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CHARACTERIZATION OF ALUMINIUM AND TITANIUM CARBIDE METAL MATRIX COMPOSITES PRODUCED VIA FRICITION STIR WELDING

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AUTHOR’S DECLARATION

I, Abegunde, Olayinka Oluwatosin hereby declares that:

- The work done in this dissertation is my own;
- All sources used or referred to have been documented and recognized, and
- This dissertation has not been previously submitted in full or partial fulfillment of the requirements for an equivalent qualification at any other educational institution.

Author’s Signature

Date: December, 2015
DEDICATION

I dedicate this work to the virtuous woman in my life, the woman that brought me into this world and the love of my life, My Mother Victoria Bolanle Abegunde and to a man of honour, My late Dad, Mr. kayode Abegunde.
ACKNOWLEDGEMENT

My profound gratitude goes to the Almighty God, the author and finisher of my faith, for giving me the grace to transform this research work into a reality and not an illusion.

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ABSTRACT

The Friction Stir Welding (FSW) process was invented and developed at The Welding Institute of United Kingdom in the year 1991 for solid state joining of aluminum and its alloys. Subsequently, this welding process has been used for joining other materials like magnesium, titanium and copper alloys, stainless steels and thermoplastics.

In this research work, ample study was conducted on the material characterization of aluminium (Al) and titanium carbide (TiC) metal matrix composites produced via friction stir welding. Different process parameters were employed for the welding process. Rotational speeds of 1600 rpm to 2000 rpm at an interval of 200 rpm and transverse speeds of 100 to 300 mm/min at an interval of 100 mm/min were employed for the welding on an Intelligent Stir Welding for Industry and Research (I-STIR) Process development System (PDS) platform. The process parameters were carefully selected to represent low, medium and high for the rotation and the translation of the tool.

The characterizations carried out include optical microscopy and the scanning electron microscopy analyses combined with Energy Dispersive Spectroscopy (SEM/EDS) techniques to investigate the particle distribution, microstructural evolution and the chemical analysis of the welded samples. Vickers microhardness tests was used to determine the hardness distribution of the welded zone and tensile testing was conducted to quantify the strength of the welded area to the base metal in order to establish the optimal process parameters.

Based on the results obtained from the characterization analysis, it was found that the process parameters played a major role in the microstructural evolution. Homogenous distribution of the TiC particles was observed at high rotational speed of 2000 rpm and low transverse speed of 100 mm/min. The highest hardness value was measured at the stir zone of the weld due to the presence of the TiC reinforcement particles. The tensile strength also increased as the rotational speed increased and 92% joint efficiency was found in a sample produced at 2000 rpm and 100 mm/min. The EDS analysis revealed that Al, Ti and C made up the composition formed at the stir zone. The optimum process parameter setting was found to be at 2000 rpm and 100 mm/min and can be recommended.
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ABBREVIATION

AL - Aluminium
Al-TiC - Aluminium titanium carbide
AMC - Aluminium matrix composite
AS - Advancing side
EBW - Electron beam welding
EDS - Energy dispersive spectroscopy
FSLW - Friction stir lap welding
FSP - Friction stir processing
FSW - Friction stir welding
GMAW - Gas metal arc welding
HAZ - Heat affected zone
HV - Vickers hardness
LBW - Laser beam welding
MIG - Metal inert gas welding
MM/MIN - Millimeter per minute
MMC - Metal matrix composite
OM - Optical microscope
RP - Revolution per minute
RS - Retreating side
SEM - Scanning electron microscope
SZ - Stir zone
TiC - Titanium carbide
TIG - Tungsten inert gas welding
TMAZ - Thermo-mechanical affected zone
TWI - The welding institute
UTS - Ultimate tensile strength
XRD - X-ray diffraction
NOMENCLATURE

EST - Effective sheet thickness

$F_x$ - X-Direction or transverse force

$F_y$ - Y-Direction or lateral force

$F_z$ - Z-Directional or downward force

$\omega$ - Rotational speed

$v$ - Transverse speed

$P$ - Power

$Q$ - Heat input

$T$ - Torque

$\eta$ - Efficiency factor
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GLOSSARY OF TERMS

A

- **Advancing side** - The advancing side is the side where the tool rotation direction (sense of tangential velocity) is the same as the tool travel direction
- **Alloys** - An alloy is a material composed of two or more metals or a metal and a nonmetal that cannot be easily separated by physical means
- **Aluminium** - Aluminium is one of the chemical elements that belongs to the boron group with symbol Al, atomic number 13 and atomic weight of 26.982
- **Aluminium matrix composite** - Is a composite material in which the matrix is Aluminium and the other material is the reinforcement

B

- **Base metal** - A common metal not considered expensive and precious
- **Butt weld** - A type of weld configuration formed between the squared ends of the two joining pieces, which come together but do not overlap

C

- **Chemical Bonding** - The interaction that binds two or more atoms together which leads to formation of familiar chemical substances.
- **Clad metal** - A composite metal containing two or more layers that have been bonded together
- **Coalescence** - When two or possibly more pieces of metal are bonded together by liquefying the place where they are to be bonded resulting to formation of one continuous solid at the end of the welding
- **Cold weld** - The solid state bonding process during which two materials are forced to form a single piece under high pressure and vacuum without the use of heat
- **Composite** - A material in which two or more distinct, structurally complementary materials, usually a matrix material and a reinforcing material are combined to produce structural properties not present in any individual component
- **Compressive stress** - The stress on material that lead to smaller volume of material
• **Corrosion**- The chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.

D

• **Debonding**- When the physical, chemical or mechanical forces that hold a bond together got broken with or without the presence of an external force causing the adhesive to stop adhering to the substrate material.

• **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.

• **Delamination**- Is a type of failure that occurs often in composite materials when the layers of reinforcement separated from each other caused by poor processing during production.

• **Diffusion welding**- a solid state welding process that produces coalescence of the faying surface by the application of pressure at elevated temperature.

• **Dislocation**- A crystallographic defect or irregularity within a crystal structure that alter the properties of the material.

• **Dislocation density**- The measure of how many dislocations that are present in a quantity of a material which is the total length of dislocation per unit volume.

• **Double pass FSW**- When the welding processes are pass twice on the same weld line using the same welding parameters.

• **Ductility**- Ability of a material to absorb energy and plastically deform without fracturing.

• **Dynamic recrystallization**- A process by which deformed grains are replaced by a new set of undeformed grains that nucleate and grow until the original grains have been entirely consumed.

E

• **Electric arc**- Is the visible plasma discharge between two electrodes that is caused by electrical current ionizing gasses in the air.

• **Electrical conductivity**- Measures the amount of electrical current a material can carry.
- **Electron beam welding** - Is a fusion welding in which a beam of high velocity electrons is applied to two materials to be joined

- **Explosive welding** - Solid state welding that uses controlled explosion to weld members together

- **Extensometer or strain transducer** - An instrument used for measuring the degree of deformation of material under stress.

- **Extrusion** - A manufacturing process in which a material is forced through a shaped metal piece die to produce a continuous ribbon of the formed product

**F**

- **Fatigue** - Failure of a material by cracking resulting from repeated or cyclic

- **Filler materials** - These are materials added in making a sound welded joint

- **Forge welding** - Is a solid state welding process that joins two pieces of metal by heating them to a high temperature and then hammering them together.

- **Fracture** - Is a form of failure characterized as the separation or fragmentation of a solid

- **Friction** - The resistance of motion of one object moving against another

- **Friction coefficient** - The ratio of the force of friction between an object and a surface to the frictional force resisting the motion of the object.

- **Friction stir lap weld** - This is a variant of friction stir welding in which the metals to be welded are lapping over each other and result into lap configuration type of weld

- **Friction stir welding** - A solid state joining process that uses a third body tool to join two facing surfaces without melting the metals

- **Friction welding** - A welding process in which the heat is produced by rotating one component against a stationary component under compression resulting in solid state weld

- **Fusion welding** - A welding process that melts the base metals to be welded at the joint before forming coalescence joint.

**G**

- **Gas shielding** - These are inert or semi-inert gases commonly used in several welding process like gas metal arc welding and tungsten arc welding.
- **Grain**: An individual crystal in a polycrystalline metal or ceramic
- **Grain growth**: The enlargement or coarsening of the individual grains within the metal or alloy during heating at a temperature above the recrystallization temperature.
- **Grain size**: This refers to the diameter of individual grains of sediment in a material
- **Green Technology**: Technology that mitigates the effect of human activities on the environment
- **Grinding**: removing material from the surface of a work piece by using a grinding wheel or abrasive grinding papers

**H**
- **Hardness**: The measure of a material's resistance to deformation by surface indentation or by abrasion
- **Hardness test**: A mechanical test to determine the relative hardness property of a material
- **Heat affected zone**: The area of base material which is not melted and has had its microstructure and properties altered by welding or heat intensive cutting operations
- **Homogenous**: a chemical composition and physical state of any physical small portion, and that is the same as that of any other portion
- **Hooking effect**: Is a geometrical defect that originates at the weld interface extremities of two welded sheets, which are in lap configuration.
- **Hot cracking**: Is a welding defect caused by formation of shrinkage cracks during the solidification of weld metals.

**I**
- **Indentation**: this is used to determine the hardness of a material to deformation made by pressing a specified indenter into the surface of a material under specified static loading conditions
- **Inhomogeneous**: When the chemical and physical properties distribution of a material vary from one point to another without uniformity
- **Instron testing machine**: This is a machine used for determining the tensile property of materials
• **Intermetallic compounds**- These are solid state materials composed of two or more types of metal atoms which exist as homogenous, fixed stoichiometry, well defined but differ discontinuously in structure from that of the constituent metals.

**K**

• **Kissing bond**- A defect that occurs when two surfaces lying extremely close together but not close enough for the majority of the original surface asperities to have deformed sufficiently in contact for atomic bonds to be created.

**L**

• **Lap joint**- A joint configuration in which two pieces of metal which edges are overlapped and fastened together to produce a continuous or flush surface.

• **Laser**- A device that generates an intense beam of coherent monochromatic light by stimulated emission of photons from excited atoms or molecules.

• **Laser welding**- A non-contact process which requires access to the weld zone from one side of the parts being welded through the use of laser.

• **Load transducer or Load cell**- A transducer that converts an input mechanical force into an electrical output signal whose magnitude is directly proportional to the force being measured.

**M**

• **Machineability**- Is the ease with which a metal can be worked on which depends on the material's properties and manufacturing process.

• **Magnetically impelled arc butt welding**- A rapid, clean, and reliable arc welding process that employs forging to produce the finished weld.

• **Manufacturing techniques**- These are processes employed to transform raw materials into finished products.

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

• **Mechanical property**- Property that reveals the reaction, either elastic or plastic, of a metal to an applied stress and shows the relationship between stress and strain to an applied force.

• **Melting point**- The temperature at which a given solid will melt.
• **Metal Matrix composite**- A composite material with at least two constituent, one being a metal and the other material maybe a different metal, ceramic or organic compound.

• **Metallurgy**- The science and engineering that studies the physical and chemical behavior of metallic elements, their intermetallic compounds and their mixtures called alloys.

• **Microhardness**- The hardness of a material gauged with instruments using small indenters that penetrates microscopic areas.

• **Microsegregation**- A chemical separation and concentration of alloy elements or impurities within microscopic grains.

• **Microstructure**- The fine structure (in a metal or other material) that can be made visible and examined with a microscope.

• **Modulus of elasticity**- The ratio of the stress applied to a material to the resulting strain resistance produced within the elastic limit.

• **Onion ring**- These are elliptical rings formed in the weld zone due to stirring and movement of the material.

• **Optical microscope**- An optical instrument that uses a lens or a combination of lenses to produce magnified images of small objects, especially of objects too small to be seen by the unaided eye.

• **Oxidation**- Addition of oxygen to a compound.

• **Plastic deformation**- A process in which enough stress is placed on metal or plastic to cause the object to change its size or shape permanently without fracture in a way that is not reversible.

• **Plastic flow**- A solid mechanics theory that is used to describe the plastic behavior of materials.

• **Plunge depth**- This is the length of penetration of the tool into the materials to be welded.

• **Polishing**- Producing a smooth and shiny surface to reveal the grains structure of the materials under microscopic observation.
• **Porosity**- Open spaces between grains or trapped gas in grains in a microstructure.

• **Precipitation hardening (Strengthening precipitate)** - A heat treatment technique used to increase the hardness of malleable materials to cause a second phase to precipitate out.

**R**

• **Reinforcement**- Materials that usually improve the mechanical properties and impedes crack propagation of the matrix.

• **Residual stress**- Stress in a material, on a microscopic scale and resulting from non-uniform thermal changes, plastic deformation, or other causes aside from temporary external forces or applications of heat when the material is at rest.

• **Resistance welding**- A thermo-electric process where heat is generated at the interface of the parts to be joined by passing an electrical current through them or a precisely controlled time and under a controlled pressure.

• **Retreating side**- The retreating side is the side where the tool rotation direction (sense of tangential velocity) is in different direction as the tool travel speed.

• **Rotational speed** - the tool rotation speed is the rate of angular rotation (usually specified in rpm) of the tool about its rotational axis.

**S**

• **Sample**- A small part or quantity intended to show the physical and chemical properties of the whole material.

• **Scanning electron microscope**- an electron microscope in which a beam of focused electrons moves across the object with the secondary electrons produced by the object and the electrons scattered by the object being collected to form a three-dimensional image on a display screen.

• **Shear stress**- Is the force that acted parallel to the surface of the material, as opposed to normal stress when the stress is vertical to the surface causing layers or parts to slide upon each other in opposite directions.

• **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; this is termed side flash.
- **Single pass FSW** - When the welding process is pass once on the same weld line using the same welding parameters.
- **Solid state** - The state of matter in which materials are not fluid but retain their boundaries without support, the atoms or molecules occupying fixed positions with respect to one another and unable to move freely.
- **Solid state welding** - Is a group of welding processes which produces coalescence at temperatures essentially below the melting point of the base materials being joined with or without the addition of brazing filler metal.
- **Solidification** - A process of changing the phase of a matter from liquid to solid state when its temperature is below freezing point.
- **Solidus** - Is the locus of temperatures below which a given substance is completely solid.
- **Spindle speed** - Also referred to as the rotational speed, is the speed of relative motion between the tool and workpiece in the main direction of operation.
- **Stir zone** - Is the region that is subjected to severe plastic deformation and dynamic recrystallization close to the location of the pin during welding. It's also called weld nugget zone.
- **Strain** - A deformation of a solid due to applied stress.

T

- **Temperature** - The intensity of heat present in a substance which can be measured using thermometer.
- **Tensile strength** - Maximum amount of tensile stress a material can resist before deformation.
- **Tensile stress** - Ability of a material to withstand pulling force.
- **Tensile Test** - A fundamental materials science test that determines the overall strength of a material by subjecting it to a controlled tension until failure occurs. It can also be called tension test.
- **Thermal conductivity coefficient** - The rate at which heat is transferred by conduction through a unit cross-sectional area of material when a temperature gradient exists perpendicular to the area.
- **Thermal expansion coefficient** - The fractional change in length (or sometimes in volume, when specified) of a material for a unit change in temperature.
**Thermo-mechanical affected zone** - Forms on either side of the stir zone with lower amount of strain and temperature which is not enough to complete dynamic recrystallization process thereby limiting the effect of rotating tool on the microstructure of the material.

**Thermoplastic** - The tendency of a material to soften when heat is applied and harden when cooled without any change of inherent properties.

**Thinning effect** - Thinning effect is the up/down-turning of original joint line faying surface caused by excessive vertical flow (hot weld), which may decrease shear strength.

**Titanium carbide** - Is an extremely hard refractory ceramic material used as reinforcement because of its high strength and resistance to wear.

**Tool geometry** - This refers to the shape of the pin and the shoulder used during welding process.

**Tool pin** - The part of the tool inserted into the workpiece and 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 shoulder** - The part of the welding tool that flushes with the edge of the workpiece and rotates around the workpiece, thereby generating frictional heat. It's normally disk-shaped.

**Tool tilt angle** - The angle at which the FSW tool is positioned relative to the workpiece surface; that is, zero tilt tools are positioned perpendicular to the workpiece surface (degrees).

**Torque** - The amount of force acting on the tool that causes it to rotate around the workpiece.

**Transverse speed** - The speed at which the tool translates along the workpiece and it sometime called feed rate.

**Tungsten inert gas welding** - An arc welding process that uses a non-consumable tungsten electrode to produce the weld.

**Vickers hardness test** - A method of determining the hardness of materials whereby a diamond pyramid is pressed into the polished surface of the specimen and the diagonals of the impression are measured with a microscope fitted with a micrometer eye piece.
- **Viscous flow**- A type of material movement in which the particles flow in a line parallel to the axis of the containing material with little or no mixing or turbidity. It is common in liquid.

**W**

- **Water jet**- An industrial cutting machine that uses high pressurized jet of water or mixture of water and abrasive substance to cut variety of materials.
- **Wear**- The removal of material's layers due to mechanical process under conditions of sliding, rolling or reacted impact.
- **Wear resistance**- Ability of a material to withstand wear when in use.
- **Weld pool**- Commonly refers to the dime-sized workable portion of a weld where the base metal has reached its melting point and is ready to be infused with filler material. It is central to the success of the welding process.
- **Weld quality assurance**- The use of technological methods and actions to test and assure the quality of welds, and secondarily to confirm the presence, location and coverage of welds before applications.
- **Weld seam, weld zone or joint line**- This is the pathway in which the weld is produced for efficient joint.
- **Welding**- A joining process where two or more materials are joined by the application of heat and pressure and by facilitating the flow of the metals causing coalescence.
- **Welding flux** - This is cleaning agent that protects the weld from atmosphere and dirt. Its also acts as a deoxidizer, pulling oxygen and nitrogen from the weld pool to the surface, preventing porosity.
- **Welding process or process parameter**- These are variables that determines the weld quality of a material e.g. transverse speed and rotational speed.
- **Workpiece**- The materials that are needed to be welded together.
- **Wormhole**- A welding defect which occurs due to excessive welding speed and improper mixing and re-bonding of materials normally on the advancing side of the weld.
X

- **X-ray diffraction** - The scattering of x-rays by crystal atoms, producing a pattern that yield useful information about the structure of the crystal.

Y

- **Yield strength** - The stress at which a material begins to deform plastically
CHAPTER 1  INTRODUCTION

1.1  THEORETICAL BACKGROUND

The Friction Stir Welding (FSW) process was invented and developed at The Welding Institute of United Kingdom in the year 1991 for joining aluminum alloys in solid state without reaching their melting point [1]. Subsequently, this welding process has been used for joining other materials like magnesium, titanium and copper alloys, stainless steels and thermoplastics. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint as shown in Figure 1.1. The tool serves two primary functions: (a) the heating of the workpiece, and (b) the movement of the material being welded to produce the joint. The heating is accomplished by friction between the tool and the workpiece and the plastic deformation of the workpiece. The localized heating softens the material around the pin and the combination of the tool rotation and the translation leads to the movement of material from the front of the pin to the back of the pin. As a result of this process, a joint is produced in ‘solid state’. Because of the various geometrical features of the tool, the material movement around the pin can be quite complex [2]. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in the generation of fine and equiaxed recrystallized grains [3-6]. The fine microstructure in friction stir welds produces good mechanical properties.

Figure 1.1  Schematic of friction stir welding [2]
The need to use welded metal composites often comes up during manufacturing. The joining of the composites of aluminium (Al) infused titanium carbide (TiC) as reinforcement is highly sought. Titanium carbide offers great strength and resistance to corrosion. The ratio of strength to weight of aluminium is favourable due to the light nature of the material. The joining of these aluminium matrix composite plates can offer weight savings in an automotive industry and industrial applications where weight saving is of paramount importance. The joining of aluminium incorporated with titanium carbide (Al-TiC) metal matrix composite can be a challenging task by conventional fusion welding techniques without compromising the chemical and the mechanical properties of the material. Therefore, friction stir lap weld (FSLW), which is a type of joint configuration in FSW, can be used in place of the conventional fusion welding to produce the weld since the operating temperature is below the melting point of the base material and the reinforcement particles.

FSLW is a process of lapping where the surfaces of the top and the bottom plates is stirred and mixed in the stir zone, thus forming a weld behind the tool as depicted in Figure 1.2.

![Figure 1.2 Schematic of friction stir lap welding](image)

FSLW is made up of two sides which are the advancing and the retreating sides. The advancing side (AS) of the weld is the side of the tool where the rotation of the tool and the welding direction are the same while the retreating side (RS) is the side of the tool where the rotation
of the tool is opposite that of the welding direction. Friction stir welding of lap joints is currently used in a number of applications such as joining in space shuttle tanks, which is considered as unweldable using fusion welding, and has potential for wider applications.

1.2 PROBLEM STATEMENT

The need for joining materials of different thicknesses and sizes in lap configuration is currently on high demand in industries like automobile, railways, marine, aeronautic etc. Riveting and bolting are the two major joining processes being used for lap joining of materials, but they are not very reliable because of the development of stress concentration. Though, joining techniques such as bolting and riveting require no or little heat but are not totally reliable because they facilitate the development of stress concentrations which promote the initiation and the propagation of cracks due to the presence of rivet and bolt. Another technique employed is fusion welding. Fusion welding affects the properties of material being welded due to the enormous heat generated during welding and it is difficult to weld thin materials in lap configuration using this technique.

FSLW provides a potential alternative over the conventional welding and joining techniques. Experimental and research outcomes on the FSLW have shown that it is possible to employ FSLW on metal alloys with the possibility of minimal outcome defects compared to fusion welding. The process can be regarded as a transient process since it takes a fewer period to complete the welding process and it is envisaged to produce better outcomes with improved mechanical and metallurgical properties that supersede the outcomes of the conventional welding and joining techniques. This will improve efficiency and productive rates and reduce the tendency of failure of materials in service, which are very essential and applicable for any joint configuration.

1.3 MOTIVATION OF RESEARCH

The preference of FSW for welding of Al-TiC composite is to avoid delamination (a failure when laminated material becomes separated, perhaps induced by poor processing during production, impact in service, or some other means which leads to separations of layers of reinforcement), debonding (when two materials stop adhering to each other), incompatible mixing of base materials and filler materials, presence of porosity, inhomogeneous distribution
(clustering), segregation of grain at boundaries, wetting of the particles, excess eutectic formation, formation of undesirable deleterious phase usually experienced in other welding techniques and fulfill the welding condition criteria listed.

1.4 AIM AND OBJECTIVES

The aim of this research work is to characterize Al-TiC metal matrix composites produced via friction stir lap welding.

1.5 OBJECTIVES

The objectives of this research work are stated below:

- To conduct detailed literature study on the current state of friction stir welding technology
- Determine the process window for joining 3 mm thick Al with TiC particles embedded at the weld interface in lap weld configuration, create experimental setup, run experiment to collect the output data and report the output responses (forces and torque) that acted during the welding process
- Analyze the data, microstructural analyses and microhardness profile of the lap joint at different process parameters
- Investigate the tensile strength and the fracture type of the lap welds at various rotational and transverse speeds
- Draw conclusions and recommendations

1.6 HYPOTHESIS

FSLW of aluminum with titanium carbide particles incorporated at the weld interface was conducted by employing different welding parameters. The welded joints were characterized through the microstructure, microhardness, and the shear strength. It was expected that the material characterization techniques employed in this research study will ultimately lead to the
optimization for the best methodology for processing FSLW of aluminum with titanium carbide incorporated at the weld interface.

1.7 METHODOLOGY

To investigate and analyze the material characterization of friction stir lap welds of aluminium with titanium carbide infused at the weld interface, different process parameters were utilized for producing the welds in lap joints configuration on I-STIR Process Development System (PDS) Friction Stir Welding Machine. The samples obtained from different process parameters of lap welds were studied and investigated under the same experimental condition adhering to standard methods. Microstructure and macrostructure analyses were investigated using optical microscope. Chemical analysis, fractography and microstructural evolution at higher magnification were carried out using the scanning electron microscope (SEM). Vickers hardness was employed to determine the microhardness of the samples, tensile strength was conducted using Instron testing machine. Critical considerations and analyses were given to the outcomes of the result obtained from different tests. ASTM standards were adhered to for all the mechanical and metallographic tests.

1.8 DELIMITATION

The aim of this research work is to characterize friction stir lap weld of Al-TiC metal matrix composites. The characterization was limited to the metallurgy (microstructure), mechanical (microhardness and tensile strength) of the welds and chemical analysis. Only sheets of 3 mm thickness were used in the lap joint configuration and the welds were produced using position control on the FSW platform. The parameters varied were limited to rotational speeds of 1600 rpm, 1800 rpm, 2000 rpm and transverse speeds of 100 mm/min, 200 mm/min and 300 mm/min while other variables were kept constant. No pre or post heat treatment was done on the samples and the temperature distribution was not measured during welding.
1.9 SIGNIFICANCE OF THE RESEARCH

This research study broadens the available knowledge and information on friction stir welding in the context of academics and industrial applications in the selection and forming of materials for manufacturers, especially where weight and strength of the materials are of paramount importance and major factors of production. Since this study is original, it will broaden the research area and open doors of opportunity to new innovations and study.

2.0 ORGANIZATION OF DISSERTATION

The aim of this research is to characterize the friction stir lap weld of Al-TiC metal matrix composite. In this dissertation, the relevant background of the study was discussed in chapter 1.

Chapter 2 describes the theoretical background related to welding and FSW. Published literature on friction stir lap weld of aluminium with titanium carbide composite were critically reviewed and presented in the chapter.

Chapter 3 narrates the methodology and the experimental procedures used for the characterization of the welds.

Chapter 4 describes, in detail, the results and discusses the data generated from the mechanical and metallurgical evaluation carried out on the weld.

Chapter 5 focuses on the conclusions derived from the work carried out and the scope for further or future work is also presented.
CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

Welding, in a pure sense, is a joining process where two or more materials are fused by the application of heat and pressure, and by facilitating the flow of the metals. Welding processes can be used to fabricate complex geometries and structures not possible with manufacturing techniques such as machining and forming. They can also be used to build up near net shape parts or structures out of sheet or plate at lower material utilization rates than machining from plate, bar, extrusions or forgings coupled with the potential to provide the most efficient use of materials and highest cost savings.

In this chapter, the available literature related to this research topic is presented. The review is focused on

- Welding process
- FSW configuration which includes the different types of FSW joints, tool designs and process parameters
- Metallurgy which consists of microstructure of the welds: weld nugget, heat affected zone (HAZ), and thermo-mechanical affected zone (TMAZ)
- Mechanical properties i.e. microhardness, tensile strength, grain size, thermal cycle, material flow, defect and distortion in FSW
- Brief discussion on composite, metal matrix composite, aluminium and titanium carbide composite since these are the materials of interest in this study
- Review of available literature on friction stir weld of composite materials which is the area of particular interest in the current study.

2.2 WELDING TECHNOLOGY

Welding is a technique of joining two or more materials (usually metals) through localized coalescence resulting from a suitable combination of temperature, pressure and metallurgical conditions. Welding technology has evolved from only metallic materials to thermoplastics depending upon the combination of temperature and pressure from a high temperature with no pressure to a high pressure with low temperature. A wide range of welding processes have been
developed and the two major variants are fusion and solid state welding processes. Fusion welding requires the melting of the weld surface / interface while solid state welding is created by a fully solid diffusion bond between the two surfaces. Table 2.1 highlights the advantages and the limitations of different welding processes used for joining of materials (metals and thermoplastics). These welding processes are categorized under fusion and solid state welding processes.

Table 2.1: Advantages and limitations of welding processes [7-10]

<table>
<thead>
<tr>
<th>Welding processes</th>
<th>Category</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten Inert Gas (TIG) or Metal Inert Gas (MIG)</td>
<td>Fusion welding</td>
<td>Standard equipment, filler wire can be easily used to facilitate welding process, relatively well developed, good affordability</td>
<td>Possibility of chemical reaction, low weld strength with unreinforced filler wire, reinforcement segregation, porosity</td>
</tr>
<tr>
<td>Electron Beam Welding (EBW)</td>
<td>Fusion welding</td>
<td>Relatively high speed, deep and narrow welds</td>
<td>Possibility of chemical reaction, vacuum required</td>
</tr>
<tr>
<td>Laser Beam Welding (LBW)</td>
<td>Fusion welding</td>
<td>High speed welding, no vacuum required, deep and narrow welds, low distortion, greater accuracy</td>
<td>Possibility of chemical reaction, shielding gas required, high beam coupling</td>
</tr>
<tr>
<td>Resistance Welding</td>
<td>Fusion welding</td>
<td>Short thermal cycle and thus less dissolution / reaction of reinforcement</td>
<td>Possible segregation of reinforcing particles, geometry limitations</td>
</tr>
<tr>
<td>Process</td>
<td>Bonding Type</td>
<td>Interlayer Requirement</td>
<td>Bond Properties</td>
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<td>--------------------------------------------------------------------------------</td>
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<tr>
<td>Diffusion Bonding</td>
<td>Solid state welding</td>
<td>Interlayer may be</td>
<td>Insufficient or excessive mass transport may produce poor bond, long thermal</td>
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<td></td>
<td></td>
<td>required for optimum</td>
<td>cycle</td>
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<tr>
<td></td>
<td></td>
<td>bond properties, no</td>
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<td></td>
<td></td>
<td>particle-matrix</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>interaction</td>
<td></td>
</tr>
<tr>
<td>Explosive welding</td>
<td>Solid state welding</td>
<td>Ease of process, free</td>
<td>Cause lots of noise and vibration, scare of materials, cannot be used on</td>
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<tr>
<td></td>
<td></td>
<td>from warmth affected</td>
<td>materials, cannot be used on materials thicker than 62 mm and harder than 50</td>
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<td></td>
<td></td>
<td>zone, heat treated</td>
<td>RC easily.</td>
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<td>metals can be welded</td>
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<td>without affecting their</td>
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<td>microstructures, lack</td>
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<td>of porosity, phase</td>
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<td>change and structural</td>
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<td>changes</td>
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<tr>
<td>Friction Welding</td>
<td>Solid state welding</td>
<td>No particle-matrix</td>
<td>Small axis-symmetric parts required, high stress applied, flash requires</td>
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<td></td>
<td>interaction, full bond</td>
<td>removal</td>
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<td>strength achievable</td>
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<td>after heat-treatment</td>
<td></td>
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<tr>
<td>Friction Stir Welding</td>
<td>Solid state welding</td>
<td>No particle-matrix</td>
<td>Large and expensive equipment.</td>
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<tr>
<td></td>
<td></td>
<td>interaction, cracking,</td>
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<td>porosity, filler metals,</td>
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<td>and shielding gas;</td>
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<td>simple weld preparation,</td>
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<td>distortion; full bond</td>
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<td>strength achievable</td>
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There are numerous variations in welding processes, leading to various welding techniques that are currently employed globally around the world. The two major welding techniques namely fusion and solid state welding processes are discussed below.

**2.2.1 FUSION WELDING**

The fusion welding process involves chemical bonding of the metal in the molten stage and may need a filler material such as a consumable electrode or a spool of wire of the filler material. The process may also need an inert ambience in order to avoid oxidation of the molten metal, which is achievable by a flux material or an inert gas shield in the weld zone. There could also be a need for adequate surface preparations. Common examples of fusion welding processes are the metal inert gas welding (MIG), tungsten inert gas welding (TIG) and laser welding which are discussed in the following sections.

**2.2.1.1. TUNGSTEN INERT GAS WELDING**

Tungsten inert gas (TIG) welding also known as gas tungsten arc welding (GTAW), is a welding process that uses the heat produced by an electric arc created between non-consumable tungsten electrode and the weld pool. This electric arc is produced by the passage of current through a conductive ionized inert gas that also provides shielding of the electrode, molten weld pool and solidifying weld metal from contamination by the atmosphere as shown in Figure 2.1. The process may be used with or without the addition of filler metal using metal rods as substitute.

![Figure 2.1 Schematic of Tungsten Inert Gas Welding](image-url)
It is used extensively in the aerospace and nuclear industries. Often, it is used for small jobs, maintenance and repair work because of its flexibility and ease of control. However, it requires great care and skill from the welder.

### 2.2.1.2. METAL INERT GAS WELDING

Metal Inert Gas (MIG) welding is a welding process that uses the heat generated by a direct current electric arc to fuse the metal in the joint area. A continuous electrode wire (solid or cored) is fed by powered feed rolls (wire feeder or copper nozzle) into the weld pool. An electric arc is created between the tip of the wire and the weld pool. The wire is progressively melted at the same speed at which it is being fed and forms part of the weld pool. Both the arc and the weld pool are protected against atmospheric contamination by a shield of inert (non-reactive) gas as shown in Figure 2.2. It is also called gas metal arc welding (GMAW) and this process can be semi-automatic or automatic.

![Figure 2.2 Schematic of Metal Inert Gas Welding](image)

The welding parameters of MIG include the voltage, travel speed, arc (stick-out) length and wire feed rate. Carbon steels, low alloy steels, stainless steels, most aluminium alloys, zinc based copper alloys can be welded using this welding process.
2.2.1.3 LASER WELDING

Laser welding is a non-contact process which requires access to the weld zone from only one side of the parts being welded. The laser weld is formed as the intense laser light rapidly heats the material as shown in Figure 2.3. The flexibility of the laser offers three types of welds, namely conduction mode, conduction/penetration mode, and the penetration/keyhole mode.

![Figure 2.3 Schematic of Laser Welding](image)

Peak power density, duration of pulse, welding speed, part alignment, joint design and close fit-up define the quality of the weld seam and are essential welding parameters for laser welding. Laser welding can be used to weld a wide range of steels, nickel alloys, titanium, aluminum, and copper.

There are many disadvantages in fusion welding techniques where the metal is heated to its melting temperatures and left to solidify in order to form the joint. The melting and the solidification processes cause the mechanical properties of the weld to deteriorate in forms such as low tensile strength, fatigue strength and ductility. The disadvantages also include porosity, oxidation, microsegregation, hot cracking and other microstructural defects in the joint. The process also limits the combination of the metals that can be joined because of the different thermal coefficients of conductivity and expansion of different metals.


2.2.2 SOLID STATE WELDING

The solid state welding is the process where coalescence is produced at temperatures below the melting temperatures of the base metal without any need of filler material or any inert ambience because the metal does not reach its melting temperature for oxidation to occur. Examples of solid state welding processes are friction welding, friction stir welding which is a variant of friction welding, explosive welding, forge welding, hot pressure welding and ultrasonic welding. Friction welding and friction stir welding which is the area of interest are discussed in due course. The three important parameters for solid state welding are time, temperature and pressure, which, individually or in combinations, produce the joint in the base metal. Since the metal in solid state welding does not reach its melting temperatures, there are fewer defects caused due to the deformation of the metal. In solid state welding, the metals being joined retain their original properties as melting does not occur in the joint and the heat affected zone (HAZ) is also very small compared to fusion welding techniques where most of the deterioration of the strengths and ductility begins. Dissimilar metals and metal matrix composite can be joined with ease as the thermal expansion coefficients and the thermal conductivity coefficients are less important compared to fusion welding.

2.2.2.1 EXPLOSIVE WELDING (EXW)

Explosive welding (EXW) is a solid state metal joining process produced by means of a high velocity impact of one metallic mass onto another, aided by a controlled detonation with an explosive charge used to create a metallurgical bond between two similar or dissimilar metals as shown in Figure 2.4.

![Figure 2. 4 Schematic of Explosive Welding [7]](image-url)
In explosive welding, perfectly clean surfaces (clad metal and base metal) are brought together under very high pressure. The high velocity oblique collision will produce high temperature and high shear strain near the collision point in a very short time which causes local melting of the bonded metals simultaneously with the local plastic deformation in a very short period. This process is most commonly utilized to clad carbon steel plate with a thin layer of corrosion resistant material (e.g. stainless steel, nickel alloy, titanium or zirconium). Due to the nature of this process, producible geometries are very limited. They must be simple. Typical geometries produced include plates, tubing and tube sheets.

2.2.2.2 FRICTION WELDING

Friction welding (FRW) is a solid state welding process that produces coalescence by heat generated through mechanical friction between a moving workpiece and a stationary component, with the addition of a lateral compressive force called upset to plastically displace and fuse the materials as shown in Figure 2.5. The welding is done by moving the part to be joined relative to a stationary part along a common interface while also applying compressive forces across the joint. The frictional heat generated at the interface due to rubbing softens the metal and the soft metal gets extruded due to the compressive forces and the joint forms in the clear material. The relative motion is stopped and compressive forces are increased to form a sound weld before the weld is allowed to cool.

Figure 2.5 Schematic of Friction Welding [7]
Sometimes it is referred to as spin welding, because one part is rotated in the process. Areas of applications include aerospace industries where there is need to join dissimilar metals together like aluminium and steel, construction of nuclear reactors and marine industries. It can also be used to join metal and thermoplastics. This study focuses on friction stir welding (FSW) and will therefore be discussed in more detail.

2.3 FRICTION STIR WELDING

FSW is variant of solid state welding that is gradually replacing friction welding in different industries like the aerospace, marine, automobile, etc. FSW is a joining process of two materials in a way that the parent materials are not melted during the process. It is used to weld all range of thicknesses of aluminum alloys including large pieces of materials, which cannot be heat treated easily to recover temper characteristic and aluminum alloys categorized as unweldable due to poor metallurgical bond formed when welded together using fusion welding techniques. It requires no need for filler materials, welding flux or gas shielding and classified as a green technology due to its energy efficiency, environment friendliness and versatility.

FSW provides several advantages over the traditional fusion welding methods. The biggest advantage of FSW over fusion welding is that since FSW is solid state and no melting occurs, the elevated temperatures combined with the plastic deformation of the work piece during the process result in a fine equiaxed microstructure [7]. The fine-grained structure produced during FSW is very different from the cast type structure formed during the melt pool solidification in fusion welds. This fine-grained structure in Friction Stir welds can lead to improved mechanical properties, such as tensile strength and high cycle fatigue, which are key design metrics in many applications and industries. Table 2.2 summarizes the benefits of friction stir welding over other solid state joining methods.

Table 2. 2 Key benefits of friction stir welding [7]

<table>
<thead>
<tr>
<th>Metallurgical benefits</th>
<th>Environmental benefit</th>
<th>Energy benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid phase process</td>
<td>No shielding gas required</td>
<td>Improved materials use (e.g., joining different thickness) allows reduction in weight</td>
</tr>
<tr>
<td>Low distortion of workpiece</td>
<td>No surface cleaning required</td>
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</tr>
<tr>
<td>Good dimensional stability and repeatability</td>
<td>Eliminate grinding wastes</td>
<td></td>
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<td></td>
<td>Eliminate solvents</td>
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</tbody>
</table>
No loss of alloying elements
Excellent metallurgical properties in the joint area
Fine microstructure
Absence of cracking
Replace multiple parts joined by fasteners

required for degreasing
Consumable materials saving,
such as rugs, wire or any other gases

Only 2.5% of the energy needed for a laser weld
Decreased fuel consumption in light weight aircraft, automotive and ship applications

Joints can easily be formed between different metals and alloys using FSW and the resulting weld is homogenous and has low distortion, no inclusion, reduction in size of materials does not manifest and it is very advantageous where the original characteristic of metals must remain unchanged as far as possible. The formation of a joint between the two materials depends on the formation of an intermixed zone at temperatures near the solidus of the materials, and involves the viscous flow of plasticized material immediately adjacent to the rotating tool and dynamic recrystallization.

Joining composite metals by conventional fusion welding methods is rather complicated and can be quite difficult, and, as a result, many investigations [5-12] have been reported on the application of the solid state bonding to form metal joints. Although, FSW is a solid state joining process developed for welding aluminium alloys due to the metallurgical defects found during the welding of aluminium using fusion welding, it has also been successfully applied for lap joining of other dissimilar and similar metals like Aluminium-to-Aluminium, Aluminium-to-steel, Aluminium-to magnesium, Aluminium-to-zinc and Aluminium-to-copper [7, 12].

FSW has been successfully used on relatively low strength, low temperature alloys such as aluminium, magnesium and copper and also capable of joining high strength alloys that are generally considered unweldable [7]. FSW of high strength and high temperature alloys, such as steel and titanium, has been limited due to the difficulties associated with identifying tooling materials capable of withstanding the forces and temperatures associated with friction stir welding these alloys and the cost of production of these tools.

FSW has been put to use in different industries to develop mechanical components that are not feasible or difficult to weld using fusion welding. The aerospace industries are known for patronizing high strength to weight materials like the seven thousand series aluminium alloys
for structures like fuselage, wing sections, fins, fuel tanks, etc. Unfortunately, such aluminum alloys are difficult to weld using the convectional fusion welding due to the occurrence of hot cracking during welding which limits the safety measure for aerospace applications, thereby requiring the use of riveting or solid state joining processes. Large liquid propellant dome tanks shown in Figure 2.6b was developed using FSW and spin forming by MT Aerospace and NASA using high strength 2195 Aluminum-Lithium, thereby reducing the weight by 25% compared to the convectional tank [13].

Other noticeable applications in the aerospace industry include wings, fuselages and empennages, cryogenic fuel tanks for space vehicles, aviation fuel tanks, external throw away tanks for military aircraft, military and scientific rockets, repair of faulty MIG welds, cargo barrier beam and floor panel and toe nail ramp of aircraft. In the marine and the shipping industries, it has been used to build panels for decks, sides, bulkheads and floors construction, aluminium extrusions, armour plating for amphibious assault ship, boat sections, hulls and superstructures, helicopter landing platforms, offshore accommodation, marine structures like honey comb panels and corrosion resistant panel, masts and booms, e.g. for sailing boats and refrigeration plant and fish freezer panels. In the automobile industries, engine and chassis
cradles, wheel rims, advanced amphibious assault vehicle, armour plate vehicle, suspension struts, tailored blanks, e.g. welding of different sheet thicknesses like boots, magnesium and magnesium/aluminium joints, space frames, e.g. welding extruded tubes to cast nodes and attachment to hydroformed tubes, truck bodies, tail lifts for lorries, mobile crane and fuel tankers, caravans, buses and airfield transportation vehicles, HVAC pistons and engine tunnel and repair of aluminium cars were fabricated using FSW. Also in the railway sector, FSW was employed to manufacture high speed trains, rolling stock of railways, underground carriages, trams, railway tankers and goods wagons, container bodies, curved side and roof panels, heat sinks for cooling high power and floor panels for double decker rails. FSW is also used for the fabrication and the construction of aluminium bridges, facade panels made from aluminium, copper or titanium, window frames, aluminium reactors for power plants and the chemical industry, heat exchangers and air conditioners, pipe fabrication and pressure vessel, refrigeration panels, cooking equipment and kitchens, gas tanks and gas cylinders, connecting of aluminium or copper coils in rolling mills and aluminium pipelines, motorcycle and bicycle frame, X-ray vacuum vessels, electric motor housings, bus bars, electrical connectors and encapsulation of electronics[13-17].

Fundamental understandings between the welding parameters (such as spindle speed, transverse speed and tool geometry), joint configuration, material flow and microstructures are needed to fully characterize and understand the process.

2.3.1 JOINT CONFIGURATIONS

There are numerous weld configurations that are in use, depending on the application and these are shown in Figure 2.7
In a butt joint, the two work pieces to be welded with square mating edges are clamped on a rigid back plate. The tool is slowly plunged into the work piece at the butt line until the shoulder penetrates the top work piece surfaces and the pin is a short distance from the back plate [6]. Research has shown that during friction stir butt welding of aluminium alloys, an improved metallurgical bonding and good mixing of the metals are achieved at the lowest traverse speed and constant rotational speed. The ultimate tensile strength of the welds tends to decrease with an increase in the welding speed [12].

In lap joint, the materials joined overlap and the tool pin run through the top material pressing it onto the bottom material as shown in Figure 2.8. It is better to increase the width of the weld region to achieve a better bond during lap weld [7].
Lap joints have adequate static and fatigue properties to replace fastened joints. Factors affecting these properties of lap joints include geometry of notch on either side of the joint, inadequate disruption of the oxides at the interface, inadequate penetration of the bottom member, overlapping area and adverse interface reorientation. Packing pieces should be used in grip regions as shown in Figure 2.9 to prevent bending stress that may occur due to the offset of axes of the members loaded in tension-shear. Thinning of the top material may occur due to the metal movement in the direction of the top material if the proper tool design is not used. The thinning may affect the strength of the joint. Inadequate bonding, contamination and lifting of the top material may occur if there is cladding at the interface [12].

![Figure 2.9 Packing Pieces in Single Lap Configuration](image)

An investigation was reported by Khaled [6] on the feasibility of producing FS welded lap joints between A1100-H24 and Al sheet stock. It was observed that the fracture load tends to increase with an increase in the rotational speed and a decrease in the travel speed. By using tension peel test, intermetallic compounds and bonding have been noticed at the higher rotational speeds and lower travel speeds. There was little or no bonding that occurred at the lowest rotational speed. It was reported that the formation of the intermetallic compounds need to be minimized to obtain good quality joints [6].

### 2.3.2 TOOL DESIGNS

The simplest tool geometry consists of a round shoulder and a cylindrical pin as shown in Figure 2.10. The sizes of the shoulder and the pin play a large role in the amount of heat
generated during the welding process. Special features such as threads and flutes can be machined on the pin to control the material flow. Threads, or scrolls, can also be machined on the shoulder to enhance material flow. Typically, the scrolls are in the opposite direction of the tool rotation so that the shoulder actually pulls material into the center of the weld to aid consolidation instead of casting it out of the weld zone. Threads on the pin are typically oriented to push material down in the weld zone, but can also be reversed to pull the material up during the welding process.

![Featureless Shoulder and Scrolled Shoulder](image)

**Figure 2.** Schematic of a typical FSW tool [11]

Different tool designs have different effects on the heat generation, plastic flow, the required power, and the welded joint uniformity. The joint integrity of FS welds depends upon the nature of the tool design used in the process. In friction stir welding, the rotating shoulder generates considerable heat, while in stationary shoulder friction stir welding; the stationary shoulder generates much less heat compared to the conventional friction stir welding. When welding thin sheets, the main source of heat is from the shoulder of the tool. As the material thickness increases, more heat must be supplied by the friction between the rotating pin and the material. In addition, the main function of the pin is to ensure sufficient working of the material at the weld joint, and to control the flow of the material around the tool, in order to form a quality weld [18]. FSW tool design includes material selection and the tool geometry. It is one of the
most important factors that influence heat generation, plastic flow, joint integrity, the resulting microstructure and the mechanical properties. The tool geometry is concerned with the shape and the size of the pin and shoulder while friction coefficient, welding process, heat generation, wear resistance, reactivity and the machineability are being considered for material selection of the tool [6, 19]. The tool shoulder does not only generate heat but also prevents the plasticized material from flowing away from the work piece. An increase in the tool shoulder diameters leads to a significant increase in the Stir Zone (SZ) and the Thermo-Mechanically Affected Zone (TMAZ) of the welds due to an increase in the heat input which increases as the shoulder diameter increases [18, 19]. The shoulder and the tool pin design affect the material flow and are important in characterizing the microstructure of the welds. Table 2.3 shows different tool designs that are used in FSW process.

Table 2.3 Different tools used in FSW [18, 19]

<table>
<thead>
<tr>
<th>Tool</th>
<th>Cylindrical</th>
<th>Whorl™</th>
<th>MX triflute™</th>
<th>Flared triflute™</th>
<th>A-skew™</th>
<th>Re-stir™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool pin shape</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>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>
<td>0.4</td>
</tr>
<tr>
<td>Swept volume to pin volume ratio</td>
<td>1.1</td>
<td>1.8</td>
<td>1.6</td>
<td>2.6</td>
<td>depends on pin angle</td>
<td>1.8</td>
</tr>
<tr>
<td>Rotary reversal</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Application</td>
<td>Butt welding; fails in lap welding</td>
<td>Butt welding with lower welding torque</td>
<td>Butt welding with further lower welding torque</td>
<td>Lap welding with lower thinning of upper plate</td>
<td>Lap welding with lower thinning of upper plate</td>
<td>When minimum asymmetry in weld property is desired</td>
</tr>
</tbody>
</table>

2.3.3 WELDING PARAMETERS

The main processing parameters of FSW include rotational (ω) and welding speed (ν), spindle or tool tilt angle, Target depth, preheating and post heating. The variation of the rotational speed of the welding tool to the welding speed (ω/ν) called the weld pitch, forms a major factor to control the integrity, microstructures and mechanical properties of the weld. It is important
to select right welding parameters so that optimum process response (torque T, X-direction or transverse force F_x, Y-direction or lateral force F_y, Z-direction or downward force F_z, power P) and welding quality can be achieved. Torque is an indicator of shear stress around the tool which is required to rotate the tool, the amount of which rely on the friction coefficient, force response and the flow strength of the material in the surrounding region. Reducing torque minimize the total power required, thus enhance the energy efficiency. A downward force, (F_z), is necessary to maintain the position of the tool at or below the material surface and lateral force, (F_y) acts perpendicularly to the tool traverse direction. The traverse force, (F_x or X-force) acts parallel to the tool motion and is positive in the traverse direction. Since this force arises as a result of the resistance of the material to the motion of the tool, it is expected that this force will decrease as the temperature of the material around the tool is increased. X-force is an indicator of tool failure. Excessive X-force will cause tool failure [4, 20]. Torque decreases with increasing rotation speed due to higher temperature caused by higher heat generation rate (heat input/time), whose indicator is power input. The effect of the welding speed on torque is not significant in FSW [20]. Although, increasing the rotational speed sometimes showed the tendency to reduce the X-force, the relationship between the X-force and the rotational speed is not clear [21]. The above mentioned parameters were optimized in the course of this research work to achieve the best result and the responses under different process parameters were compared.

2.3.3.1 ROTATION AND WELDING SPEEDS

The tool rotation rate (ω, usually in rpm) rotates in clockwise or counterclockwise direction and the tool traverse speed (v in mm/min) moves along the joint line are the two most important welding parameters in FSW. The tool rotation results in the stirring and the mixing of the material around the rotating pin, and the translation of the tool moves the stirred material from the front to the back of the pin and completes the welding process. Higher tool rotation rates generate higher heat input because of higher friction heating and result in more intense stirring and the mixing of material. However, it should be noted that the frictional coupling of the tool surface with the workpiece governs the heating. So, a monotonic increase in the heating with increasing tool rotation rate is not expected as the coefficient of friction at interface changes with increasing tool rotation rate [7].
2.3.3.2 SPINDLE OR TOOL TILT ANGLE

The spindle head or the tool has to be forward tilted in a small angle with respect to the workpiece surface. A suitable tilt of the spindle towards the welding direction ensures that the shoulder of the tool holds the stirred material by the threaded pin and moves the workpiece material efficiently from the front of the pin to the back [4]. A recent development of the 'scrolled' tool shoulder allows FSW with a 0° tool tilt. Such tools are particularly preferred for curved joints [7]. Common tool tilt angles successfully employed in the literature include from 1 to 4 degree tilt. Pankaj and Deepak concluded in their study of effect of tool rotation speed and tilt angle on friction stir welding of Al-6075 that the tensile strength of the welded joint increases as the tilt angle increases. They considered tilt angle of 0°, 1.5° and 3° respectively and recorded the highest tensile strength of around 120 N/mm at 3° tilt angle and lowest of 76 N/mm at 0° tilt angle. This shows that tilt angle is also a determinant of the final overall strength of the weld and 3° tilt angle was adopted in this study.

2.3.3.3 TARGET DEPTH (PLUNGE DEPTH)

This parameter is important for producing sound welds with smooth tool shoulders. The insertion depth of the pin is associated with the pin height and the thickness of the material being joined. If the insertion depth is too shallow, it cannot contact properly with the workpiece surface and, thus, the shoulder cannot move the stirred material efficiently from the front side to back. In such a case, defects like inner channel or surface groove may occur. When the insertion depth is too deep, the shoulder creates excessive flash. In this case, a significantly concave weld is produced, leading to local thinning of the welded plates. For butt welds, it is usually suggested that the pin length is selected slightly less than the thickness of the workpiece and for lap weld joints, the pin length is always bigger than the thickness of the top sheet [7].

2.3.3.4 PREHEATING AND POSTHEATING

In case of welding a material with a high melting point such as steel and titanium or high conductivity such as copper, frictional heat and stirring may not be sufficient to make a sound weld. In these cases, preheating or additional external heating source (e.g., laser beam) can help increase the heat input and improve the material flow. On the other hand, cooling can be used for materials with a lower melting point such as aluminium and magnesium to reduce extensive
growth of recrystallized grains and the dissolution of strengthening precipitates in and around the stirred zone [7].

2.4 MICROSTRUCTURAL EVOLUTION

Classification of friction stir weld microstructures was conducted by Theadgill [22]. His classification was based only on the information available from aluminium alloy welds. It is now generally accepted that there are four distinct zones across a friction stir welded joint as shown in Figure 2.11, namely the base metal zone, the heat-affected zone (HAZ), the thermomechanically affected zone (TMAZ) (which is also called the heat and deformation-affected zone, or HDAZ), and the weld nugget (or the stir zone).

**Figure 2.11 Typical macrograph showing different weld zones in friction stir weld [22]**

2.4.1 BASE METAL

The base metal zone or the parent material refers to the material sufficiently remote from the weld center, such that its microstructure and mechanical properties are not affected by heating or deformation, although it may have experienced both during the welding process.

2.4.2 WELD NUGGET

The nugget (also called the stir zone or the dynamically recrystallized zone) is the region that is subjected to severe plastic deformation and dynamic recrystallization. This area is close to the location of the pin during the welding process. The equiaxed grains within the stir zone are
often much smaller than the grains in the base material [23]. Both elliptical and basin-shaped nugget zone were observed for FSW lap joint [24]. A unique feature of the stir zone is the common occurrence of several concentric rings which has been referred to as an 'onion-ring' structure. Wayne Thomas, the inventor of the FSW process, named the onion ring features as materials flow pattern [25]. It was suggested that the friction stir welding process can be thought to be simply extruding one layer of semi cylinder in one rotation of the tool and a cross-sectional slice through such a set of semi cylinder results in the familiar onion ring structure [26]. It was also suggested by Biallas et al. [27] that the formation of onion rings was as a result of the reflection of material flow approximately at the imaginary walls of the groove that would be formed in the case of regular milling of the metal. The induced circular movement leads to circles that decrease in radii and form the tube system. In this case, it is believed that there should be thorough mixing of material in the nugget region [7]. Some investigators reported that the small recrystallized grains of the nugget zone contain high density of sub-boundaries [28], sub grains [29], and dislocations [30]. The interface between the recrystallized nugget zone and the parent metal is relatively diffuse on the retreating side of the tool, but quite sharp on the advancing side of the tool [31]. Various mechanisms have been proposed for dynamic recrystallization of aluminium alloys during FSW, such as discontinuous dynamic recrystallization (DDRX), continuous dynamic recrystallization (CDRX), and geometric dynamic recrystallization (GDRX) [7, 29-31]. The special feature of friction stir weld microstructure appearance "onion ring" pattern has attracted several explanations so far regarding their formation. Biallas et al. [27] suggested that material flowing around the pin is reflected at the walls of the groove, and the induced circular motion leads to circles that decrease in radii and form a tube-like system. Krishnan [26] explained that the onion ring pattern is formed due to the process of frictional heating generated by the rotation of the tool and due to the fact that the forward tool movement extrudes the workpiece material against the retreating side of the tool. Threadgill [22] observed that the spacing of the onion rings is equal to forward movement of the tool in one revolution, which was confirmed by Krishnan [26] and Sutton et al. [32]. Sutton et al. [32] also found that the onion ring patterns in Al 2024 welds consist of alternating regions of high and low particle densities. Lienert and Grylls [33] investigated correlation between various aspects of the weld microstructure in Al 6061-T651 with information of estimated temperatures, strains and strain rates during the welding process. They found that microstructural development in FSW is a strong function of the local thermomechanical cycle experienced. The thermal cycle experienced at the nugget zone is stipulated to be 0.6 - 0.9 of the melting point of the material [34, 35]. Akbari et al. [36] and Bisadi et al
observed that the size of the nugget zone of fiction stir lap weld decreases with decrease in rotational speed and increase in welding speed due to lower heat input and lower peak temperature associated with faster welding speed. This shows that the area of the weld zone is significantly dependent on the heat generation during FSW. During the course of this research work, the current author investigated the relationship of the process parameters on the microstructural evolution of the friction stir lap-welded zone with respect to the thermal cycle experienced at the weld zone.

2.4.3 THERMO-MECHANICALLY AFFECTED ZONE (TMAZ)

The thermo-mechanically affected zone (TMAZ) forms on either side of the stir zone. This interface represents the salient difference between the structure of the metal grains and the structure of the grains obtained from dynamical recrystallization process in the nugget zone. In this region, the amount of strain and temperature is not enough to complete dynamic recrystallization process and therefore the effect of rotating tool on the microstructure is correspondingly smaller. Hence, unlike the nugget, the microstructure is recognizably that of the base material, although significant plastic deformation and rotated grains can still be seen and the grains in the TMAZ usually contain a high density of sub-boundaries [7].

2.4.4 HEAT-AFFECTED ZONE (HAZ)

The heat-affected zone (HAZ) is the area which can be seen in almost all welding processes. As indicated by the name, this region is subjected to the frictional heat but not deformed during welding. The temperatures are lower than those in the TMAZ but may still have a significant effect if the microstructure is thermally unstable. Grain growth and over aging of precipitations are the common unfavorable phenomena that happen in this area [7].

2.5 MECHANICAL PROPERTIES

Metallurgical evaluations of welds provide a fundamental understanding of the impact of welding process on the microstructures of the materials, but the mechanical property evaluations are required prior to using this process outcome to fabricate any actual part. As
discussed above, FSW produced significant microstructural changes in the workpiece, which have a substantial influence on the weld mechanical properties. Area of interest of this research work includes tensile properties, microhardness and effect of different welding parameters on the evolving mechanical properties of the welds. Focuses of discussion are microhardness, residual stress, tensile strength, defect, and distortion. A review of residual stress, tensile strength, microhardness, defect, distortion and defect will be provided below as a reference for FSLW.

2.5.1 RESIDUAL STRESS AND TENSILE STRENGTH

During fusion welding, residual stresses are generated due to the application of localized heating and melting in the weld zone in conjunction with the restraints of the surrounding material. When welded, the joint expands due to the heat, and upon cooling and solidifying, it contracts but is restrained by the adjacent base material. This results in tensile residual stresses that can approach the yield stress of the material [25]. It has been speculated that the residual stresses in FSW may be lower than fusion welds because it is a solid state process and the temperatures are lower. However, in FSW, the feature is typically more constrictive and there is a high degree of mechanical work applied to the weld zone. These would both contribute to increase residual stresses in the longitudinal and transverse directions. Residual stresses are important to characterize because large stresses will have a negative impact on the mechanical performance of the joint, particularly in fatigue. In general, tensile stresses are present in the longitudinal direction while compressive stresses are found in the transverse directions. Typically, the most common measure of quality of materials is its tensile properties, stress versus strain behavior and the fracture load per width versus displacement. The first two are used for butt welding while the latter is employed during lap welding. Tensile residual stress is known to decrease fatigue life and corrosion resistance which is mainly caused by uneven expansion and contraction due to heating. Tensile properties of the friction stir welds have been proven to be related to the hardness distribution, so the location of fracture in transverse tension is also at hardness minimum in HAZ [38]. Rotational speed and transverse speed are also determinants of tensile behavior of friction stir welds of aluminium. Tensile elongation decreased with decreasing traverse speed or increasing rotating speed and presence of defects and intermetallic compound [37].
2.5.2 MICROHARDNESS

The hardness of a weld can provide insight into the expected performance of the joint. Softening will likely cause a decrease in the strength and an increase in elongation while hardening will increase strength and decrease elongation. It is also common for the HAZ to be softer than both the base material and the weld nugget particularly in heat treatable alloys. It has been suggested that the hardness of friction stir lap welding is controlled more by grain size and dislocation density [39]. Hardness distributions depend on local thermal history and heat treatment of the base materials. Hardness distribution usually has a “W” shape curve with the lowest point occurring in HAZ [7]. In HAZ, the hardness decreases due to the accelerated ageing and recovering of the weld thermal cycle [33]. The highest hardness often happens at the nugget area. There is a sudden decrease in hardness on both sides of the nugget, falling through the TMAZ, and lowest hardness happens at the HAZ [39, 40]. It is observed that in FSLW, the hardness distribution of the top sheet differs from the bottom sheet due to different thermal cycle experienced by both sheets. The top sheet exhibits low hardness profile due to high heat input that leads to an increase in the grain size of the sheet compared to the bottom sheet.

2.5.3 DEFECT CHARACTERIZATION

Defects in FSW may result from improper process parameter and temperature, tool geometry, material flow and joint geometry. Common defect in FSW is wormhole, which often happens in cold weld due to excessive welding speed. FSW lap joint may likely introduce top sheet thinning and hooking defects, which are inherent features in lap joint. Sheet thinning is the up/down-turning of original joint line faying surface caused by excessive vertical flow (hot weld), which may decrease shear strength. Hooking is geometrical defect that originates at the weld interface caused by the flow of material from the bottom sheet to the upper sheet resulting in adverse interface reorientation that causes sharp discontinuities along the interface which create acute tip for stress concentration [41, 42]. The tip of the hooking defect usually extends into the top sheet thereby affecting the effective sheet interface (EST), which is the minimum sheet thickness determined by measuring the smallest distance between any un-bonded interface and the top surface sheet or the bottom surface of the lower sheet [24]. Hooking effect is also a major determinant of the fracture shear strength of the welded area. Because of the
high temperature of the advancing side, hooking defect is more obvious in this area while thinning occurs at the opposite side, which is the retreating side [37]. Kissing bond defect is another feature defect of FSW lap joint. The kissing bond defect is the separation of the interfaces due to insufficient heat transferred and high thermal gradient (cold weld). It is one of the most probable defects in FSW lap joints [40].

2.5.4 DISTORTION

Although FSW results in a low distortion (undesired change), there are situations that distortions of different degrees can happen in FSW. With the wide application of FSW, more studies on distortion are needed. Literatures on distortion on aluminium alloy revealed that the distortion after FSW process generally displays a saddle shape. This is caused by extrusion difference between top and bottom surface during FSW process. The downward tool pressure can release some of the local plastic deformation due to welding thermal cycles and constraint thereby helping to reduce the distortion [43]. Good clamping fixtures need to be used to prevent distortion in FSW.

2.5.5 MATERIAL FLOW

Flow pattern of material in FSW affects the thermo-mechanical histories and welding parameters. Typically, there are two kinds of material movement in FSW. One is extrusion around the pin: a) Material on advancing side is highly deformed and sloughs off behind the pin forming arc-shape. b) Material on the retreating side fills in material on its own side and never rotates around the pin [44]. The other is extrusion from upper portion of the pin welding path, which material is forced down by the pin thread and deposited in the weld nugget by compressive pressure [45]. A low welding speed to rotation speed ratio, also referred to as hot weld, often caused more vertical material transport. On the other hand, a high welding speed to rotation speed ratio, also referred as “cold weld”, often caused less vertical transport [39].

2.6 WELDABILITY

The weldability of a material is the ease of the material to form coalescence bond when being welded into a desired structure with properties and characteristic that meet the required
specifications. The weldability of aluminium alloys with titanium carbide is hereafter discussed.

2.6.1 ALUMINIUM ALLOYS

Aluminium alloys have a wide range of properties that are suitable for engineering structures. The most important characteristics of aluminium and its alloys, which make them paramount for a wide variety of applications, are their weight, appearance, strength and resistance to corrosion. The suitable properties possessed by aluminium alloys made it possible to be applicable in different industries for building of structural components. Table 2.4 summarizes the area of application of these aluminium alloys.

Aluminium alloys are designated in two categories. Cast alloys and wrought alloys, which can be further categorized as heat treatable which strength of the material depends on alloy composition and heat treatment (solution heat treatment and quenching followed by either natural or artificial ageing produces a fine dispersion of the alloying constituents) or non-heat treatable which can be hardened by work hardening or solid solution hardening. The typical alloying elements are copper, magnesium, manganese, silicon, tin and zinc.

Table 2.4 Areas of applications of aluminium alloys

<table>
<thead>
<tr>
<th>Aluminium alloys</th>
<th>Typical use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>Electrical current cables</td>
</tr>
<tr>
<td></td>
<td>Corrosion resistant in specific environment</td>
</tr>
<tr>
<td>2xxx</td>
<td>Aerospace, automobile engineering</td>
</tr>
<tr>
<td>3xxx</td>
<td>Heat exchanger, Air conditioners, vehicle engineering, Food industry</td>
</tr>
<tr>
<td>4xxx</td>
<td>Welding or brazing filler alloy, architecture, anodizing quality</td>
</tr>
<tr>
<td>5xxx</td>
<td>Automobile, shipping engineering, apparatus, architecture</td>
</tr>
</tbody>
</table>
The sensitive nature of the properties of aluminium alloys made it almost impossible to weld some series of this alloys. Prior to the invention of FSW, most aluminum alloys (1xxx, 3xxx, 4xxx, 5xxx and 6xxx) could be fusion welded with minimal impairment of the corrosion and mechanical properties of the materials using GTAW, GMAW or oxyfuel process. However, some (2xxx and 7xxx) are regarded as unweldable because of the poor solidification microstructure, liquation and porosity in the fusion zone. The welding methods currently being used for welding these alloys are shown in Table 2.5. The selection method depends on many factors, such as geometry of the joint, material to be joined, the required strength of the joint, number of parts to be joined, the aesthetic appeal of the joint, and finally, the service conditions, such as moisture, temperature, inert atmosphere and corrosion.

<table>
<thead>
<tr>
<th>Aluminium Alloys Series</th>
<th>Mechanical Property</th>
<th>Weldability</th>
<th>Welding Consumable for Fusion welding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx Pure</td>
<td>Non-heat Treatable</td>
<td>Fusion Welding</td>
<td>Friction Stir Welding</td>
</tr>
<tr>
<td>2xxx Copper</td>
<td>Heat Treatable</td>
<td>Friction Stir Welding</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.5 Welding methods used for joining aluminium alloys [45]
The difficulty of making high-strength, fatigue and fracture resistant welds in aerospace aluminum alloys, such as highly alloyed 2XXX and 7XXX series, has long inhibited the wide use of welding for joining aerospace structures. Though, some aluminum alloys can be resistance welded, the surface preparation is expensive, with surface oxide being a major problem. The technique of Friction Stir Welding is particularly suited to aluminium alloys. It is capable of producing sound welds in many alloys, including those heat treatable alloys, which are prone to hot cracking during fusion welding.
2.6.2 TITANIUM CARBIDE

Titanium Carbide, TiC, is used as the reinforcement powder in this research study. It is an extremely hard (Mohs 9-9.5) refractory ceramic material, similar to tungsten carbide. It has the appearance of black powder with NaCl-type face centered cubic crystal structure. It is one of the hardest natural carbides [46]. TiC was introduced as a superior candidate for improving the mechanical properties of different kinds of tool wear and cermet. TiC can be used as a substrate or coating. The reasons might be as follows, it has a high modulus of elasticity (410-450 GPa), high electrical conductivity (39×10⁶ S/Cm), high melting temperature (3067°C°), low friction coefficient, perfect chemical stability and good wettability and weldability. Because of high wettability and weldability of TiC, it can easily match with matrix i.e. Al and Fe. Titanium carbide (TiC) is used extensively for cutting tools and preparation of cermet which are frequently used for machine steel materials because of its combination of good wear resistance and high hardness [46].

2.7 COMPOSITES

A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone. In contrast to metallic alloys, each material retains its separate chemical, physical, and mechanical properties. The two constituents are a reinforcement and a matrix. The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared to bulk materials, allowing for a weight reduction in the finished part. The reinforcing phase provides strength and stiffness. Various types of composite include organic matrix composite, metal matrix composite, ceramic matrix composite and polymer matrix composite. Several techniques have been reported to produce metal matrix composite (MMC). Plasma air spraying, stir casting, squeeze casting, molten metal infiltration and powder metallurgy were reported for producing bulk composites while high energy laser melt injection, plasma spraying, cast sinter and electron beam irradiation have been used for producing surface composites[47, 48]. MMCs have already found commercial applications in defense industries, aerospace, automobile and marine due to their favorable metallurgical properties [47]. Research activities [49-51] have been reported on friction stir processing of MMCs. These studies concluded that the metallurgical properties can be improved and more uniform
homogenous particle distribution was observed during double passes. Dhayalan et al.[52] investigated the characterization of AA6063/SiC-Gr surface composites produced by FSP technique and concluded that the grain sizes were refined and homogenous mixture distribution of ceramic particulates was noticed at the stir zone. Puviyarasan and Praveen[53] studied fabrication and analysis of bulk SiCp reinforced aluminium metal matrix composites using FSP and observed good interface formation between the particles and the base metal.

2.8 METAL MATRIX COMPOSITES

Metal matrix composite (MMC) is a composite material with at least two constituent parts, one being a metal. The other material is the reinforcement, which may be a different metal or another material, such as a ceramic or organic compound. This reinforcement can either be discontinuous or continuous e.g. carbon fibre, titanium carbide, silicon fibre etc. MMCs are important engineering materials for their property advantages compared to monolithic metals. Their main advantages are their high strength and stiffness, combined with low density when compared with bulk materials, allowing for a weight reduction in the finished part, better wear resistance and superior properties at elevated temperature because they provide the opportunity of combining various properties of the matrix and the reinforcement. Due to their properties, MMCs have a wide range of applications like automotive, nuclear reactor, construction, aerospace and defence industries where cost isn’t a primary factor in determining production. Al-TiC is a typical example of MMC. Aluminium is the matrix and TiC is the reinforcement. Table 2.6 summarizes the area of application of some MMCs currently in use in different sectors of operation [54-58].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Application examples</th>
<th>Properties of main concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-SiC</td>
<td>Brake components on passenger vehicle</td>
<td>Good wear resistance, high thermal conductivity, reduced braking distance</td>
</tr>
<tr>
<td>Al-Al2O3</td>
<td>Piston, various components in cylinder head</td>
<td>Improved wear and fatigue resistance, reduced thermal expansion coefficient</td>
</tr>
<tr>
<td>Material</td>
<td>Application</td>
<td>Properties</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Al-TiC</td>
<td>Structural materials, marine, aeronautic or aerospace body, gas turbine engine, cutting tool</td>
<td>high hardness, high compressive strength in combination with good chemical and thermal stability, high wear resistance</td>
</tr>
<tr>
<td>Al-B</td>
<td>Frames and rib truss members in mid fuselage section of space shuttle</td>
<td>High specific strength and stiffness</td>
</tr>
<tr>
<td>Al-C</td>
<td>High gain antenna boom for Hubble space telescope</td>
<td>Increased stiffness, low thermal expansion coefficient, excellent electrical conductivity and high dimensional stability</td>
</tr>
<tr>
<td>Al-B₄C</td>
<td>Nuclear transport containers</td>
<td>High neutron absorption capability, superior thermal conductivity and high specific strength</td>
</tr>
<tr>
<td>Mg-SiC</td>
<td>Electronic packaging</td>
<td>Low thermal expansion coefficient, high thermal conductivity</td>
</tr>
<tr>
<td>Mg-Al₂O₃</td>
<td>Automotive engine components</td>
<td>High specific strength and stiffness, low thermal expansion coefficient</td>
</tr>
<tr>
<td>Mg-C</td>
<td>Large space mirrors</td>
<td>High modulus of elasticity, near-zero coefficient of thermal expansion, low density and high thermal conductivity</td>
</tr>
<tr>
<td>Ti-SiC</td>
<td>Nozzle actuator links in General electric F110 engine</td>
<td>Elevated temperature strength, high corrosion resistance</td>
</tr>
<tr>
<td>Material</td>
<td>Application</td>
<td>Properties</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Ti-TiB</td>
<td>Intake and exhaust valves in Toyota Altezza engine</td>
<td>Elevated temperature strength, high corrosion resistance</td>
</tr>
<tr>
<td>Cu-W</td>
<td>Spot welding electrode</td>
<td>Burn up resistance</td>
</tr>
<tr>
<td>Cu-C</td>
<td>Electric carbon brushes</td>
<td>High electrical and thermal conductivity, good wear resistance</td>
</tr>
<tr>
<td>Fe-TiC</td>
<td>Cutting, rolling, piercing, punching components</td>
<td>Ultra hardness, high wear resistance</td>
</tr>
</tbody>
</table>

Several techniques for joining MMCs have been explored in the past but they all come with limitations that vastly influences the weld seam negatively and compromise the properties of the weld integrity. For welding techniques to be generally accepted for joining MMCs in order to produce good weld seam and durable joint that guaranty safety in services, they must fulfill the following criteria,

- produce void free joints
- maintain mechanical properties of the base, limit matrix grain growth, limit fiber/reinforcement reaction zone growth and maintain matrix phases such that material strength is maximized
- produce joints with strengths comparable to the base material;
- maintain joint strength at service temperatures;
- be operated at a reasonable cost.

The preference of FSW for welding of Al-TiC composite is to avoid delamination, debonding, incompatible mixing of base materials and filler materials, presence of porosity, inhomogeneous distribution (clustering), segregation of grain at boundaries, wetting of the particles, excess eutectic formation, formation of undesirable deleterious phase usually experienced in other welding techniques and fulfill the welding condition criteria listed. Though the capital cost for FSW is high, in aerospace and defense sectors where cost is a secondary factor and quality is the determinant factor, it remains the best available option. In any event, the running or maintenance cost is relatively cheap.
2.9 FRICTION STIR LAP WELDING AND FRICTION STIR PROCESSING (FSP) OF METAL MATRIX COMPOSITES

Joining of aluminium in lap configuration has found wide range of applications in different manufacturing industries like the aerospace, marine, automobile, etc. It is essential to produce lap joints with optimal performance properties. Different welding and joining techniques like MIG, TIG, riveting, brazing and fastening have been employed to produce aluminium joints in lap configuration but the sensitive and volatile nature of the metallurgical and mechanical properties of aluminium makes it difficult to obtain contaminants-free and strong metallurgical bonds. Though, joining techniques such as bolting and riveting require no or little heat, they are not totally reliable because the bolt and rivet holes serve as nucleation sites for stress concentrations which facilitate the initiation and propagation of cracks and reduce the effective performance of the joint.

The use of FSLW in place of fusion welding, riveting and fastening can help to realize significant weight and cost savings with improved mechanical performance and reduce the manufacturing complexity. Cederqvist and Reynolds [59] investigated the factors affecting the properties of friction stir welded lap joints between Al 2024-T3 and 7075-T6 alloys. A joint efficiency of 86% was reported in the friction stir welded lap joints which was much higher than what they could achieve with riveting and resistance spot welding. Babu et al [36] studied the microstructure and the mechanical properties of FSLW Al 5083-O alloys and reported that the FSL welds exhibit much higher lap shear strength compared to rivet joints. Joints produced with FSLW exhibited a lap-shear failure load of 16.5 kN and 19.5 kN respectively, while the average failure load for standard riveted joint with one rivet was only 3.4 kN.

Bisadi et al [60] investigated the effect of tool rotational and welding speeds on the evolving microstructure and the mechanical properties of the welded lap joint of Al 5083 alloys. They noticed that low welding temperature leads to some defects like channels that showed up at a region near the sheets interface and extremely high process temperature leads to some cavities appearance at the interface which in turn, affected the tensile strength of the welds. An increase in the size of the cavity reduces the ultimate tensile strength. The maximum hardness was observed at the area with the finest gain size which is the stir zone.

Bisadi et al [37] conducted research on the influence of process parameters on microstructure and mechanical properties of friction stir welded Al 5083 alloy lap joint. The friction stir welding process was used to make lap joints of 5083 aluminum alloy. For optimizing the joint properties, different parameters including different rotational and welding speeds were
experimented and different testing methods were carried out. At lower rotational speeds, lower welding speed leads to better properties of the weld joint. But at higher rotational speeds, changing of the welding speed has an inverse effect on the joint properties. At lower rotational speeds, because of lower degree of the material flow, lower welding speed is needed to decrease the welded joint defects by increasing the heat generation and decreasing the heat gradient at the joint areas during the process. Furthermore, at higher rotational speeds, higher welding speeds should be applied to increase the thermal gradient at the weld zone because of the large amount of material flow that can cause several defects on the joint at high rotational speed. At the higher rotational speeds, excessive heat transferred to the weld area causes many defects like hooking at the thermo-mechanical zone on the advancing side. The nugget of the weld has the finest grain size and highest hardness among the other welding areas and the base material, in contrast to the heat affected zone that has the highest grain size and lower strength.

When FSLW is conducted on two intrinsically dissimilar or same materials, the rotating tool pin is generally penetrated into the lower plate to a certain depth through the plate interface during its translation. Until they are deposited behind the welding tool, the plasticized materials undergo rotational, horizontal and vertical flows, which break up thin oxide films at the plate interface around the tool pin and subsequently contributes to partial or complete metallurgical bonding between the two overlapped metal plates. Intrinsically, the removal of surface oxide layers at the sheet interface is more difficult to accomplish in lap welding than in butt welding. Meanwhile, the plate interface close to the pin is bent upwards to accommodate the tool penetration and translation, resulting in the formation of a hook-shaped macrostructure. During FSLW, plastic flows on the two sides of the welding tool are asymmetric: on the advancing side (AS) the tool rotation and translation provide the forces for plastic flow along the same direction (both are the driving forces), while on the retreating side (RS), they provide the forces in opposite directions (the driving force due to the tool rotation and the resistance due to the tool translation). As such, the hook geometries on these two sides also show dissimilarity. The existence of hooking defects in FSW lap-welded joints is the key factor to reduce the fatigue strengths and the load carrying capacity when FSL welded sheet is loaded. The hooking defect is one of the interface reorientation defects located in the TMAZ of FSW lap-welded joints, which can obviously decrease the effective sheet thickness of lap-welded joints and produce severe stress concentrations. Fatigue cracks always initiate at the tip of hooking defect and then propagate into the stir zone leading to the final fracture of fatigue specimens.
Although, the mechanical properties of friction stir processed material within the weld region affects strength of a lap joint, increasing the effective thickness of the upper plate (designated as ‘load-carrying thickness’ hereafter) by suppressing the hook could be more effective to enhance joint strength.

In essence, to produce a satisfactory friction stir lap weld, it is necessary to maximize the width of the weld interface and to suppress hook formation. Hook suppression has been achieved by two approaches in aluminum friction stir lap welds. One approach includes lowering welding heat input and employing double weld passes from the perspective of welding operation. Lowering welding heat input is achieved through decreasing tool rotation speed and/or increasing travel speed. During double-pass welding, welding orientation is reversed to switch the AS and RS of the two parallel weld passes so that the side (AS or RS) having the higher resistance to failure is placed as a loading side on both the upper and lower plates. Though, the approach of the double-pass welding was proven to effectively improve joint strength of a friction stir lap linear weld when the AS and RS of a friction stir weld have significantly different mechanical properties. Xiao dong et al [24] discovered in their study on microstructures and fatigue properties of friction stir lap welds in AA6061-T6 alloy that effective sheet thickness EST is approximately the 84.3% of the top sheet thickness for the single pass weld (SPW) joint and 75.8% for the double pass weld (DPW) joint. Therefore, the DPW processes does not reduce the severe degree of hooking defects, but increases. The existence of the zigzag-line defect and the severity of hooking defects and the quality of the lap-welds could not be improved by the DPW process, compared to the SPW process. In contrast, the DPW process will produce the more serious hooking defects, lead to the decrease of effective sheet thickness and finally reduce the fatigue strength of FSW lap-welded joints. Dubourg et al [61] reported in their study of process optimization and mechanical properties of friction stir lap welds of 7075-T6 stringers on 2024-T3 skin that the increase of the travel speed or the decrease of the rotational speed caused a reduction of the hooking size. However, this defect may not be fully eliminated by varying the travel and rotational speeds. Double pass welds, by overlapping the advancing sides, significantly improved the weld quality by overriding the hooking defect.

The other is from the perspective of tool design, to use specially-profiled tools for welding. Flared -Triflute, A-Skew, Skew-Stir, Re-Stir, Trivex and Cylindrical tools have been developed and used for FSLW. Buffa et al [62] investigated FSW of lap joints in 3.2 mm thick sheets of Al alloy 2198-T4, focusing on the effects of tool geometry and process parameters on...
the joint strength. They have shown that a taper cylindrical tool is more appropriate for making lap joints than a straight cylindrical tool and that the hook orientation relative to the loading directions of the upper and lower sheets plays an important role in determining the joint strength.

From the literature review, it is obvious that most of the research studies have focused on the effect of process parameters on the mechanical and microstructure features of lap welding and that welding parameters and geometry of tool have a ripple effect on the final properties of the weld. These include the softening of the surface, formation of hooking, shear strength and the fracture mode. In order to curtail these defects and improve the mechanical and metallurgical properties, a novel technique was explored in this research study by adding reinforcement particle to the weld interface. Reinforcement particles are known to enhance effective performance and aid mechanical properties.

Thangarasu et al [50] investigated the microstructure and microhardness of TiC particulate reinforced aluminum 1050 matrix composite (AMC) fabricated using FSW and reported that the TiC particulate reinforced aluminium matrix composite layer was well-bonded to the aluminum substrate. The TiC particles were distributed homogeneously in the FSP zone and the hardness of the FSW zone increased by 45%, higher than that of the matrix alloy, however, limited process parameters were considered and reported in this study.

Jerome et al [51] investigated the influence of microstructure and experimental parameters on the mechanical and the wear properties of Al 1050-TiC surface composite by FSW process and reported that defect free composites were achieved during the FSW processes. Based on the microstructural observations, it was found that the distribution of particles was noticeable in the advancing side and the stir zone. Double pass in opposite direction resulted in more uniform distribution of the particles. For the single pass FSP with groove design, the average hardness along the top surface was found to increase by 22.72%, compared to that of the base metal, whereas in the case of surface composite developed by double pass FSP in the same and opposite directions, the average hardness along the top surface was found to increase by 25% and 27.27% respectively, compared to that of the base metal. The maximum average depth of surface composite was found to be 250 μm in hole-design.

Akinlabi et al [49] investigated the processing parameters’ influence on wear resistance behaviour of friction stir processed Al 1050-TiC composites and reported that friction stir processing (FSP) can be used to improve the mechanical properties of a material and the
production of surface layer composites. The rotational speed and the feed rate affect the wear resistance property of the Al - TiC composite produced. At low rotational speed, there was insufficient melting of the TiC powder which resulted in surface defect. Additionally, high rotational speed generated excessive heat that resulted in lots of dilution of the TiC and Al which reduced the wear resistance property. A moderately high rotational speed of 1200 rpm and a low speed of 100 mm/min produced the surface composited layer with the best wear resistance property.

Bauri et al [63] investigated the effect of friction stir processing (FSP) on microstructure and properties of Al 1050–TiC in situ composite and reported that friction stir processing (FSP) can be used effectively to homogenize the particle distribution in Al–TiC in situ composites. A single pass of FSP was enough to break the particle segregation from the grain boundaries and improve distribution. Two passes of FSP resulted in complete homogenization and elimination of casting defects. The grain size and mechanical properties also improved after the second pass. Better mechanical and metallurgical properties were achieved when reinforcement was added.

Though numerous research has been conducted on the addition of reinforcement particles, it is limited to surface modification. It is envisaged that the addition of ceramic particles to the weld interface will eliminate or mitigate the formation of top sheet hooking and thinning defects, thereby increasing the effective sheet thickness of the weld and resist instant shear fracture under tensile loading, which in turn lead to improved shear fatigue strength at the welded interface; this research study is therefore focused on the friction stir lap welding of aluminium with TiC powder as a reinforcement.

2.10 SUMMARY

Welding of aluminium is a core demand of many industrial applications like automotive industries, aerospace industries, defense (marine), etc. to substitute the traditional joining technologies with low costs and high efficiency techniques. However, in the studies performed on FSW, it is observed that enormous work has been done on characterization of friction stir welds of dissimilar metals but researchers have not yet been drawn to study the FSLW of aluminium with titanium carbide powder incorporated at the weld interface. Based on the available literature, previous research works have been limited to surface composite using FSW process and lap welding without addition of reinforcement particle to the weld interface,
whereas such strategy provides a novel means in the weld joint. Literature suggests that no attempts have been made to produce lap welds with Titanium Carbide (TiC) incorporated as reinforcement particles to form aluminium metal matrix composites. The addition of the TiC ceramics particles is due to its favourable mechanical and metallurgical properties.

In the present work, aluminium lap joints reinforced with TiC powder at the weld interfaces were produced via FSLW and the effect of the process parameters on the weld integrity was studied. Furthermore, the microstructure distribution of the lap joint interfaces of the Al-TiC composites produced and the mechanical properties of the welds were equally analyzed. The outcome will be of great benefit to different areas of application and will widen the existing knowledge on the FSLW. Reviews of the literature pertaining to this research work were discussed in this chapter and the next chapter will focus on the methodology used in the course of this research work.
CHAPTER 3 METHODOLOGY

3.1 INTRODUCTION

This chapter explains the methodology employed in this research work. The aim of this chapter is to document the welding process of Al-TiC MMCs in lap configuration, the output response from the FSW platform and the characterization of the welds produced. The techniques used for characterizing the weld interfaces are tensile strength, microhardness and microstructure. Brief introductions of the techniques used for characterization, equipment used, and the laboratory procedures for using the equipment are presented and discussed.

3.2 MATERIALS USED

Aluminium 1050 alloy sheets of 300 mm × 200 mm × 3 mm with good surface finishing were used for this research work. These materials were manufactured and supplied by Metal tool and trade, South Africa. The chemical composition of the aluminium obtained from the material safety data sheet (MSDS) of the supplier is shown in Table 3.1.

Table 3.1 Chemical composition of the Al 1050

<table>
<thead>
<tr>
<th>%</th>
<th>Manganese (Mn)</th>
<th>Iron (Fe)</th>
<th>Copper (Cu)</th>
<th>Magnesium (Mg)</th>
<th>Silicon (Si)</th>
<th>Zinc (Zn)</th>
<th>Titanium (Ti)</th>
<th>Aluminium (Al)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>0.05</td>
<td>0.04</td>
<td>0.05</td>
<td>0.05</td>
<td>0.25</td>
<td>0.07</td>
<td>0.05</td>
<td>Balance</td>
</tr>
</tbody>
</table>

3.3.1 FRICTION STIR WELDING EQUIPMENT

The friction stir lap welding was conducted on an Intelligent Stir Welding for Industry and Research (I-STIR) Process Development System (PDS) shown in Figure 3.1 at the Friction Processing Research Institute of Nelson Mandela Metropolitan University, Port Elizabeth, South Africa. The I-STIR PDS is a robust self-contained system that is capable of welding ferrous and non-ferrous materials.
The ISTIR PDS can support 5-degree of freedom (x-axis, y-axis, z-axis, pitch axis "adjustable pin" and roll axis "adjustable bed) shown in Figure 3.2 to produce welds with double curvature.
It can be operated either in force controlled where the force applied during the welding will be uniform or position controlled that varies the force with respect to the real time response during the welding process. The specification of the I-STIR PDS is listed in Table 3.2

Table 3.2 I-STIR PDS Specifications

<table>
<thead>
<tr>
<th>Axis</th>
<th>Stroke</th>
<th>Speed</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1041 mm</td>
<td>0 to 2000 mm/min</td>
<td>0.88 to 66.7 kN</td>
</tr>
<tr>
<td>Y</td>
<td>1524 mm</td>
<td>0 to 2000 mm/min</td>
<td>0.88 to 36 kN</td>
</tr>
<tr>
<td>Z</td>
<td>610 mm</td>
<td>2.5 to 1400 mm/min</td>
<td>133 kN (tension)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22.24 kN (compression)</td>
</tr>
<tr>
<td>Tool rotation</td>
<td>Infinite clockwise and counter clockwise</td>
<td>200 to 2500 rpm</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 4:1)</td>
</tr>
<tr>
<td>Pitch adjustment</td>
<td>±15°</td>
<td>0.1 to 300 °/mm</td>
<td>0.88 to 66.7 kN</td>
</tr>
<tr>
<td>Adjustable pin</td>
<td>±15 mm</td>
<td>2.54 to 1279 mm/min</td>
<td>±89 kN</td>
</tr>
</tbody>
</table>

A cylindrical H13 steel tool hardened to about 52 HRC used for the weld is shown in Figure 3.3.

Figure 3.3 Tool profile
The diameter of the tool pin is 6 mm with tool length of 5.7 mm and diameter of the tool shoulder is thrice the pin diameter (18 mm). The backing plate used in this research work is a mild steel plate of $25 \times 650 \times 265$ mm bolted to the welding bed.

### 3.3.2. THE WELDING PROCESS

Before the welding process, V- grooves with depth of 1.5 mm and width of 3 mm was made on all the aluminium sheets using a milling machine and the titanium carbide particles were filled and compacted into the grooves as shown schematically in Figure 3.4a. The experimental setup of the samples properly positioned and firmly clamped on the backing plate is shown in Figure 3.4b. The choice of the backing plate is for proper dissipation of heat during the welding process. A supporting plate of the same thickness was placed underneath the upper plate to help align and stabilize the sheets to be joined during welding.
The welds were done in position control since the thickness and the position of the materials during the welding process were kept constant. The welding programme of the FSW platform was first completed before welding could take place. This welding programme includes the transverse speed, rotational speed, acceleration, tilt angle, dwell time, weld length, deceleration, x-axis, y-axis and z-axis. All these parameters help define the integrity and the quality of the weld produced on the FSW platform. After completing the welding programme, the pendant attached to the FSW machine was then used to control the movement of the tool during the welding process. After the welding process, the specimen was cut using water-jet cutting to avoid limiting the risk of heat energy induced into the material which may alter the microstructure and the tensile properties. Shown in Figure 3.5 is the specimen geometry used for cutting the welded plates.
Figure 3.5 Configuration of specimen geometry removed on the welded plates (T-Tensile and M-Microstructure)

Where; T1, T2 and T3 are the three tensile samples respectively and the M1 and M2 are the microstructural and microhardness samples

### 3.4 MICROSTRUCTURAL CHARACTERIZATION

Optical and Scanning electron microscope were used for the microstructural characterization. ASTM standard was taken into cognizance for all the sample preparations and standard sample preparation techniques were employed.

#### 3.4.1 SAMPLE PREPARATION

The welded samples were transversely sectioned and mounted using an automated Struers Cito Press. The press used is pneumatic and uses water for cooling of samples. Figure 3.6a shows
the Struers Cito Press mounting machine and Figure 3.6b shows the grinding and polishing machine. ASTM E3-95 [64] was applied for the metallographic analysis.

![Struers Cito mounting Press](image1)

![Grinding and polishing machine](image2)

**Figure 3.6** (a) Struers Cito mounting Press (b) Grinding and polishing machine

After mounting the samples by using the appropriate mounting resin (Polyfast), the samples were then ground and polished using the Struers grinding and polishing machine present in Figure 3.6b to obtain mirror finished samples. The consumables used for grinding and polishing of the metallographic sample are summarized in Table 3.3 and 3.4 respectively.
Table 3.3 Procedure for metallographic grinding

<table>
<thead>
<tr>
<th>Step</th>
<th>Plane Grinding</th>
<th>Final Grinding 1</th>
<th>Final Grinding 2</th>
<th>Final Grinding 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>SiC Paper</td>
<td>SiC Paper</td>
<td>SiC Paper</td>
<td>SiC Paper</td>
</tr>
<tr>
<td>Grit/Suspension</td>
<td>320</td>
<td>800</td>
<td>1200</td>
<td>4000</td>
</tr>
<tr>
<td>Lubricant</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
</tr>
<tr>
<td>RPM</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Force (N)</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Time (Sec)</td>
<td>Until plane</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3.4 Procedure for metallographic polishing

<table>
<thead>
<tr>
<th>Step</th>
<th>Initial Polishing</th>
<th>Final polishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>MD-Mol</td>
<td>OP-Chem</td>
</tr>
<tr>
<td>Suspension</td>
<td>DiaPro Mol</td>
<td>OP-s</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 (Min)</td>
<td>4</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The samples were etched after polishing to reveal the microstructure clearly. The etchant used for aluminum alloys is Weck's double etch cycle reagent. The samples were pre etched for 1 minute using 2 grammes of Sodium Hydroxide (NaOH) and 100 ml distilled water and immediately deepened in less than 15 seconds in 4 grammes of Potassium Permanganates (KMnO4), 1 gramm of NaOH and 100 ml of distilled water. The etchant attacked the grain boundaries and gave a clear image of the size of the grains. The etched samples were analyzed under the microscope.

3.4.2 OPTICAL MICROSCOPY

Macrostructural and microstructural examinations were performed to reveal the shape of the stir zone, distribution of the reinforcement particles and analyze the effect of the process parameters on the microscopy evolution of the welded samples using Olympus DP 25 microscope presented in Figure 3.7.
3.4.3 SCANNING ELECTRON MICROSCOPY

The TESCAN Scanning Electron Microscope (SEM) equipped with Oxford Instrument presented in Figure 3.8 was used to analyze the distribution of the particles and surface morphology at higher magnification.
The Energy Dispersive Spectroscopy (EDS) software on the SEM was used to investigate the chemical composition of the welds.

3.5 MECHANICAL TESTS

Tensile shear and microhardness tests were conducted on the welded samples. The outcome of the tests provided tangible information about the microhardness profiling of the welded samples, the fracture behavior, joint efficiency and the shear strength of the joints.

3.5.1 TENSILE TESTING

The tensile tester used is an Instron 5500R electromechanical tensile testing machine located in the department of Mechanical Engineering Science, University of Johannesburg shown in Figure 3.9.

![Intron 5500R Electromechanical Tensile Testing Machine](image)

Figure 3.9 Intron 5500R Electromechanical Tensile Testing Machine

A load cell capacity of 100 kN at crosshead rate of 1 mm/min was used. No fewer than three lap tests were done for each process parameter. Since there is no test standard for friction stir
lap joints, ASTM E8/E8M-13a and ASTM D1002 [65, 66] for shear strength of single lap joint adhesively bonded metal specimen (tension loading of metal-to-metal) were used as the reference test standard for lap shear test. The cutting was done with the aid of a water jet-cutting machine into a rectangular shape. The strength of the lap joint was examined by lap shear test and the lap shear strength was computed as the ratio of the load at failure to the initial width of the sample.

3.5.2 MICROHARDNESS INDENTATION

The microhardness tests were conducted on the digital microhardness tester with diamond indenter in accordance to ASTM E92-82 [67] standard. Figure 3.10 shows the machine used. Microhardness values helps to determine the resistance of the sample to plastic deformation, strength of sample and the wear resistance of the sample.

![Indentec hardness testing machine](image)

Figure 3. 10 Indentec hardness testing machine
The indenter was pressed into the sample by an accurately controlled test force. The force of 100 g was maintained for a specific dwell time of 15 seconds. After the dwell time is completed, the indenter was removed leaving an indent on the sample that appears rhombic shaped on the surface. The size of the indent was determined optically by measuring the two diagonals of the square indent. Using the size of the indentation obtained, the hardness values of the sample were obtained.

3.6 SUMMARY

The methodologies used for the characterization of the welds were presented in this chapter. For each process parameter, metallurgical evaluations were performed to determine weld quality and the mechanical testing was conducted. Mechanical tests included microhardness and tensile strength. The next chapter discusses the results obtained from the characterizations done on the welds. The effect of process parameters, such as the spindle speed and the feed rate on the evolving microstructures, material flow and the tensile strength were also established. These relationships provide insight into the mechanics of the process, and provide a process window of opportunities that can be explored further, which would enable manufacturing engineers to develop weld procedures for a specific joint configuration.
CHAPTER 4  RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

The previous chapter depicted the methodologies used for the characterizations of the weld outcomes. The results obtained from the different metallurgical and mechanical tests conducted on the FSWed joints are presented and discussed in this chapter. The comparison analysis was adopted for the process parameters used and the optimum process parameter was established.

4.2 PROCESS PARAMETER AND OUTPUT RESPONSE

The major input process parameters that determine the integrity of the final weld on FSW platform are the rotational and the transverse speeds. The rotational and the transverse speeds employed in this research study are presented in Table 4.1. Also shown in Table 4.1 is the weld number assigned to each sample and the weld pitch, which is the ratio of transverse speed to the rotational speed. The range of the weld pitch is between 0.063 and 0.188.

Table 4.1 Input process parameters of the weld

<table>
<thead>
<tr>
<th>Weld number</th>
<th>Rotational speed (rpm)</th>
<th>Transverse speed (mm/min)</th>
<th>Weld Interface configuration</th>
<th>Weld Pitch (mm/rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1600</td>
<td>100</td>
<td>With TiC</td>
<td>0.063</td>
</tr>
<tr>
<td>A2</td>
<td>1600</td>
<td>200</td>
<td>With TiC</td>
<td>0.125</td>
</tr>
<tr>
<td>A3</td>
<td>1600</td>
<td>300</td>
<td>With TiC</td>
<td>0.188</td>
</tr>
<tr>
<td>B1</td>
<td>1800</td>
<td>100</td>
<td>With TiC</td>
<td>0.056</td>
</tr>
<tr>
<td>B2</td>
<td>1800</td>
<td>200</td>
<td>With TiC</td>
<td>0.111</td>
</tr>
<tr>
<td>B3</td>
<td>1800</td>
<td>300</td>
<td>With TiC</td>
<td>0.167</td>
</tr>
<tr>
<td>C1</td>
<td>2000</td>
<td>100</td>
<td>With TiC</td>
<td>0.050</td>
</tr>
<tr>
<td>C2</td>
<td>2000</td>
<td>200</td>
<td>With TiC</td>
<td>0.100</td>
</tr>
<tr>
<td>C3</td>
<td>2000</td>
<td>300</td>
<td>With TiC</td>
<td>0.150</td>
</tr>
<tr>
<td>D1</td>
<td>1600</td>
<td>200</td>
<td>Without TiC</td>
<td>0.125</td>
</tr>
<tr>
<td>D2</td>
<td>1800</td>
<td>200</td>
<td>Without TiC</td>
<td>0.111</td>
</tr>
<tr>
<td>D3</td>
<td>2000</td>
<td>200</td>
<td>Without TiC</td>
<td>0.100</td>
</tr>
</tbody>
</table>
The output response parameters (\(F_x\), \(F_y\), \(F_z\) and Torque) taken from the FSW platform is presented in Table 4.2. A typical output response graph is shown in Figure 4.1 and the remaining graphs are presented in Appendix A. These data were taken in the steady state region when all the welding parameters are nearly constant i.e. the period during which the force, torque and heat output reach a near equilibrium state. Once the thermal equilibrium has been reached, these output response parameters become constant [18].

**Table 4.2 Average FSW feedback**

<table>
<thead>
<tr>
<th>Weld number</th>
<th>Weld Pitch (mm)</th>
<th>(F_x) Force (kN)</th>
<th>(F_y) Force (kN)</th>
<th>(F_z) Force (kN)</th>
<th>Torque (KNm)</th>
<th>Heat output (J/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.063</td>
<td>1.47</td>
<td>-0.29</td>
<td>6.81</td>
<td>14.57</td>
<td>1318.43</td>
</tr>
<tr>
<td>A2</td>
<td>0.125</td>
<td>1.31</td>
<td>-0.20</td>
<td>7.25</td>
<td>15.97</td>
<td>722.56</td>
</tr>
<tr>
<td>A3</td>
<td>0.188</td>
<td>1.18</td>
<td>-0.18</td>
<td>8.43</td>
<td>17.50</td>
<td>527.856</td>
</tr>
<tr>
<td>B1</td>
<td>0.056</td>
<td>1.11</td>
<td>-0.15</td>
<td>6.57</td>
<td>11.90</td>
<td>1211.43</td>
</tr>
<tr>
<td>B2</td>
<td>0.111</td>
<td>1.27</td>
<td>-0.10</td>
<td>7.17</td>
<td>13.96</td>
<td>710.57</td>
</tr>
<tr>
<td>B3</td>
<td>0.167</td>
<td>1.31</td>
<td>-0.24</td>
<td>8.01</td>
<td>15.23</td>
<td>516.81</td>
</tr>
<tr>
<td>C1</td>
<td>0.050</td>
<td>0.89</td>
<td>-0.18</td>
<td>5.75</td>
<td>10.67</td>
<td>1206.91</td>
</tr>
<tr>
<td>C2</td>
<td>0.100</td>
<td>1.05</td>
<td>-0.11</td>
<td>6.78</td>
<td>12.08</td>
<td>683.19</td>
</tr>
<tr>
<td>C3</td>
<td>0.150</td>
<td>1.27</td>
<td>-0.08</td>
<td>7.25</td>
<td>14.58</td>
<td>549.72</td>
</tr>
<tr>
<td>D1</td>
<td>0.125</td>
<td>2.34</td>
<td>-0.19</td>
<td>6.59</td>
<td>16.31</td>
<td>737.94</td>
</tr>
<tr>
<td>D2</td>
<td>0.111</td>
<td>1.27</td>
<td>-0.14</td>
<td>5.98</td>
<td>14.99</td>
<td>763.00</td>
</tr>
<tr>
<td>D3</td>
<td>0.100</td>
<td>1.17</td>
<td>-0.15</td>
<td>5.49</td>
<td>13.65</td>
<td>771.99</td>
</tr>
</tbody>
</table>

The heat input was calculated using equation 4.1. This is given by Lambard [68]

\[
Q = \eta \frac{2\pi \omega T}{v} \tag{4.1}
\]

Where

\(Q\) = heat input

\(\eta\) = efficiency factor = 0.9 for Aluminium
\( \omega = \) rotational speed (rev/min)

\( v = \) Transverse speed (mm/min)

\( T = \) Torque

\( \pi = \) Pi = 3.142

From the data obtained, it was observed that as the rotational speed increases, the torque and \( F_z \) force decrease. Since the degree of the output \( F_z \) force is determined by the resistance of the material to the motion of the tool [21], it can be said that increase in the rotational speed led to an increase in the temperature, thereby reducing the amount of force required. Long et al. [21] reported that torque decreases with increasing rotation speed due to higher temperature caused by higher heat generation rate (heat input/time), whose indicator is power input, which was observed also.

It should be noted that all the weld produced at the lowest transverse speed of 100 mm/min has the highest heat input as expected since the heat input is dependent on the travel speed. This is
due to the fact that at low transverse speed of 100 mm/min, the shoulder of the tool has ample
time to interact with the surface of the workpiece, thereby generating more heat compared to
the weld produced at 200 mm/min and 300 mm/min respectively. Also, it was noticed that
with the same input process parameter for welds A2 and D1, B2 and D2 and C2 and D3, the
output parameters were different. This shows that the composition of the material is also a
factor that determines the output response. The output downward force $F_z$ and in welds A2, B2
and C2 are higher due to presence of TiC particles with lower heat input compare to D1, D2
and D3 respectively.

4.3 WELD SURFACE VISUAL OBSERVATION

The top surfaces of the welded samples under different welding process parameters are shown
in Figure 4.2. The welding was carried out using the process parameters shown in Table 4.1

![Processed FSLW samples at different process parameters](image)

The results show that no typical physical defect of FSW like wormhole, cracks and void
observed on the surface with good appearance and continuous surface defect free, which
implies that the process parameters used were optimized. In the absence of surface asperities,
进一步的特征化被做在所有的样品。半圆形的波纹效应由工具肩部的行动造成。
This effect is referred to as *wake effect*.
The shape of the weld seam is slightly convex in nature, which is similar to the conventional weld surface. This is caused by the rotating effect of the tool shoulder geometry on the material and the tilt angle of contact of the tool shoulder, thereby displacing the top layer of the material for proper stirring and the movement of the processed interface and enables the trailing edge of the shoulder tool to extrude the processed material during FSW. A smooth surface is essential for all the FSLWed samples because surface imperfections lead to various internal deficiencies which compromise the mechanical and metallurgical properties of the welded materials.

The retraction of the tool pin at the end of the weld led to formation of keyhole seen in Figure 4.2. The depth of the keyhole shows the extent of penetration of the pin from the top of the material to the bottom material [6]. Khaled [6] observed that, as the depth of the keyhole increases, the tool pin adequately interact with the top and bottom sheets and the strength of the weld increases too.

Flashes were observed for all the process parameters used and most of the flashes were located on the retreating side of the weld. The movement of the material by the tool pin from the advancing side to the retracting side resulted in the deposition of the flashes on the retreating side of the weld where the tool rotation was opposite to the translation direction of the tool. As the transverse speed increases, the flashes generated along the weld seam decreases due to less interactive time for material flow along the weld path and lower temperature distribution associated with higher transverse speed. Another notable feature is the quantity of the flashes presence at the weld without reinforcement particles compare to the welds with reinforcement particles as seen in Figure 4.1. Excessive expulsion of material on the top surface leaving a corrugated or ribbon like effect along the retreating side was observed in weld numbers D1, D2 and D3 (welds without reinforcement) while meager flashes were seen in the welds with reinforcement particles. The presence of the reinforcement particles in the weld seam constraint the excessive flow of material and the heat distribution around the tool and the workpiece, thereby reducing the flow rate of the materials and mitigating the flashes generated during the welding of the aluminium sheets with TiC reinforcement. Since there is no restraining particle at the processed interface of D1, D2 and D3, more turbulent flow of materials occurred, resulting in a joint surface quality reduction and increasing in the flash defect. The forge load, plunge depth and the hot weld might have resulted into the increment of the weld flashes.
4.4 MACROSTRUCTURE

The macrostructure of FSLW depicts the geometry and the size of the weld zone, which provides insight understanding of the durability of the metallurgical bonding formed during the welding process. Table 4.3 summarizes the macrostructure pictures at cross section of the weld zone under different process parameters. In agreement with the literature reviewed, the two different shapes, elliptical and basin shape reported on the nugget zone were also detected [2, 7].

Table 4.3 Macrostructural features at different process parameters

<table>
<thead>
<tr>
<th>Weld number</th>
<th>Macrostructure</th>
<th>Nugget shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td><img src="image1" alt="Macrostructure Image" /></td>
<td>Elliptical</td>
</tr>
<tr>
<td>A2</td>
<td><img src="image2" alt="Macrostructure Image" /></td>
<td>Basin</td>
</tr>
<tr>
<td>A3</td>
<td><img src="image3" alt="Macrostructure Image" /></td>
<td>Basin</td>
</tr>
<tr>
<td>B1</td>
<td><img src="image4" alt="Macrostructure Image" /></td>
<td>Elliptical</td>
</tr>
</tbody>
</table>
From Table 4.3, it can be seen that the process parameters have significant effect on the orientation of the FSW macrostructure. As the transverse speed increased from 100 mm/min to 300 mm/min using the same tool geometry, the shape of the nugget zone metamorphosed from elliptical shape to basin-like shape. It is important to note that the formation of the basin shape is due to the effect of thermal heat transfer from the shoulder of the tool to the sheets. At high transverse speed of 300 mm/min, the heat generated is lower and most of the heat built up at the top sheet with minimal proportion of the heat sink into the bottom sheet. This makes the top sheet to undergo more thermal cycle by direct contact with the tool shoulder and severe plastic deformation than the bottom sheet causing the basin like shape to form.

The intense plastic deformation and high temperature exposure experienced at the lower transverse speed resulted into the elliptical shape. In the elliptical shape, the formation of the elliptical ring commonly referred to as onion ring in the literature review is more obvious and
laminar flow was found at higher transverse speed that produced basin like shape. Onion rings are distinctly observed at the lowest welding speed (100 mm/min on samples A1, B1 and C1) and laminar flows were found at the transverse speed of 200 mm/min and 300 mm/min respectively and can be regarded as a particular feature in FSLWed of metal matrix composites. Onion rings are commonly observed in FS welds. There are several theories in the literatures to explain onion rings occurrence [1-7]. Formation of onion ring in FSW is a synergistic effect of the rotational speed and the transverse speed and direct evidence of characteristic material flow phenomena occurring during FSW. At low transverse speed, more heat is generated and sufficient material flow is obtained, thus onion rings are easily formed. This serves as a confirmation of fine recrystallized grains in the processed zone.

4.5 MICROSTRUCTURAL EVOLUTION

As a result of the friction stir lap welding process, the processed regions or welded zones experienced microstructural evolution. The microstructural evolutions observed are discussed in this section.

4.5.1 TIC POWDER

Figure 4.3 shows the micrograph under SEM of the TiC powder used as the reinforcement in this research study.

![Figure 4.3 SEM Photomicrograph of TiC Powder](image)

The morphology of the TiC powder revealed irregular shaped ball milled powder and grain size of about 2 microns.
4.5.2 FSLW

The pictorial overview of the microstructural evolution across different zones after FSW is presented in Figure 4.4. All the four zones, namely BM close to the HAZ, HAZ that is sandwiched by the BM and TMAZ, TMAZ found on both side of the SZ and the SZ were exhibited in the micrograph taken from the processed zones. As expected, the base metal retains its original microstructural features. The TMAZ and HAZ were formed on both the retreating and advancing sides of the welds. The grain structure in the HAZ shows elongated grain growth slightly different from the base material. The temperature experienced in the HAZ was enough to thermally activate grain growth but not sufficient enough to plastically deform the grain. In TMAZ, severely deformed grains are found, which are induced by drastic plastic deformation of SZ during FSW. In the SZ, the microstructure is characterized by dynamically recrystallized fine equiaxed grains owing to the drastic deformation induced by the sufficient stirring during welding are noticeable in the stir zone of the top and bottom sheet. The distribution of the TiC reinforcement particles is a salient feature observed between the top and the bottom sheets around the SZ. At the top SZ, the presence of TiC is negligible and scanty but significant distribution was found at the bottom of the sheet. This indicates that during the welding process, the reinforcement particle experienced both downward and horizontal flow around the stirred zone. The downward forge force (Fz) pushed and retained the reinforcement downward towards the tip of the bottom sheets and the rotation of the tool transported the particle and deposited the majority of the reinforcement on the advancing side of the weld. Grains in the upper SZ are coarser than those in the bottom SZ. The heat during the FSW process mainly originates from the tool shoulder friction with the surface of the top sheet. Additionally, the heat in the bottom SZ can easily transfer into the bottom sheet and the backing plate. Therefore, the heat cycle of the bottom SZ is relatively lower. The grains in the upper SZ have more time to grow due to the higher temperature gradient.
Another notable observation from the microstructure is the transition region on the advancing side and the retreating side. On the advancing side, the transition region is sharper and well defined and on the retreating side, the transition region diffuse into the parent material making it difficult to differentiate the different regions on this side as shown in Figure 4.5. The diffusivity nature and plastic deforming direction at the RS made it difficult to identify the existence of different zones. On the AS, the plastic deformation direction of the processed zone and the BM are in opposite direction, which resulted in enormous relative deformation and the homogenous distribution of the TiC particles between the BM and the processed zone at the AS but the BM distorted and diffused smoothly together with the processed zone at the RS resulting on clustering of the reinforcement.
It can be observed that the TiC reinforcement within the processed zone had undergone intense mixing and stirring resulting in breakup of the coarse TiC morphology. As the rotational speed of the weld increased from 1600 rpm to 2000 rpm, the distribution of TiC becomes more homogenous as shown in Figure 4.6. At rotational speed of 1600 rpm, the particles clustered together around the bottom sheet and at 2000 rpm, the particles were uniformly distributed around the stir zone.
The contribution of intense deformation and high temperature exposure within the stirred zone resulted into fragmentation, recrystallization and the development of refined texture within and around the stirred zone at rotational speed of 2000 rpm. In addition, increase in transverse speed caused the particles to agglomerate in the stirred zone. As transverse speed decreased, the grain size also decreased in the composite but increased in the pure aluminium samples without the reinforcement. This might be due to high heat input associated with low transverse speed. The phenomenal effect of particle reinforcement on grain size refinement of the matrix is reported as pinning effect. According to pinning effect, the grain refinement by reinforcement particles increases with the decrease in the particle size and increase in volume fraction of the particles. Adequate heat input and stirring are responsible for deformation and recrystallization of the
matrix with the reinforcement. At higher rotational speed of 2000 rpm and transverse speed of 100 mm/min, better uniform distribution of the TiC particles were found.

4.5.3 ENERGY DISPERSIVE SPECTROSCOPY RESULTS

EDS analysis was performed on all the welds with reinforcement. The uniformly distributed particle was confirmed to be titanium and carbon as shown in Figure 4.7 which is the scan of the weld interface of the sample produced at rotational speed 2000 rpm and transverse speed 100 mm/min. The EDS analyses for the remaining process parameters are presented in Appendix B.

![Figure 4.7 EDS from the weld interface at rotational speed of 2000 rpm and transverse speed of 100 mm/min](image)

The elemental composition by atomic weight at the stir zone is confirmed to be 72.04% of aluminium, 23.71% of carbon and 4.34% of titanium.

4.6 TENSILE RESULTS

The shear strengths of all the FSLW joints were carried out to evaluate the effects of process parameters and the addition of the TiC reinforcement particles on the tensile properties. For comparison, the shear strength of the welded samples without the TiC reinforcement at
rotational speeds of 1600 rpm, 1800 rpm and 2000 rpm and constant transverse speed of 200 mm/min were also evaluated. In order to quantify the mechanical resistance of the FSLWed joints, the ratio between the maximum transferred load by the specimens in shear test to the width of the specimen itself was considered. In this way, the values are shown for all the considered case studies. The average results of the three replica samples carried out are reported. Every sample was tested to failure. The shear fracture load per unit width of the FSLWed of Al with and without the TiC composite at different process parameters are presented in Table 4.3 and Figure 4.8 shows the load against extension graph for 2000 rpm at 100 mm/min. The graphs of the remaining process parameters are as illustrated in Appendix C.

Table 4.4 Tensile behaviour from different welds

<table>
<thead>
<tr>
<th>Weld number</th>
<th>Rotational speed (rpm)</th>
<th>Transverse speed (mm/min)</th>
<th>Weld Pitch (mm/rpm)</th>
<th>Shear Fracture load per unit width (N/mm)</th>
<th>Average Shear Fracture Load per unit width (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T1</td>
<td>T2</td>
</tr>
<tr>
<td>A1</td>
<td>1600</td>
<td>100</td>
<td>0.063</td>
<td>159</td>
<td>175</td>
</tr>
<tr>
<td>A2</td>
<td>1600</td>
<td>200</td>
<td>0.125</td>
<td>150</td>
<td>148</td>
</tr>
<tr>
<td>A3</td>
<td>1600</td>
<td>300</td>
<td>0.188</td>
<td>147</td>
<td>122</td>
</tr>
<tr>
<td>B1</td>
<td>1800</td>
<td>100</td>
<td>0.056</td>
<td>142</td>
<td>148</td>
</tr>
<tr>
<td>B2</td>
<td>1800</td>
<td>200</td>
<td>0.111</td>
<td>178</td>
<td>192</td>
</tr>
<tr>
<td>B3</td>
<td>1800</td>
<td>300</td>
<td>0.167</td>
<td>101</td>
<td>118</td>
</tr>
<tr>
<td>C1</td>
<td>2000</td>
<td>100</td>
<td>0.050</td>
<td>245</td>
<td>209</td>
</tr>
<tr>
<td>C2</td>
<td>2000</td>
<td>200</td>
<td>0.100</td>
<td>200</td>
<td>193</td>
</tr>
<tr>
<td>C3</td>
<td>2000</td>
<td>300</td>
<td>0.150</td>
<td>184</td>
<td>142</td>
</tr>
<tr>
<td>D1</td>
<td>1600</td>
<td>200</td>
<td>0.125</td>
<td>197</td>
<td>185</td>
</tr>
<tr>
<td>D2</td>
<td>1800</td>
<td>200</td>
<td>0.111</td>
<td>187</td>
<td>194</td>
</tr>
<tr>
<td>D3</td>
<td>2000</td>
<td>200</td>
<td>0.100</td>
<td>139</td>
<td>186</td>
</tr>
</tbody>
</table>
From the result obtained, it was found that the maximum shear strength was observed at rotational speed of 2000 rpm and transverse speed of 100 mm/min and the minimum was observed at rotational speed of 1600 rpm and transverse speed of 300 mm/min. Both the maximum and the minimum shear strengths were observed when the TiC reinforcement particles were added but at different rotational and transverse speeds respectively.

From the results, the relationship between the fracture load and the transverse speed is inversely proportional. Increase in the transverse speed causes the fracture load to reduce. Shorter reaction time and lower reaction temperature is associated with higher transverse speed and this led to a decrease in the stirring period and the vertical movement of the material with the reinforcement, thereby affecting the strength of the bonding at the interface. It is obvious that the fracture load increases with an increase in the rotational speed for all the samples with reinforcement. As the rotational speed increased from 1600 rpm to 2000 rpm, substantial increase in the fracture load was observed. Higher rotational speed generate higher heat input because of higher friction heating which resulted in more intense stirring and the mixing of the material.

It should be noted that the fracture load behaviour that occurred in the samples without reinforcement is opposite. The absence of the ceramic particle along the path of the weld seam exposed the weld interface to higher degree of thermal reaction, thereby making it to be very sensitive to temperature changes. As the rotational speed increases, the temperature around the weld zone increases, causing high turbulent mixture and stirring of the materials. Since there is no intermediate particle to balance the temperature change, the strength of the bonding will...
be compromised. However, once a sufficient rotational speed is achieved, further increase is not beneficiary to the mechanical properties.

Figure 4.9 shows the relationship between the weld pitch and the fracture load. High weld pitch corresponds to high stirring speed, which implies low heat input to homogenously mix the material with the reinforcement. As the weld pitch increases, the fracture strength of the weld decreases.

![Figure 4.9 Fracture load against the weld pitch](image)

Figure 4.10 shows the effect of the reinforcement particle on the fracture load. As can be seen, the presence of the TiC reinforcement particles contributed an appreciable strength change to the fracture load at higher rotating speed of 2000 rpm and do not show a remarkable improvement to the fracture load at rotational speed of 1600 rpm and 1800 rpm respectively, instead, it had an inverse effect on the strength.
At rotational speed of 2000 rpm, the TiC homogenously mixed with the Al alloys properly, thereby forming a well-bonded matrix that yielded higher fracture strength. The presence of the ceramics particles constrained easy failure of material when under loading, thereby improved the performance efficiency of the matrix.

**4.6.1 JOINT EFFICIENCY**

To estimate the joint efficiency of FSL welds, the ratio of the tensile strength of lap shear specimens were compared to the tensile strength of the base metals. According to studies [24], the tensile strength of lap shear specimen is derived from the fracture load per unit width to the effective sheet thickness (EST).

\[
Tensile \ strength \ of \ lap \ shear \ specimen = \frac{Fracture \ load \ per \ unit \ width}{EST} \quad (4.2)
\]

The EST is defined as the minimum sheet thickness determined by measuring the smallest distance between any un-bonded interface and the top surface of the upper sheet or the bottom surface of the lower sheet. These phenomena should have apparent influences on the bearing-load of FSW lap-welded joints. Shown in Table 4.5 is the shear strength and the joint efficiency.
of the FSLWed samples at different process parameters and the bar chart variation of the joint efficiency is present in Figure 4.11.

Table 4.5 Joint efficiency of the Welds

<table>
<thead>
<tr>
<th>Weld number</th>
<th>Tensile strength of lap shear specimen (N/mm²)</th>
<th>Joint efficiency %</th>
<th>Elongation</th>
<th>Average elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>A1</td>
<td>111.19</td>
<td>79.4</td>
<td>2.44</td>
<td>3.36</td>
</tr>
<tr>
<td>A2</td>
<td>85.23</td>
<td>60.8</td>
<td>3.9</td>
<td>1.71</td>
</tr>
<tr>
<td>A3</td>
<td>74.15</td>
<td>52.97</td>
<td>2.94</td>
<td>11.63</td>
</tr>
<tr>
<td>B1</td>
<td>126.71</td>
<td>90.51</td>
<td>4.6</td>
<td>5.56</td>
</tr>
<tr>
<td>B2</td>
<td>108.53</td>
<td>77.53</td>
<td>1.54</td>
<td>2.85</td>
</tr>
<tr>
<td>B3</td>
<td>96.05</td>
<td>68.60</td>
<td>2.11</td>
<td>6.58</td>
</tr>
<tr>
<td>C1</td>
<td>129.00</td>
<td>92.14</td>
<td>4.58</td>
<td>5.31</td>
</tr>
<tr>
<td>C2</td>
<td>120.34</td>
<td>85.96</td>
<td>5.59</td>
<td>5.04</td>
</tr>
<tr>
<td>C3</td>
<td>97.22</td>
<td>69.44</td>
<td>5.53</td>
<td>4.99</td>
</tr>
<tr>
<td>D1</td>
<td>114.22</td>
<td>81.67</td>
<td>5.98</td>
<td>7.29</td>
</tr>
<tr>
<td>D2</td>
<td>114.02</td>
<td>81.45</td>
<td>4.64</td>
<td>9.32</td>
</tr>
<tr>
<td>D3</td>
<td>97.74</td>
<td>69.81</td>
<td>4.99</td>
<td>4.66</td>
</tr>
</tbody>
</table>

From the Table 4.5, the joint efficiency ranges from 52% to 92%. The highest was found at rotational speed of 2000 rpm and transverse speed of 100 mm/min. This superseded the standard shear strength of 60% of the base metal tensile yield strength for shear fracture. Majority of the welds have acceptable weld joint efficiency above 60%.
The effect of the transverse speed on the EST was studied. Figure 4.12 shows the graphical relationship between the EST versus transverse speed. Transverse speed exhibits a linear relationship with the EST. As the transverse speed increased, the dimension of the EST also increased, thereby reducing the area of metallurgical bond that exists at the processed interface. Since the strength of the weld interface depends on the area of the metallurgical bond during the welding process, then it is apparent that the relationship between the EST and the overall strength of the processed zone is exponential.
4.6.2 FRACTURE BEHAVIOUR

According to the fracture locations of the lap shear specimens observed, four different modes of failure were noticed at the joint interfaces as illustrated in Figure 4.13. They are namely fracture mode (FM) 1, shear fracture that occurred due to lack of joint formation along the original interface of the two sheets. This led to pseudo metallurgical bond between the two sheets and the bond shear under tensile loading. Fracture mode 2 occurred on the advancing size hooking in which the crack initiates from the tip of the hook on the AS, propagates upward along the SZ/TMAZ interface and finally, the fracture at the SZ. Fracture mode 3 was noticed on the retreating side softening initiated from the hook and then linked to pores on the bottom plates caused by the diffusion of the bottom plate with the backing plate. The crack follows the sharp end of the groove to the other end. Fracture mode 4 failure took place close the base metal but the weld actually failed at the HAZ on the advancing side of the weld. Table 4.5 lists the failure modes observed for each process parameter combination.

Figure 4.13 Fracture mode of the welded samples at different process parameters

FM 1 was found at low rotational speed of 1600 rpm and high transverse speed of 300 mm/min. The dominant fracture modes are FM 3 and FM 4.
Table 4.6 Mode of fracture at different process parameters

<table>
<thead>
<tr>
<th>Weld number</th>
<th>Rotational speed (rpm)</th>
<th>Transverse speed (mm/min)</th>
<th>Fracture Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1600</td>
<td>100</td>
<td>FM 1/FM 2</td>
</tr>
<tr>
<td>A2</td>
<td>1600</td>
<td>200</td>
<td>FM 2</td>
</tr>
<tr>
<td>A3</td>
<td>1600</td>
<td>300</td>
<td>FM 1</td>
</tr>
<tr>
<td>B1</td>
<td>1800</td>
<td>100</td>
<td>FM 3</td>
</tr>
<tr>
<td>B2</td>
<td>1800</td>
<td>200</td>
<td>FM 3</td>
</tr>
<tr>
<td>B3</td>
<td>1800</td>
<td>300</td>
<td>FM 4</td>
</tr>
<tr>
<td>C1</td>
<td>2000</td>
<td>100</td>
<td>FM 3/FM 4</td>
</tr>
<tr>
<td>C2</td>
<td>2000</td>
<td>200</td>
<td>FM 3</td>
</tr>
<tr>
<td>C3</td>
<td>2000</td>
<td>300</td>
<td>FM 4</td>
</tr>
<tr>
<td>D1</td>
<td>1600</td>
<td>200</td>
<td>FM 3</td>
</tr>
<tr>
<td>D2</td>
<td>1800</td>
<td>200</td>
<td>FM 4</td>
</tr>
<tr>
<td>D3</td>
<td>2000</td>
<td>200</td>
<td>FM 4</td>
</tr>
</tbody>
</table>

FM 1 is observed at low rotational speed and high transverse speed. A process condition associated with low heat input that resulted in insufficient deformation and flow of the material. The crack initiation occurs through the gap tip of the unwelded area and went through the stir zone making the weld to shear into two at the welded area. This usually occurs when insufficient metallurgical bond is formed between the sheets.

FM 2 and FM 3 are the most dominating failure modes. The fracture mode is similar to normal tensile behaviour of aluminium alloy. The material went through necking for a period before eventually fracturing at the weakest zone.

The SEM images of the fracture surfaces were taken to determine the mode of fracture. Figure 4.14 illustrates the typical fractography features of surface failure.
The morphology of the failure mode shows large amount of fine dimples which confirm the amount of plastic flow prior to failure under tensile loading. The fine dimple feature found indicate that the behaviour of fracture is ductile which implies that the lap joints exhibited ductile fracture during the lap shear tests.

4.7 MICROHARDNESS PROFILING

The Vickers hardness distribution is illustrated in Figure 4.15. The shape of the hardness distribution is a "W-sinusoidal". The lowest hardness value was found at the HAZ and the highest hardness value at the SZ. The hardness value of the SZ increased by 58% when compared to the base metal for sample C1. Thangarasu et al [50] suggested four methods of hardening in FSW MMC namely:

- Orowan strengthening.
- Grain and substructure strengthening.
- Quench hardening resulting from the dislocations generated to accommodate the differential thermal contraction between the reinforcing particles and the matrix.
- Work hardening due to the strain misfit between the elastic reinforcing particles and the plastic matrix.

The increment in the hardness value at the SZ is attributed to grain refinement and the presence of reinforcement particles. Fragmentation of bigger TiC particles gave rise to dislocation density and dynamics recrystallization during welding, thereby producing finer grain size in the stir zone. These factors are responsible for higher hardness value in the stir zone of welds with the reinforcement particles. The minimum hardness value appeared at the HAZ. This is due to the thermal history experienced at this zone which resulted in the coarsening of the precipitates.

![Figure 4.15 Hardness Profile of the FSL Welds](image_url)

Because of the distribution and the deposition of the TiC particles around the AS of the welded zone, AS size shows higher hardness value than the RS due to the fact that materials on the RS has lower time to rotate since the current flow of material is directly proportional to the time of flow on this side.

Figure 4.16 also illustrated the comparative study between welds B2 and D2.
The hardness profile of D2 (welds without TiC) is roughly uniform with the highest hardness value found at the base metal. It was found that B2 has higher hardness value than D2. The enhancement in the hardness is attributed to the deposition of the reinforcement particle in the stir zone of B2.

4.8 SUMMARY

Different characterizations were performed on the welds and the results obtained from all the analysis were presented and have been discussed in this chapter. The visual inspection shows good surface quality with no asperities and further characterizations were performed on all the welds. The shape of the weld nugget changes with respect to the process parameter and the microstructural evolution revealed that most of the TiC particles imbedded in the stir zone were deposited in the bottom plate. The highest hardness value was noticeable at the stir zone and the fracture load increases with an increase in the rotational speed. The next chapter focuses on the conclusions and future work suggestions.
CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 INTRODUCTION

Extensive works on the characterization of Al-TiC metal matrix composites produced via friction stir welding have been reported in this work with critical review of the available literatures. Different tests were performed on the welded samples in order to achieve the set aim and the objectives of this study. The observations from this study are listed below.

5.2 CONCLUSIONS

The following conclusions can be drawn from this study:

- The macrograph changes with respect to the process parameters. As the transverse speed increases, the macrograph changed from elliptical to basin like shape.
- The micrograph revealed that the majority of the TiC particles were transported from the weld interface and deposited in the bottom sheet. The EDS analysis confirmed that no intermetallic compound was formed during the welding operation.
- The highest tensile value of 218 N/mm and joint efficiency of 92\% were noticed at high rotational speed of 2000 rpm and low transverse speed of 100 mm/min. This parameter combination setting can be recommended.
- The maximum hardness occurred at the stir zone and the minimum at the HAZ. The AS exhibited higher hardness distribution compared to the RS.

5.3 FUTURE WORK

However, a lot of work has been done in this study but there is still room for further investigation. These include:

- Double pass FSW could be performed on the weld seam to improve and homogenize the distribution of the particles.
- Further characterizations like residual stress, wear and corrosion can also be investigated on the samples to gain insight into the tribology behavior of the welds.
• Different tool geometries can be employed for welding purpose and a comparative analysis could be done to optimize the process.
• Post heat treatment can be conducted to improve the performance efficiency of the weld and different particle sizes can also be considered.
REFERENCES


APPENDIX A OUTPUT RESPONSE

Weld. 1 1600 rpm, 100 mm/min

Weld. 2 1600 rpm, 200 mm/min

Weld. 3 1600 rpm, 300 mm/min
Weld. 4 1800 rpm, 100 mm/min

Weld. 5 1800 rpm, 200 mm/min

Weld. 6 1800 rpm, 300 mm/min
Weld. 7 2000 rpm, 100 mm/min

Weld. 8 2000 rpm, 200 mm/min

Weld. 9 2000 rpm, 300 mm/min
Weld. 10 1600 rpm, 100 mm/min without reinforcement

Weld. 11 1800 rpm, 100 mm/min without reinforcement

Weld. 12 2000 rpm, 100 mm/min without reinforcement
APPENDIX B EDS ANALYSIS

Weld 1 1600 rpm 100 mm/min

Weld 2 1600 rpm 200 mm/min
Weld 3 1600 rpm 300 mm/min

Weld 4 1800 rpm 100 mm/min
Weld 5 1800 rpm 200 mm/min

Weld 6 1800 rpm 300 mm/min
Weld 7 2000 rpm, 100 mm/min

Weld 8 2000 rpm 200 mm/min
Weld 9 2000 rpm 300 mm/min
APPENDIX C TENSILE GRAPH OF FRACTURE LOAD VERSUS EXTENSION

Weld No: 1 1600 rpm, 100 mm/min
Weld No: 2 1600 rpm, 200 mm/min
Weld No: 3 1600 rpm, 300 mm/min
Weld No: 4 1800 rpm, 100 mm/min
Weld No: S 1800 rpm, 200 mm/min
Weld No: 6 1800 rpm, 300 mm/min
Weld No: 7 2000 rpm, 100 mm/min
Weld No: 8 2000 rpm, 200 mm/min
Weld No: 9 2000 rpm, 300 mm/min
Weld No: 10 1600 rpm, 200 mm/min without TiC
Weld No: 11 1800 rpm, 200 mm/min without TiC
Weld No: 12 2000 rpm, 200 mm/min without TiC