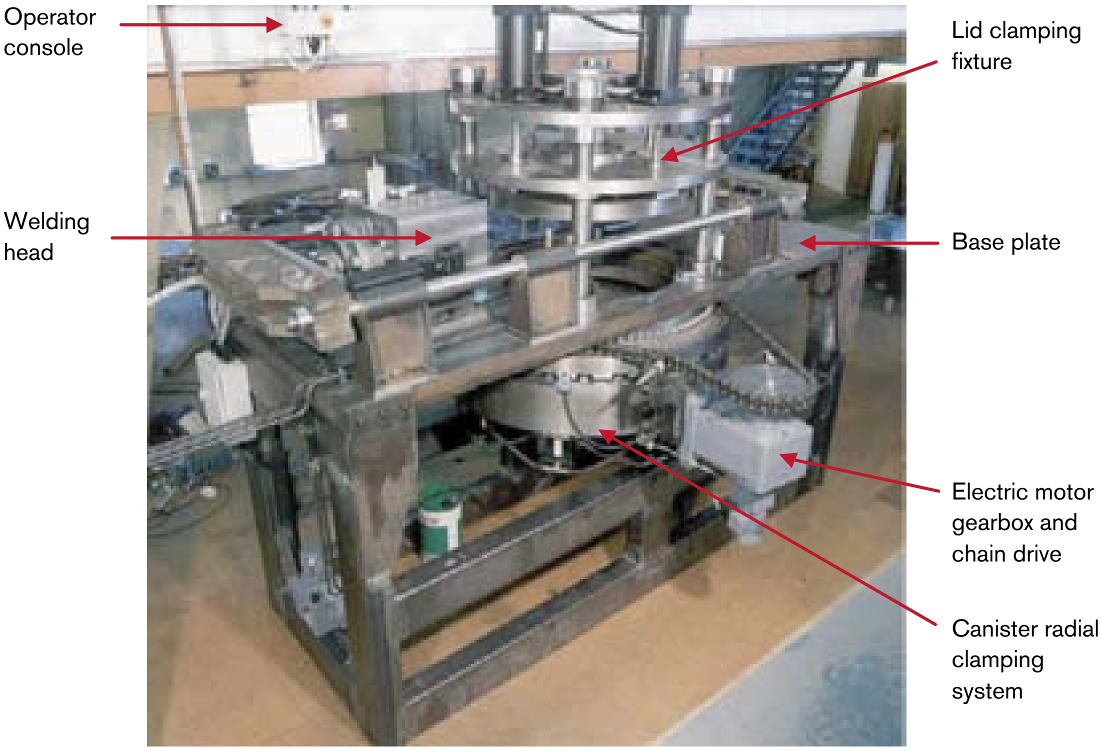


Figure 5-2. *The general arrangement of the FSW machine before the operator walkway was fitted.*

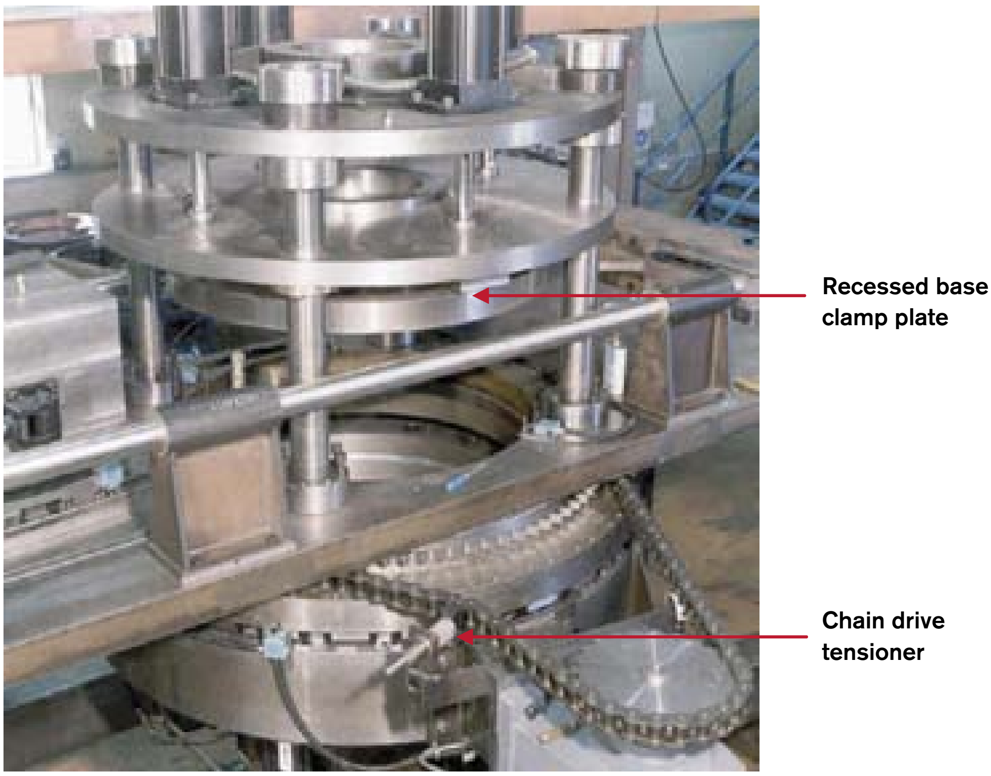


Figure 5-3. *The experimental canister/base welding machine showing the canister clamp drive system.*

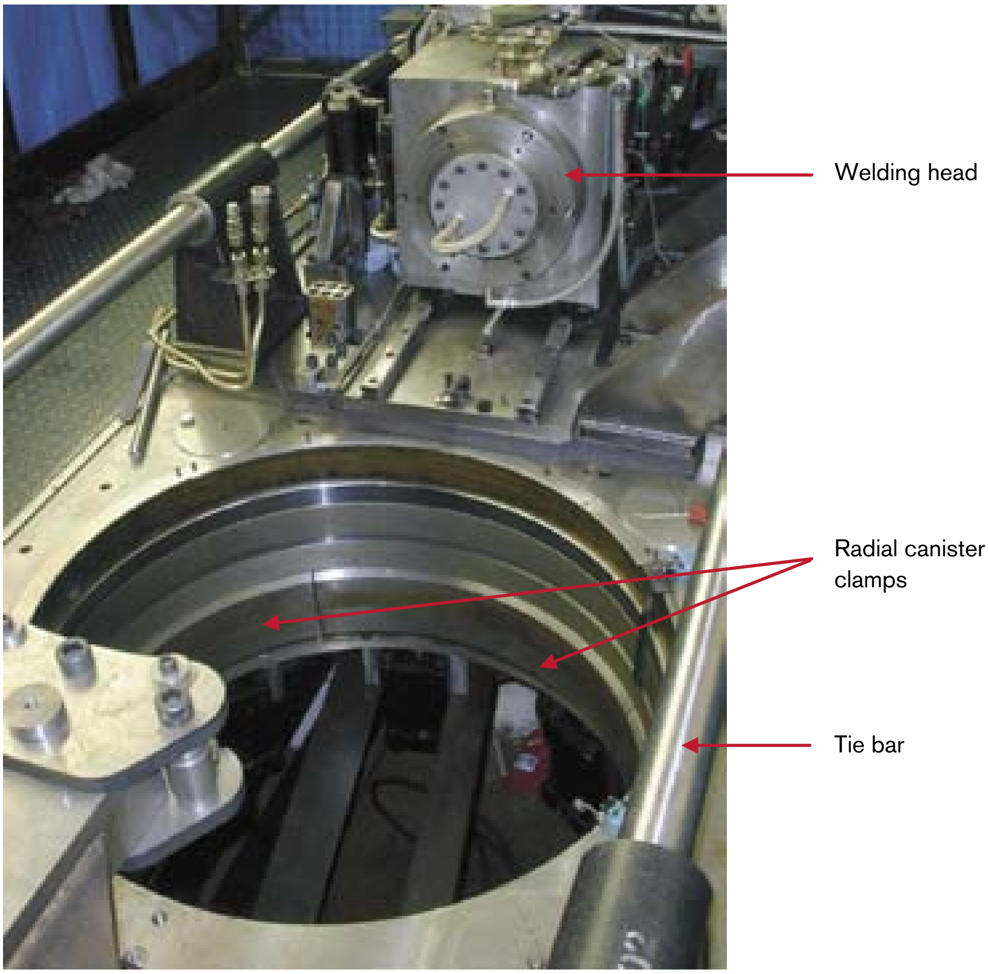


Figure 5-4. View of the canister clamp showing two of the four circumferential clamps.

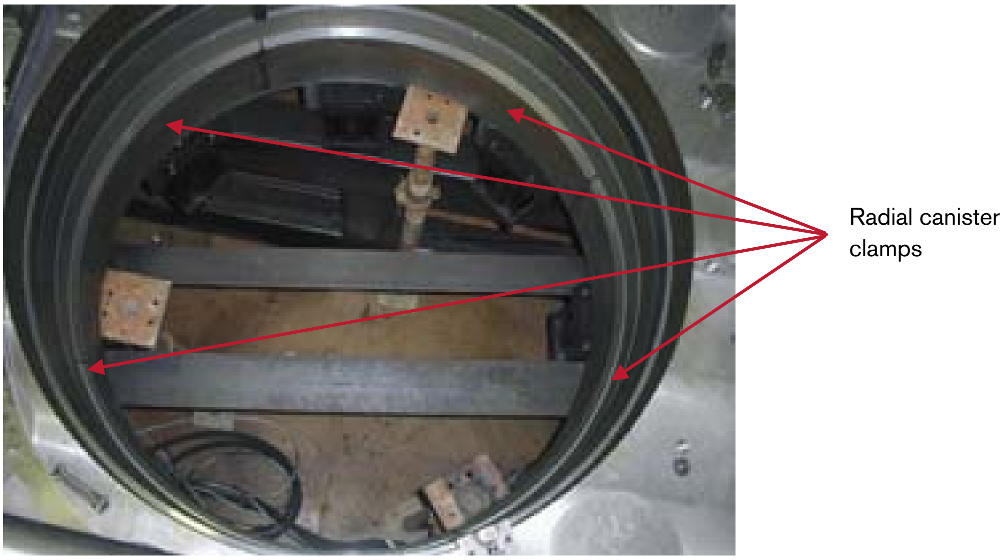


Figure 5-5. The circumferential canister clamp.

c) Lid or base clamp

The purpose of the lid clamp is to force the lid and canister into intimate contact during the weld cycle using a predetermined downforce. The magnitude of the applied force is sufficient to prevent the lid and canister opening up as the FSW tool probes progresses around the joint interface. Four hydraulic cylinders are used to apply a maximum downforce of 800 kN. Accurate application of the downforce, or clamping force is considered to be important for welding thick section material and is regarded a welding parameter, which greatly influences weld integrity. The lid clamp is shown in Figure 5-2 to 5-8.

d) Welding Head

The major component of the welding head is a 190 mm diameter rotating oil cooled spindle assembly located on one end. This spindle is located in a 400 mm × 400 mm square steel housing, which is mounted onto two parallel linear ball bearing tracks, which permit it to move away from or towards the canister. This movement is achieved using two 150 kN capacity hydraulic cylinders, which are mounted on either side of the housing. The welding head is shown in Figure 5-2 to 5-7.

The applied welding force is reacted against the canister wall and, in turn, on the opposite side, against a roller backstop, which prevents deflection of the canister lid with respect to the canister, this is shown in Figure 5-8. Forces generated during the weld cycle are confined to the rectangular force frame, which is connected together by 75 mm diameter steel tie bars, which are in turn bolted to the 100 mm thick machine base plate. An FSW tilt angle of 3º from a position normal to the canister surface has been found to be most suitable when welding pure copper and this angle is obtained using an angle plate between the bearing housing and the back of the force reaction frame. The angle plate is shown in Figure 5-7.

Drive to the rotating spindle is provided by a hydraulic motor with a 1500 Nm torque capability and is shown in Figure 5-6. A purpose built tooling plate is mounted onto the front end of the spindle in which the FSW tool shoulder and probe are securely clamped.

It was possible at a later stage in the development programme to measure the real time probe temperature, and also control the probe temperature during a weld cycle. This facility proved to be an extremely valuable addition for the control of production welding, and is the subject of an SKB/TWI patent application.

The experimental machine can either be operated in fully manual weld cycle mode, or in a semi-automatic mode, which consists of the following three sequences:

- FSW tool plunge, preheat and then accelerate at a controlled welding speed to the steady state welding conditions.
- Maintain steady state welding conditions via force control, or welding speed control, or thermal management.
- Pass over the weld start position and park the tool probe exit hole above the weld interface using force control, or welding speed control or thermal management.

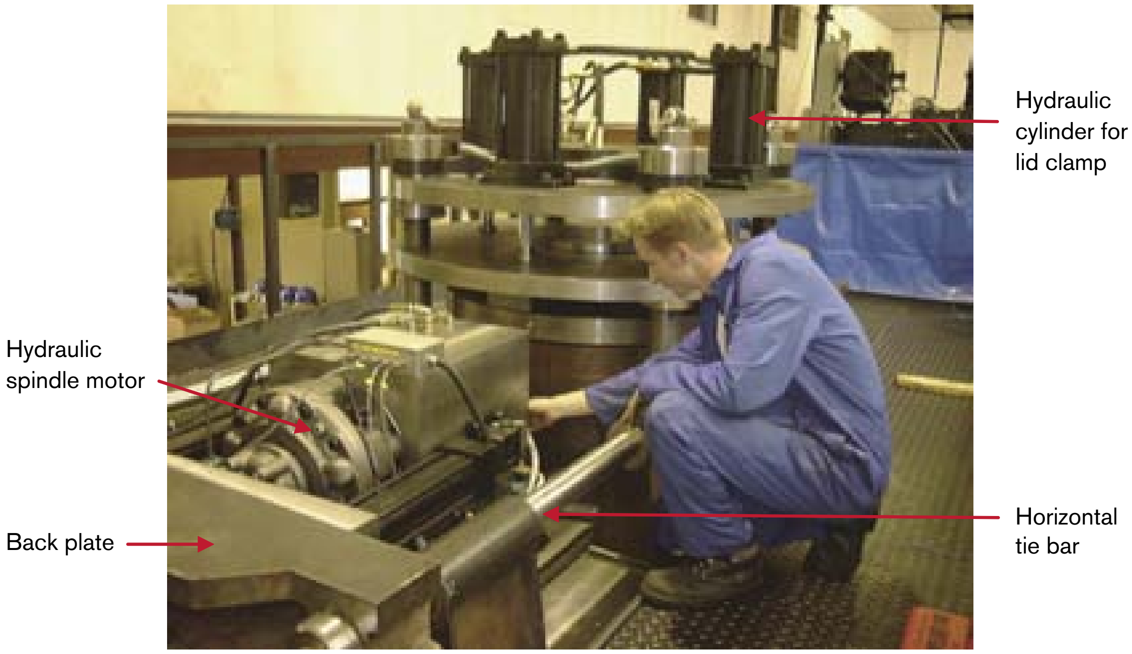


Figure 5-6. *Location of the welding head and lid clamp.*

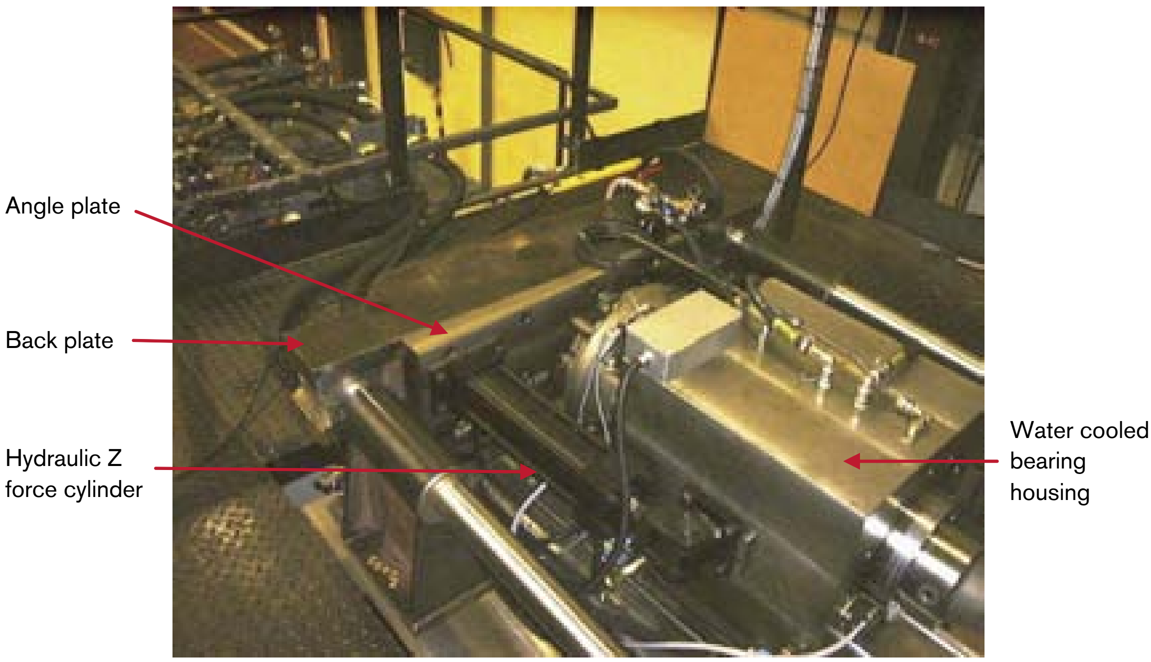


Figure 5-7. *The experimental canister/base welding machine showing the welding head and angle plate.*

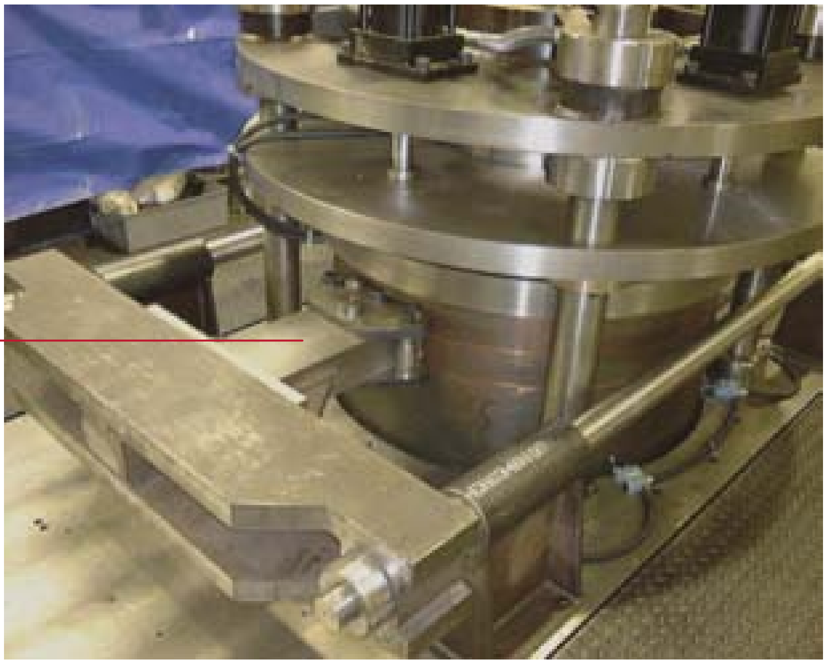


Figure 5-8. *The experimental canister base welding machine showing the roller backstop.*

5.3 In-process weld parameter monitoring

The in-process parameter monitoring methods that had been developed, and tested on the large milling machine described in Section 4 were adapted and interfaced with the experimental canister FSW machine. A weld record that effectively provided a history of the welding conditions used for each weld was regarded as an essential tool in the development of FSW of thick section copper. The information provided an insight into the force regime an FSW tool probe was exposed to, and later in the development the actual probe temperature.

In the early stage of development, all welds were made using manual operation of the welding machine. Manual operation permitted changes to weld parameters such as the z welding force, or the welding speed throughout the weld cycle. The effects of these changes on weld stability and integrity were investigated to assist identification of optimum welding conditions. As knowledge and experience increased it became clear that certain monitored weld condition indicators could be used to automatically control a weld cycle. This realisation provided additional confidence in FSW as a potential production process. Methods explored are described in Section 9.

The weld parameters that were monitored and the methods used are described in Table 5-1 below.

Table 5-1. Instrumentation used on the experimental FSW machine.

Weld parameter	Instrumentation
Welding force kN.	Pressure transducer.
Tool rotation speed rev/min.	Magnetic sensor.
Welding speed mm/min.	Directly from electric motor inverter.
Distance traversed mm.	Extending wire transducer.
Tool plunge depth mm.	Linear transducer.
Torque Nm.	Hydraulic motor oil demand v flow return – calculated value.
Power kW.	As above.
Tool probe temperature °C.	Thermocouple located at the axis of the probe.
Cooling water temperature in and out of the lid clamp. °C.	Thermocouple located in the water flow pipe.
Cooling water temperature in and out of the welding head. °C.	Thermocouple located in the water flow pipe.
Cooling water flow to the welding head l/min.	Electronic flow meter.
Lid clamp force kN.	Calculated via pressure gauge.
Canister clamp force kN.	Calculated via pressure gauge.

5.4 Weld samples used with the experimental FSW machine

Throughout the period during which the experimental canister welding machine was being built, the type of weld sample that would most closely represent a lid to canister weld was being carefully considered. In the early exploratory stage of the project, real canisters and lids could not be considered due to the costs involved, if the estimated 200 welding parameter development trial welds were made.

5.4.1 Canister simulation

A weld sample type was conceived which was not only effective but also provided a realistic large volume of copper. The samples consisted of 120° segments cut from ~1.0 m diameter × 100 mm wide × ~50 mm thick canister rings.

Two 120° ring segments representing the canister wall were clamped one on top of the other in combination with a simulated canister lid to provide a realistic set-up for welding trials, as shown in Figure 5-9. These two ring segments were fitted into a similar 240° ring segment, which was permanently bolted to a 1 m long section of canister as shown Figure 5-10. The use of these 120° ring segments enabled the welding procedure to be developed with much reduced material and labour costs. The reduced size and weight of weld trial samples permitted easy handling and quick preparation of metallurgical test samples.

Once confidence had been generated in the weld procedure, tool probe design and tool materials when using these 120° ring segments, it was possible to complete circumferential welds. The work programme with the TWI experimental machine culminated with the welding of real canister lids to canisters.

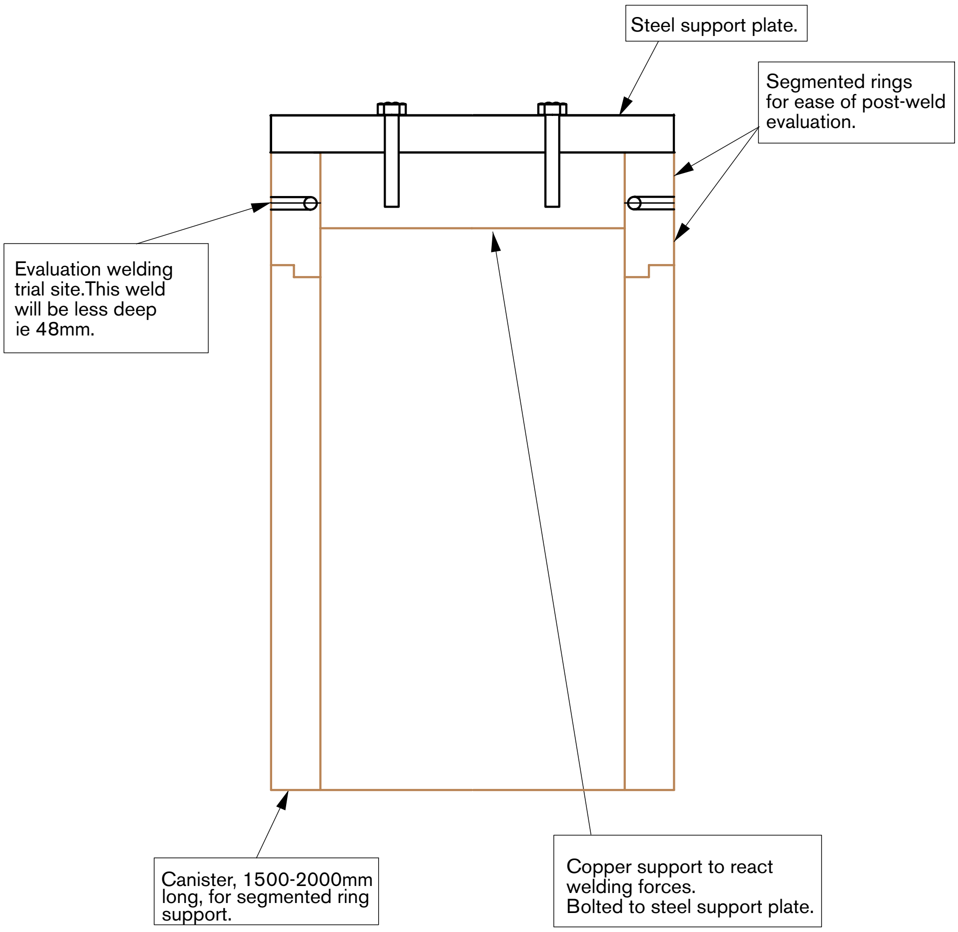


Figure 5-9. *The lid to canister weld simulation.*

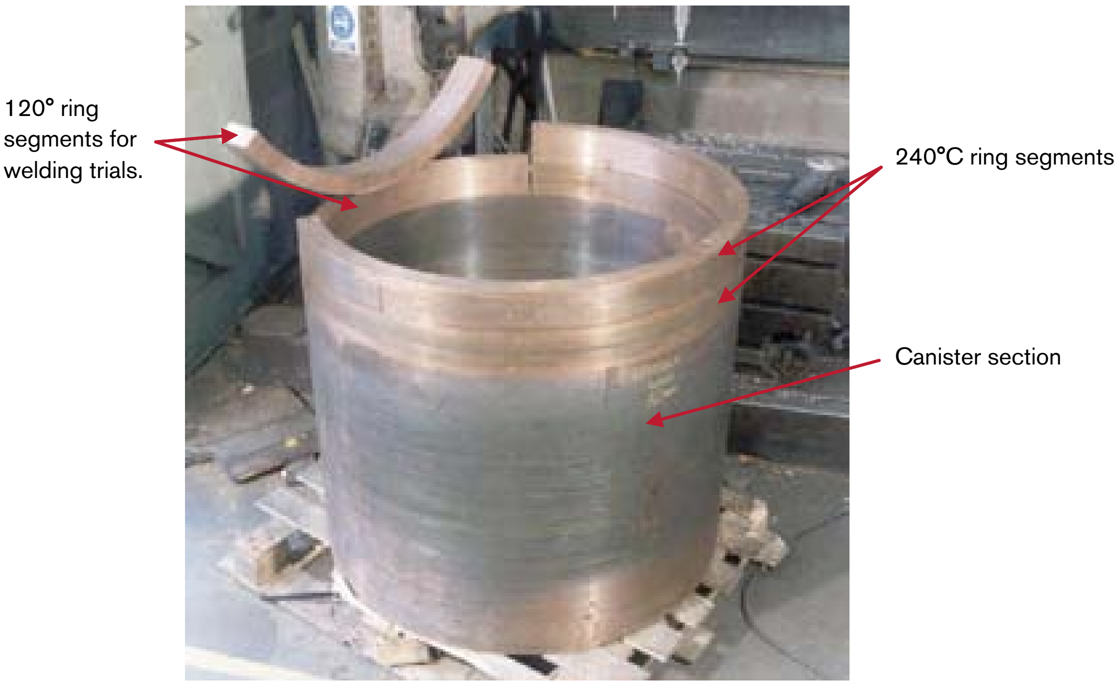


Figure 5-10. *Canister Simulation.*

5.4.2 Lid simulation

The use of real lids during the development trials could not be justified on the basis of cost. Therefore, a lid simulation was manufactured that could be used many times in conjunction with the 100 mm long ring sample described in Section 5.4.1. The lid simulation consisted of a steel support plate with a thick copper disc bolted to it. This copper disc had a volume equivalent to a real lid. The assembled lid simulation is shown suspended from lifting eyes as shown in Figure 5-11.

In contrast to a copper lid, which would only be fitted into a canister once and then welded, the lid simulation was designed to be used many times. The lid simulation had to withstand being lifted out of the canister section many times and also the forces exerted by the FSW process. It must be appreciated that the welding operation was confined to the two 50 mm thick canister ring segments and the lid simulation was not welded to these segments. The purpose of the lid simulation was to react the welding forces and provide a large heat sink. A 950 mm diameter × 150 mm thick disc of copper provided material for force reaction and for heat dissipation, and was bolted to an upper circular steel support plate, 1050 mm diameter × 40 mm thick. This can be seen in Figure 5-9.

The steel support plate was chosen for the outer part of the lid simulation for strength and wear resistance, and four threaded holes were machined into it to locate the lifting eyes. With the lifting eyes screwed into steel rather than copper, there was less danger of the threaded holes distorting and stripping, as a consequence of repeated lifting.

There was also a possibility that when the two ring segments were being welded, the lid simulation be welded to them. Action was taken to avoid this situation and to ensure that the lid could be used numerous times without being indented or deformed as the development programme was undertaken. This was accomplished using a steel strip 45 mm wide × 3 mm thick which was bolted into a slot, located directly at the axis of the FSW stir tool probe. This steel strip can be seen in Figure 5-11 and in greater detail in Figure 5-12. The lid simulation being lowered into the canister is shown in Figure 5-13.

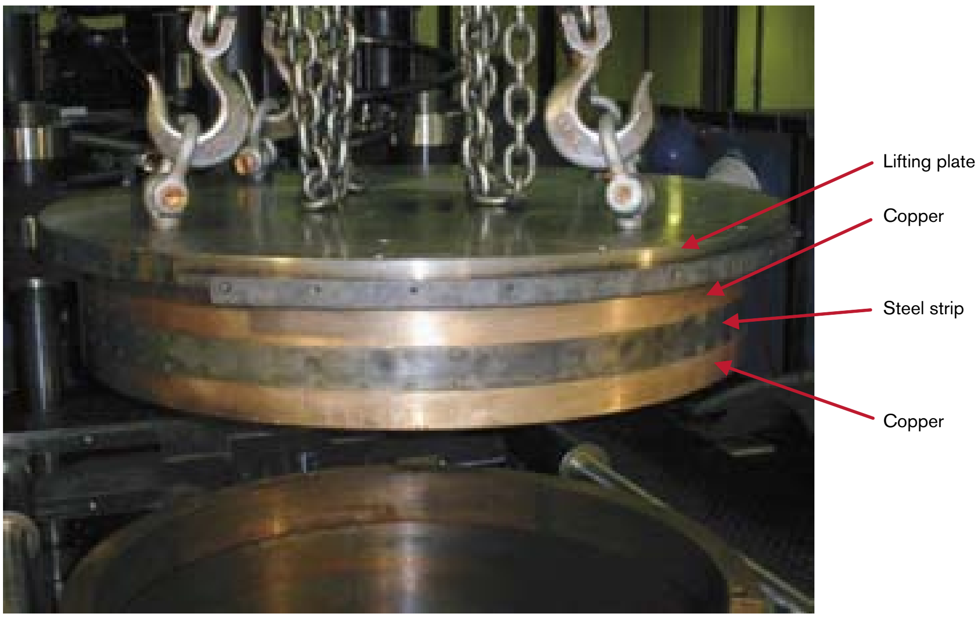


Figure 5-11. *The canister base simulation suspended from four lifting eyes.*

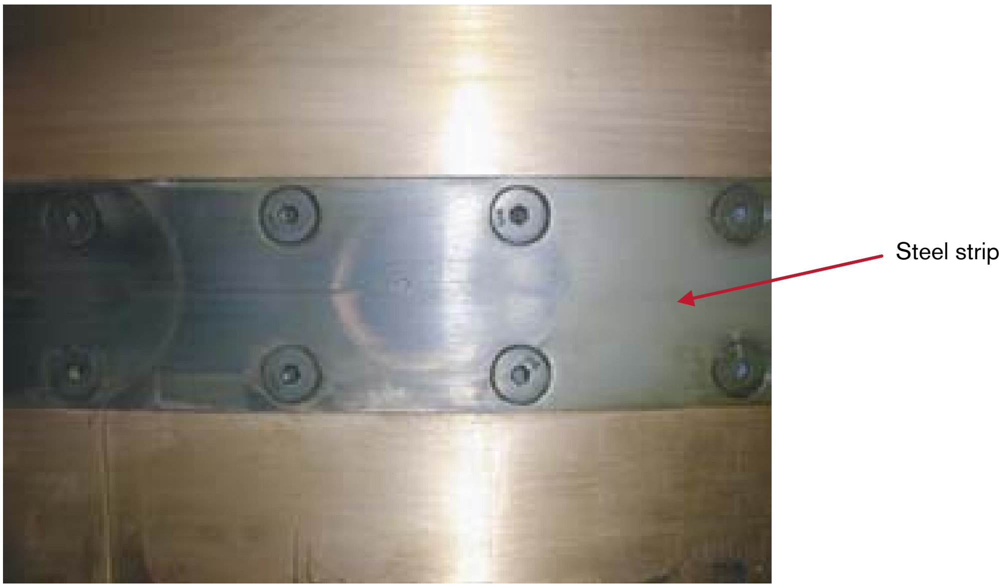


Figure 5-12. *The steel strip bolted into a slot directly opposite the axis of the FSW tool probe.*

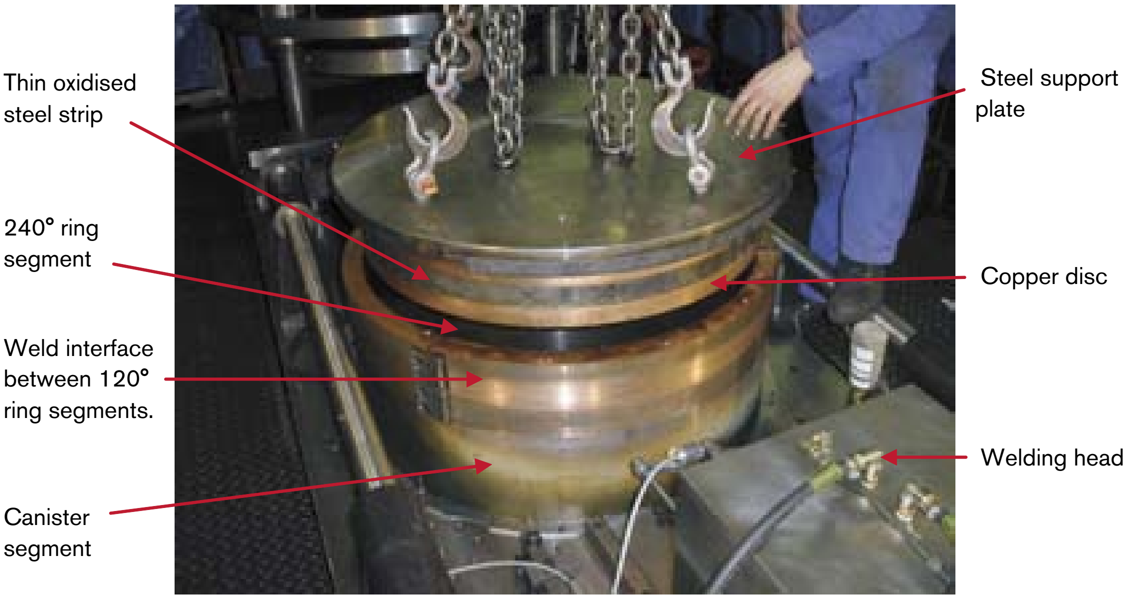


Figure 5-13. *The lid simulation being lowered into the canister section.*

The large mass of copper suspended underneath the steel plate combined with the canister section was aimed to represent a full size lid to canister weld set up. Once welding trials has been completed, the lid simulation was withdrawn from the weld ring sample and the 120° segment removed for subsequent examination.

Welding conditions or FSW tool designs could not have been developed within the available project budget and timescale without the lid simulation. The lid simulation combined with the ring samples permitted rapid development in the most cost effective way.

6 Development programme for producing canister ring welds and ultimately lid to canister welds

6.1 Welding parameter guidelines developed for 50 mm thick copper plates

When welding 50 mm thick plates, guidelines were generated, as reported in Section 4.2.3, that enabled good quality welds to be made. These guidelines covered two main subjects:

- Welding technique.
- FSW tools.

The process development in each subject area and the influence on FSW integrity and process viability is dealt with separately to avoid confusion. However, when the subjects are intrinsically linked, the connection is highlighted. In this section the development of the welding technique is described, and in Section 7 the FSW tool development is described.

As discussed in Section 4.2.3 it had become clear that the “start welding” procedure had a major influence on the ability to produce a successful friction stir weld. In order to generate sufficient heating and softening of copper to produce a friction stir weld, an applied welding force in combination with the rotating FSW tool is required, in simple terms. However, there are a number of factors influencing heat generation which are itemised below:

- Thermal mass of weld zone and rate of heat transfer away from weld zone.
- Fit up dimensional tolerance between canister and lid.
- Welding (z) force, the rate at which it is applied and its magnitude.
- Rotation speed of FSW tool.
- Diameter of shoulder and geometry.
- Diameter/length of tool probe and geometry.
- Size and shape of the pilot hole.
- The rate at which the canister rotation speed is increased.
- Cooling water temperature to the welding head.
- Cooling water flow rate to the welding head and its influence on heat extraction from the weld zone.
- Cooling water pressure to the welding head.
- Cooling water temperature and flow rate to the lid clamp.

Excessive heat input at the start of a weld results in overheating and over softening of a larger volume of copper than necessary. In this situation, the softened canister wall provides insufficient force reaction against the constantly applied welding force. This causes the FSW tool to penetrate into the 50 mm wall of the canister until corrective action can be made.

Identification of the wide range of factors that govern the heat input into the weld zone indicated that reproducible weld quality could only be achieved if careful control of weld parameter settings, and process procedures was adopted. This requirement led directly to the generation of a pre-weld checklist used for all subsequent welds made at TWI. The list of parameters set and procedures adopted in shown in the table below:

1.	**Preparation**
a	Weld surface cleaning method and recording the time between cleaning and welding
2.	**Tool probe and shoulder**
a	FSW tool probe type/ identification number and drawing number
b	FSW tool probe material
c	FSW tool probe heat treatment and surface treatment
d	FSW tool probe diameter at the top and bottom before and after welding
e	FSW tool probe length before and after welding
f	FSW tool shoulder type/identification number and drawing number
g	FSW tool shoulder heat treatment and surface treatment
h	FSW tool shoulder visual check after each weld
i	FSW tool probe and shoulder cleaning method and frequency
3.	**Pilot Hole**
a	Pilot hole diameter and depth or alternative geometry such as tapered or variable diameters
4.	**Welding conditions – pre-set values**
a	FSW tool tilt angle away from the location which is at 90° to the canister surface, and away from the welding direction
b	FSW tool rotation speed
c	Welding head rate of movement towards the canister during the FSW tool plunge sequence
d	Welding *z* force
e	Lid clamp force
f	Temperature of the cooling water feed to the welding head
5.	**Variable welding conditions – changed during the weld cycle**
a	Start welding speed
b	Welding speed ramp rate up to the steady state speed
c	Cooling water flow rate to the welding head
d	Rate at which the welding speed is changed during the travel away from the weld interface to the position where the FSW tool is retracted i.e. park position

6.2 Welding on the experimental canister FSW machine

6.2.1 Lid simulation and canister assembly method

In Figure 5-13 the lid simulation is shown being lowered into the canister, once in place, the water cooled lid clamp, with the primary function of forcing the lid simulation into contact with the canister, is lowered into position as shown in Figure 6-1a and b. Each of the four vertical steel tie bars are then bolted to the base plate of the machine to provide force reaction. Once the lid clamp is secured, the four hydraulic cylinders can be operated, and the clamp is forced into contact with the lid simulation. A force of between 400–440 kN was found to be sufficient to keep the two components firmly clamped together during the weld cycle. This force was projected from the results of the plate welding trials described in section 4.2.2.

a)

b)

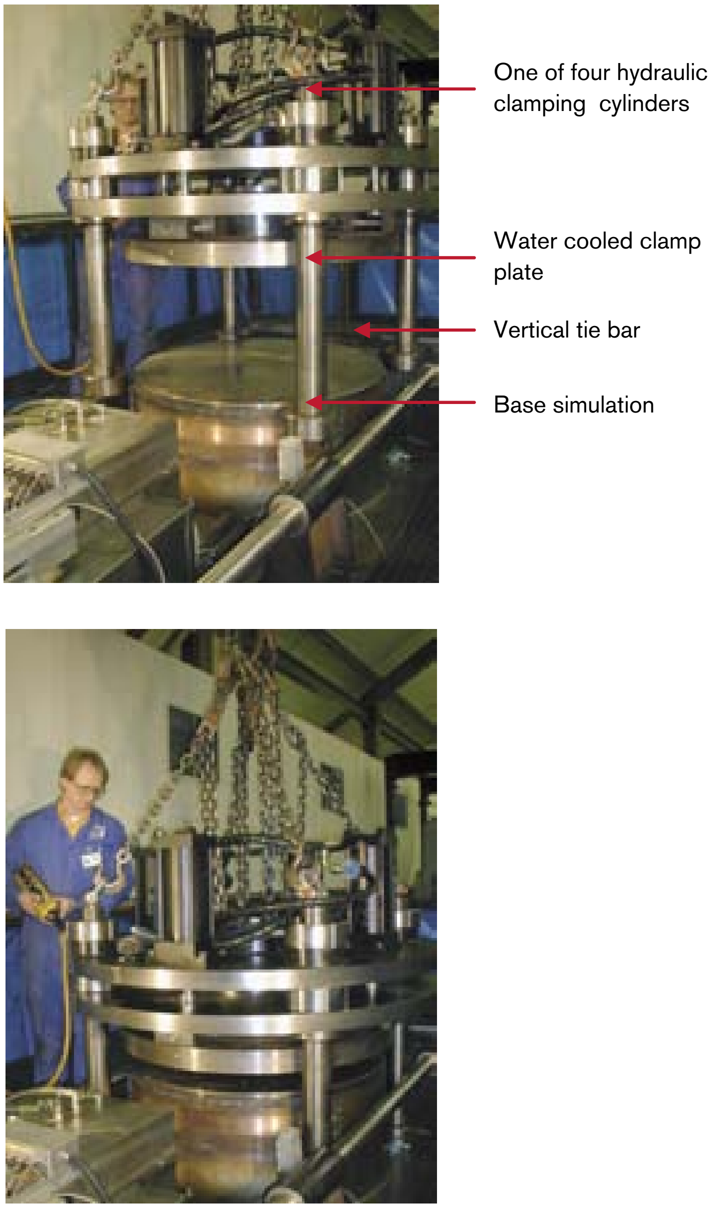


Figure 6-1. *Lowering the base clamping fixture into position.*

Before final assembly of the lid simulation and the canister sections, the weld interface and also the canister surface on which the FSW tool shoulder rotated were cleaned. The purpose of the cleaning procedure was to remove oxidation and surface contamination.

Initially Scotchbrite™ abrasive plastic wool was used, but it was found by optical examination that numerous very small pieces of this material became embedded in the soft copper surface. At the welding temperature of up to 950°C, it is likely that the embedded material would degrade and cause surface contamination, which in turn could affect weld integrity.

Scotchbrite™ was replaced by stainless steel wire brushes and no evidence of stainless steel wire was detected on the copper surface prior to welding. Thus the possibility of contamination was reduced.

The abraded surface was degreased using petroleum ether or acetone on white paper tissues until no discolouration of the tissue occurred.

It should be appreciated that the fit-up tolerance between the lid simulation and the canister segments was, by necessity, larger than a normal lid to canister tolerance, simply to allow the lid simulation to be inserted relatively easily and then withdrawn after welding. Later in the development programme it was recognised that fit-up tolerance had a much greater influence on weld integrity than had been expected when the experimental FSW machine welding trials first started, and consequences are described in Section 11.

6.2.2 The welding head features

The original method of holding FSW tool assemblies in the welding head was a robust system, which incorporated a collet chuck and a hexagonal drive to ensure that the FSW tool did not slip when subjected to high torque. A photograph of this tool holder assembly is shown in Figure 6-2. The holder assembly comprised an hexagonal drive at the end of the 205 mm long holder shaft, located with a female hexagonal shaped socket, which was connected to the rotating spindle assembly, mounted in the welding head.

A re-circulating oil cooling system both cooled and lubricated the rotating spindle bearings and, to a minor degree, cooled the hexagonal drive region of the FSS tool holder. However, no major cooling was applied to the tool shoulder/probe region where temperatures are known to reach up to 900°C. This system worked well when welding 120° ring segments and did not suffer any thermal damage. However, it was thought that the system might not be able to withstand exposure to the welding temperature when making full circumferential welds, which could take up to 45 minutes to complete. A further concern was that the tool probe might not be able to withstand constant exposure to the welding forces at up to 900°C for this period of time.

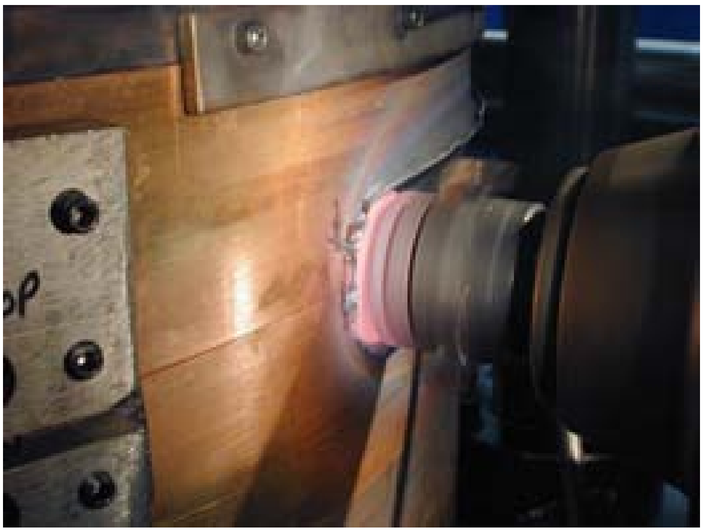


Figure 6-2. *The original experimental FSW canister welding machine's welding head operating at a temperature between 800–900°C.*

In order to provide a more robust system that could be used to control the temperature of tool holder components working near to the weld zone, a water-cooled head was designed and is shown in Figure 6-3. The major feature of the design is the circular water-cooling channels, which are located at a distance of 10 mm from the end of the tool probe and collet. This feature was designed to increase heat exchange from the tool probe and shoulder, aimed at improving their operating strength by preventing them from overheating.

The basic components of the water-cooled welding head can be seen in Figure 6.3. Water was fed into the lower inlet of the outer stationary water receiver and then into the two water channels that are machined into the inner rotating water receiver. Water leakage from the receivers was prevented by seals that can operate up to 260°C and are manufactured in a polymer material known commercially as Tercon T40. The water passed from the receivers through to the instrumentation block onto the back of the tooling flange. If the water-cooling proved to be too effective and prevented sufficient heating, then it was planned that the water could be replaced with oil and/or the flow reduced.

An important feature of this water-cooled head design was the instrumentation block. Originally a miniature data logging system was housed within this block to record the temperature measured by a thermocouple inserted into a hole drilled into the axis of the tool probe. The location of the thermocouple is shown in Figure 6-3. Once a weld had been completed the temperature profile data stored in the logger was downloaded and transposed directly onto the main weld record.

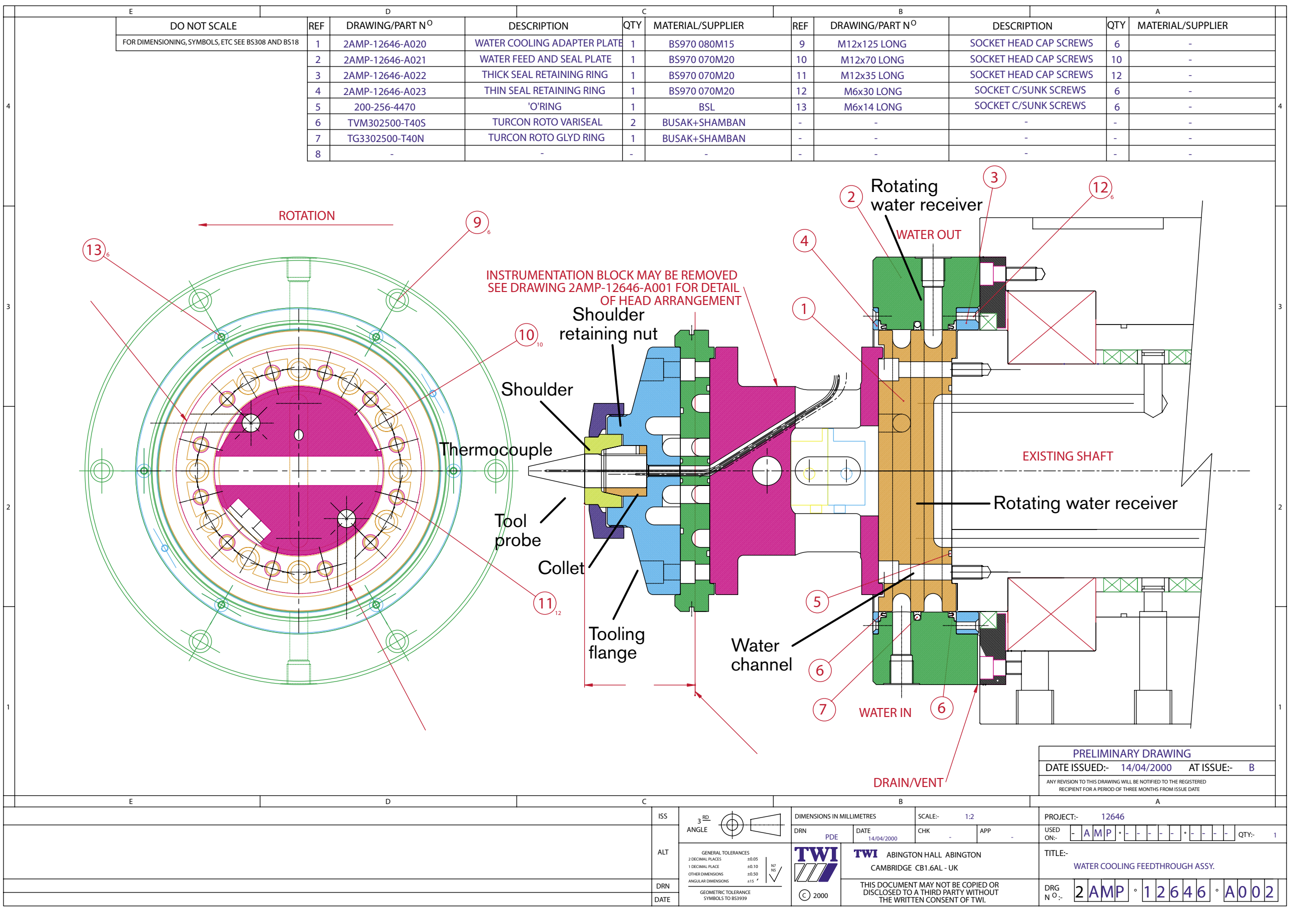


Figure 6-3. *The water-cooled welding head.*

This data provided information on the maximum and minimum temperatures experienced by the tool probe and indicated the control that could be achieved using the water or oil cooling. Direct measurement at the tool probe showed that the temperature constantly increased as the FSW tool progressed around a canister if weld parameter adjustments were not made.

Temperature measurement within the core of the tool probe provided a unique insight into the mechanism of the FSW process. These measurements assisted with the on-going selection of tool probe material and establishing the correct operating procedure for production welding. Additionally, it was possible to measure the inlet and outlet water temperatures meaning that the water-cooled head could be considered a calorimeter. This feature provided the opportunity for the various temperature measurements to be incorporated into a process control loop for accurate welding condition control when welding production canisters.

A series of photographs Figure 6-4 to 6-8 show the way in which the water-cooled head was assembled. Cooling water passed through the instrumentation block to the tool flange and then back to the outlet. The assembly is shown in Figure 6-4. The hexagonal drive that located with the tool probe collet and the shoulder is shown in Figure 6-5 and Figure 6-6. A tapered region on the collet and underside of the tool shoulder were forced together by the large retaining nut, which clamps all the components tightly together, shown in Figure 6-7 and Figure 6-8. This method prevented movement of the tool probe and was considered a significant improvement over the original method.

To complete the assembly, the shoulder was engaged into the large hexagonal drive in the tooling flange, see Figure 6-7, followed by the retaining nut, which clamps the tool assembly together as shown in Figure 6-8.

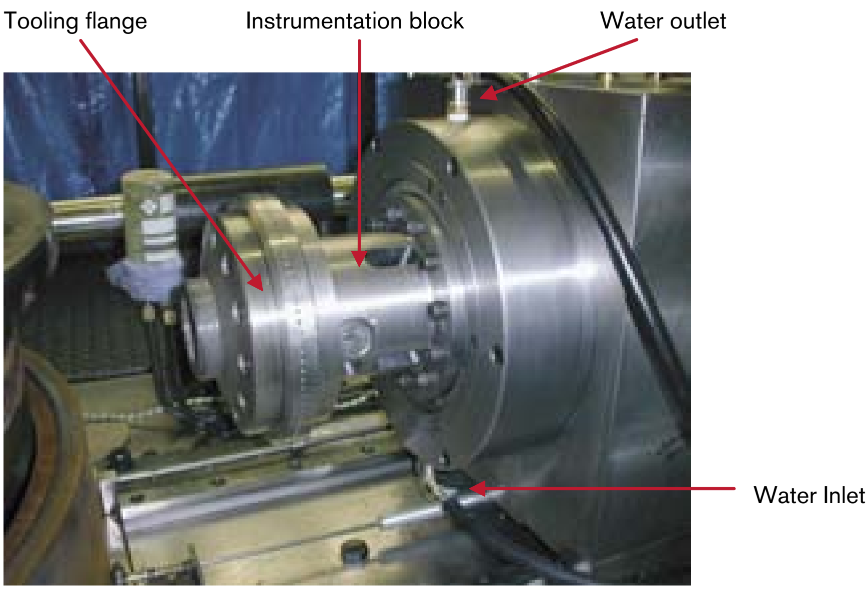


Figure 6-4. *The instrumentation block and the tooling flange bolted to the water receivers.*

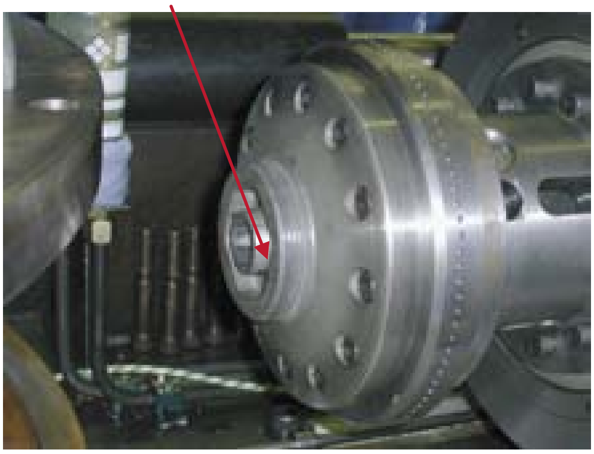


Figure 6-5. The tooling flange with the collet in position.

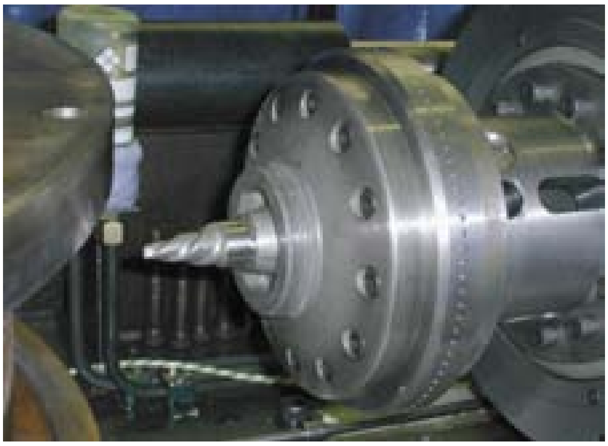


Figure 6-6. The FSW tool probe inserted into the collet.

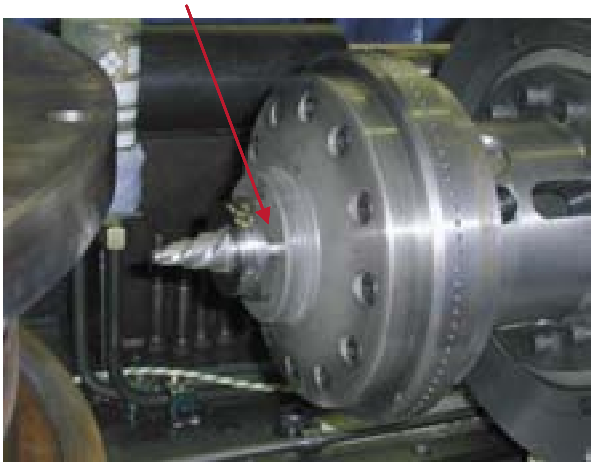


Figure 6-7. The Densimet D176 tool shoulder in position.

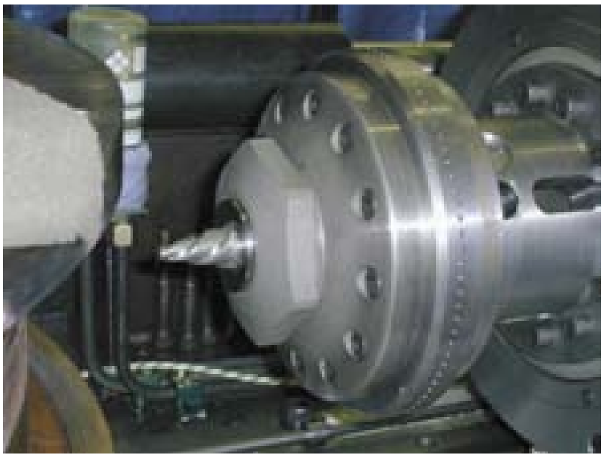


Figure 6-8. The shoulder retaining nut screwed up against the tool shoulder and probe.

6.2.3 Temperature measurement

When the original plate welding trials were being undertaken on the large milling machine as described in Section 4.2.1 an infrared thermometer (a non-contact temperature measurement method) had been used to measure the temperature of the rotating FSW tool shoulder. However, due to progressive oxidation of the surface of the FSW tool shoulder, the accuracy of the temperature measurements was affected by continuous changes in emissivity, making calibration difficult. Infra red thermometry was not pursued at this early stage in the project due to these calibration problems and the time scale and equipment costs. However, it was suggested that the technique should be revisited in the future if it was considered that a non-contact temperature measurement system was essential for production welding. SKB expressed doubt that infra red thermometry was suitable for use in the hot cell production environment.

At this early stage in the development programme, it was clear that measurement of the tool probe temperature was essential for designing probes capable of producing complete circumferential welds. Therefore, the new welding head was designed to accommodate a 1.5 mm diameter, stainless steel sheathed Type K thermocouple at the axis of the tool probe, extending 10 mm beyond the working face of the FSW shoulder. This was judged to be the hottest region of the weld zone, from examination of metallurgical samples.

The way in which the thermocouple was housed in the welding head is shown in Figure 6-9 and 6-10.

The output emf of the thermocouple was recorded on a Tinytag data logger housed within the rotating head as shown in Figure 6-11. This data logger sampled at a frequency of once per second and the data recorded was transposed onto the main weld record.

Weld parameter changes, such as an increase or decrease in welding force, could be directly related to temperature change and the temperature at which welds were made could be more closely controlled. This was the first time that a true weld condition indicator had been isolated and it provided the possibility of using the FSW tool probe temperature to control a weld cycle.

The ability to determine weld temperature was regarded as a significant breakthrough because, at that time, most FSW production machines were operated on so called position control of welding head or by controlling the welding force. Both systems had been explored as this development progressed, but both were judged to lack control sensitivity as no monitored weld condition indicator was being used to adjust weld parameters.

The major drawback of the Tinytag data logger was that it was housed inside the rotating welding head instrumentation block and the stored information could only be accessed once the rotation had stopped i.e. the welding cycle was complete. As the weld temperature data had proved to be so valuable, it was obvious that access to real time temperature would be even more useful.

There are several methods of making electrical connections with a rotating shaft, as follows:

- Slip rings and brushes.
- Rotary transformers.
- Radio telemetry.

The slip ring and brush method was selected from the three candidate methods because design was simple and construction could start quickly. Slip ring and brush assemblies were available commercially, but none were large enough to slide onto the rotating shaft onto which the FSW tool was mounted. Therefore a purpose built system was developed which finally included three copper slip rings and three spring tensioned brush assemblies, which had sintered powdered copper and graphite brushes. Two of the assemblies were used to access the thermocouple output and the third for providing electrical power to a processing unit.

One problem associated with brush and slip ring assemblies is electrical noise caused by slight variations in the resistance between brushes and slip rings, which could swamp the small voltage generated by the thermocouple. This problem was overcome by converting the thermocouple output from analogue to digital form before it was transferred across the rotary slip rings. Once transferred, the digital signal was converted back to analogue form, shown on an LED display and monitored by a PLC data logging system. This three brush/ slip ring assembly is shown in Figure 6-12.

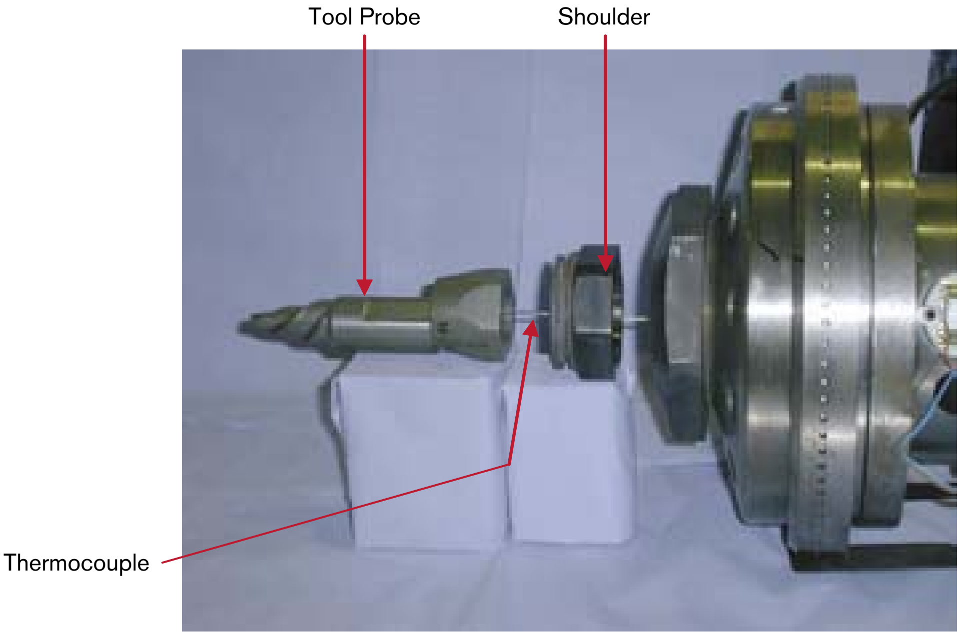


Figure 6-9. *Thermocouple passing through water-cooled head.*

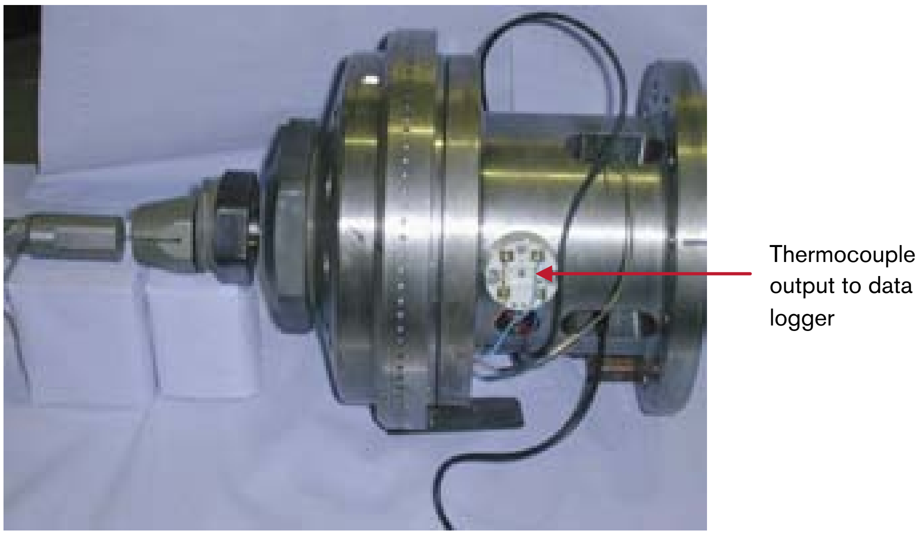


Figure 6-10. *Thermocouple output into instrumentation block.*

Figure 6-11. *Tinytag data logger.*

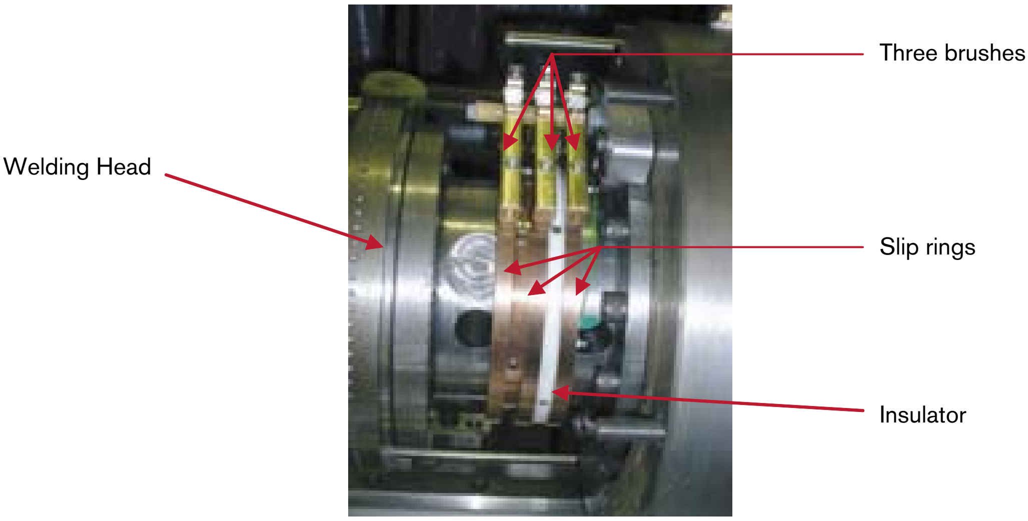


Figure 6-12. *Three brush/slip ring assembly.*

6.2.4 The effect of pilot hole geometry on heat input to the weld zone

When FSW was developed for welding aluminium alloy plates of 3–12 mm thickness, the first stage of the welding cycle was to plunge the rotating FSW tool probe into the interface between the abutted plates, until the shoulder contacted the plate surface. The purpose of the plunge sequence was to generate sufficient frictional heating to locally soften the material surrounding the probe. Once it was judged that adequate softening had occurred, the FSW tool was traversed along the joint interface. This procedure has worked very well for welding relatively thin aluminium plate where the softening temperature rarely exceeds 500°C.

In contrast, it was found that this direct plunge procedure could not be used to penetrate the joint interface in 50 mm thick copper at ambient temperature. The reason for this was that as heat was generated by the small contact area of the tip of the rotating FSW tool probe, it was rapidly dissipated into the bulk of the copper and thus insufficient softening occurred.

A pilot hole was drilled at the start of the weld in order to assist stir tool probe penetration into the copper plate and to minimise transient torque. The diameter of this pilot hole was normally slightly smaller than that of the probe diameter to enable sufficient frictional heat to be developed. However, as FSW tool probe geometry changed from a standard parallel profile to more complex shapes, the dimensions and geometry of the pilot hole were altered accordingly. The pilot hole was drilled using the rotating spindle of the friction stir welding machine in order to match the tilt angle of the stir welding tool.

The plunge sequence in thick copper was accomplished by feeding the rotating stir welding tool at a pre-set advance rate into the pilot hole, until the tool shoulder had just touched or penetrated the plate surface, thereby generating sufficient frictional heating to initiate a friction stir weld. However it was found that if the pilot hole was too small, the FSW tool experienced high transient torque, accompanied by seizure, as it was forced into the hole, leading to premature tool damage. In order to optimise the pilot hole, trials were undertaken in which the pilot hole size and geometry were progressively changed, as was the FSW tool probe plunge rate into the copper.

These trials demonstrated that the diameter, depth and shape of the pilot hole were extremely important FSW weld parameters. It was found that the pilot hole geometry strongly influenced tool probe survival during the plunge sequence. This was particularly true for probes used in the early stage of this development, which had limited ductility. A range of hole geometries was tested, from plain parallel, through variable diameter, to a conical shape matching the shape of the FSW tool probe. However, as much tougher tool probe materials became available, it was proven to be possible to use a simple fixed diameter parallel hole, made using a standard drill. The diameter of this type of pilot hole was equal to the mid-point diameter of the conical tool probe.

Due to its inherent softness, copper is a difficult material to drill or machine, and it is also difficult to hold close dimensional machining tolerance. The soft copper tends to fill up the flutes of a drill, and then rapidly cool causing a blockage and, subsequently, tearing which in turn can cause fracture of the drill. Remnants of fractured drill embedded in the interface between a lid and canister would be almost impossible to remove, and could lead to the canister, containing nuclear waste being scrapped. It was fortunate that specially shaped, purpose built, pilot hole cutters were not necessary, as they would cost much more than standard drills and possibly be more prone to fracture. The fact that parallel, standard drills could be used to drill the pilot hole minimised the risk of drill fracture and simplified production lid to canister welding.

Not only was pilot hole drilling simpler due to the use of tough tool materials, but the reproducible welding trial results provided an insight into the effect that the shape of the pilot hole had on the heat input to a weld. The sketch shown in Figure 6-13 demonstrates how it is thought that the heat input into a parallel pilot hole is progressive, providing even heating to the complete weld zone. This limits torque variation during the tool plunge sequence and results in extended tool life.

The plunge sequence for a lid to canister weld shown in Figure 6-13a, shows the conical surface of the rotating tool probe just contacting the upper edges of a parallel pilot hole. Heat input to the copper plate starts at this point and, as the tool probe continues to enter the hole heat is continuously generated as shown in Figure 6-13b. Hot softened copper is extruded out of the top of the hole in the form of flash but also is extruded to fill up the bottom of the hole. Finally as shown in Figure 6-13c, the FSW shoulder contacts the canister wall and heat is generated evenly around the tool probe profile. More complicated pilot hole shapes resulted in either insufficient, or excess heat at the start of weld, which proved much more difficult to stabilise.

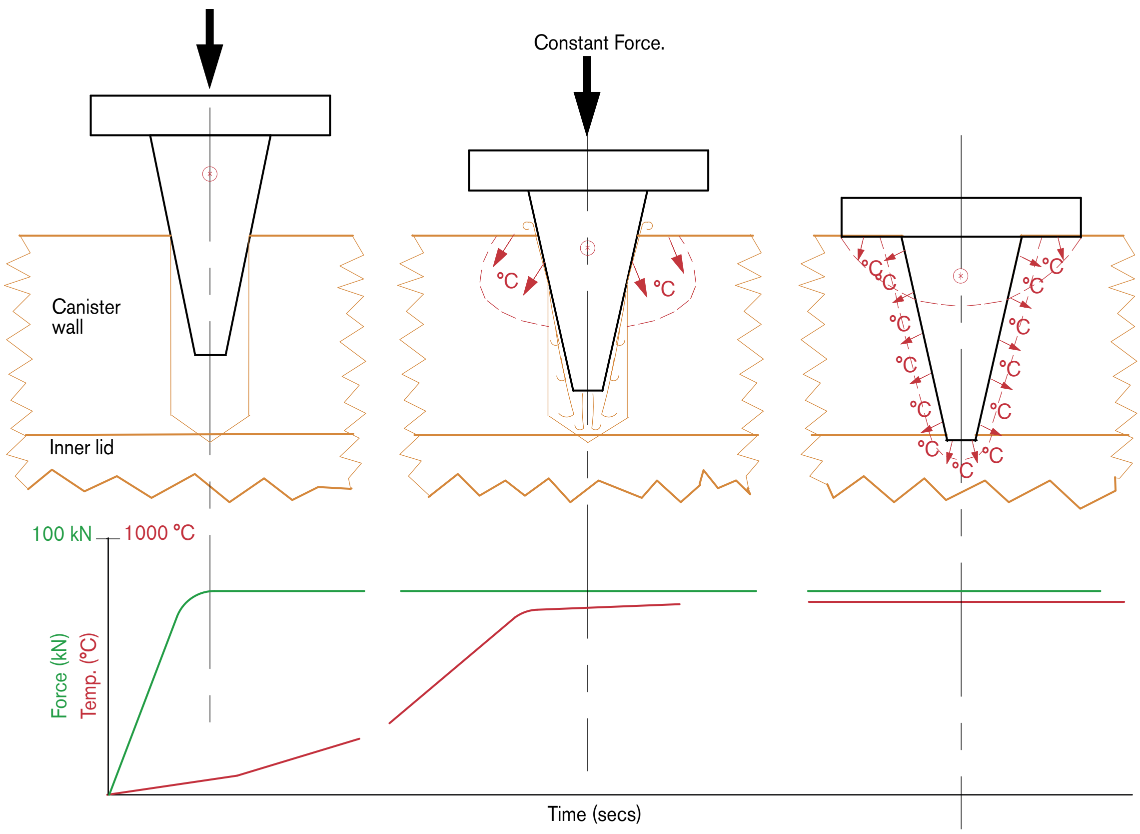


Figure 6-13. *A parallel pilot hole.*

These objectives were based on examination of metallurgical sections cut through welds where the tool probe had fractured, either on contact with the pilot hole or at various times during the plunge sequence. However, it was acknowledged that as the development of FSW for lid to canister welds progressed further improvements would be made.

6.2.5 Welding trials with 120° canister segments

As had been described in detail in Section 5.4.1. two 100 mm long, 120° canister segments were placed on top of one another to simulate a weld interface. These 120° segments were slotted into a 240° canister segment completing a 360° canister assembly. In order to simulate a longer canister section, the 360° segment assembly was bolted to a ~1.5 m long canister section.

Movement between the 360° assembly and the canister section was restricted by a mating machined rebate (or recess). This set-up is shown in Figure 6-14 and the dowel pin holes in the surface of the 120° segment were provided to prevent movement between it and the lid simulation illustrated in Figure 5-11, 5-12 and 5-13.

Welding of 120° canister segments is shown in Figure 6-2. It is important to remember that 120° canister segments enabled the welding procedure to be developed with reduced material and labour costs as stated earlier. More importantly it permitted confidence in welding 50 mm thick copper to be developed in terms of weld parameters, procedures, FSW tools, control systems and modifications to the experimental FSW machine as described in Section 6. An example of a welded 120° canister segment showing smooth surface texture and minimum side flash is shown in Figure 6-15.

Figure 6-14. Location of the canister segments on the canister section in preparation for welding trials.

Figure 6-15. The external appearance of Weld No. CW62.

6.2.6 Complete 360° circumferential welds

As stated in Section 6.2.5, the welding procedure developed using 120° canister segments led to good weld integrity. The next major project milestone was to demonstrate that full circumferential welds of high integrity could be produced, and it was recognised that this would require precise control of the FSW process. At this stage in the project the FSW process was controlled by variation of one or combinations of the following major weld parameters:

- Tool rotation (increasing speed increased heat input and vice versa).
- The welding force (increasing force increased heat input and vice versa).
- The welding speed (increasing welding speed *reduced* the heat input and vice versa).

Using these control methods, on the 120° canister segment welding trials showed that thermal lag prevented sufficiently precise control over the heat input to the weld. As parameter changes were made, such as a reduction in welding force, to reduce heat input to the weld, the resulting temperature changes were slow and produced the desired effect only some 10–30 seconds after the adjustment was made. Force reduction tended to generate surface or sub-surface voids. Formation of these voids could be minimised by increasing the welding force again, which in turn would generate excessive heat input. Similarly, flaws were developed when the welding speed or the FSW tool rotation speed were varied.

The response of thick section (50 mm) copper to weld parameter variation was obviously not the same as that experienced when welding aluminium alloys. This meant that the weld process control methods used for aluminium welding could not be used for copper. Effort concentrated on identification of weld parameters, or weld condition indicators that could be used to achieve a balanced, controllable heat input to the weld.

Welding trials demonstrated that an FSW tool rotation speed of 400 rev/min was optimum for the size of FSW tool being used. The size of the tool and the tool materials used were governed by the welding temperature, and the force regime experienced during the weld cycle. When the tool rotation speed was progressively lowered below 400 rev/min, the torque increased dramatically to a level at which the probe hot sheared. Conversely, when the rotation speed was progressively increased above 400 rev/min the outer surface of the canister rapidly became hot and soft under the tool shoulder before the underlying copper attained the same state. This caused the FSW tool shoulder to over-plunge into the softened surface, and it proved very difficult to control the weld temperature.

FSW tool rotation speed had the most significant effect on weld stability in 50 mm copper. After exploring how the heat input and stability were influenced by the other weld parameters, it was confirmed that it was advisable to keep as many of the major welding parameters as possible at a constant value. The most precise method of process control developed for the early welds, was to progressively increase welding speed up to a steady state value. Weld stability was interpreted from the FSW tool probe temperature, which was held at a reasonably constant (±10°C) value by slight changes in welding speed. An example of the welding record obtained when producing a complete circumferential weld, CW78, is shown in Figure 6-16. The welding speed was the only weld parameter that was varied in making this weld.

The FSW tool plunge sequence was achieved in 2.0 minutes and a further 3.5 minutes was required to achieve the steady state welding speed of 86 mm/min. This weld is illustrated in Figure 6-17. On completion of this weld the shrinkage across the weld that resulted from the welding process was measured. Where the FSW tool probe had passed once through the weld interface, shrinkage varied from 0.5 – 0.8 mm but where it had passed through twice, at the start and finish location, shrinkage increased to 1.0–1.3 mm.

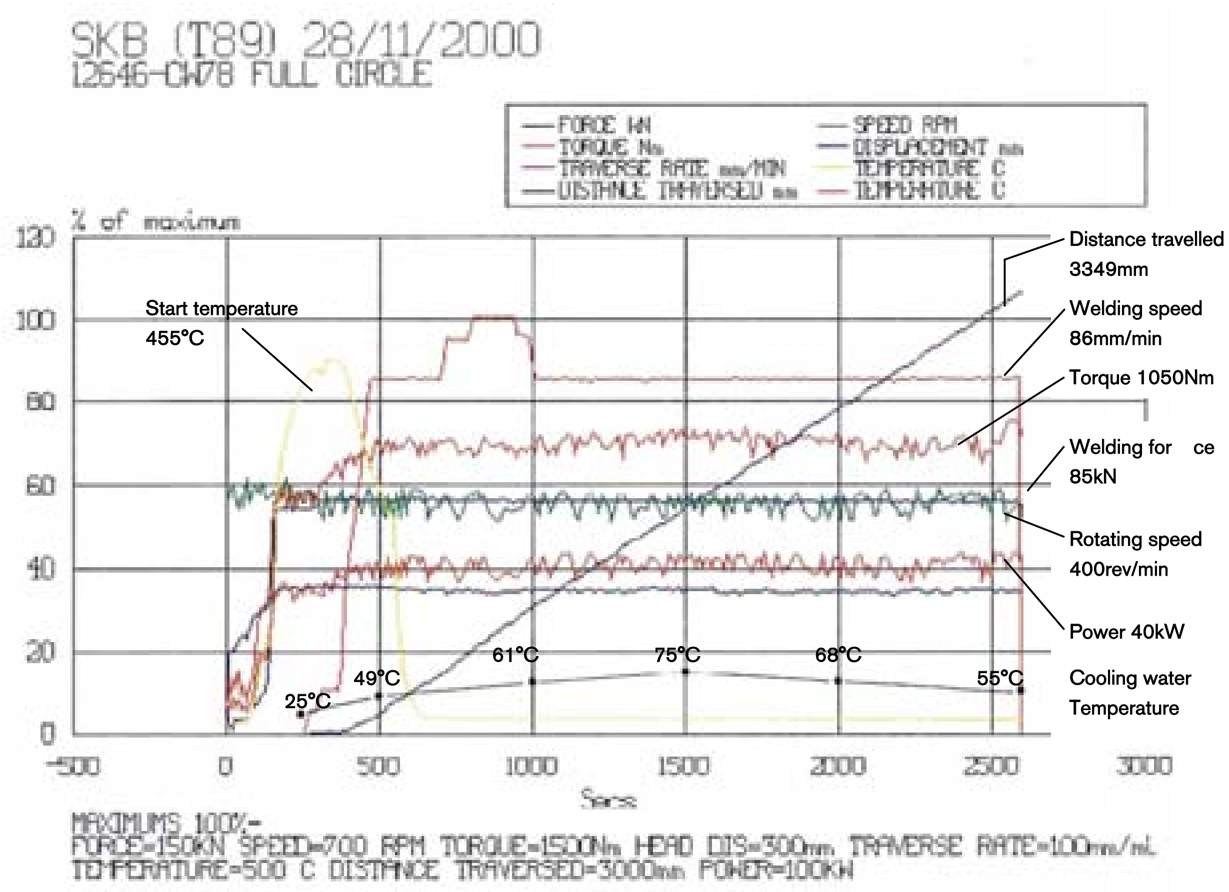


Figure 6-16. *CW78 Complete circumferential canister weld.*

Figure 6-17. *CW78 a complete circumferential weld.*

Although the production of complete circumferential welds was a project milestone, there was no doubt that before FSW could be seriously considered for lid to canister welding, improved control systems, dedicated to 50 mm thick copper were required. The main observations from the circumferential welding trials were as follows:

- At a welding speed of 86 mm/min the weld was completed in 38 minutes, which is acceptable for production.
- Welding speeds faster than 86 mm/min exposed the FSW tool probes to higher force and torque.
- The outlet water temperature from the welding head could provide an extremely powerful method of monitoring the actual temperature at the axis of a tool probe and could potentially provide the basis of a feedback control method for the FSW process.

6.2.7 Full penetration welds

As has been reported earlier, the lid simulation used for making 120° canister segment and complete circumferential welds could be used numerous times, unlike a real lid. All welds made in lid simulations penetrated 49.0 mm into the 50 mm thick canister wall. However, in a real lid to canister weld, the weld would extend through the 50 mm thick canister wall and then a further 2–3 mm into the body of the lid.

It was now necessary to determine if longer FSW tool probes (52–53 mm long), would require weld procedure changes to achieve the same level of weld integrity as seen with 49.0 mm long probes. Modifications to the lid simulation were necessary to allow full penetration welding to be explored. These modifications allowed, as before, the lid simulation to be used many times. A cross section through the full penetration configuration is shown in Figue 6-18.

The copper bung in combination with the split hoop and top/bottom rings closely matched the volume of copper in a real lid and canister assembly. To ensure that all components fitted together as closely as possible, a 3 mm wide slice was removed from a 25 mm thick copper backing ring so that it could be compressed to fit into a slightly smaller diameter recess. This backing ring, identified in Figure 6-18 as a split hoop, represented the region of the lid into which the FSW tool probe penetrated.

As stated in Section 6.2.1 the dimensional fit up tolerance between the lid simulation and canister was larger than the tolerance between a real lid and canister, simply because the lid simulation was used for numerous welds.

Welding trials indicated that initially weld parameter changes needed to be made to compensate for the improved heat transfer resulting from the improved fit up. The parameter changes generated less heat input involving a slight welding z force reduction, and also a reduction in the flow rate of cooling water to the welding head and the lid clamp. Excellent weld integrity was achieved once the welding temperature exceeded 750°C and stable welding conditions had been achieved. This was another major project milestone, because the longer FSW tool probe which represented real lid/canister dimensions, survived a complete circumferential weld, and there was no deterioration in weld integrity.

A longitudinal metallurgical section cut through the axis of weld No CW136 is shown in Figure 6-19. This section was cut near the end of the weld so that the area around the FSW tool probe exit hole could be examined. The weld interface between the canister and the backing ring can be clearly seen in sections H and I, due to the differences in grain size between the two components. No evidence of voids can be seen in either section.

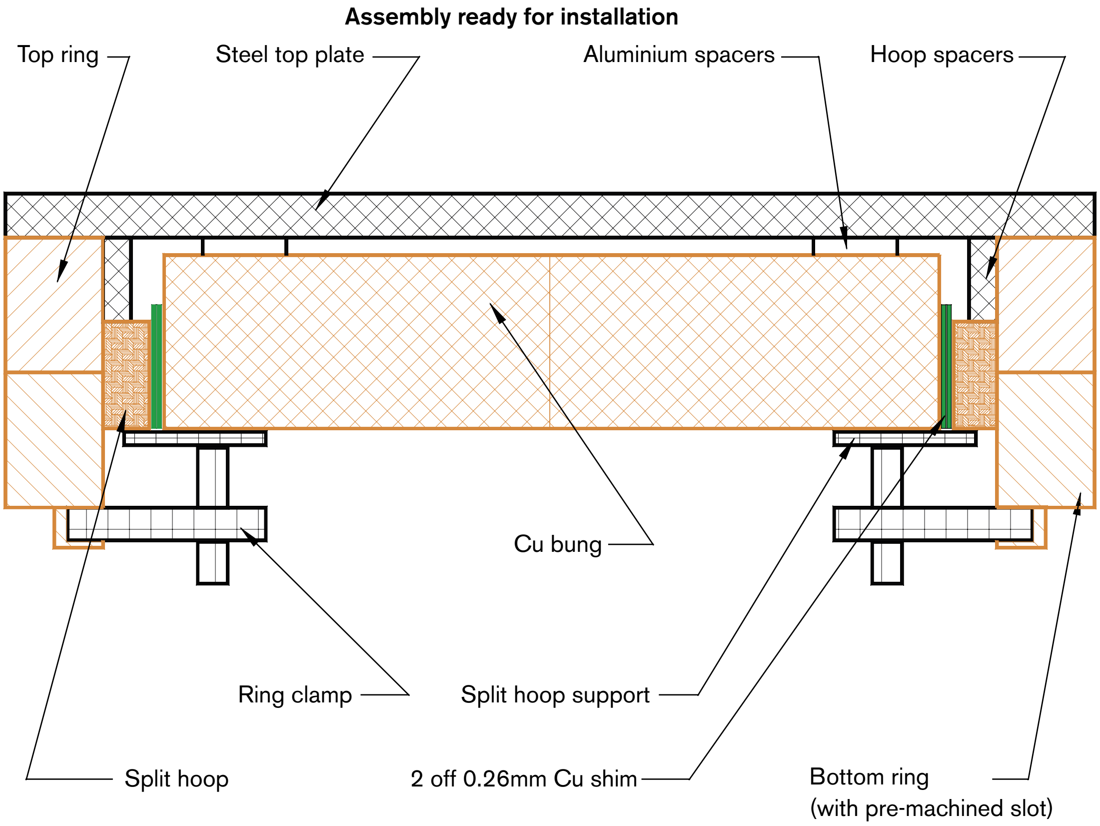


Figure 6-18. Cross-section through the full penetration weld set up.

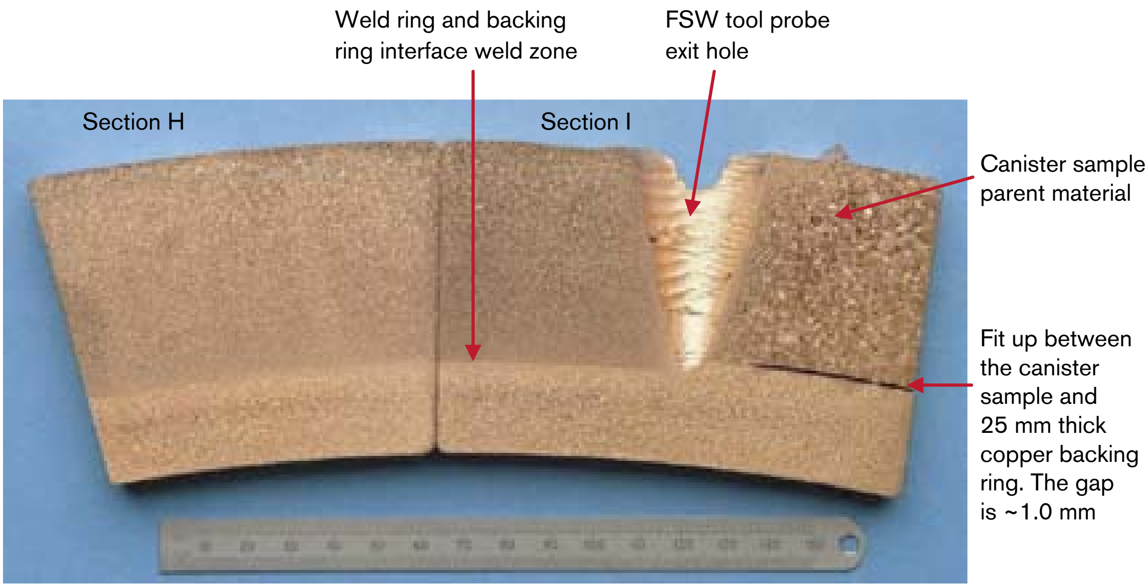


Figure 6-19. Canister weld CW136 showing longitudinal metallurgical section.

Of note is the grain refinement that occurred in the welded region of the canister in Section H compared with the larger grains in the parent material seen on the right side of the tool probe exit hole in Section I. There was no doubt that full penetration welding to a depth of 52 mm had been achieved, and that the fit up gap between the lid simulation and the canister has been accommodated by the FSW process. This was an encouraging result, because the fit up gap between the real lids and canisters will not be greater than 0.5 mm. In addition, this result provided confidence that FSW could be considered seriously as a candidate method for sealing lids to canisters in the Encapsulation Plant.

6.2.8 Lid to canister welds

Once it had been demonstrated that good quality complete circumferential and full penetration welds could be made, the final stage in this development was to demonstrate that real lids could be welded to canisters. As described in the previous sections, the FSW tools, weld parameters and welding procedures had been developed using a lid simulation for economic reasons and also because it was relatively easy to prepare test samples.

In December 2002 the first real lids that had been designed specifically for the FSW process were shipped to TWI. Unfortunately only two of these lids were available for welding trials on the TWI experimental FSW machine. Obviously these lids could not be welded to canister sections until a welding procedure and optimum weld parameters had been developed. It was fortunate that an electron beam welded (EBW) lid to canister assembly was available for FSW development trials. The only surface preparation required was outside diameter machining to remove the raised electron beam weld bead. Although this lid and canister assembly had already been welded together, the "bead on plate" FSW trials helped greatly to optimise welding conditions.

There was, of course, zero fit up gap between the two welded components, and all previous welds had been made with a relatively large fit up gap. The influence of the fit up on weld quality and reproducibility had been recognised early in 2001, but not until this EB weld lid/canister assembly, and real lids became available, was the full impact understood. Small fit up gap dimensions in fact greatly improved weld quality. The reason for this improvement was that the canister wall did not have to be deformed across a wide gap before contacting the surface of the lid. Until the canister wall and lid contacted one another, the hydraulically actuated z welding force was not fully reacted and thus not able to reach the maximum set value.

The welding trials indicated that incomplete welding force reaction and the continuous movement of copper across the fit up gap contributed to the formation of surface breaking and sub-surface flaws, as well as the generation of non-reproducible thermal profiles.

To prevent distortion, the annular recess machined into the lid as a location point for a canister lifting fixture had a steel support plate inserted during the FSW cycle. The steel support plate was needed to prevent the raised edge of the lid from bending inwards towards its centre, when the copper was sufficiently hot and soft to distort during the welding cycle. The support plate located in the lid recess is shown in Figure 6-20.

The steel support plate was initially constructed as two sections that could be expanded against the walls of the recess using two bolts. Once the welding trials using this support plate had been completed, difficulty was experienced on removal, particularly at the joint between the plates. The canister rim had deflected slightly and the support plate had to be modified before welding trials with a real lid were carried out. The plate was cut into four separate segments and machined to assist removal as shown in Figure 6-21.

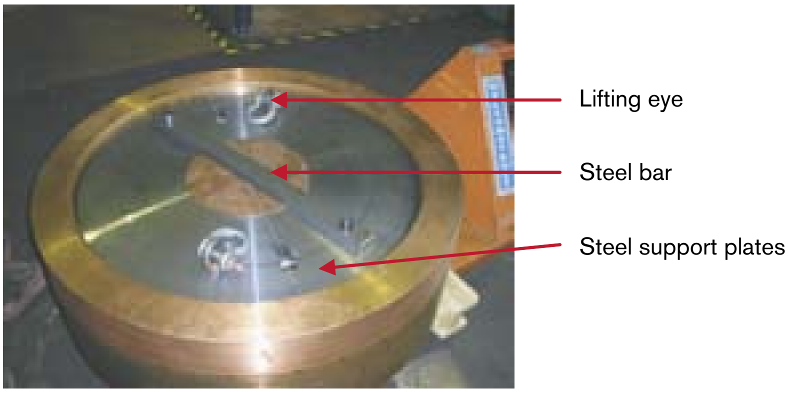


Figure 6-20. *The steel support plate located in the lid recess.*

Figure 6-21. *The lid support plate with four adjustable sections.*

This lid support plate worked well and prevented any measurable distortion of the rim of the lid.

Welding parameters only required minor modification and, in conjunction with a dedicated process control system (as described in Section 9) it proved possible to produce good quality lid to canister welds. The second real lid to canister weld, Weld No CW189 is shown in Figure 6-22 and a transverse metallurgical section cut through the weld zone is shown in Figure 6-23. It is difficult to distinguish the weld zone because the grain size is similar to that of the parent metal.

A weld record for Weld No. CW189 showing the set weld parameters and the two weld condition indicators, weld temperature and torque is shown in Section 9.

__Figure 6-22.__ A lid to canister weld CW189.

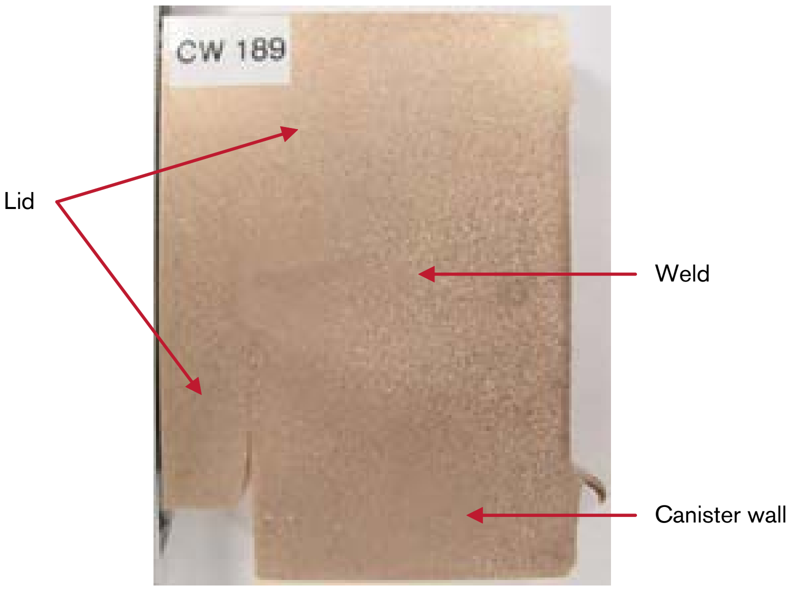


__Figure 6-23.__ A metallurgical section cut through a lid to canister weld.

When welding thick section components by fusion techniques it is common practice to tack weld at a series of positions along the weld interface. These tacks prevent movement caused by thermal expansion when heat is applied by the thick section welding method. In the early days of FSW of copper plate, it was thought that tack welding was not necessary due to the rigid welding fixture holding the plates tightly together and preventing movement. However, when the complete circumferential canister segment welds were made it was observed that the lower canister segment tended to expand away from the lid simulation. It was thought that this effect might become more pronounced when real lid to canister segment welds were made and thus a method of constraining the weld interface movement was devised.

A simple step or rebate had been used with success to prevent movement between the lower canister segment and the longer canister section and this method was used to prevent movement at the lid/canister weld interface. A sketch showing the rebate restraint method is shown in Figure 6-24. The dimensions of the rebate were varied up to a step height of 3 mm and a width of 25 mm. No evidence of remnants of the rebate could be detected by metallurgical examination of welds.

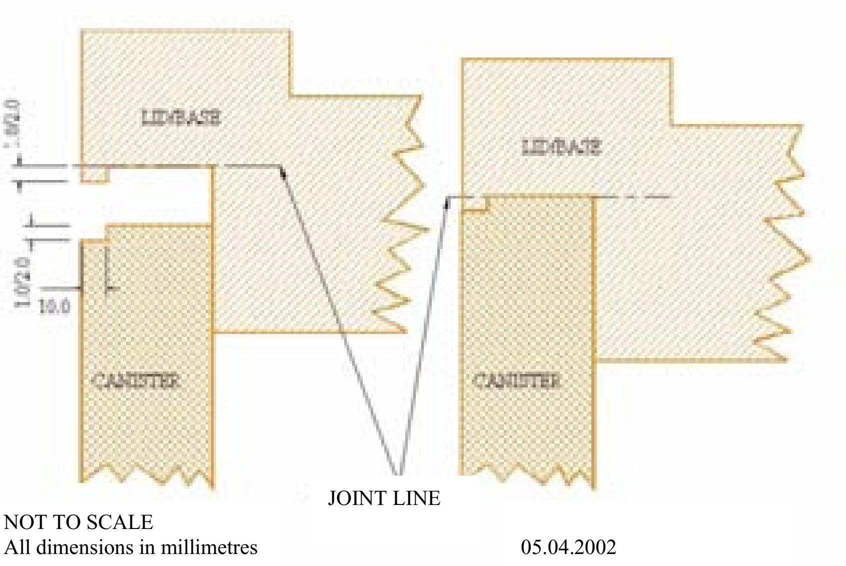


Figure 6-24. *A method of preventing movement between lid and canister.*

7 FSW tool design and material

7.1 Development of the FSW tool probe profile

7.1.1 FSW tool probes for 10 mm thick copper

When the development programme for friction stir welding of 10 mm thick copper plate started, the technology was still in its infancy and was focussed on welding relatively thin section aluminium plate. The geometry of the FSW tool probes at the time was either cylindrical or slightly conical with a diameter to length ratio usually 1:1 or 1:1.5. A left hand thread form of varying pitch and depth was machined onto the probe. When this geometry was rotated in a clockwise direction the thread form transported softened copper downward, producing a solid state weld as described in Section 2.

This type of tool probe belonged to a family of probes known as the Whorl™ type, as shown in Figure 7-1. The Whorl™ probe made it possible to make good quality welds as described in Section 4.1.2.

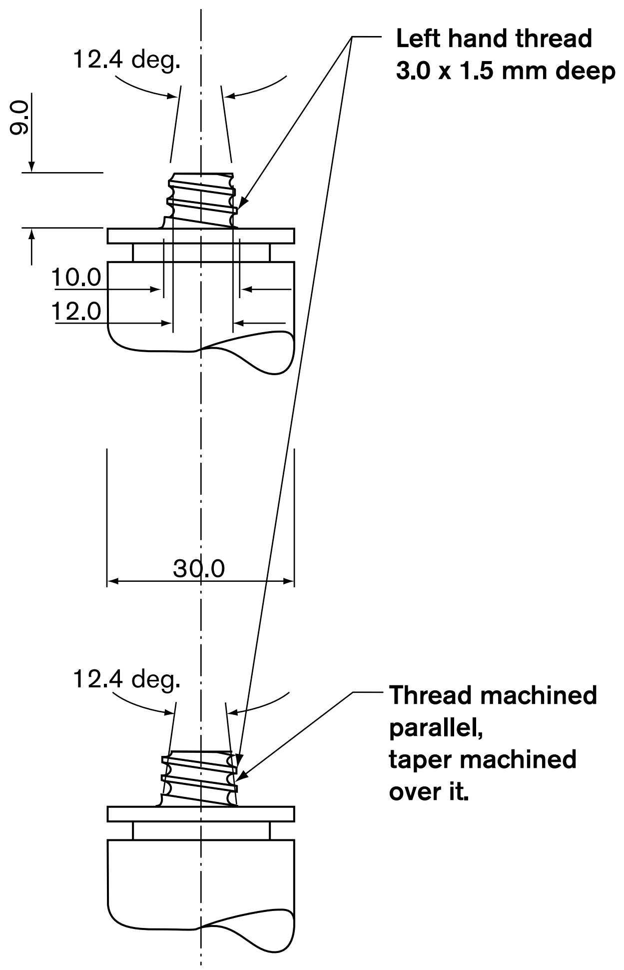


Figure 7-1. *The 1997 FSW tool probe (Whorl™ type) used for welding 10 mm thick copper plate.*

7.1.2 Problems encountered with FSW tool probes for welding 20–50 mm thick copper plate

The results of the 10 mm thick plate welding trials demonstrated that the FSW tool probe and shoulder constituted the most important part of the FSW process. These two components would be required ultimately to withstand the high process temperature (800–900°C) and complex, high force regime, experienced during production of a 3.3 m weld in 50 mm thick copper taking approximately 45 minutes.

As welding trials on increasingly thick copper plate progressed, it became clear that the Whorl™ type tool could not be scaled up to weld 50 mm thick plate. The reason for this can be seen in the tool sketches in Figure 7-2.

In Figure 7-2 an FSW tool probe and shoulder suitable for welding 10 mm thick plate are shown. The diameter of the probe is slightly larger than the length. This probe diameter to length ratio of 1:0.9 ensured sufficient strength and stiffness so that the probe was not deflected. Deflection is caused by the x force acting on the front face of the probe during

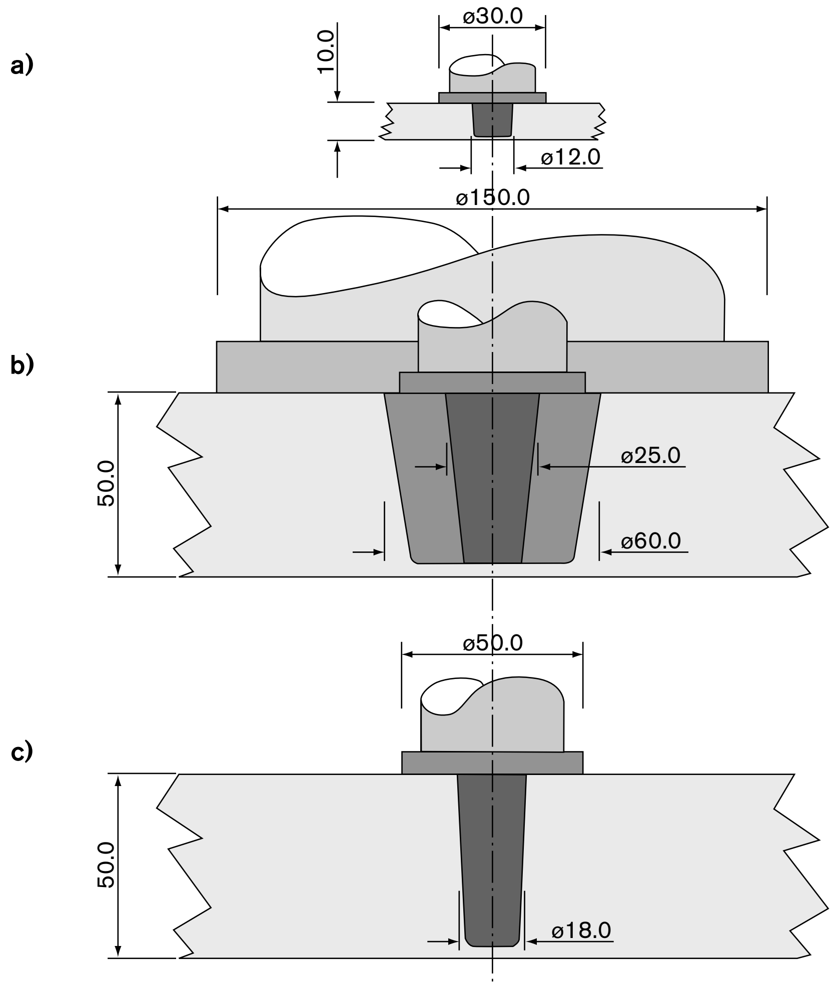


Figure 7-2. *Sketches showing the tool probe dimensions used to weld 10 mm thick copper plate scaled up to weld 50 mm thick plate.*

welding. A scaled up version of this type of probe is shown in Figure 7-2b with a shoulder diameter of 150 mm and a maximum probe diameter of 60 mm. An FSW machine with very high transmission power would be required to rotate such a tool and to also translate it along the weld interface. More importantly it would have been difficult to generate sufficient heat input to soften such a large weld volume. Even the experimental FSW machine with a 100 kW motor, could not drive an FSW tool of the dimensions shown in Figure 7-2b.

The maximum tool probe size compatible with the capabilities of the FSW machine was quickly established by plunge sequence trials and is shown superimposed over the larger tool in Figure 7-21b and c. It can be seen that the probe volume has been reduced, with a diameter to length ratio of 1:1.8. Unfortunately this ratio reduced rigidity, and probes were more likely to deflect when subjected to fast welding speeds, which in turn generated larger x forces.

7.1.3 The MX Triflute™ FSW tool probe

It was fortunate that at the time when welding of thicker section copper started a new type of FSW tool probe called the MX Triflute™ had just been developed at TWI. An example of this type of probe is illustrated in Figure 7-3.

As reported by Thomas et al [4] the strength of Triflute probes is superior to that of cylindrical or multi-flute style probes. The improved flow path combined with a probe material that has adequate strength at temperatures up to 950°C permits the use of tapered probes with a top diameter to length ratio of 1:1.8. It is this much reduced probe volume in combination with a high strength material and a probe temperature control facility that permitted 50 mm thick copper to be welded successfully.

Many variants of this probe type were designed and tested but it proved difficult to eradicate a roughly triangular shaped flaw located on the advancing side of the weld, (for this location refer to Figure 2-1) An extreme example of this flaw type is shown in Figure 7-4, typically flaw length was found to vary from ~0.5 mm to 8.0 mm.

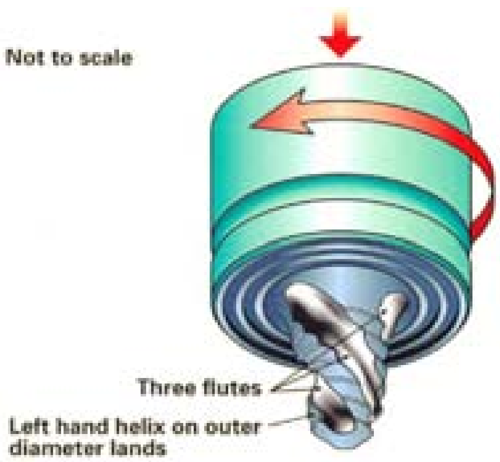


Figure 7-3. The MX Triflute™ concept.

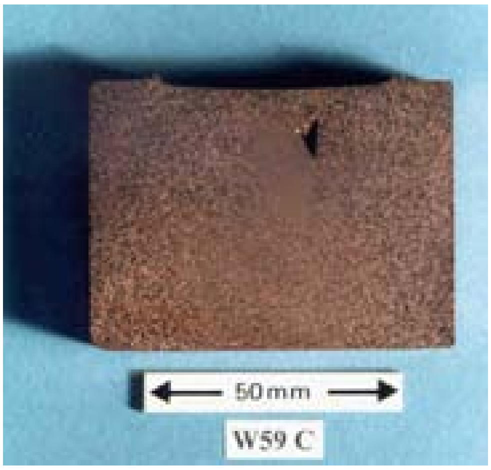


Figure 7-4. The triangular shaped flaw located on the advancing side, near the top surface of 50 mm FSW copper plates.

The MX Triflute™ probe design proved to be a project breakthrough as it permitted up to 50 mm thick copper to be welded, but importantly at welding speeds up to 40 mm/min. However, the solution to eradicating the advancing side flaw remained elusive until an important observation was made.

7.1.4 Improvements to the MX Triflute™ probe

Examination of an MX Triflute™ probe variant just after it had been used revealed a greater build up of copper at the tip of the probe on the three leading edges (working edges) of the land (location shown in Figure 7-5). In comparison, there was very little build up on the leading edges adjacent to the working face of the FSW tool shoulder. The location of the advancing side flaw was aligned with this region.

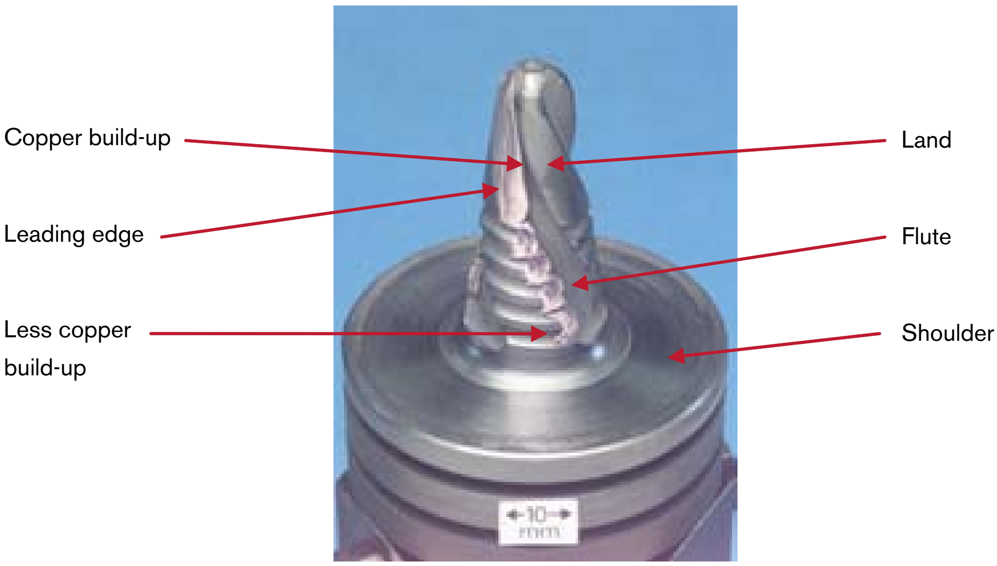


Figure 7-5. MX Triflute™ probe showing the build up of copper on the leading edge of the flute.

This was not an isolated observation. The same phenomenon was observed when the tool probe was withdrawn from the end of a further six welds. In contrast, when the MX Triflute™ probe was used to weld aluminium alloys the flutes were always completely filled on retraction of the probe from the weld. These observations made when welding copper suggested that copper is much less 'fluid' at the FSW temperature of 800–900°C than aluminium alloy at ~550°C, and thus is not able to flow into, and fill, the flutes. This incomplete filling of the flutes was thought to be associated with the occurrence of the triangular flaw. A sketch showing this concept is included in Figure 7-6a.

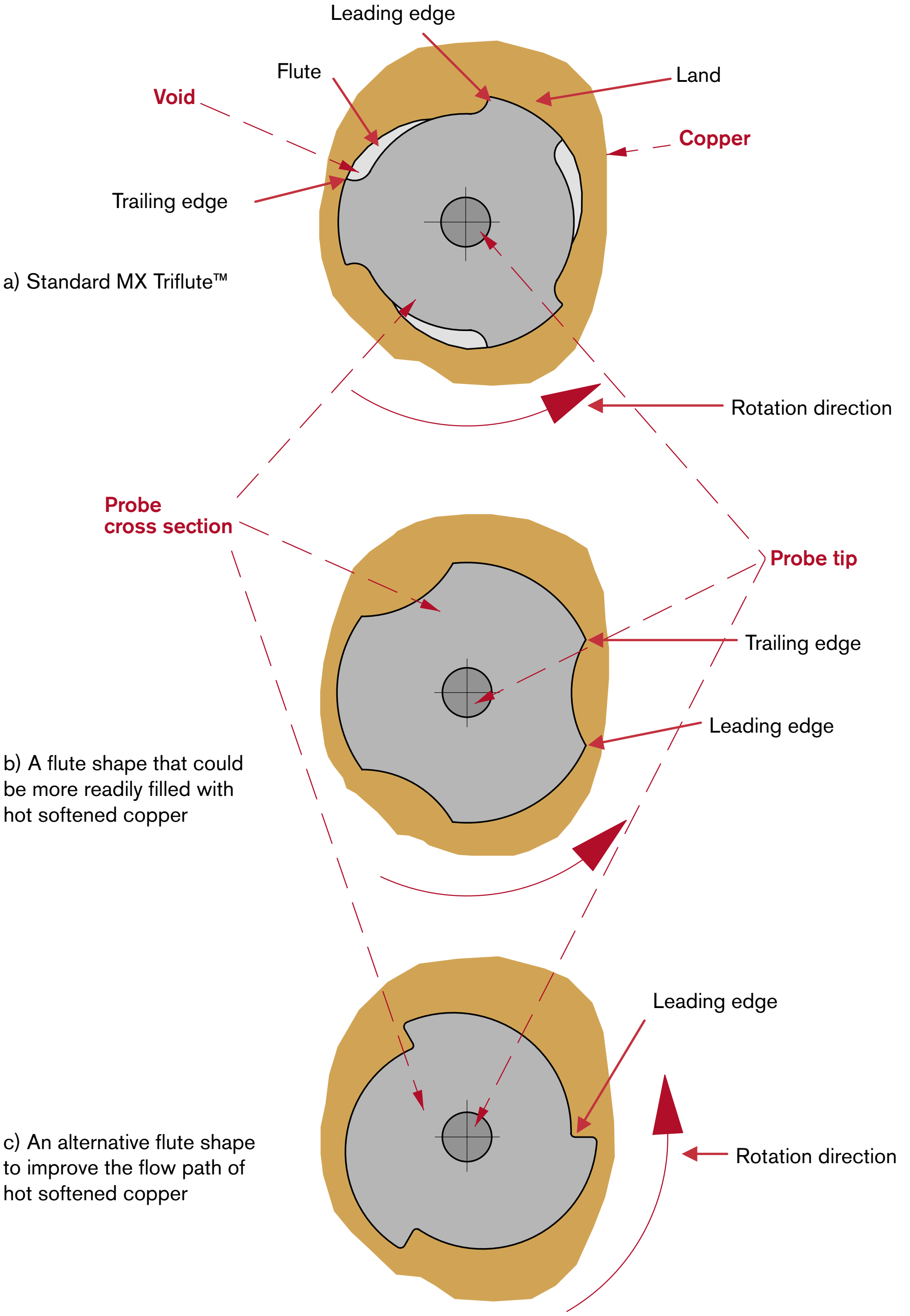


Figure 7-6. *Illustrations of a cross section through FSW Triflute™ tool probes showing concepts to eliminate voids.*

In an effort to provide an easier path for the flow of hot softened copper to fill the probe flutes and at the same time to provide an adequate stirring action, probe concepts such as shown in Figure 7-6b and c were investigated. The probe shape shown in Figure 7-6c proved to be very successful allowing flaw free welds to be produced at a welding speed of up to 100 mm/min, which permitted a complete circumferential weld to be made in 33 minutes. However, to reduce the x force being reacted on the front face of the probe, a welding speed of ~80 mm/min was normally used.

The MX designation for this probe type referred to an additional thread form machined onto the probes lands. This feature was initially added as a left handed thread form but was later modified to a right handed thread in opposition to the left hand direction of the flutes. The purpose of the MX feature was to further increase the flow path for the hot, softened copper. Additionally the right hand thread redirected some of the copper up toward the working face of the shoulder. The concept was intended to continually supply copper to the hemispherical cavity directly under the working face of the FSW shoulder, with the purpose of reducing flaw formation adjacent to the surface. The concept proved to be sound, and using optimised welding conditions flaw free welds could be produced on a regular basis. This tool probe development was seen as a major step forward in the production application and a patent [5] application was made. The purpose of the patent was defensive to ensure that SKB would not have to pay a licence fee to any other organisation that may have independently invented the same probe concept and patented it. Once the patent was in the public domain, no other organisation could claim the probe concept.

7.1.5 The final MX Triflute™ variant in the TWI work programme

An example of a MX Triflute™ probe with the relevant features identified is shown in Figure 7-7 and 7-8. The TWI identification for this type of probe was A023 MK7.

The A023 MK7 probe type made good quality complete circumferential welds in an acceptable timescale and the design was not changed further during the development programme. The reason for not making any additional changes was partly due to difficulties associated with isolation of the precise effects of geometrical and dimensional changes to probes on weld integrity. Problems associated with poor fit up between the lid and canister, or rapid welding parameter changes confused the analysis of the effect of probe features on weld integrity, which was evaluated by metallurgical examination for evidence of flaws.

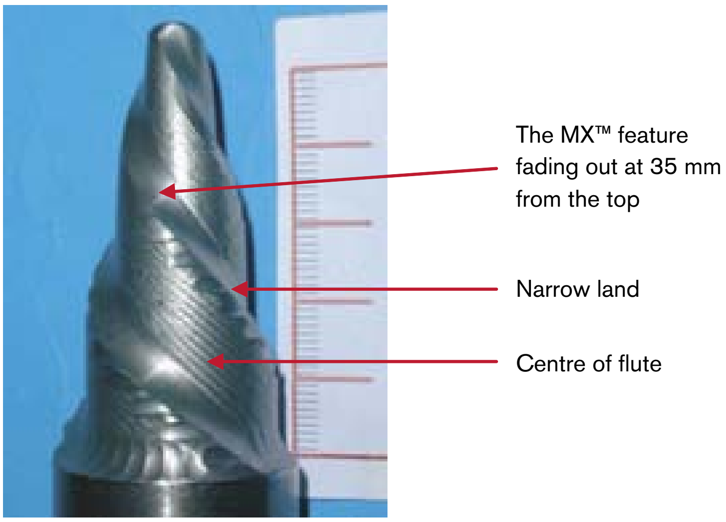


Figure 7-7. *An A023 MK7 FSW tool probe.*

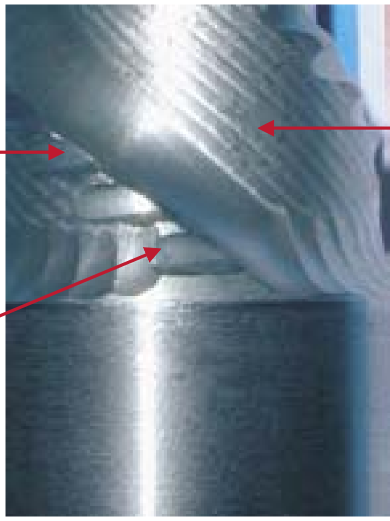


Figure 7-8. *An A023 MK7 FSW tool probe.*

It is certain that the AD023 MK7 FSW tool probe is not a fully optimised design, and it is likely that improvements will be made in the future.

However, the A023 MK7 probe satisfied the objective of the FSW development programme at TWI in terms of weld quality, timescale and ability to work at the weld temperature for ~40 minutes without failure. This success was achieved because a suitable probe material was identified that could withstand the process temperature and force regime as described in Section 7.1.4.

The incidence of probe failure was very much reduced with the A023 MK7 when compared with the standard MX Triflute™ probe. With reference to Figure 7-6a, the standard MX Triflute™ type had flutes with both a leading and trailing edge, thus creating a more complicated flow path for hot softened copper. In addition, the improved strength of the A023 MK7 probe was explained by examination of a longitudinal section cut through the probe axis. In contrast to standard Triflute™ probes, the features machined on the probe were all equi-distant from the probe axis. Standard Triflute™ probes failed at the point where the probe features were closest to the axis creating a region of localised stress concentration. The improved strength of the A023 MK7 probe was one of the claims that permitted a patent to be granted.

7.2 FSW tool probe material

7.2.1 FSW tool probe requirements

FSW of copper provided a challenge in terms of the selection of probe material with suitable physical properties. The major requirements of an FSW tool probe to weld thick section copper were identified as:

- To have sufficient fracture toughness to survive the initial stage, or plunge sequence.
- To have adequate high temperature strength to withstand the high compressive and shear loads experienced throughout the weld cycle.
- To be economically viable to generate a probe geometry that provides sufficient friction heating and metal movement.

- The probe must not lose dimensions or shape when producing welds up to 3.5 m long.
- To be inert when welding copper.

In the assessment of and search for tool probe materials for this high temperature application, seventeen different materials were evaluated. As sufficient fracture toughness was a prime requirement, attention was focussed on bulk hardness verses transverse rupture strength. The materials evaluated and the level of success achieved is described in the following sections.

7.2.2 Cemented carbides

The majority of the candidate FSW probe materials identified were often difficult or impossible to obtain in small amounts for evaluation. Even in small amounts, the cost could be prohibitive. Therefore, the capability of cemented carbide was first evaluated for the following reasons:

- Readily available.
- Acceptable costs.
- High modulus of elasticity.
- High compressive strength.
- High hardness.
- Moderately good high temperature properties.

However, a major drawback was the relatively low transverse rupture strength of cemented carbide, which made it brittle with virtually no plastic deformation preceding fracture.

FSW tool probes were either diamond ground from fully sintered cemented carbide rod, which was the most expensive option, or had the major features machined at +20% on final dimensions, when the material was in the part sintered, relatively soft condition. In the latter case shrinkage occurred on sintering resulting in a requirement for minimal final grinding.

The cemented carbide consisted of tungsten carbide particles of various sizes in a cobalt matrix. The volume % of tungsten carbide varied from 10–20%. Various grades of this material were tested with different carbide particle sizes and also alternative matrix materials.

Although cemented carbide had been selected for tool probes for the reasons listed earlier in this section, numerous failures occurred particularly during the initial plunge sequence. An MX Triflute™ FSW tool probe that fractured during the plunge sequence at the junction between the top of the probe and the FSW tool shoulder is shown in Figure 7-9. This was at the time when the shape of the MX Triflute™ probes were being progressively developed. Unfortunately the unpredictable failure mode of these probes made it difficult to gather evidence of the effect of probe geometry on weld integrity.

As a result of failures of this type, the viability and future of FSW of thick section copper was questioned and had to be seriously addressed. A grade of cemented carbide made by Sandvik and identified as H10F with a chemical composition of WC/10%Co was first used for probe manufacture. The reason for selecting the H10F grade was simply because it was used for manufacturing ~95% of cemented carbide products and thus readily available.

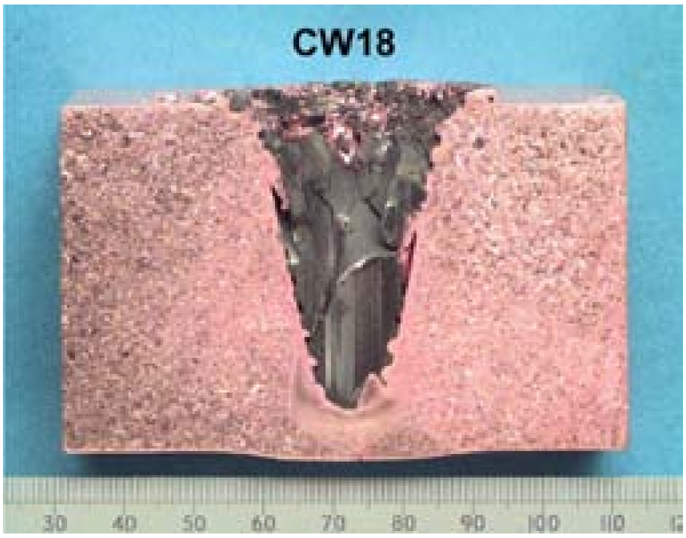


Figure 7-9. *A cemented carbide MX Triflute™ probe that fractured during the plunge sequence.*

On reflection Sandvik, based in Stockholm, thought that the WC/10%Co (H10F) grade of cemented carbide might be too hard, at 1450HV3 for the FSW of copper application, because so many tool probe failures were experienced. Analysis of the tool probe fracture faces confirmed this and also revealed that surface oxidation of the WC particles had created numerous fracture initiation sites. It was concluded by Sandvik that the choice of H10F grade was not correct for this application, but that it provided a starting material and its response to the FSW process helped to guide the selection of more appropriate cemented carbides.

Sandvik recommended that two new tougher grades of cemented carbide were assessed as follows:

- Grade C10C – a corrosion and oxidation resistant grade containing nickel. This grade was softer at 1100HV3 than the H10F grade at 1450HV3.
- Grade H762 – resists heat cracking and has good thermal conductivity. This grade was even softer at 1000HV3 than the H10F grade.

Tool probes in both grades of cemented carbide were manufactured in December 1999. Both tool probes survived the plunge sequence and produced ~800 mm long welds in 120° canister segments. No sign of wear could be detected on the surface of either type of probe.

Examples of tool probes that had been used in welding trials were sent to Sandvik for analysis of the response of each cemented carbide grade to the FSW process.

Sandvik concluded that the matt grey surface of either probe consisted of a thin but adherent layer of tungsten oxide. This oxide layer was thinner for the oxidation resistant C10C grade. More importantly, no cracks were observed in the surface of the tool. However, copper was attached at various locations on the leading edge of the flutes on probes in either grade of cemented carbide. Sandvik suggested that a coating of TiN or (Ti, Al) N applied by PVD (physical vapour deposition) or CVD (chemical vapour deposition) could be used to prevent oxidation and copper sticking to the cemented carbide. Sandvik further recommended that the C10C grade should be used, as it is less prone to oxidation.

Cemented carbide FSW tool probe development was not continued. There was no doubt that cemented carbides had proved to be invaluable for the initial development of welding parameters, welding machine specifications and for providing confidence in the technique. However, the unpredictable instantaneous rupture, which left the probe buried at the weld interface was not acceptable. These results suggested that a material with lower hardness and higher transverse rupture strength would be necessary for a higher strength probe.

In addition, Sandvik stressed that the FSW tool probe life was closely associated with the amount of eccentricity or "run out" in the FSW machines rotating spindle. The specification of extremely accurate spindle bearings for an FSW machine would result in a price increase, which could possibly make the FSW process non-viable for the canister welding application. It was considered that with sufficient development with Sandvik a reliable cemented carbide probe could have been identified, but the project scope and timescale did not allow this.

7.2.3 Ceramics and cubic boron nitride

The work with cemented carbide probes described in the previous section suggested that any material with a lower transverse rupture strength would not be worth considering for this application. Despite these conclusions, significant public domain documentation suggested that the high temperature capabilities of cubic boron nitride, alumino-silicate and yttria stabilised zirconium oxide should not be dismissed. In addition, these materials were relatively easy to obtain at acceptable prices, but diamond grinding the required geometrical features onto the probes proved costly. It was thought possible that if probes were manufactured in large numbers to the desired geometry at an early stage then production costs could drop dramatically. Some probes in these materials were procured and tested.

FSW probes manufactured in both materials exhibited a very short life, failing during the plunge sequence or the heating sequence, by sudden rupture. No further work was carried out with these probe materials, although it was accepted that premature failure could have resulted from eccentricity in the FSW machine's rotating spindle bearings.

7.2.4 Refractory metals

The very high melting point and maintenance of strength in the copper welding temperature range of 800–900°C made the refractory metals and alloys appear attractive for use as FSW probes. As the majority of the metals and alloys were available, albeit at high prices, those listed below were evaluated:

- Molybdenum.
- TZM molybdenum alloy.
- Molybdenum plus zirconium oxide cermet (Cermotherm-Plansee).
- MHC (Molybdenum/hafnium carbide material – Plansee).
- Tungsten.
- Densimet alloy (sintered tungsten).
- Tungsten-rhenium alloy.

None of these materials in the probe shape and dimensions required, consistently survived the FSW probe plunge sequence and all suffered minor dimensional loss after producing a weld of only 1.0 m length. The tungsten-25% rhenium alloy and the MHC had the best operating performance, as they did not fracture and evidence of wear was slight. However, the cost of probe material for this application was prohibitive at ~£1,500 and machining was difficult and costly.

Further work with refractory materials was discontinued due to the generally poor performance. In particular the cermet material was thought to be unsuitable because zirconium oxide particles became detached from the molybdenum matrix during welding and were then entrained into the weld zone. The formation of a toxic oxide above 500°C precluded the use of molybdenum and its alloys from any future work programmes. The exceptional strength of the tungsten-rhenium alloy and MHC material warrants additional assessment in future development work. Oxidation of the probe surface could be reduced by surface engineering such as carburising or silicide coating.

7.2.5 Superalloys

As described in preceding sections, this study started with the evaluation of cemented carbide and refractory metal FSW probes, but even at this early stage of the FSW development the potential of the large number of superalloys was always recognised. If the decision had been made to evaluate the superalloys first, then problems with procurement, availability and the high cost of minimum amounts would have delayed the demonstration of the feasibility of FSW 50 mm thick copper by a year.

Therefore, in the period that feasibility was being established, the search for suitable superalloys took place. The materials that were available were in essentially three different forms as follows:

- Forged (or wrought).
- Cast (some alloys also hot worked).
- Powder + HIP (hot isostatic pressing).

The alloys that were obtained within the project timescale and budget are listed below:

Forged:	**Cast:**	**Powder metallurgy:**
– Nimonic 90 alloy	– MAR-M-002	– IN 100 alloy
– Inconel 718 alloy	– Stellite 12 (not considered a Superalloy but based on a Ternary system cobalt-chromium-tungsten)	– PM 3030 (ODS alloy)
– Waspaloy		
– Nimonic 105 alloy		

The performance of these materials is described below:

a) The forged alloys

The nickel-based superalloys both forged and cast have the capability of being used at temperatures of up to 900°C. They also have much improved fracture toughness when compared with the cemented carbide material that was initially used for FSW probes in this study. Obviously the alloys with the highest temperature strength were thought to be the most attractive for use as probes, but were difficult to acquire.

Alloys used in this study were heat treated to the manufacturers recommendations, albeit to achieve material properties suited for use in gas turbine engines, and not necessarily ideal for FSW probes. Unlike the materials described in the previous sub-sections, all the superalloys survived the tool plunge sequence. Differences in performance became more obvious during the steady state welding conditions at 800–900°C.

The forged alloys, Nimonic 90, Inconel 718 alloys and Waspaloy tool probes all proved capable of producing welds up to 3.3 m long. However, after welding, visual examination revealed that the probes had started to twist, which caused a reduction in length. Metallurgical examination showed that these materials had started to hot shear which suggested that temperatures in excess of ~830°C had been experienced.

In contrast, the performance of the FSW probes manufactured in Nimonic 105 alloy provided a major milestone in this development, because they were less prone to twist or loss of dimensions. Also they were capable of producing many meters of weld (up to 20 m with no failure or loss of dimension). Nimonic 105 alloy probes did not fracture during an FSW cycle when the welding temperature was correctly controlled, and the only mode of failure seen was hot shearing which occurred when the probe was heated above ~1000°C.

The good creep rupture properties of Nimonic 105 alloy up to 875°C guaranteed that it would be possible to have reliable FSW probes for 50 mm thick copper. All the nickel based alloys evaluated were precipitation hardenable via the precipitation hardening constituent γ^1. Compared with Nimonic 90 alloy, the increased additions of Al, Ti and Nb in Nimonic 105 alloy produce a larger volume of γ^1 and molybdenum assists solid solution strengthening.

There is no doubt that superior tool probe materials to Nimonic 105 alloy for welding copper exist, but increases in the strength of forged alloys are obtained through increased additions of Al and Ti. These additions decrease the solidus and liquidus temperatures but increase the solution temperature of the γ^1 hardening phase. This results in a large decrease in the hot working temperature range for the strongest high strength alloys such as Nimonic 115 and Udimet 700 alloys, and they are thus difficult to hot work. These stronger alloys also have reduced elongation values of ~10% at the copper welding temperature compared with ~20% for Nimonic 105 alloy. The considerable ductility of Nimonic 105 alloy from ambient temperature to ~900°C was also crucial to its successful application as an FSW probe.

Nimonic 105 alloy is not a state of the art material, as it was first developed and manufactured by Henry Wiggin Co Ltd (UK) in 1995. It can still be purchased from the same company, now known as Special Metals Wiggin Ltd, in specific batch sizes. The minimum order size of 250 kg was purchased for this FSW development programme, which was sufficient for the manufacture of approximately 400 probes. Ageing (or precipitation hardening) for 17 hours at 850°C and then air cool followed by 750°C for 24 hours was selected at TWI to precipitate the hardening phase in a form that provided an FSW tool probe with sufficient strength and wear resistance. This heat treatment possibly does not provide the optimum material properties when operating at the welding temperature of ~860°C, but enabled complete circumferential lid to canister welds to be made. There was insufficient time available in the work programme to explore alternative heat treatment regimes. It may prove possible as the FSW development continues in the SKB Canister Laboratory at Oskarshamn, to establish a relationship between heat treatment, microstructure and properties to ensure optimum tool probe performance.

Selected Nimonic 105 alloy FSW tool probes were subjected to the Tuftride process on the advice of TTI Ltd, Letchworth, UK, a heat treatment company who work closely with the UK aerospace industry. The Tuftride process increased the surface hardness of aged Nimonic 105 alloy from ~380HV to 650HV. This surface layer was approximately 10 μm thick. Tuftriding is a readily available, relatively cheap thermo-chemical treatment, which is carried out at 560°C and introduces carbon and nitrogen into the surface layers. There are other thermo-chemical surface treatments and various coating methods which may prove to be more suitable that Tuftriding, and should be assessed in future work programmes at the SKB Canister Laboratory. Tuftriding did help reduce the amount of copper adhering to the leading edges of the FSW tool probe. In addition, the conclusions of an examination of a Tuftrided that the hardened surface layers had reduced incidence of grain boundary thermal cracking at the surface, thereby lessening the chance of the probe shearing when used to make more than one weld.

b) Cast alloys

FSW tool probes manufactured in cast alloys MAR-M-002 and Stellite 12 produced 1.0 m long welds without fracture or loss of dimensions. MAR-M-002 alloy can operate at ~1000°C but metallurgical examination revealed significant porosity which might be expected to result in premature failure.

Although both cast alloys behaved well as FSW probes they were not used again due to porosity and an essentially brittle microstructure.

c) Powder metallurgy alloys

The powder metallurgy ODS alloy PM3030 produced 1.0 m long welds without fracture. However, the IN100 alloy fractured abruptly after producing 150 mm of weld. The high temperature capability of IN100 alloy for 1000-hour life at 138 N/mm² is 960°C compared with 870°C for Nimonic 105 alloy. The fracture face was typical of components that have been produced by hot iso-static pressing (HIP). A brittle carbide film is located at the prior powder particle boundaries, which can lead to failure at certain temperatures and stresses.

This result stopped further evaluation of powder metallurgy alloys despite impressive high temperature strength properties associated with these materials.

Although Nimonic 105 alloy provided the most reliable performance at the welding temperature of ~860°C for the TWI FSW development, it is almost certainly not the optimum material. Therefore, to substantially reduce the risk of a probe hot shearing while producing a circumferential weld, the search for a tool probe material that will operate more reliably at higher temperature should be continued.

7.3 FSW tool shoulders

The majority of FSW tool shoulders have been machined from the sintered tungsten alloy Densimet 1765. Its high temperature capability, good machining characteristics and high thermal conductivity (80W/m°C) make it an ideal shoulder material. Other materials with lower thermal conductivities such as the nickel based (10.89W/m°C) and cobalt-based superalloys have also been assessed. However, the rapid rate at which Densimet attained red heat (650–700°C in ~3 min), using preferred FSW conditions has not been matched by any other material to date. In contrast a Nimonic 90 nickel based alloy shoulder took 15 minutes to reach 500°C.

An FSW tool shoulder is shown in Figure 7-10 with the major features identified. The slot has two functions, firstly it allows the shoulder to be pulled out of the water-cooled welding head when FSW tool changes are made. Secondly the slot appeared to behave as a thermal barrier, which limited the volume of Densimet 176S that gets heated to the welding

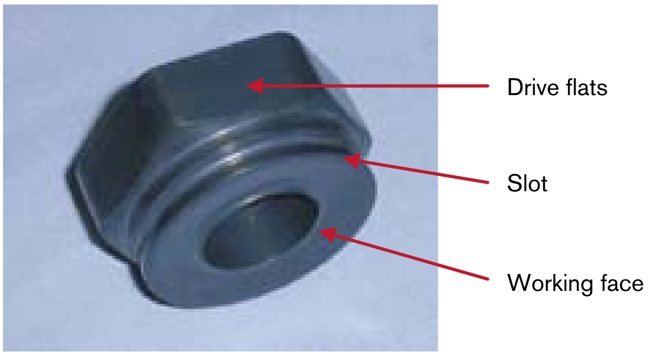


Figure 7-10. *An FSW tool shoulder.*

temperature. Welding trial results established that it was essential for the shoulder to attain red heat before the welding process could start. It became clear that the volume of the shoulder at red heat was in fact an additional, not predicted, weld parameter. This volume of material behaved essentially as a reservoir of heat, maintaining a balanced transfer of heat into the weld zone.

The diameter of the shoulder also is an important parameter identified by welding trials. Diameters between 40–70 mm operating at periphal velocities of 0.03–0.05 m/sec provided the correct level of heat input into the weld zone.

Finally the contact face of the shoulder was machined to a variety of geometrics including scroll and spiral features. The best weld quality was produced using a plain concave shape with a re-entrant angle of ~5°. It may be necessary in future work to produce an FSW tool shoulder less prone to distortion for use in the production environment.

8 The FSW tool probe exit hole

8.1 Terminating a friction stir weld

A lid to canister circumferential weld progresses to completion by passing over the 0°/360°, start/finish, position to typically the 380 – 400° position, which is welded twice. The purpose of this procedure is to eradicate, or at least minimise, any flaws that were created during the period when the weld was started. During this period, the weld temperature rose from ambient to the steady state temperature of ~860°C, and the weld speed increased from 0 mm/min to 80 mm/min.

As soon as the 380° position was reached, the weld could be terminated by stopping rotation and withdrawing the FSW tool probe. A 50 mm deep hole is left on the weld interface as shown in Figure 6-19. Clearly, a hole on the weld interface of a copper canister with the primary purpose of being a corrosion barrier, was unacceptable. Early in the development of FSW of copper, a solution to this problem was sought, and a small amount of effort was put into the development of a solid phase welding hole fill technique. This was based on the two friction processes known as Friction Taper Plug Welding (FTPW) and Friction Hydro Pillar Processing (FHPP).

In the simplest form, a round bar consumable was rotated within the FSW tool probe exit hole under an axial load. In combination, the rotation and force generated frictional heating and solid-state bonding. The results of hole filling trials were not encouraging as weld formation was hampered by the high thermal conductivity of copper, which led to the rapid heating and softening of the rotating consumable rod. The welding force required to generate solid phase bonding rapidly decreased as the softened copper rod collapsed. However, the conditions required to produce a copper hole fill were identified and a concept was developed for future consideration if needed.

8.2 Parking the tool probe exit hole

In view of time constraints on the completion of the FSW of copper work programme, a system to allow parking of the exit hole was designed by TWI and approved by SKB. It involved raising the welding head up by more than 50 mm from the weld interface to park the exit hole in the lid.

The probe exit hole parking concept required modification to the experimental canister welding machine, which permitted the complete welding head to be lifted using the hydraulic jack assembly as shown in Figure 8-1.

The welding head was mounted on the support plate, which pivoted on the right side and was connected to the hydraulic jack assembly on the left side. This allowed the FSW welding tool to describe an arc away from the weld interface as the left side of the support plate was raised or lowered. The maximum height the head could be lifted was 44 mm, which was sufficient to demonstrate the principle of parking the tool probe exit hole. This assembly is shown in Figure 8-2. It was possible to vary the rate at which the welding head was lifted and monitor both the lift rate and the applied force. The FSW tool probe parking procedure was accomplished by lifting the welding head as soon as the 380° position at the interface had been passed. Changes to the welding speed (canister rotation speed) could be made, and the angle at which the weld moved away from lid/canister interface was directly related to the rate at which the welding head was lifted.

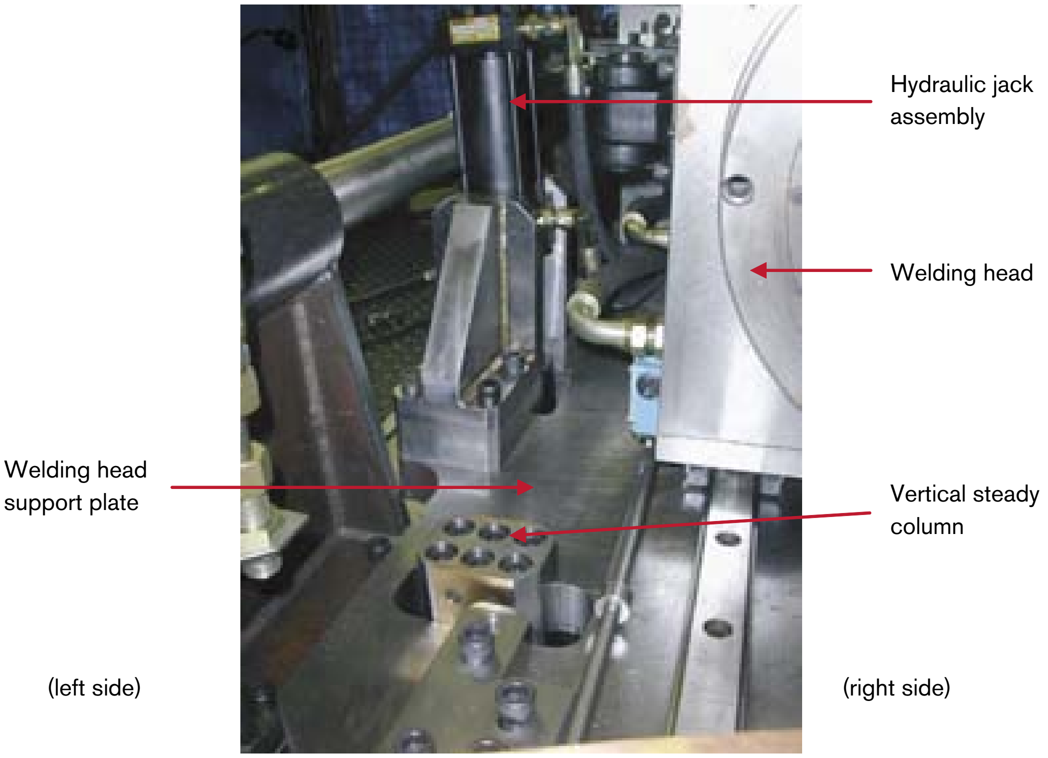


Figure 8-1. *The hydraulic jack assembly.*

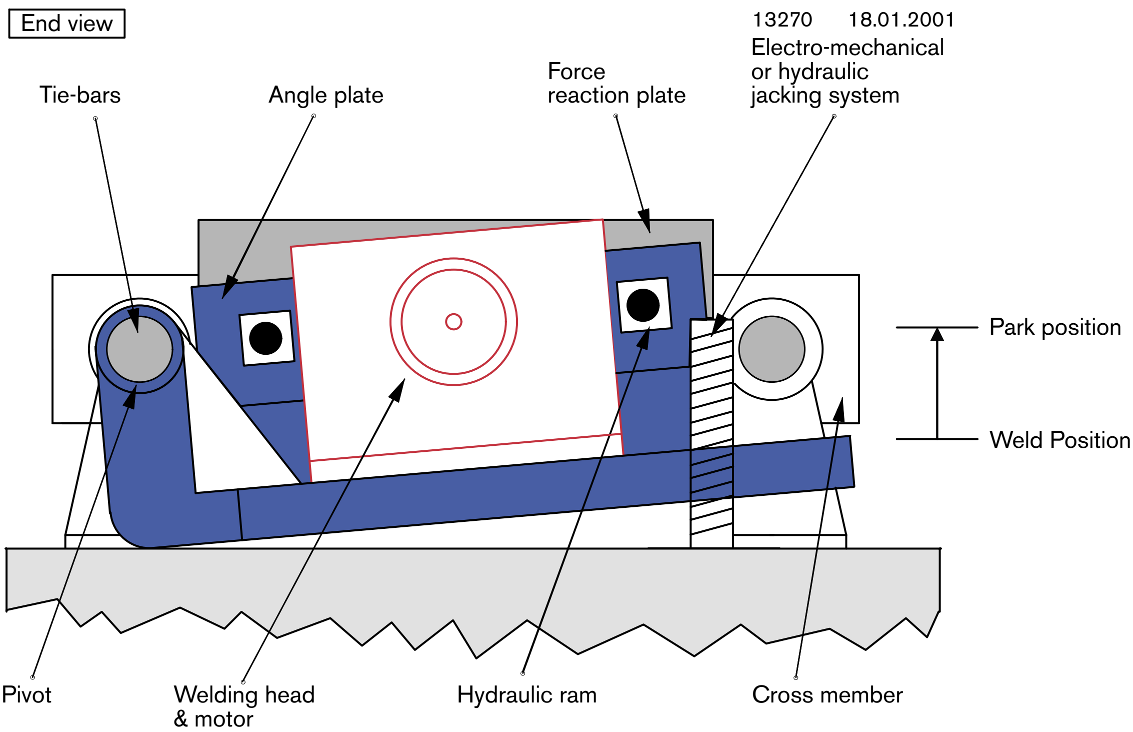


Figure 8-2. *Scheme of a tool probe exit hole parking system.*

The results of a series of FSW tool probe parking trials revealed that an angle of 25° between the lid/canister weld interface and the tool probe exit path did not result in a major increase or decrease in the welding temperature. An example of a 25° exit path is shown in Figure 8-3.

It was observed on the tool probe exit path that the advancing side flash was much more pronounced than on the retreating side. The excessive flash production was generated as the welding head was lifted at an angle of 25°, because the tool probe tilt angle of 3° is no longer correctly orientated. The tool tilt angle is set at 3° away from the normal to the canister surface and tilted away from the welding direction. It was not possible to adjust the position of the FSW tool shoulder when the welding head was lifted. A multi-axis spindle would be required to accomplish such an adjustment, to ensure that the FSW tool shoulder was always orientated correctly. However, the cost of a multi-axis welding spindle capable of transmitting a welding force in excess of 100 kN was beyond the FSW project budget available. It was established, by welding trials, that if the welding speed was not excessive, flaw free welds could be produced without the need for a multi-axis welding spindle. An example of a transverse metallurgical section cut through an exit path is shown in Figure 8-4 in which the location of a small flaw is identified. However, it was significant that the fit up distance between the canister wall and the lid simulation in this case was 3.3 mm. This distance was approximately six times greater than a normal lid to canister fit up tolerance and the resulting deformation of material on the back face of the weld results in a welding force reduction and consequent generation of flaws.

The tool probe exit hole parking trials demonstrated the operation of a procedure that could provide a satisfactory method of terminating a lid to canister circumferential weld.

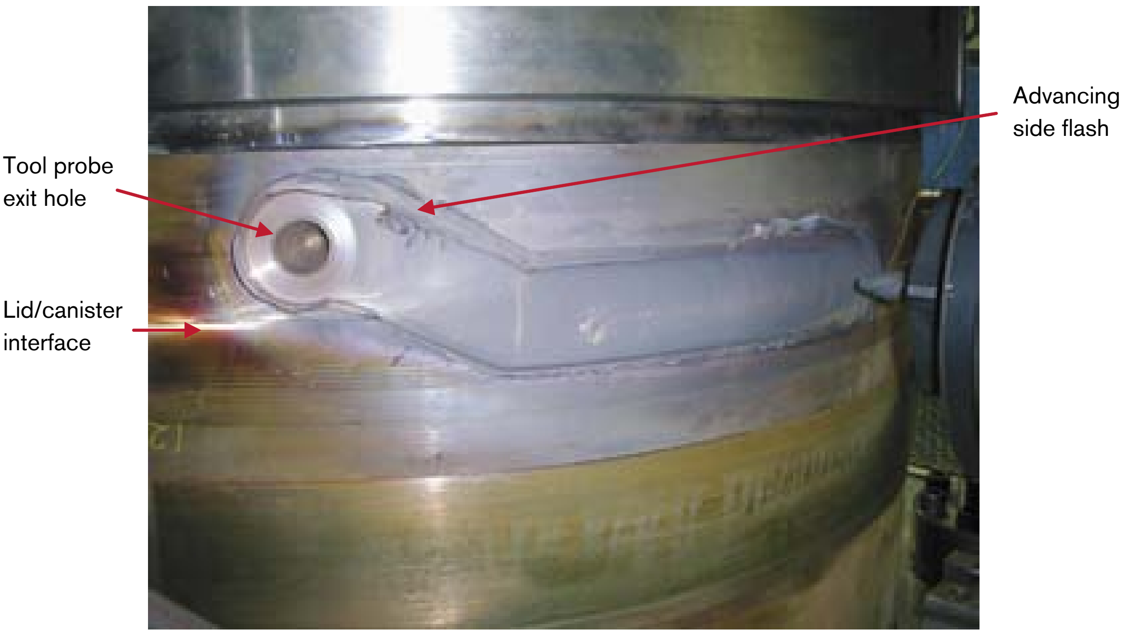


Figure 8-3. *A tool probe exit path at 25° to the lid/canister interface.*

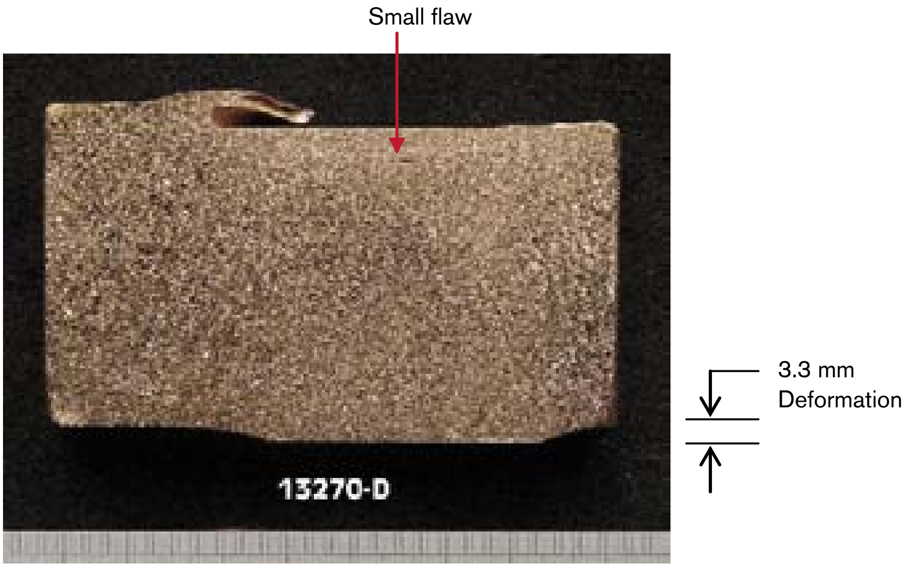


Figure 8-4. *Weld No CW100. Section D.*

9 Weld control methods

9.1 Evaluation of established FSW machine control methods for 50 mm thick copper

The TWI FSW canister welding machine was designed and built to be an experimental test bed to enable the exploration of the major machine component parts required for making full circumferential lid/base to canister welds. Initially, this machine was conceived to be operated manually, to identify the base line welding parameters for producing 3.3 m long welds in 50 mm thick copper. However, once FSW tools and weld parameters had been developed that produced this type of weld, a major priority was to address reproducibility. The work programme at TWI was always focussed on the viability of making the FSW process developed in the laboratory, transferable to production welding. This approach required the identification of the simplest technique for automatically controlling the weld parameters whilst maintaining excellent weld integrity and reproducibility.

As has been described in Section 6 the FSW procedure breaks down into three stages as follows:

Stage 1: Weld start sequence

The rotating FSW tool is plunged into a pre-drilled pilot hole in order to pre-heat the surrounding copper to the required temperature. When this pre-heat temperature is attained, the welding head or canister starts to move at a low rotation (welding) speed (5–10 mm/min). As the welding temperature increases, the welding speed is progressively ramped up to the steady state value of 80–100 mm/min. The welding force is held at a constant level.

Stage 2: Steady state welding procedure

The welding z force and welding temperature are held at a constant value. Methods investigated for maintaining the temperature at a constant value included the following:

- Manual adjustment of the welding speed. A reduction in welding speed allowed the welding temperature to increase, and increased welding speed caused a temperature reduction.
- Manual adjustment of the welding z force increased or decreased the rotating spindle torque and hence the welding temperature.

Stage 3: Weld completion and parking of the tool exit hole

Welding continues beyond the start weld location to the 380°–400° position, and then the welding head is raised at least 50 mm away from the weld interface, and the FSW tool probe is withdrawn to complete the weld cycle.

These three stages were controlled manually until good weld quality was achieved and then the work programme was aimed at developing a robust, simple, automatic weld process control system for the eventual production application. The two most popular methods of controlling FSW machines at the time were Positional Control and Force Control.

9.1.1 Positional control

The Positional Control method involves the maintenance of a set shoulder plunge depth below the surface of the components being friction stir welded. This plunge distance is offset from a constant zero position. When welding flat plates, the zero position is the surface of the base plate they are clamped to. Plunge depth is maintained by reduction or increase of the z welding force.

Efforts were made to make this type of operating system compatible with canisters, however, the axis alignment and canister dimensional variations however small, badly affected this method of process control. The required plunge depth setting had to precisely follow the variable position of the canister wall (or zero reference point). This approach did not prove possible to implement within this project.

The practical canister wall positional variability of 0–3 mm made it virtually impossible to maintain a shoulder plunge depth of ~0.5 mm. It was suggested that a system may work with two position transducers known as LVDT's, where one LDVT is used to establish the canister wall profile and the second LVDT is used to maintain a set plunge depth relative to the first one. The positioning of two sensitive transducers in contact with the hot canister wall, only 100 mm away from the weld zone at ~850°C, led to concerns about thermal damage. The transducers were also very prone to accidental mechanical damage. This method was not pursued.

9.1.2 Force control

Constant application of the welding force throughout the weld cycle is the main feature of Force Control welds made on the experimental canister machine. To maintain the shoulder plunge depth at a constant value the welding speed was varied. An example of this type of weld is shown in Figure 9-1. Radiography revealed that sub surface voids were present at the positions indicated by dotted lines. Of particular importance, the weld record shows that at the location of the flaws the tool probe temperature has begun to drop. Although, remedial action was taken, by reducing the welding speed by 10 mm/min. the response to the speed change was very slow, taking ~45 seconds for the temperature to raise again. The type of flaw associated with the welding speed changes is shown in the transverse metallurgical section. Where welds were produced with no changes to the welding speed, no flaws were detected. It was observed that the welding speed changes increased or reduced the torque, which in turn directly influenced the welding temperature.

This study showed that, when welding thick section copper, all welding condition changes affected process stability and generated flaws.

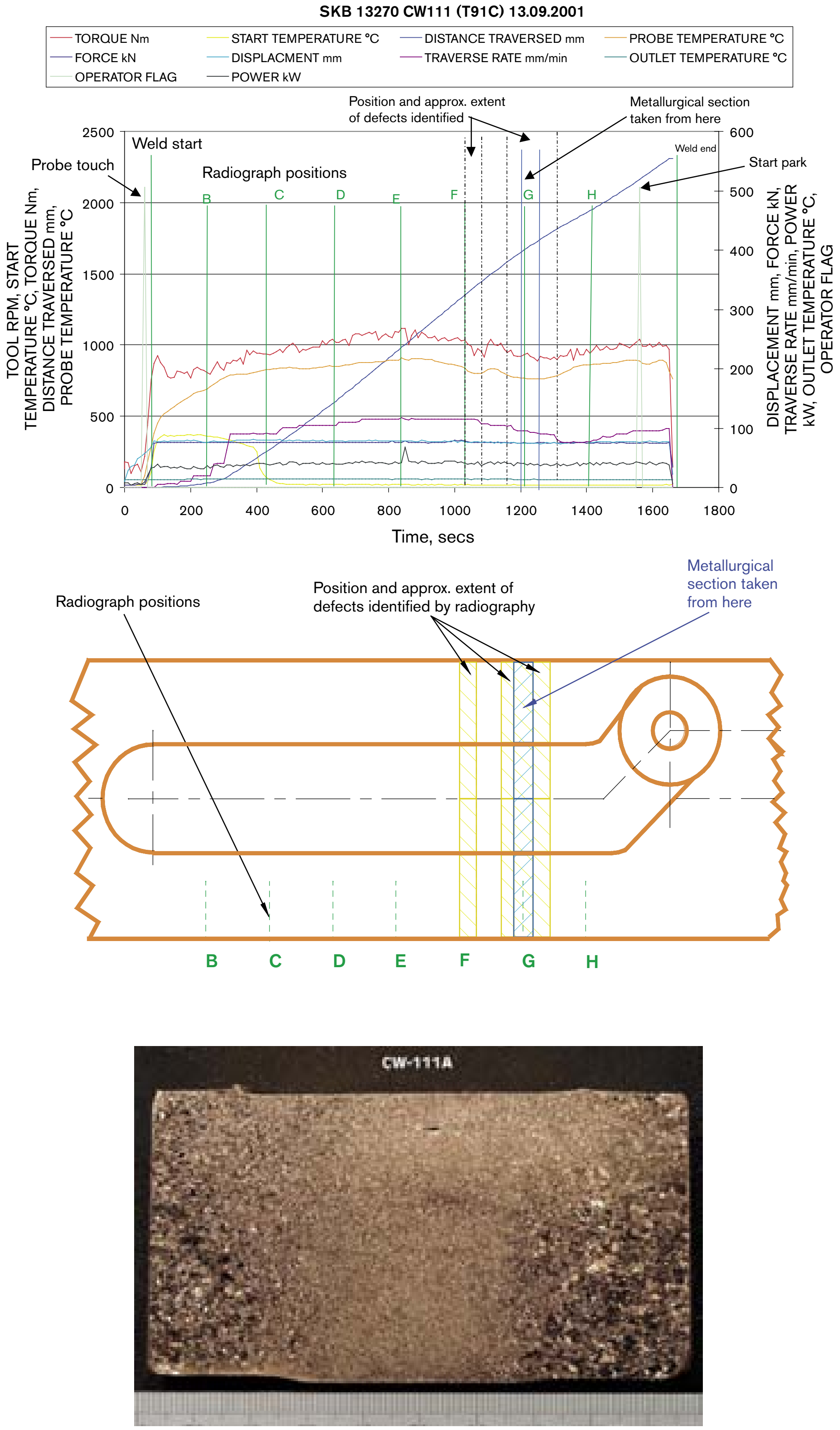


Figure 9-1. Effect of changing the welding speed.

9.2 Procedures and weld condition indicators needed for reproducible weld production

9.2.1 Fit up between the lid simulation and the canister segments

Canister segment samples that were used for welding trials were not all completely round, which may have resulted from damage during transportation, sawing or machining. Additionally, the wall thickness of the various canisters used was not constant and thus the inside diameter of the segments did not closely match the diameter of the lid simulation.

The segments were cut from positions all along the length of a canister, and apart from either end, the machined (or turned finish) was very coarse. In fact, in the worst case, there was a difference of ~1.0 mm between the height crests and troughs of the rough turned thread form. Invariably it was not possible to machine this rough feature to a finer finish, because to do so would result in the ring inside diameter increasing by yet another ~1.0 mm and causing an even greater gap between lid simulation and ring.

An example of how fit up can affect weld integrity is shown in Figure 9-2.

The dimensional variability of canisters supplied for the TWI FSW work programme masked the effect of weld parameter changes and greatly hindered the production of reproducible weld quality.

As shown in Figure 9-2, poor fit up caused excessive penetration of the FSW tool shoulder into the weld interface. This, in turn, created excessive flash, which rubbed on the sides of the shoulder causing excessive shoulder and weld zone heating. Continuous overheating greatly affected the stability of the FSW process.

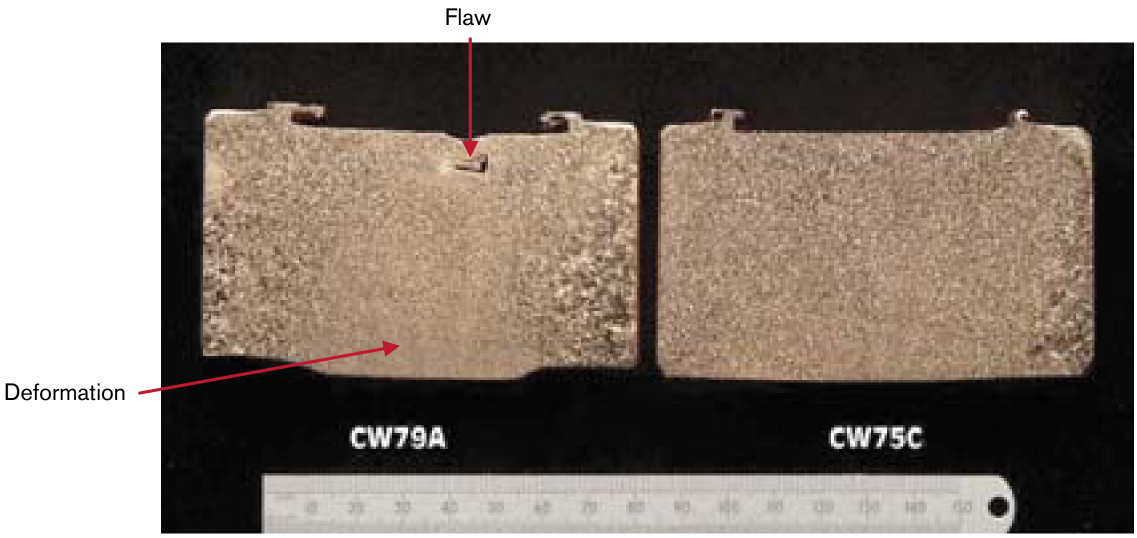


Figure 9-2. *A comparison of Weld No CW79 (poor fit up and a large flaw) and CW75 (good fit up and no flaw) showing that fit up affects the weld integrity.*

9.2.2 Real time weld temperature measurement

The method used to measure and record the temperature at the core of an FSW tool probe was described in Section 6.2.3. This information has proved to be invaluable for improving the understanding of weld formation and FSW tool probe performance. However, having the ability to monitor the temperature of the FSW tool probe in real time provided even greater opportunities, such as being able to control the welding process via a feedback control loop.

The use of an FSW tool probe temperature measuring system proved to be essential for the production of complete circumferential welds as it enabled the temperature of tool probes to be held at a reasonably constant value. As a result no hot shearing of tool probes was experienced using this system. An additional reason why a tool probe temperature control system was needed for FSW of 50 mm thick canisters was that it helped to achieve reproducible weld quality combined with a known grain size.

When using the Positional and Force Control methods there was no weld condition indicator that could be measured.

9.3 Automatic start weld procedure

It was recognised that when manually operating the weld start procedure, the heat input was greatly influenced by inconsistently adjusted weld parameter settings. Achievement of a steady state welding temperature of ~860°C that could be constantly maintained, relied on the weld start procedure being executed in a reproducible manner.

An automatic weld start system was devised which used a pressure transducer that sensed when the set welding z force had been attained. The automatic system initiated a series of hold times and progressively increasing welding speed up to the steady state welding speed. These welding speed changes and hold periods permitted the weld temperature profile to develop at the preferred rate to the steady state value, however, due to time restrictions this system was not fully explored.

9.4 Thermal management method of FSW process control

Evaluation of established FSW process control methods as described in Section 9.1 demonstrated that variation of the major FSW weld parameters led to process instability resulting in the generation of flaws. This indicated that weld parameters should be held at a constant value during a circumferential weld not only for weld process stability but also to provide a simple production welding method.

However, one of the undesirable consequences of set welding conditions was an increase in FSW tool probe temperature to a maximum value, which would exceed the melting point of copper. However, it proved possible to control this monitored value accurately using a purpose built thermal management system, which controlled the heat input to the FSW tool by a water-cooling system. Using a PC based closed loop control system operated on the basis of the signal from the thermocouple located at the axis of the probe, the welding temperature could be accurately maintained.

Advantages of this control system for production welding were that set welding conditions simplified the operating procedure, and the FSW tool probe was not exposed to excessive temperatures. Also of importance for 50 mm thick copper, the temperature and hence the grain size could be closely controlled, which will help to maintain the creep properties of a copper canister in service. In order that SKB could continue to use this system, a patent application was filed in 2001.

The thermal management package consisted of the water-cooled welding head described in Section 6.2.2, which was connected to a water chiller system, which could be set to temperatures as low as 8°C. The potential of this system was first recognised when manual adjustment of the cooling water rate to the welding head was shown to dramatically influence the temperature of the FSW probe when welding as measured by the thermocouple located at the probe axis.

Initially, with all the weld parameters kept at a constant value apart from the welding speed changes up to the steady state value, the welding temperature was maintained within a narrow range by progressively increasing the cooling water flow to the welding head. This procedure controlled the heat input into the weld zone by removal of excess heat into the cooling water. Once the steady state value had been achieved, only small adjustments were necessary.

A further refinement of this FSW tool cooling or thermal management technique involved replacement of the manually operated flow control valve with an electronically operated flow valve. This valve could be opened or closed depending on the temperature of the FSW tool probe in a feedback control loop. An upper and lower steady state welding temperature was selected and water flow was increased to prevent the temperature exceeding the upper limit and decreased to prevent it going below the lower limit.

This Low Flow Valve in conjunction with an electronic flow meter (0–20l/min) was fitted into the water-cooling circuit, which was connected to a chiller unit and pump. The valve is shown in Figure 9-3.

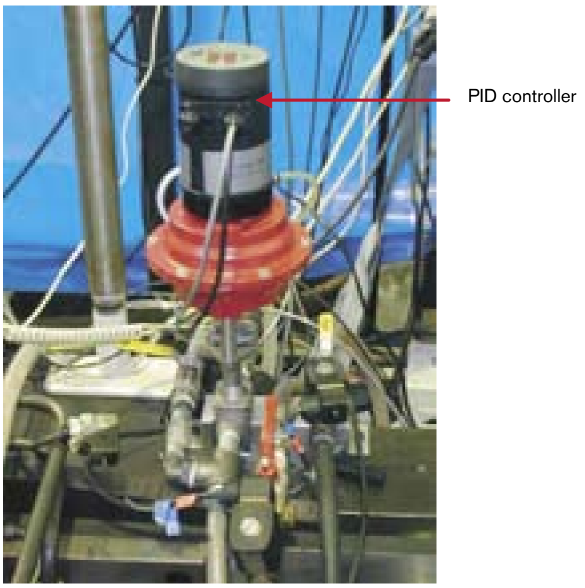


Figure 9-3. *The Low Flow Valve with an integrated positioner.*

A PID controller was mounted on top of the Low Flow Valve. PID stands for Proportional, Integral, Derivative and this type of controller was designed to eliminate the need for constant operator input. An example of commercial application is a thermostat, where the controller is used to adjust the variable (temperature) within a certain range and hold it. During the very limited period (2 months) in which this device was used at TWI, it was operated only in the Proportional mode.

However, the final results of this work programme were very rewarding, because the Low Flow Valve proved to be capable of automatically controlling the weld temperature within the required range. A good example of this control method in operation with a real canister lid which had a good fit-up with the canister section was Weld No. CW189. The weld record for CW189 is shown in Figure 9-4 (next page) and a temperature of between 865–885°C was maintained.

This method of controlling welding by thermal management could be used in production and avoid process instability caused by welding parameter changes. Figure 9-5 shows Weld No CW189 being made.

This system of controlling FSW welding machines is covered by SKB/TWI patent application No. 0103533-6 which was made public in April 2004. The purpose of this application is to protect SKB in the pursuance of this technology. There could have been other FSW research projects of which SKB/TWI have no knowledge that addressed the same subject. The application will help SKB avoid having to pay a licence fee to other organisations working in the same technology. This patent, now in the public domain, will probably be dropped.

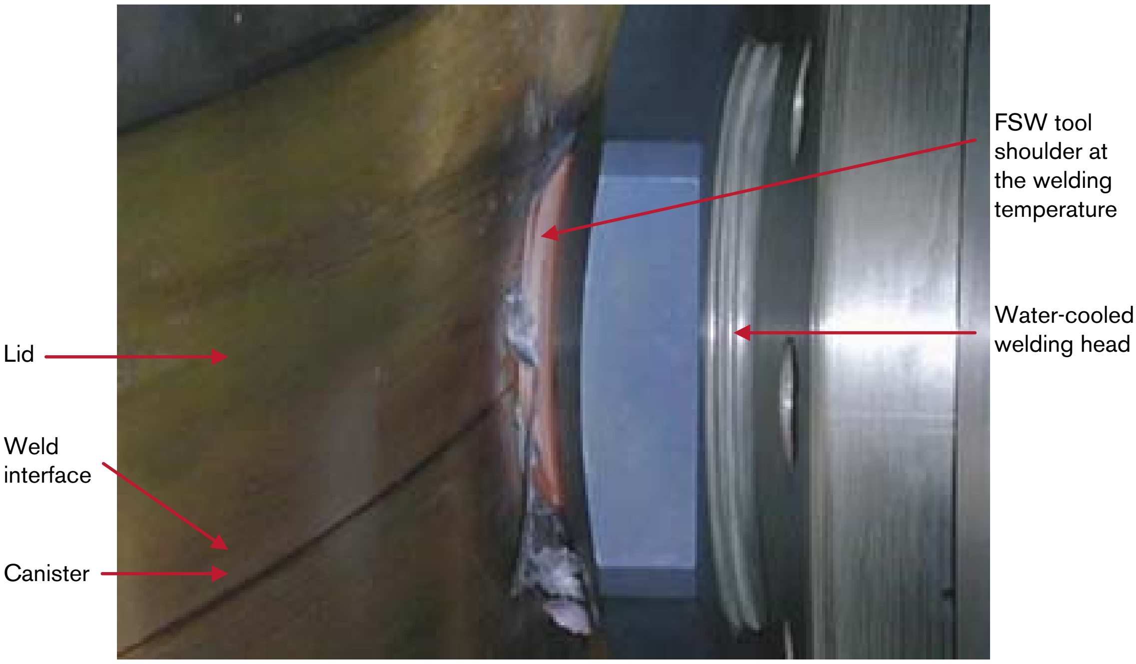


Figure 9-5. *Weld No. CW189 being made in the steady state condition.*

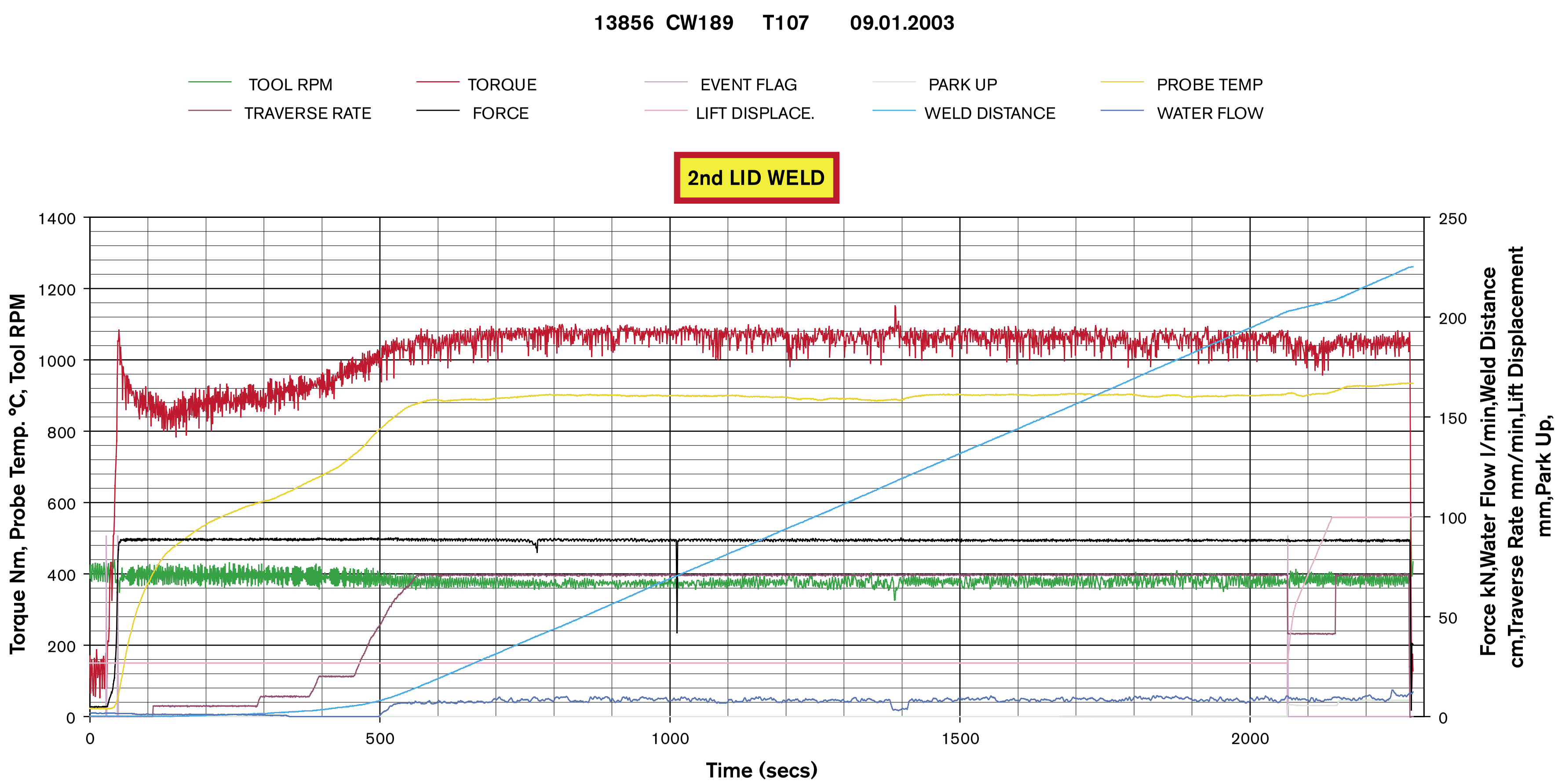


Figure 9-4. *A real lid to canister weld, in which all the weld parameters are held constant when in the steady state welding stage. Weld temperature is controlled by the Low Flow Valve and PID controller.*

10 Evaluation of weld integrity and flaw analysis

10.1 Weld integrity evaluation

10.1.1 Metallurgical sections

Metallurgical examination of transverse and longitudinal sections cut through the start, middle and end of a weld was the major method of assessing weld integrity in the TWI work programme. The reason for using this method was simply because the TWI radiographic facility could not fully penetrate a 50 mm thick lid to canister weld. In addition, ultrasonic testing methods were not sufficiently advanced at TWI for FSW and the lid to canister configuration. However, advanced non-destructive testing facilities were available at the SKB Canister Laboratory at Oskarshamn, with on going process development projects being undertaken by CSM Materialteknik. Thus any non-destructive testing was carried out in Sweden.

Many examples of metallurgical sections have been included in the preceding text, and were used particularly to illustrate the influence of weld parameter changes, tool probe geometry changes, FSW machine operation or fit up dimensional tolerance on the weld integrity. For quick reference to these metallurgical sections they are listed in the following table:

Table 10-1. The location of metallurgical section in the text.

Section	Fig.	Flaw/Reason
4.2.2	4-10	Triangular flaw/Insufficient clamping force
4.2.2	4-11	No flaw/Increased clamping force
4.2.2	4-12	No flaw/Increased clamping force
6.2.7	6-19	No flaw/Full penetration weld
6.2.8	6-23	No flaw/Rebated weld interface
7.1.4	7-4	Triangular flaw/Tool probe geometry
7.2.2	7-9	Tool probe fracture/Probe material
8.2	8-4	Small flaw/Incorrect shoulder orientation
9.1.2	9-1	Small flaw/Welding speed change
9.2.1	9-2	Flaw/Poor fit up tolerance

Flaws that have not been previously described are surface breaking voids at the start of a weld and were usually associated with a low z welding force and thus insufficient heat input into the weld zone, which did not permit solid state weld formation to occur. Examples of this type of void are shown in Figure 10-1 and Figure 10-2.

When producing full penetration welds using steady state welding conditions, it was assumed that good process stability existed, but very small sub-surface voids were identified in the transverse metallurgical section shown in Figure 10-3. These voids were attributed to the relatively large fit-up gap between the canister ring segments and the lid simulation.

Figure 10-1. A surface breaking void at the start of the weld (CW160).

Figure 10-2. An extreme example of a surface breaking void (CW157).

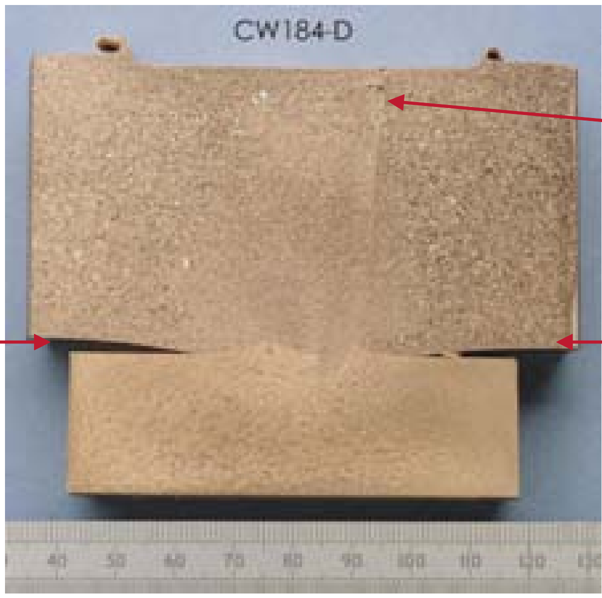


Figure 10-3. Typical sub-surface void size associated with large fit up gap.

Very small flaws were always present directly at the start of a weld as shown in Figure 10-4. The presence of the voids was not associated with incorrect weld parameters or tool probes, but more simply because the weld temperature at this start location is always very low and the copper not sufficiently softened to be fully forged by the rotating FSW tool probe. Fortunately this region at the 0°/360° position on the weld interface will be welded twice and these voids eradicated.

Finally, when full penetration and real lid to canister welds were being made, a new flaw type was revealed at the interface between the inside diameter of the canister and the side of the lid. This unwelded interface was diverted through ~90° by the rotating motion of the FSW tool probe. This flaw type, always occurred at the location where the tool probe penetrates into the lid. In fact it is comparable to the weld interface diversion previously observed when producing lap welds between two aluminium alloy plates by FSW. Two examples of this type of flaw are shown in Figure 10-5, where a lid simulation has been used with two canister rings. This set up permits two interfaces between the lid and rings on either side of the FSW tool probe, which would not be seen in the real lid/canister weld.

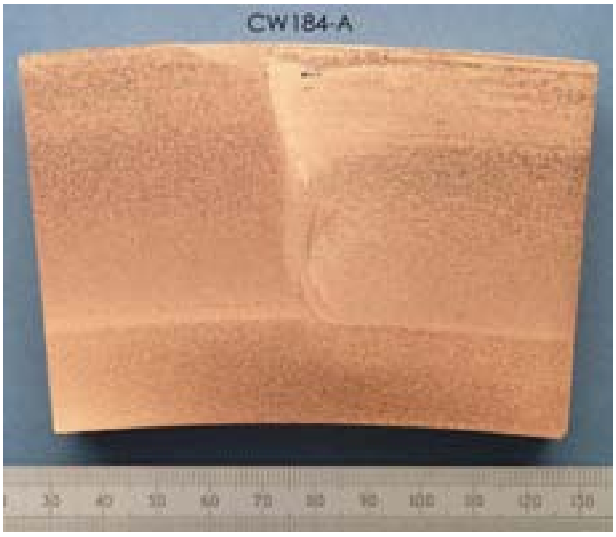


Figure 10-4. *A longitudinal section through the start region of Weld No CW184.*

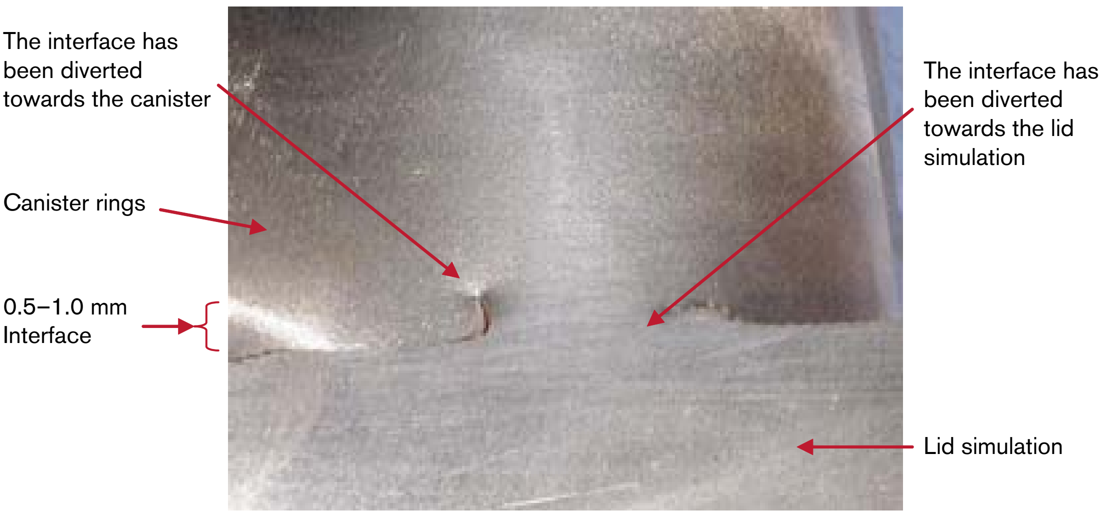


Figure 10-5. *Weld interface deformation.*

The interface can be diverted into the canister wall, or into the lid depending on the direction of welding. It was concluded that as this phenomenon is not part of the weld, but in fact a deformed region of the interface between the lid and canister, it could be tolerated.

10.2 Bend and tensile tests

The major method of weld integrity assessment used was metallurgical examination as described in Section 10.1, because tensile tests were insensitive to the presence of voids of less than 0.5 mm in diameter, the only information produced by a tensile test carried out on thick section copper welds was that the weld zone was stronger than the parent metal. For failure to occur in the weld zone, large continuous voids or weld interface non-bonded regions would need to be present. Few tensile tests were carried out because the results were predictable.

Bend testing was found to be a much more sensitive method of detecting weld zone flaws by simply bending the sample around a 4t former (where t = the thickness of the sample) until opening of a flaw was detected. The angle at which the flaw occurred was recorded. Bend tests were carried out on welds in which void formation had been detected by metallurgical examination. Bend test results are shown for a full penetration weld, Weld No CW38 (Figure 10-6) demonstrating that a 180° bend test could be achieved.

When testing the full penetration weld set up it was not quite representative of a real lid to canister weld, because there was a continuous interface between the canister wall segment samples and the split copper hoop representing the lid. However, the test demonstrated that full penetration welding had been achieved with no obvious weakness in the weld zone as shown in Figure 10-7.

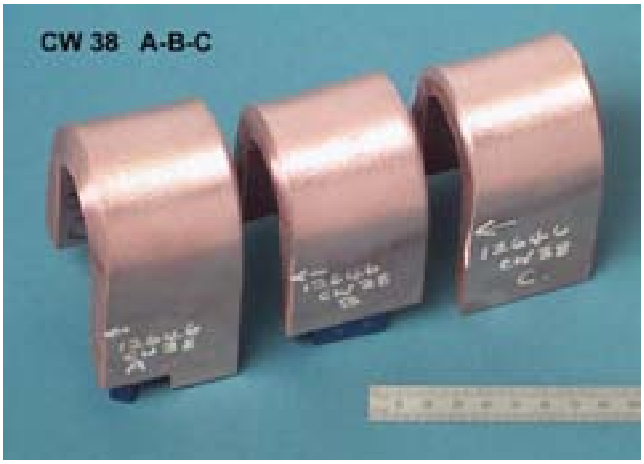


Figure 10-6. *Side bend test sections A, B and C cut from Weld No. CW38.*

Figure 10-7. Weld No.CW160 bent through 130°.

10.3 Detailed metallurgical examination

Detailed metallurgical examination of TWI FSW samples was carried out at TWI and at the Swedish Institute for Materials Research, Stockholm (SIMR reported separately). The TWI study was limited to assessment of grain size variation throughout a weld zone. An example of the cutting plan through a transverse section cut through Weld No. CW32 Section C is shown in Figure 10-8.

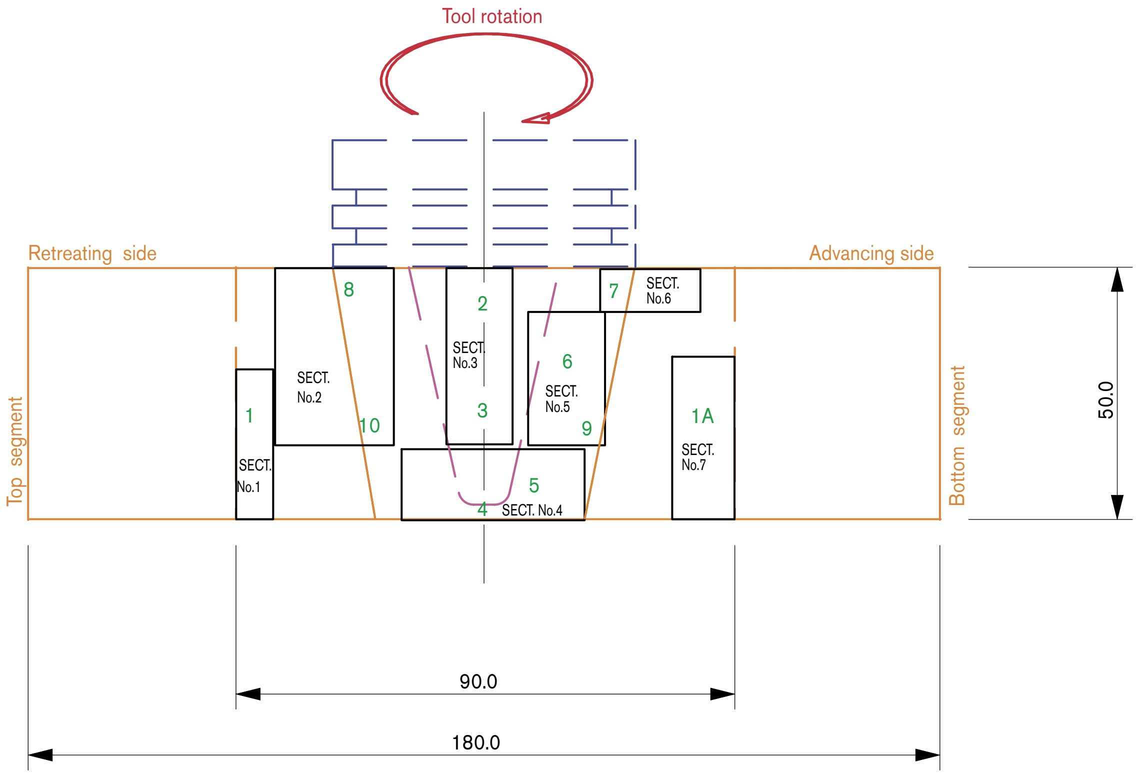


Figure 10-8. Metallurgical section cutting plan through a transverse section cut through Weld No. CW32, Section C.

The grain size of the region at the greatest distance from the influence of the tool probe and shoulder, Section No.1, Area 1, shown in Figure 10-9, varied between 0.1 mm and 0.3 mm. Two areas in the thermally affected region in Section No.2, Areas 8 and 10, illustrated in Figure 10-9b and c respectively, experienced some grain growth with an increased size of between 0.4 mm and 0.6 mm.

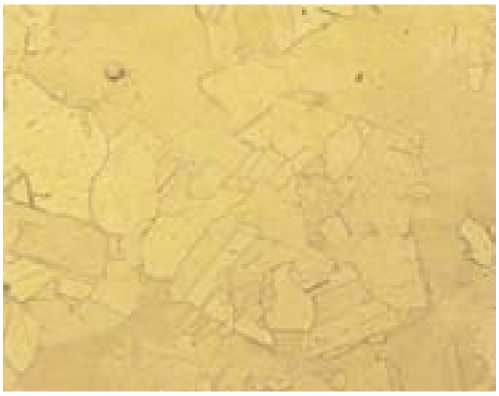
Section No.3, Area 2, shown in Figure 10-10, is very near to the outer surface and the influence of the tool shoulder and also the thermo-mechanical influence of the tool probe. The section had a mixed grain size varying from 0.1 mm to 0.6 mm. Towards the centre of the 50 mm thick section at Area 3, shown in Figure 10-10, the grain size was similar.

However, towards the inside diameter of the section at a point where the least heat is generated, the grain size is considerably smaller, varying between 0.02 mm and 0.3 mm. Areas 4 and 5 from Section 4 are shown in Figure 10-11a and b respectively.

The advancing side of the weld is normally the cooler side of the weld zone and this comment is substantiated if the photomicrographs shown in Figure 10-9b and c are compared with those in Figure 10-12a and b. Areas 6 and 9 from Section No.5 illustrated in Figure 10-12a and b are on the advancing side of the weld with a grain size of between 0.1 mm and 0.4 mm, whereas on the retreating side of the weld the grain size was between 0.4 mm and 0.6 mm (Figure 10-9b and c).

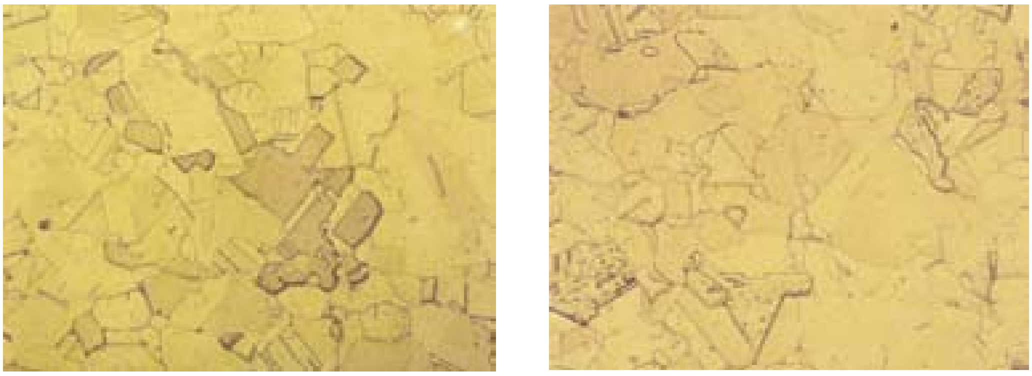
a) Section 1, Area 1

b) Section 2, Area 8



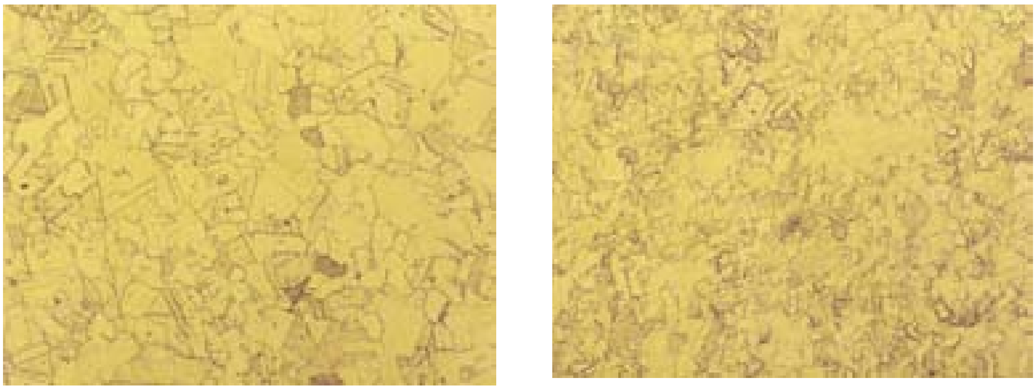
c) Section 2, Area 10

Figure 10-9. *A transverse metallurgical section cut through Weld No. CW32C, Sections 1 and 2 (see Figure 10-8 for location).*



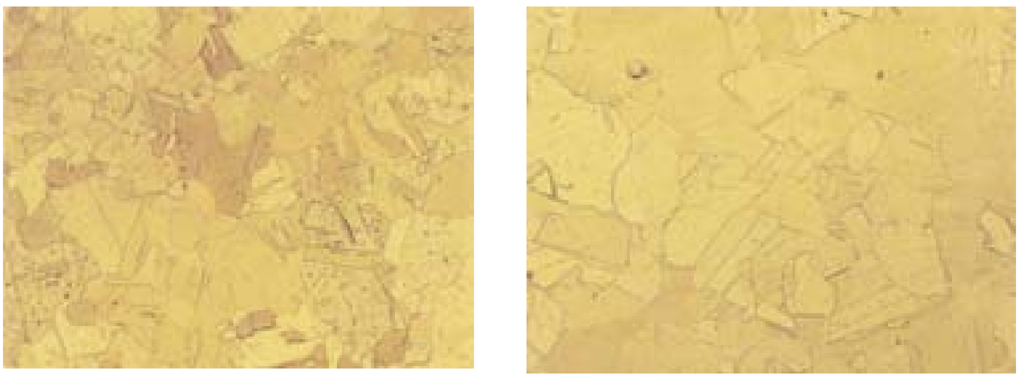
a) Section 3, Area 2 *b) Section 3, Area 3*

Figure 10-10. *A transverse metallurgical section cut through Weld No. CW32C, Section 3 (see Figure 10-8 for location).*



a) Section 4, Area 4 *b) Section 4, Area 4*

Figure 10-11. *A transverse metallurgical section cut through Weld No. CW32C, Section 4 (see Figure 10-8 for location).*



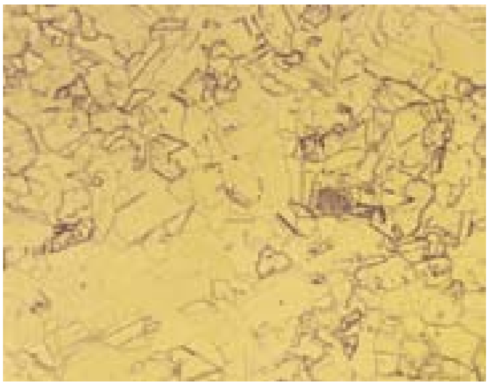
a) Section 5, Area 6 *b) Section 5, Area 9*

Figure 10-12. *A transverse metallurgical section cut through Weld No. CW32C, Section 5 (see Figure 10-8 for location).*

Finally, Section No.6, Area 7 and Section No.7, Area 1A on the advancing side of the weld, shown in Figure 10-13a and b, have very similar grain sizes to those shown in Figure 10-9a, b and c, which are on the retreating side. The grain size at the greatest distance from the weld interface varied from 0.1 mm to 0.3 mm and copper that had been thermally and thermo-mechanically affected varied in grain size from 0.2 mm to 0.6 mm.

Earlier in the development of FSW of copper, small particles that were described as oxide, but were never analysed, were found near the top surface on the advancing side of a weld by SIMR. The location at which this oxide entrapment would be expected to be found in Weld No. CW32C would be Section No.6, Area &, Figure 10-13a. This metallurgical section was examined optically, but there was no evidence of oxide particles.

a) Section 6, Area 7



b) Section 6, Area 1A

Figure 10-13. *A transverse metallurgical section cut through Weld No. CW32C, Sections 6 and 7 (see Figure 10-8 for location).*

11 Development of a specification for an SKB FSW machine for use in the canister laboratory

In 2001 the feasibility of using FSW to weld 50 mm thick copper had been proved without doubt, and good quality complete circumferential simulated and real lid welds had been produced on the TWI built, full size experimental lid to canister FSW machine.

The results of the developmental programme provided SKB with the potential of using an additional and complimentary method for sealing canisters. SKB proposed that a new production size FSW machine should be built to operate in the Canister Laboratory, Oskarshamn, where the FSW process would be assessed for production welding.

TWI and BNFL were asked to support SKB in the procurement of an FSW machine and assessment of the machines performance. The tasks allocated to TWI were as follows:

- Specification of FSW machine requirements.
- Production of machine drawings.
- Production of procurement documentation.

A list of FSW parameters used at TWI and the tolerances permitted as determined by welding trials was included in the Invitation to Tender documentation as the operating specification for a full size FSW machine as shown in Table 11-1.

Table 11-1. List of FSW parameters that are currently used to produce welds on the TWI lid to canister FSW machine.

Sub-section	Title	Ramp Up Time (mins)	Angle	Rate (mm/min)	Force (kN)	Heat to be Dissipated (kW)	Temp (°C)	Torque (Nm)	Rotation Speed (rev/min)	Hole Diameter × Depth (mm)	Clamping force (kN)	Vertical Tolerance (mm)	Comments
2.1.1	Location	–	–	–	–	–	–	–	–	–	–	–	BNFL to advise on positional accuracy
2.1.2	Position of FSW tool probe axis to weld surface	–	–	–	–	–	–	–	–	–	–	± 1 (± 0.75)	–
2.1.3	Canister (radial) clamping force	–	–	–	–	–	–	–	–	–	See comments	–	Sufficient clamping force must be available to resist a vertical downforce of 800 kN ± 10 kN (600 kN ± 10 kN). TWI experimental FSW machine uses 8 × 200 kN hydraulic jacks through taper wedges
2.1.4	Lid clamping system	–	–	–	–	–	–	–	–	–	800 ± 10 (600 ± 10)	–	–
	Pilot hole	–	–	–	–	–	–	–	–	20 ± 0.2 (15 ± 0.2) x52 ± 0.5 (32 ± 0.5)	–	–	Allowance should be made for drills up to 25 mm diameter with standard 120° points
2.3.2	Rotating Spindle	–	–	–	–	–	–	Up to 1500 ± 100	100 – 600 ± 10	–		–	Infinitely variable but controlled at ± 10 rev/min about selected value and sufficient torque to maintain that value
2.3.3	Tool water cooling	–	–	–	–	10 kW	23 ± 10 in to 45 ± 10 out	–	–	–	–	–	–
2.3.4	Axial welding force	–	–	–	Up to 100 ± 1	–	–	–	–	–	–	–	Infinitely variable but capable of being controlled at a set value at ± 1 kN
2.3.4	Welding head	–	–	Up to 100 ± 2	–	–	–	–	–	–	–	–	Infinitely variable 0–100 ± 2 mm/min
2.3.6	Tool tilt angle	–	Up to 5 ± 0.25	–	–	–	–	–	–	–	–	–	Infinitely variable 0.5 ± 0.25°
2.3.7	Force reacting on leading edge of tool	–	Up to 100 ± 1 (80 ± 1)	–	–	–	–	–	–	–	–	–	Repeated application of force
2.3.8	Parking exit hole movement	–	–	Up to 150 ± 2 (150 ± 2)	–	–	–	–	–	–	–	–	–
2.3.9	Canister rotation	Up to 5 ± 2 sec	400 ± 1	Up to 150 ± 2	–	–	–	–	–	–	–	–	Ramp up times has a set dwell period

12 Discussion

SKB has worked in co-operation with TWI from 1997 to 2003 to progressively explore the potential of the Friction Stir Welding (FSW) technique as a method for sealing copper nuclear waste storage canisters. In 1997, FSW was described as an alternative, or complimentary method to the Electron Beam Welding (EBW) process for producing high integrity joints between the lid or base, and the cylindrical canister.

The feasibility of using FSW to join 50 mm thick copper plates as described in the processing sections was demonstrated without doubt in 2000. This project milestone provided sufficient confidence and process information for the manufacture of a full size experimental canister-welding machine at TWI. Rapid development of the FSW technology was essential to satisfy the SKB canister development schedule. However, an option was always available in the event of insurmountable technical difficulties, to terminate the programme and thus limit financial risk to SKB. It did not prove necessary to use this option.

The second major milestone achievement was the production of full size lid to canister welds in 2001–2002. This demonstrated that FSW could be considered as a viable method for the future production sealing of copper canisters. Information generated was translated into an FSW machine operation specification and the design, and manufacture of a purpose built FSW canister machine for operation in SKB's Canister Laboratory followed.

The development of FSW as described in the preceding sections can be condensed into four main interrelated subjects. The first of these was the development of an FSW tool probe geometry that could generate flaw free welds at welding speeds of up to 100 mm/min. This welding speed was essential to limit the total welding cycle time to between 30–40 minutes. Management of the heat generated by longer weld cycle times (2.75 hours was predicted by the results of early work) would have proved very difficult and would have caused degradation of the weld zone mechanical and physical properties.

The second of the main development subjects was the identification and procurement of an FSW tool probe material that could withstand the copper FSW operating temperatures of 860 – 900°C and also the aggressive force regime without failure, during the weld cycle.

This task proved difficult until Nimonic 105 alloy, a superalloy, was used. Provided close control of the welding temperature was maintained throughout a weld cycle, Nimonic 105 alloy tool probes could operate successfully without failure for 40 minutes at 860°C. There is no doubt that, without the development of this tool probe design (a variant of the TWI Triflute probe) manufactured in Nimonic 105 alloy, FSW of copper could not have been possible in the timescale required. To minimise the risk of probe failure in production, materials with higher temperature strength capability still must be identified, procured and tested before work starts in the Encapsulation Plant in the future.

The feasibility of FSW of 50 mm thick copper was demonstrated on a large milling machine. It proved possible to translate the linear welding parameters developed on this machine into the operating specification for the TWI experimental full size FSW for circumferential welding of lids to canisters.

The third main subject of the work was the design and manufacture of the experimental FSW machine to allow the progressive process development required to demonstrate that circumferential welds could be made. This machine proved to be sufficiently stiff and strong to react all the process forces. In addition, the spindle rotation mechanism and all the various force and drive systems were more than adequate for the task. At no time during the FSW development was there a major machine breakdown.

Throughout the development programme, flaws of various shapes and sizes were found to be associated with certain welding procedures and parameters. It became clear that the origin of the flaws was process instability introduced by incorrect manual weld parameter changes. A weld zone FSW probe temperature measuring system provided a very valuable weld condition indicator, which was used to provide the basis of a weld process control system. The fourth main subject covered in the work, was the development of a thermal management system, which enabled the weld temperature to be held at a constant value. An added advantage of this control method was that the tool probe was not exposed to temperatures above 900°C, thus reducing the risk of failure during the weld cycle. Due to its inherent simplicity, this system of process was well suited to production welding.

A successful conclusion to the TWI development was that NDT and metallurgical examination did not reveal any significant flaws in the lid to canister section welds. This result strongly suggests that FSW should be favourably considered as the method selected as the canister sealing method to be used in the production environment in the Encapsulation Plant, as it has been shown to allow good quality, reproducible welds to be produced and to be both simple and robust in operation.

13 Conclusions

The overall conclusion to this FSW development is that there is no doubt that the FSW process could be used to produce full size copper lid to canister sealing welds in a production environment. However, more focussed conclusions directly associated with a series of project objectives are listed below:

- It is feasible to FSW 10 mm thick copper plate.
- It is feasible to FSW 50 mm thick copper plate.
- A fully operational experimental FSW canister welding machine was designed and built.
- Procedures for FSW of lids to canisters were successfully developed.
- Complete circumferential full penetration welds were successfully made on a routine basis.
- Good quality complete circumferential, full penetration lid/base to canister welds could be made on a routine basis, with no FSW tool probe failures, evidence of wear or contamination of the weld zone.

14 Recommendations

The overall recommendation is that the FSW development should be continued at the SKB Canister Laboratory to a stage where it can be used reliably in production. It is also recommended that SKB consider keeping TWI personnel involved in the FSW development programme in a similar manner to the EBW development. A benefit of this continued collaboration would be that relevant TWI FSW developments in FSW tools, materials, process control methods and procedures could be rapidly assimilated into the SKB development programme. TWI now have a large, powerful thick section FSW machine at the TWI Sheffield facility which has the capacity of welding full size copper canisters. The sophisticated operating specification could greatly help in the development of the FSW machine which will eventually be used in the Encapsulation Plant.

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