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EFFECT OF TOOL GEOMETRIES ON BUTT DISSIMILAR FRICTION STIR
WELDS OF 5754 ALUMINIUM

for

MASTERS DISSERTATION

by

RANDALL DWAIN REDDY (200834027)

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at the

UNIVERSITY OF JOHANNESBURG

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CO-SUPERVISOR: MR. D. MADYIRA

OCTOBER, 2015
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ABSTRACT

Friction Stir Welding (FSW) is regarded as the most significant development in joining over the past two decades. In FSW, process parameters and tool geometry play a fundamental role in obtaining desirable mechanical properties and microstructures in the welded zone. The tool geometry plays an important role in producing sound friction stir welds. Tool designs are however, generally propriety to individual researchers and only limited information is available in open literature. There are however, continuous efforts to understand the material flow and the influence that the FSW tool design has on the friction stir welded material. Within industries that use various welding techniques it well known that FSW is particularly suited for the welding of aluminium; there is great potential for FSW of copper. Given the limited supply, high cost, copper theft and commercial demand associated with copper, engineers and scientists will either attempt to reduce the quantity of copper consumed by industries or alternatively replace copper with a substitute metal that exhibits similar attributable properties. On account of the limited supply and consequently the high cost associated with copper and copper alloys; the need to join aluminium and copper and its’ alloys is anticipated to increase in the near future. FSW of dissimilar alloys/metals has attracted extensive research interest due to potential engineering prominence and inherent problems associated with conventional welding methods.

This research identifies the choice of suitable tool designs and process parameters to produce sound dissimilar friction stir welds of 5754 aluminium and C11000 copper. This research focuses primarily on determining the effect of FSW process parameters on the forces experienced by the FSW tool and the relationship that this has on the electrical conductivity properties of the friction stir dissimilar weld.

The experimental work was performed by completing dissimilar friction stir welds on 3 mm thick butt welds of the two materials by means of an I-stir FSW platform. During the experimental work, the rotational speed was varied between 600 and 1200 rpm in intervals on 300 related to low, medium and high rotational speeds respectively and four different FSW tool geometries were tested. The first tool was a new design with a unique shoulder topography and a cylindrical pin named the “Reddy tool”. The second tool was a tool consisted of a concave shoulder and conical pin. Tests were performed using the second tool at a 0 degree tilt and at a 2 degree tilt relative to the work-piece. The third tool consisted of a concave shoulder and cylindrical pin. The forth tool design consisted of a flat shoulder and a cylindrical pin.

This research forms part of the initial experimental work to determine the forces and electrical resistance of dissimilar friction stir welds of aluminium and copper by employing different tool shoulder designs. The welds were characterised through visual inspection, weld defect and material flow analysis, microstructural evaluation, electrical resistance measurements and tool forces and tool torque analysis.

Microstructural evaluation results revealed complex flow patterns of copper and aluminium material. Lamellae structures composed of copper particles with a streamline shape and continuous aluminium strips were present. Some evidence of dynamic recrystallization was observed in the nugget of the defect free welds. Based on material flow evaluation and defect formation results, the Reddy tool design is most suitable for high and low rotational speeds, the conical Shoulder tool at no tilt is most suitable for medium rotational speeds, the conical shoulder tool at a two degree tool tilt is most suitable for medium rotational speeds, the
concave tool is most suitable for medium rotational speeds and the flat shoulder tool is most suitable for low rotational speeds. Weld defect and material flow results indicate that the material flow pattern changed significantly according to the tool shoulder geometry. Defects were observed in a majority of the dissimilar friction stir welds however defect free welds were achieved with the concave shoulder tool design and conical shoulder tool design at 0-degree tilt angle at a rotational speed of 900 rpm. A comparison of the suitability of the tool shoulder design according to rotational speed showed a 40% accuracy between deductions made from the top surface of the weld and the weld cross sectional area.

Electrical resistivity measurements revealed that the relationship between tool shoulder geometry and the electrical resistivity is complex in nature. No evident pattern was observed and each tool shoulder geometry varied in effect due to the change in rotational speed. Despite large defects, the dissimilar friction stir welds contained good electrical resistivity properties. Besides the Reddy tool, which was found to be inappropriate to achieve welds with low electrical resistivity properties, the remaining tool designs all had a similar electrical resistivity and when grouped according to the rotational speed parameter fall within the range of 0.06Ω-0.104Ω for a low rotational speed of 600 rpm, 0.194Ω-0.225Ω for a medium rotational speed of 900 rpm and 0.046Ω-0.393Ω for a high rotational speed of 1200 rpm.

Tool force and torque analysis revealed that for dissimilar friction stir welds between aluminium and copper the tool shoulder design substantially affect the instantaneous forces and torque experienced by the tool. Findings suggest that the tool shoulder geometry can affect the uniformity and weld properties along the length of a friction stir weld. Results for the averaged forces indicate that the downward force, transverse force and side force all decreases with an increase in rotational speed. Each tool design was however influenced differently with an increase in rotational speed. The axial force, transverse force and tool torque follow a similar trend to each other. The side force follows no apparent relationship with the axial force or transverse force however; the magnitude of the side force is considerably less when compared to the axial and transverse force. Results show that the rotational speed and tool design both significantly affect the torque experienced by the tool. The “flat shoulder type” referring to the Reddy tool and flat shoulder tool appears to have a high torque at low rotational speeds and a low torque at high rotational speeds. Low rotational speeds have little effect on the tool torque, as the rotational speed transitions between the medium and high rotational speeds the tool torque is significantly effected and the tool shoulder design plays a more significant role. Results show that the rotational speed effects the torque on the employed tool designs as follows: The most effected tool was the flat shoulder followed in order of highest to lowest effect by the conical shoulder tool at a 2 degree tilt, the concave shoulder tool, the Reddy tool and lastly the conical shoulder tool at 0 degree tilt. Therefore selection of the appropriate rotational speed for each tool design is an extremely important when completing dissimilar friction stir welds of aluminium and copper.
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<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>FSW</td>
<td>Friction Stir Welding</td>
</tr>
<tr>
<td>HAZ</td>
<td>Heat affected zone</td>
</tr>
<tr>
<td>MPa</td>
<td>Mega Pascal</td>
</tr>
<tr>
<td>mm/min</td>
<td>Millimetre per minute</td>
</tr>
<tr>
<td>rpm</td>
<td>Revolutions per minute</td>
</tr>
<tr>
<td>SZ</td>
<td>Stir Zone</td>
</tr>
<tr>
<td>TMAZ</td>
<td>Thermo-mechanically affected zone</td>
</tr>
<tr>
<td>TWI</td>
<td>The Welding Institute</td>
</tr>
<tr>
<td>HV</td>
<td>Vickers hardness</td>
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NOMENCLATURE

\( T_a \)  
Ambient temperature

\( \theta \)  
Angle between radial vector and work piece

\( A \)  
Area

\( \rho \)  
Density

\( \epsilon \)  
Emissivity

\( \zeta \)  
Extent of slip

\( \beta \)  
Factor of plastic deformation

\( \mu \)  
Friction co-efficient

\( J_w \)  
Heat generated by work piece

\( J_T \)  
Heat generated by tool

\( h_b \)  
heat transfer coefficient at bottom

\( S_b \)  
Heat generation rate per unit volume

\( \dot{e}_f \)  
Heat generated through friction

\( \dot{e}_s \)  
Heat generated through plastic deformation

\( \dot{e}_p \)  
Local heat generation

\( \Phi \)  
Material flow field condition

\( \gamma \)  
Non-Newtonian viscosity

\( \Omega \)  
Ohm

\( P \)  
Pressure

\( r \)  
Radial distance from tool centroid axis

\( \omega \)  
Rotational speed

\( \tau \)  
Shear yield stress

\( C_p \)  
Specific heat capacity at constant pressure
<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant</td>
</tr>
<tr>
<td>$R$</td>
<td>Surface radius of tool</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
</tr>
<tr>
<td>$U$</td>
<td>Welding speed</td>
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GLOSSARY OF TERMS

A

- **Advancing side** – the advancing side is the side of the weld where the local direction of the rotating tool is in the same direction of traverse.
- **Alloy** – A substance having metallic properties and being composed of two or more chemical elements of which at least one is a metal.
- **Alloying element** – An element added to and remaining in metal that changes structure and properties.

B

- **Backing plate** – A layer of material that is placed below the joint interfaces of the materials to be welded. It provides a surface to oppose the vertical downward force on the material and protects the machine bed.
- **Butt weld** – A welded joint formed between the squared ends of the two joining pieces, which come together but not overlap.

C

- **Clamping System** – the device used to hold, locate and prevent the work piece from moving during the large force involved in the FSW process.

D

- **Defect** - A discontinuity or discontinuities that accumulate to render a weld or part unable to meet minimum acceptance standards or criteria of the design specifications.
- **Deformation** – is a change in the form of a body due to stress, thermal, or other causes.
- **Ductility** – the ability of a material to deform plastically before fracture.
- **Dwell time** – the period of time after the rotating tool has been plunged into the work and for which it remains stationary, generating frictional heat and plasticizing the materials, before commencing the traverse along the joint (seconds).

E

- **Equilibrium** – a state of dynamic balance between the opposing actions, reactions, or velocities of a reversible process.
- **Etchant** – a chemical solution used to etch a metal to reveal structural details.
• **Etching** – subjecting the surface of a metal to preferential chemical or electrolytic attack to reveal structural details for metallographic examination.

• **Extrusion** – the process where a material is shaped by force or squeezed through a die or nozzle.

• **Exit hole** – a hole left at the end of the weld when the FSW tool is withdrawn, resulting from displacement of material during the plunge. Some special techniques are in-use to fill or prevent the occurrence of this hole.

F

• **Fusion** – the melting together of filler metal and base metal, or of base metal only, which results in coalescence.

• **Fusion welding** – any welding process that uses fusion of the fusion of the base metal to make the weld.

• **Friction** – the force required to cause one body in contact with another to begin to move.

• **Friction Stir Welding** – is a process developed at The Welding Institute (TWI) that utilizes local friction heating to produce continuous solid – state seams. It allows butt and lap joints to be made without the use of filler metals. The solid – state low distortion welds produced are achieved with relatively low costs using simple and energy – efficient mechanical equipment.

G

• **Grain** – an individual crystallite in metals.

• **Grain growth** – an interface separating two grains at which the orientation of the lattice changes from that of one grain to that of the other. When the orientation change is very small, the boundary is sometimes referred to as a sub-boundary structure.

• **Grain size** – a measure of the areas or volumes of grains in a polycrystalline metal or alloy, usually expressed as an average when the individual sizes are fairly uniform. Grain size is reported in terms of number of grains per unit area or volume, average diameter, or as a number derived from area measurements.

• **Grain boundary** – an interface separating two grains, where the orientation of the lattice changes from that of one grain to that of the other.

• **Grinding** – removing material from the surface of a work piece using a grinding wheel or abrasive grinding papers.

H

• **Hardness** – a term used for describing the resistance of a material to plastic deformation.

• **Hardness test** – measures the resistance of a material to penetration by a sharp object.

• **Hardening** – increasing hardness by suitable treatment.

• **Heat- Affected Zone** - The portion of the base metal which has not been melted, but whose mechanical properties have been altered by the heat of welding or cutting.

• **Homogenous** – a chemical composition and physical state of any physical small portion and are the same as those of any other portion.
• **Hot working** – deformation under condition that results in recrystallization.

I

• **Indentation hardness** – is it the hardness as evaluated from measurements of an area of an indentation made by pressing a specified indenter into the surface of a material under specified static loading conditions.

• **Intermetallic compounds** – is any solid material, composed of two or more metal atoms in a definite proportion, which has a definite structure which differs from those of its constituent metals.

J

• **Joint efficiency** - The ratio of the strength of a joint to the strength of the base metal, expressed in percent.

M

• **Macrograph** – a graphic reproduction of a prepared surface of a specimen at a magnification not exceeding 25x.

• **Macrostructure** – the structure of metals as revealed by macroscopic examination of the etched surface of a polished specimen.

• **Magnification** – the ratio of the length of a line in the image plane to the length of a line on the imaged material.

• **Mechanical properties** – the properties of a material that reveal its elastic or inelastic behaviour when force is applied, indicates the suitable mechanical applications.

• **Mechanical testing** – the determination of mechanical properties.

• **Metallurgy** – The science and technology of metals and their alloys including methods of extraction and use.

• **Microstructure** – The structure of a prepared surface of a metal as revealed by a microscope at a magnification.

O

• **Onion-skin flow pattern** – a characteristic weld pattern featuring a cyclic ring or onion skin-like profile.

• **Oxidation** – the addition of oxygen to a compound
Parameter – The minimum and maximum parameters will describe the operating range of a variable.

Parent material – this is the sheet metal plate in its as manufactured form, as supplied.

Plastic deformation – is the distortion of material continuously and permanently in any direction. The deformation that remains or will remain permanent after the release of the stress that caused it.

Plasticity – capacity of a metal to deform non-elastically without rupturing.

Polished surface – a surface that reflects a large proportion of the incident light in a peculiar manner.

Plunge depth – the plunge depth is the maximum depth that the tool shoulder penetrates into the weld plates.

Plunge force – during the plunging stage of the tool pin in FSW, the vertical force in the direction of the Z-axis movement is normally referred to as the plunging force.

Porosity - A rounded or elongated cavity formed by gas entrapment during cool down or solidification

Recrystallization – a change from one crystal structure to another, such as that occurring upon heating and / or cooling through a critical temperature.

Residual stress – stress in a body which is at rest and in equilibrium and at uniform temperature in the absence of external and mass force.

Retreating side – the retreating side of the tool is where the local direction of the weld surface due to tool rotation and the direction of the traverse are in the opposite direction.

Rotational speed – the tool rotation speed is the rate of angular rotation (usually specified in rpm) of the tool about its axis.

Scanning Electron Microscope – an electron microscope in which the image is formed by a beam operating simultaneous with an electron probe scanning the object.

Side flash – in FSW, a build-up of weld material, normally on the retreating side of the rotating tool, which has a ‘peel-like’ effect is termed side flash.

Solid – phase – A physically homogenous and distinct portion of a material system in the solid state.

Spindle speed – also referred to as the rotational speed, is the speed of the work holding device (chuck), measured in revolutions per minute.

Spindle torque – the spindle torque required to rotate the FSW tool when plunging into and traversing through the work piece along the joint (Nm).
**T**

- **Tensile strength** – the maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried out to rupture, and the original cross-sectional area of the specimen.
- **Tensile test** – measures the response of a material to a slowly applied axial force. The yield strength, tensile strength, modulus of elasticity and ductility are obtained.
- **Tool shoulder** – part of the welding tool which rotates and is normally disk-shaped.
- **Tool pin** – the part of the tool that rotates in contact with the surface of the work piece.
- **Tool plunge** – the process of forcing the tool into the material at the start of the weld.
- **Tool tilt angle** – the angle at which the FSW tool is positioned relative to the work piece surface, that is, zero tilt tool are positioned perpendicular to the work piece surface (degrees).
- **Traverse speed** – also referred to as feed rate, it is the speed at which the rotating FSW tool is translated along the joint line (mm/min).

**U**

- **Unaffected material** – the bulk of material which is not affected by either heat or deformation during the welding process.

**V**

- **Vickers hardness number** – a number related to the applied load and the surface area of the permanent impression made by a square-based pyramid diamond indenter.
- **Void** – the space that exist between particles or grains. Normally in welding, voids are associated with defects and incomplete penetration.

**W**

- **Welding** – the process of joining, in which materials are enabled to form metallurgical bonds under the combined action of heat and pressure.
- **Weld nugget or stir zone** – the recrystallized central area of the joint interface.
- **Weld root** – the part of the joint profile opposite the shoulder is designated the root of the weld.
- **Welding speed** – also known as the traverse speed is the speed (usually specified in mm/min) of the tool traverse along the work piece per specified time.
- **Work piece** – the component to be welded.
- **Worm holes** – a defect in FSW, usually on the advancing side of the rotating tool, due to lack of mixing and re-bonding of the plasticized material.

**X**

- **x-axis** – relating to a specific axis (horizontal) or a fixed line determining the direction of movement or placement in a 2 Dimensional or 3 Dimensional coordinate system.
**Y**

- **y-axis** – relating to a specific axis (perpendicular to x-axis) or a fixed line determining the direction of movement or placement in a 2D or 3D coordinate system.

**Z**

- **z-axis** – relating to a specific axis (vertical) or a fixed line determining the direction of movement or placement in a 2D or 3D coordinate system.
1. Background

Friction Stir Welding (FSW) is considered to be the most significant development in joining over the past two decades. FSW was invented and validated by Wayne Thomas and his team in 1991 at The Welding Institute (TWI), of the United Kingdom, as a solid-state joining technique. [47]

Friction Stir Welding (FSW) has made it possible to join materials that were previously difficult to weld in a reliable manner. After recognising the superiority of FSW as a solid state welding technique and due to successful industrial applications in the rolling stock-, automobile-, shipbuilding and aircraft- industry research work has increased substantially in recent years. This is considered to be abnormal because conventionally research of technologies usually precedes industrial applications. [48] Among other research topics a substantial amount of research effort has been put into understanding the FSW process parameters and its effect on the mechanical properties, heat input and generation, microstructural evolution, the movement and mixing of the welded material and process tolerances. Early research was first concentrated on establishing the process windows for similar aluminium alloys. Studies show that the 6XXX series has a much larger process windows than other series aluminium alloys. FSW then progressed to investigations of dissimilar aluminium alloys. The rapid development of the FSW process in aluminium alloys (similar and dissimilar) and its successful implementation into commercial applications has motivated its application to other non-ferrous materials (Mg, Cu, Ti as well as their composites), steel and thermoplastics. FSW has become increasingly popular in applications in aviation, manufacturing, electrical and automobile industries owing to the energy efficiency, the environmental friendliness and versatility of the FSW technique. Mishra [1] has compiled an excellent literature review for FSW. Mishra states that it is widely accepted that material flow within the weld during FSW is very complex and still poorly understood.

Welding parameters such as the tool design, tool rotation speed, transverse speed, tool tilt angle, target depth are all crucial to produce a sound and defect-free friction stir weld. The tool geometry plays an important role in producing sound friction stir welds. Tool designs are however, generally propriety to individual researchers and only limited information is available in open literature. There are however continuous efforts to understand the material flow and the influence that the FSW tool design has on the friction stir welded material. Within industries that use various welding techniques it well known that FSW is particularly suited for the welding of aluminium; there is great potential for FSW of copper. Copper and copper-based alloys are widely used in the electrical and process industries because copper is an excellent conductor, is corrosion resistant, and is easily shaped (malleable). [4] Typical applications for copper include: magnetic resonators, heat exchangers, air conditioners, coolers for metallurgical ovens, bus bars for electrolysis and superconductors. Given the limited supply, high cost, copper theft and commercial demand associated with copper, engineers and scientists will either attempt to reduce the quantity of copper consumed by industries or alternatively replace copper with a substitute metal that exhibits similar attributable properties. On account of the limited supply and consequently the high cost associated with copper and copper
alloys; the need to join aluminium and copper and its’ alloys is anticipated to increase in the near future.

Aluminium has several properties that set the metal apart from other metals. Aluminium is a third of the weight of steel, has a high strength-to-weight ratio, is corrosion resistant and aluminium possesses good thermal and electrical conductivity properties. In fact, aluminium has about 60% of the conductivity of copper and incorporating the densities of the two materials, aluminium has a relatively higher conductivity than copper per unit mass. [3] Aluminium is therefore an attractive substitute material for copper. Friction Stir Welding (FSW) of aluminium and copper is advantageous because alloying of copper to aluminium is done to enhance the mechanical strength of the material through solid-solution strengthening which tends to diminish resistance to corrosion and alloying of aluminium to copper is done to enhance strength.

Joining of dissimilar materials is one of the challenging tasks facing modern manufactures. The FSW process is a solid-state joining technique and an alloy is essentially created at the joint interface between dissimilar materials. The weldability of dissimilar metals is determined by their atomic diameter, crystal structure and compositional solubility in the liquid and solid states. Friction Stir Welding (FSW) aluminium and copper provides an opportunity to reduce the quantity of copper consumed by industries by offering an effective substitute ‘material’ that portray similar mechanical, electrical and thermal properties to copper. Combining these two materials offers various engineering and industrial benefits, particularly for electrical-, heat-exchanger- and condenser- applications.

The Friction Stir Welding (FSW) process involves plunging a non-consumable tool between the abutting edges of the two plates to be butt-welded, transversing the tool along the joint line (at a predetermined rotational speed and feed rate), and at the end retracting the tool from the welded materials [2]. The FSW process may seem remarkably simple however FSW involves some rather complex thermal and material flow dynamics. Many weld configurations are achievable using the FSW process. This research was limited to conventional butt dissimilar friction stir welds of aluminium and copper. The fundamental difference between conventional welding techniques and the solid-state FSW technique is that no heat is added to the ‘system’; instead heat is generated internally by means of friction between the tool-material interface and plastic deformation.

The tool is the fundamental component of Friction Stir Welding (FSW) and has evolved empirically based on observations of forces, weld defects, rotational speeds, transverse speeds and material flow [2].
1.1 Welding of Aluminium and Copper

1.1.1 Aluminium

Aluminium (Al) is the second most popular welded metal because of the material’s unique combination of light weight and high strength. Aluminium is however difficult to weld using conventional methods.

Welding of aluminium and its alloys differs from the welding of steels in that aluminium has a:

- Aluminium oxide surface coating.
- High thermal conductivity.
- High thermal expansion coefficient.
- Low melting temperature.

Aluminium is an active material that reacts with oxygen present in air. The reaction forms a thin hard aluminium oxide film on the surface of the aluminium. This is significant to welding of aluminium because the melting point of aluminium oxide is 1926 °C which is approximately three times that of pure aluminium (660 °C). Thickening of the aluminium oxide film allows absorption of moisture present in air. Moisture is a source of hydrogen which causes porosity in aluminium welds. Hydrogen is an important consideration when welding aluminium because hydrogen is soluble in molten aluminium and rejected during solidification. Rapid cooling rates of aluminium welds causes preservation of free hydrogen. Free hydrogen causes porosity which decreases the weld strength and ductility and can be highly detrimental depending on the amount formed.

Prior to completing welds of aluminium or its alloys, the aluminium oxide film needs to be removed. If the film is not removed, solid oxide will be trapped in the weld pool. The result is a reduction in ductility and a lack of fusion; both of which initiate weld cracks. Aluminium welding is different to carbon steel welds due to the material’s thermal conductivity and melting point. Due to the high thermal conductivity of aluminium, preheating is frequently used for the welding of thicker sections. The thermal expansion of aluminium is twice that of steel and a change in dimension may cause distortion or cracking of the weld. Although welding aluminium has its difficulties when compared to carbon steels; high quality welds are possible if all the welding process variables are adequately controlled.
1.1.2 Copper (Cu)

Copper and copper-based alloys are widely used in the electrical and process industries. Copper has high conductivity and corrosion resistant properties. Copper -similar to aluminium- requires extra considerations compared to welding of steels.

Listed below are copper alloy properties that require special attention when welding copper:

- High thermal conductivity.
- High thermal expansion coefficient.
- High melting point of 1085°C.
- Copper is hot short (brittle at elevated temperatures).
- Copper has high electrical conductivity.
- Copper owes much of its strength to cold working.

Copper has the highest thermal conductivity of all commercial metals and a greater thermal conductivity than aluminium. Copper has a relatively high coefficient of thermal expansion which is approximately 1.5 that of carbon steels. Copper alloys are brittle at elevated temperatures because the alloying elements form oxides at the grain boundaries which results in embrittlement of the material. All copper alloys derive their strength from cold working. The heat of welding anneals the copper in the Heat Affected Zone (HAZ) adjacent to the weld and reduces the strength provided by cold working [2]. The weldability of copper and aluminium is presented in Table 1.1.

Table 1.1 indicates the importance of Friction Stir Welding (FSW) in the joining of aluminium and copper. Six out of the ten considered common welding techniques either cannot or provide difficulty when attempting to weld aluminium or copper. Joining copper and aluminium together is even more difficult due the significant difference between the melting points of aluminium and copper. Melting of material has it’s disadvantageous since the process often involves pre and post processing to ensure material properties are not critically altered.

Welding aluminium and copper provides many restrictions and challenges. Additionally welding these two precious metals together is extremely difficult to accomplish. In recent years, considerable research has been conducted in the welding of non-ferrous materials. Two non-ferrous materials, aluminium (Al) and copper (Cu) are particularly difficult to join. Aluminium and copper both exhibit excellent combinations of mechanical, electrical and thermal properties. Combining these two materials offers various engineering benefits, particularly in electrical and thermal applications.
Table 1.1: Weldability of aluminium and copper [45].

<table>
<thead>
<tr>
<th></th>
<th>Aluminium</th>
<th>Copper</th>
<th>Weldability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction Stir Weld</td>
<td>A</td>
<td>A</td>
<td>EASY/RECOMMENDED</td>
</tr>
<tr>
<td>Gas</td>
<td>B</td>
<td>A</td>
<td>DIFFICULT/RESTRICTED</td>
</tr>
<tr>
<td>Braze</td>
<td>B</td>
<td>A</td>
<td>DIFFICULT/RESTRICTED</td>
</tr>
<tr>
<td>Electroslag</td>
<td>EXP</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Flux Cored Arc</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Gas Metal Arc</td>
<td>A</td>
<td>A</td>
<td>EASY/RECOMMENDED</td>
</tr>
<tr>
<td>Submerged Arc</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Plasma Arc</td>
<td>A</td>
<td>A</td>
<td>EASY/RECOMMENDED</td>
</tr>
<tr>
<td>Gas Tungsten Arc</td>
<td>A</td>
<td>A</td>
<td>EASY/RECOMMENDED</td>
</tr>
<tr>
<td>Shielding Metal Arc</td>
<td>C</td>
<td>C</td>
<td>DIFFICULT/RESTRICTED</td>
</tr>
</tbody>
</table>

A- Recommended or easily weldable; B- Acceptable but not best selection or weldable with precautions; C- restricted use or difficult to weld; NO- Not recommended and not weldable; EXP- experimental.
1.2 Problem Statement

Earlier investigations into Friction Stir Welding (FSW) aluminium and copper both separately and together have demonstrated a promising prospect for the application of FSW for joining various alloys of aluminium and copper. From the time it was achieved, continuous efforts has been put into optimisation of the FSW parameters to produce defect free welds. While trying to optimise the FSW process engineers and researchers have attempted to form an understanding of the microstructural evolution during FSW, which is a critical issue surrounding FSW of aluminium and copper.

This research identified the choice of suitable tool designs and process parameters to produce sound dissimilar friction stir welds of aluminium and copper. Joining these two materials together offers various engineering and industrial benefits, particularly in electrical and thermal applications. The research focused primarily on determining the effect of FSW process parameters on the forces experienced by the FSW tool and the relationship that this has to the mechanical and electrical conductivity properties of the friction stir dissimilar weld.

1.3 Objective

An investigation was done to achieve dissimilar friction stir welds of 3 mm thick plates of 5754 aluminium and C11000 copper using four tool designs, each with a different shoulder topography. The rotational speed was varied over a range of 600-1200 rpm and feed rate was fixed at 150 mm/min. The tools were selected because they are common tool designs used by industry. A new FSW tool was designed and the common tools were used as a benchmark to evaluate the effectiveness of the new tool design and the process parameters. After welding, force analysis, macro and micro-structure evaluation and electrical conductivity of the friction stir welded 5754 aluminium alloy and C11000 copper was completed. These tests were evaluated according to employed FSW process parameters to determine the effect of the process parameters on the mechanical and electrical properties.

The sub-objectives of the research were listed as follows:

1) To research and write a literature review regarding the Friction Stir Welding (FSW) process, FSW parameters, mechanisms involved during FSW and to complete a feasibility study on joining 5457 aluminium and C11000 copper using FSW.

2) To form structured approaches to analyse the behaviour of the materials following friction stir welding.

3) To analyses the friction stir welded cross-sectional area macroscopically and microscopically.
1.4 **Hypothesis Statement**

To investigate the effect of the tool shoulder design on the forces, torque experienced during friction stir welding as well as the electrical conductivity of the dissimilar friction stir weld upon completion. This research focuses only on butt welds of 3 mm thick plates of 5754 aluminium and C11000 copper for rotational speeds of 600 rpm, 900 rpm and 1200 rpm respectively and at a fixed feed rate of 150 mm/min. It was expected that the tool designs and the process parameters employed in joining the dissimilar friction stir butt welds will affect the evolving weld material properties.

1.5 **Research Methods**

Test samples of the research base metals were of dimensions 120 mm x 600 mm x 3 mm and the weld configuration was a butt weld. A butt weld is a joint formed between the square ends that do not overlap. The dimensions of each parent material plate and an example of a butt weld is presented in Figure 1.2 and Figure 1.3 respectively.

An extensive literature study was completed to ensure complete understanding of the Friction Stir Welding (FSW) tool design, process parameters and their influence on friction stir weld and feasibility of forming dissimilar friction stir welds between aluminium and copper.

Analysis and characterisation of the welded samples was evaluated by conducting macro and micro evaluation to determine material properties across the joint. Characterisation of the friction welds were completed using visual inspection, microscopy, force and torque analysis and electrical resistivity test.

1.6 **Delimitation of Research**

The following limitations were experienced in this research work:

- The project was limited to joining of 5754 aluminium alloy and C11000 copper.
- Only sheets of 3 mm thickness were used.
1.7 Assumptions

- The oxidation during the weld had negligible effect on the weld quality.
- All samples from the same batch had identical material properties.

1.8 Significance of Research

Within the University of Johannesburg: Expanding the research field of Friction Stir Welding.

General: Characterisation of the material properties attributable to fundamental process parameters of Friction Stir Welding (FSW) will further technical knowledge and understanding regarding the FSW process. Understanding the influence of tested process parameters on dissimilar friction stir butt welds of aluminium (Al) and copper (Cu) may expand the industrial use of FSW within the South African and international manufacturing industry in an effort to reduce the consumption of copper and its alloys. There is a deficiency of information regarding the tool forces and electrical conductivity of dissimilar friction stir welds between aluminium and copper. The current report forms part of the initial experimental work to determine the influence of fundamental process parameters (tool design and rotational speed) on the tool forces and conductivity of dissimilar friction stir welded aluminium (Al) and copper (Cu).

1.9 Organisation of the mini-dissertation

To ensure a systematic and effective approach was accomplished, the following flow of information is a guideline for the reader. Chapter 1 presented aims and objectives of the research project. A brief description was done on the FSW process and difficulties associated with conventional welding techniques for the welding of aluminium and copper.

An extensive literature review is presented in Chapter 2 discussing the fundamentals of the FSW process and the significance of FSW process parameters attributable to the FSW welding technique. Material properties of 5754 aluminium alloy and C11000 copper are discussed and the aluminium-copper metallurgy system is presented. The knowledge gap identified in researched literature was that there are no existing reports that fully characterise the influence of tool design on tool forces and torques as well as the electrical conductivity for dissimilar friction stir welds of aluminium and copper.

In chapter 3, the testing technology and experiment specimens used to conduct required analysis is presented so that confirmation of results can be achieved should it be required. To ensure valid results are obtained testing must adhere to required testing standards because even though an instrument may itself be highly accurate, the way in which it is applied can render results highly inaccurate [6]. In order to obtain valid comparisons for the considered FSW process parameters test conditions must be similar and repeatable.
Chapter 4 presents and discusses results in a systematic order. Results include macro and micro material mixing, mechanical properties, electrical resistivity analysis followed by tool force and tool torque analysis.

Chapter 5 includes conclusions made from completed test results and any future work that may be of interest or is necessary to fully characterise the tool design and electrical resistivity of dissimilar friction stir welds of 5754 aluminium and C11000 copper.
2. Introduction

This chapter forms the basis for understanding the fundamentals of the friction stir weld process and its parameters providing a foundation for the analysis of friction stir welds. The first section introduces the fundamental components of Friction Stir Welding (FSW) such as terminology applicable to FSW, process parameters, fundamental friction stir welding mechanisms and weldability of material and dissimilar friction stir welds. The second section discusses the metallurgical aspects of copper and aluminium including among other details such as the material properties and alloying ability of copper and aluminium. The material properties and solubility of the materials being friction stir welded is of imperial importance because friction stir welding is a solid-state joining technique that involves forms a solution of material at elevated temperatures at the joint. The third and concluding section of the literature review focuses on tool design and the effect the tool has the friction stir welding.

2.1. Friction Stir Welding

Friction Stir Welding (FSW) is a solid–state joining technique. During the FSW process, a non-consumable tool is plunged into the abutting edges of the plates and then moved along the joint line. In FSW the materials to be friction stir welded together the process parameters and tool geometry play fundamental roles and can significantly influence the joint integrity. The pin and shoulder are familiar features of the FSW tool and it is because of these features that FSW is possible. The FSW tool facilitates heat generation, containment of heat, containment of material and mixing of the two materials to produce the joint. Figure 2.1 depicts two separate plates undergoing the FSW process, in a configuration of the conventional butt-weld. The FSW process can be separated into three steps: 1) The FSW tool is plunged into the material, 2) The FSW tool is displaced in the direction of the weld at a certain rotational and transverse speed and 3) The FSW tool is withdrawn from the material.

![Figure 2.1: Steps of the friction stir weld process [22]](image)

It is common among welding engineers that the quality of a weld is dependent on both the weld parameters during welding and weld preparation prior to welding. Weld preparation for friction stir welds is minimal and involves the removal of surface oxides and
contaminates. Removal of the surface oxides and contaminates is essential for all welding techniques as these contaminates more often than not have a detrimental effect on the weld.

After completion of the necessary weld preparation activities, which include cleaning, clamping, and alignment of the tool and the material surfaces, the FSW machine is set to a predetermined rotation and transverse speed. The tool is plunged into the material to a specific plunge depth that is calculated taking into account the thickness of the work-piece, the desired depth of material mixing and any tool tilt used for the friction stir weld. The plunge depth taking into account the angle of approach is calculated using Figure 2.2 below.

![Figure 2.2: Calculation of plunge depth for tool tilt](image)

When the tool is plunged into the material the tool rotates but remains stationary in the transverse direction for a period of time referred to as the dwell time. The dwell time allows for a sufficient amount of heat to be generated from friction. The perpendicular force exerted - between the Friction Stir Welding (FSW) tool and the material welded - results in friction that generates intense, local heat. The FSW tool is transversed on top of the two surfaces to be welded at a constant feed rate and rotational speed. FSW can be completed using either position or force control. An interesting detail of the FSW process is that the surfaces of the abutting materials to be Friction Stir Welded are heated by both friction and plastic work [7]. Heat generated from friction is present to facilitate plastic deformation and the mixing of material; it must be noted however that the generated heat is not sufficient to melt the material undergoing the friction stir weld process. Due to this, the material properties across the joint show very little change to the parent material and it is for this reason that FSW is considered to be an effective welding technique.

The heat acquired from friction and plastic deformation during the FSW process softens the material and enables movement. Only material around the vicinity of the plunged hole is affected during the friction stir welding process. Material in direct contact with the tool displaces from the front to the back of the pin while the tool shoulder ensures that material is contained below the tool. As the pin travels tangential to the two abutting edges the work-piece material fills a hole created by the tool and results in a friction stir welded joint.
The main difference between conventional welding techniques and the solid-state Friction Stir Welding (FSW) technique is that no heat is added to the ‘system’; instead, heat is generated internally by means of friction between the tool-material interface and plastic deformation [8]. The generation of heat internally revolutionised the welding industry because no pre-heating, post-heating or brazing fluxes are necessary for FSW. No pre or post preparation is required because the FSW is a comparatively stable joining technique where the material is joined without melting. Thanks to FSW, materials with considerably different melting points that couldn’t be joined via conventional welding techniques can now be successfully welded together.

Friction Stir Welding (FSW) has become increasingly popular in applications in aviation, manufacturing, electrical and automobile industries owing to the energy efficiency, the environmental friendliness and versatility of the FSW technique [49, 50]. The number of applications is anticipated to grow exponentially as fabricators learn of the ease of application and property benefits attributed to FSW. Table 2.1 lists the fundamental benefits of FSW and is the justification on the growth potential of FSW.

Table 2.1: Key benefits of Friction Stir Welding [1]

<table>
<thead>
<tr>
<th>Metallurgical benefits</th>
<th>Environmental benefits</th>
<th>Energy benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid-phase process</td>
<td>No shielding gas required</td>
<td>Improved material use</td>
</tr>
<tr>
<td>Low distortion</td>
<td>Minimum surface cleaning required</td>
<td>Reduction in weight</td>
</tr>
<tr>
<td>Good dimensional stability and repeatability</td>
<td>Eliminate grinding waste</td>
<td>Only 2.5% of the energy needed for laser weld</td>
</tr>
<tr>
<td>No loss of alloying elements</td>
<td>Eliminate solvents required for degreasing</td>
<td>Decreased fuel consumption in aircraft, automotive and ship applications</td>
</tr>
<tr>
<td>Excellent mechanical properties in the joint area</td>
<td>Consumable materials saving, such as rugs and wires</td>
<td></td>
</tr>
<tr>
<td>Fine re-crystallized microstructure</td>
<td>No harmful emissions</td>
<td></td>
</tr>
<tr>
<td>Absence of solidification cracking</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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2.2. Friction Stir Welding Terminology

This section will describe typical weld regions and terminology used to describe friction stir weld joints.

2.2.1. Related weld regions for Friction Stir Welds

The welding terminology used for friction stir welds can most effectively be illustrated by use of a schematic. Figure 2.3 shows a typical cross sectional view of a friction stir welded specimen. As a result of the heat generated, heat transfer and the material flow, friction stir welded specimens, to some extent, all portray similar properties.

![Cross sectional view of friction stir weld showing microstructure regions](image)

Figure 2.3: Cross sectional view of friction stir weld showing microstructure regions [1]

Essentially, three regions are of interest in the friction stir welded cross sectional area. The regions are namely the weld nugget, Thermo-Mechanically Affected Zone (TMAZ) and the Heat Affected Zone (HAZ). The joint integrity is highly dependent on the properties of the weld nugget, TMAZ and HAZ regions.

2.2.1.1. Weld nugget

The weld nugget in Figure 2.3 is located close to the centre of the weld. This is where a majority of material mixing occurs. Material in the weld nugget region has undergone sufficient deformation at an elevated temperatures to hopefully achieve dynamic recrystallisation. The weld nugget consists of a very fine grain, 1-10μm grain size. Most of the grain boundaries within the nugget zone are high angled (disorientation between grains greater than 15°.) The two main variables that determine the properties of the material in the weld nugget are the peak temperature and the quenching rate from that temperature. Experimentation completed by TWI has shown that the region is influenced substantially by the combination of the tool design, welding parameters and alloy composition. [18] An interesting phenomenon that forms in the weld nugget is the formation on ring patterns. This has been studied by Fratini et al. [51] Fratini et al. [51]
explained through numerical modelling that the material on the retreating side of the tool enters the volume and rotates at the back of the tool. Krishan [52] conducted a similar study and explained through using a clay model that the formation of the onion ring is a geometric effect, he further stated that semi-cylindrical sheets of material is extruded for each rotation of the tool and cross sectional slice through the semi cylinders results in the onion ring pattern. One of the main requirements for a sound friction stir weld is to achieve dynamic recrystalisation within the weld nugget.

2.2.1.2. Thermo-Mechanically Affected Zone (TMAZ)

The Thermo-Mechanically Affected Zone (TMAZ) is the immediate region surrounding the nugget zone, lying between the Heat Affected Zone (HAZ) and nugget. The material in the TMAZ has been both heated and deformed but to a less extent to that experienced in the weld nugget. The TMAZ leads to a region of partially re-crystallised grains in which many of the fibrous grains are normally rotated. [8]

2.2.1.3. Heat Affected Zone (HAZ)

The Heat Affected Zone (HAZ) is similar to those in conventional welds although the maximum peak temperature is significantly less than the solidus temperature and the heat–source is rather diffuse.

2.3. Principles of heat generation

A significant feature of the Friction Stir Welding (FSW) that makes this welding technique unique to other welding techniques is that no heat is added to the system, the required heat is generated locally instead. As the name “Friction Stir Welding” suggests, heat is predominately generated by friction between the FSW tool and the surfaces undergoing the FSW process. As a result of the locally generated heat, compared to conventional welding techniques FSW is considered to consume substantially less energy and the material being welded is not subjected to sufficient heat energy to cause melting. FSW is considered to be a cold welding process as a result of the heat distribution which consequently causes a low level of residual stress and distortion within both materials [2].

Besides the initial and final periods of welding (i.e. during insertion and extraction of the pin) heat generation occurs at a fairly constant rate. Thus a steady state process – with regards to heat transfer – is created which by definition is the condition that prevails when the temperatures of fixed points within a heat-conducting body do not change with time and the time rate of heat flow between any two selected points is constant [9]. The steady-state assumption besides the initial and final periods of welding is further justified by the fact that the weld profile and properties remain roughly constant during the welding phase [7].

The National Research Council of Canada (NRCC) found that localised heat for the FSW process is generated by friction and plastic deformation. [8] Figure 2.4 depicts results of a simulation completed by Dong et al. [46]; the authors were able to show that heat generated by tool friction and plastic work. The model provides evidence that if the heat generated by friction is super-imposed with the heat generated by plastic deformation that
the maximum amount of heat energy exists directly below the FSW tool pin. As a result of this the maximum temperature also occurs at this point. Measurement of the temperature of the area directly below the tool is for practical purposes particularly difficult. Dong et al. [46] modelling played an important role in understanding the FSW process. However, little can be predicted concerning the location and intensity of the heat dissipation through plastic deformation during FSW, except that it occurs in the Thermo-Mechanically Affected Zone (TMAZ). [10]

Nadan et al. [7] stated that the maximum temperature occurs directly below the tool. This is due to the downward force exerted by the tool onto the work-piece. The friction generated heat between the FSW tool and the work-piece provides the thermo-mechanical deformation and intense plastic deformation to facilitate the flow of the plasticised metal. Dong et al. [46] and Nadan et al. [7] are both in agreement.

Heat generation is influenced by the tool rotation speed \( \omega \), the feed rate \( f \), the z-axis force \( F \), the angle between the radial vector and the work piece \( \theta \), the tangential speed of the tool with respect to the work-piece \( V \), the radial distance from the tool centroid \( r \), extent of slip \( \zeta \), the shear yield stress related to that in tension by the von Mises criterion \( \tau \) and the friction coefficient \( \mu \). Heat generated through friction and heat generated by plastic deformation can be represented by Equations 2.1 and 2.2 respectively.

Heat generated through friction [7]:

\[
d\dot{e}_f \approx \zeta(\omega r - f \sin \theta)\mu F dA
\]  

(2.1)

Heat generated through plastic deformation [7]:

\[
d\dot{e}_s = (1 - \zeta)(\omega r - f \sin \theta)\tau dA
\]

(2.2) 

Equation 2.2 is an approximating function and assumes 100% efficiency of deformational work into heat.
With regards to Equations 2.1 and 2.2:

When the extent of slip ($\zeta$) is equal to one; no material sticks to the tool and all the heat is generated by friction. In contrast, when the extent of slip ($\zeta$) is zero; all the heat is generated by plastic deformation. The local interfacial heat generation due to friction is the product of frictional force and the sliding velocity. The interfacial deformation heat is the product of shear stress and the velocity of the work-piece material which attaches to the tool as it moves.

Equation 2.3 shows that the power ($H$) of a Friction Stir Weld is directly proportional to the friction coefficient ($\mu$), the forging force/ the normal load acting by the tool ($F_z$), the rotational speed ($\omega$) and the shoulder diameter ($R$).

$$H = 4\pi\mu F_z\omega R$$

(2.3)

Given the extreme difficulty associated with measuring the extent of slip in Equations 2.1 and 2.2; a heat generation relationship was required for direct FSW process parameters. Equation 2.4 estimates the amount of heat generated ($Q$) as a function of the rotational speed ($\omega$), torque ($T$), efficiency factor (0.9 for aluminium and copper) and feed rate ($f$).

$$Q = \eta \frac{2\pi\omega T}{f}$$

(2.4)

Friction in front of the tool generates a plastic-like zone, the “plasticized material” travels around the tool and is deposited on the retreating side. This process is considered continuous along the work-piece. Should melting occur in front of the tool due to excessive heating, there is less friction and a reduced amount of heat is generated. Reduced heat generation is due to sticking and sliding, depicted in Figure 2.5, between the tool and the molten metal. As the temperature decreases, the material returns to a solid state and vice versa. This phenomenon limits the use of high tool rotations and correspondingly the use of high transverse speeds during the FSW process. Heat generation is a fundamental component of Friction Stir Welding (FSW) and is dependent on various parameters. Control the parameters during FSW is important if you wish to achieve sound and defect free friction stir welds. Heat generated is directly linked to the properties in the nugget and the Heat Affected Zone (HAZ) which significantly contributes towards the strength of friction stir weld joint.

![Figure 2.5: Illustration of sticking and sliding which affects the amount of heat generated due to contact interface between the tool and work-piece [1]](image-url)
2.4. Material flow

Material flow is another fundamental component of Friction Stir Welding (FSW) that makes this type of welding different from other conventional welding techniques. Material flow is the mechanism that enables the joining of materials to occur. Due to the fact that FSW is a recent development and the variety of tool tip configurations that is available, material flow is not currently fully understood. Engineers have however successfully modelled and experimentally proven material flow for some tool shoulder and tip configurations. [56,57] Askari et al. [56] developed code to solve time-dependant equations of continuum mechanics and thermodynamics. The model predicts strains, strain rates, and the temperature distribution. Most of these studies have been conducted on threaded pins and as a result a majority of industrial applications presently use threaded pins.

Material flow, similar to heat generation, is dependent on several parameters. The dominant parameters are namely the downward force, rotation speed, cutting velocity and the FSW tool design. The most material flow occurs through the retreating side and transports the plasticized material behind the tool which forms the welded joint and is the main reason for the asymmetrical cross sectional area of the weld nugget.

When the tool is used to complete the friction stir weld material from the leading edge is progressively plasticised and transported to the trailing edge through the retreating side. The friction between the tool and the material generates frictional heat which softens the material and transforms it into a pasty state. This allows the pin to go easier through the material. Finally, the coupling between the rotational and the translational motion of the tool stirs the material around the pin. After the pass of the tool, cooling of the plates takes place and finishes the welding. [11]

The complex flow around the FSW tool can be decomposed into three simpler flow components. Smith et al [57] developed a thermo-mechanical flow model using STRI-3D. It was indicated that three distinct flows were formed below the tool. The first of the flow components is a rigid body rotation separated from the rest of the weld metal by a cylindrical shearing surface. A very sharp division exists between the re-crystallized metal adjacent to the pin-tool and the parent metal is apparent. The sharply defined circular boundary between the re-crystallized metal and the parent metal suggests a shear circle discontinuity around the tool much like the shear plane encountered ahead of a metal-cutting tool. [8] This rotating cylinder is shown in Figure 2.6 a) and is conceived as being attached to the FSW tool and has a rotational speed that is equal to that of the tool spindle. In the case of thinner materials, this cylinder may be defined as a conical region to take into account the shorter pin length. The shearing surface is located between the shoulder corner and the bottom of the tool pin. [8]

The second flow component is a homogeneous and isotropic flow field equal to and opposite to the welding speed, the second flow component is shown in Figure 2.6 b) [8]. As seen from the FSW tool, a metal element in the combined flow field: (1) approaches the tool at the weld traverse speed, (2) enters the rotating plug at the shear surface and is stirred rapidly around the tool at the rotational field surface speed in a slightly laterally
offset circular arc and (3) exits at the rear of the tool to move progressively away at the tool traverse speed. Seen from the welded metal, the metal element: (1) remains motionless until contacted by the shear surface of the rotational field, (2) is engulfed by the rotational field and covered by subsequently engulfed elements as it is stirred rapidly around the tool, and (3) is gradually uncovered as the elements between it and the shearing surface are left behind the tool and is finally abandoned itself as the rotational field moves on. This mechanism has been referred to as the “wiping metal transfer mechanism.” [9]

The third component is a ring vortex flow that encircles the tool and carries metal up on the outside, in at the shoulder, down on the inside and out again on the lower regions of the pin shown in Figure 2.6 c). This flow is driven by the threads and/or flutes on the pin and can be reversed if the direction of the threads or the tool rotation is reversed. [8] When all three flows are superimposed the result is shown on Figure 2.6 d).

Kumar and Kailas [58] investigated the role of the friction stir welding tool on material flow and weld formation. They found that there are two different modes of material flow regimes involved in the friction stir weld formation; namely “pin-driven flow” and “shoulder driven flow”. Figure 2.7 depicts a summary of the material flow at different shoulder interaction in the transverse section of the friction stir weld.
Material flow at different shoulder interaction in the transverse section of the weld. a) Creation of the weld cavity during plunging, b) Cross-section of the layers in the pin-driven flow, c) Merging of pin- and shoulder-driven material flows and d) Drawing of base material into the weld nugget. [58]

It is important to highlight that the material flow during FSW is complicated and an understanding regarding the deformation process is still limited due to the large number of factors which influence the material flow. This is even more significant in dissimilar metal joining.

2.5. Welding Parameters

As previously discussed, many process parameters influence heat generation, heat transfer and material flow. In addition, the main process parameters that influence the friction stir weld are: the joint to be welded, the material/s to be welded, the tool tip-shoulder configuration, downward force, plunge depth, tool tilt angle, thickness mismatch, plate thickness variation, rotation speed and transverse speed. Figure 2.8 shows major input and output parameters of the friction stir weld process. [61]
2.5.1. Joint Design

FSW has many advantages as listed in Table 1.1. One of the many advantages of this solid state welding process is the variety of joints that can be welded. Types of welds that can be achieved are to name a few; a butt weld, lap weld and corner fillet welds. Shown below in Figure 2.9.

![Figure 2.9: Weld configurations that can be completed using friction stir welding, a) Square butt, b) Combined butt and lap, c) Single lap, d) Multiple lap, e) 3 pieces T-butt, f) 2 piece T-butt, g) Edge butt, h) Corner fillet weld [ref]](image)

Whilst the FSW process was developed initially for aluminium alloys, over the past decade the number of materials found to be collaborative to FSW has increased remarkably, with the process quickly finding a wide range of commercial applications. Listed below are some materials that have been successfully friction stir welded:

- Aluminium and its alloys [21, 22]
- Copper and its alloys [24]
- Titanium and its alloys [25]
- Magnesium alloys [26]
- Steels [27, 28]
- Dissimilar materials [20, 23, 34]

2.5.3. Tool Pin-Shoulder configuration

The tool pin-shoulder configuration (a fundamental parameter to consider) influences the...
quantity of heat generated and consequently the temperature of the weld. The temperature of the weld is important since this determines the degree of material flow and microstructural properties associated with the weld nugget, the Thermo-mechanically Affected Zone (TMAZ) and the Heat Affected Zone (HAZ). The temperature therefore greatly affects integrity of the weld. Figure 2.10 shows a modelled temperature variation schematic for a specific tip-shoulder, rotational speed, transverse speed, plunge depth and downward force. If any of the above mentioned parameters are changed results will differ significantly. The tool pin and shoulder design will be discussed in further detail in Section 2.13 Tool design.

2.5.4. Rotation speed

Rotational speed influences the heat generated, heat transfer, material flow and forces on the Friction Stir Welding (FSW) tool. In terms of the overall effect on the weld the main part of the weld that changes is the microstructure, which is evident from the macrostructure. Microstructure properties determine the strength, ductility and hardness of the material. The joint integrity of the weld is therefore highly dependent on the rotational speed of the tool. Figure 2.11 shows results obtained by Addison and Robelou [30]. Figure 2.11 shows the difference in material flow and macrostructure of the welded area for 1000, 1500, 2000 and 2500 rpm.

![Figure 2.11: Difference in material flow and macrostructure of the welded area for various rotational speeds [30]](image)

From Figure 2.11 it can be also be seen that at the surface, material is forced upwards in all welds. This is due to the high rotational speed used for testing by Addison and
Robelou [30]. The material that is forced upward is referred to as flash. For increased spindle speeds the quantity of material pushed upwards increases. The area of welded material also increases in direct relation to the rotation speed (due to depth of mixing). The effect of the rotational speed on the tool design shall be discussed in further detail in Section 2.13 - Tool design.

2.5.5. Transverse Speed

The transverse speed affects heat generation, heat transfer, material flow and forces on the Friction Stir Welding (FSW) tool. In terms of the overall effect on the weld the main part of the weld that is affected by the transverse speed is the weld nugget and Thermomechanically Affected Zone (TMAZ) which are critical regions of the weld where re-crystallisation occurs. The re-crystallisation process is crucial and directly influences the mechanical properties of the welded region. Figure 2.12 below shows a cross sectional views of the important Friction Stir Weld regions for various transverse weld speeds.

![Figure 2.12: Macroscopic view of welded region for specified transverse speeds [31]](image)

Equations presented in Sections 2.2.1 and 2.2.1 suggests that increasing rotation speed will result in higher temperatures and more heat transfer. Logically, an increased transverse speed will also lower plastic deformation due to the fact that less time is allowed for the rotational mixing of materials. Figure 2.12 shows that this may be true due to the mixing area decreasing with an increase in transverse speed; also the mixture has a higher uniformity for lower transverse speed as compared to the higher transverse
speed. Lower transverse speeds result in a more defined nugget, Thermo-mechanically Affected Zone (TMAZ) and Heat Affected Zone (HAZ). Due to a higher degree of material flow occurring at lower transverse speeds the strength of the weld is expected to decrease with an increase in transverse speed.

2.6. Aluminium

2.6.1.1. Overview of Aluminium

Aluminium was first produced in a laboratory in 1825 by reducing aluminium chloride. Aluminium is said to be second only to steel in importance for the modern world [45]. Perhaps due to this, aluminium is also the second most welded material besides steel. It is considered to be a “new” metal and has only been available as a commodity for about 60 years. The earth has an abundant supply of aluminium that approximately makes up 8% of the earth crust. Unfortunately, aluminium does not occur naturally in its metallic form but rather as silicates and other complex compounds. As a result aluminium was initially an expensive metal, but due to improvements in refining techniques aluminium has become a reasonably priced material and is used in applications such as machines, construction, aircraft and automobiles. Aspects to be discussed about aluminium are the materials general characteristics, alloying ability, physical properties and mechanical properties of 5754 aluminium.

2.6.1.2. General Characteristics

Aluminium has several properties that set the metal apart from other metals. Aluminium is a third of the weight of steel, has good thermal and electrical conductivity, is corrosion resistant in common environments, has a high strength-to-weight ratio, can be surface hardened by anodizing and hard-coating, most alloys are weld-able, has a high reflectivity, can be die casted, easily machined, good formability, is nonmagnetic, nontoxic and is one-third the stiffness of steel.[1] Aluminium has about 60% of the conductivity of copper and in regards to the materials’ densities aluminium has a relatively higher conductivity than copper per unit mass.

2.6.1.3. Alloying Ability of Aluminium

An alloy is a metallic substance that is composed of two or more elements. The alloying ability of aluminium is one of the reasons why aluminium is widely used in Friction Stir Welding (FSW). Due to the nature of the FSW process, for dissimilar friction stir welds alloying occurs at the Friction Stir welded joint assisted by elevated temperature and forces associated with the process. When FSW of dissimilar materials is performed, a joint is formed which displays similar properties to alloys of the parent materials.

Alloying of aluminium is done mainly to enhance the mechanical strength of the material through solid-solution strengthening however this process tends to diminish resistance to corrosion. Principal alloying elements include iron, manganese, silicon, copper, magnesium, zinc, chromium, titanium, lead/bismuth, zirconium and lithium. Shown
below in Table 2.2 are the effects of principal alloying elements. Due to Friction Stir Welding (FSW) being a solid-solution joining technique, solubility is an important aspect.

Aluminium alloys can be categorised into eight groups based on the alloys primary alloying element and its ability to respond to thermal and mechanical treatment. There are two numbering / identification systems for aluminium which are namely the wrought- and cast- alloy designation system. The wrought system has a four digit system and cast system has a 3 digit and 1 decimal system. The current discussion will be limited only to the wrought alloy designation system. In the wrought system the first digit (Xxxx) is used to indicate the principal alloying agent which separated aluminium alloys into eight series: 1xxx – 99% minimum Aluminium, 2xxx – Copper, 3xxx – Manganese, 4xxx – Silicon, 5xxx- Magnesium, 6xxx- Magnesium and silicon, 7xxx- Zinc, 8xxx- other elements. Currently there are over 400 wrought aluminium and wrought aluminium alloys, it is therefore of no added benefit to attempt to describe each aluminium alloy. Rather it is better to describe the aluminium series alloys and their characteristics which determines the application of use.

2xxx Series Alloys- The aluminium-copper alloys typically contain 2-10% copper. Copper provides an increase in strength and facilitates precipitation hardening but also reduces ductility and corrosion resistance. These alloys can be considered to be the most difficult to weld due to solidification cracking. These alloys are heat treatable and the most common applications are for aerospace, military vehicles and rocket fins.

3xxx Series Alloys- Manganese in the aluminium increase strength through solid solution strengthening and improves strain hardening. These are non-heat treatable but they retain strength at elevated temperatures. The most common applications for this alloy are radiators, condensers, evaporators and heat exchangers.

4xxx Series Alloys- Silicon in aluminium reduces the melting temperature. Silicon alone in aluminium produces a non-heat treatable alloy but should manganese be added the alloy becomes heat treatable. Therefore there are both heat- and non-heat- treatable alloys in 4 series aluminium alloys. The most common applications are fusion welding wires.

5xxx Series Alloys- Magnesium in aluminium increases strength through solid solution strengthening and improves the strain hardening ability. These alloys are non-heat treatable but possess high weldability, machinability and corrosion resistance properties. Typical applications include truck and train bodies, chemical tanks, pressure vessels and armoured vehicles.

6xxx Series Alloys- the addition of magnesium and silicon improves the strength through solid solution strengthening and these alloys are heat treatable. Common applications include automobile frames, drive shafts, boats and many other structural applications.

7xxx Series Alloys- The addition of zinc to aluminium is usually completed in conjunction with some other elements such as magnesium or copper. This produces a heat treatable alloy of the highest strength. These alloys are however susceptible to stress
Some common applications are for aerospace, armoured vehicles and bicycle frames.

Table 2.2: Alloying elements and effects of these elements in aluminium [45]

<table>
<thead>
<tr>
<th>Alloying Element</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>Naturally occurs as an impurity in aluminium ores; small percentages increase the strength and hardness of some alloys and reduce hot cracking tendencies in castings; reduces pickup in die-casting cavities.</td>
</tr>
<tr>
<td>Manganese</td>
<td>Used in combination with iron to improve castability; alters the nature of the intermetallic compounds and reduces shrinkage; the effect on mechanical properties is improved ductility and impact strength</td>
</tr>
<tr>
<td>Silicon</td>
<td>Increases fluidity in castings and welding alloys and reduces solidification and hot-cracking tendencies; additions in excess of 13% make the alloy extremely difficult to machine; improves corrosion resistance</td>
</tr>
<tr>
<td>Copper</td>
<td>Increases strength up to about 12%; higher concentrations cause brittleness; improves elevated temperature properties and machinability; concentrations over 5% reduce ability to hard coat</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Improves strength but solid solution strengthening and alloys with over about 3% (0.5% when 0.5% silicon is added) will precipitation harden; aluminium-magnesium alloys are difficult to cast because the molten alloy tends to &quot;skin-over&quot; (dross) in contact with air.</td>
</tr>
<tr>
<td>Zinc</td>
<td>Lowers castability; high zinc alloys are prone to hot cracking and high shrinkage; percentages over 10% produce tendencies for stress corrosion cracking; in combination with other elements, zinc promotes very high strength; low concentrations in binary alloys (&lt;3%) produce no useful effects.</td>
</tr>
<tr>
<td>Chromium</td>
<td>Improves conductivity in some alloys and in small concentration (&lt;0.35%) it acts as a grain refiner.</td>
</tr>
<tr>
<td>Titanium</td>
<td>Naturally occurs as in impurity in aluminium ores, but it is intentionally added to some alloys as a grain refiner.</td>
</tr>
<tr>
<td>Lead/Bismuth</td>
<td>Added to some alloys to improve machinability; 2011 and 6062 are screw machine alloys containing Pb and Bi.</td>
</tr>
<tr>
<td>Zirconium</td>
<td>Used as a grain refiner in some aerospace alloys.</td>
</tr>
<tr>
<td>Lithium</td>
<td>Added to some aerospace alloys (Space Shuttle fuel tanks) to reduce weight. These alloys need a protective atmosphere when being cast.</td>
</tr>
</tbody>
</table>
There are many aluminium alloys used in industry. Today’s aluminium alloys comprise a wide and versatile range of manufacturing materials. One of the most important considerations during welding aluminium is identification of the base alloy. The applications of these alloys must be considered and in order to determine the different welding requirements it is first important to be familiar with the identification systems, available alloys and their characteristics.

Research in Friction Stir Welding (FSW) of aluminium is well established. This is because FSW is particularly suited for welding aluminium and its alloys. Aluminium alloys of the various series have been successfully friction stir welded:

- 1xxx [69, 70]
- 2xxx [21, 66, 71, 72]
- 3xxx, 4xxx,
- 5xxx [73, 70],
- 6xxx [68,74,75],
- 7xxx [19, 76, 77],

6xxx alloys have a much wider friction stir weld window that the other alloys. 7xxx and 2xxx have proven to be the most difficult to friction stir weld[78].

2.7. Friction Stir Welding of Aluminium

Aluminium is used in many industries and is becoming increasingly popular due to advances in refining and mining technology, this has resulted in aluminium’s growing popularity in industrial applications. Steel has had a profound influence in industrial applications from the time of its introduction and the author believes that aluminium will follow in a similar trend. Aluminium however still provides difficulty using conventional welding techniques. This had promoted research into friction stir welding of aluminium. There is a lot of information available information regarding friction stir welding of aluminium. Some of the research completed is discussed below.

Fujii et al. [101] successfully friction stir welded 5mm thick plates of aluminium alloys. Their research aimed to determine the effect of tool shape on the mechanical properties and microstructure of friction stir welded aluminium alloys. For their research they used a 15mm diameter concave shoulder tool, the tool material was not specified in the report. Three pin types were used for their research investigation which included the straight circular pin, straight circular threaded pin and a triangular pin with lengths of 4.7mm and 6mm respectively. Testing was completed with a rotational speed ranging between 600-1500 rev/min, a transverse speed of 25-1000 mm/min and at a 3 degree tool tilt. Peak joint efficiencies were recorded to be between 70-100%

Kumar et al. [105] successfully friction stir welded 4 mm thick plates of 7020-T6 aluminium. Their research aimed to characterise the influence of tool geometry in friction stir welded. The friction stir welding tool was made using tool steel. The tool diameter ranged between 10-20mm and pin diameter between 3-8mm. The shoulder shape was
selected to be of a concave design and the pin length was selected to be 4.2mm with a straight-circular and frustum design. Testing was completed at a rotational speed of 1400 rev/min and a transverse speed of 80 mm/min. The peak joint efficiency was reported to be 92%. Rodriguez et al. [106] successfully welded 6 mm thick plates of A319 and A413 aluminium alloys. Tool steel was selected for the friction stir welding tool. The pin diameter was 6mm and testing was completed at a rotational speed of 1000 rev/min and a transverse speed of 120 mm/min. No property degradation was recorded in the weld metal. Lorrain et al. [107] successfully friction stir welded 4 mm thick plates of 7020-T6 aluminium. Their research centred on understanding the material flow path of the friction stir welding process using unthreaded tools. For their research they used a high carbon steel tool material. The tool was a concave shoulder type with a diameter of 13mm. The pin shapes were straight circular and tapered circular with three flats. The pin length was 3.19mm and the pin diameter was 5 mm. Tests were completed at a rotational speed varying between 300-1620 rev/min, a transverse speed between 100-900 mm/min and a tool tilt of 2.5 degrees. Table 2.3 presents a summary of the above discussion.

Table 2.3: Summary of discussion on welding of aluminium including tool specification and process parameters

<table>
<thead>
<tr>
<th>Work Piece Material</th>
<th>Tool Material</th>
<th>Tool Shape and Size</th>
<th>Operating Parameters</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al alloys 5mm Thick Plate</td>
<td>Shoulder Shape: Concave</td>
<td>600-1500 Rev/min 25-1000 mm/min 3 deg. Tilt</td>
<td>[104]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shoulder Diameter: 15 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pin Shape: Straight Circular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Straight Circular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Threaded Triangular</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pin Length: 4.7 mm &amp; 6 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7020-T6 Al alloy 4 mm Thick Plate</td>
<td>Shoulder Shape: Concave</td>
<td>1400 rev/min 80 mm/min</td>
<td>[105]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shoulder Diameter: 10-20 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pin Diameter: 3-8 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pin Shape: Straight Circular Frustum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pin Length: 4.2mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A319 and A413 Al alloy 4 mm Thick Plate</td>
<td>Tool Steel</td>
<td>Pin Diameter: 6 mm</td>
<td>1000 rev/min 120 mm/min</td>
<td>[106]</td>
</tr>
<tr>
<td>7020-T6 Al 4mm Thick Plate</td>
<td>High Carbon Steel</td>
<td>Shoulder Shape: Concave</td>
<td>300-1620 rev/min 100-900 mm/min 2.5 deg. Tilt</td>
<td>[107]</td>
</tr>
<tr>
<td></td>
<td>Shoulder Diameter: 13 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pin Diameter: 5 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pin Shape: Straight Circular Tapered Circular with 3 flats</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pin Length: 3.19 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.8. Copper

2.8.1.1. Overview of Copper
Copper is the oldest tool material and was used by ancient civilizations for various applications due to the material's malleability. In the twenty-first century, copper is used mainly because of its high electrical conductivity. Mass copper can be obtained by crushing rocks and physically removing lumps of copper but at present day, most copper is obtained from copper ores that at best have 1.5% copper by weight. This is the root cause for the high cost of copper when compared to other metal commodities such as steels. Qualities to be discussed about copper are the material's general characteristics, alloying ability, physical properties, and mechanical properties of C11000 copper.

2.8.1.2. General Characteristics
Copper is an excellent conductor; it is corrosion resistant, and easily shaped (malleable.) Copper has a low yield strength and is generally considered a ductile material. The ductility of copper is not significantly affected by low temperatures; copper does not become brittle or very hard. It is not suited for service at elevated temperatures; it is wear resistant and is used widely for bearings. However, when subjected to abrasive environments such as impellers for pumps, the material is susceptible to corrosion.

2.8.1.3. Alloying Ability of Copper
Alloying of copper is a frequent phenomenon, this is because unalloyed copper is soft and ductile which makes the material difficult to machine because pure copper essentially has an unlimited capacity to be cold worked. Alloying of copper is done to improve mechanical and corrosion-resistant properties. Most copper alloys cannot be hardened or strengthened through heat treatment procedures and consequently either solid-solution strengthening or cold working must be used to improve its mechanical properties. Alloying elements for copper include zinc, phosphorous, beryllium, iron, tin, lead, aluminium, silicon, and nickel. Common copper alloys include brasses and bronzes. Brasses are predominantly alloyed with zinc which makes the copper harder and stronger. Table 2.4 shows compositions, mechanical properties, and typical applications of eight common copper alloys.

2.9. Friction Stir Welding of Copper
Copper is extremely difficult to weld using conventional welding techniques. Welding of copper has proven difficult since it has a much higher thermal diffusivity than steel, therefore the heat input required to weld copper is much higher than conventional materials that are welded using Friction Stir Welding (FSW). FSW is particularly suited to weld aluminium and its alloys, for this reason, most research work has focused on welding aluminium. After researching open and closed sourced research it was found that there are a limited amount of papers on the FSW process for pure copper, where the melting point and material properties in copper are significantly different from those in
aluminium and its alloys. Although information regarding friction stir welding copper is limited, copper plates of 1.5-50 mm have been successfully friction stir welded [79, 80, 81].

Table 2.4: Compositions, mechanical properties and typical applications of common copper alloys [13]

<table>
<thead>
<tr>
<th>Alloy Name</th>
<th>UNS Number</th>
<th>Composition (wt%)</th>
<th>Condition</th>
<th>Tensile Strength (Mpa)</th>
<th>Yield Strength (MPa)</th>
<th>Ductility (% EL in 50 mm)</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrought Alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolytic tough pitch</td>
<td>C11000</td>
<td>0.04 O</td>
<td>Annealed</td>
<td>220</td>
<td>69</td>
<td>45</td>
<td>Electrical wire, rivets, screening, gaskets, pans, nails, roofing</td>
</tr>
<tr>
<td>Beryllium copper</td>
<td>C17200</td>
<td>1.9 Be, 0.20 Co</td>
<td>Precipitation hardened</td>
<td>1140-1310</td>
<td>690-860</td>
<td>4-10.</td>
<td>Springs, bellows, firing pins, bushings, valves, diaphragms</td>
</tr>
<tr>
<td>Cartridge brass</td>
<td>C26000</td>
<td>30 Zn</td>
<td>Annealed Cold-worked (H04 hard)</td>
<td>300</td>
<td>525</td>
<td>68</td>
<td>Automotive radiator cores, ammunition components, lamp fixtures</td>
</tr>
<tr>
<td>Phosphor bronze 5% A</td>
<td>C51000</td>
<td>5 Sn, 0.2 P</td>
<td>Annealed Cold-worked (H04 hard)</td>
<td>325</td>
<td>560</td>
<td>64</td>
<td>Clutch disks, fuse clips, springs, welding rods</td>
</tr>
<tr>
<td>Copper-nickel 30%</td>
<td>C71500</td>
<td>30 Ni</td>
<td>Annealed Cold-worked (H02 hard)</td>
<td>380</td>
<td>515</td>
<td>36</td>
<td>Condenser and heat exchanger components, salt water piping</td>
</tr>
<tr>
<td>Cast Alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaded yellow brass</td>
<td>C85400</td>
<td>29 Zn, 3 Pb 1 Sn</td>
<td>As Cast</td>
<td>560</td>
<td>83</td>
<td>35</td>
<td>Furniture hardware, radiator fittings, light fixtures</td>
</tr>
<tr>
<td>Tin Bronze</td>
<td>C90500</td>
<td>10 Sn, 2 Zn</td>
<td>As Cast</td>
<td>380</td>
<td>152</td>
<td>25</td>
<td>Bearings, bushings, piston rings, gears</td>
</tr>
<tr>
<td>Aluminium bronze</td>
<td>C95400</td>
<td>4 Fe, 11 Al</td>
<td>As Cast</td>
<td>515</td>
<td>241</td>
<td>18</td>
<td>Bearings, gears, bushings, valve seats</td>
</tr>
</tbody>
</table>
FSW has been successfully used to weld 50 mm thick copper canisters for containment of nuclear waste. [79] Kallgren and Sandstom [82] used FSW to weld 50 mm plates of copper which is used for nuclear waste canisters. They examined the variation in grain size and hardness as a function of the welding parameters. A number on deductions were made, one being that a higher temperature gives smaller grain sizes and the hardness decreases as the temperature increases. Okamoto et al. [83] friction stir welded 6 mm oxygen free copper plates used for semi-conductor- and liquid crystal- devices. They studied the mechanical and metallurgical properties of the friction stir welded copper. The concluded that the experiment achieved defect free welds and that the 0.2 % proof stress, ultimate tensile stress strength and elongation of friction stir welded joints were slightly higher than electron beam welded joints.

Savollainen et al. [84] studied factors affecting friction stir weldability of copper and its alloys to determine the correct welding parameters and tool material. They completed double sided butt weld in 10-11 mm thick copper plates of electrolytically refined oxygen-free copper, phosphorus-deoxidized copper with high residual phosphorus, aluminium bronze and copper nickel. The performance of eight tools were used. The tool materials used during welding were an H13 type tool steel (Uddeholm QRO 90 SUPREME), Ni-based super alloys IN738LC, IN939 and their combination IN738LCmod (90 % IN739LC, 10 % IN939), sintered TiC : Ni : W (2 : 1 : 1), HIPed TiC : Ni : Mo (3 : 2 : 1) pure tungsten and polycrystalline cubic boron nitride (PCBN).

They were able to make s number of deductions, important deductions relevant to the current study are that it is possible to produce good quality welds of copper and it alloys, the friction stir weldability of oxygen free copper is good based on the weld parameter window, frequency of defects and tools performance. Cu-OF and Cu-DHP were susceptible to hydrogen sickness due to entrapped oxide particles. From the tool materials that were studied, PCBN had the best performance, Ni-based super alloys were less brittle than PCBN but only suitable for FSW of Cu-OF and Cu-DHP and CuAl₅Zn₅Sn. Hot work tool steel Uddeholm QRO 90 SUPREME and pure tungsten were suitable for FSW of Cu-OF and Cu-DHP. Table 2.5 shows comments regarding tool material and the tested copper and it alloys.

Table 2.5: Tool material for welding of copper [84]

<table>
<thead>
<tr>
<th>TOOL MATERIAL</th>
<th>Cu-OF</th>
<th>Cu-DHP</th>
<th>AP205</th>
<th>NK25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uddeholm QRO 90 SUPREME</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Very Poor</td>
</tr>
<tr>
<td>IN738LC, IN738LCmod, IN939</td>
<td>Very good</td>
<td>Very good</td>
<td>Intermediate</td>
<td>Very Poor</td>
</tr>
<tr>
<td>HIPed TiC-NiW</td>
<td>Very Poor</td>
<td>Very Poor</td>
<td>Very Poor</td>
<td>Very Poor</td>
</tr>
<tr>
<td>Sintered TiC-NiW</td>
<td>Very Poor</td>
<td>Very Poor</td>
<td>Very Poor</td>
<td>Very Poor</td>
</tr>
<tr>
<td>Tungsten</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Very Poor</td>
</tr>
</tbody>
</table>
Hwang et al. [88] investigated the thermal history of friction stir butt welded 3 mm thick C11000 copper using a concave tool. They were able to determine the appropriate temperature required in order to successfully weld the 3 mm thick C11000 copper plates. The temperature range was found to be 460°C-530°C. Figure 2.13 shows the results of their study showing the Vickers hardness distribution on the welds.

![Figure 2.13: Vickers hardness distribution on C11000 3mm plates using concave tool [88]](image)

Their results indicate that there is no significance difference between the hardness of the advancing and retreating sides and they explained that the hardness of the joint is below the base metal because of dynamic recovery and dynamic crystallisation. This is generally the same tendency for friction stir welded aluminium and steel.

Figure 2.14 shows Scanning Electron Microscope (SEM) pictures courtesy of Kallgren and Sandstrom. [82] The images show that there is a large difference between the grain size between the nugget, TMAZ and HAZ which also further explains the differences for the hardness values due to dynamic recovery and dynamic crystallisation.

![Figure 2.14: 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 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 [82]](image)

Although there is limited studies completed on FSW copper, it is clear that FSW has great potential for the joining of copper.
2.10. Dissimilar Metal Joining

Most combinations of dissimilar metals can be joined by solid-state welding techniques such as diffusion welding, explosive welding, ultrasonic welding and Friction Stir Welding (FSW). FSW is one of the most popular welding techniques for joining dissimilar materials; however, the joining technique used is subject to the desired joint properties and application. There is great interest in joining magnesium, steel, titanium and copper to aluminium alloys. The need for dissimilar joints is driven by industrial application of a complex function. Improved solutions are required for dissimilar metal joints for the tank container, automotive and aerospace applications. [15, 35-37] Joining of dissimilar metals is currently used in the power generation, chemical, petrochemical, nuclear, transportation and electrical industries for combined performance properties of weight reduction. [5]

There are many factors to consider when welding dissimilar metals. Among other factors, the weldability of dissimilar metals is highly dependent on their atomic diameter, crystal structure and their compositional solubility in their liquid and solid states. Due to the chemical, mechanical and thermal property differences of materials, dissimilar metal joining is more challenging. Dissimilar metal joining presents more problems compared to similar material joining.

2.10.1. Metallurgy of Aluminium-Copper system

Although the temperatures involved in the friction stir weld process are lower than the melting points of the weld materials, pure copper has a Face Centre Cubic (FCC) crystal structure; similarly, aluminium also has a FCC crystal structure. For many alloys, there is a maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution; this is known as the solubility limit. The addition of solute in excess of the solubility limit results in the formation of another solid solution or compound that has a distinctly different composition.

If attention is confined to binary alloys, alloying behaviour may be classified in three groups:

1) **Complete solid solubility** in which every alloy is a solid solution.
2) **Partial solid solubility**, where each metal has a limited amount of the other metal that it can dissolve. The two constituents interlock with each other.
3) **One or more compounds may form**. In this group, there is a degree of terminal solid solubility. Some alloys will consist purely of the terminal solid solutions, and others will consist only of compounds.

Figure 2.15 presents a phase diagram of aluminium and copper, which shows the different solubility phases of copper and aluminium; solubility is dependent on temperature. Table 2.6 shows the phase atomic weight for the various phases. A phase is defined as a homogeneous portion of a system that has uniform physical and chemical characteristics. All pure metals, solids, liquid and gases are considered to be phases. In the copper-aluminium phase diagram (shown in Figure 2.15), when more than one phase is present in...
a system each phase will have its own distinct properties. The boundary separating the phases shows where there will be discontinuous and abrupt changes in physical and/or chemical characteristics.
Table 2.6: Phase atomic and weight composition, chemical formula and formation temperature [53]

<table>
<thead>
<tr>
<th>Phase</th>
<th>Composition, atomic %Cu</th>
<th>Composition weight %Cu</th>
<th>Chemical formula</th>
<th>Temperature at which they are formed (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Al)</td>
<td>0 to 2.48</td>
<td>0</td>
<td>Al</td>
<td>0</td>
</tr>
<tr>
<td>θ</td>
<td>31.9 to 33.0</td>
<td>54</td>
<td>Al₂Cu</td>
<td>550</td>
</tr>
<tr>
<td>η₁</td>
<td>49.8 to 52.4</td>
<td>70</td>
<td>AlCu</td>
<td>591</td>
</tr>
<tr>
<td>η₂</td>
<td>49.8 to 52.3</td>
<td>70</td>
<td>AlCu</td>
<td>591</td>
</tr>
<tr>
<td>ζ₁</td>
<td>55.2 to 59.8</td>
<td>76</td>
<td>Al₃Cu₄</td>
<td>624</td>
</tr>
<tr>
<td>ζ₂</td>
<td>55.2 to 56.3</td>
<td>76</td>
<td>Al₃Cu₄</td>
<td>624</td>
</tr>
<tr>
<td>ε₁</td>
<td>59.4 to 62.1</td>
<td>76</td>
<td>Al₃Cu₅</td>
<td>620</td>
</tr>
<tr>
<td>ε₂</td>
<td>55.0 to 61.1</td>
<td>77</td>
<td>Al₃Cu₅</td>
<td>620</td>
</tr>
<tr>
<td>δ</td>
<td>59.3 to 61.9</td>
<td>78</td>
<td>Al₂Cu₃</td>
<td>700</td>
</tr>
<tr>
<td>γ₀</td>
<td>59.8 to 69</td>
<td>84</td>
<td>Al₂Cu₉</td>
<td>950</td>
</tr>
<tr>
<td>γ₁</td>
<td>62.5 to 69</td>
<td>84</td>
<td>Al₂Cu₉</td>
<td>950</td>
</tr>
<tr>
<td>β₀</td>
<td>67.6 to 70.2</td>
<td>88</td>
<td>AlCu₃</td>
<td>1048</td>
</tr>
<tr>
<td>β</td>
<td>70.6 to 82.0</td>
<td>88</td>
<td>AlCu₃</td>
<td>1048</td>
</tr>
<tr>
<td>α₂</td>
<td>76.5 to 78</td>
<td>88</td>
<td>AlCu₃</td>
<td>1030</td>
</tr>
<tr>
<td>Cu</td>
<td>80.3 to 100</td>
<td>89 to 100</td>
<td>Cu</td>
<td>1083</td>
</tr>
</tbody>
</table>
2.11. Friction Stir Welding of Aluminium and Copper

Friction Stir Welding is an innovative solid state joining process that has been proven to be an effective way for joining materials with poor fusion weldability and has become particularly valuable for joining dissimilar metals [1]. Copper (Cu) and Aluminium (Al) are not compatible metals. These metals are difficult to join because they have a high affinity to each other at temperatures higher than 120°C and produce hard, brittle, low strength and high electrical resistance intermetallics on their interface. Aluminium and copper also both have limited solubility in the solid state. FSW has shown to be a sound welding technique for welding these precious metals together.

Akinlabi [53] conducted a study to characterise dissimilar welds between 5754 aluminium alloy and C11000 copper. She characterised the welds through microstructural evaluation, tensile testing, microhardness profiling, X-Ray diffraction analysis and electrical resistivity tests. It was found that the 18mm shoulder diameter produced the best weld at 950 rpm and low to medium feed rate between 50 and 150 rpm.

Ouyang [125] conducted a study on dissimilar friction stir welds of 12.7 mm thick 6061 aluminium and copper. This research found that it is difficult to weld 6061 aluminium to copper due to the brittle nature of the intermetallic compounds formed in the weld nugget. From his research it was observed that the majority of the friction stir welds exhibited discontinuity and crack propagation and could not be considered to be good welds. Due to intermetallic compounds and material flow patterns there were fluctuating hardness values in the weld nugget which were also related to differences in microstructures. The research concluded that the mechanically mixed region in the dissimilar weld consists of several intermetallic compounds, also distributed at the bottom of the weld nugget are the deformed copper lamellae with a solid solubility of aluminium.

Murr et al. [111] friction stir welded dissimilar aluminium alloys (1100 and 6061) and 6061aluminium/copper that were 6mm thick. Their research showed that in dissimilar joints of aluminium alloys the microstructures in the nugget represent some degree of dynamic recrystallization. The feature observed is indicative of a specific stirring sequence which influences the actual weld contiguity, however, the details of these phenomena were unknown, and the Vickers microhardness profiles observed were relatively low at the weld zones. From all of the above, they concluded that additional work is required for further investigation and observation.

Genevois et al. [113] welded commercially pure copper and 1050 aluminium. The tool pin was however located exclusively on the aluminium side which resulted in no mixing of material through the weld. The bonding resulted from reactive interdiffusion and the process was named friction stir diffusion bonding. This process was found to create a very thin layer of intermetallic, the layer of intermetallic thickness was reported to be about 200 nm.

Xue et al. [115] conducted research on dissimilar friction stir welds between 1060 Aluminium and copper. They found that the nugget was significantly strengthened by intermetallic particles dispersed in the aluminium matrix and for large copper particles in
the nugget zone the intermetallic layers formed sound metallurgical bonds in the aluminium matrix as well. Reinforcing particles were mainly composed of \( \text{Al}_2\text{Cu} \), \( \text{Al}_4\text{Cu}_9 \) and \( \text{AlCu} \).

Further research conducted by Xue et al. [116] on dissimilar friction stir welds between 1060 Aluminium and copper on 5 mm thick plates found that defect free welds can only be obtained when Cu was placed on the advancing side. They also found that a proper tool pin offset (Not less than 2 mm in aluminium) and proper rotational speed is required to obtain excellent metallurgical bonding. When the intermetallic layer is too thick the mechanical properties of the joint becomes poor.

The mixing pattern adopted by the mixture of phases depends on the Friction Stir Welding process. Galvao et al. [117] investigated the influence of shoulder geometry on the formation and distribution of brittle structures in friction stir welding of aluminium and copper. They found that the under the same welding parameters but with different tools (scrolled and conical shoulder) the nugget of the welds had completely different intermetallic content. The scrolled tool promoted the formation of a mixing region almost exclusively composed of \( \text{CuAl}_2 \) and the conical tool promoted the formation of \( \text{CuAl}_2 \) and \( \text{Cu}_9\text{Al}_4 \) mixture with higher heterogeneity and lower intermetallic content.

Galvao et al. [118] studied the effect of tool offsetting on the structure and morphology of dissimilar welds of copper-DHP and 6082-T6 aluminium. They found that the tool offset could be used to control the formation of intermetallic rich structures. The tool offset significantly changed the Al/Cu weld morphologies.

Galvao et al.[119] conducted a study to compare the influence of welding conditions on torque evolution between similar and dissimilar friction stir butt welding of 5083-H11 aluminium alloy and copper-DHP. They found that the average torque is significantly influenced by the materials being welded. In their research, dissimilar welds always registered the lowest torque values. They found that a decrease in torque values were achieved when increasing the rotational speed and that the transverse speed had no significant impact on the torque. The decrease in torque values for dissimilar friction stir welds were explained to be a result of a smaller volume of material being dragged by the tool for each revolution and tool slippage.

Liu et al. [122] friction stir welded copper (T2) and aluminium alloy (5A06). The best results were achieved when the rotational speed was set to 950 rev/min and the transverse speed to 150 mm/min. The best weld achieved a tensile strength of 296 MPa. Microstructural analysis indicated that the copper and aluminium close to copper side in the weld nugget zone showed a lamellar alternating structure; the XRD analysis indicated that there were no new Al-Cu intermetallics in the weld nugget zone. As a result, the structure of the weld nugget zone was mainly plastic diffusion combination of aluminium and copper, the tensile strength of the FSW joints was also conducted and it was observed that they all fractured in the copper side of the weld nugget zone. This research also focused only on microstructural evaluation and tensile tests of the welded samples. Table 2.7 shows some experimental studies that has been conducted to friction stir weld copper and aluminium.
Table 2.7: Summary for dissimilar friction stir welding of aluminium and copper research and process parameters

<table>
<thead>
<tr>
<th>No</th>
<th>Sheet Metals</th>
<th>Thickness (mm)</th>
<th>Rotational Speed (rpm)</th>
<th>Feed rate (mm/min)</th>
<th>Tilt Angle (deg.)</th>
<th>Offset (mm)</th>
<th>Tool Design</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al 5754 - Cu</td>
<td>3</td>
<td>600-1200</td>
<td>50-300</td>
<td>1-3</td>
<td>3</td>
<td>Threaded pin and concave shoulder (Tool diameter 15 mm, 18 mm and 25 mm)</td>
<td>[53]</td>
</tr>
<tr>
<td>2</td>
<td>Al 6061 - Cu</td>
<td>12.7</td>
<td>151-1400</td>
<td>57-330</td>
<td>-</td>
<td>-</td>
<td>Tool Steel Threaded Pin 12 mm Pin diameter</td>
<td>[125]</td>
</tr>
<tr>
<td>4</td>
<td>Al 2024 - Cu</td>
<td>-</td>
<td>650</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[111]</td>
</tr>
<tr>
<td>6</td>
<td>Al 1050 - Cu</td>
<td>4</td>
<td>900</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>Unthreaded Tool</td>
<td>[113]</td>
</tr>
<tr>
<td>8</td>
<td>Al 1060 - Cu</td>
<td>5</td>
<td>600</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[115]</td>
</tr>
<tr>
<td>9</td>
<td>Al 1060 - Cu</td>
<td>5</td>
<td>400-1000</td>
<td>100</td>
<td>-</td>
<td>0-3</td>
<td>Heat treated tool steel 6mm Pin Diameter 20mm Shoulder Diameter 4.8mm pin length</td>
<td>[116]</td>
</tr>
<tr>
<td>10</td>
<td>AA5083-H111 Cu-DHP, R240</td>
<td>1</td>
<td>750</td>
<td>160</td>
<td>Conical Shoulder 2</td>
<td>-</td>
<td>H13 Tool Steel 1) Conical Shoulder and smooth pin 2) Scrolled Shoulder and threaded pin 3mm Pin Diameter 14 mm Shoulder Diameter 0.9 Pin Length</td>
<td>[117]</td>
</tr>
<tr>
<td>11</td>
<td>Al 6082-T6 Cu-DHP, R240</td>
<td>3</td>
<td>1000</td>
<td>200</td>
<td>3</td>
<td>0-2.5</td>
<td>H13 Tool Steel 16mm Shoulder Diameter 5mm Pin Diameter smooth Pin 2.9mm Pin length</td>
<td>[118]</td>
</tr>
<tr>
<td>12</td>
<td>Al 5083-H111 Cu-DHP, R240</td>
<td>1</td>
<td>750-1250</td>
<td>160-250</td>
<td>2</td>
<td>-</td>
<td>Conical Shoulder with 3 deg shoulder cavity 14mm Shoulder Diameter 3mm Pin Diameter</td>
<td>[119]</td>
</tr>
<tr>
<td>13</td>
<td>AA 5A06 Cu-T2</td>
<td>3</td>
<td>950-1180</td>
<td>150-235</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[122]</td>
</tr>
</tbody>
</table>
Researchers have previously studied various input control parameters and their relationship to the output responses. The objectives all differ but the underlying principle is to further analyse the fundamentals of the friction stir welding process. Previous studies have mainly addressed the microstructure and mechanical properties of Al-Cu dissimilar joint. In this research work, the author intends to achieve defect-free welds of 5754 aluminium alloy and C11000 copper using different tool shoulder designs to understand the tool forces involved for the employed tool shoulder designs and its effect on the joint. In addition, characterisation of the electrical resistivity of friction stir welded joints of Al-Cu to the employed process parameters is very significant considering the major application of aluminium/copper joints in the electrical industry. No literature was found to exist which characterises the effect of the tool shoulder geometry on friction stir welded aluminium and copper joints.

2.12. Tool design

This section describes different tool designs. The tool is the fundamental component of Friction Stir Welding (FSW). FSW has evolved empirically based on observations of forces, defects, rotational speeds, transverse speeds and material flow. Tool design is one of the most important factors to consider when designing a FSW joining process. The tool must perform many functions, including but not limited to the generation of heat through friction, promotion of mixing, dispersion of oxide layers, creation of forging pressure, containing material within the joint, the prevention of surface weld flash and minimisation of defects. Additionally, the tool geometry must also facilitate a stable force and torque control to be compatible with the plunge depth. [62]

Some of the first FSW tool design innovations were developed by Thomas et al. [65] at The Welding Institute (TWI). The first innovations were developed to increase interfacial oxide layer disruption and increasing the Thermo-Mechanical Heat Affected Zone (TMAZ) width. Designs that arose from the work were the Flared-Triflute™ tool and the Skew-Stir™ which promoted mixing via an off axis probe that increased the dynamically volume. These tool are included in Table 2.8 [7].

<table>
<thead>
<tr>
<th>Tool</th>
<th>Cylindrical</th>
<th>Whoof™</th>
<th>MX triflute™</th>
<th>Flared triflute™</th>
<th>A-skew™</th>
<th>Re-stir™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schematics</td>
<td>Cylindrical with threads</td>
<td>Tapered with threads</td>
<td>Threaded, tapered with three flutes</td>
<td>Tri-flute with flute ends flared out</td>
<td>Inclined cylindrical with threads</td>
<td>Tapered with threads</td>
</tr>
<tr>
<td>Tool pin shape</td>
<td>Ratio of pin volume to cylindrical pin volume</td>
<td>1</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>Swept volume to pin volume ratio</td>
<td>1.1</td>
<td>1.8</td>
<td>2.6</td>
<td>2.6</td>
<td>depends on pin angle</td>
<td>1.8</td>
</tr>
<tr>
<td>Rotary reversal</td>
<td>Application</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
There have been numerous studies conducted to advance the science of tool design to deepen the understanding of tool geometries and their influence on weld properties. Although of this has been into research for aluminium [66,67,68] additional tool designs include the threaded counter flow, the variable penetration tool and self-reacting tool to name a few. Efforts made in the past to develop has been put to make cost effective and reusable tools, most of these efforts have been empirical in nature and further work is required to advance the practice of FSW.

2.13. Tool Material

Material selection and design profoundly influence the performance of the tool, weld quality and cost. As the application of Friction Stir Welding (FSW) evolved from softer materials to harder materials such as steels and titanium alloys so has the material used for the FSW tool also evolved. Commonly used tool materials include tool steels, Polycrystalline Cubic Boron Nitride (pcBN) and tungsten based material. The material selected for the FSW tool is highly dependent of the material properties of the materials to be friction stir welded, the tool design and the operating parameters employed during FSW. Each material selected for the FSW tool has certain advantages and disadvantages.

In order to make FSW financially viable and to ensure a sound friction weld is achieved it is important to consider the temperature at which welding will occur, the yield stress of materials to be welded and the forces associated with the friction stir welding of different materials. This information must then be compared to the properties of the tool material to be selected. Important properties of the tool material are: 1) The coefficient of thermal expansion of the tool material, 2) The thermal conductivity of the tool material, 3) The yield strength of the tool material, 4) The hardness of the tool material, 5) The tool design and associated wear rates and 6) The cost of producing the tool. These properties and comparisons then determine which type of tool design (shoulder diameter, shoulder profile, pin diameter and pin profile) are feasible for specific operating parameters on particular materials when performing friction stir welding process. The properties of the common tool materials is summarised in Table 2.9.

The thermal conductivity of the tool material determines the rate of heat removal and affects the temperature fields, flow stresses and weld microstructure. The appropriate value of thermal conductivity depends on the process variables, work-piece material and other tool material properties. [129] Conditions that prevail during friction stir welding the materials directly influences the weld quality but it is also important to consider tool wear. In addition to the above-mentioned material properties of the Friction Stir Welding (FSW) tool the hardness, ductility and reactivity of the tool in comparison to the work-piece is also of importance. These properties are important to consider to avoid surface erosion which will mix within the welded material which may be detrimental weld quality. Tool erosion may be further deteriorated by reactions with the work-piece or oxygen in the atmosphere. The tendency of a pure metal to react with oxygen is given by the standard Gibbs energy of oxidation for 1 mol of oxygen.
Figure 2.16 shows the Ellingham diagram for some metals used for FSW tools. An Ellingham diagram is a graph showing the temperature dependence of the stability for compounds. The diagrams are useful in predicting the conditions under which an ore will be reduced to its metal and are thermodynamic in nature. Metals higher up on the diagram are less likely to react compared to those below them. This property can be further enhanced by alloying elements or coatings to reduce tool wear. [129]
Table 2.9 summarises fundamental properties of PcBN, cp-W, WC and 4340 steel tool materials and includes the advantages and disadvantages of each of the above mentioned tool materials. The appropriate coefficient of thermal expansion, thermal conductivity, yield strength and hardness depends on the process variables, workpiece material, expected tool life, tool geometry and forces associated with the process parameters and material being welded.

### Table 2.9: Tool material specific details including advantages and disadvantages. [108]

<table>
<thead>
<tr>
<th>Tool Mater.</th>
<th>Coefficient of thermal expansion ((10^{-6} \text{ K}^{-1}))</th>
<th>Thermal Conductivity ((\text{Wm}^{-1}\text{K}^{-1}))</th>
<th>Yield Strength ((\text{Mpa}))</th>
<th>Hardness ((\text{HV}))</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| PcBN        | 4.6-4.9                                          | 100-250                                          | -                               | 2600-3500       | **Advantages:** High hardness value  
**Disadvantages:** Susceptible to cracks; high cost |
| cp-W        | Approx. 4.6 @ 20-1000 deg. Celsius               | 167 at 20 deg. Celsius  
111 at 1000 deg. Celsius | Approx. 100 @ 1000 deg. Celsius | 360-500 | **Advantages:** High strength at elevated temperature  
**Disadvantages:** Low toughness at room temperature |
| WC          | 4.9-5.1                                          | 95                                               | -                               | 1300-1600       | **Advantages:** High strength at elevated temperatures, high hardness value  
**Disadvantages:** Wear occurs at high temperatures due to oxidation |
| 4340 Steel  | 11.2-14.3                                       | 48                                               | -                               | 280             | **Advantages:** Low thermal conductivity  
**Disadvantages:** Low strength at high temperatures |
2.14. Tool Forces

Beside heat generation, heat transfer and material flow the tool must also be able to withstand the substantial forces associated with the friction stir weld process. Applying Newton III, the forces associated with the material being friction stir welded is also exerted onto the FSW tool. The force along the tool axis is known as the axial force (Fz). This force is the most influential force, if the force is too low this results in defects such as pin holes and tunnels, if this force is too high it results in overheating and thinning of the joint. The force acting in the direction of the tool translation along the joint is known as the transverse force (Fx). The transverse force decreases with an increase in the temperature of the material to be friction stir welded because the force required to overcome the resistance of the material decreases due to the material becoming malleable with an increase in temperature. The force perpendicular to the direction of the tool rotation, directed towards the advancing side is known as the lateral force (Fy). Figure 2.17 shows a FSW tool and the direction of the axial force (Fz), transverse force (Fx) and lateral force (Fy) during the FSW process. [67]

FSW can be said to be similar to the milling process however considerably larger forces are generated. Characterisation of these forces are important to develop and improve tool designs, to improve clamping arrangements, to reduce machine complexity, to reduce operation cost and to improve productivity.

![Figure 2.17: Illustration of forces and torque and the respective positive direction vectors](#)

To date there has been little quantitative data published regarding process forces generated in dissimilar friction stir welds. There have been attempts to numerically model these forces but these has not been achieved with sufficient accuracy. Rather these
numeric models rely on temperature comparisons to experimental results to predict the forces generated. Melendez et al. [93] attached strain gauges to the material and successfully measured the transverse and side force but were unable to measure the axial force. Yang. et al.[94] developed an algorithm to detect the gap occurring between the work-piece and the tool using a load cell which is now known as force controlled FSW. Colegrove and Shercliff [95] used Computational Fluid Dynamics (CFD) software for a 2D and 3D numerical investigation of the influence of pin geometry during FSW. They were however not able to accurately predict the welding forces. Buffa et. al [59] successfully modelled the FSW process using DEFORM-3D and validated it through experimental and predicted temperatures. They however only considered a cylindrical smooth tool pin. Some research work has successfully modelled the forces experienced during FSW however the an understanding the influence of the tool geometry on the FSW process is currently extremely limited in published works. [39-44] To date no research has been conducted on forces generated in dissimilar friction stir welds of aluminium and copper due to different tool shoulder geometry.

Figure 2.18 presents the common forces and spindle torque evolution throughout the Friction Stir Welding process. This provides evidence the axial force ($F_z$) is prominent and important force to consider during friction stir welding. The transversing force ($F_x$), the side force ($F_y$) and the spindle torque are all fairly consistent, when compared to the axial force ($F_z$), during the FSW process.

![Figure 2.18: An example of forces and torque measurements][97]
2.15. Tool Geometry

The Friction Stir Welding pin-shoulder configuration was previously briefly discussed. The geometry of the FSW tool shoulder and pin can significantly influence the quality of a friction stir weld. The tool geometry affects the heat generation, heat transfer rate, forces, torque, material mixing and overall thermomechanical environment experience by the tool. Important features of the tool geometry are the shoulder diameter, shoulder surface angle, shoulder topography, pin diameter, pin shape, pin length and the nature of the tool surfaces.

The tool shoulder is where more of the heat is generated and the way it interfaces with the plasticised material establishes the material flow field. Heat is generated by sliding and sticking and material flow is influenced by sticking. Elangovan and Balasubramanian [91] showed that only a tool with an optimal shoulder diameter results in the highest strength of the AA 6061 FSW joints. Arora et al. [126] proposed a method to determine the optimal shoulder diameter by considering sticking (MT), sliding (ML) components of torque. Their results showed that the sliding torques increased continuously with the FSW tool diameter and the sticking torque increase, comes to a maximum and decreases. They then suggested that the optimum shoulder diameter should correspond to the maximum sticking torque for a given set of welding parameters and work-pieces.

Buffa et al. [59] numerically investigated the effect of the tool pin angle on the various weld area, grain size and welding forces showing a good agreement between the numerical and experimental results. Kumar and Kailas [58] carried out experimental work using different tool geometries explaining the effect of the shoulder diameter, pin diameter and pin profiles on the size and location of defects, mechanical properties and the grain sizes in the weld areas. They explained that there exist “pin-driven flow” and “shoulder-driven flow” which is determined by design for the friction stir weld tool. “Pin-driven flow” is influence by the tool pin and can be described as the effectiveness of the pin to constrain the material into the weld cavity. Therefore design of the pin should be such that the maximum amount of transferred material is retained in the weld cavity. “Shoulder-driven flow” can be described as the effectiveness of the shoulder to keep the material in the weld cavity. Therefore, the tool shoulder should be designed such that the maximum amount of the ejected material from the weld cavity by the pin is reflected back into the weld cavity. Mishra and Ma [1] explained that most of the tool design is based on intuitive concepts and they believe that the first step in deriving the concept of FSW tool design is to understand the role of the tool in friction stir weld formation. Figure 2.19 shows the stages of a model with the starting point, tool features, process settings and physics whereby the FSW tool engages to produce a weld. This diagram can be utilised to design a friction stir weld joint which is highly dependent on the process parameters and selection of the tool features.
The FSW tool shoulder and tool pin play fundamental roles in the friction stir weld process. The heat added to the system is generated mainly by the shoulder through friction against the base metal which brings the metal to a plastic-like state. The pin stirs the adjoining materials together to form a homogenous weld (for specific process parameters). In addition, the shoulder ensures that no material escapes upwards and facilitates material flow on the top of the friction stir weld. [58]

Parameters of the FSW tool shoulder that are variable include the diameter, material (coefficient of friction) and topography (influencing contact between the FSW tool and material to Friction Stir Welded). The tool tip is primarily responsible for generation of heat and mixing of materials. The tool tip diameter determines the thickness of the
Friction Stir Weld and the tool tip length determines the depth of material mixing. The tool diameter and tip both also determine the quantity of material mixed.

Buffa et al. [59] numerically modelled the FSW process with varying the FSW tool pin geometry. They were able to predict the material flow pattern and grain sizes for the welded joint. Figure 2.20 shows the material flow pattern at different pin angles.

Figure 2.20: Material flow directions for different pin angles. (transverse speed- 100 mm/min) [59]

While conducting their research they found that while friction stir welding the stresses subjected to the tool vary with the pin angle if the tool sinking is kept constant. They also found that a small vertical flow occurs with a cylindrical pin, the conical pin causes a downward flow pattern that increase when the pin angle increases and that a helical movement is produced by the conical pin which is favourable for achieving a fine grain size microstructure.
2.16. Electrical Properties

As noted previously, the joining of aluminum and copper may contribute significantly to the electrical industry and for electrical products. Friction stir welding could be an effective method of joining these two precious metals without damaging the good electrical properties that both metals already possess. Electrical resistivity is a measure of how strongly a material opposes the flow of electric current. A low resistivity indicates a material/joint that readily allows the movement of electrical charge. More specifically, resistivity is defined as the electrical resistance of a body of unit length and unit cross-sectional area or weight. There are two types of resistivity, namely volume resistivity and weight resistivity.

Volume resistivity is usually expressed in ohms for a theoretical conductor of unit length and cross-sectional area in Ω. mm²/m. The volume resistivity is calculated according to Equation 2.5.

\[ \rho = \frac{R}{L} \times \frac{A}{L} \]  \hspace{1cm} [2.5]

Where \( \rho \) = Electrical resistivity, \( R \) = Resistance, \( A \) = Cross-sectional area, \( L \) = Length of the sample

Weight resistivity is expressed in ohms for a theoretical conductor of unit length and weight. Only the volume resistivity will be measured in this research work.

There are different methods used in measuring electrical resistance, the Four-Point probe meter was used in this research work and the resistivity calculated using expression 2.6.

\[ \rho = 2\pi s \left( \frac{V}{I} \right) \] \hspace{1cm} [2.6]

Where \( \rho \) = Electrical resistivity, \( s \) = Probe spacing (m), \( V \) = voltage drop, \( I \) = Current, \( \frac{V}{I} \) = Resistance

The probe spacing, ‘s’ is a constant and equal to 1.6 mm, the \( 2\pi s \) becomes unity, and \( \rho \) becomes simply the relationship shown in expression 2.7:

\[ \rho = \frac{V}{I} = R \] \hspace{1cm} [2.7]

Limited information exists on resistivity measurement of weld cross-sections in FSW. The only reports being that conducted by Savolainen et al. [127] and Akinlabi et al. [128]. Savolainen et al. [127] included electrical resistivity a preliminary study on friction stir welding of dissimilar metal joints of copper and aluminium in which the electrical resistivity of the joint was measured and found to be relatively low compared to the base material. Akinlabi et al.[128] found that the electrical resistivities of dissimilar butt welds of aluminium and copper produced within their parameter settings, rotational speed
between 600 and 1200 rpm and transverse speed between 50 and 300 mm/min, increased as the heat input to the welds increased.

This research work forms part of the initial electrical conductivity tests performed on friction stir welds. The electrical resistance of each parameter setting will be measured and compared to the base materials in order to determine which process parameter and tool shoulder design produced good welds with relatively good electrical resistance properties to the base metals.

### 2.17. Friction Stir Welding Defects

One of the major advantages of utilising Friction Stir Welding (FSW) instead of conventional arc welding is the low incidence of weld flaws once the friction stir welding process has been optimised. Generally, friction stir welds are known to be free from defects like porosity, slag inclusion, solidification cracks etc. which are usually generated in fusion welding of aluminium which disintegrate the weld quality and joint properties [101]. Rather FSW joints are prone to other defects such as pin hole, tunnel defect, piping defect, kissing bond and cracks due to insufficient material flow. [102] Insufficient material flow can be due to poorly selected tool design and processing parameters. Defects in welded joints are important to identify while designing a friction stir welding process because these defects have led to lower tensile and fatigue strengths. [91, 92] Figure 2.21 shows some of the defects observed in friction stir welds. It also shows a graph that specifies a good process window for welding the particular material.

![Friction stir weld defects](image)

**Figure 2.2: Friction stir weld defects [60]**
2.17.1. Voids

Voids usually occur on the advancing side, between the weld nugget and the Thermo-mechanically Affected Zone (TMAZ), refer to Figure 2.22. Limiting the forging pressure generates a void; inadequate clamping also contributes towards void formation, if the welding pressure were to instantaneously vary during welding. Voids are generated at high rotational speeds; this is because the material receives less work per unit length that result in the plasticised material being cooler and more difficult for the shoulder to forge.

![Figure 2.22: Example of a void where material does not mix due to receiving less work per unit length [32]](image)

2.17.2. Joint Line Remnants

A joint line remnant is also referred to as a kissing bond, lazy S or entrapped oxide defect. A joint line remnant shown by macrograph and at an increase magnification is shown in Figure 2.23. This Friction Stir Weld (FSW) defect is a direct result of a semi-continuous layer of oxide through the weld nugget. The semi-continuous layer of oxide in the nugget is originally from a continuous layer of oxide present on the surfaces of the plates to be joined. Joint line remnants occur because of insufficient cleaning prior to welding, insufficient deformation of the work-piece - due to incorrect tool location relative to the joint line and too high rotational/transverse weld speeds.

![Figure 2.23: Joint line remnant imperfections in a friction stir weld shown by a) Macrograph and b) Magnification of oxide debris that causes the joint remnant [1]](image)
2.17.3. Root defects

Root defects also known as incomplete penetration is shown in Figure 2.24. Root defects result from a local variation in plate thickness, poor alignment of the tool to joint interface and improper tool design. Root defects require that an area exists that is un-deformed and as a result the materials are not properly joined. Butt welds require sufficient depth of deformation to eliminate the incomplete root penetration while ensuring the pin does not touch the back anvil. [1]

![Image of incomplete root penetration](image)

**Figure 2.24:** Schematic of incomplete root penetration. a) Micrograph and b) Fracture location [1]

2.18. Summary

Recent studies of joining aluminium and copper using the friction stir welding process focuses on microstructural evaluation and few on mechanical testing. The measurement of electrical properties is of high importance to the electrical / electronic industries in terms of application of aluminium and copper. The forces present between the interface of the FSW tool and dissimilar aluminium and copper joint is important to understand the influence of the tool design on the joint formed and further understanding will provide a opportunity to reduce costs by increasing tool life therefore making FSW a attractive process for joining aluminium and copper in industrial applications.

Electrical properties and tool forces present for dissimilar friction stir welds of aluminium and copper was found to be inadequately researched and reported. There was no existing reports on detailed characterisation of dissimilar friction stir welds of Al and Cu for varying tool shoulder designs and rotational speeds. In this study, the FSW of Al / Cu will be produced using different FSW tools and the welds will be characterised through microstructural evaluation, weld defect analysis, electrical resistance measurements and force analysis to validate the mechanical and electrical properties of the welded samples compared to the base materials. A process window to join both metals shall be established using a matrix of 15 combinations of the process parameters.

The review of literature related to this research project has been fully discussed in this chapter. The next chapter will focus on the experimental set-up procedures employed in the course of this research study.
CHAPTER 3 – EXPERIMENTAL SETUP
3. Introduction

This chapter presents all details and experimental procedures and methods of analysis in this research work. First, the material properties of 5754 aluminium and C11000 copper are presented, the FSW platform and welding process is discussed and this chapter concludes with a description of the experimental procedure employed for each test completed in this research project.

3.1. Mechanical and Physical Properties of 5754 Aluminium

The chemical composition of 5754 aluminium is presented in Table 3.1 and Table 3.2 shows properties of heat treated and annealed 5754 aluminium. The presence of 0.40% silicon improves the weldability and prevents cracking at elevated temperatures, 0.40% iron improves strength and hardness and reduces cracking while machining, 0.50% manganese improves ductility and impact strength, 2.6-3.2% magnesium improves strength through solid-solution strengthening. When considering the chemical composition and alloying effects of the respective elements, 5754 aluminium exhibits material properties that are suited for Friction Stir Welding (FSW).

Table 3.1: Element contribution for 5754 aluminium [97]

<table>
<thead>
<tr>
<th>Element</th>
<th>% Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon (Si)</td>
<td>0.40%</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>0.40%</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>0.50%</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>2.6-3.2%</td>
</tr>
<tr>
<td>Aluminium (Al)</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 3.2: Physical properties of 5457 aluminium [97]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2.66 g/cm³</td>
</tr>
<tr>
<td>Melting Point</td>
<td>600°C</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>68 GPa</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>0.049x10⁻⁶ Ω.m</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>147 W/m.K</td>
</tr>
<tr>
<td>Thermal Expansion</td>
<td>24x10⁻⁶ /K</td>
</tr>
</tbody>
</table>
3.2. Mechanical and Physical properties of C11000 Copper

Pure copper contains silver oxygen. The amount of oxygen present is dependent on the process required to make the specimen. The chemical composition of C11000 copper and its mechanical properties are presented in Table 3.3 and Table 3.4.

Table 3.3: Chemical composition of C11000 copper [97]

<table>
<thead>
<tr>
<th>Element</th>
<th>% Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>99.90%</td>
</tr>
<tr>
<td>Oxygen (minimum)</td>
<td>0.04%</td>
</tr>
</tbody>
</table>

Table 3.4: Mechanical properties of C11000 copper [97]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Range</td>
<td>1083°C</td>
</tr>
<tr>
<td>Density</td>
<td>8.89 g/cm@ 20°C</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>8.94</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>0.0000173 /K</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>934 W/m.K</td>
</tr>
<tr>
<td>Electrical Resistivity (Annealed)</td>
<td>1.71 x10⁻⁶ Ω.m</td>
</tr>
<tr>
<td>Modulus of Elasticity (tension)</td>
<td>121 MPa</td>
</tr>
<tr>
<td>Annealing Temperature</td>
<td>375-650°C</td>
</tr>
</tbody>
</table>
3.3. Friction Stir Welding

3.3.1. Friction Stir Welding Platform

The FSW machine used to produce the welds is an Intelligent Stir Welding for Industry and Research (I-STIR) Process Development System (PDS). The I-STIR PDS is a robust self-contained system that is capable of welding ferrous and non-ferrous materials. The platform of this machine is shown in Figure 3.1. The system specification for the I-STIR PDS FSW platform is included and described in Appendix B.

![Figure 3.1: Friction Stir Welding I-STIR platform.](image)

3.3.2. The clamping system and backing plate

Sufficient clamping of the plate is essential to achieve ‘good’ Friction Stir Welds. Clamping is necessary due to the magnitude of perpendicular and side forces that tend to lift and push plates apart during the FSW process. For the achieved Friction Stir Welds, the clamping system of the I-STIR PDS FSW platform supported with flat bars machined with steps to accommodate the tool holder during welding. This clamping system was designed beforehand by Akinlabi et. al [53]. The backing plate used is a mild steel plate of 25 x 650 x 265 mm bolted to the weld bed. The clamping system used is shown in Figure 3.2.
3.3.3. The Welding Process

3.3.3.1. Position of plates

Positioning of the plates is important due to mixing of the materials, which was, discussed in the literature review. Investigations by Galvao et al. [54] found that the base materials positioning has a strong influence on butt welds morphology and structure. The welds performed with the aluminium placed at the advancing side of the tool were morphologically very irregular due to the expulsion of the aluminium from the weld area. Copper placed on the retreating side produced results with bad surface finishes and substantial thickness reduction. Material with the higher melting point should be placed on the advancing side during the welding process [53]. For this reason, copper was placed on the advancing side and aluminium was placed on the retreating side.

3.3.3.2. Welding process

There are three primary control parameters available in Friction Stir Welding (FSW): rotational speed, feed rate and tool vertical position. To achieve sound friction stir welds, the important process parameters that affect the weld outcome should be identified and characterised in terms of the sensitivity of these parameters on the weld.
For dissimilar friction stir welds of aluminium and copper researchers have previously various input parameters. The objectives all differ however the purpose is to further analyse the fundamentals of the FSW process and explore the relationships between inputs and outputs.

The rotational used for this research are 600 rpm, 900 rpm and 1200 rpm which correspond to low, medium and high settings.

For the weld process, the following procedure was executed:

1. Plates were placed on the respective retreating and advancing sides and clamped with sufficient force.
2. The weld surface was cleaned with Silicon Carbide paper and then cleaned with acetone. The Silicon Carbide paper removes the oxide layer and the acetone ensures that there are no weld contaminates.
3. The weld head was moved to the start position.
4. The spindle is set to rotate at a specific speed.
5. The tool was plunged into the workpiece and allowed to rotate for about 2 seconds to obtained sufficient frictional heat and to allow the material to reach a plasticised state.
6. The tool was then set to transverse at a specific feed rate and the weld seam was formed.
7. The pin was extracted from the workpiece.
8. The weld head was moved to the next starting position.

To ensure consistency the weld tool was cooled to room temperature using compressed air after every weld. The deposited material on the tool pin and shoulder by soaking in a solution of 20g of Sodium Hydroxide (NaOH) and 100 ml of water for approximately 4 hours. If re-machining was deemed necessary, it was also completed.

The weld test matrix is shown in Table 3.5. The designation system for these process parameters are presented in Chapter 4. The designation system was based on attempting to select visually distinctive letter and numbers to avoid mix up of samples and to allow labelling for small areas on specimens if necessary. Reference for respective process parameters from henceforth will be made according to the established designation matrix.
Please take note that Concave shoulder and Conical Pin tool shall henceforth be referred to as conical shoulder tool and the conical shoulder with cylindrical pin tool shall be referred to as concave shoulder tool.

This was done in order to improve readability of this report and avoid confusion of the two tools during the discussions.

HENCE:

Concave shoulder and Conical Pin tool ➤ Conical Shoulder tool

Concave shoulder with cylindrical pin ➤ Concave shoulder tool

**Table 3.5: Weld matrix**

<table>
<thead>
<tr>
<th>Weld No.</th>
<th>Feed rate (mm/min)</th>
<th>Rotational Speed (rpm)</th>
<th>Weld Pitch (mm/rpm)</th>
<th>Tool Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td>Reddy Design</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td>Concave Shoulder and Conical Pin@ no tilt</td>
</tr>
<tr>
<td>6</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td>Concave Shoulder and Conical Pin@ 2 deg. tilt</td>
</tr>
<tr>
<td>10</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td></td>
</tr>
</tbody>
</table>
3.3.3.3. Friction Stir Weld tool used for testing

The dimensions and features of the tool used are presented in Table 3.6. The working drawing for the FSW tools are presented in Appendix C1.

Table 3.6: Features and dimensions of the FSW tool design

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Tool 1</th>
<th>Tool 2</th>
<th>Tool 3</th>
<th>Tool 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin Φ (mm)</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Pin Length (mm)</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Shoulder Φ (mm)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Features</td>
<td>Unique Reddy design</td>
<td>Conical Shoulder</td>
<td>Concave shoulder</td>
<td>Flat Shoulder</td>
</tr>
</tbody>
</table>

3.4. Purpose of testing

Succeeding Friction Stir Welding (FSW) 3mm thick plates of 5754 aluminium and C11000 copper. A number of tests were conducted and Figure 3.3 shows a breakdown of the tests completed and Table 3.7 shows the test, sample size and standard adhered during testing.
Table 3.7: Test completed, sample size and standard adhered for testing

<table>
<thead>
<tr>
<th>No.</th>
<th>Test</th>
<th>Sample size</th>
<th>Standard for testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Force analysis</td>
<td>Instantaneous measurement during welding</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Micro-structure Analysis</td>
<td>10 mm 25 mm</td>
<td>Stuers sample preparation for Aluminium and Copper materials [130, 131]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 mm 25 mm</td>
<td>Preparation of Metallographic Specimens</td>
</tr>
<tr>
<td>3</td>
<td>Electrical Resistivity</td>
<td>25 mm 25 mm</td>
<td>ASTM D116-86 [49]</td>
</tr>
</tbody>
</table>

**Samples will not be taken from the first 10 mm from the plunge point due to instability in the weld**

Parent material samples of aluminium and copper specimens were also analysed.

3.4.1. Optical Microscopy

Samples of size 25 x 10 x 3 mm were sectioned and mounted in polyfast thermoplastic hot resin. The samples were mounted such that the advancing side of the weld was always to the right. The mounted samples were prepared using standard metallographic procedures presented in this section. Observations of the microstructures were performed using an Olympus PMG3 optical microscope.

3.4.2. Grinding

The procedure for metallographic sample preparation is presented in Table 3.8. Where reference is made to:

RG – Rough Grinding

FG – Fine Grinding

Grinding of the specimens was done through combining the recommendations of Struers reports done for the preparation of aluminium and aluminium alloys and for the preparation of copper and copper alloys. [130, 131]
### 3.4.3. Polishing

The procedure employed to polish the samples is presented in Table 3.9 according to recommendations of Struers reports done for the preparation of aluminium and aluminium alloys and for the preparation of copper and copper alloys. [130, 131]

#### Table 3.9: Polishing procedure

<table>
<thead>
<tr>
<th>Step</th>
<th>DP</th>
<th>OP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>MD-mol</td>
<td>OP-Chem</td>
</tr>
<tr>
<td>Grit</td>
<td>Diapro Mol</td>
<td>OP-U</td>
</tr>
<tr>
<td>Rpm</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Force (N)</td>
<td>150</td>
<td>90</td>
</tr>
<tr>
<td>Time</td>
<td>4 min</td>
<td>2 min</td>
</tr>
</tbody>
</table>

### 3.4.4. Etching

Etching of the copper and aluminium welds was particularly difficult due to the differences in etching required for each respective material. First, the aluminium was etched using the chemical specified in Table 3.10 follow by etching of the copper material. Etching was only done on specimens after conducting preliminary tests on spare specimens and evaluating the results of the etchant solution under a microscope.
Table 3.10: Etching chemical solution for Aluminium and copper

<table>
<thead>
<tr>
<th>Macro-etching</th>
<th>3 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>For pure Aluminium</td>
<td>90 ml Water</td>
</tr>
<tr>
<td></td>
<td>15 ml Hydrochloric acid</td>
</tr>
<tr>
<td></td>
<td>10 ml Hydrofluoric acid</td>
</tr>
</tbody>
</table>

Table 3.10: Etching chemical solution for Aluminium and copper continued

<table>
<thead>
<tr>
<th>Macro-etching</th>
<th>3 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>For pure Copper</td>
<td>120 ml Water</td>
</tr>
<tr>
<td></td>
<td>20 ml Hydrochloric acid</td>
</tr>
<tr>
<td></td>
<td>7g Iron (III) chloride</td>
</tr>
</tbody>
</table>

3.4.5. Electrical Resistivity Determination

The resistivity of the joint was determined by calculation derived from the measurement of electrical resistances across the welds. The sample size for the electrical resistance measurement was 25 x 25 x 3 mm. A Signatone (s-302-4) Four-Point probe meter with 1.6 mm probe spacing was used to measure the electrical resistance; the circuit diagram is presented in Figure 3.4.

![Circuit diagram of the electrical resistance measurement.](image)

The electrical resistance of the samples were measured in accordance with ASTM D11686. [49] The Four-Point probe meter consists of two probes carrying the current and the other two probes sensing the voltage. The probes are generally collinear, that is, they are arranged in-line with equal probe spacing.
3.5. Summary

This chapter details some of the main material properties of 5754 aluminium and C11000 copper and describes the friction stir welding process and tests completed for this research. This chapter contains information about the friction stir welding platform used for the experiment, the clamping system, the procedure followed during welding, the weld test matrix. Some details regarding the FSW tool designs used for the experiment is presented as well as the employed standard and a summarised procedure for preparation of weld samples to be used for the choice of test equipment utilised for the analysis of the friction stir welds. Further information about the key subsystems of the I-stir FSW platform and the I-stir technical specification is made available in Appendix B. Information regarding the details of the FSW tool designs and code written to operate the FSW platform is made available in Appendix C. The results of the experimental work conducted shall be discussed in the next chapter.
CHAPTER 4 – RESULTS AND DISCUSSION
4. **Introduction**

This chapter reports the results obtained from the experimental tests discussed in Chapter 3. The welds were investigated by visual inspection, microscopy, force and torque analysis and electrical resistivity tests. Table 4.1 is repeated below with the designation system to be used as a reference to discuss the results reported in this chapter.

<table>
<thead>
<tr>
<th>Weld No.</th>
<th>Designation</th>
<th>Feed rate (mm/min)</th>
<th>Rotational Speed (rpm)</th>
<th>Weld Pitch (mm/rpm)</th>
<th>Tool Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RD1</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td>Reddy Design</td>
</tr>
<tr>
<td>2</td>
<td>RD2</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>RD3</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>C1</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td>Conical Shoulder @ no tilt</td>
</tr>
<tr>
<td>5</td>
<td>C2</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>C3</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>CS01</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td>Conical Shoulder @ 2 deg. tilt</td>
</tr>
<tr>
<td>8</td>
<td>CS02</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>CS03</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>CS1</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td>Concave Shoulder</td>
</tr>
<tr>
<td>11</td>
<td>CS2</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>CS3</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>F1</td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td>Flat Shoulder</td>
</tr>
<tr>
<td>14</td>
<td>F2</td>
<td>150</td>
<td>900</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>F3</td>
<td>150</td>
<td>1200</td>
<td>0.125</td>
<td></td>
</tr>
</tbody>
</table>

Process parameters selected for this research were based on previous research conducted by Akinlabi. [53] Given that the tool rotational speed would significantly influence the tool forces and heat generated through friction, the rotational speed was selected as the process parameter to be varied for this investigation. A feed rate of 150 mm/min was selected based on previous investigations completed for dissimilar friction stir welds
between aluminium and copper. [53] No investigation to date has been completed to characterise tool forces as a result of employing different tool shoulder geometries for dissimilar friction stir welds of aluminium and copper.

The tool designs used for this research are described in Table 4.2. A new tool design referred to as the Reddy Design was designed and tested. Common tool designs such as the conical, concave and flat shoulder tool were used not only as a reference but also to better understand the influence of the tool shoulder topography on dissimilar friction stir welds of aluminium and copper. The working drawings for the employed tool designs are made available in Appendix C1.

<table>
<thead>
<tr>
<th>Tool Design Used</th>
<th>Feed rate</th>
<th>150 mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rotational Speed</td>
<td>600 rpm</td>
</tr>
<tr>
<td>Reddy Design</td>
<td>RD1</td>
<td>RD2</td>
</tr>
<tr>
<td>Conical Shoulder @ no tilt</td>
<td>C1</td>
<td>C2</td>
</tr>
<tr>
<td>Conical Shoulder @ 2 deg. tilt</td>
<td>CS01</td>
<td>CS02</td>
</tr>
<tr>
<td>Concave Shoulder</td>
<td>CS1</td>
<td>CS2</td>
</tr>
<tr>
<td>Flat Shoulder</td>
<td>F1</td>
<td>F2</td>
</tr>
</tbody>
</table>

**Table 4.2: Test matrix with designation**

4.1. Preliminary Visual Inspection

Dissimilar friction stir welds were produced in 3mm plate material of 5754 aluminium and C11000 copper. Friction stir welds were completed according to the order shown in Table 4.1.

Table 4.3 specifies the process parameter tested, the surface visual image and observations. The Reddy, conical shoulder, concave and flat shoulder tool designs were used to complete dissimilar friction stir welds at rotational speeds of 600-, 900-, and 1200-rpm, the transverse speed was fixed at 150 mm/min. This section describes preliminary macro-examination of the top surface of the welds immediately after completing the welds and prior to cutting for test samples.
Table 4.3: Top weld surface according to parametric settings and observations

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>SURFACE VISUAL INSPECTION</th>
<th>OBSERVATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD1</td>
<td></td>
<td>Intermediate surface finish with signs of insufficient material mixing at the weld centre.</td>
</tr>
<tr>
<td>Reddy Tool</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>600 rpm</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td></td>
<td>Excellent surface finish with little flash formed. Signs of voids present.</td>
</tr>
<tr>
<td>Conical Shoulder (0° Tilt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>600 rpm</td>
<td></td>
</tr>
<tr>
<td>CS01</td>
<td></td>
<td>Intermediate surface finish with signs of inconsistent material mixing at beginning and flash formed on retreating side (in aluminium)</td>
</tr>
<tr>
<td>Conical Shoulder (2° Tilt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>600 rpm</td>
<td></td>
</tr>
<tr>
<td>CS1</td>
<td></td>
<td>Intermediate surface finish with flash formed at the beginning of the weld on advancing side (in Copper)</td>
</tr>
<tr>
<td>Concave Shoulder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>600 rpm</td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td></td>
<td>Excellent surface finish with signs of consistent material mixing, however excessive flash formed on both the advancing and retreating side</td>
</tr>
<tr>
<td>Flat Shoulder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>600 rpm</td>
<td></td>
</tr>
<tr>
<td>PARAMETERS</td>
<td>SURFACE VISUAL INSPECTION</td>
<td>OBSERVATION</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>RD2 Reddy Shoulder</td>
<td>Excellent surface finish at the beginning; large void created at the end showing bad signs of material mixing. Flash formed on advancing and retreating sides</td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>900 rpm</td>
<td></td>
</tr>
<tr>
<td>C2 Conical Shoulder (0° Tilt)</td>
<td>Intermediate surface finish with signs of consistent mixing and no flash formed</td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>900 rpm</td>
<td></td>
</tr>
<tr>
<td>CS02 Conical Shoulder (2° Tilt)</td>
<td>Excellent surface finish with signs of consistent material mixing and flash formed on retreating side towards the end of the weld</td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>900 rpm</td>
<td></td>
</tr>
<tr>
<td>CS2 Concave Shoulder</td>
<td>Excellent surface finish with signs of consistent material mixing and minimal flash formed on advancing and retreating sides</td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>900 rpm</td>
<td></td>
</tr>
<tr>
<td>F2 Flat Shoulder</td>
<td>Excellent surface finish with signs of consistent material mixing and minimal flash formed on advancing at the middle of the weld and retreating side at the end</td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>900 rpm</td>
<td></td>
</tr>
<tr>
<td>PARAMETERS</td>
<td>SURFACE VISUAL INSPECTION</td>
<td>OBSERVATION</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>RD3</td>
<td></td>
<td>Bad surface finish with signs of inconsistent material mixing on advancing side (in Copper) and no flash formation</td>
</tr>
<tr>
<td>Reddy Tool</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>1200 rpm</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td></td>
<td>Intermediate surface finish with signs of consistent material flow and flash formation on advancing and retreating sides of the weld</td>
</tr>
<tr>
<td>Conical Shoulder (0° Tilt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>1200 rpm</td>
<td></td>
</tr>
<tr>
<td>CS03</td>
<td></td>
<td>Excellent surface finish with signs of consistent material mixing and no flash formed</td>
</tr>
<tr>
<td>Conical Shoulder (2° Tilt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>1200 rpm</td>
<td></td>
</tr>
<tr>
<td>CS3</td>
<td></td>
<td>Excellent surface finish with consistent mixing however excessive flash created on advancing and retreating sides</td>
</tr>
<tr>
<td>Concave Shoulder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>1200 rpm</td>
<td></td>
</tr>
<tr>
<td>F3</td>
<td></td>
<td>Intermediate surface finish with signs of inconsistent material mixing and no flash formed</td>
</tr>
<tr>
<td>Flat Shoulder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>1200 rpm</td>
<td></td>
</tr>
</tbody>
</table>
4.1.1. Discussion of preliminary visual inspection results

Preliminary visual inspections of the welds were compared according to tool shoulder design and rotational speeds, which were the process parameters that were varied during the tests.

4.1.1.1. Preliminary visual inspection discussion based on rotational speed variation

For a rotational speed of 600 rpm, preliminary inspection shows that the best surface finish was achieved with the conical shoulder tool at 0-degree tool tilt. The conical shoulder tool at a 2-degree tool tilt resulted in a lower amount of aluminium being mixed within the weld interface and the formation of flash. The flat shoulder tool created an excellent surface finish however, excess flash was formed on the advancing and retreating sides of the weld. All welds show signs of sufficient material mixing. The Reddy tool results show the formation of a large number of discontinuities at a rotational speed of 600 rpm.

4.1.1.2. For a rotational speed of 900 rpm

All welds showed improvements in surface finish quality when the rotational speed was increased from 600 rpm to 900 rpm. The Reddy shoulder tool however created a large discontinuity towards the end of the weld suggesting that insufficient material mixing occurred at this process parameter setting. The concave shoulder tool and flat shoulder tool shows a good surface finish at a rotational speed of 900 rpm.

4.1.1.3. For a rotational speed of 1200 rpm

Excess flash was created for the conical shoulder tool at 0-degree tool tilt and concave shoulder tool. The best surface finish was achieved by the conical shoulder tool at a 2-degree tool tilt.

Visual inspection is an overall weld quality examination. This inspection relies on the use of the naked eye and is not often a true indication of the weld quality. Results obtained in this manner are influenced by a large variety of FSW related factors. However, despite this, visual inspection allows researchers to form some preliminary deductions fairly quickly and early in the research investigation. Dominant aspects that influence visual inspection of friction stir welds are placement of materials on the retreating or advancing side and the FSW tool design. The differences in the weld quality can be easily seen for employed rotational speeds for the various FSW tool designs. This indicates that a suitable range of rotational speeds was completed.

Visual inspection is a general evaluation test from which a small amount of deductions can be reached. For this reason, visual inspection was done as a preliminary investigation to characterise the visual surface finish quality and any noticeably large-scale defects.
4.1.1.4. Visual Inspection for employed tool design surface finish

Table 4.4 shows the deductions made on the surface quality of the welds completed as a particular rotational speed and with a particular tool design.

<table>
<thead>
<tr>
<th>Tool Design Used</th>
<th>Feed rate</th>
<th>150 mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rotational Speed</td>
<td>600 rpm</td>
</tr>
<tr>
<td>Reddy Design</td>
<td>Intermediate</td>
<td>Poor</td>
</tr>
<tr>
<td>Conical Shoulder @ no tilt</td>
<td>Best</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Conical Shoulder @ 2 deg. tilt</td>
<td>Best</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Concave Shoulder</td>
<td>Poor</td>
<td>Best</td>
</tr>
<tr>
<td>Flat Shoulder</td>
<td>Intermediate</td>
<td>Best</td>
</tr>
</tbody>
</table>

Based on the preliminary visual inspection results the following information can be deduced:

The Reddy tool design should be employed for high rotational speed process parameters and can also produce an intermediate surface finish for welds completed at a lower rotational speed.

The conical shoulder tool at no tilt achieved the best surface finish at a low rotational speed and a poor surface finish at a high rotational speed. With regards to surface finish, tool tilt angle did not seem to have a significant effect on the surface finish of the weld.

The concave shoulder achieved the best surface finish at a medium rotational speed and the worst surface finish at a low rotational speed. The flat shoulder achieved the best surface finish at a medium rotational speed and the worst surface finish at a high rotational speed.

Table 4.5 shows the suitability of the tested tool designs according to the rotational speed process parameter. The result shown in Table 4.5 is based only on the top surface appearance of the dissimilar friction stir weld and is therefore only applicable with reference to obtaining a good surface finish of the weld.
### Table 4.5: Suitability of tool design for tested rotational speeds based on surface finish observations

<table>
<thead>
<tr>
<th>TOOL DESIGN</th>
<th>SURFACE FINISH DEDUCTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reddy Design</td>
<td>Suitable for high and low rotational speeds</td>
</tr>
<tr>
<td>Conical Shoulder @ no tilt</td>
<td>Suitable for low rotational speeds</td>
</tr>
<tr>
<td>Conical Shoulder @ 2 deg. tilt</td>
<td>Suitable for low rotational speeds</td>
</tr>
<tr>
<td>Concave Shoulder</td>
<td>Suitable for medium rotational speeds</td>
</tr>
<tr>
<td>Flat Shoulder</td>
<td>Suitable for medium rotational speeds</td>
</tr>
</tbody>
</table>

Ideally, to achieve a sound dissimilar friction stir weld of aluminium and copper a low rotational speed is desired since this will result in the lowest amount of energy being consumed during the friction stir welding process. For this reason and based on the preliminary visual inspection results, the conical shoulder tool design shows to be the most promising design for dissimilar friction stir welds of 3mm thick aluminium and copper plates for the adopted experimental process parameters.
4.2. Heat generation

Equation 2.4 was used to calculate the heat generated for each process parameter used in the current investigation. The instantaneous torque on the tool was measured during process tests and the results were then averaged. The average torque result was inserted into Equation 2.4 along with the respective feed rate and rotational speed. An estimation of the heat generated for each tool design and the corresponding rotational speed tested is plotted in Figure 4.1.

![Figure 4.1: Heat generation Vs. Rotational speed](image)

Figure 4.1 shows that although Equation 2.4 is directly proportional to the rotational speed, an increase in rotational speed does not necessarily result in an increase in the amount of heat generated in the case of dissimilar butt welds between aluminium and copper. This may be due to the plasticising of the material being friction stir welded. An increased amount of heat results in plasticising of the material. This increased heat allows the material to deform easier resulting in a lowered torque measurement. At a high rotational speed of 1200 rpm, almost no opposing resistant was presented by aluminium and copper on the FSW tool.
4.3. **Weld Defects and material flow**

Weld samples for each process parameter were mounted, etched and observed under an optical microscope to study the material flow mixing of aluminium and copper for each tool shoulder design and the corresponding rotational speeds employed during testing.

Observations are presented in Table 4.6 and are followed by a discussion at the end of this section.

**Table 4.6: Weld Defects and material flow**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>OBSERVATION</th>
<th>RD1</th>
<th>RD2</th>
<th>RD3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate</td>
<td>Weld formed in nugget center and retreating side of weld due to insufficient material flow</td>
<td>150 mm/min</td>
<td>150 mm/min</td>
<td>150 mm/min</td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>600 rpm</td>
<td>900 rpm</td>
<td>1200 rpm</td>
<td></td>
</tr>
<tr>
<td>PARAMETERS</td>
<td>OBSERVATION</td>
<td>ADVANCING SIDE OF NUGGET</td>
<td>RETREATING SIDE OF NUGGET</td>
<td></td>
</tr>
<tr>
<td>------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------------------------</td>
<td>---------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>C1</strong></td>
<td>Good material mixing of aluminium in copper and minimal mixing of copper in aluminium. Large void at bottom of nugget on retreating side</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conical Shoulder (0° Tilt)</td>
<td></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>150 mm/min</td>
<td></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>600 rpm</td>
<td></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td><strong>C2</strong></td>
<td>High volume of material mixing and material deformation in elongated state. Defect free</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conical Shoulder (0° Tilt)</td>
<td></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td></td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>150 mm/min</td>
<td></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td></td>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>900 rpm</td>
<td></td>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td><strong>C3</strong></td>
<td>High volume of material mixing and deposited in fine elongated state. Large voids located at bottom of nugget region in centre of the welded region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conical Shoulder (0° Tilt)</td>
<td></td>
<td><img src="image21.png" alt="Image" /></td>
<td><img src="image22.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td></td>
<td><img src="image23.png" alt="Image" /></td>
<td><img src="image24.png" alt="Image" /></td>
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<tr>
<td>150 mm/min</td>
<td></td>
<td><img src="image25.png" alt="Image" /></td>
<td><img src="image26.png" alt="Image" /></td>
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</tr>
<tr>
<td>Rotational Speed</td>
<td></td>
<td><img src="image27.png" alt="Image" /></td>
<td><img src="image28.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>1200 rpm</td>
<td></td>
<td><img src="image29.png" alt="Image" /></td>
<td><img src="image30.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Parameters</td>
<td>Observation</td>
<td>Advancing Side of Nugget</td>
<td>Retreating Side of Nugget</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------------------------------------------------------------------------</td>
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<td></td>
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<tr>
<td><strong>CS01</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conical Shoulder</td>
<td>Minimal material mixing. No void</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2° Tilt)</td>
<td>on advancing side of weld. Void on</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>600 rpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CS02</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conical Shoulder</td>
<td>High volume of displaced material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2° Tilt)</td>
<td>however insufficient mixing of material and a void was formed on</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>900 rpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CS03</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conical Shoulder</td>
<td>High volume of material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2° Tilt)</td>
<td>deformation and good material mixing however void created in</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>1200 rpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PARAMETERS</td>
<td>OBSERVATION</td>
<td>ADVANCING SIDE OF NUGGET</td>
<td>RETREATING SIDE OF NUGGET</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------------------------------------------</td>
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</tr>
<tr>
<td>CS1</td>
<td>Low Volume of material deformation and mixing</td>
<td><img src="image1" alt="Advancing side of Nugget" /></td>
<td><img src="image2" alt="Retreating side of Nugget" /></td>
<td></td>
</tr>
<tr>
<td>Concave Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>600 rpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS2</td>
<td>High volume of material deformation and good material mixing. No defect</td>
<td><img src="image3" alt="Advancing side of Nugget" /></td>
<td><img src="image4" alt="Retreating side of Nugget" /></td>
<td></td>
</tr>
<tr>
<td>Concave Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>900 rpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS3</td>
<td>High volume of material deformation and good material mixing. Very small defect at top of nugget.</td>
<td><img src="image5" alt="Advancing side of Nugget" /></td>
<td><img src="image6" alt="Retreating side of Nugget" /></td>
<td></td>
</tr>
<tr>
<td>Concave Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>1200 rpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PARAMETERS</td>
<td>OBSERVATION</td>
<td>ADVANCING SIDE OF NUGGET</td>
<td>RETREATING SIDE OF NUGGET</td>
<td></td>
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<td>---------------------</td>
<td>------------------------------------------------------------------------------</td>
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<td></td>
</tr>
<tr>
<td><strong>F1</strong></td>
<td>High volume of material deformation with some mixing of material. Small voids created on retreating side of weld located at the bottom.</td>
<td><img src="#" alt="Image 1" /></td>
<td><img src="#" alt="Image 2" /></td>
<td></td>
</tr>
<tr>
<td>Flat Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>600 rpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>F2</strong></td>
<td>High volume of material deformation with substantial material mixing however large voids formed on retreating side of weld</td>
<td><img src="#" alt="Image 3" /></td>
<td><img src="#" alt="Image 4" /></td>
<td></td>
</tr>
<tr>
<td>Flat Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>900 rpm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>F3</strong></td>
<td>High volume of material deformation and material mixing however large elongated voids formed on advancing side and retreating side of weld</td>
<td><img src="#" alt="Image 5" /></td>
<td><img src="#" alt="Image 6" /></td>
<td></td>
</tr>
<tr>
<td>Flat Shoulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>150 mm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Speed</td>
<td>1200 rpm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.3.1. Discussion on preliminary material flow results and defect analysis

From the material flow results, it can be observed that the material mixing pattern changes significantly according to the tool shoulder geometry during dissimilar FSW of aluminium and copper.

Defects were observed in a majority of the welds. For both low and high rotational speeds of 600 rpm and 1200 rpm, all the friction stir welds contained defects. The only defect free welds was achieved at a rotational speed of 900 rpm and a transverse speed on 150 mm/min using the concave shoulder tool and the conical shoulder tool at 0-degree tool tilt. Table 4.7 provides details regarding the defects found in welds completed with a particular tool design at a specific rotational speed.

At a low rotational speed the material flow patterns suggests that all the employed tool designs do not generate enough heat to ensure proper plasticisation of the aluminium and copper. At a medium rotational speed the material flow patterns suggests that the employed tool designs show signs of improved material mixing compared to a low rotational speed and two defect free joints were achieved. For a high rotational speed of 1200 rpm, a large amount of material mixing occurred in the welds however, no defect free welds were formed.

Table 4.7: Defect formation results

<table>
<thead>
<tr>
<th>Tool Design</th>
<th>Rotational Speed 600 rpm</th>
<th>Rotational Speed 900 rpm</th>
<th>Rotational Speed 1200 rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reddy Tool design</td>
<td>Void formed in nugget centre and retreating side of weld</td>
<td>Large void formed on advancing side of weld and small void on retreating side</td>
<td>Good material mixing however void formed on retreating side of weld</td>
</tr>
<tr>
<td>Conical Shoulder 0 degree tilt</td>
<td>Large void at bottom of nugget at the retreating side</td>
<td>Defect free joint</td>
<td>Large voids located at bottom of nugget region</td>
</tr>
<tr>
<td>Conical Shoulder 2 degree tilt</td>
<td>Void on retreating side of weld</td>
<td>Void on retreating side of weld</td>
<td>Void created in middle of nugget region</td>
</tr>
<tr>
<td>Concave shoulder</td>
<td>Low volume of material mixing</td>
<td>Defect free joint</td>
<td>Defect at top of nugget</td>
</tr>
<tr>
<td>Flat shoulder</td>
<td>Small voids created on retreating side</td>
<td>Voids created on retreating side of weld</td>
<td>Voids created on advancing and retreating side of weld</td>
</tr>
</tbody>
</table>

In addition to the comparison of tool shoulder design and rotation speed, the conical shoulder tool at 0 degree tool tilt produced a relatively bad friction stir weld at 1200 rpm whereas the conical shoulder at a 2 degree tool tilt at this same process parameter
produced relatively good material mixing properties but unfortunately formed a void, as a result of insufficient mixing of the material around the tool pin, on the retreating side.

This finding suggests that the tool tilt angle for the conical shoulder tool was an important consideration as the tool tilt significantly affected the material mixing in the friction stir weld. Mehta and Badheka [139] investigated the effect of tool tilt angle on dissimilar friction stir welds of 6061-T651 aluminium and C11000 copper using a cylindrical threaded pin profile FSW tool. They found that the nugget became triangular as the tool tilt angle was increased from 0 to 4 degrees. A similar result occurred in this research work regarding the shape of the nuggets created by the conical shoulder tool when comparing the cross sectional area of the nugget formed at 0 degree and 2 degrees tool tilt. Based on results of the defect formation analysis and observations of material mixing the suitability of the tool design and rotational speed is presented in Table 4.8.

<table>
<thead>
<tr>
<th>TOOL DESIGN</th>
<th>MATERIAL MIXING AND DEFECT DEDUCTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reddy Design</td>
<td>Suitable for high and low rotational speeds</td>
</tr>
<tr>
<td>Conical Shoulder @ no tilt</td>
<td>Suitable for medium rotational speed</td>
</tr>
<tr>
<td>Conical Shoulder @ 2 deg. tilt</td>
<td>Suitable for medium rotational speed</td>
</tr>
<tr>
<td>Concave Shoulder</td>
<td>Suitable for medium rotational speeds</td>
</tr>
<tr>
<td>Flat Shoulder</td>
<td>Suitable for low rotational speeds</td>
</tr>
</tbody>
</table>

A comparison of Table 4.5 (page 91), completed for visual inspection of the top surface of the weld, and Table 4.8 agreement of the results are only similar for the Reddy shoulder tool and the concave shoulder tool. This means that despite the good top surface appearance of the weld, the cross sectional area and hence material mixing in the weld can show completely different results. For this research, there was only a 40% accuracy and therefore visual inspection of the top surface of the friction stir weld is a very rough approximation of the weld quality.

The cross sectional area of the weld better indicates the weld quality and Table 4.8 is in fact a better indication of the tool design performance and appropriate rotation speed for friction stir welding aluminium and copper. Both tables are however valuable because joining of materials can be used in a vast number of applications and the cost of joining the material plays a vital role, particularly in industrial applications. Depending on the weld application it is sometimes more desirable to have a good surface finish (corrosion resistant applications) and at other times good material mixing (strength applications). A good top surface finishes and good material mixing would both be achieved once the friction stir welding process has been optimised.
4.4. Microstructural Evaluation

In order to be familiar with the microstructure of the friction stir welded samples joined by the employed tool designs and process parameters, samples were prepared and etched; the micrographs of the two defect free dissimilar friction stir welds are presented in Figure 4.2 and Figure 4.3.
Figure 4.3: Macrograph and micrographs showing the regions of the friction stir weld completed using concave shoulder tool. Rotational speed 900 rpm, feed rate 150 mm/min
Typical FSW microstructure zones as were identified in all the welds produced using an optical microscope however only the defect free welds shall be presented in this report. Friction Stir Welding of dissimilar material systems is different from same material systems by the formation of complex, interacted vortex and related flow patterns. [132]

One of the objectives of creating a sound friction stir weld is to allow for extreme deformation of the material to create dynamic recrystallization, which permits flow in the solid-state by sliding between recrystallized, equiaxed and usually submicron grain in the weld zone. The resulting macrostructures of welds is known to be greatly influenced by the heat input into the welds. It was observed that the nuggets of all the welds are characterised by mixture of layers containing aluminium and copper as a result of the stirring action of the tools. These observations agree with many reports on microstructural characterisation of dissimilar friction stir welds between aluminium and copper. [132, 134, 135] Moreover, the intermixing of copper and aluminium is complicated and different microstructures are formed in different regions of the nugget. In Figure 4.2 and Figure 4.3 the nuggets are considerably different. The differences in microstructure and material flow observed in the cross section of the welds further highlights the significant role that the tool shoulder geometry has on the properties of the friction stir weld joint. Due to the complex material flow attributable to the tool shoulder design, the size, shape and distribution of copper and aluminium are not homogeneous in the dissimilar friction stirred nuggets.

The typical onion ring structure, a special case of flow lines that arises when the flow lines form complete concentric circles, were not observed at the nuggets of the welds produced in this research work. This onion ring is usually formed in similar material butt welding and is well known to result from good material flow during the FSW process. Although, onion ring structure patterns are rarely seen in FSW of aluminium and copper, signs of the slight formation of onion ring structures can be observed as semi-circular flow lines in Figure 4.2.

Figure 4.2 shows the optical microstructures of the dissimilar joint. There are four different regions in the dissimilar joints including Base Material (BM), Heat Affected Zone (HAZ), Thermo-Mechanically Affected Zone (TMAZ) and nugget. Some onion-ring-vortex-like structures have started to form in this weld although the complete nugget does not show the onion-vortex.

Figure 4.3 shows the optical microstructures of the dissimilar joint. Complex flow patterns of copper and aluminium occurred on the cross section of this weld. A lamellae structure composed of copper particles with a streamline shape and continuous aluminium strips are present in this weld. This interlaced structure formed by aluminium and copper indicates that the dissimilar sheets are bonded together firmly in these regions. The interacted vortex structure is a manifestation of the solid-state flow in dissimilar FSW, in which complex inter-diffusion and interaction of the two materials take place. [125, 135] Due to the complex material flow; the size, shape and distribution of copper phases are not homogeneous in the dissimilar nugget.
By inspection of the cross sectional areas of the friction stir welds presented in Figure 4.2 and Figure 4.3, it can be seen that compared to the base material, both the aluminium and copper microstructure are greatly refined during forming the solid-state mixed dissimilar friction stir weld joint. A comparison of Figure 4.2 and Figure 4.3 shows that the conical shoulder tool achieved more stirring of the material and fine lamellae deposits of material with signs of the formation of an onion-vortex-like-pattern suggesting that dynamic recrystallization may have occurred in this weld.

In Figure 4.2 and Figure 4.3, the grains become coarser in the HAZ and nugget of both friction stir welds. Looking more closely at the weld micrographs it was also noticed that the grains coarseness is different at different heights of the cross sectional area of the weld. This may be due to the deformation process with insufficient stirring occurring at the bottom due to the pin.

Lakshminararayanan et al. [133] suggested that the top portion is coarser due to excess heat input caused by shoulder to work-piece interface. The high temperature region very near to the heat source (tool shoulder) leads to the formation of coarse grains due to slow cooling resulting in the lowest hardness values occurring at the top region compared to the bottom region which is far away from the heat source where fine grains can be observed from rapid cooling.

### 4.5. Electrical Resistivity

Figure 4.4 shows the electrical resistivity of the welds versus the rotational speed during friction stir welding. Details regarding the testing method were discussed previously in Chapter 3.

#### 4.5.1. Electrical Resistivity Results Discussion

The four point probe method measurement was completed four times for each respective weld test sample; the four measurements were then averaged and plotted in Figure 4.4. A lower value in Figure 4.4 indicates a low electrical resistivity property which is preferred for electrical applications since less energy is consumed while trying to overcome the resistance to the electrical current. It is possible to deduce that friction stir welding of aluminum and copper for all tool designs produces good electrical resistivity properties. The only tool design that produced a relatively high electrical resistivity is the Reddy tool. Therefore the Reddy tool design is not ideal to achieve friction stir welds with a low electrical resistivity.
Based on electrical resistivity measurements the following information can be observed:

The Reddy tool design has the highest electrical resistivity value for all welds produced. The relationship between the electrical resistance and rotational speed is linear in nature for the Reddy tool.

The Conical shoulder tool at no tilt and 2 degree tilt recorded very similar electrical resistivity values for a low rotational speed of 600 rpm. At 900 rpm, the electrical resistivity of the conical shoulder weld with a 2-degree tilt had a higher electrical resistance measurement than the weld created with no tilt. At 1200 rpm, the conical shoulder tool with no tilt increased sharply in electrical resistance and the electrical resistivity of the weld formed with the conical shoulder at a 2-degree tilt increased at a slightly lower rate. The relationship between electrical resistance and rotational speed for the conical shoulder tool with a 2-degree tilt appears to be linear.

The concave shoulder tool recorded a relatively low electrical resistance at a low rotational speed of 600 rpm and increased sharply at a medium rotational speed of 900 rpm. At a high rotational speed of 1200 rpm, the electrical resistivity decreased sharply to achieve a similar electrical resistance as the 5754 aluminium base metal.

The flat shoulder recorded the lowest electrical resistance for a low rotational speed of 600 rpm. The electrical resistance increased marginally at a medium speed of 900 rpm and decreased slightly at a high rotational speed of 1200 rpm.
The relationship between tool shoulder design and electrical resistance appears to be complex. There is no apparent trend shown by all tools. Rather each tool design had a different performance with a change in rotational speed. The Reddy tool appears to be inappropriate to achieve a dissimilar friction stir welds with a low electrical resistivity. For low rotational speeds the conical shoulder tool at 0 and 2 degree tilt, the concave shoulder tool and flat shoulder tool all produced welds with relatively low electrical resistance.

An increase in rotational speed from a low rotational speed of 600 rpm to a medium rotational speed of 900 rpm resulted in an increase in electrical resistivity for all welds. The conical shoulder with no degree tilt achieved the lowest electrical resistivity at 600 rpm. For a high rotational speed of 1200 rpm the tool shoulder design and rotational speed, influences on the electrical resistivity of the weld in a complex manner. At a high rotational speed of 1200 rpm, the conical shoulder tool showed a large increase in electrical resistivity whereas the concave shoulder tool showed a sharp decrease in electrical resistivity. The concave shoulder tool design recorded the lowest electrical resistivity out of all the employed tool designs.

It should be noted that good electrical properties were measured despite many of the samples having substantial defects. Besides the Reddy tool, the remaining tool designs all have a similar electrical resistivity and fall within the range of 0.06-0.104 for a low rotational speed of 600 rpm, 0.194-0.225 for a medium rotational speed of 900 rpm and 0.046-0.393 for a high rotational speed of 1200 rpm.

The welds produced with the conical shoulder at 0 and 2 degrees tool tilt, the flat shoulder and concave shoulder tools are relatively consistent in electrical properties and a satisfactory electrical performance is expected despite the large amount of defects observed. The Reddy shoulder tool was the only tool that showed an extreme increase in electrical resistivity. This may be due to the high number of intermetallics and micro-constituents created in the weld due to this tool shoulder design. From the heat generation discussion and Figure 4.1, it is interesting to note that, the heat estimation is not significantly higher than other tool designs. This suggests that the material flow due to the tool shoulder either created a large number of intermetallics and micro-constituents or the heat estimation (Equation 2.4) produced an inaccurate heat generation estimation for this research work.

Friction Stir welding changed the electrical conductivity of the welded materials; it is believed to be due to the microstructural modifications in the different zones of the weld. Since electrical conductivity is subject to electrical mobility, which is effected by the crystal defects further research is required to quantify the scalability of the electrical resistivity in dissimilar friction stir welds of aluminium and copper.
4.6. Tool Forces

The I-stir friction stir welding platform was setup to measure the axial, transverse and side forces and the torque on the tool. Figure 4.5 depicts the measured forces and torque against travel distance for the concave shoulder at 150 mm/min and 900 rpm. This is a typical force and torque vs. time plot for FSW of aluminium and copper. In general, there were approximately 2000 measurements recorded for each axial-, transversing- and side-force and the torque for each process parameter that was tested. From Figure 4.5 it is apparent that the axial force (Z-direction) is the largest in magnitude, the transverse force is the intermediate and the side force is the lowest magnitude force of the friction stir welding process.

![Figure 4.5: Force and torque vs. Distance for CS2- Concave Shoulder, 150 mm/min, 900 rpm](image)

Referring to Figure 4.5 the following information can be established. During plunging of the tool, the load increased initially when the tool pin made contact with the cold workpiece. The plunging stage lasted (0-6 s). Dwell stage lasted 2 s (no linear movement but allows heat generate by friction to build up). During the plunging stage, the output torques of both axis the Z-axis motor and the main spindle motor rise quickly and then decrease as the plunge depth increases and local softening extent around the tool pin is improved. When the shoulder of the tool is immersed into the work piece, the output torques of both the Z-axis motor and the main spindle motor rise again and reaches a second peak value. As soon as the welding starts, all three output torques of the Z-axis motor reach steady states promptly and remain relatively stable during the remainder of the weld.

This is similar to results found by Trimble et al. [64] and Su et al. [99], the research by both authors were completed using Aluminium 2024-T3. Dissimilar Friction stir welds of
aluminium and copper show similar trends to their tool force findings. To improve the life of the FSW tool it is necessary to develop ways to lower the force experienced on the tool during the plunging stage of the FSW process. The load quickly dropped as the material was softened due to heating. When the tool was transversed, the softened material was then displaced until the pin encountered colder material and the process was repeated. Load and torque curves display high frequency fluctuations at nearly constant and equal frequencies. The instantaneous rapid fluctuations correspond to discrete stick-slip events that occur during friction stir welding however, the general trend of the FSW after plunging is relatively steady state.

The Force and torque measurements can be used to make a number of deductions. This report documents the first study to be completed on the tool forces generated due to different shoulder geometry tool designs in dissimilar friction stir welds of aluminium and copper and an effort will be made to deduce as much information as possible from the data gathered. When considering the results found by Trimble et al. [64] and Su et al. [99], the forces and torques on the weld follow an almost steady state behaviour. However, data captured on the forces present of the dissimilar friction stir welds of aluminium and copper suggests that a steady state only occurs for the CS2 welding process parameters. Please refer to Appendix C3 for all weld forces and torques.

From the graphed instantaneous forces and tool torquein Appendix C, it is possible to see that the tool forces and torque are significantly influenced by the tool shoulder design and rotational speed. Although all forces are of importance, the most significant process parameters are the axial force (Z-force) and torque.

Using the trends on the instantaneous measurement graph plots made available in Appendix C3, it is possible to deduce that the Reddy tool shoulder design forces and torque are most stable at 900 rpm. The conical shoulder tool forces and torques shows more consistent instantaneous forces and torque at a 2 degree tilt compared to a 0-degree tool tilt. Furthermore, the conical shoulder tool at 0-degree tool tilt achieved the most stable forces and torque at 600 rpm. The conical shoulder tool at a 2-degree tilt achieves the most stable instantaneous forces and torque at 900 rpm and appears to be consistent in a frequency related manner. The concave shoulder tool is most stable at 900 rpm and is the most stable weld completed in all the experimental work. The flat shoulder tool shows the most consistent forces and torque at 900 rpm.

The instantaneous measurements for stabilised values of the forces and torques were averaged for each respective process parameter, averaged results for transverse force (Fx), side force (Fy), axial force (Fz) and torque (T) are presented in Table 4.9.
Table 4.9: Averaged forces and torque results recording during friction stir welding

<table>
<thead>
<tr>
<th>Weld No.</th>
<th>Tool Design</th>
<th>Designation</th>
<th>Process Parameters</th>
<th>Fx (kN)</th>
<th>Fy (kN)</th>
<th>Fz (kN)</th>
<th>Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reddy Tool</td>
<td>RD1</td>
<td>600 rpm 150 mm/min</td>
<td>3.448</td>
<td>0.297</td>
<td>6.783</td>
<td>7.093</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>RD2</td>
<td>900 rpm 150 mm/min</td>
<td>3.305</td>
<td>0.297</td>
<td>6.364</td>
<td>8.397</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>RD3</td>
<td>1200 rpm 150 mm/min</td>
<td>2.939</td>
<td>1.016</td>
<td>4.211</td>
<td>-3.100</td>
</tr>
<tr>
<td>4</td>
<td>Conical Shoulder (0° Tilt)</td>
<td>C1</td>
<td>600 rpm 150 mm/min</td>
<td>4.144</td>
<td>0.349</td>
<td>5.793</td>
<td>3.977</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>C2</td>
<td>900 rpm 150 mm/min</td>
<td>3.115</td>
<td>0.587</td>
<td>4.681</td>
<td>2.781</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>C3</td>
<td>1200 rpm 150 mm/min</td>
<td>2.303</td>
<td>-0.109</td>
<td>3.847</td>
<td>-1.398</td>
</tr>
<tr>
<td>7</td>
<td>Conical Shoulder (2° Tilt)</td>
<td>CS01</td>
<td>600 rpm 150 mm/min</td>
<td>4.243</td>
<td>1.537</td>
<td>10.489</td>
<td>9.364</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>CS02</td>
<td>900 rpm 150 mm/min</td>
<td>3.320</td>
<td>1.318</td>
<td>6.487</td>
<td>0.115</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>CS03</td>
<td>1200 rpm 150 mm/min</td>
<td>2.89</td>
<td>1.449</td>
<td>5.646</td>
<td>-0.401</td>
</tr>
<tr>
<td>10</td>
<td>Concave Shoulder</td>
<td>CS1</td>
<td>600 rpm 150 mm/min</td>
<td>4.519</td>
<td>3.869</td>
<td>10.501</td>
<td>4.329</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>CS2</td>
<td>900 rpm 150 mm/min</td>
<td>2.576</td>
<td>1.853</td>
<td>8.245</td>
<td>4.284</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>CS3</td>
<td>1200 rpm 150 mm/min</td>
<td>2.017</td>
<td>0.755</td>
<td>2.508</td>
<td>-6.616</td>
</tr>
<tr>
<td>13</td>
<td>Flat Shoulder</td>
<td>F1</td>
<td>600 rpm 150 mm/min</td>
<td>3.720</td>
<td>1.491</td>
<td>8.013</td>
<td>14.250</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>F2</td>
<td>900 rpm 150 mm/min</td>
<td>2.347</td>
<td>0.546</td>
<td>4.419</td>
<td>1.032</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>F3</td>
<td>1200 rpm 150 mm/min</td>
<td>1.470</td>
<td>0.308</td>
<td>2.057</td>
<td>-8.375</td>
</tr>
</tbody>
</table>
4.6.1. Axial force

The axial force is the most dominate force during friction stir welding and it is known to have a great influence over the properties of friction stir welded joint. Figure 4.6 shows the averaged axial force (Z Force) versus rotational speed. An increase in rotational speed resulted in a decrease in the axial force. This is in agreement with Melendez et al. [104] where the axial forced decreased in a linear manner with an increase in rotational speed from 650 rpm to 1200 rpm while measuring the tool forces on friction stir welded Al2195 and Al 6061.

At a rotational speed of 600 rpm, the conical shoulder tool at a 2-degree tilt experienced an average axial force of 10.48 kN and the concave shoulder tool measured an axial force of 10.5 kN. These two tool shoulder designs recorded the highest axial forces during the tested process parameters. The flat shoulder averaged to a force of 8.01 kN, the Reddy shoulder measured 6.78 kN. The lowest force at this process parameter was achieved with the conical shoulder at 0-degree tilt and measured 5.79 kN. To accurately calculate these forces is extremely difficult and complex therefore these forces are only accurately measured through conducting physical tests.

An increase in rotational speed to 900 rpm influenced the tool forces in different ways. The concave shoulder tool remains the highest at 8.24 kN. Both the conical shoulder tool at a 2-degree tilt and flat shoulder tool drop substantially to 6.48 kN and 4.41 kN respectively. The conical shoulder tool shows the lowest decrease and measured a force of 4.68 kN.
At a relatively high rotational speed of 1200 rpm, the concave shoulder axial force dropped drastically to 2.51 kN. The flat shoulder and Reddy shoulder dropped at a similar rate to 2.05 kN and 4.21 kN respectively at 1200 rpm. The conical shoulder at a 0-degree tilt and 2-degree tilt dropped similarly to 3.84 kN and 5.64 kN respectively.

Figure 4.7 shows the percentage decrease in axial force versus the percentage increase in rotational speed.

![Figure 4.7: Axial force decrease as a percentage Vs. Rotational speed increase as a percentage](image_url)

From the above analysis and Figure 4.7 it is evident that an increase in the rotational speed results in a decrease in the axial force, however the differences recorded for the axial forces were found to be different for each tool design. Flat shoulder tools such as the Reddy shoulder and flat shoulder experience high axial forces at low rpms and low axial forces at high rotational speeds. A tool tilt on the conical shoulder tool between 0 degree and 2 degrees introduced completely different axial force measurement recordings. The conical tool at 0 degree tilt showed a consistent drop in axial force with an increase in rotational speed whereas the a transition from low (600 rpm ) to medium (900 rpm) rotational speeds had a pronounced decreasing effect on the axial force for the conical shoulder tool at a 2 degree tilt. The axial force measurements were higher for a tool tilt angle than with no tilt angle, which is consistent with the findings of Mehta and Badheka. [139] The concave shoulder tool design had the largest percentage decrease in axial force out of all the tested tool designs between medium (900 rpm) and high (1200 rpm) rotational speeds.

The axial force is plotted against the tested tool designs and the rotational speeds used during the experiment in Figure 4.8. It can be seen that the axial force exerted by the tool show similar downward forces for low to medium rotational speeds. At higher rotational speeds, however the tool shoulder design significantly influences the axial force experienced by the FSW tool.
An increase in rotational speed influences each tool shoulder design differently because the contact interface between the tool and the work piece are different for each tool shoulder topography. The friction stir welding process is highly dependent on the generation of heat locally by the interaction between the friction stir welding tool and the work piece. Results show that even a slight change in the friction process such as the tool tilt angle has a significant effect on the forces experienced by the tool. This phenomenon can be best be explained by the variations in frictional heat generated through contact with the work piece which affects plasticising of the material and the amount of energy required to mix materials resulting in complex differences in sticking and sliding motion of the material on the friction stir welding tool.
4.6.2. Transverse Force

The transverse force is not as significant as the axial force for the weld characteristics however, this force affects mixing of material and tool wear. Figure 4.9 shows the averaged transverse force (X Force) versus rotational speed.

![Figure 4.9: Transverse speed Vs. Rotational speed](image)

An increase in rotational speed resulted in a decrease in the transverse force for all the employed tool designs. An increase in rotational speed affected each tool design differently. The 2 degree tilt on the conical shoulder tool had no effect on the transverse force at a low rotational speed of 600 rpm however as the rotational speed was increased to 900 rpm the tool with 0 degree tilt experienced a lower transverse force compared to the tool at a 2 degree tilt. The flat shoulder had the overall lowest transverse force magnitude for the experimented rotational speeds and decreased in a linear fashion as the rotational speed was increased. The Reddy tool design showed the lowest decrease in transverse force with an increase in rotational speed and almost remained constant between 600 rpm and 900 rpm rotational speeds. The concave shoulder tool design showed a sharp decrease in transverse force between 600 rpm and 900 rpm and a more gradual decrease between 900 rpm and 1200 rpm.

Figure 4.10 shows a 3D plot of the transverse force, rotational speed and tool designs. The transverse forces are considerably lower than the downward force. When comparing Figure 4.8 and Figure 4.10 it is evident that the transverse force follows a similar trend to the downward force.
The decrease in transversing force can be linked to the energy required to cause deformation of the material. An increase in rotational speed results in an increased amount of heat generated due to friction between the FSW tool and the material. At elevated temperatures metallic materials tend to deform easier. Each tool design was influenced differently with an increase in rotational speed. The flat shoulder and conical shoulder at 0 degree tilt tranverse forces showed a linear relationship with the rotational speed. Results show that the rotational speed substantialy influences the transverse force for all tool designs and the least affected was the Reddy tool design.

**4.6.3. Side force**

Figure 4.11 shows the side force versus the rotational speed and tool design. The side force is the lowest force in magnitude when friction stir welding aluminium and copper. The side force does not follow a similar trend like the downward force and transverse force.
The side force results do not show a well defined increase or decrease due to an increase in rotational speed. Rather, an increase in rotational speed influenced the side force in a unique manner. The concave shoulder shows a drastic and consistent decrease in side force magnitude with an increase in rotational speed. The flat shoulder tool also shows a steady decrease in side force with an increase in rotational speed but is however not as significant as the concave shoulder tool. The conical shoulder tool at a 2 degree tilt side force seemed to be unaffected by an increase in rotational speed. The conical shoulder tool at a 0 degree tilt side force increased slightly between 600 rpm and 900 rpm and then dropped to almost 0 at 1200 rpm. The conical shoulder tool at 0 degree tilt measured the overall lowest side force magnitude in for the weld parameters tested in this research.

Figure 4.11: Side force Vs. Rotational Speed

Figure 4.12 shows a 3D plot of the averaged side force measurement, rotational speed and tool design. No apparent trend is evident with regards to changes in rotational speed and the side force magnitude as with the axial force and transverse force. The inconsistent response of the side force with an increase in rotational speed is believed to be due to the complex material flow patterns involved. This statement is supported by the varience in morphology of the welds. From the results it can be concluded that the way the material mixes has high a significant effect on the side force exerted on the friction stir welding tool.
4.6.4. Torque

The torque experienced on the tool during friction stir welding aluminium and copper decreases with an increase in rotational speed. Figure 4.13 shows the average tool torque measurements as a function of the experimented rotational speeds. Results show a gradual decrease in torque between 600 and 900 rpm and a rapid decrease between 900 and 1200 rpm for the conical shoulder tool at no tilt and concave shoulder tool. This may be due to the higher amount of heat generated at high rotational speed which results in less resistance imposed by the materials being joined.

![Figure 4.12: 3D plot of average side force, rotational speed and tool design](image)

![Figure 4.13: Torque Vs. Rotational speed](image)
The “flat shoulder type” referring to the Reddy tool and flat shoulder tool appears to have high torques at low rotational speeds and a low torque at high rotational speeds.

The tool tilt completed for the conical shoulder tool shows significantly different results. At a 0-degree tilt, the torque on the tool is low for all tested rotational speeds. At a 2 degree, tilt the tool experiences a high torque at low rotational speeds and almost no torque at medium and high rotational speeds of 900- and 1200- rpm respectively. The torque experienced by the tool is directly related to the interaction between the tool and the material. These results shows that a tool tilt of 2 degrees has a significant impact on the interface and behaviour of the material to the friction stir welding tool. This further emphasises the importance of performing friction stir welding in a controlled environment. A comparison of the axial force measurements shown in Figure 4.6 and the torque measurements shown in Figure 4.13 shows that the torque generally follows a similar trend to the axial force. A similar result was found by Crawford et al. [100] however; in their result, they related the axial force and torque to a change in weld pitch whereas this research result is related only to the rotational speed.

Figure 4.14 shows the torque decrease versus the rotational speed increase, both as percentages. The relationship shows that when friction stir welding aluminium and copper the rotational speed and tool design significantly effect the torque experienced by the tool. The rotational speed effects each tool design differently however the overall effect of the rotational speed is apparent.

Low rotational speeds have little effect on the tool torque, as the rotational speed transitions between the medium and high rotational speeds the tool torque is significantly effected and the tool shoulder design plays a more significant role. Results show that the rotational speed effects the torque on the employed tool designs as follows: The most effected tool was the flat shoulder followed in order of highest to lowest effect by the conical shoulder tool at a 2 degree tilt, the concave shoulder tool, the reddy tool and lastly the conical shoulder tool at 0 degree tilt. Therefore selection of the appropriate rotational speed for each tool design is an extremely important when completing dissimilar friction stir welds of aluminium and copper.
Figure 4.14: Torque decrease as a percentage Vs. Rotational speed increase as a percentage

Figure 4.15 shows a 3D plot of the torque as a function of the rotational speed and tool designs used during the experiment. Results show that the rotational speed and tool design both significantly affect the torque experienced by the tool. The flat shoulder tool was the most effected with a considerably high torque at a 600 rpm and a high torque at 1200 rpm. It is evident that an inverse relationship exists between the torque experienced by the FSW tool and the rotational speed while friction stir welding aluminium and copper.

Figure 4.15: 3D plot of average torque, rotational speed and tool design
CHAPTER 5- CONCLUSIONS AND FUTURE WORK
5.0. Introduction

The objective of this research work was to investigate the effect of the tool shoulder design on the forces, torque experienced during friction stir welding, material flow characterisation and to determine the electrical conductivity of the dissimilar friction stir welds for employed tool shoulder designs. The following conclusions can be made regarding the results obtained from this experimental work.

5.1. Conclusions

Top surface visual inspection results indicate that to achieve a good surface finish at a low rotational speed of 600 rpm the conical shoulder tool at a 0 and 2 degree tilt and the Reddy design tool are most appropriate. For a medium rotational speed of 900 rpm, the concave shoulder tool and flat shoulder tool are most appropriate and at a high rotational speed of 1200 rpm the Reddy tool design is appropriate.

Weld defect and material flow results indicate that the material flow pattern changed significantly according to the tool shoulder geometry. Defects were observed in a majority of the dissimilar friction stir welds however defect free welds were achieved with the concave shoulder tool design and conical shoulder tool design at 0-degree tilt angle at a rotational speed of 900 rpm. A comparison of the suitability of the tool shoulder design according to rotational speed showed a 40% accuracy between deductions made from the top surface of the weld and the weld cross sectional area.

The nuggets of friction stir welds formed from the conical shoulder tool at 0 and 2 degree became triangular as the tilt angle increased from 0 to 2 degrees. Microstructural evaluation results revealed complex flow patterns of copper and aluminium material. Lamellae structures composed of copper particles with a streamline shape and continuous aluminium strips were present. Some evidence of dynamic recrystallization was observed in the nugget of the defect free welds. The gains of aluminium and copper became courser in the Heat Affected Zone (HAZ), Thermo-mechanical Heat Affected Zone (TMAZ) and the nugget. The grain coarseness was observed to be different at different heights of the above mentioned area’s along the cross sectional area of the dissimilar friction stir weld.

Electrical resistivity measurements revealed that the relationship between tool shoulder geometry and the electrical resistivity is complex in nature. No evident pattern was observed and each tool shoulder geometry varied in effect due to the change in rotational speed. Despite large defects, the dissimilar friction stir welds contained good electrical resistivity properties. Besides the Reddy tool, which is inappropriate to achieve welds with low electrical resistivity properties, the remaining tool designs all had a similar electrical resistivity and when grouped according to the rotational speed parameter fall within the range of 0.06Ω-0.104Ω for a low rotational speed of 600 rpm, 0.194Ω-0.225Ω for a medium rotational speed of 900 rpm and 0.046Ω-0.393Ω for a high rotational speed of 1200 rpm.

Tool forces and torque analysis revealed that for dissimilar friction stir welds between aluminium and copper the tool shoulder design substantially affect the instantaneous...
forces and torque experienced by the tool. Findings suggest that the tool shoulder geometry can affect the uniformity and weld properties along the length of a friction stir weld. Further evidence of non-uniformity was found during macroscopic examination of the top section of the dissimilar friction stir welds.

Results for the averaged forces indicate that the downward force, transverse force and side force all decreases with an increase in rotational speed. The decrease all tool forces can be linked to the energy required to cause deformation of the material. An increase in rotational speed results in an increased amount of heat generated due to friction between the FSW tool and the material. At elevated temperatures metallic materials tend to deform easier. Each tool design was influenced differently with an increase in rotational speed. This phenomenon can be best be explained by the variations in frictional heat generated through contact with the work piece which affects plasticising of the material and the amount of energy required to mix materials resulting in complex differences in sticking and sliding motion of the material on the friction stir welding tool.

The 3D plot of the axial force, tool design and rotational speed and the 3D plot of the transverse force, tool design and rotational speed shows that these two forces follow a similar trend to each other. A comparison of the axial force measurements and torque measurements suggests that the torque generally follows a similar trend to the axial force.

The side force follows no apparent relationship with the axial force or transverse force however; the magnitude of the side force is considerably less when compared to the axial and transverse force. The inconsistent response of the side force with an increase in rotational speed is believed to be due to the complex material flow patterns involved. This statement was supported by the variance in morphology of the welds. From the results it can be concluded that the way the material mixes has a significant effect on the side force exerted on the friction stir welding tool.

Results show that the rotational speed and tool design both significantly affect the torque experienced by the tool. The “flat shoulder type” referring to the Reddy tool and flat shoulder tool appears to have a high torque at low rotational speeds and a low torque at high rotational speeds. Low rotational speeds have little effect on the tool torque, as the rotational speed transitions between the medium and high rotational speeds the tool torque is significantly effected and the tool shoulder design plays a more significant role. Results show that the rotational speed effects the torque on the employed tool designs as follows: The most effected tool was the flat shoulder followed in order of highest to lowest effect by the conical shoulder tool at a 2 degree tilt, the concave shoulder tool, the Reddy tool and lastly the conical shoulder tool at 0 degree tilt. Therefore selection of the appropriate rotational speed for each tool design is an extremely important when completing dissimilar friction stir welds of aluminium and copper.
5.2. Future work

Further research is required to find tools that create steady state force conditions during dissimilar friction stir welding, steady state forces are difficult to achieve due to the complex thermal and material mixing that occurs in dissimilar friction stir welds of aluminium and copper.

Research is required to determine ways to lower the initial plunge force experienced by the tool which may be substantially beneficial to improving the tool life.

Further research is required to determine the electrical resistivity and tool forces as a function of other weld process parameters other than tool shoulder design and rotational speed. This research will allow us to better understand the influence of the tool on the forces experienced during welding and the electrical properties of the welds. Since the transverse force is mainly influenced by the tool pin cross sectional area, further characterization of the transverse force should be completed by varying the weld speed for different FSW tool tip designs.

Since electrical conductivity is subject to electrical mobility, which is affected by the crystal defects further research is also required to quantify the scalability of the electrical resistivity.

Although, at this point in time it is extremely difficult to accurately model dissimilar friction stir welding of aluminium and copper due to the differences in material properties and behavior. Results show that a complicated relationship exists between the forces experienced on the FSW tool due to different shoulder designs and rotational speeds. Further research and modeling of the process may be beneficially in optimization of achieving optimized dissimilar friction stir welds of aluminium and copper.

Further research should be completed to determine the coarseness variations in HAZ, TMAZ areas of the cross sectional area (top and bottom as well as across) in the dissimilar friction stir welds of aluminium and copper.
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APPENDICES

APPENDIX A – in combination with Chapter 2

Weight percentage calculation of Aluminum and copper in the intermetallic compounds.

The formula used is stated below:

\[
\% \text{ Element} = \frac{\text{Atomic weight} \times \text{No. of atoms in compound}}{\text{Total weight of compound}}
\]

Note: the atomic weight of Aluminium = 26.98
Atomic weight of Copper = 63.55

1. **AlCu**

\[
\% \text{ Al} = \frac{26.98}{26.98 + 63.55} \times 100 = 30\%
\]

\[
\% \text{ Cu} = \frac{63.55}{26.98 + 63.55} \times 100 = 70\%
\]

2. **Al}_2^{\text{Cu}}

\[
\% \text{ Al} = \frac{26.98 \times 2}{(26.98 \times 2) + 63.55} \times 100 = 46\%
\]

\[
\% \text{ Cu} = \frac{63.55}{(26.98 \times 2) + 63.55} \times 100 = 54\%
\]

3. **Al}_3^{\text{Cu}_4}

\[
\% \text{ Al} = \frac{26.98 \times 3}{(26.98 \times 3) + (63.55 \times 4)} \times 100 = 24\%
\]

\[
\% \text{ Cu} = \frac{63.55 \times 4}{(26.98 \times 3) + (63.55 \times 4)} \times 100 = 76\%
\]
4. $\text{Al}_4\text{Cu}_9$

\[
\% \text{ Al} = \frac{(26.98 \times 4)}{(26.98 \times 4) + (63.55 \times 9)} \times 100
\]

\% \text{ Al} = 16\% \text{ and } \% \text{ Cu} = 84\% 

5. $\text{AlCu}_3$

\[
\% \text{ Al} = \frac{(26.98)}{(26.98) + (63.55 \times 3)} \times 100
\]

\% \text{ Al} = 12\% \text{ and } \% \text{ Cu} = 88\% 

6. $\text{Al}_2\text{Cu}_3$

\[
\% \text{ Al} = \frac{(26.98 \times 2)}{(26.98 \times 2) + (63.55 \times 3)} \times 100
\]

\% \text{ Al} = 22\% \text{ and } \% \text{ Cu} = 78\%
APPENDIX B – In combination with Chapter 3

B1. THE KEY SUBSYSTEMS OF THE I-STIR PDS FSW PLATFORM

The key subsystems of the I-STIR PDS FSW platform are described briefly below:

**Pin / adapter tooling**: one tool holder is provided to allow for three welding modes which include the adjustable pin, self-reacting pin and fixed pin. Only the fixed pin tool was used in this research work. The tool holder that is shown in Figure B1a provides mechanical innerves for the tool.

![Figure B1: FSW Tool holder](image)

**Machine base**: the machine base acts as the foundation for the I-STIR PDS system.

**Weld head assembly**: the custom weld head assembly attaches the I-STIR PDS pin tool to the rotational drive system.

**Z axis manipulator and self-reacting load table**: the I-STIR PDS is equipped with a z-axis manipulation system and self-reacting load table. The z axis manipulation system allows the weld head to be raised for workpiece set up. The load reaction table limits the magnitude of forces induced on the foundation to the static weight of the I-STIR PDS.

**X axis manipulator**: the I-STIR PDS is equipped with an x-axis manipulation system and hydraulically controlled pitch. The x-axis actuator is used to drive the head assembly along the weld path.

**Y axis manipulator**: the I-STIR PDS is also equipped with a y-axis table. The y-axis actuator is used to drive the weld table ±305mm.

**Pitch axis and pitch adjustment**: the pitch axis is gimbal axis that primarily moves the weld head in the X-Z plane. The forge beam assembly allows pitch (±15°) adjustment of the weld head.
Measurement and control sensors: the I-STIR PDS is instrumented to accurately measure, control and monitor the key process parameters such as the pin rotation, torque, forge force and traverse loads, displacement, tool cooling flow, and temperature.

Specimen welding table: the specimen welding table serves as a 1651 mm long by 1016 mm wide by 92.25 mm high generic clamping surface.

Hydraulic distribution system: the hydraulic distribution system is made of the Hydraulic Power Unit (HPU), the Hydraulic Service Manifold (HSM) and the hose distribution. The HPU is an assembly of three separate pump modules and has an internal fluid circulation function that provides the source of hydraulic fluid for cooling the spindle and spindle hydraulic motor. The HSM provides the on / off separation of the machine and the HPU. In addition, the HSM incorporates filtration and ramping up or down of downstream pressure.

MTS Schema™ VME Digital control system: An MTS Schema™ VME digital control platform has an interface and control system that enables the operator to conveniently select, control, modify, and record I-STIR PDS processing parameters. A PC serves as the main operator interface.

Remote station control pendant: The remote station control pendant is used to manually position each of the machine’s axes and also to make trim adjustments during a weld.
### B2. THE I-STIR PDS FSW SYSTEM SPECIFICATIONS

Table 1 below lists the I-STIR PDS specifications for each system axis.

Table 1: System specifications. [137]

<table>
<thead>
<tr>
<th>Axis</th>
<th>Stroke</th>
<th>Speed</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X</strong></td>
<td>1041mm stroke, 1524 mm work envelop</td>
<td>0 to 2000 mm/min</td>
<td>0.88 to 66.7 kN</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>610 mm stroke</td>
<td>0 to 2000 mm/min</td>
<td>0.88 to 36 kN</td>
</tr>
<tr>
<td><strong>Z</strong></td>
<td>317.5 mm stroke</td>
<td>2.5 to 1400 mm/min</td>
<td>133 kN tension</td>
</tr>
<tr>
<td><strong>Tool rotation</strong></td>
<td>Infinite Clockwise/Counter Clockwise</td>
<td>200 to 2000 rpm (unloaded)</td>
<td>180 Nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 to 800 rpm (with gear reducer)</td>
<td>565 Nm (with gear reducer)</td>
</tr>
<tr>
<td><strong>Pitch adjustment</strong></td>
<td>±15°</td>
<td>0.1 to 300 °/min (unloaded)</td>
<td>0.88 to 66.7 kN</td>
</tr>
<tr>
<td><strong>Adjustable pin (optional)</strong></td>
<td>±15 mm</td>
<td>2.54 to 1270 mm/min (unloaded)</td>
<td>±89kN</td>
</tr>
</tbody>
</table>
APPENDIX C – In combination with Chapter 4

C1. Tool Design
Angle on conical shoulder made to 25°.
C2. Code to Operate Friction Stir Welding Platform

COORDS/PART
BREAK/"PRESS RESUME WHEN READY"

#3
FEEDRATE/RATE,400,RAMP,2000
FORGEMOVE/POSITION,5.0,RATE,500,RAMP,500
GOTO/430,0,0,-2
FORGEMOVE/TOUCH,0,RATE,25,OVERTRAVEL,35,FORCE,1.2
FORGEMOVE/POSITION,1.0,RATE,100,RAMP,500,RELATIVE

SPINDLE/RPM,900,RAMP,500
DELAY/SEC,2.0

# Plunge
FORGEMOVE/POSITION,-1,RATE,10,RAMP,240,RELATIVE

FORGEMOVE/POSITION,-2.65,RATE,5,RAMP,240,RELATIVE
DELAY/SEC,3

#Ramp up over 20mm then proceed in position control
FEEDRATE/RATE,50,ACCEL,9.375,DECEL,700
GOTO/550,0,0

# RETRACT TOOL
FORGEMOVE/POSITION,5,RATE,100,RAMP,200,RELATIVE
SPINDLE/RPM,0,RAMP,600

FEEDRATE/RATE,800,RAMP,2000
GOTO/550,0,30
C3. Force Graph Plots for Instantaneous Force and Torque Measurements
C2 - Conical Shoulder 0° Tilt, 150 rev/min, 900 rpm

- X Force
- Y Force
- Z Force
- Torque

Force (kN) vs Distance (mm)

Torque (Nm) vs Distance (mm)
CS02 - Conical Shoulder 2° Tilt, 150 rev/min, 900 rpm

Force (kN) vs Distance (mm)

- X Force
- Y Force
- Z Force
- Torque (Nm)
CS1 - Concave Shoulder, 150 rev/min, 600 rpm
CS3- Concave Shoulder, 150 rev/min, 1200 rpm

Graph showing variations in force and torque with distance.
F3- Flat Shouder, 150 rev/min, 1200 rpm

Diagram showing force (kN) and torque (Nm) vs distance (mm) for different forces (X, Y, Z) and torque over a range of distances.