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An Investigation on the Performance of Rotary Friction welding of Titanium alloy (Ti-6Al-4V)

By

M.C. Zulu

(215086813)

A dissertation submitted in fulfilment of the requirements for the degree of

Masters Technologiea

In

Mechanical Engineering

Faculty of Engineering and the Built Environment

Department of Mechanical and Industrial Engineering Technology

University of Johannesburg

Supervisor: Dr. P.M. Mashinini

September 2018
Declaration

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Date: 19 September 2018
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- Finally, I would like to express my profound gratitude to the department of Mechanical and Industrial Engineering Technology for giving me the opportunities to study and work with them.
Dedication

I dedicate this dissertation to my mother Ntombi Zungu, to my sister Samke Zungu and to my family as a whole. I also like to dedicate this research work to my extended families, Lebani and Bhengu, and lastly, to the University of Johannesburg Mechanical and Industrial Engineering Technology stuff.
Abstract

Rotary friction welding (RFW) is a solid-state joining process that has been adopted by several industries and fabricators worldwide. It is one typical joining process that produces a weld joint with greater or similar properties to that of the parent material. This process has been an attraction due to an ability to weld materials, which were previously considered difficult to weld using conventional welding processes, such as Titanium alloys.

Titanium alloy (Ti-6Al-4V) was welded with continuous-drive friction welding technique. The main aim was to evaluate the performance of Ti-6Al-4V weld joint in comparison to the parent material and to evaluate the integrity of the weld joint. This was accomplished by varying process parameters during welding. Axial pressure ranging from 25 MPa to 140 MPa and rotational speed ranging from 1600 RPM to 2700 RPM were utilized. Rotary friction welded material and parent material samples of Ti-6Al-4V were examined in terms of mechanical properties and microstructure characterization. The microstructures for weld joint and parent material were analyzed using Optical Microscope. Mechanical properties including tensile strength and micro-hardness were evaluated and analyzed.

The weld results showed that the weld joint of Ti-6Al-4V produced from RFW process is very similar to that of LFW process. The variation in microstructure from the weld center to the parent material revealed different weld zones present in a weld joint namely WN, TMAZ and HAZ which are a typically representation of friction processing. The micro-hardness plots revealed an increase in hardness at the weld joint, with the
highest hardness of 375 HV obtained at the WN. The variation in rotational speed did not have a significant impact on the WN hardness.

The tensile results revealed that the UTS of welded specimen is relatively high compared to the parent material. The maximum UTS obtained was 1040 MPa. The variation in rotational speed as well as friction pressure did not have significant effect on the tensile properties of the weld joint. However, at an elevated friction pressure, variation in rotational speed have a significant influence on the failure location as well as the percentage elongation. In addition, the width of weld joint was mostly influenced by rotational speed and axial pressure. The weld width was proportional to rotational speed and inversely proportional to the axial pressure.
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<td>American Machine and Foundry</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>AWS</td>
<td>American Welding Society</td>
</tr>
<tr>
<td>BCC</td>
<td>Body Center Cubic</td>
</tr>
<tr>
<td>FSW</td>
<td>Friction Stir Welding</td>
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<tr>
<td>HAZ</td>
<td>Heat Affected Zone</td>
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<tr>
<td>HCP</td>
<td>Hexagonal Closed Pack</td>
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<td>LFW</td>
<td>Linear Friction welding</td>
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<tr>
<td>OM</td>
<td>Optical Microscope</td>
</tr>
<tr>
<td>OCTG</td>
<td>Oil Country Tubular Goods</td>
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<tr>
<td>PM</td>
<td>Parent Material</td>
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<td>RFW</td>
<td>Rotary Friction welding</td>
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<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>TYS</td>
<td>Tensile Yield Strength</td>
</tr>
<tr>
<td>TWI</td>
<td>The Welding Institute</td>
</tr>
<tr>
<td>UTS</td>
<td>Ultimate Tensile Strength</td>
</tr>
<tr>
<td>WN</td>
<td>Weld Nugget</td>
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<tr>
<td>α</td>
<td>Alpha</td>
</tr>
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<td>β</td>
<td>Beta</td>
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Glossary of terms

A

- **Alloy**: A metallic compound made by two or more metallic elements, especially to give best mechanical properties.
- **Alpha**: A Titanium’s low temperature allotrope that occurs below β –transus temperature.
- **Alpha stabilizer**: The alloying element that raises the temperature at which the alloy will transform completely to β-phase.
- **Alpha-Beta alloy**: An alloy that contains both α and β stabilisers, such as Ti-6Al-4V.

B

- **Beta (β)**: A Titanium’s high temperature allotrope, which occurs above β –transus temperature.
- **Beta stabiliser**: An alloying element that reduces the transformation temperature and stabilises β –phase.
- **β –transus temperature**: The lowest temperature at which a 100-percent β-phase can exist.

C

- **cryogenic**: Relating to the production or applications of low temperatures.
- **Crystal**: A continuous group of atoms aligned and packed together exactly the same way.

D

- **Deformation**: Change in the body form due to an application of heat or pressure.
• **Dwell time**: Time taken for the rotating part to settle around their common axis after both parts (rotating and stationary) are brought together.

E

• **Embrittlement**: It is a partial or complete loss of ductility of a material, making it brittle. It is normally caused by contamination of gases in RFW.

• **Equiaxed grains**: A structure in which grains have the same dimensions in all directions.

• **Etchant**: An acid or corrosive chemical solution used to soak the metal for etching.

• **Etching**: A process of soaking a metal in an etchant to reveal microstructure details.

F

• **Flashing**: A plastically deformed material over the thermo-mechanical affected zone (TMAZ).

• **Friction pressure**: An axially applied pressure to enhance plasticisation at the interface of two bonding parts.

• **Forging pressure**: an axially applied pressure to enhance consolidation of joining parts that have been frictionally plasticised.

G

• **Grain**: a single crystal surrounded by other crystals of the same type, but at different orientation (polycrystalline).

H

• **Hardness**: An ability of a material to resist plastic deformation under an action of a compressive force.
• **Heat-affected zone (HAZ):** An area of a parent or base material that has its properties been altered due to heat generated during welding.

**M**

• **Martensitic transformation:**

• **Microstructure:** A very small-scale structure of a material that can only be seen with a microscope of high magnification.

**O**

• **Oxidation:** Absorption of contaminants gases when a material is exposed for long term at elevated temperatures. This normally occurs during welding process and such gases include hydrogen, oxygen and nitrogen.

**P**

• **Polycrystalline:** A number of crystallites of different sizes and orientation.

• **Parent material:** The material in a form of manufacturer’s specification.

**R**

• **Recrystallization:** When deformed grains are replaced by a new set of grains, usually as a result of temperature being beyond transus temperature.

**T**

• **Tensile strength (UTS):** The maximum load that a material can withstand before fracture.

**V**

• **Void:** During welding process absorbed contaminant gases become trapped in the welded material when released on solidification. These traps are called voids.
W

- **Weld width**: it is referred to as a distance from the weld nugget to the outermost edge of the heat-affected zone.

- **Weld Nugget (WN)**: A central region of weldment with very fine grain structure.

- **Widmanstatten Transformation**: A formation of new phases within the grain boundaries of the PM because of recrystallization, usually increasing the hardness and brittleness of the material.
Chapter 1: Introduction

1.1 Introduction

Titanium and its alloys are materials that can be welded by various types of welding techniques like conventional welding techniques (such as arc welding). Most of these welding techniques have been used historically to join more common metals, Titanium and its alloys [1]. Many new metal-joining processes have been used successfully in industrial production and in a wide range of experimental applications. It is highly expected that the past established metal-joining methods will continue to be used successfully, and that the application of the newer welding processes will gain a wide range of use for Titanium and its alloys as more knowledge and experience is developed, applied, invented and familiarised [2, 3].

When reviewing the newer welding practices, friction welding process has been the most experimented and efficient type of welding in joining of Titanium and its alloys. This type of welding technique has shown great performance when compared to conventional welding techniques as it does not include any filler material [4]. Friction welding is a solid-state joining technique developed by the Soviet Union, with the first experiment conducted by American companies, Caterpillar and Rockwell International [5]. In 1991, Wayne M Thomas [6] patented friction welding under The Welding Institute (TWI) and developed tools and process technologies for rotary friction welding [6].

Furthermore, the friction welding technique, also referred to as rotary friction welding (RFW), consists of two bonding parts, one of them placed in a stationary fixture and
the other rotating around their common axis [7]. The first period of the RFW process is referred to as the friction period, a clamp brings the parts together until the surfaces get in touch and the friction phenomenon starts. The second period involves consolidation. RFW operation is divided into two categories namely the heating phase and forging phase. In the heating phase, the interaction between the process parameters aim at eliminating the film of oxides and impurities of the interfaces of materials to be joined. The friction between the joining surfaces effectively does this, elevating the temperature up to a certain value close but less than the melting point with the application of the pressure in the time interval [8]. In the forging phase, relative motion is stopped and greater pressure is applied to displaced material affected by frictional heat [8, 9, 3]. Practically, because no melt occurs, RFW is not actually a welding process in the traditional sense, but a falsifying technique. Perhaps, it is a most efficient technique in joining similar and dissimilar materials. Figure 1 - 1 shows RFW sequence.

Figure 1 - 1: Rotary friction welding sequence [10]
The difficulties in welding of Titanium and its alloys originate from several sources. The high reactivity of Titanium with the environment at 610 °C, poor cleaning of welding surfaces before joining and inadequate shielding during welding leads to contaminations, porosity and embrittlement of the completed joint [11, 9]. The successful joining of various Titanium and alloy products is accomplished with the use of best welding practices and a knowledge of the factors that affect Titanium weld-joint quality [2, 5].

Titanium and Titanium alloys have desirable properties which when combined make the metal to be the best material for the different service applications. These applications include but are not limited to [4]:

- Aircraft turbines
- Engine components
- Aircraft structural components
- Aerospace fasteners
- High-performance automatic parts
- Marine applications
- Sports equipment
- Medical facilities and biomechanics application, such as implants.
- Chemical industries and gas turbines

This project aims at revealing the behavioural change and performance of Titanium alloy grade 5 (Ti-6Al-4V) after being welded. This will be achieved by the use of rotary friction welding technique to join two similar Titanium rods. Various testing and analyses equipment will be utilised to test the welded samples. An analysis on tensile strength, micro-hardness and microstructure of the weld joint will be evaluated.
1.2 Research significance

The use of Titanium alloy Ti-6Al-4V has increased worldwide and currently accounts for 50 percent (%) of the total Titanium usage the world over [11]. The information and knowledge concerning mechanical properties, best welding techniques and the behaviour of this material before and after welding is limited. With the lack of information and knowledge, it becomes a challenge for fabricators and design engineers to select, weld and use this material in various forms of applications as applicable to the relevant industries. From an engineering point of view, it is too risky to use and rely on the material to satisfy the application’s needs if most of its mechanical properties are limited.

From this project investigation, information and knowledge pertaining to Titanium alloy (Ti-6Al-4V) welding will be shared and familiarised so that the body of knowledge in welding of this material can be improved. It will also help to familiarise the rotary friction welding technique as one of the best techniques for circular Titanium welding to the fabricators and engineers who may have interest in this material and its welding technique. In addition, a great collaboration between the universities both locally and internationally will be created as rotary friction welding is a unique process both nationally and internationally. The success of this research work will enable a transfer of knowledge to industry towards the applications of Titanium alloys.

1.3 Objective

The main objective of this research project is to evaluate the weld integrity, the performance behaviour and microstructure characterization of rotary friction welded Ti-6Al-4V alloy rods.
1.4 Hypotheses

The mechanical properties of the weld-joint will be influenced by the rotary friction welding process parameters. The hardness and microstructure will change because of the frictional heat generated during the joining process of Ti-6Al-4V alloy rods.

1.5 Problem statement

Most fabricators that are currently joining Titanium and Titanium alloys with various welding techniques have had challenges to accomplish a good weld joint for different Titanium components. These difficulties actually instigate from different sources from industries. The selection of the best welding technique, the reactivity of Titanium with the environment, pour cleaning of surfaces before welding, inadequate shielding during welding process and incorrect process parameters are the main sources of difficulties when joining Titanium and Titanium alloys products.

1.6 Limitations

The limitations of this research project are:

1. Material to be welded is Ti-6Al-4V alloy rod.
2. Size of the Titanium rods is 25.4 mm diameter
3. Argon gas for shielding

1.7 Research methodology

The research was conducted as follows:

- The methodology of this project includes reviewing literature concerning what other researchers have done pertaining to rotary friction welding and friction
welding processes. The literature review was conducted on a continuous basis throughout the entire project. The review of literature helped the researcher to gain the required knowledge towards building a better understanding of conducting the project experiments and analyses. It also assisted in selecting relevant process parameters that were used for the preliminary and final welding processes experiments.

- Preliminary welding is the primary welding or preparation that were done prior to the final welding. This part of the welding process gave a clear vision of the significance of the process parameters chosen. In addition, physical observations were done to assess the weld formation on the joined Titanium rods.

- The final welding was conducted after the preliminary welding analysis had been finalised. A final welding process parameter matrix was done to fulfil the final welding procedure.

- When the final welding had been successfully conducted, samples were cut according to the standard metallurgical procedures (that is according to ASTM standards) to enable testing for the hardness, tensile strength and microstructure evaluation.

- The results obtained from the tests were analysed, interpreted and compared to the results published by other researchers.

- A conference paper was produced with the results obtained.

- Lastly, a dissertation was compiled to fulfil the requirements of the Master’s Technologiae in Mechanical Engineering.
The summarised steps of the research project are as follows:

**An Investigation on the Performance of Rotary Friction Welding of Titanium alloy (Ti-6Al-4V)**

- Literature Review
- Parameter selection based on Literature
- Preliminary welding
- Preliminary welding analyses and design of the final welding set-up
- Final welding, Tests and analyses
- Results interpretation and report drafting

Figure 1 - 2: Research methodology
1.8 Project plan

The Table 1 - 1 below shows the project research period and time-lines

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<th>Start date</th>
<th>End date</th>
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<td>May 2017</td>
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<td>Literature review (Continuous)</td>
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1.9 Dissertation Layout

The formal presentation of this research is divided into various Chapters, including an introduction, the review of what other researchers have done experimental procedure, results and discussion as well as the conclusion and recommendations.

Chapter one (1) presents the introduction focusing on the type of material and the welding technique, the solid-state welding process, utilised in this project investigation. This will give an idea to the readers about the general characteristics of the material, the important aspects of welding technique chosen as well as its significant process parameters that perfect welding. The motive behind this project investigation as well as the objectives and limitations are covered as well. In this chapter, the significance of friction welding process on the advance materials of different engineering applications is also highlighted.

Chapter two (2) presents a literature review of the rotary friction welding (RFW) process, the material (Ti6-Al-4V) and its mechanical and metallurgical properties. The history as well as rotary friction welding theory is also presented in this chapter to give a full understanding of the welding technique chosen for the investigation. In addition, the review of what other researchers have done in relation to friction welding is also presented.

Chapter three (3) gives a detailed description of the experimental procedure used in this project investigation showing the mechanical and metallurgical techniques used to characterize the resultant weld joints based on the parent material. The welding
matrix of rotary friction welding is also presented showing the joining process parameters used to perform the welding.

Chapter four (4) presents the results and discussion of this investigation. A detailed metallurgical and mechanical characterisation of the weld joint as well as the base material in determination of property relationships is presented.

Finally, Chapter five (5) presents the concluding remarks and recommendations for the possible future research work.
Chapter 2: Literature review

2.1 Introduction

This Chapter mainly focuses on rotary friction welding, and Titanium and its alloys, the history, applications, process theory and sequence. The general process parameters, advantages and disadvantages of rotary friction welding are discussed. In addition, classifications, applications and general properties of Titanium alloys are also covered in this Chapter. The purpose of this Chapter is to reflect on what other researchers have done pertaining to RFW and Titanium alloys.

2.2 Friction welding process

The joining of two materials has always been a big challenge as it causes a change and deterioration of the original mechanical properties and microstructure at the weld interface. Friction welding is a process that produces coalescence at a temperature below melting point of a parent material without the addition of a filler material. In simple terms, friction welding involves bringing atoms of both workpieces together to permit inter-atomic force to bridge the interface [12, 13].

However, there are major difficulties associated with friction welding. Firstly, friction welding is a solid-state welding and metal surfaces of workpieces are rough at an atomic scale. Therefore, when low force is applied only fewer sections of the interface get into contact. Secondly, an increased force amount increases the number of contact surfaces, but the oxides layer and the occluded gas that is present in all metals under normal atmospheric condition (as shown in Figure 2 - 1) is encountered. For the welding to occur successfully, these layers have to be removed [12, 14, 15].
The temperature, weld force and time to achieve a weld joint in a solid-state friction welding are adjusted according to the material being joined as well as the workpiece geometry. According to the recommended practice standard for friction welding, the effective welding temperature is at least 70 percent (%) of the workpieces melting temperature. The amount of the welding pressure applied depends upon the materials properties and the configuration of the workpiece as well as the overall deformation. The weld time is kept at a predetermined range to ensure sufficient intimacy on the faying surfaces, developing interatomic bond and ensuring disappearance of interfacial oxide voids [4, 16].
2.3 Rotary friction welding

Rotary friction welding (RFW) is a solid-state joining process. It was first developed in 1956 and was formally defined by the American Welding Society (AWS) in 2008. This technique is also known as spin welding, and involves one part being spun at a high rotational speed against the other part, which is mounted on the stationary fixture. The rotation of the rotating part is designed to keep rotation around their common axis. After a pre-determined time, frictional heat generated, that is, when the interface temperature is adequate enough to cause plastic state, both parts are forged together with a pressure greater that frictional pressure. During forging the relative torque causing rotation is removed and both parts are joined while they cool [17]. A typical RFW weld is shown in Figure 2 - 2.

![Figure 2 - 2: Rotary friction welding [17]](image)

RFW is divided into two categories, namely direct-drive rotary friction welding and inertia friction welding (as shown in Figure 2 - 3). The difference between these processes is that direct-drive RFW has a drive motor directly coupled to the gyrating chuck, continuously feeds drive energy to keep and maintain rotational speed constant and at a controlled level, while the inertia RFW has a flywheel that stores the rotational
kinetic energy of the welding machine. Usually the stored rotational kinetic energy is used during the forging phase. When the drive motor is disengaged, the flywheel continues to spin the chuck that holds one part until it stops when the weld zone seizes [13, 5].

As rotary friction welding is divided into two categories, continuous drive or direct-drive friction welding is used mostly in Europe, while Inertia drive is mostly used in America. An advantageous feature of inertia friction welding is that the rate of energy transfer is bigger at the start of the welding and decreases as the welding progresses, whereas in the continuous-drive friction welding the rate of energy transfer is more or less constant. Even though there is metallurgical difference in the welds made by these processes, the end results are similar [19]. A brief comparison of the process parameters between continuous-drive and inertia friction welding processes are presented in the Table 2 - 1 below [20, 21, 22].
Table 2-1: Comparison of process parameters of continuous drive friction welding and inertia welding [20, 21, 22]

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Continuous drive FW</th>
<th>Inertia FW</th>
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<tbody>
<tr>
<td>Welding parameters</td>
<td>• Rotational speed</td>
<td>• Rotational speed</td>
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<tr>
<td></td>
<td>• Welding force</td>
<td>• Welding force</td>
</tr>
<tr>
<td></td>
<td>• Upset distance</td>
<td>• Moment of inertia</td>
</tr>
<tr>
<td>Energy conversion to frictional heat</td>
<td>Constant energy in a pre-set duration of rotation</td>
<td>Fixed energy in fly wheel rotational time</td>
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<tr>
<td>Energy input</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Heat generation rate</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>HAZ width</td>
<td>Wide</td>
<td>Narrower</td>
</tr>
<tr>
<td>Weld time</td>
<td>Similar</td>
<td></td>
</tr>
<tr>
<td>Weld joint properties</td>
<td>Similar</td>
<td></td>
</tr>
</tbody>
</table>

Rotary friction welding is divided into various phases that differ from author to author. AWS [21] as well as Elmer and Kautz [23] divided RFW process in two phases; 1) the friction phase, when both workpieces come together and rubbing takes place until the interface is soft. 2) Forging phase, application of higher compressive pressure to join and displace soft material causing sudden shortening [21, 23].

Duffin and Bahrani [24] divided RFW process into two distinct phases, friction and forging phase. Each phase was divided into two stages. Considering friction phase, it is divided into dry friction, when workpieces come together and shearing occurs, and
equilibrium stage, when the interface material is very plastic. Forging phase is divided into relative motion being stopped and application of compressive pressure [24].

Vill [25] divided the process into three (3) phases as well; Exterior dry friction, Appearance of seizure and high temperature phase, during which the process can become stationary as a result of motion being removed and application of high compressive pressure. Crossland [20] separated friction welding process into four stages; 1) Dry friction exists; 2) Seizure takes place and large torque rise; 3) Temperature rise resulting from shearing of an increased seizure area; 4) Relative motion is eliminated and applied load is increased. Any plastic material is pushed out of the interface forming flash. Ellis [26] also separated the process into 5 steps; 1) Contact and initial friction; 2) Viscous interface start; 3) Equilibrium is Achieved; 4) Relative motion is stopped and forging begins; 5) Welding complete [26].

Rotary friction welding is the most efficient welding technique in joining similar and dissimilar materials although it is generally limited to the cylindrical or circular components [17]. Most RFW developments so far have been a motive to the aerospace industries and in a wide range of manufacturing industries as it exhibits better performance on the critical components when compared to the traditional welding processes. In addition, a substantial number of researchers have been funded by manufactures, yet very few reports and journal articles are available in the public domain or databases [27].

The main aim of rotary friction welding is to produce a hundred percent weld throughout the full joint interface. This means that, given suitable material, the weld
cross-section will have properties equal to or greater than that of the parent material. RFW produces a weld with high strength, low residual stresses, small heat-affected zone weld with no porosity and eliminates the need of pre-machining [28].

2.3.1 Theory of rotary friction welding

Traditionally, rotary friction welding is conducted by rotating one-part relative to the other along their common axis. This is done while applying compressive frictional and then forging pressures perpendicular to the joint to complete welding. The interface material is heated by frictional heat until it becomes soft for both joining parts. When they reach the temperature that induces plastic state, the interface material is displaced out of the edges leaving the clean material from each part. This is a very important phase of welding as all impurities, including any oxides or other contaminants that may have been on the interface before welding, are ejected [7, 5, 27]. The plasticised segment of both bonding parts is effectively prevented from becoming a liquid (melting) due to the nature of this process, as it cannot transmit the required stress for heat generation. The liquid material begins to act as a lubricant instead of producing frictional heat. Therefore, it is recommended to select welding speed within the limits of optimum speeds, as each material to be welded has recommended welding speeds for RFW [9, 21].

The final compressive forging pressure, greater than the frictional pressure, is then applied axially to the joining parts after stopping relative motion to consolidate the weld before the material is allowed to cool [4]. In this phase too, the plasticised material is pushed through the edges forming a flash outside bonding parts. The joint formed contains a heat-affected zone (HAZ) and features the plastically deformed material
over the thermomechanical heat-affected zone (TMAZ) [27]. By producing a full cross-section welding, RFW yields a very high strength and low stress weld with no voids.

Unlike any other welding methods, RFW is a low temperature process and has a very small amount of heat-affected zone (HAZ). In most cases, material's macrostructure and most other mechanical properties are usually maintained. In other words, there is no significant change in the macrostructure and mechanical properties with rotary friction welding when compare to the parent material. In general, this process joins many combinations of materials which are not considered weldable, without using any filler material. Since there is no filler material, it eliminates the undesirable effect of low temperature segregation and problems caused by poor selection of filler material [29, 30, 31].

In summary, rotary friction welding consist of three phases, friction phase, braking phase and forging phase. The friction phase occurs when rotating and static parts are brought together and a compressive frictional pressure is applied axial to enhance burn-off and generate heat that plasticises the interface. Braking occurs after friction phase and it involves eliminating relative motion. The forging phase is reached when a compressive pressure higher than frictional pressure is axially applied to displace the plasticised material after the relative motion has been stopped. In addition, the forging pressure is quickly removed at the end of welding process. Lastly, the plastic state flash is removed before the joint cools off completely [29, 32]. A typical RFW sequence from Figure 2 - 4 to Figure 2 - 8.

One part is rotating and the other part is stationary.
Both parts are bought to be in contact and compressive frictional pressure is applied.

The frictional heart is generated and the plastic state is reached at the interface.

The relative motion is stopped and the compressive forging force is axially applied displacing plasticised material over thermo-mechanical affected zone.

A full cross-section weld in the parent material is generated and the plastic state flashing is removed.
Many dissimilar metals of cylindrical or circular form are joined using rotary friction welding. Most fabricators have used this process in joining of mild steel to aluminium, steel to ceramics, copper to steel and most other dissimilar materials [33, 34]. The voice of gratitude has been noted in many manufacturing industries regarding the effectiveness that rotary friction welding has brought into the welding environment. Although welding of dissimilar material is not as difficult as it sounds, certain precautionous measures have to be undertaken to successfully perform a weld-joint with no complications. Failing to undertake these precautions leads to the imperfect weld-joint with reduced quality of weld and embrittlement [33, 34, 35].

2.3.2 History and background of rotary friction welding

In the past two-decade friction rotary welding has been the most efficient and successful welding technique for joining all hard cylindrical and circular materials. During joining, the number of welding parameters were and are still controlled based on the materials to be joined to produce a quality and non-complicated weld-joints [36]. RFW has been the most commonly used form of friction welding for the production of heavy-duty components. Numerous structural metallic materials of similar and dissimilar joints have been welded with RFW process. Perhaps, the most attention is paid on the process parameters, joint microstructure and mechanical properties used and produced by this welding technique [37].
Over fifty years TWI along with expertise have been at the forefront in developing rotary friction welding technique. Through these developments, various experiments and tests have been conducted to improve the effectiveness of this process. Most of these experiments were conducted with Titanium and its alloys, as the use of these materials was constantly increasing worldwide. The aim was to investigate what happens to the properties of the Titanium material after welding process. Some findings acquired revealed that there were no significant changes in the mechanical properties as well as the microstructure [18].

RFW was the first of the friction welding processes to be established and used commercially. Its important features are the ability to weld without any additional filler material, to weld Titanium components and to weld Titanium to other materials in a solid-state. With its ability to weld similar and dissimilar material, RFW has been regarded as robust for the generous range of parameters that gives a perfect and satisfactory weld [6, 19]. In addition, RFW is widely used in the Oil Country Tubular Goods (OCTG) industries for welding drill pipe [19].

According to AWS [21], rotary friction welding was established in 1891, when the first patent on the process was issued in America. Bevington [38], the founder of friction welding, realised an opportunity to use friction to generate heat for both forming and welding by spinning tubes and welding their ends together, in 1891 to 1893. He revealed that the importance was an ability to produce a product in a solid-state, without melting [38]. From 1920 to 1944 more patents were issued in Europe as more work was in progress. In the 1950’s the use of friction for welding came to prominence when Bishop [38] reported many applications of Russian origin [38].
Multi big companies, such as American Machine and Foundry (AMF), Caterpillar and Rockwell International, further developed rotary friction welding in USA in the early 1960’s. AMF and Caterpillar designed and produced machines to weld steering worm shafts, and to weld turbochargers and hydraulic cylinders respectively, while Rockwell International built the machine to weld spindles [5, 29]. Also, in 1960’s, the world scale revealed that the process had gained acceptability for a high number of production and its ability to join a wide range of distinct materials in like and dissimilar combinations [38]. Further to that, the process was adopted by automotive industries for the welding of front and rear shafts, axle casings and bimetallic exhaust valves, while on the electrical industries was used to weld a millions of copper and aluminium connectors [5, 29, 38].

Almost all applications that involved cylindrical or circular parts, as rotary friction welding was the primary one available, were being the easiest and cheapest to produce. In the mid 1970’s the change came when orbital and linear reciprocating motions arrived. This granted an opportunity to introduce the new type of friction welding that was used in joining non-round parts with accurate angular alignment [38]. In 1991 Wayne Thomas [17] of the TWI invented and patented friction stir welding for the welding of metal plates [17]. In 2008, AWS re-invented and formally defined rotary friction welding in the recommended practices for the welding industries [39].

2.3.3 Advantages of rotary friction welding

Rotary friction welding is economical and it is used worldwide for joining together different materials in a short period. One of its favourable features is the high quality of weld produced at a minimal cost. In addition, the weld cycle is extremely short which
makes productivity to be very attractive. This probable means that it is suitable for the mass production. Rotary friction welding process is highly notable for its ability to produce heterogeneous joints involving materials having different chemical, mechanical and thermal properties. A wide variety of materials that were previously not able to be joined using conventional or traditional welding techniques can be welded using rotary friction welding. RFW can join two dissimilar materials in a full-strength weld without sacrificing weld integrity or strength [40]. This process has been adopted by many automation industries for robot use [4].

Most manufacturing industries adopted this process for many reasons. One of them is that rotary friction welding is a self-cleaning process that reduces or eradicates the additional energy and labour costs associated with surface preparations [41]. Joint preparation is not critical as machined and hacksaw-cut surfaces are friction weldable. Moreover, because RFW is a fume free type of welding, it is a friendly joining technique to the environment. In addition, the joints of this process have reliable integrity. In other words, the final joint becomes stronger than that of the parent material [41]. RFW offers more alternatives and greater flexibility to the design engineers to create near high quality strength components instead of cast or forged parts. Other advantages are as follows [5, 29, 39]:

- The heat-affected zone (HAZ) has a fine grain hot-worked structure, not like a cast structure found with traditional welding.
- Material and machine cost savings.
- The weld is fume free, friendly to environment and minimises energy consumption and no gasses or wastes are generated.
- High production rate and extremely short welding cycle.
The joint produce is equal or stronger than parent material, with excellent fatigue resistance.

Joint is formed at a minimal cost, lighter or tubular material to expensive materials.

Saves labour, material and operations through near net size design.

Its joins highly dissimilar metal combination to optimise your product’s quality and properties.

It is more efficient than other welding technologies.

No filler or catalytic material is required for this welding.

No porosity and spatter.

Solid-state process.

Suitable for diverse quantity and has a great design flexibility.

Consistent and repetitive process of complete metal fusion.

Excellent mechanical properties, tensile and bending tests.

Joining of similar and dissimilar material with no fluxes.

Hundred percent bond of full cross-section.

2.3.4 Disadvantages of rotary friction welding

The disadvantages of rotary friction welding are that a machine of sufficient power is needed, for a short run, the process may not be economical and not every configuration is feasible. Perhaps the most obvious disadvantage is that this process is only limited to cylindrical or circular parts. Apart from being circular limited, friction rotary welding process has some costs in tooling and set-up that must be considered when calculating the cost per weld. Other disadvantages are as follows [41, 42]:

For high carbon steels it is difficult to remove flash.
> It requires heavy rigid machines due to high thrust pressure.
> It requires large axial pressure with heavy duty clamping.
> Less flexible than manual and arc processes.
> In RFW there is nothing called weld fixing, if the weld is broken it has to be done afresh.
> It requires shielding for the elimination of contaminants gases especially for materials that react with air including Titanium alloys.

2.3.5 Applications of rotary friction welding

Rotary friction welding process is especially useful for the various production industries. This process brings the balance in the production environment for higher production rate with lower labour requirement. The several dimensions that this process holds could assist hardware adjustment. Moreover, this technique is also useful for the production of relatively smaller parts. With these advantages, rotary friction welding has widened its applications in the industries [43, 44].

Rotary friction welding can be used regularly in the following industrial applications listed as follows [45]:

> Machine production and spare part industry: cogwheels, piston rods, radial pomp pistons, shaft with worm screw, crankshafts, drill bits, valves.
> Automotive industry: valves, clack valve, drive shafts, gear levers, axle fasteners, break spindles, transmission mechanisms, preheat rooms, pipe spindles, banjo axles.
> Aviation and space industry: repulsion jets, combustion chambers, spindles, turbines, rotors, pipes, fittings, flanges.
> Work set industry: spiral drills, milling cutters, borers, reamers, cutting tools.
> Electrical, electronics, and chemical industry: receiver camera for gas analysis, segregation columns for chromatograph, electrical connectors, continuous solder top, swing contacts, pipe fittings.

Many of the commercial components are candidates of rotary friction welding due to the quicker accomplishment of the weld and with the minimal clean-up. With the weld having a hundred percent full cross-section, it provides components stronger than that of traditional welds. In addition, full strength rotary welded components are applied in a wide range of aerospace applications [44]. Figure 2 - 9 shows a typical commercial use of RFW in shafts.

![Figure 2 - 9: Pump shaft [46]](image)

The agriculture components, which forms another part of commercial components, normally handle high stresses and torque from the heavy machinery components. In fact, agricultural trucking is one of the parts that exhibit lot of stresses and toque. Therefore, the components used in these operations require a weld with full strength and best mechanical properties to be able to adapt in these environments without fatigue [47].
Cylinders and valves are the main candidates for the usage of RFW process. Most Mechanical cylinders are machined and the caps are welded afterwards with this friction process. Furthermore, as it is known that hydraulic cylinder works with higher pressures and forces, therefore a full cross-section weld joint with best mechanical properties is required to overcome any thrusts produced by high-pressure fluid [48, 49].

Moreover, Rotary friction welding, as a solid-state process, has been used with success since 1960’s to join various metals that are usually considered not weldable. The products of bi-metal weldments (as seen in Figure 2 - 10), produced by RFW, ranges from vacuum and pressure systems, satellite heat pipes and pressure storage systems, cryogenic fittings and glass to metal seals [40].

![Figure 2 - 10: Bi-metal component: A) Stainless steel, B) Aluminium, C) Copper and D) Steel [28, 50]](image)

### 2.3.6 Rotary friction welding parameters

As compared to traditional welding techniques, several welding parameters are controlled in rotary friction welding. These parameters include the diameter of the material (geometry) to be welded, rotational speed of the part, friction time, forging delay time (braking), forging time, friction pressure and forging pressure. Other parameters such as geometry of parts and material properties are also important. It should be acknowledged that the selection of the best process parameters lies in the
geometry and the properties of the materials to be welded. For example, the frictional
time for aluminium will never be the same as that of steel material. Therefore, the
difference in properties plays a vital role in the selection of the correct parameters [31].

The rotational speed, friction time, friction pressure, forging pressure and time are the
process parameters that need to be taken into consideration while optimizing the
welding process. A successful welding process can occur if parameters are optimized
[44]. The lower speed of rotating part causes enormous moments and non-uniform
heating. On the other hand, lower speed minimizes formation of intermetallic
compounds. To prevent overheating in the welding region, friction pressure and friction
time have to be carefully controlled [37].

The magnitude of pressure applied in welding is very important as it controls the
temperature gradient and affects rotational torque as well as power. The geometry
and materials properties are directly proportional to the friction and forging pressures
and have a wide range. Over-applying friction pressure increases power needs
accordingly, and the increase in energy input accelerates metal displacement ratio
and reduces welding time resulting in heat band on the boundary. The variation of
pressure input can be controlled by the temperature in weldment or weld interface.
Ideal friction pressure must be applied to materials in order to get uniform deformations
and uniform plasticity throughout the interface [48].

Friction pressure has to be adequate to allow for the removal of oxides, to interrupt the
affinity between surfaces and the air, and to get uniform heating throughout the
interface. The application of forging pressure especially during the friction process
improves the welding properties. Forging pressure depends on the heat yield stress of the material [4]. The diffusion of macro particles from surfaces to surfaces occurs during forging. The maximum bonding has to occur in the beginning of forging on the surface as the permanent bonds are the lastly formed bonds. The interaction of bonding parts is very crucial and the forging pressure should not be decreased until the weld-joint heat has cooled down [44].

Friction and forging times are directly proportional to material's properties. The friction time should be sufficient in order to allow for plasticisation and the removal of residuals and particles. For a high-quality weld-joint, adequate plastic deformation has to occur. This means that the minimum friction time has to be exceeded. Low friction time results in a non-uniform heating, which results in non-joined areas at the interface as well as inadequate plastic deformation. Without any further explanation, it can be imagined that this brings a problem of a low-quality weld [4, 44, 51]. On the other hand, more than enough friction time causes rough structures, wide HAZ and TMAZ regions, overheating and material loss. Moreover, the importance of the process parameters for different materials should be taken as most important because poor mechanical properties and a poor weld-joint will result if the parameters are not controlled correctly [45].

Figure 2 - 11 shows the process parameters of rotary friction welding. At the start of the welding (part A), the stationary and rotating parts come into contact and the friction pressure is applied. At this stage impact torque and dwell time are achieved. Impact torque is the maximum torque that occurs due to the application of friction pressure
when both parts come together, while dwell time is the time it takes for the rotating part to settle around their common axis. It is also referred to as settling time [52].

![Diagram](image_url)

Figure 2 - 11 : RFW process parameters and response graph [53]

Part B is the end of friction processes and the start point of braking (Forging delay time). At this stage, the torque increases to a maximum due to the application of breaks to stop the relative motion of rotating component before forging. Part C is the end of the braking process, which is referred to as the end of forging delay time. At this point forging pressure, which is greater than friction pressure, is applied to displace the plasticised material and create a joint. The end of welding occurs after forging at part D.

The microscopic feature of the rotary friction welding is divided into four sections. The first section (outer part) is the base material, the second section (second outer part) is a heat-affected zone, the third section (inner part) is the thermo-mechanically affected zone and the last section (weld nugget) is the centre weld zone [54, 55, 56]. These regions are briefly discussed below.
2.3.7 The weld nugget (WN) in RFW

Weld nugget is a central part of the weld joint. It is a region formed after both rotating and standstill workpieces are extremely exposed in friction heat and axial pressures. The heating and cooling cycles during welding results in a formation of this zone. Complete recrystallization as well as transformation occur in this region because of elevated temperature. The microstructure of this region is very fine as compared to a parent material [57].

Weld nugget exhibit very fine equiaxed grained microstructure with transformed β grains. In most cases, the weld nugget of the friction welded Titanium has elevated micro-hardness as a result of the recrystallization that occurred and fine-grained microstructure. In summary, mechanical properties of this region are usually elevated as compared to that of the parent materials. In addition, good mechanical properties at this region are usually linked to a faster cooling rate and longer period of exposure to higher temperatures [27, 51].

2.3.8 The thermo-mechanically affected zone (TMAZ) in RFW.

The thermo-mechanically affected zone (TMAZ) occurs between the heat affected zone (HAZ) and the weld nugget (WN). In this region the grains of the original microstructure are retained, but in a deformed state. The thermo-mechanically affected zone of a rotary friction welding has a characteristic microstructure, with equiaxed grains with several reduced sizes as compared to the parent material. This zone is much wide than WN most likely due to the less rapid cooling with this region [37, 54]. The inner part of the TMAZ has many similar features to that of a weld nugget,
such as fine grain size and acicular \( \alpha \). In addition, TMAZ gets to be exposed to a temperature around \( \beta \) - transus temperature for a very short period. This prevents complete homogenisation on the microstructure and causes the partial precipitation of \( \alpha \) precipitates [55].

It is a well-known fact that the RFW process, when applied to Titanium alloys, generally produces three distinct regions, weld zone, TMAZ and HAZ. However, there are still some debates about the existence of TMAZ for Titanium alloys. da Silva [12] and Mashinini [58] obtained a weld joint of Titanium alloys with no TMAZ. However, Dalgaard [27] and Yates [37] found a narrow TMAZ in a weld joint of the friction welded Titanium alloy. The presence of TMAZ in friction welding is relatively small, but it is of great significance to clarify the microstructural evaluation. It is important to understand how the microstructure of a welded zone has transformed when compared to the parent material [59].

### 2.3.9 The heat-affected zone (HAZ) in RFW

Generally, the heat-affected zone is an area of the parent material (PM), either metal or thermoplastic, which is not plasticized and has its chemical and mechanical properties altered by high temperature (heat) exposure. This phenomenon primarily occurs during the welding process. The higher temperature from the welding and sudden cooling causes the change from the weld interface to the sensitizing temperature end in the metal [60, 57]. Both areas, HAZ and PM, can be different in size and level of strength.
The metallurgical changes that occur at the heat affect zone tends to generate stresses causing a reduction in the mechanical properties of the material. To highlight on the reduction in mechanical properties, it usually suffers from a decrease in resistance to corrosion and cracking [23]. Moreover, the change in microstructure at the HAZ usually increases the materials hardness when compared to the parent material as a result of more transformed beta boundaries. In addition, the chances that occur in or near HAZ, such as hardness, high stresses and sensitization are usually controlled by pre- and post-weld heat treatment [37].

On the other hand, the size of the HAZ is determined by several factors. The duration of welding or weld time, which is the duration at which the material is exposed to heat, is the biggest factor influencing the HAZ size. The less the weld time, the less the HAZ. Also, during welding, the faster the welding speed tends to produce smaller HAZ [60]. Figure 2 - 12 shows a typical TMAZ and HAZ on the rotary friction welded material.

![Figure 2 - 12: HAZ and TMAZ](image)

The heat-affected zone of RFW has the following typical characteristics [37, 60]:
Less extensive than traditional weld HAZ.

It has narrower width.

Usually have similar mechanical properties as the base material depending on the process temperatures, cooling rate and post weld heat treatment.

The HAZ is typically 1 mm to 3 mm in length depending on the material and diameter.

There is no surface contamination, free of voids and oxide inclusions.

### 2.3.10 The weld width in RFW.

An increase in the axially applied pressure (friction and forging) reduces the width of the heat-affected zone due to an increase in upset. This means that when the axial pressure is increased more material is pushed out in the form of a flash. However, the increase in welding speed has the opposite effect. The increase in welding speed generates more energy, which result in excessive friction heat, when the two components come into contact. This leads to a dissipation of heat through the material further increasing the width of the plasticised region and therefore increasing the weld zone size [37, 61].

On the other hand, the friction time of the rotary friction welding plays a vital role in the weld width. Longer friction time results in an increased weld width provided the axial pressure is kept constant. Due to the rotational nature and the two components coming together, the higher heat concentration is at the centre as compared to the edges of the interface. The weld of RFW welding appears as a bi-concave shape with the visibly thicker material at the edges than at the centre [37].
2.3.11 The weld void in RFW.

Some of the rotary friction weld joints exhibit voids that run along the weld. The weld defects in RFW are normally called void in friction welding, also referred to as small spaces that occur between the successive grains or particles of a microstructure, which contains no material. The usual position of the void in solid-state welding is typically from the nugget to the remainder of the thermo-mechanically affected zone (TAMZ) [62]. Figure 2 - 13 shows the typical micrograph of the friction weld obtained after etching the weld cross. The microstructure contains voids caused by lack of penetration.

![Typical voids in welding](image)

Figure 2 - 13: Typical voids in welding [62]

Insufficient rotational speed and frictional pressure prevent adequate plasticisation and proper blending. This is explained by the formation of voids in the weld. Secondly, the voids are caused by the insufficient forging pressure that results in a lack of bonding at the interface. Limiting process parameters may result in a formation of the weld joint with voids [62].

The presence of voids in a weld joint reduces the weld integrity and performance. For example, the micro-hardness and tensile strength properties of the weld joint with voids are far less than that of the perfect weld [63]. Such components with voids at the
weld joint can never be trusted for the critical applications such as hydraulic cylinder shafts [23].

2.4 Titanium and Titanium alloys

Titanium alloy is a non-ferrous material. It has outstanding properties as compared to the other alloys in the same group. It has a high corrosion resistance, low weight ratio and high strength. These properties have brought about a wide range of applications that require a high level of reliability and excellent performance in surgery and mechanics as well as in the automotive industries, chemical plants, marine, aerospace industries, and also for bio-medical body implants. In a wide range of engineering applications, Titanium alloys takes over heavier and bigger weight materials. Titanium alloys are as strong as steel alloys, yet they are about 45 percent (%) lighter in weight. Titanium and its alloys work continuously up to 600 degrees Celsius (ºC) without loss of mechanical properties [18, 64].

The availability of Titanium enables engineering designers and fabricators to use this material for critical applications. Although Titanium has acceptable mechanical properties and has been used for orthopaedic and dental implants, in most applications Titanium is alloyed with small amounts of vanadium and aluminium. In addition, producing near net shape Titanium parts has an obvious economic advantage, but on the other hand, Titanium and its alloys are not only difficult to recycle through conventional re-melting process but are also difficult to machine [18, 65].
2.4.1 Phase and structures of Titanium and Titanium alloys

The material Titanium exists in two crystallographic forms. At a room temperature, pure Titanium has a hexagonal close packed (hcp) crystal structure, which is referred to as alpha phase. At a temperature between 882 °C and 885 °C unalloyed Titanium undergoes an allotropic transformation to beta phase, which is recognised with a crystal structure of a body-centered cubic (bcc). The allotropic or phase transformation temperature is known as beta (β) – transus temperature. This transformation allows the complex variations in the microstructure and more diverse strengthening opportunities as compared to other non-ferrous alloys [12] [66].

Beta (β) – transus temperature of Titanium is defined as the minimum equilibrium temperature at which Titanium is 100 percent (%) beta. When pure Titanium is heated to a temperature of 1000 °C, it transforms to a crystal structure of 100 percent (%) beta (β). In addition, the phase transformation temperature of Titanium can be altered by the addition of alloying elements depending on the amount and type of alloy contents [66] [32]. Above all, the microstructure of pure Titanium depends upon the type of annealing and whether it has been cold-worked or not. Figure 2 - 14 shows Titanium crystallographic structures that can be obtained.

Figure 2 - 14: Typical crystallographic structures in Titanium [67].
2.4.2 Classifications of Titanium alloys

Titanium is considered to be a single alloy with very specific properties. However, the real fact is that there are various distinct forms of Titanium alloys. These forms of Titanium alloys can be widely classified depending on the alloying elements present [68]. As the alloying elements within Titanium alloy govern β - transus temperature and therefore phase transformation. Alloying elements are classified as alpha, beta and neutral stabilisers [37, 69]. These stabilizers govern alpha, beta, alpha-beta and neutral Titanium alloys. Alloying elements and Titanium alloy classifications are briefly discussed as follows.

> **α - stabilisers** : Oxygen, nitrogen, carbon and aluminium. These elements raise the temperature at which the alloy will be transformed completely to the β - phase. Oxygen and aluminium are the most commonly added elements to Titanium in order to increase its strength and quality.

> **β - stabilisers** : Molybdenum, vanadium, chromium, manganese and nickel. These elements cause a gradual decrease in the transformation temperature, which in turn results in the formation of a two-phase structure.

> **Neutral** : Silicon, tin and zirconium. These elements have a negligible effect on transformation temperature [37].

This then leads to the three typical classifications of Titanium alloys, which are as follows:
2.4.2.1 α - Titanium alloys

The α - Titanium alloys contain either α - stabilisers or both α - stabilisers and neutral alloying elements. Titanium alloys with α –stabiliser whether single or in combination have an hcp crystal structure at an ordinary temperature. The α – alloys are generally very weldable, they are non-heat treatable and they have a low to medium strength, good notch toughness, good ductility and at cryogenic temperature have outstanding properties [37] [11]. In addition, α – alloys are used for corrosion resistance applications where cost, ease of fabrication and welding are important, and the absence of ductile-brittle transformation renders α – alloys suitable for cryogenic applications [12].

2.4.2.2 β - Titanium alloys

These alloys contain a large number of transition metals, among others which can be β – stabilisers. The β – stabilisers lower the transformation temperature and stabilise β – phase [37]. β –alloys have high hardenability, excellent forgeability, good cold formability in the solution treated condition, are heat treatable, offer high strength and are generally weldable [11]. These alloys play a significant application role in both military and commercial aircrafts [70].

2.4.2.3 α + β Titanium alloys

These Titanium alloys are such that at equilibrium they support the mixture of α and β phase, usually at a room temperature. In practice α + β alloys contain mixtures of both α and β stabilizers, and they usually retain more β phase after the final heat treatment depending on the specific amount of β stabilizers present and the type of heat treatment. One example of these alloys is Ti-6Al-4V and is a very common material used in medical facilities and aerospace industries. The α + β Titanium alloys are heart
treatable to varying extents and most of them are weldable. Although most of them are weldable, they have the risk of loss of ductility in weld area [71].

Figure 2 - 15 shows the range of Titanium alloys. These Titanium alloys are classified according to their phases at room temperature, as $\alpha$, $\alpha + \beta$ and $\beta$ [27]. The division lines between the columns can be termed as the concentration of $\alpha$ and $\beta$ stabilisers. The red dotted lines represent metastatic start (Ms) and metastatic final (Mf) temperatures.

Figure 2 - 15: Titanium phase diagram [27]
2.4.3 Properties of Titanium and Titanium alloys

The following table shows the typical mechanical and physical properties of Titanium and its alloys.

Table 2 - 2: Mechanical and physical properties of Titanium and its alloys [18]

<table>
<thead>
<tr>
<th>Designation</th>
<th>Commercial Pure Titanium</th>
<th>Medium strength alloys</th>
<th>High strength alloys</th>
<th>Highest strength alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy type</td>
<td>Alpha</td>
<td>Alpha-Beta</td>
<td>Alpha-Beta</td>
<td>Beta</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>480 - 620</td>
<td>600 - 650</td>
<td>830 - 1100</td>
<td>1200 - 1500</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>20 – 25</td>
<td>15 – 20</td>
<td>8 - 15</td>
<td>6 – 12</td>
</tr>
<tr>
<td>Tensile modulus (MPa)</td>
<td>103</td>
<td>104</td>
<td>110 - 125</td>
<td>69 – 110</td>
</tr>
<tr>
<td>Torsion Modulus (MPa)</td>
<td>45</td>
<td>43</td>
<td>40 - 48</td>
<td>38 – 45</td>
</tr>
<tr>
<td>Density (kg/cm³)</td>
<td>4.51</td>
<td>4.48 – 4.51</td>
<td>4.43 – 4.60</td>
<td>4.81 – 4.93</td>
</tr>
<tr>
<td>Hardness (HV)</td>
<td>160 - 220</td>
<td>200 - 280</td>
<td>300 - 400</td>
<td>360 – 450</td>
</tr>
</tbody>
</table>

2.4.4 Ti-6Al-4V

Ti-6Al-4V, referred to by its traders as Ti-64, is one of the most popular $\alpha + \beta$ Titanium alloy used within the aerospace industry. It is the material under investigation for this work. The presence of $\alpha + \beta$ transformation means that different microstructures and property combinations can be obtained through thermos-mechanical processing. This permits the adaptation of properties to specific applications [68]. This $\alpha + \beta$ alloy has attracted a huge number of significant researchers and numerous amounts of work has been done to improve its mechanical properties through heat treatment [72]. In many occasions, Ti-6Al-4V has been used where low density and excellent strength is necessary such as bio-medical applications for implants, prostheses and orthopaedic, and aerospace industry [14].
This widely used alloy has aluminium to promote α stabilization for strengthening as well as a slight decrease in density, while vanadium raises the hot workability and heat-treating capability by stabilizing the β phase. In addition, Ti-6Al-4V is widely available in forgings, sheets, rods, tubes and as well as in castings [27].

2.3.3.1 Mechanical properties of Ti-6Al-4V

To date, Ti-6Al-4V alloy is the most used of all Ti-alloys and is characterised by an optimum combination of properties namely, high strength at low temperatures and excellent machinability, while having a large processing window [14].

2.3.3.1.1 Tensile strength

Titanium alloys, particularly Ti-6Al-4V, have the reasonably high tensile strength. At room temperature Ti-6Al-4V of density 4500 kg/m³ and Young Modulus (E) of 113.8 GPa has an Ultimate Tensile Strength (UTS) of 990 MPa, Tensile Yield Strength (TYS) of 880 MPa and it can elongate up to 16 percent (%) before fracture occurs [73, 1, 74].

2.3.3.1.2 Hardness

Hardness of the material can be represented in different measuring methods. Some researchers measure hardness in Rockwell, others in Vickers, Shore, Brinell and Knoop [75]. However, whichever hardness technique used a relationship can be drawn to determine another technique. David [1] measured the Vickers hardness of Ti-6Al-4V at a room temperature and obtained a value of 331 HV. In addition, the material's resistance to deformation depends on the Young modulus [19].
Figure 2 - 16 shows a typical friction welded Ti-6Al-4V hardness test graph, with the maximum value of hardness occurring at the weld nugget. At both ends of the graph, the hardness is almost similar which reveals the presence of the parent material.

![Figure 2 - 16: Typical Hardness test graph of friction welded Ti-6Al-4V [19]](image)

2.3.3.1.3 Microstructure

Ti-6Al-4V is widely known to be suitable for heat treatment, with numerous different microstructures attainable through distinct heat treatment processes, thus permitting the adaptation of properties to specific applications. At room temperature, Ti-6Al-4V alloy has an equiaxed microstructure. It has about 90 percent (%) α (as seen in Figure 2 - 17) and the α - phase dominates the physical and mechanical properties of this alloy [76]. The β phase can be manipulated in amount and composition through heat treatment process [77]. At a temperature of 995 degrees Celsius (°C), which is regarded as β-transus temperature, Ti-6Al-4V undergoes phase transformation (as seen in Figure 2 - 17). The alloy changes to β phase [68].
Figure 2 - 17: Volume fraction of α and β Phases Vs temperature in Ti-6Al-4V [78]

2.3.3.1.4 Summary of Ti-6Al-4V properties

Table 2 - 3 shows the manufactures specifications of Ti-6Al-4V.

Table 2 - 3: Properties of Ti-6Al-4V [73]

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, Vickers</td>
<td>340-353 HV</td>
</tr>
<tr>
<td>Tensile Strength, Ultimate</td>
<td>950-1080 MPa</td>
</tr>
<tr>
<td>Tensile Strength, Yield</td>
<td>870-980 MPa</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>12-15 %</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>113.8 GPa</td>
</tr>
<tr>
<td>Melting Point</td>
<td>1604 - 1660 °C</td>
</tr>
<tr>
<td>Solidus</td>
<td>1604 °C</td>
</tr>
<tr>
<td>Liquidus</td>
<td>1660 °C</td>
</tr>
<tr>
<td>Beta Transus</td>
<td>980-995 °C</td>
</tr>
</tbody>
</table>
2.3.3.2 Weldability of Ti-6Al-4V

Metallic structures are a common sight everywhere and anywhere. The high strength and attractive metal structures camouflage the reason behind their existence for welding. The welding process has played a vital role in these products for many years than one can ever imagine. Perhaps welding is a method of repairing or creating metal structures by joining numerous pieces of metals through fusion or solid-state welding techniques. Generally, for these techniques heat is used to join or weld the materials [16].

Since Ti-6Al-4V is the most used Titanium alloy with excellent corrosion resistance, high specific tensile strength and good workability, it can be fusion welded or can be joined by any form of solid-state welding process. However, as far as it can be welded by any form of welding technique, there are number of challenges that need special attention when it comes to its weldability. During the welding process, Ti-6Al-4V is heated. As a result, it easily reacts with the environment, hence absorbing oxygen and nitrogen in the air. This results in oxidation and embrittlement that eventually deteriorates the weld joint mechanical properties [18], [16]. Moreover, during welding Ti-6Al-4V is exposed to the air, hence it is necessary to provide sufficient shielding with argon or helium gas to eliminate embrittlement and minimise oxidation [18].

Welds in Ti-6Al-4V are immune to many of the cracking problems that cause a big mountain to climb for alloy fabrications. Because of these challenges, some engineers believe that Ti-6Al-4V is still hard to weld, also taking into consideration the requirements that need to be adhered to, such as special handling and gas shielding. When reflecting on the fusion of Ti-6Al-4V, embrittlement through contamination with
air and carbonaceous materials pose a big challenge to the successful completion of the weld, so requiring weldments to be cleaned and covered with inert gas [32].

In most cases, it is hard to obtain a weld with the best mechanical properties through fusion welding processes. Indeed, fusion welding is the most challenging welding technique in the joining of Ti-6Al-4V when compared to the solid-state welding. For example, fusion welding requires the interface to be clean prior to the welding while solid-state welding, such as RFW, does not because it is a self-cleaning welding method. In fact, most fabricators in various industries prefer solid-state welding process due to it being a melt free welding, short production time and ability to weld dissimilar material [19].

2.3.3.3 Ti-6Al-4V and RFW
Friction welding has been a challenging type of welding. The challenge lies in choosing the correct parameters for each type of material to be welded. Commonly, it becomes more difficult to choose parameters to favour both materials if joining of distinct materials has to be conducted. Munchen [2] introduced a friction coefficient that changes together with the rotational speed and pressure. This was done in order to calculate and estimate the feed rate that is required for superb welding. It has been suggested that the correct design of a manufacturing process with a significant role of friction, like friction welding requires one to determine the friction characteristics of the material used in the given conditions [2].

Ghent [34] determined the distributions of temperature and deformations in the friction welding process of Titanium alloys in the developed model of inertia welding of two
similar specimens. The researcher revealed that in the existence of intermetallic phase, welding of non-ferrous metals is very difficult. However, a continuous drive friction welding method can fittingly be approved for the welding of dissimilar ferrous and non-ferrous materials. Seshagirirao et al. [79] examined that the friction welding process was very proficient in the welding of the different materials such as aluminium and stainless steel. This was shown by the results of tension mechanical tests that presented mechanical properties which are not possible to achieve by means of conventional welding processes [79].

Morton [80] reviewed the comparison of solid-state welding to fusion welding processes. The continuous drive friction welding shows high material saving, low producing time, high quality, high efficiency and high reliability characteristics [80]. Experiments have been conducted on similar and dissimilar materials and the same results were obtained. Several trials were carried out to perform different types of welding on lathe machine including rotary friction welding. However, with proper attachments rotary friction welding can be performed on lathe machine without any aggravations. Rotary friction welding experimentation was carried out on three combination sets of specimen materials of diameters 10 mm and 12 mm respectively at four variable speeds. The temperature was measured with the help of Laser or Infrared pyrometer [80].

Alves et al. [52] conducted several studies concerning the joining of dissimilar materials and wrote articles on the mechanical properties, metallurgical and thermal effects of the welded parts using RFW. In this study, a Thermocouple Data Logger for monitoring the temperature in the bonding interface in time operation of dissimilar materials was
used. Through this system, it was possible to monitor, determine the beginning and the end of each stage of welding, to analyse the different heating and cooling rates, and characterize all stages of the process through time versus temperature curves in real time [52].

Bohme et al. [31] conducted an experiment to join Ti-6Al-4V tubes of diameter 50 mm and thickness of 10 mm with continuous drive friction welding. He conducted three experiments with different friction times. All experiments were carried out without the shielding gas. The parameters used were friction speed of 2500 RPM, friction pressure of 40 MPa, friction times of 1 s, 1.35 s and 1.5 s, forge time of 0.4 s and, Forge pressure of 50 MPa. Tensile tests were carried out on the tubes with wall segment of 10 mm thickness, 7 mm cross section and 40 mm length. The average tensile strength obtained ranged from 1020 MPa to 1026 MPa. Hardness ranged from 310 HV to 330 HV from the base material with 385 HV obtained at the weld nugget [31]. The microstructure of the alloy, as-received base material, revealed rounded Alpha-mixed crystals and some lamellar-type alpha. In the area of the heat-affected zone (HAZ), the microstructure consisted of pure, elongated equiaxed alpha accompanied by low beta portions. In addition, there is a decrement in the size of the grains when moving from the parent material to the weld center [31].

Tolvanen [32] conducted an experiment to investigate the microstructure and mechanical properties of Ti-6Al-4V welds produced with different welding processes. The researcher revealed that the microstructure formed in high-energy intensity processes, such as RFW process, have typically higher hardness and strength than the welds produced by conventional welding processes. With the RFW processes, the
tensile strength obtained was from 925 MPa to 1060 MPa, tensile elongation of 6 percent (%) and the hardness of 390 HV occurring at the center of the weld-joint. The fine lamellar microstructure was formed at the weld region, thermo-mechanically affected zone (TMAZ) and at the heat-affected zone (HAZ), with the grain size decreasing from the heat-affected zone to the welded zone. The hardness increases from the HAZ to the weld nugget when compared to the parent material due to the reduction in grain size as it appears in the microstructure [32].

Dippenaar et al [72] also conducted an experiment to reveal the effect of microstructural morphology on the mechanical properties of Titanium alloy. The experiment was conducted with the Ti-6Al-4V rods with a diameter of 12.7 mm. The results revealed that the microstructure sample consisted of α grains within the prior course β grains. On some selected β grain boundaries α plate nucleated and grow towards β grains interior. Also, a thin layer of α was observed in some regions of prior β grains boundaries. Perhaps different forms of microstructure are achieved based on the type of heat treatment used [72].

Wisbey et al [81] obtained the tensile strength of 1030 MPa, ductility of 15 percent (%) and a hardness of 390 HV after conducting an experiment on a 60 mm diameter cylinder with 20 mm wall thickness, using the process parameters of 900 RPM rotational speed and 1000 kN maximum welding force. The weld microstructure after the alloy treatment and over ageing heat treatment showed coarser alpha laths throughout the prior beta grains and again with grain boundary alpha present. The resulting high impact toughness after the heat treatment was associated with the relatively coarse Alpha laths present, giving a tortuous crack path [81].
Dalaard [27] conducted an investigation to determine the evolution of microstructure, micro-texture and mechanical properties in friction welded Titanium alloys. One of the alloys used in this investigation for experiment was Ti-6Al-4V of 26 mm in diameter, and the process parameters were 50 kN of frictional force, 60 kN of forging force and 3.6 seconds of welding time. A micro hardness of 400 HV and the ultimate tensile strength of 1004 MPa were respectively obtained after testing. The microstructure obtained consisted of acicular alpha grains surrounded by grain boundary beta [27].

Threadgill [19] welded Ti-6Al-4V pipes of diameters 246 mm and 584 mm with wall thicknesses of 14 mm and 4.75 mm respectively. Both experiments were conducted with continuous drive friction welding and inertia friction welding without any shielding gas. Typical conditions used were 1500 RPM rotation speed, with a force of 222 kN. The ultimate tensile strength for both experiments average between 1028 MPa to 1034 MPa. The microstructure obtained was reported to have completely recrystallized at the area of the weld and close to the bond line, and to consist of fine equiaxed grains showing the typical Widmanstatten transformation or Thomson structures products. It also reveals the clear evidence for beta grain growth just outside this area, together with indications of the intense plastic deformation [19]. Figure 2 - 18 show a microstructure of rotary friction welded Ti-6Al-4V.

Figure 2 - 18: A- weld center, B- heat-affected zone [19]
2.5 Summary

Rotary friction welding is a solid-state consolidation process that is limited to cylindrical shaped materials. The process is controlled by various process parameters that work together to produce a successful weld joint. Such parameters include rotational speed, axial pressure, upset distance and welding time. The selection of process parameters is based on the material properties as well as the geometry of the workpieces to be bonded.

The process is suitable for welding different materials without complications and produces weld joint with four regions. Most industries as well as fabricators have adopted this type of welding because of its ability to produce high strength weld joints with properties that are similar to the parent material. It is regarded as a best welding technique because materials that are difficult to weld such as Ti-Alloys can be welded, without the use of any filler material.

As the usage of Ti-6Al-4V has grown worldwide, the conventional welding processes show difficulties in joining this material. RFW has therefore been the best Ti-6Al-4V joining technique. From the literature review, successful welds have been reported in various sizes of Ti-6Al-4V alloys for different industrial applications. In addition, different microstructures have been used to distinguish various regions of Ti-6Al-4V weld joint produced for the RFW process.
Chapter 3: Methodology and set-up

3.1 Introduction

This Chapter focuses on the methodology used for the RFW experiments and analysis process. At first, the Chapter discusses the platform used for the preliminary and final welding experiments. The Chapter also discusses the selection of process parameters as well as the analysis of the preliminary welds to identify the defects, weld geometry distortion and flash amount.

3.2 Research platform

3.2.1 RFW platform

The platform used for this research work is illustrated in Figure 3 - 1. The platform is a process development system for friction welding. It was designed and developed by Nelson Mandela University in Port Elizabeth South Africa to facilitate the friction welding process and development for research purposes and production.

![Figure 3 - 1: Rotary Friction welding Platform](image-url)
The welding platform is a fully automatic machine with a computer interface, allowing for the entering of process parameters and data collection. With this unique welding platform, perfect weld joints were achieved through the engagement and collaboration of different process parameters. Such parameters include rotational speed (N), axial pressures (friction (Pr) and forging (Pf)), Heating time (tH), forging time (tf) and upsetting (S). In addition, the platform is capable of welding high temperature materials.

Both stationary and rotating fixtures (as seen in Figure 3 - 1) were designed to hold workpieces securely in a vertical position. This also minimised misalignment between both joining parts. The blue tubes connected to the shielding glass supply shielding gas that prevents oxidation during welding. The collets in both fixtures have gap screws that assist with holding the workpieces tightly during welding process.

### 3.2.2 Platform control

The control of the platform is carried out by a computer interface, which allows the switch between different process parameters to perfect welding process. The welding platform operation is in 4-axis. The machine operates in X-, Y-, Z- and the pitch axis (as shown in Figure 3 - 2 and Figure 3 - 3 ). The stationary fixture’s movement is in X-, and Y- directions while the rotating fixture moves in a Z- direction. During welding process, axial pressures (friction and forging) are applied in a Z- direction by a hydraulic cylinder mounted vertically downwards. Figure 3 - 2 and Figure 3 - 3 shows the entire operating axis.
Figure 3 - 2: RFW operation axes

Figure 3 - 3: Operation axes for RFW (PDS) machine
3.2.3 Platform specifications

Precision in rotary friction welding is very important. Accurate results are obtained from accurate RFW platform. The calibration of the equipment was performed before the start of the welding process with the computer interface followed by physical check-ups. This was done to check the alignment and concentricity of both stationary and rotating workpiece holders (collets). After both workpieces have been mounted, the uniformity of rotation was checked. This was done to ensure that there was no wobbling that could affect the weld quality and possibly cause deformation on the workpieces [58]. Table 3 - 1 shows additional specifications of PDS equipment.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Travel range</th>
<th>Drive</th>
<th>Load output</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>600 [mm]</td>
<td>Automated</td>
<td>40 [kN]</td>
</tr>
<tr>
<td>Y</td>
<td>300 [mm]</td>
<td>Automated</td>
<td>40 [kN]</td>
</tr>
<tr>
<td>Z</td>
<td>200 [mm]</td>
<td>Automated</td>
<td>100 [kN]</td>
</tr>
<tr>
<td></td>
<td>500 [mm]</td>
<td>Manual</td>
<td>n/a</td>
</tr>
<tr>
<td>Tz</td>
<td>Spindle torque</td>
<td>Automated</td>
<td>200 [Nm]</td>
</tr>
<tr>
<td>Nz</td>
<td>Spindle speed</td>
<td>Automated</td>
<td>10000 [RPM]</td>
</tr>
</tbody>
</table>

3.2.4 Workpiece holder (collet)

The holder mechanism (collet) of the RFW platform consist of a gap screw, which helps in holding the workpieces tight in a vertical direction and concentrically to another workpiece. The gap screw also ensures that workpieces do not experience
slippage during welding. For a high strength grab, workpieces ware design with a flat surface to provide a full contact area to the screw.

### 3.2.5 Shielding mechanism

It was highlighted previously in Chapter 1 that Ti-6Al-4V alloy begins to react with environment at a temperature of 550 °C to 610 °C, therefore it is of vital importance, when joining Titanium alloys, to protect the weld interface from oxidation. Figure 3 - 4 demonstrates the shielding mechanism on the friction wielding process of Ti-6Al-4V. The oxidation of material is a big concern during welding as it affects the colour of a weld joint and reduces its quality.

![RFW shielding mechanism](image)

Ti-6Al-4V welds were protected with argon shielding gas to prevent oxidation. Argon gas was supplied through tubes to a shielding glass (as show in Figure 3 - 4). The glass was used to trap shielding gas around the weld interface. The supply of the gas commenced few minutes prior to the welding process to prevent any further discolouration of the weld joint.
The shielding mechanism was designed to accommodate workpieces of up to 200 mm in diameter. In most cases, the weld interface was aligned with the bottom half of the shielding glass. With the welding process producing toxic gases, the top section of the glass was left open to allow these gases to escape. Generally, shielding gas remained at the bottom half of the glass, as it has larger specific gravity (density) than air, pressurising gases from welding to escape [58].

3.3 Weld preparation

3.3.1 Rotary friction welding studs’ configuration

Figure 3 - 5 illustrates the stud configuration used for the preliminary welds. All dimensions were developed based on the specifications of the RFW platform and from the ASTM standard of testing. Both stationary and rotating workpieces have the same geometry of 20 mm, 25 mm and 16 mm diameters, with the lengths of 30 mm, 35 mm and 30 mm respectively. The upper section of the stud (20 mm diameter section) had a 12 mm width of flat cut for a length of 30 mm. The flat cut provided a contact area to the gap screw to hold the stud standstill against the holder during welding process.
3.3.2 Rotary friction welding process parameters

The development of rotary friction welding process has been conducted several times by means of testing a selection of appropriate process parameters for producing an acceptable Titanium weld joint. In this project investigation, process parameters have been evaluated by viewing the definition of parametric field leading to a satisfactory weld joint. At first, the weld joint was evaluated by visual examination and the microstructure analysis. An updated process matrix was compounded and further evaluated for rotary friction welding process. The process matrix evaluation was
conducted based on the recommended standard set by American Welding Society (AWS) [9].

Table 3 - 2 Illustrates RFW process matrix that was used for the preliminary welds. The matrix was developed based on the literature and from the recommended friction welding standard set by AWS [9]. The rotational speed, friction pressure and forging pressure were varied in order to check the behaviour and response of material over different process parameters and welding conditions. The preliminary welds were conducted with the same upset distance. Other process parameters such as forging and heating times we kept constant.

<table>
<thead>
<tr>
<th>Weld Number</th>
<th>Rotational speed [N] (RPM)</th>
<th>Friction Pressure (MPa)</th>
<th>Forging Pressure (MPa)</th>
<th>Forging time (s)</th>
<th>Upset distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFW1</td>
<td>1600</td>
<td>25</td>
<td>60</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>RFW2</td>
<td>1900</td>
<td>30</td>
<td>60</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>RFW3</td>
<td>2300</td>
<td>60</td>
<td>109</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>RFW4</td>
<td>2700</td>
<td>60</td>
<td>109</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>RFW5</td>
<td>2700</td>
<td>85</td>
<td>140</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>RFW6</td>
<td>2700</td>
<td>85</td>
<td>140</td>
<td>25</td>
<td>2</td>
</tr>
</tbody>
</table>

The physical evaluation and microstructure analysis of the joints were done in all welded specimens. RFW1 to RFW3 were chosen for further investigation for mechanical and metallurgical evaluation, with the process pressure and rotational speed kept within the recommended standard for friction welding of Titanium alloys. During the evaluation of welded specimens for preliminary matrix, the factors/features that were discovered were lack of bonding, weld distortion (component deformation),
formation and amount of flash, presence of contaminations and incomplete welding. Figure 3 - 6 illustrate the procedure followed for the analysis of the welds produced from preliminary welding matrix.

![Figure 3-6: Flowchart showing the procedure followed for the analysis of preliminary welding matrix](image)

The weld samples selected for further investigation after preliminary welding analysis were RFW1 to RFW3 from Table 3 - 2. In the final welding attempts, friction pressure was maintained within the optimum axial pressures for FW of Titanium alloys. Upset distance, forging time and forging pressure were kept constant. Table 3 - 3 shows the process matrix for the final welds investigation.
Table 3 - 3: Final welding process parameter matrix of the RFW welding process

<table>
<thead>
<tr>
<th>Weld Number</th>
<th>Rotational speed [N] (RPM)</th>
<th>Friction Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFW1</td>
<td>1600</td>
<td>40</td>
</tr>
<tr>
<td>RFW2</td>
<td>1900</td>
<td>40</td>
</tr>
<tr>
<td>RFW3</td>
<td>2300</td>
<td>40</td>
</tr>
<tr>
<td>RFW4</td>
<td>1600</td>
<td>60</td>
</tr>
<tr>
<td>RFW5</td>
<td>1900</td>
<td>60</td>
</tr>
<tr>
<td>RFW6</td>
<td>2300</td>
<td>60</td>
</tr>
</tbody>
</table>

All welds of final process parameter matrix were conducted with a welding time of 45 seconds, upset distance of 2 mm and forging pressure of 95 MPa. Figure 3 - 7 demonstrates the procedure used to conduct the evaluation and analysis of final welds. The addition of mechanical evaluation (tensile and hardness tests) makes this procedure distinct from the procedure used to examine preliminary welds.

![Flowchart showing the procedure followed to analyse final welds](figure37.png)

**Figure 3 - 7:** Flowchart showing the procedure followed to analyse final welds
3.3.3 Rotary welding stud modification

Figure 3 - 8 illustrates the stud configuration used for the final welds. Both (stationary and rotating) studs have same dimensions of 20 mm, 22 mm and 12.5 mm diameters, with the lengths of 30.5 mm and 5 mm and 38.5 mm respectively to the diameters. The upper part of the stud (20 mm diameter) has a 12 mm flat cut for 30 mm length.

The configuration of preliminary welds studs was modified for the final welding process, as shown in Figure 3 - 8. This modification was performed after a careful consideration of the effect caused by post machining. This therefore eliminated heat stresses caused by machining, which may have influenced the mechanical evaluation and metallurgical analysis of the specimen.

![Figure 3 - 8: RFW stud's configuration for final welds (all dimension in millimetres)](image-url)
3.4 Material Characteristics

Apart from metallurgical evaluation, mechanical analysis was conducted in the friction welded joints as well as in the parent material in order to determine the mechanical properties and relate them to the metallurgical feature of the weld joint. Different mechanical testing methods were performed to study the mechanical properties of the weldment and parent material. Such mechanical testing methods were performed at laboratory temperature and they include micro-hardness and tensile testing. These methods are discussed in the next sections.

3.4.1 Tensile testing

Standard tensile test specimens were precision prepared from the friction welded material as well as from the parent material. As it has been mentioned previously in this Chapter, the configuration of the studs was designed to attain the geometry of the standard tensile test specimen after being friction welded.

The tensile testing process was carried out in the laboratory at room temperature and the equipment utilised for tensile testing was Zwick/Roell Z250 tensile testing machine, with the load capacity of 250 kN. Tensile test specimens were tested and the data was collected via the computer interface connected to the testing platform. All tensile tests were performed according to the ASTM E8/E8M-13a testing standard. Figure 3 - 9 shows the standard tensile test specimen configuration.
Another set of tensile tests were performed on the parent material to determine the variation of mechanical properties from the Ti-6Al-4V specifications provided by the supplier. Tests were done with four tensile test specimens that were prepared from the parent material. The test results are shown in Table 3-4 below with the ranges of Ti-6Al-4V mechanical specifications.

Table 3-4: Manufacturers specifications VS Tensile test performed

<table>
<thead>
<tr>
<th>Data</th>
<th>Ultimate Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V specification by manufacturer</td>
<td>960 - 1100</td>
</tr>
<tr>
<td>Ti-6Al-4V tests</td>
<td>995 ± 40</td>
</tr>
</tbody>
</table>

3.4.2 Micro-hardness test

The conventional Vickers micro-hardness measurement was used to perform micro-hardness test across the weld joint at some specific locations, following the hardness test standard ASTM E 92. The platform used for this type of testing is Time Vickers Micro-Hardness Tester with a self-screen displacement. The hardness was measured across the weld joint to identify the hardness of the material at different locations.

The micro-hardness test samples were cut and prepared from the friction welded specimen across the weld, with the weld joint located at the centre of the test sample.
The test samples were hot mounted, grounded and polished according to the standard practice for microstructure and hardness testing. The indentations were taken throughout the sample with the spacing of 0.5 mm to provide accurate profile hardness measurements across the weld over a long range. The load used for indents was 300 gf.

### 3.4.3 Percentage elongation

The percentage elongation of the tensile test specimen was determined. The initial and the final lengths of the specimen were measured before and after the tensile test process was carried out respectively. The percentage elongation of the Ti-6Al-4V was calculated using Equation 1 and the result are presented on Table 3 - 5 In comparison to the manufacturer's specification.

\[
\%E = \frac{\Delta L}{L_i} \times 100 \%
\]

Eq. 1

Where:

- \(\%E\) : Percent elongation
- \(\Delta L\) : Change in length \((L_f - L_i)\)
- \(L_i\) : Original length
- \(L_f\) : Final length

<table>
<thead>
<tr>
<th>Data</th>
<th>% Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V specification by manufacturer</td>
<td>8 - 17</td>
</tr>
<tr>
<td>Ti-6Al-4V tests</td>
<td>13.5 ± 1.5</td>
</tr>
</tbody>
</table>
3.4.4 Microstructure

The microstructure analysis of Ti-6Al-4V was performed across the weld, from the parent material to the weld nugget (WN), to evaluate the variation in the micrograph of different regions of the weld joint.

A sample of material was cut from each welded specimen with the weld joint accumulating the center of the sample. All samples were prepared according to the standard for preparation of metallographic specimens ASTM E3-01 and were evaluated using an optical microscope.

Samples were hot mounted in a PolyFast resin using Struers CitoPress-1 mounting machine. They were then wet ground with progressively finer grades of silicon carbide impregnated emery paper using copious amount of water to both cool and lubricate, and polished with DiaPro Allogro diamond paste and Colloidal silica with grain sizes of 9 micrometers and 0.04 micrometer respectively. The equipment used was Stuers LeboPol-25 polishing machine. All polished samples were etched with Kroll’s reagent (100ml water, 6 ml Nitric acid and 3 ml hydrofluoric acid) for a period of 30 seconds. Etched samples were evaluated for microstructural analysis at 100X magnification using OLYMPUS SZX16 optical microscope.

3.5 Preliminary welding Analyses

3.5.1 General process analyses

Figure 3 - 10 and Figure 3 - 11 illustrate rotary friction welding process graphs obtained at different rotational speeds and pressures. The graphs present different process
parameters and response against welding time. The welding time as well as the upset distance were kept constant for the preliminary welding process.

Figure 3 - 10: RFW response graph 1

Figure 3 - 11: RFW response graph 2
The general observation on the graphs revealed that the period of friction was less when compared to the forging period. This affected the shape of the graphs negatively as they reveal noticeable differences from the typical continuous-drive friction welding graph (as seen in Figure 2 - 11). This effect may be linked to a poor selection of process parameters, specifically rotational speed and axial pressures. Yates [37] revealed that axial pressures (friction and forging) have a significant effect on the feedback curves. Higher axial pressures significantly reduce heating time resulting in an improper torque curve [37, 13]. As a result, it is impossible to identify the positions of peak and equilibrium torques.

On the other hand, the rate at with the process reached the pre-set friction and forging pressures had a significant role in determining the pressure-curve. If this rate is kept constant even when the friction and pressures are increased, pressure-curve without constant heating result (as seen in Figure 3 - 11). Further clarity was given by AWS [9] that the rate at which the process reaches the pre-set friction pressure and/ or forging pressure depends upon the axially applied pressures as well as the length of the welding [9]. The increase in pressure increases the ramp rate. This indicated a direct proportionality between the ramp rate and axial pressure.

Furthermore, the minimum period of heating stage strongly alarms the negative impact on the integrity of the weld joint. Uzkut et al [82] reported that the FW process with minimum friction time (as seen in Figure 3 - 11) might result in a production of weld joint with unjointed sections [82]. This may be due to insufficient plasticisation at the interface because of a shorter heating time. The friction stage in RFW process ensures full plasticity at the interface before forging. This is achieved by having a constant
shearing at a constant frictional pressure raising the interface temperature to be about but less than the melting temperature of the material. In addition, minimum heating stage may reduce mechanical properties of the weld joint. According to Vill [25] as well as Kahl [83], the presence of unjointed sections reduces the mechanical strength of the weld and strongly reduces the percentage elongation value, the micro-hardness is reduced as well [25, 83].

Moreover, the least friction stage the torque-curve differs to that of typical RFW process. However, the initial contact and braking peaks are recognisable in both Figure 3 - 10 and Figure 3 - 11, but there is no visible equilibrium region between the initial phase and braking stage. This may be attributed to the absence or minimum constant heating that promotes equilibrium on the feedback torque. According to AWS [13, 21], equilibrium torque feedback is achieved with a constant heat [13, 21]. This occurs between the initial contact and braking stage.

3.5.2 Visual Examination

3.5.2.1 Distortion and Flash amount

Preliminary welds examination revealed signs of visible physical deformation and torsional effect on specimens at 85 MPa friction pressure. Torsional effect can be linked to the elevated friction coefficient at the interface that prevents rotation resulting in twisting. Physical deformation may be attributed to the larger forging pressure.

In friction welding, process parameters are the significant and sensible inputs that determine the end quality of a successful weld joint. The physical character of the welded specimen depends on the process parameter matrix selected for that particular
welding process. Rotational speed, heating time as well as axial pressures (friction and forging) are the sensible process parameters that determine the physical character of the welded specimen [31, 52].

An increase in rotational speed prolonged heating time, which promoted the heat propagation rate on the workpieces in an axial direction. Larger volume of material was affected by heat resulting in a reduction of torsional stiffness. Visible twisted material on the welded specimen was observed. However, in most cases this type of deformation was clearly visible on the optical microscope, during microstructure analysis.

Moreover, the amount of flash depended on the process parameters utilised. Generally, the flash amount increases with an increase in rotational speed and decreases with an increase in frictional pressure [26]. However, since the upset distance was selected as the primary process parameter over welding time, there was no change in the flash amount irrespective of the change in rotational speed and axial pressure (as seen in Figure 3 - 12). On the other hand, flash formation rate was observed to decrease with an increase in rotational speed or decrease in axial pressure. The amount of flash is basically controlled by two significant process parameter, namely rotational speed as well as axial pressure. Yates [37] said this was only true when heating time was selected as the primary process parameter over upset distance. Such cases are common during welding of metals with rough surfaces. Figure 3 - 12 shows the amount of flash obtained at different rotational speeds.
3.5.3 Microstructure evaluation

3.5.3.1 Weld defects and weld Geometry

Rotary friction welding is one type of friction welding with less defects as compared to other types of welding processes. In RFW process, common weld defects include presence of voids and lack of bonding. These weld defects occur due to the poor selection of process parameters based on the material properties as well as workpiece geometry. Figure 3 - 13 shows two microstructures of the weld joints produced from 25 MPa and 60 MPa axial pressures.

The preliminary welds analysis revealed the presence of voids and lack of bonding in some regions on the weld joint produced at 25 MPa axial pressure (as seen in Figure 3 - 13 A). This may be attributed to insufficient plasticisation at the interface because of low friction pressure to generate adequate heat at a pre-set rotational speed. This may also be linked to inadequate shielding resulting in oxidation and further discolouration at the weld joint, as seen from Figure 3 - 12 B to Figure 3 - 12 D. On the other hand, a solid weld joint without defects was achieved with an axial pressure of 60 MPa, as seen in Figure 3 - 12 A and Figure 3 - 13 B.
In general, voids in RFW originate from surface contamination as well as oxidation during welding. Usually, absorption of contaminants gases (oxygen, hydrogen and nitrogen) during welding, which when released during solidification become trapped in the weld material, causing voids. These gases strengthen the Titanium alloy, but small amounts also impair ductility and hardness of weld joint [64]. This is the result of poor shielding and insufficient axial pressures during heating and consolidation phases [84].

The unjointed sections occur mainly because of insufficient plasticisation and forging. Forging together workpieces before fully plasticity results in a production of a weld joint with unbonded sections due to a low temperature segregation. This originates from insufficient heating time, low axial pressure as well as high rotational speed. In most cases, unjointed regions are mostly observed towards the center of the welded specimen due to a low shearing velocity at this region.

![Figure 3 - 13: Optical micrograph showing microstructures of welds at A) 25 MPa B) 60 MPa axial pressure](image-url)
Figure 3 - 14 shows microstructures of weld zones obtained at different welding speeds. A) and B) at 1900 RPM, C) and D) at 2300 RPM, and E) and F) at 2700 RPM. The corresponding axial pressures are 60 MPa, 109 MPa and 140 MPa respectively. At these weld joints, the analyse revealed no signs of weld defects. The resultant microstructures at the WN are similar to the microstructures obtained by Threadgill [19] when he welded Ti-6Al-4V pipes of diameters 246 mm and 584 mm with wall thicknesses of 14 mm and 4.75 mm respectively [19].

![Optical micrographs showing microstructure of welds at different speeds](image)

**Figure 3 - 14**: Optical micrograph showing microstructure of welds at different speeds

The geometry of the weld joint is shown in Figure 3 - 15. It was observed that the RFW process produces a bi-concave weld geometry. This is caused by the variation in peripheral speed and heating density along the weld interface of the workpieces [27]. The heating density is higher at the center of the interface and progressively
reduces towards the edges of the interface as said by Vill [25] and Yates [37]. Peripheral velocity increase with an increase in diameter. Heating density is inversely proportional to peripheral velocity and heating rate. An increase in heating density results in a decrease in shearing effect and heating rate. In addition, heating rate and shearing effect increase with an increase in the weld interface diameter.

Figure 3 - 15 A shows the weld joint produced at a higher speed while Figure 3 - 15 B illustrates the weld joint produced at a lower speed. It was seen that the weld zone A is wider than weld zone B. This may be due to a low heating rate at higher rotational speed resulting in a larger volume of material affected by heat because of the heat propagation rate. This resulted in a wider weld joint.

![Figure 3 - 15 : RFW weld geometry](image-url)
3.6 Summary

The RFW process was conducted with two sets of workpiece configurations. The preliminary welds workpiece configuration was modified for the final welding process due to machining that had to be performed on the specimen after welding. The preliminary welded specimens, which were welded at various rotational speeds and pressures, were visually examined for the amount of flash and distortion, as well as the microstructure analyses for the weld defects and geometry. The microstructure analysis was done using an optical microscope.

The visual examination of the welds revealed that the amount of flash was controlled by the amount of rotational speed. The probability of visible physical torsion effect depended on the amount of axial pressure applied as well as rotational speed. The analysis of the welds revealed that the volume of flash was applicable if the heating time was selected as the primary process parameter over upset distance. Additionally, Microstructure analysis revealed that weld joints of Ti-6Al-4V produced from lower axial pressure has weld defects. Such weld defects were voids and unjointed regions. The analysis also revealed that regions with lack of bonding were towards the center of the weld interface.
Chapter 4: Results and Discussion

4.1 Introduction

This Chapter focuses on the analysis and interpretation of final welding process results. The RFW process cycle obtained at a rotational speed of 1600 RPM and friction pressure of 40 MPa is discussed in details. Different weld regions obtained as a result of variation in microstructure are also discussed. Mechanical properties of weld joint in relation to microstructures obtained are also discussed. Finally, the influence of the process parameters on the weld joint properties is also highlighted in this Chapter.

4.2 Results and discussions

4.2.1 Analysis of RFW process

Figure 4 - 1 illustrates the rotary friction welding process cycle of Ti-6Al-4V that was recorded at a rotational speed of 1600 RPM. Other process cycles are shown in the Appendices. The different process parameters used as well as the responses are graphically represented against the welding time. The graph reveals significant similarities with an established rotary friction welding cycle as well as the process cycles obtained by Palanival et al [30] and da Silva [12] on the continuous-drive friction welding of Titanium alloys. The process is made out of three (3) stages (as clearly marked with the letters in Figure 4 - 1) and these stages are friction stage [A], braking stage [B] and forging stage [C]. Friction stage is divided into Initial phase and constant heating phase.
The pre-determined value of friction pressure (40 MPa) as well as rotational speed (1600 RPM) were reached during the initial phase of the friction stage. These values were reached through a constant increment known as the ramp rate. At this phase, the initial contact of both stationary and gyrating workpieces causes a feedback torque to increase, and reach its first peak value when the pre-set friction pressure is reached. This is attributed to a higher friction coefficient because of the low temperature on both joining surfaces. As the interface temperature elevated though the progress of the constant heating phase, the coefficient of friction decreased causing a drop in torque to some value. The temperature rate at the interface is inversely proportional to the coefficient of friction and rotational speed. This was backed up by Dalgaard [27] on the LFW of Titanium alloys.

Figure 4 - 1: RFW process cycle 1 [A - friction stage, B - Braking stage and C – Forging stage]
The feedback torque dropped further to some extent value that was considered as an equilibrium torque value as the heating stage progressed further. This may be correlated to a high temperature being reached at the interface causing a further decrease in the wear rate and friction coefficient. This may also be linked to the interface material getting softer and pushed out because of frictional heat and pressure. The torque continued to oscillate along its equilibrium value and suddenly increased at a minimum gradient through the remainder of the constant heating stage. This was due to the self-cooling process of Ti-6Al-4V. In addition, there is a noticeable axial shortening at this stage (as seen in Figure 4 - 1) as a result of the friction pressure pushing the soft material out.

At the braking stage, the drive motor was dis-engaged and application of breaks commenced. This was done to stop the relative motion before the consolidation. At this stage, the feedback torque increased and reached its second peak value and this was the maximum torque of the welding cycle. This was caused by an increase in rotation resistance. Additionally, an increase in axial pressure to the pre-determined forging pressure of 95 MPa resulted in a rapid increase in axial shortening. This was achieved by pushing more soft material out in the form of a flash.

The braking stage was followed by the forging stage. In this stage, a forging pressure of 95 MPa was applied to the stationary workpieces with soft interface material. This resulted in a further increase of upsetting to a pre-set value of 2 mm. Forging pressure was maintained at a pre-determined value for a period of 20 seconds to allow consolidation and self-cooling of material affected by the frictional heat. At the end of the stage, forging pressure was quickly removed and Ti-6Al-4V weld joint was formed.
4.2.2 Microstructure analyses

4.2.2.1 Parent material analysis

The microstructure of a material is a significant aspect that determines its mechanical behaviour in various applications. Such mechanical behaviour includes tensile strength and micro-hardness. The microstructure of Ti-6Al-4V samples, cut from parent material, revealed a bi-modal microstructure. The alpha phase grains (light) were interspersed in a matrix of a transformed beta (dark) (as seen in Figure 4 - 2). In some regions, there is secondary alpha (coarse acicular alpha) within the transformed beta matrix.

![Equiaxed Alpha, Acicular Alpha, Transformed Beta]

Figure 4 - 2 : Equiaxed Alpha within transformed Beta (at X100 magnification)

The microstructure of equiaxed globular alpha grains that are well distributed in a transformed beta is the result of prior processing and heat treatment. This was achieved through various processes of Titanium grade 5 processing. These various processes give Titanium its unique properties as it allows alpha and beta stabilisers (Aluminium and Vanadium) to diffuse through the structure. The presence of
aluminium stabilises alpha phase and improve the ductility property of Ti-6Al-4V alloy, while the presence of vanadium in an alloy helps to gradually lower the transformation temperature (Beta- transus temperature) [11].

It can be seen (form Figure 2 - 14) that the optical micrograph of Ti-6Al-4V material is composed of approximately 90 percent (%) to 93 percent (%) of alpha phase and 7 percent (%) to 10 percent (%) beta phase [65, 78]. Different types of micrograph of Ti-6Al-4V can be achieved through the different heating and cooling processes.

4.2.2.2  Weld joint micrograph

Different microstructures were observed across the weld zone and evaluated. The observation revealed that the RFW of Ti-6Al-4V produces a weld joint with three distinct microstructures. The WN, TMAZ and HAZ were identified on the weld joint based on the variation of microstructure from the weld nugget to the parent material. It is these microstructural observations that govern the mechanical behaviour of a welded component with RFW process. Figure 4 - 3 Illustrates different microstructural regions of Ti-6Al-4V weld joint produced from the RFW process.
As shown in Figure 4 - 4, there is an obvious bi-concave shape of the weld joint. It can also be seen that the weld width is wider at the edges of the interface than at the center. This is a result of higher shearing effect at the edges as compared to the center of the interface and this shearing effect depends on the heat density [37]. The heat density is higher at the weld center and gradually reduces at the edges. This was confirmed by Muller et al [85] and Dalgaard [27] in a linear friction welding of Titanium Ti-6Al-4V [27, 85]. The increase in the heat density decreases the friction coefficient resulting in a low heating rate.
At the weld center, the weld width was 96.1538 µm, at the edges the weld width was almost twice the center weld width, as shown in Figure 4 - 4. This variation in the weld width was attributed to the selected process parameters, material properties as well as the variation in peripheral velocity at the interface. In addition, the variation in rotational speed as well as axial pressure had a significant impact on the weld width. An increase in rotational speed increased the weld width while an increase in axial pressure decreased the weld thickness. In summary, the weld width had a direct proportionality to the rotational speed and inverse proportionality to the axial pressure.

Generally, at a higher rotational speed the coefficient of friction is lower. This means that longer heating time is needed to raise the interface temperature. Again, an increase in heating time increases the heat dissipation rate on the workpieces. This then results in a larger volume of material being affected by the heat, which causes a
larger volume of material to be pushed out in the form of a flash and a formation of a joint with a wider width. The application of a larger axial pressure promotes the friction coefficient. In this case, plasticisation happens quicker. With less heating time, the heat dissipation rate is low. The production of a weld joint with narrower width and flash amount is thus achieved.

However, the impact of rotational speed and/or axial pressure on the weld joint properties was clearly visible as certain process parameters remained unchanged during the process. This was also highlighted by Dinaharan et al [30] when they friction welded 60 mm diameter Titanium grade 2 of 3.9 mm wall thickness to investigate the impact of rotational speed on the properties of the weld joint [30].

The initial contact of the workpieces to be joined increased the amount of energy that raised the interface temperature beyond the beta-transus temperature for the formation of perfect weld joint. A perfect weld joint is shown in Figure 4 - 4 and Figure 4 - 3 as an optical image of low magnification.

The cooling rate in friction welding is very important in the production of a solid weld joint. It is the main factor that determines the quality and mechanical performance of friction welded component. The weld interface of friction welding has a very fast cooling rate once the pre-set upsetting has been reached. This is associated with the dissipation of heat from the weld joint to the parent material and a high temperature gradient between these regions. Tolvanen [32] reported the same effect of cooling rate during the investigation of Ti-6Al-4V welds produced from different techniques.
4.2.2.3 Weld nugget (WN)

Figure 4 - 5 shows optical images of the weld nugget obtained at different magnifications. The weld nugget is the central location of the weld joint. This region was formed after rotating and standstill workpieces were brought together and extremely exposed in friction heat and axial pressure. The heating and cooling cycles during welding resulted in the formation of this region.

![Weld nugget microstructure images](image)

Figure 4 - 5: OM images of weld nugget at different magnification A) 10X, B) 20X, C) 50X, D) 100X

The analysis of the weld nugget (WN) microstructure revealed a complete recrystallization and Widmanstatten transformation. The observation revealed very fine equiaxed alpha grains in a matrix of Widmanstatten beta. This very fine equiaxed...
grains observed in the welds may be attributed to the recrystallization that occurred because of elevated temperature beyond beta transus and application of axial pressure. On the other hand, the analysis of the weld nugget revealed a basket-weave microstructure containing very fine acicular alpha particles (as seen in Figure 4 - 5 D).

The formation of very fine acicular alpha grains is the result of the cooling process from the temperature above beta-transus temperature. The same microstructure analysis was reported by Bhadeshia [86] and Threadgill [19]. In addition, the Ti-6Al-4V weld nugget microstructure produced at a lower rotational speed had more refined grains than that of higher rotational speed, although they were all equiaxed. Yates [37] mentioned the same observation. Lower rotational speed has a faster cooling rate due to a higher temperature gradient between the weld interface and the parent material.

Moreover, the very fine martensitic ‘Needle like’ alpha grains within the matrix of re-crystallised beta were also observed towards the boundaries of WN and TMAZ. This type of grains was more visible in the weld nuggets produced at a friction pressure of 60 MPa and rotational speeds of 1600 RPM and 1900 RPM. This was due to the heating and cooling processes at elevated temperature in a short period. Higher pressure and lower rotational speed have faster heating and cooling rates due to higher friction coefficient and lower heat propagation rate. The martensitic grains microstructure is shown in Figure 4 - 6.
4.2.2.4 Thermo-mechanically affected zone (TMAZ)

The thermo-mechanically affected zone is the region situated between WN and HAZ, as seen in Figure 4 - 7. The existence of this region in friction welded Titanium alloys is negligibly small. It appears better on the weld joints of wider width. In most cases, it is very difficult to identify and distinguish this region as it exhibits similar properties to the WN. However, it is essential to understand and clarify the evolution of TMAZ microstructure from the parent material, as it may become the point of failure during the tensile test of friction welded specimens. In addition, this region may exhibit the lowest mechanical properties as it is not physically involved in the joining process but extremely exposed to high temperatures.
On the other hand, most researchers [59, 87] believe that TMAZ does not have a significant contribution to the performance of the weld joint as it is very small [59]. The existence of this zone is still a big debate as different researchers have different opinions. Sato et al [88] reported no TMAZ in friction stir welded Ti-6Al-4V, while Tang et al [89] suggested a narrow TMAZ with a microstructural evolution of beta phase in a friction stir welded mill-annealed Ti-6Al-4V [88, 89]. As TMAZ cannot be concluded, more research is needed to investigate its existence on a friction welded Titanium alloys. The microstructure of TMAZ of friction welded Ti-6Al-4V is shown in Figure 4 - 8 in an optical image.
As observed, this region contains very fine equiaxed alpha grains. When moving closer to the WN, there is a presence of martensitic alpha grains. This is because this region is exposed to extreme temperature (equivalent or greater than transus temperature), which therefore means that there is a possible recrystallization. On the other hand, this region is almost similar to the WN. This then implies that other properties of WN are present in the TMAZ. When moving away from weld nugget, “needle like” alpha grains become coarse. The temperature at this location is extreme for the short period, therefore allowing a partial dynamic recovery. This means that some grains will be in alpha phase and some will be in beta phase due to the temperature being equal to or less than beta-transus temperature. Yates [37] also confirmed this.

Another steps further away from weld nugget towards HAZ, alpha and beta grains are elongated. This is a consequence of plastic deformation that occurred which in turn
resulted in a loss of torsional resistance. Zhang et al [88] and Zhou [87] also mentioned that at this location there is a possibility of grain growth due to a reduced cooling rate [87, 88]. The reduced cooling rate may be due to the lower temperature gradient at this region and the parent material. In addition, the noticeable difference in the grain size is the result of heat propagation and axial pressure effect. An increase in grain size, as you move away from WN, means that heat and axial pressure had less effect as compared to WN. Based on the analysis and observation, TMAZ can be divided into inner (similar to WN) and outer regions (similar to HAZ).

4.2.2.5 Heat affected zone (HAZ)

The next region from TMAZ towards PM is HAZ, as shown in Figure 4 - 7. It is the last region with a distinguishable difference that can be observed from the parent material. Literature suggests different interpretations of this zone by various researchers. Some researchers believe that this region forms a part of the parent material as it has almost similar properties. Others report that it is a zone on its own due to the fact of it being affected by the weld interface temperature [26, 31]. However, it all depends on how different researchers analyse the weld joint of friction welded Ti-6Al-4V.

The HAZ was observed to have the material flow in one direction, as shown in Figure 4 - 9. This may be due to the rotational nature of the continuous-drive friction welding process. The same observation was made by Halford [51] on the investigation of fatigue crack of inertia friction welded Titanium alloy. This region resulted in a loss of torsional resistance during welding because of heat dissipation. Therefore, an application of axial pressure during intimacy at the weld interface forced the material affected by heat to flow in an opposite direction to rotation. In addition, this kind of
observation is more common at higher rotational speed due to elevated heat propagation rate.

![Figure 4-9: HAZ Material flow A) 20X, B) 50X](image)

The observation revealed a microstructure with more elongated equiaxed grains and larger in size as compared to TMAZ. Towards the PM, the alpha grains are clearly visible and the beta phase is fully transformed. This is a result of the minimum effect of heat and axial pressure at this zone. When moving closer to TMAZ, grains are more elongated and smaller in size as compared to when moving towards PM. The material flow is more noticeable at this location. The smaller size grains is the result of the heat as well as pressure effects that are approximately but less than that of TMAZ. The HAZ microstructure is shown in Figure 4 - 10 and the variation of microstructures from WN to PM is illustrated in Figure 4 - 11.
Figure 4 - 10: HAZ (100X)

Figure 4 - 11: Microstructure variation from WN to PM (50X)
4.2.3 Mechanical Properties

4.2.3.1 Micro-hardness evaluation across the weld joint

The micro-hardness profile was performed across the Titanium grade 5 weld joint. It was done on three different locations of the same sample (at the inner, middle and outer diameters). Figure 4 - 12 illustrates the micro-hardness test results obtained at different locations of friction welded sample and Figure 4 - 13 shows micro-hardness test results obtained from the weld joints produced at different rotational speeds.

![Micro hardness test graph](image)

Figure 4 - 12: Micro-hardness profile of different locations
As observed from Figure 4 - 12, there is a micro-hardness increase at the HAZ, TMAZ and WN compared to PM. This increase may be linked to the microstructure transformations that occurred during the rotary friction welding process of Titanium grade 5. These results are very similar to those obtained by Yates [37], Dalgaard [27] and Mashinini [58] on their work in inertia, linear and stir friction welds respectively. The micro-hardness of the weld nugget is visibly greater than that of the TMAZ, HAZ and parent material. This peak micro-hardness at the WN can be attributed to a martensitic transformation that occurred and more refined grains in the microstructure achieved because of high cooling rate. With reference to the TMAZ and HAZ, the hardness increase can be due to a microstructure containing more transformed beta grains, having faster cooling rate as well as lower grain size as compared to PM.
Moreover, the tests revealed that the hardness values of the WN decreases as when moving from the weld center to the edges (as shown in Figure 4 - 12). At the inner diameter of the WN, the hardness value is 376 HV while at the edges is 370 HV. This may be much associated with an increase in the weld width as a result of peripheral velocity and heat density, and different cooling rates at these locations. This is also backed by a very fine microstructure towards the center than at the edges. However, the noticeable difference in the microstructure can only be seen if an optical microscope with a very high magnification is used.

Figure 4 - 13 illustrates micro-hardness of the parent material and weld nugget obtained at different rotational speeds of RFW process. As can be seen, the WN has a higher hardness than the parent material. This may be linked to the influence of the process parameters that result in the production of a weld joint with a fine microstructure as compare to PM. The Vickers hardness of the WN was observed to remain unchanged at different rotational speeds considering the error bars. However, when the speed was increased to 2700 RPM it is observed to decrease. This indicates that the rotational speed does not have a significant influence on the hardness of rotary friction welded Titanium alloy when it is varied within the optimum speeds of 1.25 m/s to 2.05 m/s [9].
4.2.3.2 Tensile strength evaluation

Table 4-1 shows a summary of the results obtained during tensile test of rotary friction welded Ti-6Al-4V specimens. The conditions used for the tensile test specimens’ welding are presented in previously in Chapter in Table 3-3.

Table 4-1: Tensile measurements for friction welded Ti-6Al-4V specimens

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Yield strength (TYS) [MPa]</th>
<th>Tensile strength (UTS)[MPa]</th>
<th>Elongation [%]</th>
<th>Strain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>925</td>
<td>1030</td>
<td>14</td>
<td>25.5</td>
</tr>
<tr>
<td>#2</td>
<td>927</td>
<td>1037</td>
<td>15</td>
<td>26.6</td>
</tr>
<tr>
<td>#3</td>
<td>931</td>
<td>1040</td>
<td>15</td>
<td>25.5</td>
</tr>
<tr>
<td>#4</td>
<td>922</td>
<td>1032</td>
<td>8</td>
<td>20.3</td>
</tr>
<tr>
<td>#5</td>
<td>924</td>
<td>1030</td>
<td>14</td>
<td>24.1</td>
</tr>
<tr>
<td>#6</td>
<td>925</td>
<td>1038</td>
<td>9</td>
<td>17.0</td>
</tr>
</tbody>
</table>

Figure 4-14 illustrates tensile test results of Ti-6Al-4V specimens that were friction welded at different rotational speeds and friction pressures. The tensile tests performed with Zwick/Roell Z250 machine revealed that WN, TMAZ and HAZ produced at 40 MPa friction pressure were stronger than the parent material. This was concluded after observing all failures occurring away from the welded zone, as shown in Figure 4-15 A. This may be closely linked to a finer equiaxed alpha-grained microstructure obtained at a welded zone, with the presence of martensitic grains of alpha within the matrix of recrystallized and fully transformed beta grains. Dalgaard [27] and Mashinini [58] reported the same results on their studies.
Figure 4 - 14: Tensile test graph

Figure 4 - 15: Tensile test specimens A) Failed away from weld zone and B) failed on the weld zone
On the other hand, the tensile test of specimens welded at 60 MPa friction pressure had failure point at the welded zone. This was observed from specimens welded at 1600 RPM and 2300 RPM, as shown in Figure 4 - 14 and Figure 4 - 15 B. This was attributed to the fact that these speeds are respectively close to the upper and lower limits of the optimum speeds recommended for friction welding of Ti-6Al-4V. This was also related to heating and cooling processes that reduced the ductility of weld joint, which in turn reduced percentage elongation. In addition, discolouration and oxidation in the weld join may have affected the weld joint quality. The specimen welded at 1900 RPM had a point of fracture outside the weld zone, similar to the specimens welded at 40 MPa.

The ultimate tensile properties (UTS) of all welded specimens is almost the same, with the difference of ± 0.96 percent (%), as illustrated in Figure 4 - 14 and Table 4 - 1. However, when compared to PM they were increased by up to 3.5 percent (%). This reveals that Ti-6Al-4V weld joint produced by RFW process has almost similar tensile properties to the parent material. In addition, the percentage elongation of specimens with the failure point at the welded region was least when compared to the specimens with the failure point outside of the weld zone. The process of heating and cooling that occurred reduced the ductility property of Ti-6Al-4V at a weld zone. Hasegawa [90] highlighted the effect on the friction welding of steel [90].

Moreover, the tensile test result revealed that rotational speed does not have significant effect at a friction pressure of 40 MPa. However, at a friction pressure of 60 MPa a significant effect of speed variation was observed. As can be seen in Figure 4 - 14 and Table 4 - 1, the slope of tensile curves at 60 MPa friction pressure changes
significantly with the chance in speed. In addition, there is a significant change in the percent elongation as a result of rotational speed variation. da Silver [12] and Yates [37] mentioned that variation in rotational speed has a significant influence on the properties of the weld joint [12, 37].

4.3 Effect of process parameters on Ti-6Al-4V weld joint

4.3.1 Rotational speed

Rotational speed is one of the sensitive process parameters in friction welding of Titanium alloys. It has an extensive influence on the weld joint quality if it is varied over a wide range. However, if it is varied within the optimum speeds of Titanium alloys it does not have a significant effect on the weld quality. This is against what Vill [25] and da Silva [12] mentioned. The main function of rotational speed is to generate relative motion at the weld interface to enhance the occurrence of friction stage. The efficiency of RFW is improved by using a relatively low rotational speed, which results in a reduction of weld width and energy used for welding [12, 30].

As observed in the final welding experiments, the shearing effect in the weld interface is replaced by polishing action at a higher rotational speed. This is attributed to a minimum coefficient of friction at a higher rotational speed resulting in a low heating rate that allows heat conductivity along workpieces axially. Lower heating rate prolongs heating time, which in turn causes heat loss resulting in a greater amount of energy being used for welding process. In addition, higher heat propagation rate widens the weld width because of larger volume of material being affected by frictional heat. Therefore, it can be said that higher rotational speeds demote the cooling rate, widen HAZ and hence reduces mechanical properties of the weld joint [4].
On the other hand, lower rotational speeds produce a narrower weld width in less welding time as compared to higher rotational speed (as seen in Figure 4 - 16). Therefore, lower rotational speed has higher cooling rate, lower heating time and hence improved tensile strength as said by Yates [37]. However, a further decrease in rotational speed (beyond optimum speeds of Titanium alloys) results in a sudden reduction of weld joint mechanical properties. Palanivel et al [30] reported a similar observation on a friction welded grade 2 Titanium tubes. In addition, variation in rotational speed within the optimum speeds of Ti-6Al-4V at elevated friction pressure had a significant influence on the fracture point during tensile test, but had no effect on UTS.

**4.3.2 Axial pressure**

Welding pressure is a sensitive regulator of the weld joint temperature gradient, friction power required and upsetting. Axial pressure can be varied over a wide range depending on the materials properties as well as the geometry of workpieces to be welded. The main function of axial pressure is to maintain intimate contact of the surfaces, prevent oxidation and enhance consolidation. This is achieved by choosing adequate friction and forging pressures for the welding process. da silver [12] and North [91] recommended that friction pressure should at least be half of the forging pressure for the production of defect-free weld joint.

An increase in axial pressure causes local heating to reach a higher temperature within a short period of time and rapid upsetting. This is achieved when rotational speed is maintained unchanged for the duration of the welding process [12]. Higher axial pressure produces a narrower weld joint (as seen in Figure 4 - 16) with improved
mechanical properties at a short welding time. However, material consumption is higher at higher axial pressures because of increased upsetting [12, 19]. Munchen [2] reported that an increase in axial pressure reduces heat input amount that results in higher cooling rate and hardness. Therefore, higher axial pressure leads to a higher cooling rate, higher upsetting, short welding time and hence higher hardness. On the other hand, low axial pressure promotes heat propagation along the workpieces consequently larger volume of material gets heated and a large weld joint is produced (as shown in Figure 4 - 16). This is achieved by having a low coefficient of friction on the shearing surfaces resulting in a low heating rate. Low axial pressure limits upsetting and increases the possibility of a weld joint with defects. In addition, axial pressure does not have a significant effect on the UTS but fracture point.

Figure 4 - 16 : The effect of A) rotational speed, B) axial pressure on the weld joint [12].
4.3.3 Heating time and upsetting

Heating time can be defined as the period from the initial contact of workpieces to the end of braking stage. Other researchers refer to it as friction period. Heating time is one of the sensible process parameters as it has a significant effect on the weld joint quality if it is varied over a wide range. However, Seshagiriroa [33] highly recommended selecting heating time as a primary process parameter over axial shortening. This advice was based on the fact that RFW process fully determines the energy to be utilised during welding for a given power as well as to prevent the presence of unbonded regions, especially when welding materials with rough surfaces [33]. Heating time mainly depends on the materials properties, geometry of workpieces, rotational speed and axial pressure. An increase in rotational speed means an increase in heating time, while an increase in axial pressure means the opposite. One can conclude that heating time is directly proportional to geometry of workpiece and rotational speed, and inversely proportional to axial pressure.

Upsetting, also known as burn off, is the volume of the plasticised material that leads to axial shortening. It can also be defined as the measure of the welding rate [13]. Upsetting is not a significant process parameter as it is determined by rotational speed, axial pressure as well as the weld time used during the welding process. An increase in axial pressure and/or rotational speed increases upset distance. Additionally, an increase in the welding time has an impact on the upset distance. However, upsetting becomes very significant in the friction welding processes where a certain axial shortening is required.
4.4 Summary

The RFW process cycle obtained at a rotational speed of 1600 RPM and friction pressure of 40 MPa has significant similarities with the RFW process cycle of Titanium established by different researchers. Different process parameters and response are graphically represented against welding time. The process cycle had three stages and are clearly marked with letters (A, B and C). In addition, the torque curved obtained had peak values at initial contact and braking stage.

The weld zone of RFW Ti-6Al-4V had variation in microstructure. This was observed on the prepared samples using optical microscope. The variation in microstructure revealed different typical regions of friction processing and are named WN, TMAZ and HAZ. The microstructure of WN consisted of very fine equiaxed grains. Needle like and acicular alpha grains were also observed within the matrix of re-crystalized beta grains. The HAZ had elongated alpha grains because of torsional effect. The microstructure of TMAZ had similarities to that of WN. The microstructural grain size increased as one moved away from WN.

The micro-hardness test revealed that there is hardness decrease when moving from the weld center to the edges. This was linked to different cooling rates of these regions. The micro-hardness increased at the HAZ, TMAZ and WN, with the peak hardness obtained at WN. This was correlated to a reduced microstructural grain size when compared to the parent material. It was observed that rotational speed does not have a significant effect on the micro-hardness of the weld joint if it is varied within the optimum welding speeds.
The tensile test revealed that WN, TMAZ and HAZ were stronger than PM. This was concluded after observing failures outside the weld zone. However, at an elevated friction pressure, failure points were obtained within the weld zone. This revealed that rotational speed had significant influence on the tensile properties of the weld joint at an elevated friction pressure. In addition, the UTS of all welded specimens was observed to be almost the similar. Finally, the tensile test of all welded specimen showed ductile behaviour.
Chapter 5: Conclusion and Recommendations

5.1 Experimental process

The purpose of this study was to evaluate the weld integrity and performance behaviour of rotary friction welded Ti-6Al-4V rods of 25 mm diameter. Different process parameters that were selected based on the mechanical properties and configuration of the workpieces, were used to produce weld joints. Argon gas was used for shielding to eliminate oxidation and contamination that causes discolouration of the weld joint. Preliminary welding process was conducted as a preparation for the final welding experiments. Preliminary welds visual and microstructural examinations were done to select the best welding process parameters for further investigation on the final welds.

All final welds were examined for mechanical properties and microstructural characterization. Tensile test samples were precisely prepared from rotary friction welded specimens. Micro-hardness testing was performed from the microstructural samples and it was measured across the profile of the weld joint, at the inner, middle and outer diameters of the specimen. Microstructural samples were precision cut from welded specimen, prepared according to the standard metallurgical procedures for microstructure analysis and viewed using optical microscope.
5.2 Conclusions

Titanium Ti-6Al-4V of 25 mm diameter was successfully rotary friction welded at different process parameters. Two process parameters namely, rotational speed and axial pressure were varied to obtain weld joints at different welding conditions. Torque feedback was recorded during welding process.

Weld defects, which are voids and lack of bonding, occurred at a lower friction pressures because of insufficient plasticisation. Oxidation and weld discolouration were noted as a result of inadequate shielding. The Ti-6Al-4V weld produced at a lower rotational speed had a narrower width than that produced at a higher rotational speed. This is a result of the minimum heat propagation at a lower speed because of higher heating rate. On the other hand, the weld width is narrower at the center and widens at the edges because of variation in peripheral speed and heat density. Axial pressure was found to have greater influence on the weld width.

The RFW process of Ti-6Al-4V produced three distinct weld regions, namely WN, TMAZ and HAZ, as a result of variation in microstructure due to cooling rate. The weld nugget comprised of very fine and recrystallized grains containing acicular and martensitic alpha grains within the matrix of transformed beta grains. Very fine equiaxed alpha grains were also identified. The TMAZ microstructure had fine equiaxed grains, similar to that of WN. HAZ consisted of elongated grain arranged in a certain flow pattern as a result of torsional effect. The thickness of TMAZ and HAZ was proportional to the rotational speed and inversely proportional to axial pressure.
Micro-hardness and UTS in the weld zone increased as compared to parent material hardness and UTS. Hardness increased in HAZ, TMAZ and WN, with the peak hardness of 375 HV obtained in the WN. The hardening in the Ti-6Al-4V joint is due to grain refinement and the faster cooling rate. Because of hardening, fracture point occurred outside of weld zone during tensile testing. However, a variation in rotational speed at an elevated friction pressure caused some tensile test samples to fail at the weld zone. Variation in rotational speed at higher axial pressures had a great influence on the fracture point but had no influence on the UTS. The maximum UTS of 1040 MPa was obtained in specimens welded at 1900 RPM rotational speed and 40 MPa friction pressure.

Rotational speed and axial pressure did not have significant effect on the weld joint properties when varied within the optimum range of speeds and pressures. However, there was a shift in the point of fracture and percentage elongation during tensile strength of samples welded under different conditions. On the other hand, a significant effect on the hardness was noted when rotational speed was changed over a wide range.

Therefore, Rotary Friction Welding process parameters have significant influence on the mechanical properties of the welded joints. The grains on the microstructure of the weld joint were finer than that of the parent material due to the frictional heat and the applied axial pressure. Hardness and UTS increased because of the RFW process parameters.
5.3 Recommendations and possible future work

- The variation of process parameters should be widened to evaluate more influence of process parameters on the Ti-6Al-4V. As a result, UTS and hardness plots against different process parameters will help to gain more understanding of the influence of parameters over a wide range.
- The friction coefficient measurement during welding process could help in the understanding of the RFW process, as it is a function of temperature and heat input. This can enable heat input to be plotted against welding time.
- Detailed studies pertaining evolution of weld zone microstructure will help to understand the behaviour of welded Ti-6Al-4V alloy.
- The influence of process parameters on the fatigue life and residual stresses needs to be investigated.
- The rotary friction welding process of both workpieces in rotation should be investigated as this may further decrease the production period.
- The study of heat propagation rate on the workpieces at different process parameters should be conducted as this may have a massive influence on the thickness of HAZ, TMAZ and weld width.
- The existence of TMAZ in friction welded Ti-6Al-4V should be studied more as researchers have different views and opinions regarding its existence.
References


Appendices

Figure 5-1: RFW process cycle 2

Figure 5-2: RFW process cycle 3
Figure 5-3: RFW process cycle 4

Figure 5-4: RFW process cycle 5
Figure 5 - 5: RFW process cycle 6

Figure 5 - 6: RFW process cycle 7
Published Conference Paper

The influence of rotational speed and pressure on the properties of rotary friction welded Titanium alloy (Ti-6Al-4V)
The influence of rotational speed and pressure on the properties of rotary friction welded Titanium alloy (Ti-6Al-4V)

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Abstract

This paper presents an investigation of rotary friction welding of 25.4 mm diameter Ti-6Al-4V rods. The weld process parameters used for this research were rotational speed, axial pressure and forging time. Only relative speed and axial pressure were the varied parameters while the forging time was kept constant. The mechanical properties of the weld joints were analysed and characterized. The results showed that the rotational speed and friction pressure have significant influence on the tensile strength, microstructure and weld integrity. As rotational speed increased heating time also increased in the weld, as a result, greater volume of material was affected by heat resulting in a wider width of the weld joint. Fine microstructure resulted due to an increased rotational speed and frictional pressure respectively. The oxidation and discolouration of welds were also discussed.

Keywords: Rotary friction welding; process parameters; Ti-6Al-4V; microstructure; mechanical properties
1. Introduction

Titanium alloys are non-ferrous materials that can be welded by diverse types of welding techniques. Most of the welding processes that have been used in the past with success in joining of Titanium alloys were limited to conventional welding methods [1]. With developments in technology and joining technique, new methods were established including solid-state welding process [2]. Rotary friction welding (RFW) as one of solid-state welding process has been used with success in joining Titanium alloys for industries and in a wide range of experimental applications [3]. RFW is a welding technique invented and patented American Welding Society (AWS) [4]. RFW is a joining process that utilizes frictional heat generated from the rotating rod surface abutting with a non-rotating rod because of applied pressure axial to the welded rods. A frictional time is allowed to enable the surfaces to bond as the rotating member is stopped [5]. Fig. 1 illustrates the various steps for the welding process. It is expected that RFW process will continue to be used successfully and its applications will gain a wide range of use for Titanium and its alloys as more knowledge and understanding of the process is developed especially for Titanium and Titanium alloys specifically, Ti-6Al-4V alloy as it is the mostly used alloy [5].

![Fig. 1. Sequence of RFW process [6]](image)

Titanium alloys have unique properties that makes the metal to be the best material for various applications [3, 7]. Titanium alloy components are mostly found where corrosion resistance and high strength properties are needed, such as in aerospace, marine application, chemical plants, medical applications and in the transportation sector [8, 9]. Titanium alloys have low density to high strength ratio that makes it ideal for high performance components [3, 7]. From the literature review, it was reported that it is possible to join dissimilar and similar metals with rotary friction welding technique. However, there are limited studies that have focused in welding of Titanium alloys by RFW. Therefore, the objective of this research was to join Titanium rods by rotary friction welding and present the change in microstructure and tensile properties of the weld joints in relation to parent material. RFW process is usually controlled by process parameters, which when engaged together significantly affect the joint quality. These process parameters are rotational speed (n), axial pressure (P_a), welding time (t_w) and upset distance (s) [2]. However, researchers of friction welding process have reported different opinions on the influence of process parameters on the quality of the weld joints. da Silver [10] reported that rotational speed is the least sensible process parameter therefore can be varied over a wide range without influencing the weld quality [10]. Although Beloshapkin [11] said that forging pressure is not significant in RFW, it is important to have adequate axial pressure to prevent the occurrence of oxidation of the weld. This may result in a weld joint with voids and further discoloration [12]. Just like Yates [1] and da Silva [10] who suggested that the forging pressure should at least be twice the heating pressure for the formation of weld joint with no complications [10, 1]. Vill [13] reported that each material has optimum rotational speeds for friction welding process. If rotational speed is varied within the limits of optimum speeds, it does not have significant effect on the weld quality [10]. Although Beloshapkin et al. [11] mentioned that the best quality of weld joint can be achieved when forging is not applied. Therefore, this explains that forging pressure is not significant in RFW process. They also reported that welding time is independent of workpieces diameter but depends on the properties of materials to be welded [11]. Palanivel et al. [11] reported that rotational speed as well as axial pressure have almost the same influence on the weld joint quality. As rotational speed increases or axial pressure decreases, the properties of the weld joint reduce. This was mentioned by Beloshapkin et al. [11] on their study. Although researchers have different views.
regarding the effect of parameters on the weld joint, it is of great significant to comprehend the importance of these process parameters in a formation of a high-quality weld joint. Investigating an influence of process parameters using Titanium alloy Ti-6Al-4V is important for both engineering and scientific perspective. Firstly, the use of Ti-6Al-4V has increase worldwide and currently accounts for 50% of the total usage of Titanium in the world over [14]. Secondly, RFW process has been used as an alternative joining process to be a replacement of conventional welding techniques for cylindrical components of Ti-6Al-4V. This process has been suggested to be a quick and efficient welding process, and since the process does not require any filler material, it removes the influence of low temperature segregation and prevent possibilities of weld oxidation and porosity [15, 16]. Due to a nature of RFW process, it is important to understand the procedure of process parameter selection for the production of high strength welds. Poor selection of parameters can lead to a weld joint with poor mechanical properties and thus become a point of failure during static and dynamic testing [12, 17].

2. Experiment procedure

2.1 Welding platform

Commercially available Ti-6Al-4V alloy rods of 25.4 mm diameter were used for this study. The rods were welded with continuous-drive friction welding process. The welding platform utilized for joining the Titanium rods was Process Development System (PDS) for friction welding process that is based at Nelson Mandela University in Port Elizabeth South Africa. The platform is fully automated with a computer interface that allows for the entering of input process parameters and the recorded data collection. With this unique platform, perfect weld joints are achieved through the engagement and collaboration of different process parameters. Such input parameters include axial pressures (friction and forging), rotational speed, upset distance as well as rotational speed. Fixtures to clamp the stationary and rotating rod were designed to hold securely the workpieces in a vertical position, and to have a perfect alignment between joining parts. Fig. 2 illustrates the arrangement of the fixture and the workpieces. In addition, holders were designed with the gap screws that assist in preventing slippages during welding. Shielding gas was supplied to the transparent shielding shroud through tubes (as seen in Fig. 2) to prevent oxidation and further discoloration of the weld joint. The argon gas occupied the bottom half of the glass, as it has greater density than air.

![Fig. 2. Welding platform](image-url)
2.2 Process parameters

Titanium alloy rods were welded at rotational speeds of 1600 rpm, 1900 rpm and 2300 rpm. Frictional pressures used were 40 MPa and 60 MPa. A forging pressure of 100 MPa and forging time of 25 s were used and kept constant. An upset distance \( S \) was calculated based on the final \( L_f \) and initial \( L_i \) lengths of the specimens, according to the following expression.

\[
s = L_i - L_f \tag{Eq. 1}
\]

The range of rotational speeds as well as frictional pressures were chosen based on the visual examination of the flash formation and distortion of the welds from preliminary welding. Similarly, microstructure analysis of the preliminary welds was done to identify weld defects, lack of bonding, presence voids and excessive amount of flash of which also assisted in determining the suitable weld process parameters.

2.3 Microstructure analysis

Microstructure characterization of welds was done on the samples using an optical microscope. Samples were initially prepared and cut to size suitable for standard metallurgical evaluation using electrical discharge machining (EDM) to eliminate additional heat added to the samples during cutting and preparation. The samples were hot mounted in a PolyFast resin and wet ground with progressively finer grades of silicon carbide emery papers using water to both cool and lubricate. Ground samples were polished with Diapro Allogra diamond paste of 0.04-micron grain size. Finally, polished samples were etched using Kroll’s reagent for approximately 30 s. Optical microscope was utilized to view microstructures of etched surfaces.

2.4 Tensile testing

Tensile testing was done on the samples produced. The tests were prepared using ASTM E8/E8M-13a standard test method. The gauge section of test specimens had a cross-section of 12.5 mm in diameter and a gauge length of 62.5 mm, as shown in Fig. 3. The tensile test ramp rate of 2 mm/min and a pre-load of 2 MPa were used respectively.

![Fig. 3. Tensile test specimen (All measurements in millimeters)](image)

3. Results and Discussion

3.1 Weld geometry

Fig. 4 illustrates a typical weld geometry of a weld joint obtained at a rotational speed of 1900 rpm and friction pressure of 40 MPa. The weld geometry of friction welded Titanium alloy is a significant aspect that demonstrate the quality of the weld joint produced. This can be attributed to different shapes and weld width that can be obtained in a rotary friction welding of Titanium alloys. A wider weld joint indicates that either rotational speed was high, heating time was longer or axial pressure was low. Therefore, this indicate poor weld joint properties [14, 2, 18]. Ti-6Al-4V weld joint produced at a rotational speed of 1900 rpm and 60 MPa (as seen in Fig. 4) had a very much similar shape to that of a bi-concave shape. This shape was also reported by Yate [1] on inertial friction welded Ti-6Al-4V. The width at the edges was almost twice the width at the weld center. This may be due to a variation of heat density and peripheral velocity along the weld interface. The heat density is higher at the center of the weld interface and gradually reduces at the edges. Peripheral speed increases with an increase in diameter at the interface. This was also confirmed by Vill [13] on the friction welding of metals. The heat density is inversely proportional to an increase in peripheral speed [13, 1]. The weld joint width depended mostly on rotational speed and axial pressure. At a lower rotational speed, weld joint...
was observed to have a narrower width. This may be due to the fact that at a lower rotational speed the coefficient of friction is high. Therefore, full plasticization was reached at a shorter heating time. Shorter heating time denotes heat propagation on the workpieces in an axial direction resulting in a smaller volume of material being affected by frictional heat. At a higher rotational speed, heat dissipation is promoted by longer heating time because of lower coefficient of friction. Larger volume of material got affected by frictional heat, which in turn caused a production of wider weld joint. On the other hand, friction pressure has a significant impact on the width of the weld joint as it controls the temperature gradient, energy required as well as upset distance [19]. However, specific amount of friction pressure depends upon the material to be joined and workpieces geometry. A narrower weld width was obtained at a friction pressure of 60 MPa. This may be attributed to an elevated friction coefficient caused by higher friction pressure. According to Attallah [20], heating rate increases with an increase in pressure preventing large volume of material from being affected by heat [20]. Dalgaard [19] backed this up on the linear friction welding of titanium alloys. In addition, a decrease in friction pressure limits heating with little or no upset distance. This occurs because of prolonged heating time. Greater amount of heat energy is dissipated axially through the workpieces and lost through radiation. Therefore, wider weld joint is produced from larger volume of material that plasticized. An increase in weld width increases the thickness of heat affected zone and thermos-mechanically affected zone [3, 21].

3.1 Microstructure characterization

The micrograph of the parent material revealed a modal microstructure. Alpha grains (light) were interspersed in a matrix of a transformed beta (dark), as seen in Fig. 5. The well distributed equiaxed alpha grains in a matrix of transformed beta was the result of prior processing and heat treatment of the material [3, 9, 7].
Microstructures of weld center obtained at different rotational speeds and friction pressures are shown in Fig. 6. These microstructures have significant similarities to those obtained by Threadgill [21] and Yates [1] on the friction welded Ti-6Al-4V. The weld center had very fine acicular grains within a basket-weave microstructure as a result of cooling from above beta transus temperature. Martensitic ‘Needle like’ alpha grains within the matrix of re-crystallized beta grains were observed to be more visible in the weld joints produced at a friction pressure of 60 MPa. This was due to heating and cooling processes in a short period at elevated friction pressure. Very fine equiaxed grains observed in all welds may be attributed to the recrystallization that occurred because of elevated temperature beyond beta transus and application of higher axial pressure. The microstructure of lower rotational speed was observed to have more refined grain size than that of higher rotational speed, although they are all equiaxed. This may be due to faster cooling rate at lower rotational speed as a result of higher temperature gradient between weld joint and parent material as well as low heat propagation rate of Ti-6Al-4V. This was backed up by Dalgaard [19] on the linear friction welded Ti-6Al-4V alloy [14].
The heat affected zone (HAZ), which is another region of Ti-6Al-4V weld zone, was observed to have material flow in one direction, as shown in Fig. 7. This observation was noted at higher axial pressure and rotational speed. Elongated equiaxed grains in the HAZ microstructure were arranged in a certain flow pattern. This is the result of rotation nature of RFW process. The same observation was reported by Halford [22]. At high rotational speed larger volume of material becomes soft because of high heat propagation rate. This result in a loose of torsional stiffness.

Fig. 7. Material flow in the HAZ (50X)

3.2 Tensile strength

Fig. 8 illustrates tensile test results of rotary friction welded Ti-6Al-4V specimens at different rotational speeds and friction pressure. The tensile test performed revealed that weld zones produced at 40 MPa friction pressure were stronger than the parent material. This was concluded after having fractures away from weld zone, as shown in Fig. 9A. This may be attributed to very fine equiaxed grained microstructure obtained in the weld zone, which is in agreement with the work reported by Dalgaard [19].

Fig. 8. Tensile test graph
On the other hand, the tensile test of specimens welded at 60 MPa friction pressure had specimen failures within the weld zone. This was observed from specimens welded at 1600 rpm and 2300 rpm, as seen in Fig. 9B. This was attributed to the fact that these speeds are the lower and upper limits of optimum speeds respectively. This may also be related to heating and cooling processes that reduce ductility of weld joint, which in turn reduces percentage elongation. In addition, discoloration and oxidation in the weld joint may have affected the weld joint quality.

![Fig. 9. Tensile test specimens A) Failed away from weld zone and B) failed on the weld zone](image)

The ultimate tensile strength of all friction welded specimens was almost similar to that of parent material of 1030 MPa. This was linked with specimens’ failure occurring within the parent material and weld zone. The change in rotational speed at a lower pressure did not have a significant influence on the tensile properties of the weld joint. At elevated friction pressure, significant influence of speed variation was observed on elasticity gradient and percentage elongation. An increase in rotational speed at elevated friction pressure increased gradient of elastic region and reduces elongation because of heat dissipation. This revealed that rotational speed is proportional to gradient of elastic region and inversely proportional to elongation.

4. Conclusion

Ti-6Al-4V alloy rods of 25.4 mm diameter were joined successfully using a continuous-drive friction welding process at different speeds and friction pressures. The thickness of weld joint widened with rotational speed increase because of increase in heat propagation rate. Weld width was proportional to rotational speed and inversely proportional to axially applied pressure. The weld center had basket weave microstructure containing very fine equiaxed grains relative to parent material. Martensitic alpha grains within re-crystallized beta were more visible at higher pressure and low speed. The microstructure produced at higher speed had larger grains than that produced at lower speed. The weld zone of Ti-6Al-4V was stronger that parent material due to failure occurring far away from the weld zone. Variation in rotational speed at 40 MPa friction pressure did not have effect on the tensile strength of welded Ti-6Al-4V. At rotational speed of 1600 rpm and 2300 rpm, and friction pressure of 60 MPa failure occurred within the weld zone as a result of oxidation and discoloration occurred. At 60 MPa pressure rotational speed was proportionality to gradient of elastic region and inversely proportional to percent elongation.

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