Friction Stir Welding of Copper Canisters for Nuclear Waste

Licentiate Thesis
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2005

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Friction Stir Welding of Copper Canisters for Nuclear Waste

A dissertation submitted to the Royal Institute of Technology, Stockholm, Sweden, in partial fulfilment of the requirements for the degree of Teknologie Licentiat.

ISBN 91-7283-974-0
ISRN KTH/MSE--05/02--SE+MAT/AVH

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This thesis are available in electronic version at:http://media.lib.kth.se
Printed by Universitetsservice US AB, Stockholm
ABSTRACT

The Swedish model for final disposal of nuclear fuel waste is based on copper canisters as a corrosion barrier with an inner pressure holding insert of cast iron. One of the methods to seal the copper canister is to use the Friction Stir Welding (FSW), a method invented by The Welding Institute (TWI).

This work has been focused on characterisation of the FSW joints, and modelling of the process, both analytically and numerically. The first simulations were based on Rosenthal’s analytical medium plate model. The model is simple to use, but has limitations. Finite element models were developed, initially with a two-dimensional geometry. Due to the requirements of describing both the heat flow and the tool movement, three-dimensional models were developed. These models take into account heat transfer, material flow, and continuum mechanics. The geometries of the models are based on the simulation experiments carried out at TWI and at Swedish Nuclear Fuel Waste and Management Co (SKB). Temperature distribution, material flow and their effects on the thermal expansion were predicted for a full-scale canister and lid. The steady state solutions have been compared with temperature measurements, showing good agreement.

Microstructure and hardness profiles have been investigated by optical microscope, Scanning Electron Microscope (SEM), Electron Back Scatter Diffraction (EBSD) and Rockwell hardness measurements. EBSD visualisation has been used to determine the grain size distribution and the appearance of twins and misorientation within grains. The orientation maps show a fine uniform equiaxed grain structure. The root of the weld exhibits the smallest grains and many annealing twins. This may be due to deformation after recrystallisation. The appearance of the nugget and the grain size depends on the position of the weld. A large difference can be seen both in hardness and grain size between the start of the weld and when the steady state is reached.

Keywords: Friction Stir Welding (FSW), Copper, Welding, Finite Element Method (FEM), SKB
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Paper A
Microstructure development in copper welded by the FSW-process
T. Källgren, R Sandström

Paper B
Microstructure and temperature development in copper welded by the FSW-process
T. Källgren, R Sandström
4th International Symposium on FSW, Park City, USA, April, 2003.

Paper C
Finite Element Modeling of Temperature Distribution in Friction Stir Welding Process and Its Influence on Distortion of Copper Canisters
T. Källgren, L.-Z. Jin, R Sandström

Paper D
Finite Element Modelling of Friction Stir Welding on Copper Canister
T. Källgren, L.-Z. Jin, R Sandström
ACKNOWLEDGEMENTS

First of all I would like to thank my supervisor Prof. Rolf Sandström for giving me the opportunity to work in his group. Moreover I am indebted to his valuable help and guidance. I would like to thank Dr. Lai-Zei Jing for his help and inspiring discussions especially concerning the modelling part of my research.

This project is financially supported by the Swedish Nuclear Fuel Waste and Management Co (SKB) and the Brinell centre at KTH. The members of the project committee L. Cederqvist, C.-G. Andersson, L. Werme are gratefully acknowledged.

Lena Ryde at SIMR is thanked for help with EBSD measurements and for discussions, R. E. Andrews at The Welding Institute (TWI) for his kind help. Hans Bergquist and Wen-Li Long at MSE for technical support, P-O Söderholm for all help with equipment and always a happy smile.

Thanks to all my colleagues and friends at MSE. My former room mate Henrik for intense discussions. Dennis for all the lunches and help with computers and language problems. Anna for motivating me in various fields. Thanks to Henrik at SIMR for discussions about the project and many other things.

Finally I would like to thank my family, friends, horses, horse people and most of all Ägir. To Julius…
INTRODUCTION

1.1 The Swedish programme for nuclear waste
As late as 1974, no less than 24 Swedish reactors were scheduled at Brodalen, Ringhals, Barsebäck, Oskarshamn, Södermanland, and at Forsmark [1]. At this time the waste problem was still "non-existent", but soon it became a political issue, and 1977 legislation was passed to ensure proper waste management [2]. According to the Swedish law, all of the expenses for the handling and the final disposal of nuclear waste must be paid for by those who use nuclear power. The financing system created to cover the costs of nuclear waste is based on the payment to the state by the reactor licensees of a fee per kilowatt hour of electricity produced. The fee is included in the electricity price paid by the consumer. The Swedish Nuclear Fuel and Waste Management Company (SKB) were set up by the nuclear utilities following the waste legislation to develop a comprehensive concept for disposal of spent fuel and other radioactive wastes. It is owned by Vattenfall, Forsmark, OKG and Barseback [3].

1.1.1 Spent nuclear fuel in Sweden
In 1976 the nuclear fuel safety project (KBS early SKB) was organized in order to fulfil the new Swedish law about handling spent nuclear fuel. In 1977 the first KBS report was written [2], which was a first attempt for a safe disposal. In these early days it was not yet decided if the spent nuclear fuel would be reprocessed or not. The proposed suggestion for final deposition was storage of the spent fuel in canisters made by titanium and the waste would be surrounded by lead. The canisters were planned to be put deep in the bedrock and there would be no leakage of radioactivity because of the absence of fractures in the rock. The risk of bedrock deformations and earthquakes was considered non-existent. But this is not the case in the modern geodynamic view of the continental drift theory, which had not yet been fully accepted in Sweden at that time.

In 1978 the next KBS report came [4]. The proposal was based on the fuel rods encapsulated in containers of pure copper with a wall thickness of 20 cm. The space between the rods was planned to be filled with lead and then sealed by electron beam welding. Another considered canister type was made of ceramic materials. The method
was proposed by ABB. In this canister the spent fuel would be enclosed by hot isostatic compaction of aluminium oxide powder at 1350°C and 100 MPa in a so-called Quintus press. Aluminium oxide occurs as a mineral in nature as corundum and sapphire. This mineral possesses a very high stability over long periods of time. The canister was planned to be fabricated in two parts, container and lid and enclosed by a thin metal casing and joined together by additional hot isostatic pressing [4]. The final repository had the same character as the present one, 500 metres down in the bedrock surrounded by bentonite. Bentonite is clay which swells when it absorbs water. The material has been chosen in view of its good mechanically stability, very low water permeability and long term stability. Bentonite will surround the canister and when it absorbs water it will start to swell and form homogenous clay and the only transport through this dense material is by diffusion, which takes place at a low rate.

In 1983 the KBS-3 report [5] proposed two alternative encapsulation procedures: a copper canister filled with lead and sealed with electron beam welding and another copper canister filled with copper powder and sealed by hot isostatic pressing. In this report, the final repository proposal was very much like the one today.

Over the years alternative methods to KBS-3 for disposal of spent nuclear fuel have been investigated [6].

1.1.2 The present Swedish programme for spent nuclear fuel

Sweden does not intend to reprocess spent fuel; instead a direct deep geologic disposal is planned. Today spent nuclear fuel has an initial one-year cool down period at the nuclear power facility, all spent fuel is then shipped by sea to the Central Interim Storage Facility for Spent Nuclear Fuel, or CLAB, located in Oskarshamn in southern Sweden since 1985. During the first 30-40 years at CLAB, spent nuclear fuel cools in water in an underground rock cavern [7]. According to the KBS-3 concept, the spent fuel will be inserted in an inner pressure resistant component made by nodular cast iron. The insert will be put into copper canisters with a lid and possibly a bottom sealed by Friction Stir Welding (FSW) or Electron Beam Welding (EBW). The candidate canister has a diameter of 1050 mm, a length of 4850 mm, and a wall thickness of 50 mm, see the section canister manufacturing. The copper canisters will be transported to a deep repository around 500 m in the granite bedrock. The canisters will be embedded in bentonite, which will swell and encase the canisters after groundwater fills the space between the rock and the clay, see Figure 1. The copper canister is designed to be a corrosion barrier which should stay intact for at least 100,000 years.
Site selection procedures are well advanced, and two sites have now voted to be candidate locations for a deep geological repository - Öskarshamn and Östhammar. Both these had been selected as having potentially suitable bedrock characteristics. They will now undergo more detailed site investigation, which will be followed by site characterisation at one of them.

SKB plans to submit an application for construction of a canister plant in 2006. According to these plans, a repository should be operational in 2015.

1.2 Other countries proposals for final disposal of nuclear fuel waste and international efforts

World-wide there are over 30 countries that generate electricity by using nuclear power. Totally there are between 400 and 500 reactors currently in operation. The waste from these plants and handling of it is an important environmental issue in these countries. The way the waste is handled depends on the type of waste and the local conditions. The difference between the geological conditions and the type of waste and also the laws in various countries give a large difference in storage systems, but all are land-based and all final storage systems are passive, i.e. the safety and the protection against radiation must not require any monitoring. Today there are no countries that have a complete system for final storage of spent nuclear fuel. During time for decision regarding final disposal, the waste is stored in intermediate storage, either in water or air-cooled storage systems.

**Germany:** The spent nuclear fuel is reprocessed in UK and France. Final disposal was planned to take place in salt formations, but is now open to debate.

**Belgium:** Final disposal in deep clay layers.

**Switzerland:** Looking at crystalline bedrock on clay for final disposal.

**USA:** Volcanic type of rock in Nevada for storage of spent nuclear fuel.

**Canada:** Is planning similar type as Sweden, based on copper canisters in granitic rock surrounded by bentonite clay.

**Finland:** The same principal as in Sweden, but they have already decided location of the site.
France: The spent nuclear fuel is reprocessed and the residues are vitrified and packaged in steel canister, which are stored in air-cooled chambers. Three alternatives are being examined for further management and disposal.

Japan: Spent nuclear fuel is currently reprocessed in UK and France, but a major reprocessing plant is being built in the country. The final disposal will be built in geological formations at a depth of 300 metres.

1.3 Canister manufacturing
The proposed canister according to the KBS-3 concept has a diameter of 1050 mm and a length of 4850 mm. The outer shell consists of 50 mm thick copper, and inside is an insert of nodular iron to provide sufficiently high mechanical strength, see Figure 2. The total weight is between 25 and 27 tonnes for the canister and the insert filled with fuel.

So far SKB have tested four different methods for fabricating the copper canisters: roll forming of tube halves, extrusion, pierce and draw processing as well as forging. All fabrication methods have proven to be feasible. But the last three have the advantage that the finished tube has no seams [7]. In roll forming, thick copper plates are rolled so that their cross-section forms a semi-circle. Two halves are then joined together by means of longitudinal welds to a copper tube. In the fabrication trials conducted by SKB, this welding has been done by means of electron beam welding. When using the extrusion method the starting material is a solid cylindrical copper ingot, which is heated to around 700°C and placed in a press where it is compressed to a shorter length and a larger diameter. A hole is then made in the centre with a mandrel. The cylinder is placed in an extrusion press and extruded in one step to its final size. This is a forming method with few production steps but requires high pressure force. This leads to seamless tubes with fine grain size. The tubes cool slowly, which means they do not have to be stress-relief annealed. The remaining residual stresses will not be enough to cause any distortion. To fabricate canister tubes by means of pierce and draw processing, a solid cylindrical copper ingot is used. This process expands the inside diameter of the hole, at the same time as the outside diameter is reduced and the tube is elongated. The tube must be reheated between the drawing steps. This is a process that uses many production steps but requires only moderate press forces, and leads to seamless tubes that do not need any stress-relief by annealing. In contrast to extrusion an integral bottom can be made, which means that only a lid needs to be welded to the canister.

Figure 2 Copper canister as corrosion barrier with an inner pressure resistant component made of nodular iron.
The lids and bottoms are machined from cylindrical copper ingots that have been hot forged. The ingots are then pressed in several steps to a short round cylinder. The final forming take place in a special forging die, see Figure 3.

Welding of copper material is difficult by the conventional joining methods due to the high thermal diffusivity. The required heat input must be high and the welding speed low. SKB canister laboratory in Oskarshamn works on two different welding methods to seal the copper canister, electron beam welding (EBW) and Friction Stir Welding (FSW). In the EBW technique the exceptional energy density makes this joining method one of few that can join thick sections of copper. The process variant chosen for this application is a reduced pressure (RP) EBW. After extensive development this technique can produce deep penetrations welds which are virtually free of root defects. This technique works by melting the parts together by a strong electron beam. This is so effective that it can cut through 30 cm steel in five seconds. This technique is conventional and used on a variety of industrial products. The FSW technique uses friction heat to generate a joint. The tool used is specially designed for the purpose and have a rotating shoulder that generates friction heat and a pin that generates both heat and stir the material to a good weld [8]. Welds made by the FSW method are the main topic in this thesis and the method is described in the next chapter. To detect voids in the welds, X-ray, ultrasonic and inductive testing are all used to check the joints.

1.3.1 Inserts
The canister inserts are manufactured by casting in one piece which has channels for the fuel. These have 12 cannels for boiling water reactor fuel and 4 channels for heavy water reactor fuel. During the development work the inserts have been made in both cast steel and nodular iron. Nodular iron has been chosen as material in the prototype canister partly due to the better castability. The bottom can be cast integrated when using nodular iron. The channels in which the fuel will be placed are fabricated from square, hot-drawn steel tubes, which are welded together into a cassette. The square tubes are first filled with compacted sand so that the walls will not be deformed by the pressure from the molten metal during casting. The mould is then filled with molten iron. The iron flows in and fills the spaces between the channels and also forms a shell of iron around the cassette. After casting, the insert is allowed to cool in the mould for a few days and no heat treatment is needed after casting, as for cast steel. The insert is then knocked out of the mould, cleaned and machined. The material properties of the insert vary. The ductility is dependent on the microstructure of the graphite and the presence of porosity. The nodularity of the graphite and the presence of porosity and slag particles are found by microscopy and ultrasound testing and the occurrence have varied in different inserts. Computer simulations have been

![Figure 3 a) Cylindrical copper ingots. b) The ingot is pressed in several steps. c) The forging die.](image)
made of the casting technique at each individual foundry and in this way, improvements have been achieved [8].

The concentration of Si, Ni and Mn affect the yield strength. Mn and Cu improve the properties of the ferrite, but if the concentrations are too high, pearlite is formed in the matrix. An elevated pearlite concentration reduces the ductility of the material, but raises the yield and tensile strength. It is shown that the best material properties are obtained in the lower part of the inserts [8]. This was expected for a large casting that has been cast upright in the mould. Due to the large variety of the traditional tensile testing results with test bars taken out from different places from an insert, a new specification of material requirements will be based on probabilistic approach.

1.3.2 Copper material for copper canisters and its properties
In this section high temperature strength data for copper is surveyed. Although the welds in the copper canisters for nuclear waste are not designed to be load carrying, they will be exposed to plastic strain, in particular during the early period of their life.

Initially oxygen free high conductivity copper (Cu-OFHC) was considered as a candidate material for the canisters, since its thermodynamic stability in reducing ground water of the type at the depth of a repository was well documented [4]. Earlier creep data of pure copper had been reported for temperatures from 350 to 500ºC. More recently data for Cu-OFHC has been determined at Swedish Institute for Metals Research in the interval 75 to 225ºC [9-15]. Unfortunately it turned out that the creep ductility of Cu-OFHC was inadequate, and an alternative material had to be identified. Two obvious candidates were oxygen free copper with 30-60 ppm phosphorus (Cu-OFP), and pure copper with 0.1% silver. Since Cu-OFP was expected to give the least negative influence on the corrosion properties, it was selected. In addition the cost of Cu-OFP is essentially lower than that of Cu-0.1%Ag. Copper with phosphorous has been used as pressure vessel materials for many years.

1.3.3 Creep
To avoid creep failure in the canisters the following approaches are used:

- A copper grade should be chosen with sufficient creep ductility. Since the creep deformation can take place for several hundred years, it is the ductility for that time that should be considered. Such ductility values cannot be measured directly but have to extrapolated in time. Due to the uncertainty in the extrapolation some margin in the creep ductility values must be present.

- The geometry of the copper canister should be chosen to ensure that the total creep strain is limited (< 5%). In particular creep deformation under tensile stress should be restricted.

- The welds should be positioned in such a way that they are only exposed to small creep strains. The reason is that the microstructure in the welds is likely to have a higher sensitivity to creep failure than the parent metal.

The gap between the insert and the canister is 1-2 mm. When the canister is exposed to external pressure and the initial high temperature, the copper can be deformed to up to 4% strain before the gap between the copper and iron shells is closed. Creep rupture is hence not expected to occur unless the creep ductility is below 4%.

Considering that the canister will be exposed to temperatures up to 90ºC for up to 100 years, extrapolated creep data must be available for such times. Extrapolation is performed with the help of time-temperature parameters [16].
The logarithmic rupture stress decreases approximately linear with temperature and with logarithmic time. Even more important than the rupture strength is the creep rupture ductility. The grain size influences the ductility. When the grain size exceeds 400 µm, the ductility starts to drop. For a grain size of 2000 µm the rupture time is distinctly lower. In the canisters one is aiming for a grain size of 250 µm or below. A creep elongation value exceeding 10% can be considered as satisfactory. The specifications at present stage in chemical composition, grain size and mechanical properties can be found in [7]. The grain size should be below 350 µm and the phosphor content 50 ppm.

1.4 Canister defect scenario
SKB have analysed different possible canister collapse scenarios, such as undetected defects in the canister, large changes in climate systems, earthquakes and intrusion by drilling.

A number of thermal, hydraulic, mechanical and chemical processes can take place in the repository. In the undetected defect case, canisters are postulated to have undetected defects which could eventually lead to leakage. When water enters the canister through the assumed millimetre-sized hole, conditions in the canister change radically. The water causes the cast iron insert to corrode. This corrosion process gives rise to gaseous hydrogen and solid corrosion products, which occupy a greater volume than the cast iron. Eventually, these products exert a mechanical pressure inside the canister. The radiation levels in and around the canister are, however, only affected marginally by water entering the canister [17, 18, 7].

The earth’s climate system is very complex and it is therefore not possible to know exactly when the next ice age is coming or where the location of the ice sheet will be. Most changes during a glaciation cycle take place on the earth’s surface, when the ice cap advances and retreats. Dry land is transformed into seabed and vice versa. A deep repository, should withstand an ice age with undiminished safety. The weight of the ice depresses the bedrock. The high water pressure underneath the ice sheet affects both the rock and the canister. The canisters should withstand both rock movements and pressure.

1.5 Aim of thesis
The purpose of this work is to characterise and model the friction stir welding of thick copper canisters to provide an understanding of the physical processes involved in the welding. This is needed to optimise and to produce a void free weld with satisfactory mechanical and corrosion properties.
2 MECHANISMS CONTROLLING FRICTION STIR WELDING

2.1 General

Friction Stir Welding (FSW) is a relatively new method invented by The Welding Institute (TWI) in 1991. It is a solid state welding method. Today a variety of materials can be welded such as aluminium and its alloys, copper and its alloys, lead, titanium and its alloys, magnesium alloys, zinc, plastics, and mild steel. The process uses a non-consumable tool with no filler material and with no need of shielding gas when welding aluminium. The thickness can vary from 1 mm to 50 mm depending on material or welding conditions. Since gravity has no influence on the solid-phase welding process, it can be used in many positions and geometries. The process has been used for the manufacture of butt welds, overlap welds, T-sections, fillet, and corner welds. For each of these joint geometries specific tool designs are required. The industries using FSW is the shipbuilding and marine industries, aerospace industry, railway industry, construction industry, electrical industry and many others. Applications from helicopter landing platforms to high speed trains and furniture can be welded by FSW. Although, FSW have been used for various applications, the understanding of the process is not fully understood.

FSW technology has caught the interest of industrial production communities world wide. The main advantages are that it is a rapid, clean and robust technology. One other advantage, very much appreciated by the industry, is the assured repeatability of the quality level for long periods of production. Unlike many fusion welding techniques (specially applied to advanced materials), FSW does not require skilful welding. It does require knowledge based guidelines to select the appropriate welding conditions, and optimal tool and joint geometry.

The Swedish Nuclear Fuel Waste Management Corporation (SKB) initiated collaboration with TWI in 1997 on FSW of copper [1, 19], to ensure safe deposit of spent nuclear fuel. The canister will be produced by welding a lid and possibly a bottom to a cylinder. This joining method is achieved through an extrusion action when the rotating tool is pressed forward through two parts that will be joined together. The terms defined in Table 1 are general terms relating to FSW. The tool is divided in two parts; one is the pin and the other
one shoulder. The shoulder is rotating and pressed down on the material surface. The rotating contact gives rise to friction heat. The pin will stir the material and thereby deform it, but also contribute with friction heat to the weld. The heat is due to friction between the tool and the welded material, which causes the weld material to soften at a temperature less than its melting point. When the material softens too much the friction decreases and thereby less heat is generated. The softened material underneath the shoulder is subjected to extrusion by the rotation of the tool and the traverse movement. The role of the tool shoulder is twofold as it both generates the necessary heat and controls the flow of the material. The material flows from the advancing side, across the weld centre line to the retreating side, see Figure 4. The tool can be tilted from the vertical position to increase the forging action. To provide a stable welding process the presence of a backing plate and side clamping forces are essential.

Advancing side is the side of the weld where the rotation of the tool and the forward motion are in the same direction, and the retreating side is the side where the rotation motion and the forward motion are opposite. The advancing side of the weld is normally the cooler side of the weld zone because the material flows from the advancing side, across the weld centre line to the retreating side. Cooler welding conditions provide finer grains.

Deformation together with high temperature generates recrystallisation which result in a complex microstructure in the weld zone. Recrystallisation takes place in the nugget, which is located in the middle of the weld. Some recrystallisation also occurs in the surrounding area, which is called the thermo mechanically affected zone (TMAZ). Outside this area, there is a heat affected zone (HAZ) which is similar to the HAZ in the conventional welding process. This area, in turn, is surrounded by unaffected material, see Figure 4.

**Table 1** Definition of terms.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool pin</td>
<td>Part of the welding tool which rotates; it is normally shaped as a truncated cone. The pin extends from the shoulder and enters the joint-line.</td>
</tr>
<tr>
<td>Backing plate</td>
<td>The backing plate, this is the fixture that the weld rests on. The weld is formed between the backing plate and the tool.</td>
</tr>
<tr>
<td>Tool shoulder</td>
<td>Part of the welding tool which rotates and is normally disk shaped. The shoulder forms the weld cap.</td>
</tr>
<tr>
<td>Advancing side</td>
<td>The tool advancing side is the side of the tool where the local direction of the tool surface due to tool of rotation and the direction of traverse are in the same direction.</td>
</tr>
<tr>
<td>Retreating side</td>
<td>The tool retreating side is the side of the tool where the local direction of the tool surface due to tool of rotation and the direction of traverse are in the opposite direction.</td>
</tr>
<tr>
<td>Plunge depth</td>
<td>The plunge depth is the maximum depth that the pin penetrate into the material. As the tool is tilted at an angle this is usually in the trailing edge of the tool.</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>The tool rotation speed is the rate of angular rotations per minute (rpm) of the tool around its axis.</td>
</tr>
<tr>
<td>Welding speed</td>
<td>The welding speed is the speed (mm/min) of the tool traverse through the weld joint-line.</td>
</tr>
</tbody>
</table>
The safety for long time deposit of spent nuclear fuel is quite dependent on the welding quality. Referring to the FSW process, the possible voids in the weldment are one of the critical factors. If the formation of voids can be predicted, welding quality can substantially be improved and an excellent weld with good mechanical properties can be produced.

2.2 Influence of process parameters on void formation

As for any welding process, there are a large number of process parameters that must be controlled when using the FSW method to avoid void formation, see Table 2. If the chosen parameters are not optimal, voids and excess flash can be formed, which are often combined with microstructural changes. This situation can even lead to FSW tool pin breakage. Various welding condition combinations can result in the same type of defects. Therefore it is difficult to isolate the source to the defect.

2.2.1 Temperature distribution

The energy input during FSW is primarily from friction heat generated between the rotating shoulder, pin and the work material. This fraction of the input that comes from the pin respectively shoulder is discussed in various paper: values from 2 % [20], 20% [21], 25 % [22] to 60 % [23] from the pin are observed. A certain fraction of the heat is dissipated through the backing plate and through the tool. The fraction is somewhat larger for copper than for aluminium, since the former material has a higher thermal conductivity [24]. The temperature decreases as a function of the distance from the centre of the weld. If preheat is applied to the work material, the temperature is of course raised further, although in practice it is rarely used.

Measurements of temperature profiles have shown that the maximum centreline temperatures do not exceed 0.8 $T_m$ for copper, where $T_m$ is the melting temperature. For successful welds in copper using the FSW method, the temperature must be above 700°C but the tool pin should not exceed 850°C, to prevent deformation and hot shearing of the alloy currently used for the pin [25].

2.2.2 Tool axial welding force

If the axial welding force is too low, insufficient heat will be generated at the faying surface. On the other hand, if the force is too high then the shoulder penetrates into the material and it will form excess flash at the edges of the shoulder [26]. The tool download force can also affect the surface texture [27].
Table 2 Summary of conditions that can generate voids and other defects.

<table>
<thead>
<tr>
<th>Change in parameter</th>
<th>Void formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of the weld</td>
<td>Voids in the weld root (depending on the pin length).</td>
</tr>
<tr>
<td>Tool geometry</td>
<td>Change in microstructure, closing of voids.</td>
</tr>
<tr>
<td>Side clamping force</td>
<td>Reduces the size of voids near the surface on the advancing side.</td>
</tr>
<tr>
<td>Rotation speed of the tool</td>
<td>Small triangular shaped voids on the advancing side, usually concurrent with low rotation speed and low weld temperature. High rotation speed causes overheating and grain growth.</td>
</tr>
<tr>
<td>Tilt angle</td>
<td>Can change microstructure and sub-surface void shape.</td>
</tr>
<tr>
<td>Canister rotation rate</td>
<td>Voids on the advancing side, if too fast and the weld temperature low. Grain growth, if it too slow and the temperature high.</td>
</tr>
<tr>
<td>Tool cooling</td>
<td>Surface breaking voids, grain growth (depending on effectiveness).</td>
</tr>
<tr>
<td>Tool axial welding force</td>
<td>Surface roughness, flashes at the edges of the shoulder. (Higher force reduces or eliminates voids).</td>
</tr>
<tr>
<td>Physical stops to prevent further movement of the welding head</td>
<td>Voids on the advancing side, due to large reduction in axial welding force.</td>
</tr>
<tr>
<td>Altered welding force</td>
<td>Voids on the advancing side if the force is reduced excessively.</td>
</tr>
</tbody>
</table>

2.2.3 Side clamping force

The side clamping force, which holds the base material together, needs to be greater than the force generated by the stirring tool pin because the pin tries to push the material apart. The force increases with the thickness of the plates because the dimension of the tool pin increases at the same time. It has been observed that if the clamping force is not high enough, a void is present, just below the surface on the advancing side of the weld [28].

2.2.4 Length of tool pin

To ensure sufficient plastic deformation in the root of the weld, the length of the pin should be related to the wall thickness. If the length of the pin is too short, a defect in the root can be generated and early fracture during tensile or root bend testing will occur. This type of defects can also act as crack initiation sites as well as an easy path for crack propagation. On the other hand, if the tool pin length is excessive, the tool will contact the backing plate and suffer damage.

2.2.5 Thickness

When the thickness of the substrate changes, many process parameters as well as tool design have to be adjusted, due to change in heating, stirring and height of the weld. If the material is too thick or the tool too short a region of unwelded material would exist near the weld root, therefore, it is important with a consistent thickness.
2.2.6 Tool geometry
The tool geometry is an important parameter for FSW. Tool pin shape influences the heat generation, plastic flow and the stirring action in the weld [29]. Moreover, the tool pin size is reflected in the width of the weld. The FSW shoulder and the pin geometry are adapted to the work material and its thickness. Microstructural changes can occur when the tool design is modified. The most common tool today has a threaded pin whereas the older ones had a more simple geometry. Developments of different tools at TWI have resulted in the use of Whorl\textsuperscript{TM} and Triflute\textsuperscript{TM} pin geometry for copper. The shoulder and the pin are made out of different material. The materials tested for pins and shoulders include tungsten carbides, cermets, super alloys and refractory metals.

The shoulder should act as a heat pump to assist the softening of the material around the rotating pin. The most common shoulder has a flat underside. Another, which has been tested, had a spiral scroll on the underside of the shoulder [25]. This scroll design had been tested on aluminium and resulted in improved material flow in the upper half of the stir weld with reduced extruded surface flash. It also permitted stir welds to be made without a tilt angle. It became apparent [26] that the size of the shoulder plays a less important role for thick copper sections than when welding thin sections of aluminium; the radius does not fully need to be sized up compared to the thickness. For copper welds tools with threaded pins are used. The threads force down the stirred material and lead to material rotation. The purpose of this intense stirring action is to close voids and provide a large rubbing surface to generate heat rapidly [26]. In the search for reduced size and occurrence of small voids, the Triflute\textsuperscript{TM} geometry has been further developed. This tool is designed to provide enhanced flow and adequate stirring action, and thereby reduce or eliminate the presence of voids. This feature is developed from the Whorl\textsuperscript{TM} geometry which has a seashell-shaped pin, but the pin is three sided, see Figure 5.

2.2.7 Welding speed
The current method of producing a circumferential weld on a canister includes a rotating tool pin mounted in a welding head with a fixed position and a rotating canister. Hence, the welding speed is controlled by the canister rotation rate (at TWI). In a new welding machine, situated at the canister laboratory, Oskarshamn, the welding head rotates and the canister is fixed.

![Figure 5](image-url) Examples of different tool geometries: a) Whorl\textsuperscript{TM} pin, b) Triflute\textsuperscript{TM} pins [7].
It has been observed that presence of voids is related to the welding speed [30]. A rapid increase in canister rotation speed can produce small voids. The mechanism behind this behaviour is not known at present.

2.2.8 Tool rotation speed
The tool rotation speed used so far for copper is between 235 and 518 rpm. The rotation speed must be large enough to generate sufficient heat to soften the copper, otherwise tool fracture would occur. In early copper welds small features were found in the weld zone [31], in the region near the surface. These were believed to originate from the break down of the FSW shoulder. By increasing the dimensions this problem has been solved. When the development of the process came to thicker sections of copper the rotation speed had to be increased to match the increased heat conduction away from the weld zone. The higher speed resulted in improved lifetime but a small triangular shaped void was sometime present near the top surface on the advancing side [32]. Elimination of this void was accomplished with increased side clamping force (the pressure between the two copper plates which are welded together) and axial welding force. In early welds copper plates were supported by water-cooled backing plate. In a canister weld there can be a steel ring on the inside of the copper ring. According to [33] there are few voids in the weld zone if the rotational speed and welding speed are optimised. The rotation speed is considered as a most significant process variable [34].

2.2.9 Tilt angle
Most FSW trials on copper have had a tool tilt angle of 2-3°. The reason for exploring an increased tool tilt angle is to improve the forging of the back edge of the tool shoulder. In that way, it may be possible to eliminate sub-surface voids. In [35] aluminium welds, an increase from 0° to 2° in tilt angle gives a dramatic change in the microstructure development and material flow. A larger tilt angle gives a tighter weld, and a more uniform material flow, see Figure 6. Furthermore the result shows a location in each weld with stagnant flow. This may cause a void in that position. This may be an explanation to the advancing side voids. When welding aluminium alloys it has been observed that the major effect of the tilt angle is to press down the material on the trailing edge. This material flow results in flash on both the advancing and retreating sides. This flash does not influence the weld integrity since it can be machined off from the surface.

2.2.10 Pilot hole at weld start
Before welding thick sections of copper it is desirable to drill a pilot hole into the copper plate, see Figure 7. This permits the rotating tool pin to be plunged into the copper without experiencing high torque, which could cause pin fracture. This can occur with wrong pilot-hole dimension or when misalignment between the tool and the hole appears. Carbide tool pins have little ductility and fracture readily. Now [36] stronger and tougher tool pins have been developed and a simple single diameter hole can be made. This makes the drilling of the pilot hole easier.

When the plunge action starts, the rotation speed is high, and this allows the tool pin to penetrate into the pilot hole and the shoulder to generate frictional heat quickly. Once steady state welding conditions have been achieved the tool shoulder has attained red heat, which corresponds to a temperature of 700-800 °C; the upper section of the pin also reaches this temperature.
2.2.11 Tool cooling

Tool cooling is needed in copper welding to ensure heat extraction from the tool pin and shoulder and thereby preventing them from overheating. Pin fracture can occur at the exposed junction between the top of the pin and the shoulder. The major feature of the design of the cooling system is the circular water-cooling channels, which are located at a distance of 10 mm from the end of the tool pin. This feature should ensure increased heat extraction from the tool pin and shoulder.

If the pin and shoulder are overheated it will also cause overheating and excessive softening of the surface region of the canister to. Moreover, this might initiate excessive flash generation and FSW tool shoulder penetration. The heating might also result in grain
growth. But overcooling of the tool pin would result in the formation of surface breaking voids [31] accompanied by an increase in the rotating spindle torque and machine transmission power requirements [25].

2.2.12 Tool parking
When a full circumferential weld has been made, the pilot hole will be welded over and the pin is parked above the weld. When the tool is parked, it is withdrawn and a park hole is left, see figure 8. This hole will probably be machined off from the canister or filled. Metallurgical examinations have been carried out on complete circumferential weld, at the location were the material has been welded twice. No excessive grain growth or presence of voids was observed.

Figure 8 The parking hole [25].
2.2.13 Intermittent conditions
During welding the parameters are changed as little as possible, because uniform welds are desired. In [31] a traverse metallurgical section was revealed a small round void, which was approximately 0.5 mm in diameter, situated on the top of the weld nugget. This section was taken from a welded canister using physical stops to control the welding head position. In another weld in [31] the rotating FSW tool was plunged too far under the surface of the canister ring and to prevent this, the welding force was altered several times. This weld revealed an advancing side void, located at the centre of the weld, see Figure 9. It is associated with low welding force or non-ideal FSW pin geometry. A force control system was developed to cope with the problems by setting a forward motion at a set rate and control the applied force. This system can control the tool position and the applied force. Small voids were still sometimes detected on the advancing side of the weld zone, during welding trials at TWI. The location was in the interface between the top of the fine grained weld nugget and the material was strongly influenced by the shoulder. However, as the voids always were at the same location, it would be possible to weld that region again with a shorter pin, which would make the voids disappear. This was something TWI looked at and good welds were made by welding a second time. Later, when the SKB welding machine at the canister laboratory was developed this problem disappeared with improved welding parameters.

![Figure 9 Void on the advancing side [31].](image)
3 MODELLING OF THE FRICTION STIR WELDING PROCESS

3.1 General

Although the FSW method looks as a simple welding method, without consuming material, the physics behind the process is complex. The method includes heat generation, heat and mass transport. One of the problems in understanding the method is in observing the details of the process in action. Modelling the process would require fever experiments. Moreover, understanding of why and when voids are present in the weld zone could be established. Models may be validated in a number of ways but the most convincing one is by comparison with high quality experimental data.

Modelling of the FSW process has been attempted by many authors, both by analytical and numerical models. These models have been both two and three dimensional and could be based on solid mechanical or fluid dynamic models. Some have included the material flow whereas others have neglected it, which is also the case with the effect of the threaded tool. In some models the pin is excluded from the model, in others the shoulder is excluded. In the models where the pin is excluded the authors claim that the pin does not put a large amount heat into the weld zone. The heat fraction that comes from the pin respective shoulder is discussed in various papers, the difference being as large as 2-60% from the pin [20-23]. In the case when the shoulder is excluded the main object is to understand the stir action. The modelling can sustain a wide variety of coupled equation such as heat, flow, distortion, stress, and tool loads. The first developed FSW models were made by analytical thermal models such as the Rosenthal’s equation. Later finite element models were developed.

3.1.1 Rosenthal’s analytical model

This is an analytical model based on the Rosenthal’s general medium plate solution. This model considers a point heat source moving at a constant speed across a wide plate of finite thickness d. The plate surface is assumed to be impermeable to heat. In order to maintain the net flux of heat through both boundaries equal to zero, it is necessary to
introduce mirror reflections [37] as imaginary heat sources being placed below the workpiece \( z = 0 \) and \( z = d \). The imaginary source is located symmetrically at distances \( \pm 2id \). In this way an equal amount of heat is applied back into the workpiece. Moreover, the model is based on welding parameters when the joining has reached steady state.

\[
T - T_0 = \frac{q_0}{2\pi \lambda} \exp\left(-\frac{v x}{2a}\right) \times \left[ \sum_{i=-\infty}^{\infty} \left(1/R_i\right) \exp\left(-\frac{v}{2a} R_i\right) \right]
\]

(1)

where the distance of each imaginary source \( q_i \) from the \( i \) point of interest

\[
R_i = \sqrt{x^2 + y^2 + (z - 2id)^2}
\]

(2)

\( x \) is heat sources direction of movement and \( y \) is perpendicular to that movement, \( q_0 \) is the net power received by the weld, \( v \) the welding speed, \( a = \lambda/\rho \cdot C_p \) the thermal diffusivity, \( \lambda \) the thermal conductivity, \( C_p \) the heat capacity, \( i \) is an integer, and \( v \) is the weld speed.

Russell and Shercliff [13] base the heat generation on a constant friction stress at the interface, equal to the shear yield stress at elevated temperature. The heat input is applied as a point or line source as in Rosenthal’s equations.

In [38] temperature measurements are made with embedded thermocouples during welding. An intuitive model, similar to Rosenthal's moving point source solution was developed to quantitatively correlate the temperature field in FSW to basic process variables.

### 3.1.2 FEM solid model

Chao’s and Qi’s model [39] is based on the assumption that the heat generation comes from sliding friction between the tool and material. This is done by using Coulomb’s law to estimate the friction force. Moreover, the pressure at the tool surface is set constant and thereby enabling a radially dependent surface heat flux distribution generated by the tool shoulder. In this model the heat from the pin is neglected. Xu and Reynolds [40] have used finite element models to describe the material flow around the pin. This is done by using a solid mechanical two dimensional finite element model. It includes heat transfer, material flow, and continuum mechanics. The pin is included but not the threads of the pin.

In [41], Chao uses a finite element model to formulate heat transfer of the FSW process in two boundary values problems, a steady state for the tool and one transient for the workpiece. To validate the result, the temperature was measured in the tool and in the workpiece during FSW. The heat input from the tool shoulder is assumed to be linearly proportional to the distance from the centre of the tool. Due to heat generation from friction.

\[
q(r) = \frac{3Qr}{2\pi(R_0^3 - R_i^3)} \quad \text{for} \quad r \leq R_0
\]

(3)

where \( R_0 \) is the radius of the shoulder and \( R_i \) is that of the pin. \( Q \) is related to process parameters. To model the workpiece the code WELDSIM was used. It is a transient, nonlinear, three-dimensional finite element code. In this model only half the workpiece is modelled due to symmetry. This means that no adjustment has been made between the advancing and the retreating side of the weld. The conclusions from this work indicate that 95% of the heat generated goes into the workpiece and it is only 5% that goes to the tool. This gives very high heat efficiency.

In [42] Chao presents another three-dimensional finite element model of FSW. The modelling effort includes a coupled heat transfer and a subsequent thermo-mechanical
analysis. The temperature fields during the welding, residual stress distribution and distortion of the workpiece after the FSW process are studied. The effects of the fixture used to clamp the workpiece to the backing plate and the reduction of yield strength near the weld nugget area are incorporated in the modelling.

Xu [43] has tried to optimise the welding tool design and the selection of the FSW process parameters. Variations in process conditions are made, such as tool shoulder diameter, tool advancing speed and thermal insulation conditions. The finite element simulation included heat generation due to the tool-workpiece interaction, the heat loss through the tool and the backing plate.

Zhu et al [44] use a three-dimensional nonlinear thermal and thermo-mechanical numerical model. The finite element analysis code was WELDSIM. The objective was to study the variation of transient temperature and residual stress in a friction stir welded plate of 304L stainless steel. Based on the experimental records of transient temperature, an inverse analysis method for thermal numerical simulation was developed. After the transient temperature field was determined, the residual stresses in the welded plate were then calculated using a three-dimensional elastic-plastic thermo-mechanical simulation. In this model the plastic deformation of the material is assumed to follow the von Mises yield criterion and the associated flow rule. The relationship between the rate component and thermal stresses $\sigma_{y}$ and strains, $\varepsilon_{y}$, is described by:

$$\dot{\varepsilon}_{y} = \frac{1+v}{E} \sigma_{y} - \frac{v}{E} \sigma_{kk} \delta_{y} + \lambda s_{y} + \left[ \alpha + \frac{\partial \alpha}{\partial T} (T - T_0) \right] \hat{T}$$

(4)

where $E$ is the Young’s modulus, $v$ is the Poisson’s ratio, $\alpha$ is the thermal expansion coefficient, $\lambda$ is the plastic flow factor,

$$s_{y} = \sigma_{y} - \frac{1}{3} \sigma_{kk} \delta_{y}$$

(5)

Frigaard [45] modelled heat input from the shoulder and the pin as fluxes on squared surfaces at the top and sectional planes on a three dimensional model. To control the maximum allowed temperature the friction coefficient is adjusted at elevated temperatures. Chen and Kovacevic [46] use a three-dimensional model based on a finite element method to study the thermal history and stress distribution in the weld and compute mechanical forces in the longitudinal, lateral and vertical directions. The standard heat transfer equation is used.

$$\rho \cdot C_p \frac{dT}{dt} - \nabla \cdot (\lambda \nabla T) = Q$$

(6)

where $\rho$ is the density of the material, $C_p$ the specific heat, $Q$ the heat source per unit volume, and $\lambda$ the thermal conductivity that describes the Fourier’s law of heat conduction $q = -\lambda \nabla T$. Equation 6 is used by most authors.

The rate of heat generation from the friction is:

$$\dot{q} = \frac{2}{3} \pi \omega \mu(T) p(T)(R_0^3 - R_f^3)$$

(7)
were $R_0$ is the shoulder radius and $R_i$ is the pin radius, $\mu$ is the coefficient of friction between the shoulder and the workpiece, $p$ is the pressure, $\omega$ is the angular speed, $\mu(T)$ and $p(T)$ are dependent on the local temperature. As the temperature increases the friction coefficient decreases. Also Russell and Shercliff [20, 47] used this method.

Song and Kovacevic [48] have developed a mathematical model to describe the detailed three-dimensional transient heat transfer process. Their work is both theoretical and experimental. An explicit central differential scheme is used in solving the control equations. The heat input from the tool shoulder is modelled as frictional heat and the heat from the tool pin as uniform volumetric heat generated by the plastic deformation near the pin. Moving coordinates and a non-uniform grid mesh are introduced to reduce the difficulty of modelling the heat generation due to the movement of the tool pin.

Lawrjaniec et al [47] have developed a three-dimensional numerical model to investigate residual stresses generated by FSW. The modelling is carried out using two commercial finite element codes SYSWELD and MARC. A thermal-mechanical transient state is used for the calculations. The thermal stage of the process is simulated by using two different numerical heat sources. Those numerical heat inputs are calibrated with the help of experimental results obtained by thermocouples and infra-red cameras.

Khandkar et al [49] use a finite element method based on a 3-dimensional thermal model to study the temperature distributions during the FSW process. The moving heat source generated by the rotation and linear traverse of the pin-tool has been correlated to input torque data obtained from experimental investigation of butt-welding. The moving heat source includes heat generation due to torques at the interface between the tool shoulder and the workpiece, the horizontal interface between the pin bottom and the workpiece, and the vertical interface between the cylindrical pin surface and the workpiece. Temperature-dependent properties of the weld-material have been used for the numerical modelling.

Fourment [50] tries to simulate the transient phases of FSW with FEM in the form of an Arbitrary Lagrangian Eulerian (ALE) formulation, to develop a 3-D coupled thermo-mechanical model taking large deformation into account. This method permits both transient and steady state phases. Schmidt [51] has also used the ALE formulation together with the Johnson-Cook material law. The contact is modelled by Coulomb’s law of friction. The heat is generated both by friction and plastic dissipation. Finite element software is chosen and a 3-D dynamic solid-mechanical model including material flow and heat generation can be performed. They divide the generated heat from three different areas the shoulder, pin and pin tip, and use both stick and sliding condition.

Desrayaud [52] uses a three dimensional analytical thermo-mechanical model to predict the temperature and microstructure. Strain, strain rate and temperatures are used as input data for microstructural model including both dynamic and static recrystallisation.

Schmidt et al [53, 54] have developed an analytical model for the heat generation and this is combined with an Eulerian finite element analysis of the temperature field. The heat generation is closely related to the friction condition at the contact interface between the FSW tool and the weld piece material as well as the material flow in the weld matrix. The heat generation from the tool is governed by the contact condition, i.e. whether there is sliding, sticking or partial sliding/sticking. The model includes heat generation contributions from both the conical shoulder and tool pin, and enables a contact condition which could be partial sliding/sticking. The present model uses Coulomb’s law of friction for the sliding condition and the material yield shear stress for the sticking condition to model the contact forces.
3.1.3 FEM fluid model

The contact conditions in FSW are complex, dependent on alloy, welding parameters, tool design, etc. Previous models, both analytical and numerical, for simulation of the heat generation assume a known contact condition at the contact interface, e.g. either as pure sliding or sticking. Another way of looking at the modelling is by using a fluid dynamic model.

Colegrove uses an analytic model to estimate the heat generation for tools with a threaded pin, parallel to this, Colegrove and Shercliff [55] work on a material flow model. Colegrove [56] uses a Computational Fluid Dynamics (CFD) package called FLUENT. This model is used to model viscous material flow around the FSW tool, calculating both material and thermal flow. The model can be varied and both slip and stick conditions have been used. Moreover, both 2-D and 3-D tool shapes are modelled, but, it is only the tool pin that is modelled. Four different tool shapes have been modelled. The modelling result shows that the difference between slip and stick condition is small and the pressure and forces are similar. Furthermore, pressure plots suggest that voids most likely appear at the advancing side of the tool, and this is something also seen in copper welds [31, 56]. One of the approaches to represent the flow stress was developed for modelling ballistic impacts

$$\tau = (A + B\varepsilon^n)(1 + C\ln(\varepsilon))(1 - \hat{T}^m)$$  \hspace{1cm} (8)$$

$\tau$ is the shear stress, $\varepsilon$ is the effective linear strain, A, B, n, C, m is material dependent.

$$\hat{T} = \frac{T - T_{room}}{T_{melt} - T_{room}}$$  \hspace{1cm} (9)$$

T is the temperature.

The shear flow stress is converted to viscosity $\eta$.

$$\eta = \frac{\tau}{\sqrt{3}\varepsilon}$$  \hspace{1cm} (10)$$

Reynolds et al use two models in [57] to explain the FSW process. The first is a thermal model which is used to simulate temperature profiles in friction stir welds, Equation 6. The total torque at the shoulder is divided into shoulder, pin bottom and vertical pin surfage. The required inputs for the model are total input power, tool geometry, thermo-physical properties of the material being welded, welding speed and boundary conditions. The output from the model can be used to rationalize observed hardness and microstructure distributions. The second model is a fully coupled, 2-D fluid dynamics based model that is used to make parametric studies of variations in properties of the material to be welded (mechanical and thermo-physical) and variations in welding parameters. This is done by a non slip boundary condition at the tool workpiece interface. The deformation behaviour is based on deviatoric flow stress using the Zener-Hollomon parameter [57]. Results from this model provide insight regarding the effect of material properties on friction stir weldability and on potential mechanisms of defect formation. The deviatoric stress tensor is also used by Ulysse [58] to model the stir-welding process using three-dimensional visco-plastic modelling. In this work parametric studies have been conducted to determine the effect of tool speeds on plate temperatures and to validate the model predictions with available measurements. In addition, forces acting on the tool have been computed for various welding and rotational speeds. It is found that pin forces increase with increasing welding speeds, but the opposite effect is observed for increasing rotational speeds. Numerical models such as the one presented here will be useful in designing welding tools which will yield desired thermal gradients and avoid tool breakage.
**3.2 Present work**

The aim was to predict the temperature distribution and its influence on the distortion by thermal expansion of the canister. Therefore, a direct geometry modelling of the tool itself is excluded. The effect of inward heat influx generated by the rotation of welding tool is characterised by taking the boundaries in contact with the welding tool into consideration. A boundary modelling is performed in these areas. The boundary in contact with the tool pin is approximated as a cone.

**3.2.1 Navier-Stokes equation**

During FSW, the welding tool moves along the contour of the canister. This movement is relative in nature between welding tool and canister. The velocity for welding tool passing through the contour of the canister is the same in quantity as that for the canister material passing through the tool pin, but with opposite directions. The velocity $\mathbf{u}$ can be described by incompressible Navier-Stokes equation

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \cdot (\mathbf{u} \cdot \nabla) \cdot \mathbf{u} = \mathbf{F} - \nabla p + \eta \nabla^2 \mathbf{u} \tag{11}$$

where $\mathbf{F}$ is the volume force, $\rho$ the pressure, and $\eta$ the dynamic viscosity which is temperature and strain rate dependent.

The heat transfer is governed by the heat equation

$$\rho \cdot C_p \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = Q \tag{12}$$

where $\rho$ is the density of the material, $C_p$ the specific heat, $Q$ the heat source per unit volume, and $\lambda$ the thermal conductivity that describes the Fourier’s law of heat conduction $\mathbf{q} = -\lambda \nabla T$. Due to a relative displacement between the canister and the welding tool, the effect of convective heat in the canister should be taken into account. Since there is no distributed heat source in the canister, $Q$ is equal to zero.

Due to the effect of welding heat influx, the canister could be distorted by the thermal expansion during FSW process. In general, Newton’s second law together with the constitutive relation between the stress and the strain, and the strain-displacement relation in a continuum leads to the Navier’s equation.

$$\rho \frac{\partial^2 \mathbf{u}_1}{\partial t^2} - \nabla \cdot c \nabla \mathbf{u}_1 = \mathbf{K} \tag{13}$$

where $\mathbf{K}$ the volume force, and $c$ is a tensor.

The above equations are coupled through $T$, $Q$, and $\eta$ terms. As elaborated before, the free convection exists in the model. The $Q$ term in the heat equation is thus substituted by the divergence of the convective heat flux

$$\rho \cdot C_p \cdot \mathbf{u} \cdot \nabla T \tag{14}$$

using the concept that the velocity field is divergence free. The velocity field $\mathbf{u} = (u, v, w)$ can be described by the Navier-Stokes equation, which is dependent on the temperature
through the dynamic viscosity $\eta$. The thermal expansion affects the displacement, stress and strain. This influence can be accounted for by decomposing strain $\varepsilon$ into thermal strain $\varepsilon_{th}$ and elastic strain $\varepsilon_{el}$

$$
\varepsilon = \varepsilon_{el} + \varepsilon_{th} = \varepsilon_{el} + \alpha \cdot (T - T_{ref})
$$

and by inserting it into Navier’s equation. With parameter coupling, a multiphysic finite element model describing multiphysic phenomena is established.

### 3.2.2 Heat transfer

The inward heat flux from the welding tool is simplified. A condition $T = T_0$ is used to specify the temperatures on the boundaries between the canister and tool, suggesting a very high heat transfer coefficient at these boundaries. It is reported that temperature at the tool shoulder is higher than at tool pin [14, 59]. This fact has been taken into consideration in the model. The temperatures 800 and 850 °C are used as input values for boundaries in contact with tool pin and shoulder, respectively. At the boundary of material inflow, an environmental temperature $T_0 = 23$ °C is given.
4 INVESTIGATIONS AND SUMMARY OF APPENDED PAPERS

4.1 Paper A
The purpose of paper A was to examine the variation in grain size and hardness as a function of welding conditions. In this investigation two locations of the weld were examined, one at the start of the weld, where the welding temperature rises from ambient to >800°C and the welding speed is ramped up progressively to the steady state speed. The other location is when the welding conditions have reached steady state. Moreover, the effect of the grain size on the hardness is looked at, by using the Petch-Hall equation.

4.1.1 Optical microscopy
The ring was cut transversely to the weld direction, in 15 mm thick pieces, Figure 10. The samples were ground, polished and then etched to determine the grain size distribution by optical microscope. After sample preparation the grain size was measured in a quadric grid with 1 cm side by using the ASTM standard, see Figure 11. In the figure, the left hand side corresponds to the advancing side.

![Figure 10](image1.png) Schematic view of sample cutting.

![Figure 11](image2.png) Typical grain structures in the weld zone.
In the steady state condition the nugget gets wider and the hardness is much softer than in the cold weld. This indicates that there are different flow patterns of the material for the two conditions. The nugget in both conditions are dynamically recrystallised and the thermo mechanically affected zone (TMAZ) is partially recrystallised.

4.1.3 Hardness measurements
The hardness was measured in a quadric grid with 1 cm sides, by Rockwell, HRF. The hardness is investigated in the same locations as the grain size. In paper A two locations are investigated, one in the beginning of the weld when the weld condition is cold and the other in the steady state area. The typical hardness profile in the steady state weld zone looks as in Figure 12. Looking at the cold welds the hardness is not as low as in the steady state welds in the middle of the weld i.e. nugget and in the thermal mechanical affected zone. But have the same hardness in the heat affected zone and in the base material.

![Figure 12](image)

**Figure 12** Hardness over the weld zone.

In the nugget the grain size is small and the hardness is low, this indicates that the material has softened by welding. The base material was cold deformed before welding and when the material was welded, the nugget was recrystallised. The thermal mechanical affected zone became partially recrystallised and the heat affected zone was heat treated. In this paper the affect of the grain size on the hardness were calculated by using the Petch-Hall equation. The equation illustrates the correlation between fine grain size and higher yield strength. These welds demonstrate the opposite, due to recrystallisation. Therefore, the grain size contribution to the hardness is very small.

4.2 Paper B
The purpose of paper B was to look at the weld structure, and to examine if the observed grain size by optical microscope was the same as that observed with electron back scatter diffraction (EBSD), in different locations of the weld. Moreover, the orientation and the average intra grain misorientation of the structure were investigated. Copper has annealing twins and these can be counted by using EBSD, thereby the size of the thermal mechanical affected zone can be decided. In this investigation the steady state condition was studied.

4.2.1 Scanning Electron Microscope
Scanning Electron Microscope (SEM) has been used in paper B to characterize inclusions, voids, grain size and the appearance of twins. The samples in Figure 13 are taken 25 mm from the shoulder. It can clearly be seen that there is a large difference between the grain size in the nugget (5-20 mm from the centre) and in the sample 25, 50 and 60 mm from the weld centre.
Figure 13 SEM pictures taken from the middle of the weld, 25 mm down from the shoulder, 5 mm to 60 mm from the centre. These pictures show the change from fine grain to coarse grain structure. a) 5 mm b) 10 mm c) 15 mm d) 20 mm e) 25 mm f) 50 mm g) 60 mm.

4.2.2 Electron Backscatter Diffraction
In the last ten years the Electron Backscatter Diffraction (EBSD) has become a well established technique linked to SEM to study deformed and recrystallised microstructures. The electron beam is scanned over the sample on a grid of points and at each point a diffraction pattern, so called Kikuchi pattern, are formed by back-scattered electrons. Earlier the measurements were conducted in conventional SEM but nowadays a field emission gun (FEG) SEM with a much higher resolution is used. This equipment is combined with software to analyse the diffraction patterns.

Regions less than one micrometer can be analysed crystallographically for both crystallographic structure and orientation. But, the step size is varied due to type of problem, and both a large and a small step can be used. If many patterns are taken, the texture can be mapped or pole figures constructed. Large sample areas can be measured by automatically moving the SEM stage between successive maps.

The crystal orientation map reveals the positions of grains and grain boundaries in the sample microstructure. In crystal orientation mapping a grain is defined by the collection of neighbouring pixels in the map which have a misorientation less than a certain threshold angle, in our case 10°. The distribution of grain sizes can be measured from the data collected in the map. Some boundaries satisfy certain geometrical criteria and their presence in a material may confer particular properties.
The individual crystal orientation measurements collected by crystal orientation mapping can be used to show the crystallographic textures developed in the sample. The various textures in the sample can be separated automatically, their volume fractions calculated, and the regions of the sample from which they originate shown. The technique is extremely suitable for measuring grain/sub-grains and the participation twins in recrystallised or deformed structure.

The texture can be represented as a stereographic projection (pole figure) of the directions of selected crystal planes (poles). The orientation distribution close to a particular texture will appear as a cluster of points on the pole figure. Textures can also be plotted as a three dimensional plot of the three Euler angles associated with each orientation measurement.

The orientations can be colour coded according to the Euler angles at each point and the grain boundaries can be printed as black lines. These lines will be written if the neighbouring points have a difference in orientation larger than 10°. Sub grain boundaries show a white line when the difference between the neighbouring points is more than 2°.

Intra-grain misorientation is another parameter of interest when looking at deformation and recrystallisation. When all points have received an orientation and the grain boundaries have been identified an average orientation of each grain can be obtained. The intra-grain misorientation is defined as the deviation from the average orientation, within a grain. The grains have been color coded according to the intra-grain misorientation value within each grain, giving each grain a uniform color. The change in intra-grain misorientation can be seen as a measurement of the dislocation storage and therefore it is a good representation of local deformation. Another parameter that can be calculated is the presence of twins in the material. When the grain boundary statistics are evaluated the quantity of the misoriented boundaries can be illustrated, if there is a peak at 60° it is due to annealing twins (111).

The EBSD measurements in paper B were performed in a LEO Gemini 1530 FEG-EBSD. Orientation imagines maps where the grains are colour coded according to the Euler angles, have been analysed for different locations off the weld. These maps showed that the texture is the same all over the weld-zone. In this study friction stirred welded oxygen free copper with 30-60 ppm phosphorus (Cu-OFP) has been studied, in [60] other friction stirred copper materials have been studied showing similar result.

The intra-grain misorientation and the average grain size have been calculated. The intra-grain misorientation showed a misorientation between 0° and 3°, indicating different deformation in different areas of the weld. The average grain size shows the same result as the calculated in optical microscope. The presences of twins have also been looked at, showing a large difference in different locations. There are no large misorientation within the grains in the nugget and the root, but 25 mm from the weld centre the misorientation is large. This confirms that this area lies within the Thermal Mechanical Affected Zone (TMAZ) and is partially recrystallised. Moreover, the root has many more annealing twins than the nugget. This indicates that the nugget has experienced deformation after recrystallisation. The grain size statistics show that the root of the weld has the smallest grains. Both the average and maximum grain size at 25 mm from the weld centre is considerably larger than the grains within the nugget. In this analysis, all grain measurements smaller than 5 pixel points were removed.

4.3 Paper C and D
Rosenthal’s model is used in paper C and D to compare experimental temperature data and to correlate heat flow to the grain size and the hardness distributions. The model showed good agreement with the measurements made by TWI. The outcome of the correlation between temperature, grain size and hardness showed that the steady state model shows a

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higher temperature and thereby gives smaller grain, than in the case when the welding have not yet reached steady state. A model involving heat transfer, material flow, and continuum mechanics has been developed in paper C and D. Below the modelling will be described briefly. The first model developed was two-dimensional. This model illustrates the influence of heat influx on the canister with a welding tool in a steady state, see Figure 14. But in order to simulate the effect of tool moving along the welding line, three-dimensional models were developed. The geometry models are following the development at TWI. First they used a plate model, where two plates were pressed together in a milling machine, Figure 15. The second model consists of two rings, Figure 16. The third model represents the FSW machine at SKB canister laboratory, Figure 17. This model has two different appearances, depending on development. The canister for holding nuclear fuel waste consists of a cylinder with a bottom cover, and a lid that has to be welded to the cylinder.

![Figure 14](image14.png) 2-D model of the FSW process.  
![Figure 15](image15.png) 3-D model of the plate.  

![Figure 16](image16.png) 3-D model of the ring.  
![Figure 17](image17.png) 3-D model of the full canister.

### 4.3.1 Comparisons and validation of temperature distributions predicted by different approaches

The steady-state solutions from finite element plate model in paper C and D is compared with the experimental measurements conducted by SKB and TWI [7] showing good agreement. Rosenthal’s solution is also compared with work done by SKB and TWI. Generally speaking, it yields a similar result as the experimental simulation. The maximum deviation is about 2.8%, which occurs at 47 mm from the welding centre.

The comparison shows that the partial differential equations and the boundary conditions adopted in the finite element model, in this case the plate model, are appropriate in general even though a further adjustment of physical parameters is necessary. It suggests that the
models proposed have the potential to solve similar physical problems with a more complex geometry.

The steady state solutions have been compared with experimental temperature observations as well as analytical solutions, showing good agreement. The result shows that the temperature distribution is affected by the welding speed. Moreover, for a given reference point perpendicular to the welding direction, a lower welding speed corresponds to a higher peak temperature. It also shows that the plunging position of welding tool influences the temperature distribution and therefore the displacement distribution of the weldment. This shows that it is possible to govern the weld result also with the positioning of the weld.
5 CONCLUDING REMARKS

During the first stage of the project the work concentrated on microstructure development in the FSW process. Grain size and hardness distributions were obtained by microscopic measurements.

The Electron Back Scatter Diffraction (EBSD) technique was used to study the annihilation of twins as well as the distribution of grain size. It has been observed that when a material starts to deform, dislocations gradually destroys the existing twin boundaries, and the apparent number of twins is reduced. However, a following recrystallisation will give rise to the formation of twins again. Therefore, the number of twin boundaries has been used as a marker for identifying the level of recrystallisation after welding.

Much of the later work has been focused on the characterisation of the FSW process through modelling, both analytically and numerically. The first model studied was analytical and based on Rosenthal’s medium plate temperature equations. It is simple to use, but has limitations in certain aspects. The finite element modelling was initially performed with a two-dimensional geometry. Due to the requirements of describing both the heat flow and the tool movement, three-dimensional models were developed. These models cover the principles of basic physics by taking into account heat transfer, material flow, and continuum mechanics. The geometries of the models are based on the simulation experiments that were carried out before. At the current stage, direct geometry modelling of the tool itself is excluded. The effects generated by the rotation of the welding tool are simplified by boundary modelling.

- The appearance of the nugget and the grain size depends on the position of the weld. A large difference can be seen between the start of the weld and the steady welding state. Cold weld gives a small nugget with high hardness, and steady state shows an opposite tendency.
- The EBSD orientation maps show a fine uniform equiaxed grain structure.
- There is no large misorientation within grains in the nugget and root. But at a distance of 25 mm from the weld centre line the misorientation becomes large, suggesting a partially recrystallisation occurred in the area.
• The root of the weld exhibits the smallest grains and many annealing twins. This may be due to deformation after recrystallisation.

• A finite element model including heat transfer, material flow, and continuum mechanics has been established. The steady state solutions have been compared with temperature measurements, showing good agreement.

• The temperature distribution is influenced by the welding speed. For a given reference position perpendicular to the welding direction, a lower welding speed corresponds to a higher peak temperature.

6 FUTURE WORK

The material flow in the FSW process can be divided into two components, material flow along the welding direction and material rotation around welding tool. In the current finite element model the material flow in the FSW process is simplified, and only the flow along the welding direction is considered. A new model will be developed to include both flow components. Material flow in this model will be assumed to behave as a high viscosity fluid. The available data on flow stress during hot working of copper will be used to assess the viscosity.

It is essential to compare the modelling results of material flow with the observations during FSW process. Unfortunately, the material flow is very difficult to observe in partially or fully recrystallized copper. To study the flow, special welding trials on copper with particle artefacts should be carried out. The markers will follow the flow and mix with the copper. From studies on FSW of aluminium alloys it has been demonstrated that such a mixed flow generates easily observed flow pattern if the marker material is properly chosen.

When the heat transfer and the material flow have been modelled successfully they can be used to predict the microstructure evolution. Previously, the recrystallisation and grain growth have been studied during hot working of copper. Although far from straightforward, these results will be transformed so they can be used in the present modelling.

Another very interesting question that needs to be investigated is how big the process window is and what controls the start up of the process, before steady state. How much can the rotation speed of the tool or shoulder change before void formation emerges? Which of the parameters must be closely controlled? Between which temperatures is it safe to be within? This is some of the questions regarding this but there are lot more, and these will be investigated further.
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APPENDED PAPERS

Paper A
Microstructure development in copper welded by the FSW-process
T. Källgren, R Sandström

Paper B
Microstructure and temperature development in copper welded by the FSW-process
T. Källgren, R Sandström
4th International Symposium on FSW, Park City, USA, April, 2003.

Paper C
Finite Element Modeling of Temperature Distribution in Friction Stir Welding Process and Its Influence on Distortion of Copper Canisters
T. Källgren, L.-Z. Jin, R Sandström

Paper D
Finite Element Modelling of Friction Stir Welding on Copper Canister
T. Källgren, L.-Z. Jin, R Sandström