Design and Fabrication of Friction Stir Welding Setup on Conventional Milling Machine to Join and Characterize AA 6023-T6 alloy sheet

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SCHOOL OF MECHANICAL, CHEMICAL AND MATERIAL ENGINEERING

DEPARTMENT OF MECHANICAL DESIGN AND MANUFACTURING ENGINEERING

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BY

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DECLARATION

I hereby declare that the work, which is being presented in thesis, entitled "**Design and Fabrication of Friction Stir Welding Setup on Conventional Milling Machine to Join AA 6023-T6 alloy sheet**." In partial fulfillment of the requirement for the award of the Degree of Masters of Science in Manufacturing Engineering is my own work carried out September 2017 to September 2018 under the supervision of **Dr. Perumalla Janaki Ramulu,** Program of Mechanical Design and Manufacturing Engineering, Adama Science and Technology University and **Ato. Fishaha Biruk** Lecturer at Adama Science and Technology University, Adama, Ethiopia.

The matter embodied in this thesis has not been submitted by me for the award of any other Degree or Diploma. All relevant resources of information used in this thesis have been duly acknowledge.

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This is to certify that the above declaration made by the candidate is corrected to the best of my knowledge and belief. This thesis has been submitted for examination with our approval.

Dr. Perumalla Janaki Ramulu. ____________ ____________

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ABSTRACT

Friction stir welding (FSW) is a solid-state welding process and invented for joining of non-ferrous materials specifically for aluminum alloys only, now it extended to ferrous materials also. It is running for the last two decades and developed from small scale level to high scale level of manufacturing industries by its own advantages over other conventional joining processes. This process has many process parameters in which tool geometry, rotational speed, welding speed, tilt angle etc., are the major ones. Many of the researchers evaluated and examined in an elaborate manner on the effect of process parameters on mechanical and microstructural properties of aluminum alloy welded joints. All the joints were made on Universal milling machine to friction stir welding (FSW) or on the FSW machine itself with different joint configurations. This thesis work carried out on manufacturing adjustable friction stir welding setup on a convectional vertical milling machine and FSW tool to characterize the weld joint of AA 6023-T6. The result show that AA 6023-T6 welded joints using FSW on universal milling machines grain refinement in the weld joint and defects free at optimized parameters of 2000 rpm rotational speed, 12.5 mm/min welding speed and 3˚ tilting angle. The reduction of pin length is 1 mm (reduced from 1.8 mm to 0.8 mm length) and the diameter of the pin/probe increased by 2.3 mm (increased from 3.8 mm to 6.1 mm) is observed. For welded joint hardness performance both the rotational speed and welding speed have significant influence, but tilting angle has insignificant influence on weld joint of FSW of AA 6023 T6. The hardness value has been noted as 53.63 HV that is 99.26 % of base metal hardness. For weld joint strength performance value, the rotational speed has significant influence and both welding speed and tilting angle have insignificant influence on weld joint of FSW of AA 6023 T6. The Optimized parameters tensile strength has been recorded as 194.67 MPa that is 92.70 % of base material. Rotational speed has great effect on weld joint and other parameters welding speed and tilting angle of the tool takes the second and third rank respectively.

Keywords*: FSW, Convectional milling machine, Non- ferrous metals, Mechanical property, Microstructure features.*

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ACRONYMS AND ABBREVIATION

CMM	Convectional milling machine
OM	Optical Microscope
HV	Vickers pyramid number
HAZ	Heat affected zone
TMAZ	Thermo-mechanical heat affected zone
FSW	Friction stir welding
AA	Aluminum alloy
MIG	Metal inert gas
TIG	Tungsten inert gas
Fz	Downward force
Fx	Traverse force
Fy	Lateral force
TWI	Welding institute
3D	Three dimensions
UK	United Kingdom

CHAPTER ONE

1 INTRODUCTION

1.1 Background of the study

The Friction stir welding (FSW) process is a solid-state joining process, invented at the Welding Institute (TWI) in United Kingdom (UK) in 1991 for butt and lap welding of ferrous and non-ferrous materials and recently extended to plastics **[1].** At present, aluminum and steel are widely using in automotive and aerospace industries. The friction stir welding has advantages over fusion welding in similar and dissimilar welding. Friction stir welding is an efficient method of welding aluminum to steel (Al-to-Steel) with easy setup and low cost. FSW method has been used extensively in the manufacturing methods because of its advantages such as low heat input, high production efficiency, ease of manufacture, and environment friendliness **[2]**.

For instance, defect-free welds providing good mechanical properties have been used in a variety of aluminum alloys. This approach is environmentally friendly and no filler rods are required. In addition, this type of welding is used in aeronautical industry, automobile industry, submarine industry, and other heavy industries **[2, 3]**. The conventional milling machine used to hold the tool which rotated along the weld line of plates. Plates are properly supported by backing plate and the clamps to make the movement of the work stationery on milling machine bed. The main purpose of the backing plate is to provide support to the workpiece. During welding operation, plasticized material is forged down by the tool. A backing plate ensures that the plasticized material is retained within the welding zone. It also provides safety to the top plate in case the tool tip goes beyond the workpiece thickness. A support plate, made of mild steel, facilitates uniform distribution of the tightening force over the workpiece **[4]**.

Two fusion welding methods have particularly proved to be capable of producing sound welds for aluminum alloys: Metal Inert Gas (MIG) and Tungsten Inert Gas (TIG) techniques respectively. Both processes being based on fusion of welded material and possible filler metal are characterized by the presence of metallurgical features influencing the quality of welds, such as formation of dendrites, solidification structure, liquation cracking or cold bonding; besides the results are highly dependent on the manual skills of the welder. A solution can be to use alternative joining methods in which the material remains in solid state. One such method, particularly applicable for joining aluminum alloys is Friction Stir Welding (FSW). Making structures lighter is one way to save energy **[2, 6]**. Aluminum alloys are attractive due to superior recyclability and workability. However, present structures made of stainless steels can be entirely replaced with aluminum alloy structures, considering strength, weld ability, and economics, although it is possible to replace part of a structure with aluminum alloy components.

1.2 Friction stir welding process

A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint as shown in Fig1.1. The tool serves two primary functions: (a) heating of workpiece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the workpiece to enhance plastic deformation of workpiece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin. As a result of this process a joint is produced in ‘solid state’. Because of various geometrical features of the tool, the material movement around the pin can be quite complex. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equated crystallized grains. The fine microstructure in friction stir welds produces good mechanical properties. There are two sides with respect to the welding tool during FSW **[1, 2]**. The advancing side (AS) is the side where the tool rotational motion and traverse direction are in the same direction, and the retreating side (RS) is the side where the tool rotational motion is opposite to the traverse direction.

Material on the advancing side of a weld enters into a zone that rotates and advances with the profiled probe. This material was very highly deformed and sloughs off behind the pin to form arc shaped features when viewed from above (i.e. down the tool axis). The lighter material coming from the retreating side in front of the pin and was dragged around to the rear of the tool and filled in the gaps between the arcs of advancing side material. This material did not rotate around the pin, and the lower level of deformation resulted in a larger grain size.

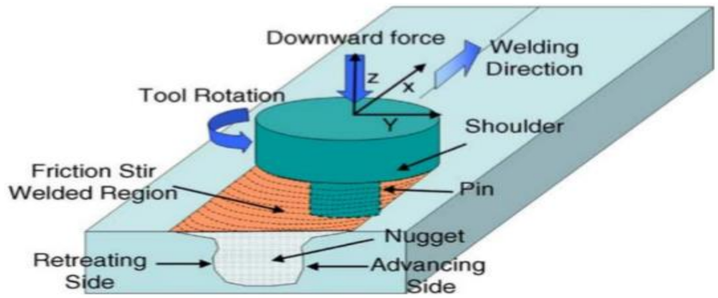


Figure 1.1 Schematic Diagram of the Friction Stir Welding Process [7]

Aluminum used in the production of bus-bars. A bus-bar is an electrical conductor that makes a common connection between several circuits; and it is found in the interconnection of the incoming and outgoing transmission lines and transformers at an electrical substation. Bus-bars are also used to connect generators and the main transformers in a power plant.

The advantages of FSW process also encompass better mechanical properties, low residual stress and deformation, and reduced occurrence of defects **[2, 9].** The friction stir welded plates, have four regions across the width of the plates: According to Thread gill the four regions are (i) Parent Material, (ii) Nugget, (iii) Heat Affected Zone (HAZ), and (iv) Thermo-Mechanically Affected Zone (TMAZ).

i. The Parent material (or base material) is the region which does not undergo deformation and the microstructure in this region is not affected by the heat produced during the process.
ii. The Nugget region is formed by the intense plastic deformation induced mainly by the tool pin and consists of fine re-crystallized grains.
iii. The heat affected zone (HAZ) is the region which is affected only by heat and there is no plastic deformation. In this region, the microstructure and/or properties are modified by the thermal heat.
iv. The thermo-mechanically affected zone (TMAZ) surrounds the nugget and it experiences lower temperatures and less deformation. Friction stir welding is regarded as an Asymmetric process.

1.3 Conventional vertical Milling Machine

The main application of milling machine was to cut the excess part of material from metal or alloy workpiece by either vertically or horizontal rotational motion of spindle. Cut spur gear, helical gear, and different types of rake and pin gear are also a duties of universal milling machine. On top of the above mentioned application, milling machine is selected in this work for friction stir welding within the boundary range of maximum power, rotational speed and torque of milling machine. To prompt out the FSW experiment a vertical milling machine is used. The tool is bestriding in the vertical arbor using an appropriate collates. The backing plates to be clamped to the horizontal milling machine bed with nil root gaps. The clamping of the test pieces is done such that the energy of the plates is totally restricted under both plunging and translational forces of the FSW tool.

Figure 1.2 Universal milling machines (CVMM code F-281)

1.4 FSW process parameters

Although, FSW gives high quality welds, proper execution of the process and control of a number of parameters is required for a successful outcome. Recent experimental and computational works have provided insight into how process parameters influence material flow in FSW. Most of the material flow occurs through the retreating side and the transport of plasticized material behind the tool forms the welded joint. Process parameters, such as tool design, welding parameters, joint configuration, forces acting on the tool during welding and the heat input during the process, are found to exert significant effects on the material flow and the temperature distribution and by implication these factors inevitably influence the microstructure evolution and mechanical properties of the materials being join.

1.4.1 The Design of Rotational Tool

During the FSW process, the welding material is in a plastic state. The material must be stirred and then mixed enough to get FSW weld. The rotational tool is made up of a shoulder and a rotational pin. During the FSW process, the tip of the rotational pin is inside the welding material in order to avoid contact between the tool and the backing plate and then the damage of the tool or backing plate. Generally speaking, the distance between the tip of pin and the bottom of the welding workpiece is 0.1~ 0.2 mm **[7]**. However, the practical distance between the tip of pin and the bottom of the workpiece is longer or shorter than 0.1~ 0.2 mm, which results in the change of workpiece thickness or the change of plunging depth of tool. The longer distance may result in the appearance of root flaws because of the lack of enough material flow **[20].** Different tool pin profiles considered are cylindrical threaded, cylindrical taper threaded and cylindrical grooved. The tools are designed using 3D modeling software and are manufactured on a Lathe machine.

In particular, for the developed processes, 2 mm thick aluminum sheet were utilized, while the tool was made from Hot-worked tool steel, such as AISI H13 has proven acceptable for welding a wide range of materials because it provides sufficient hardness, is easily available, has good machine ability, is relatively cheap and has high abrasion resistance, characterized by a 52 HRC hardness. Reynolds and Tang used 8–12 mm probe. The shoulder diameter is 2.1 times the probe diameter plus 4.8 mm. However, the most commonly used ratio of shoulder-to-probe diameter is 3 **[14].**

1.4.2 Tool pin

Friction stirring pins play significant roles in material flow during the FSW process. The pines designed to disrupt the fraying surface of the workpiece. Research work on fundamental characterization of friction stir welding process parameters was conducted. The tool used was made from heat-treated tool steel with pin profile such as a threaded pin, square, cylindrical, cylindrical grooved with a concave shoulder. The convectional cylindrical threaded pin probe is adequate for butt welding aluminum of thickness up to 12 mm **[2, 4]**. Different tool profiles are shown in Figure 1.2

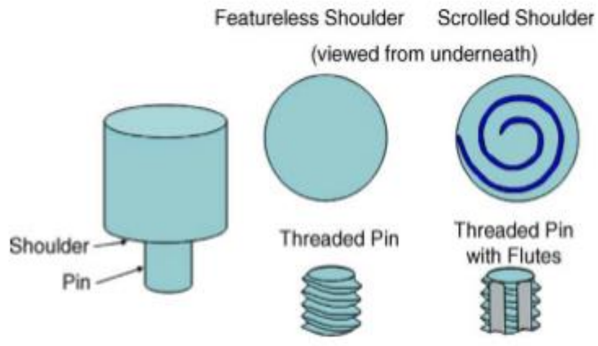


Figure 1.3 Schematic drawing of the FSW tool profiles [6]

1.4.3 Tool shoulder

Tool shoulders are designed to frictionally heat the surface regions of the workpiece, produce the downward forging action necessary for welding consolidation, and constrain the heated metal beneath the bottom shoulder surface. The shape of the shoulder outer surface (cylindrical or conical) has a great influence on the welding quality because the shoulder plunge depth is typically small (i.e. 1–5% of the gauge thickness). The concave shoulder inclines only a small angle (6–10^0) from shoulder to end surface. During tool plunging, the material displaced by the probe is fed into tool shoulder cavity. Hence, the concave surface of the tool shoulder serves as an escape volume or reservoir for the displaced material from the probe. By exerting a downward applied pressure on the tool, the displaced material held in the concave shoulder renders a forging action on the material behind the tool. Then the forward movement of the tool forces new material into the cavity under the shoulder and pushes the existing material behind the probe. The proper operation of this shoulder requires the tilting of the tool 1–3^0 from the normal of the workpiece against the direction of travel. The shoulder diameter is 2.2 times the workpiece thickness plus a constant of 7.3 mm **[14].** This relationship is reasonable considering that with increasing thickness, more energy input is necessary and hence a larger shoulder diameter is required to generate the heat. Similarly, the probe diameter is 0.8 times the sample thickness plus a constant of 2.2 mm. Reynolds and Tang used 8–12 mm probe. The shoulder diameter is 2.1 times the probe diameter plus 4.8 mm. However, the most commonly used ratio of shoulder-to-probe diameter is 3 **[14, 16]**.

1.4.4 Welding Parameters

The two most important welding parameters are the tool rotational speed in a clockwise or anticlockwise direction, and the tool traverse speed along the joint line **[2, 7 and 15]**. The rotation of the tool results in the stirring and mixing of material around the rotating pin, while the translation of the tool moves the stirred material from the front to the back of the pin and finishes the welding process. The choices of feed rate and rotational speed are crucial for heat generation, in order to create good flow of the material around the tool, while minimizing the forces on the tool. The ratio of feed rate to rotational speed is usually reduced to a single parameter referred to as pitch. The properties of the welds are usually related to the pitch, which is believed to be an important parameter in FSW.

1.5 Problem of statement

Aluminum Alloys are difficult to weld with conventional welding processes such as Arc welding, MIG welding and TIG welding. Weld cracks are unacceptable defects that can compromise the integrity of welded structures. Most cracks are the result of solidification, cooling and stresses that develop due to weld shrinkage. Weld cracking can lead to structural failures. Typical joint between Aluminum and Aluminum, like bus bars is made with the use of mechanical fasteners. It is expected that if FSW is used, it will give better contact, better current flow, less resistance, and there by save energy. FSW has many advantage over fusion welding process. Conversion of a conventional vertical milling machine to a structural multifunctional workstation in order to perform experimental friction stir weld of aluminum alloy.

1.6 Objectives

1.6.1 General objective

The main objective of this thesis is to design, manufacture, and test friction stir welding (FSW) setup on conventional vertical milling machine to join and characterize non –ferrous (AA 6023-T6) metal alloy sheets.

1.6.2 Specific objectives

The specific objectives of this thesis are to:

- Design and manufacturing friction stir welding setup and FSW too that is used on conventional milling machine;
- Analyze the FSW systems and process parameters rotational speed, welding speed and tilting angle on weld performance;
- Join non-ferrous metals with optimized process parameters and
- Evaluate the mechanical properties of FSW joints.

1.7 Scope of the study

The development of the FSW setup on conventional Vertical milling machine may be performed on various base materials. The scope of this research work is to successfully join aluminum alloys of different dimension combination of aluminum alloy 6023-T6 alloy sheet 2 mm thickness (i.e. 500 mm × 150 mm × 2 mm, 500 mm × 125 mm × 2 mm and 500 mm × 100 mm × 2 mm) by FSW process on universal milling machines using adjustable backing plate. Weld-quality and joint integrity will be quantified through microstructural evaluation and mechanical testing.

1.8 Significance of the research

The importance of the study is multi-face. In the academic context, the study will expand on the further research undertakings relative to the FSW of different similar and dissimilar materials at the include aerospace, automobile and ship, building applications. This study used adjustable fixtures on universal milling machine to perform friction stir welding process. The fixture is basically considered upon the later designs and new innovations are made to Friction-Stir weld by making adjustable in three directions.

1.9 Research motivation

Gas tungsten arc welding and gas metal arc welding are the two recommended processes for joining aluminum alloys. The gas tungsten arc is recommended for thinner sections, and the gas metal arc for thicker sections. However, the non-availability of a matching filler material restricts the application of these two processes. FSW is suitable for various material due to its advantages over fusion welding. FSW technology is not available in any industries in Ethiopia and FSW machines are expensive. This is not favorable for the small industries, university laboratory or any personnel to invest this amount of money for expensive FWS machine. FSW has many advantages over fusion welding as try to list above. So, introducing and showing possibility of FSW process on conventional vertical milling machines is the main thing in different colleges, universities, laboratories, organizational and private sectors in Ethiopian nations.

1.10 Thesis layout

Chapter one presents the background and application of friction stir welding in brief. Explain introduction of friction stir welding. Chapter two reviews the previous works done on friction stir welding and find out research gap. Chapter three focuses on the methodology and materials used to achieve the objective of this thesis work. Chapter four includes the brief description of the experimental works of these theses. Finally, Chapter five discusses the conclusion, recommendation, and future work of this thesis.

CHAPTER TWO

2 Literature Review

2.1 Frictions stir welding

FSW technique is one of the most suitable joining methods, which accounts for the considerable development efforts. Given the recent increase in industrial demand for lightweight design structures, novel joining methods are required to tackle new challenges, such as multi material joining. Even though the FSW technique was originally developed for joining aluminum alloys, the method presently being studied to weld other materials such as polymers, metallic materials, copper, and even joining dissimilar materials. One of the major obstacles to broader industrial implementation of FSW has been the affordability and suitability of FSW machines. The actual FSW machine can reach the price around one million US dollar **[2].** This is not favorable for the small industries, university laboratory or any personnel to invest this amount of money for expensive FSW machine.

2.1.1 Literature on adaptation of FSW process on milling machine

Siddiqui *et al.* (2014) [4] reviewed some techniques for modifying vertical milling machine to achieve special welding technology of friction stir welding. Reported the major applications of FSW in the field of aerospace, shipbuilding and automotive and discussed with their advantages. **Reuven Katz (2007) [5]** reported the design principles of reconfigurable machines which represent a new class of machines that bridges the gap between the high flexibility and high cost of totally flexible machines and the low flexibility and low cost of fully dedicated machine. The work shows how the suggested design principles were utilized in the design of several full-scale machine prototypes and tested experimentally. **Longhurst and Strauss (2010) [8]** investigated the use of torque instead of force to control the FSW process. Concluded that torque control is better suited for keeping a friction stir welding tool properly engaged with the workpiece for application to robotics, automation, and manufacturing. It is attractive because of its sensitivity to tool depth into the work piece. Torque control has the potential to increase the range of processing variables suitable for stable control. **Harish Bagaitkar (2008) [6]** analyzed technical feasibility of implementing Friction Stir Welding (FSW) for automobile chassis fabrication and

Design for Manufacturing (DFM) principles are applied to manufacture an aluminum automobile chassis. Studied various DFM issues such as Tool Accessibility, Joint Configuration, and Fixture Support Issues along with relevant guidelines such as component geometry change and component elimination. **Ponte *et al.* (2005) [13]** described low-cost method of transforming a conventional milling machine in to a simple FSW workstation. Reported process including the implementation of a temperature measurement, down ward and horizontal forces monitoring systems and designed tool fixing system. The adapted milling machine has success fully weld AA 6082-T6 aluminum alloy by FSW. The basic concepts relevant to the use and study of friction stir welding (FSW), including an overview of the process, a comparison to arc welding processes, a discussion of welding tool design and materials, the effect of process parameters, workpiece materials and joint geometries **[15].**

2.1.2 Literature on backing plate Design

Hasan *et al.* (2015) [17] designed simplified fixtures and backing plates to be used for friction stir welding of aluminum alloys. The workpiece was subjected to uniform lateral and vertical pressures by means of bolts and nuts. Compound backing plates and pressure bars with additional side plates were included to increase the heat sink. Several coupons of dissimilar aluminum alloys AA7075 and AA6061 were joined to inspect the validity of the design. Efficiency of the joint reached its maximum value of about 82 % with respect to the ultimate strength of the AA6061 alloy at 1100 rpm rotation speed and 300 mm/min feed. **Ramnath *et al.* (2018) [18]** designed screw clamps to hold the work pieces rigidly during Friction-Stir Welding operation. The testing of the fixture is carried out by the use of ANSYS Software. The fixture is designed and analyzed for three different materials. Analyze materials Cast Iron (C45), Die Steel (D4) and Tool Steel and Hard Alloy (H20) materials. Low stress concentration factor in all areas and stress comes around 1179.3N/mm2 has the optimal solution for friction stir welding operations and hence C45 steel material can be used as alternate fixture material compared to D4 and H20 materials.

Imam *et al.* (2015) [19] studied effects of backing plate material on macrostructure, peak midsection temperatures in heat affected and weld nugget zones, and weld mechanical properties were obtained for each of the cases. Effects of backing plate material significant in lap joint than butt welded joint. In butt as well as lap configuration, asbestos backing plate which had the lowest thermal diffusivity was observed to provide the largest process window within which defect free welds could be obtained. **Esther *et al.* (2013) [20]** reported the detailed design of a clamping and support system for a reconfigured milling machine to produce friction stir welds. Design concept, the detailed performance analysis and simulation was done to effectively clamp and support the workpiece during the process of friction stir welding to achieve a good integrity. Inexpensive milling machine adaptations allow for the conversion of any milling machine into a specialized Friction Stir Welding machine which is ideal for research purposes.

Ahmed and Saha (2018) [25] proposed simple mechanical fixture to overcome the fixture issues present in joining of thin sheets. To reduce heat loss, asbestos were used as cover plate. Discuss issues include precision in fixture, uniform and close clamping along and on both sides of the weld line and, minimizing heat loss from the thin sheets. Weld joint quality at 150 and 200 mm/min of tool travel speed of UTS (∼70% of base material UTS), percentage elongation (∼7%), and bending value (180°). **Parida *et al.* (2015) [26]** developed a clamping system and an instrumented setup for a vertical milling machine for friction stir welding (FSW) operations and measuring the process forces. Design, developed and fabricate force measurement, a strain gauge based force dynamometer. Test the developed setup in actual welding operations.

Baghel and Siddiquee (2012) [27]designed fixtures using AutoCAD software keeping certain things in view like groove of fixture to be such that it accommodates both backing plate and metal plate to be welded key is also manufactured for the purpose of fixing and balancing of plates to be welded**.** This fixture has the flexibility to weld Stainless Steel 304 plates of various thickness. Part from this clamps has been designed such that it is easy to disassemble and also easy to manufacture.

2.1.3 Literatures on FSW Tool

Thomas *et al.* [7] described recent developments in FSW butt and lap welding particularly using a Flared-Triflute TM probe and an A-Skew TM probe. Butt welds produced with Whorl TM and MX-Triflute TM frustum-shaped probes that gave acceptable weld quality. **Adesina *et al.* (2017) [24]** characterized and evaluated AlCrN coated FSW tool. Test various metallurgical hard coatings for FSW tools using cathode arc PVD coating technique for welding structural materials. Proved AlCrN coated sample exhibited improved wear resistance with weight loss of about 87% lesser compared to uncoated sample. The coated tool pin experienced considerably less reduction in dimension as compared to the uncoated tool pin for the same number of FSW plunges and passes.

Wanga *et al.* (2018) [28] developed a novel dual-rotation bobbin tool friction stir welding (DBT-FSW), in which the upper shoulder (US) and lower shoulder (LS) have different rotational speeds. Conclude that the DBT-FSW has excellent process stability, and can produce the defect-free joints in a wider range of welding parameters. **Patel *et al.* (2016) [29]** studied influence of tool pin profile and welding parameter. Test tensile strength to know the best parameter from the selected ones. The threaded straight cylindrical pin profile is suitable for good welding using selected welding parameters. **Islamic *et al* (2015) [30]** described the process of developing a stationary FSW tool for welding thin plates of dissimilar polymers. Focused on the development of FSW tools, aiming at sound and robust friction stir welding of dissimilar polymeric materials in lap joint configuration. A Teflon polymeric material stationary shoulder proved to be the best option, resulting in superior surface quality when compared to aluminum, brass, and wood shoulders. The best results were achieved using two sleeves for the stationary shoulder. In order to compensate the lack of heat by using stationary shoulder, the rotational speed of the tool must be increased.

Magadha and Kumar Adepu (2018) [31] investigated shoulder combined with various polygonal pin profiles during friction stir welding (FSW) of 6082 aluminum alloy. Finally, welding joints was subjected to radiographic and sectioned macro and microscopic observation to understand the detailed flow of marker material. The polygonal pins reduce the initial force required during the plunging phase. Superior mechanical properties were observed in welds obtained with (TR)S tool with a UTS of 199 MPa, and hardness of stir zone was around 78.4 HV which was attributed to the complete mixing of the material on both AS and RS. **Beygi *et al.* (2018) [32]** studied influence of tool geometry on material flow and mechanical properties of Al-Cu bimetallic sheets were friction stir welded by three different kinds of pin profiles (threaded cylindrical, threaded conical and pyramidal). Among the three pin geometries used, the threaded conical tool provided the best compromise between the different material flow regions and there by the fewest defects and the highest weld strength were obtained with this tool. The joint efficiency of the welds made on Al-Cu bimetals can never reach 100% due to the micro-void on the retreating side. The conical threaded pin gives the best result in terms of weld soundness and strength. **Tarasov *et al.* (2014) [33]** proposed diffusion-controlled wear mechanism of alloy steel friction stir welding (FSW) tools used on an aluminum alloy. During FSW of AMg5M aluminum alloy the latter covers the tool's working surface and then iron/aluminum reaction diffusion is initiated under the conditions of high mechanical stress and temperature, since diffusion by the former austenite grain boundaries is much faster than that of by volume an inter-metallic compound is formed inside the tool's metal. Thus, causing brittle and pulling out the tool's metal fragments. **Krasnowski *et al.* (2015) [34]** investigated the influence of tool shape and weld configuration on the microstructures and mechanical properties of Al 6082 alloy FSW joints. Three types of tool with different probe shapes and shoulder surfaces and two weld configurations (one sided and two-sided) were used in experiments. Prove the two sided welds exhibited lower mechanical properties due to greater heat transference into the material during the second pass, also shape of the tool used in the FSW process influences the mechanical properties of the joints.

Aguiara *et al.* (2016) [35] presented friction stir welding (FSW) related technique, which was labeled Tool Assisted Friction Welding (TAFW). Mechanical testing, using Digital Image Correlation (DIC) for strain data acquisition, enabled to assess welds strength and plastic properties. Prove that the TAFW technique enables to obtain very good quality welds for both on the presence or absence of galvanized coating base materials, at a very high welding speed and low tool wear/damage. No base materials inter-mixing takes place during welding, as is the case for FSW. **Sahlot *et al.* (2017) [36]** studied the difficulty of joining of high strength materials using friction stir welding (FSW) is difficult due to severe tool wear and change in the shape/size of the tool. Present quantitative wear analysis of H3 steel tool during FSW of CuCrZr alloy. Higher amount of total tool wear is observed for faster tool rotational speeds, and slower traverse speeds. Estimate and improve tool life during FSW of CuCrZr alloy or any other high melting point metallic material of similar nature. **Ravi *et al.* (2018) [38]** studied effect of tool rotational speed on mechanical and metallurgical properties of the weld joints. Observed better mechanical properties joint welded with 1000 rpm of tool rotational speed. Studied the effect of tool rotational speed on the mechanical and microstructure properties of friction stir welded Al-B4C MMCs. Recommends moderate tool speed (RPM) to get defect free single pass welds.

Microstructure studied revealed fine re-crystallized equated grains in the weld nugget due to frictional heating and extensive plastic deformation.

2.1.4 Literature on comparison between conventional welding and FSW

Smith *et al.* [38] developed the hardware, software, and process parameters which make it possible to use a standard industrial robot, such as an ABB or Kawasaki, to perform friction stir spot welding (FSW) or friction stir spot welding (FSSW). Aluminum, aluminum alloys, and magnesium in a variety of joint types can now be successfully joined. Typical automotive components being designed for FSW and FSSW include: chassis, crush horns, body enclosures, hoods, suspension links, and gas tanks. In these type applications, significant cost reductions have been realized as well as dramatic improvements in mechanical properties. **Sabari *et al.* (2016) [39]** introduced FSW for armour grade aluminum alloy to fabricate light combat vehicles in the armour application. Joining of this alloy using fusion welding resulted with solidification defects like porosity, hot cracking, etc. Enhanced the joint properties, under water friction stir welding (UWFSW) process can be adopted. Investigated the effect of tool rotation speed on the stir zone characteristics and the resultant tensile properties of the FSW and UWFSW joints, also found the UWFSW joint made using the lower tool rotation speed of 1200 rpm exhibited superior tensile properties than FSW joints. **Bodukuri *et al.* (2017) [40]** studied the comparison of AA 5083-T4 properties on Tungsten Inert Gas welding (TIGW) and Friction Stir Welding (FSW) processes. Evaluated and compared the potential of FSW and TIGW for joining similar metal. The tensile strength of friction stir welding is approximately three to four times greater than TIG welding. Heat affected zone is very less in FSW and more in TIG welding, so the properties (i.e., Microstructure, Micro Hardness and Tensile strength) changes in the weld zone, So the property of weld zone remains same as parent material in FSW. Cracks and porosity are not seen at heat affected zone in FSW welding. But in TIG welding cracks and porosity are seen in the weld zone. They evaluate FSW has higher micro hardness value than TIG welding. **Xu *et al.* (2018) [41]** reported the comparative study of the conventional single side and bobbin tool friction stir welding at different welding parameters. Indicate heat-affected zone (HAZ), the local softening region, was responsible for the early plastic deformation and also the fracture location for SS-FSW samples, while a rapid fracture was observed in weld nugget zone (WNZ) before yield behavior for all BB-FSW specimens. UTS of the SS-FSW joints is much higher than that of the BB-FSW joints, also SS-FSW joints present a much higher elongation than the slices. **Yong *et al*. (2017) [42]** investigated electrochemical corrosion behaviors of friction stir welding (FSW) and MIG (mixed inert gas) welding joints. Corrosion rate of the FSW joint is less than those of MIG joint and the parent material, also the polarization resistance of the FSW joint is greater than those of MIG joint and the parent material. **Mironov et al (2018) [43]** addressed critical issue of friction stir welding including welding tool materials and design, tool wear, processing temperature, material flow, processing window and residual stresses, also highlighted Potential engineering applications. Development of the tool design, the development of an effective thermal management system would possibly eliminate the through-thickness thermal gradient, improving the weld ability. Reports Friction-stirring is characterized by a unique combination of very large strains, high temperatures and high strain rates.

2.1.5 Literature on application of FSW

Amini *et al.* (2014) [10] explored FSW application in different industry. The process has many advantages in both mechanical properties of the welded material and the energy consumption which directly leads to lower operating costs. FSW can be used for joining many types of materials and also different material combinations, and is also applicable for material thicknesses up to 75 mm. FSW machines in industry and robotic FSW processes, and the necessary considerations needed when designing or selecting such devices.

Many researchers were studied FSW of dissimilar aluminum alloys. Successful joining of aluminum alloys was obtained between (i) AA6061 and AA7050, (ii) AA6061 & AA7075, (iii) AA6082 & AA2024, (iv) AA2024 & AA7075, (v) AA2024 & AA7075, (vi) AA5083 & AA6351, (vii) AA2219 & AA5083, (viii) AA6082 & AA7075, (ix) AA6061 &AA5086, (x) AA2219& AA7039. It appears from literature review that investigations pertaining to (i) The effect of tool pin geometry and process parameters on weld joints and (ii) The mechanical and microstructure behavior of dissimilar welded joints of AA2219 and AA7475 sheet have not been carried out so far.

From the above literature, different researchers were evaluated and examined in an elaborate manner on the effect of process parameters on mechanical and microstructural properties of aluminum alloy welded joint on converted milling machine to friction stir welding (FSW) or on the FSW machines itself. The objective of this thesis is to design, manufacture, and test adjustable friction stir welding setup on conventional vertical milling machines with existing technology to join non-ferrous (AA6023-T6) metals. There is a research gap on the material AA6023-T6 alloy and the adjustable backing plate in three dimensions.

CHAPTER THREE

3 Methodology and Materials

3.1 Methods

The general procedures of pre-welding, welding, and post- welding process of experimental works are shown by the flow chart Fig 3.1.

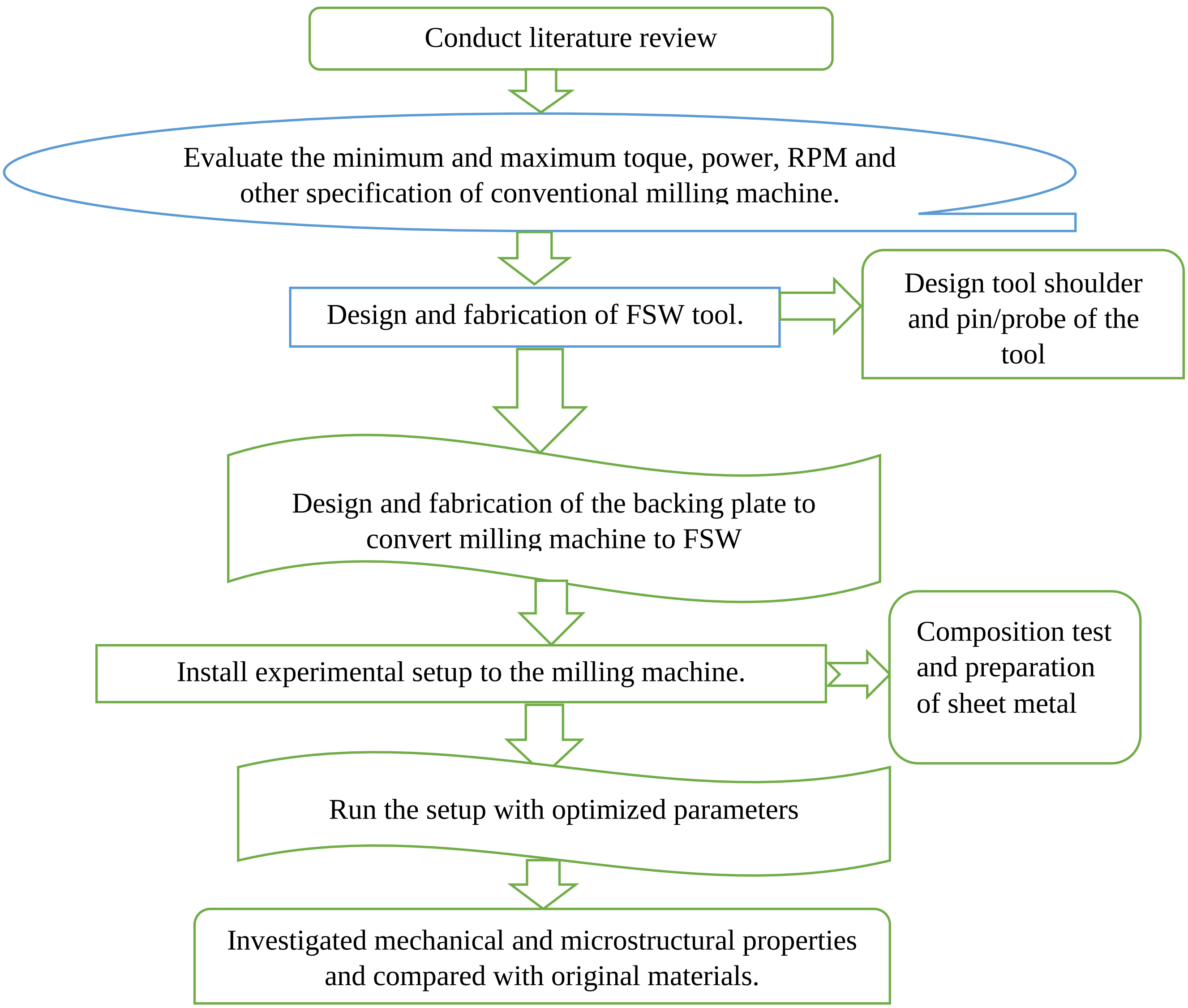


Figure 3.1 Flow chart of overall methods of experiment work and testing step

A comprehensive literature survey was conducted to gain insight relative to the FSW process. The literature survey entails information including tool materials and the geometry to FSW of aluminum alloy the availability of the parent materials and the experimental equipment needed to carry out effectively the characterization of the weld properties. All these issues were considered. After the survey of the related literature, attention was given to the actual experimental setup. Designing and manufacturing of backing plate and clamping devices to ensure stability and accuracy of the welding process. Conversion and development of a conventional milling machine into a friction Stir welding unit with an appropriate workstation to analyze data. Design and manufacturing of a tool shoulder and tool tip from hardened steel that can perform a friction stir weld joint. Concave tool shoulder diameter of pin with different profile. The length of tool plunging in to the workpiece is 80% of the workpiece thickness (0.8t). Finally, characterization mechanical properties such as tensile strength of welded joint using tensile test machine, hardness of welded joint using hardness test machine and macrostructure of the welded joint was studied.

3.2 Materials and Equipment

The material used to perform FSW on conventional milling machines and machineries to test mechanical and microstructures of this project were listed on the below table 3.1 and table 3.2 respectively.

Table 3.1 Materials used to perform FSW on conventional milling machines

No.	Materials	Tasks	Specification/Model
1.	Aluminum alloy sheet	Base material to be welded.	Aluminum alloy 6023 T6
2.	Backing plate	Holding work pieces in position during welding process.	500 mm × 320 mm × 10 mm plate.
3.	D2 steel tool	Generate heat and mechanically mixing plasticized material.	With 11.7 mm shoulder diameter and 3.8 mm pin/probe diameter.
4.	Expandable collates	To hold FSW tool on conventional milling machines.	With collates diameters of 10 mm.
5.	T- headed bolt and nuts	Rigidly clamping the backing pate on the milling machine table.	21 mm length M16 × 2 bolts.

6.	Hexagonal headed bolt and nuts	Adjusting the backing plate up and down, also rigidly fixing side supporter on backing plate.	50 mm length M18 × 2.5 bolts.
7.	Open box wrench	To tightening and opening the bolts.	27 mm, 18 mm and 10 mm wrench.

Table 3.2 Machinery for experimental and sample test

No.	Machineries	Tasks	Model
1.	Universal milling machines	To perform FSW welding process, slot and hole on the backing plate.	FU-281.
2.	Shearing machine	Cut sheet of aluminum alloy sample	Hydraulic shear
3.	Heat treatment machine	Heat treat friction stir welding tool (D2 tool steel)	Fours nagat 44550-montoir de Bretagne-france
4.	Expandable collates	To hold FSW tool on conventional milling machines.	With collates diameters of 10 mm.
5.	Optical microscopy	Microstructural test	Magnification X50, X100, X200, X500 and X1000
6.	Vickers hardness tester	Hardness test	HVS-50
7.	Lathe machine	Face turning, taper turning and groove on FSW tool	Excel XL-420
8.	Drilling machine	To make key way in chamber	Universal drill TSAR-25
9.	Grinder or polisher	Removes saw marks, level, clean and grinding little stock from sample surfaces	RB 204 Metpol-II
10.	Abrasive cutter	Cut bulk samples	RB 203 Abcut-M
11.	Hot mounting press	Sample preparation	RB 206 Metpress-A

Table 3.3 Specification of CVMM code F-281

No	Spindle description	Units.	Maximum range.
1.	Main driven range normally	RPM	40-2000
2.	Motor power	kW	5.5
3.	Maximum torque	Nm	1313.7
4.	Minimum torque	Nm	26.27
5.	Feed motor power	kW	1.5
6.	Feed motor rotational speed	RPM	920
Feed range as follows.			
		mm/min	12.5-630
		“	“
7.	Vertical, horizontal, and transverse.	“	5.2-262
8.	Gear transmission ratio	-	1:1

3.2.1 Design and fabrication of backing plate

This work used adjustable fixtures on universal milling machine to perform friction stir welding process. The fixture is basically considered upon the later designs and new innovations are made to Friction-Stir weld by making adjustable in three directions. The fixture is built upon a single hard material and is cut at intrinsic shapes in different governmental and nongovernmental industries by different machines like: automatic sheet metal cutting (hydraulic shearing) machines, milling machines and arc welding machines to attain a different slot for the insertion of workpiece and rigidly clamping on horizontal milling machine bed. The bottom backing pate modified to accommodate the fixture on the milling machine bed. The corners are filleted to reduce the deformation force caused at the corners.

FSW requires careful design of backing plate and tool **KumarBaghel *et al*. (2012) [27]** since at high temperature there is a problem on friction stir welding like: - sticking of workpiece (blanks) with bottom backing plate compromising both sound of weld joint and integrity of fixtures itself. Fixtures should with stand with forces and rising temperature during welding process without distortion in shape. Fixtures in these paper designed with CATIA V5 R20 software and fabricated with help of different industries in Adama town like: - *Yasin Ibrahim Manufacturing Industry* for cutting of mild steel plate of dimension 1000 mm × 500 mm × 10 mm in to different dimensions and shapes (i.e. bottom backing plate (500 mm × 378 mm × 10 mm), both right and left side supporter (500 mm × 40 mm × 10 mm), top backing plate (500 mm × 75 mm × 10 mm) and spacer/adjuster (100 mm × 40 mm × 10 mm) by automatic sheet metal/plate cutting machine (hydraulic shearing machine). This machine has the ability to cut plate up to 20 mm thickness. *Haromsa Advanced Manufacturing Industry* also one of the industries makes different futures in backing plate like: - holes with different dimension, key ways, threaded part of hole, welding of the assembled part according to design specifications.

3.2.1.1 Material for fixtures

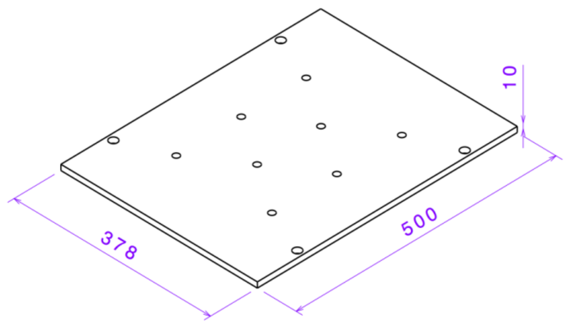
Mild steel material used for manufacturing fixtures, backing plate, top plate, side supporter, spacer (adjuster) and bottom plate, since mild steel has high strength and toughness which is required to with stand unbalanced force and pressure during friction stir welding. AISI 1018 mild/low carbon steel has excellent weldability and produces a uniform and harder case AISI 1018 mild/low carbon steel offers a good balances of toughness, strength and ductility.

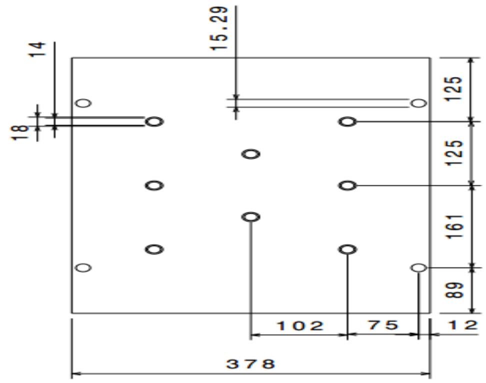
3.2.1.2 Bottom backing plate

Backing plate designed for FSW provide to support work pieces and rigidly secured on milling machine table by the T- nuts bolts of length 21 mm M16 with 2 mm pitch thread to protect the movement of blank during welding process, also ensures the plasticized material retained within the welding zone since the plasticized material is forged down by the tool. Provides safety to the milling machines bed in the case of tool tip goes beyond the work pieces thickness. Support different part of the fixtures like: - top plate, side supporter, and spacer (adjuster) to make the adjustable fixtures depend on the sheet metal/plate of different similar and dissimilar material. Backing placed under work pieces mainly for protection and the stability of blank/work pieces. Backing plate in these papers cut by hydraulic shearing machine (automatic sheet metal cutter) and the future of the backing plate part was formed in *Haromsa Advanced manufacturing engineering industry* in Adama town. Backing plate and clamping must be rigidly secured to milling machines bed to resist perpendicular forces and side forces. Fixtures designed to retain work pieces and keep them from moving parts and Materials should be mild steel, medium carbon steel

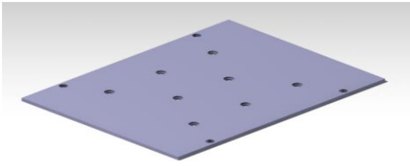
Fixtures in FSW is usually the most complicated and critical aspect of the welding process. The work pieces must be clamped to a rigid smooth backing plate and secured to resist the perpendicular and side forces that develop during the welding process. These forces tend to lift and push the work pieces apart. Fixtures are designed to restrain the work pieces and keep them from moving apart. The fixtures that hold the materials to the backing plate should be placed as close to the joint as possible to ensure that the work pieces are held in place during the welding procedure.

In this thesis work the design of backing plate depend on the conventional vertical milling machine table of FU-281. The material used for backing plate are discussed in different literatures such as **[17, 18, 25]**, those literature given the common backing plates used in the literature include medium carbon steel and mild steel H13. The backing plate used in this research work is a mild steel plate since the mild steel has high strength and toughness which is required to with stand unbalanced force and pressure during friction stir welding and additionally mild steel/low carbon steel is available in low cost. This availability of mild steel in low cost minimizes the cost of FSW setup on universal milling machines compared to expensive FSW machines.





a) 3D of bottom backing plate b) Detail dimension of backing plate

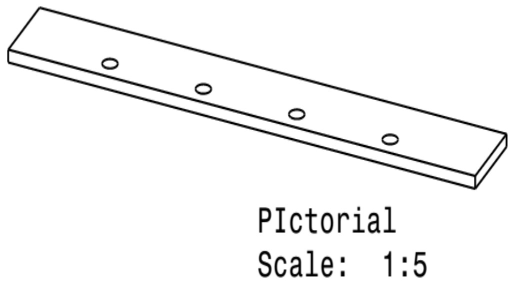


c) 3D CATIA modeling of bottom backing plate

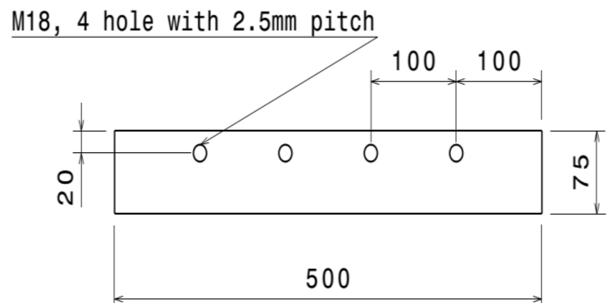
Figure 3.2 Bottom backing plate

3.2.1.3 Top plate

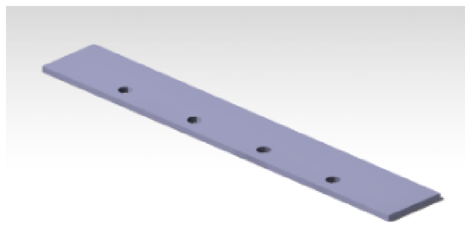
The top backing plate is usually adjusting the sheet metal/ plate thickness in different dimension (i.e. sheet metal from thickness of 0.5 mm to 5 mm and plate from 5 mm to 20 mm) and hold the workpiece rigidly in right position during welding process. Top backing plate highly affected by vertical force that comes from bolt to secure the workpiece rigidly in right position during welding process. The dimension of top plate depend on backing plate dimension. There are two top backing plate was welded on both right and left side of side supporter backing plate to fix and provide rigidity of sheet/plate during welding process. The vertical tightening force is applied through hole of 10 mm height M18 threaded hole with 2.5 pitch by the same dimension bolts of length 50 mm M18 of 2.5 mm pitch diameters to fix aluminum alloy sheet with different thickness up to 20 mm plate is possible to adjust by M18 bolts.



a) 3D view of top backing plate drawing



b) Front view, futures and dimension of 3D view of top backing plate drawing

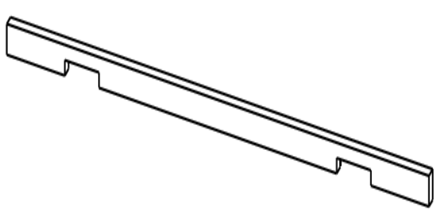


c) 3D CATIA modeling of Top backing plate

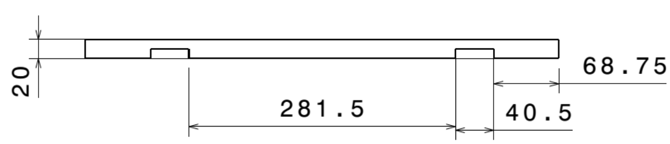
Figure 3.3 Top backing plate

3.2.1.4 Side supporter plate

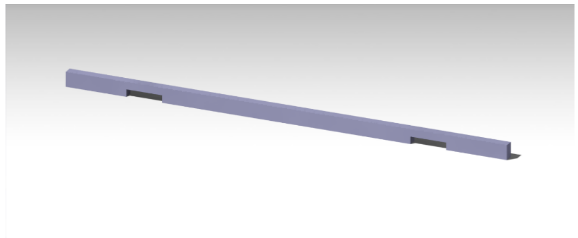
Side supporter of backing plate was the part of fixtures introduced in this study. This Side supporter backing plate support the top backing plate, also welded on the bottom backing plate and have slot future to allow spacer/adjuster rigidly and manufactured in milling machine by using end milling machine tool. Side supporter are welded in both right and left side of backing plate by manual arc welding machine.



a) 3D side supporter backing plate drawing



b) Front view, futures and dimension of side supporter backing plate drawing

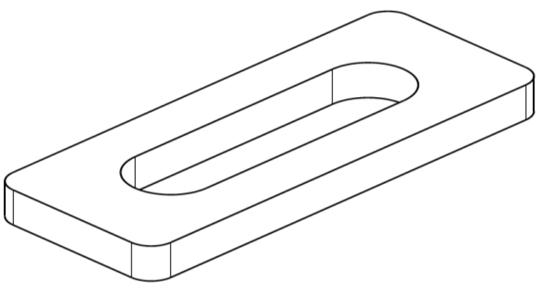


c) 3D CATIA modeling of supporter backing plate drawing

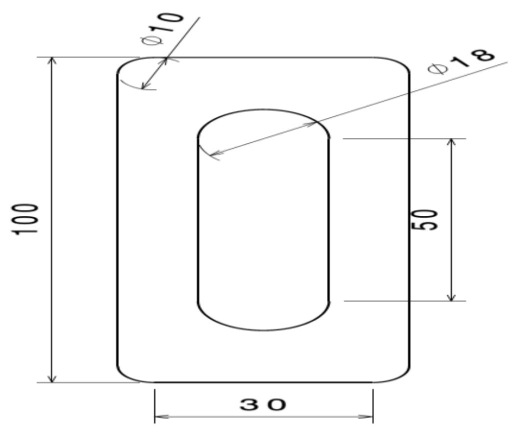
Figure 3.4 Side supporter of backing plate

3.2.1.5 Spacer (side adjuster) backing plate

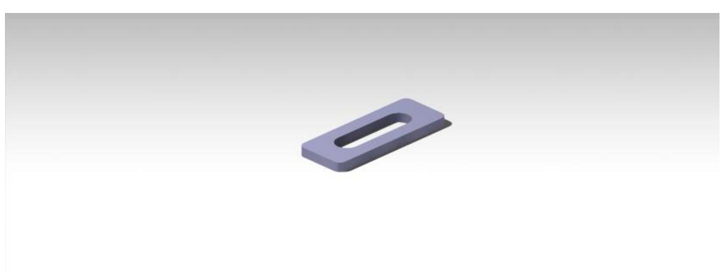
The side adjuster backing plate in this work adjusts the width of sheet/plate to be weld and additionally hold the sheet/plate to be weld against both vertical force and transverse force during plunging and welding time. The side adjuster secured through the side supporter slot and rigidly fixed with the bolt of length 50 mm M18 with 2.5 mm pitch on bottom backing plate to provide rigidly different sheet metal length and width to appropriate welding position.



a) 3D view of spacer/adjuster backing plate drawing

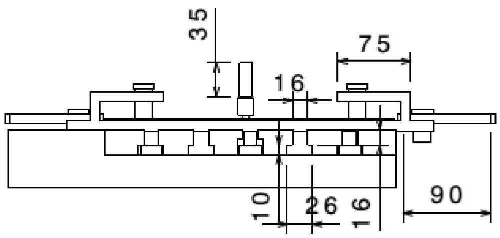


b) All dimension and futures of spacer/adjuster backing plate drawing

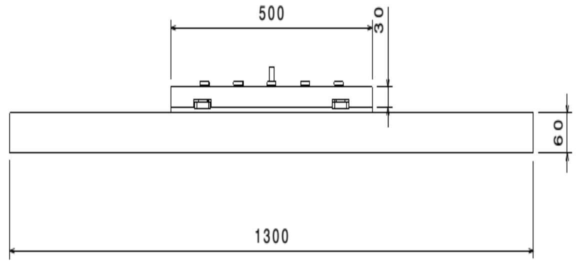


a) 3D CATIA modeling of spacer/adjuster backing plate drawing

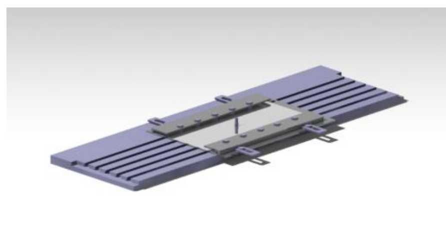
Figure 3.5 Spacer (adjuster) plate



a) Front view of milling machine bed with backing plate



b) Side view of milling machine bed with adjustable backing plate



a) 3D CATIA modeling of milling machine bed with adjustable backing plate

Figure 3.6 Secured backing plate and fixture on milling machines tables

After designing the fixture, its manufacturing was done by following operations:

1. Cutting operation: cutting operation was done on hydraulic shearing machines to specified dimensions (i.e. bottom backing plate (500 mm × 378 mm × 10 mm), both right and left side supporter (500 mm × 40 mm × 10 mm), top backing plate (500 mm × 75 mm × 10 mm) and spacer/adjuster (100 mm × 40 mm × 10 mm) and also cut the AA sheet to prepare for welding specimens.
2. Milling operation on horizontal milling machine. The milling operation was done to produce the straight an fillet on sharp edges of the backing plate. The tool used was high speed steel cutter, also some future of backing plate like grooving on side supporter backing plate, drilling of hole on all backing plate (i.e. six hole on bottom backing plate by end milling cutter of diameter 12 mm, four hole on bottom backing plate and four hole on each top backing plate by end milling cutter of diameter 15.5 mm) and slot future on adjuster backing plate was machined.

3. Threaded operation: thread operation done by hand twist-drilling machine of diameter 18 mm with pitch of 2.5 mm for thread future of four holes in each top backing plate and four hole in bottom backing plate, also drilling machine of diameter 14 mm with pitch of 2 mm.
4. Surface finishing was done using grinding operations. Surface finish using surface grinder was used for removing the roughness and providing the desired tolerance. After performing all these operations finally fixture is produced as shown in Figure 3.8.

a) Picture of welded backing plate b) **Picture of backing plate secured on VMM bed**

Figure 3.7 Manufactured backing plate

After the set-up was installed on milling machine table, FSW tool was fixed with machine spindle by using an expandable collates of diameter 10 mm.

3.2.2 Design and fabrication of tool

The design of the tool is a critical factor, as a quality tool can improve both the quality of the weld and the maximal possible welding speed. It is desirable that the tool material be sufficiently strong, tough, hard, and wear resistance at the welding temperature. Further, it should have a good oxidation resistance and a low thermal conductivity to minimize heat loss and thermal damage to the machinery further up the drive train. Improvements in tool design have been shown to cause substantial improvements in productivity and quality. TWI has developed tools specifically designed to increase the penetration depth and thus increasing the plate thicknesses that can be successfully welded. An example is the "whorl" design that uses a tapered pin with re-entrant features or a variable pitch thread to improve the downwards flow of material. The majority of tools has a concave shoulder profile, which acts as an escape volume for the material displaced by the pin, prevents material from extruding out of the sides of the shoulder and maintains downwards pressure and hence good forging of the material behind the tool.

Material selection, design, and cost are important considerations in the search for commercially useful tools for the welding of hard materials. Work is continuing to better understand the effects of tool material's composition, structure, properties, and geometry on their performance; durability and cost **[20].** Designs of tool highly depend on the thickness of sheet metal aluminum alloy. The tool consists of pin/probe and shoulder **[22]**.

3.2.2.1 Pin/probe of tool

Pin of tool is part of tool extruding from part of tools contracting surface. It can be threaded or non-threaded and also responsible to generate mechanically mixing process in plasticized material. Only fraction of total heat is generated by pin or probe of the tool. Pin or probe diameter (T) also depend on the thickness of sheet metal.

$$T = 0.8t + 2.2 \text{ mm} \tag{3.1}$$

Where, T represents pin diameters and t represents thickness of sheet metal

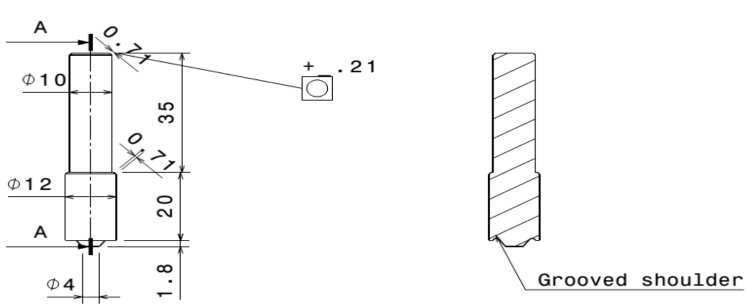
3.2.2.2 Shoulder of tool

The shoulder of tool is the cylindrical surface responsible for generating the frictional heat.

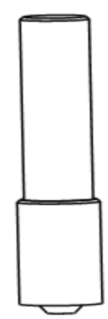
Shoulder diameter (D) also depends on the thickness of sheet metal.

$$D = 2.2\, t + 7.3 \text{ mm} \tag{3.2}$$

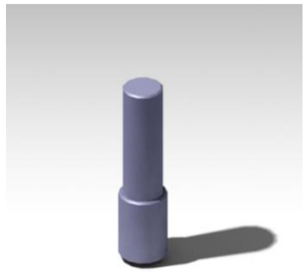
Where, D represents shoulder diameter and t is thickness of sheet metal.



a) All geometrical description of cylindrical shoulder tool



b) 3D view of FSW tool



c) 3D CATIA modeling of FSW tool

Figure 3.8 FSW tool

3.2.2.3 Properties of D2 Tool Steel

D2 steel is an air hardening, high- carbon, and high- chromium tool steel. It has high wear and abrasion resistance properties. It is heat treatable and will offer hardness in the range of 55- 62 HRC and good for short term operations. D2 is an air-hardening, high carbon, high chromium tool steel with extremely high wear resisting properties. It is a very deep hardening steel and will be practically free from size change after proper treatment. The high percentage of chromium gives it mild corrosion-resisting properties in the hardened condition. Cold-work steels should show the following physical characteristics: Low movement in hardening, High as quench hardness, Maintenance of a keen edge for cutting purposes, Résistance to mechanical shock, easily machined in annealed condition. The mechanical and physical properties of D2 tool steel was as shown blow in table 3.4.

Table 3.4 Mechanical and physical properties of D2 tool steel

Properties	Units	Quantities
Ultimate tensile strength	MPa	1917
Yield tensile strength	MPa	1476
Hardness, Vickers	HV	748
Elongation at break	%	1
Modulus of elasticity	GPa	210
Bulk modulus	MPa	160
Poisons ratio	-	0.3

Shear modulus	GPa	81.0
Density	kg/m^3	7.7
Specific gravity		7.75

Table 3.5 Identified chemical composition of D2 tool steel

Elements	C	Cr	Mn	Mo	Ni	S	P	Si	V	W
Wt %	1.61	11.50	0.30	0.43	0.15	0.014	0.018	0.25	0.16	0.077

To obtain a standard result, care must be given to the testing procedures in other to minimize error from the machine or the operator, sample preparation, and the material composition both microstructural or heat treatment processes. The presence of alloying and heat treatment can affect the values of toughness in material. Lower carbon content, which lowers strain-hardening rates of the tempered matrix martensitic, and lower alloy content, which reduces the volume fraction of hard alloy carbide particles that initiate fracture, is used to increase the fracture toughness at the expense of wear resistance.

3.2.2.4 Tool profiles

Friction stirring pins play significant roles in material flow during the FSW process. The pines designed to disrupt the fraying surface of the work piece. Research work on fundamental characterization of friction stir welding process parameters were conducted **[5]**. There is different tool profiles. For this thesis work conventional cylindrical tool was using from D2 tool steel. The convectional cylindrical pin/probe is adequate for butt welding aluminum of thickness up to 12 mm **[6]**.

3.2.2.5 Tool tilt angle

Most of literature obtains defect free welds with tilt angle below 0 to 4˚ whereas the tool with tilt angle 0˚ also reported to result in defected joints. But commonly the tool with tilt angle of 2˚ is produces defect free weld joints **[31].** This thesis highly focuses on the effects of tilting angles of tool on friction stir welding process.

Table 3.6 Tool geometry depends on sheet metal thickness [2, 14, and 18]

Thickness of sheet metal/plate	Pin/probe diameter of tool	Shoulder diameter of tool	Tilt angle of the tool
0.5 mm	2.6 mm	8.4 mm	1 to 4˚
1 mm	3 mm	9.5 mm	1 to 4˚
2 mm	**3.8 mm**	**11.7 mm**	**1, 2 and 3˚**
3 mm	4.6 mm	13.6 mm	1 to 4˚
4 mm	5.4 mm	16.1 mm	1 to 4˚
5 mm	6.2 mm	18.3 mm	1 to 4˚
6 mm	7 mm	20.5 mm	1 to 4˚
8 mm	8.6 mm	24.9 mm	1 to 4˚
10 mm	10.2 mm	29.3 mm	1 to 4˚
12 mm	11.8 mm	33.7 mm	1 to 4˚
15 mm	14.2 mm	40.3 mm	1 to 4˚
20 mm	18.2 mm	51.3 mm	1 to 4˚

Table 3.7 Specification of different FSW tool

S. No.	**Variable description**	**Specification of cylindrical pin tool**
1	Tool material	Heat treatable D2 steel tool
2	Shoulder diameter	11.7 mm
3	Shoulder chamfer	0.5 mm all around
4	Pin diameter	3.8 mm
5	Pin length	1.8 mm

The procedure followed to manufacture FSW tool was as follows; Chosen 13 mm diameter of D2 tool steel circular rod that approaches to the larger diameter with length 102 mm, Rough turn and face a full surface of chamber to remove dust particles and corrosion. The machining processed on milling machine feed rate of 0.5 mm/rev by using high carbon steel cutter, Continued turning and facing by the same cutter and machine to get 12 mm diameter and 100 mm length, Continued face turning of pin diameter to 4 mm and supporter to 11 mm, then taper turn operation was done between from one end of billet by taper angle 64.65˚. Heat treatment was performed up to HRC-54 by using heat treatment machine. Heat treatment process is deferent from the other manufacturing process by performed at high temperature oppression. First the furnace was heated up to 940 °C and D2 tool steel were inserted in the furnace. Then after 40 minutes of stay in furnace they are removed off and quenched with oil media then tempered at 400 ^{0}C to minimize brittleness of the material. Finally, surface finishing done to 65.64˚ taper facing for pin, reduced shoulder diameter to 11.7 mm and supporter to 10 mm.

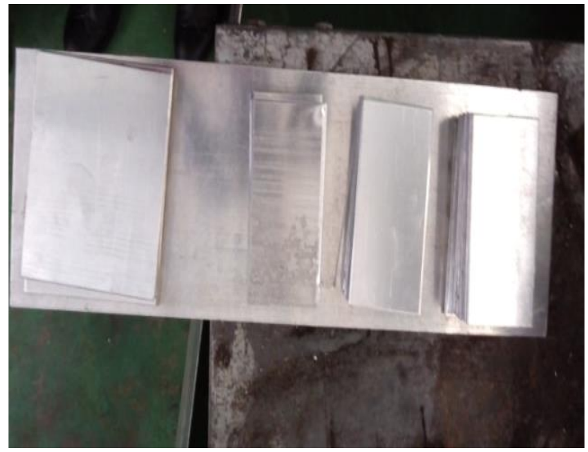
(a) FSW tool

b) Expandable collates

Figure 3.9 Manufactured FSW tool and tool with expandable collates

3.2.3 Sheet metal (AA6023-T6 sheet alloy)

6023-T6 aluminum is aluminum in T6 temper. To achieve this temper, the metal is solution heat treatable and artificially aged until it meets standard mechanical property requirements. The sheet metal used in this thesis was cut by hydraulic shearing machines in different dimension of length vary from 25 mm to 500 mm, width vary from 75 mm to 189 mm to ensure the adjustability of backing plate. AA 6023 T6 of 2 mm thickness sheet sample was cut into 50 mm × 100 mm × 2 mm, 150 mm × 500 mm × 2 mm, 125 mm × 500 mm × 2 mm and 100 mm × 500 mm × 2 mm thick sheet metal is used for this thesis work as shown on figure 3.12 (b) below. 6000 series rolled plate and sheet, High-strength structural members, (Al-Si-Mg) extrusions, forgings, vehicles, rolling stock, marine tubing and piping applications, architectural applications.



a) Hydraulic shearing machines **b) sheet metal prepared for welding sample**

Figure 3.10 Different dimension of sheet metal prepared for welding sample

In the European system the prefix 'AW' denotes a wrought product. For the wrought alloys this is followed by the four digit number which uniquely identifies the alloy. The first digit indicates the main alloying element, with numbers 1 to 9 being used, from that AW 1XXX is for pure aluminum, and AW 6XXX alloy indicate – aluminum–magnesium–silicon alloys. Beneficial effects on mechanical properties and the aluminum producers attempt to eliminate this from their products.

The mechanical properties of the alloys are affected not only by their chemical composition but also by their condition, e.g. Annealed, cold worked, precipitation hardened. It is obviously important; this condition is clearly and unequivocally identified for both the designer and the welding engineer. There are five basic designations identified by a single letter which may be followed by one or more numbers to identify the precise condition. The basic designations are as follows those are (W, F, T, F, and O): T – thermally treated. This identifies the alloys that are aged to produce a stable condition. The 'T' is always followed by one or more numbers to identify the specific heat treatment. T6 – solution heat treated and artificially aged.

Table 3.8 Chemical composition of aluminum alloy 6023 T6

Elements	C	Cr	Mn	Mo	Ni	S	P	Si	V	W
Wt %	1.61	11.50	0.30	0.43	0.15	0.014	0.018	0.25	0.16	0.077

Table 3.9 Physical and mechanical properties of aluminum alloy 6023

Properties	Units	Quantities
Ultimate tensile strength	MPa	360
Yield tensile strength	MPa	300
Elongation at break	%	11
Modulus of elasticity	GPa	69.4
Bulk modulus	MPa	160
Poisons ratio	-	0.33
Shear modulus	GPa	81.0
Density	g/cm^3	2.8
Specific gravity		7.75

3.2.4 Process parameters

In order to produce a successful weld, it is necessary that the material surrounding the tool is hot enough to enable the extensive plastic flow required and minimize the forces acting on the tool. If the material is too cold, then voids or other flaws may be present in the stir zone and in extreme cases the tool may break. Excessively high heat input, on the other hand, may be detrimental to the final properties of the weld.

There are two tool speeds to be considered in friction stir welding; How fast the tool rotates (rotational speed) and how quickly it traverses along the interface (welding speed). These two parameters have considerable importance and must be chosen with care to ensure a successful and efficient welding cycle. The process parameters tool rotation and traverse speed will produce a good quality weld **[2]**. The relationship between the rotation speed, the welding speed, and the heat input during welding is complex, but in general, it can be said that increasing the rotation speed or decreasing the traverse speed will result in a hotter weld **[21]**. Excessively high heat input, on the other hand, may be detrimental to the final properties of the weld. Theoretically, this could even result in defects due to the liquation of low melting point phases (similar to liquation cracking in fusion welds).

The most important welding parameters that determine welding joint quality and mainly studied in this thesis work was tool rotational, welding speed, tilting angle and other FSW parameters like, plunging depth, down ward force is used constant.

3.2.4.1 Tool rotational speed

The rotational speed of the tool results in the stirring and mixing of material around the rotating pin. For, this thesis is three different rotational speeds were used 1250 rpm, 1600 rpm and 2000 rpm.

3.2.4.2 Horizontal feed (welding speed for FSW)

Translation of the tool moves the stirred material from the front to the back of the pin and finishes the welding process. For this work the three different transverse speeds was used 12.5 mm/min, 25 mm/min and 50 mm/min.

3.2.4.3 Tool tilting angle and plunge depth

The plunge depth is defined as the depth of the lowest point of the shoulder below the surface of the welded plate and has been found to be a critical parameter for ensuring weld quality **[23].** Plunging the shoulder below the plate surface increases the pressure below the tool and helps ensure adequate forging of the material at the rear of the tool. Tilting the tool by 0–4 degrees, such that the rear of the tool is lower than the front, has been found to assist this forging process. The plunge depth needs to be correctly set, both to ensure the necessary downward pressure is achieved and to ensure that the tool fully penetrates the weld. Given the high loads required, the welding machine may deflect and so reduce the plunge depth compared to the nominal setting, which may result in flaws in the weld. On the other hand, an excessive plunge depth may result in the pin rubbing on the backing plate surface or a significant under match of the weld thickness compared to the base material. Variable load welders have been developed to automatically compensate for changes in the tool displacement, while the welding institute (TWI) has demonstrated a roller system that maintains the tool position above the weld plate. For this work three different tool tilting angle were selected (i.e. 1˚, 2˚ and 3˚) and the constant plunging depth of tool is 1 mm.

3.2.5 Optimizing the welding parameters

3.2.5.1 Design of Experiment

In the design of experiment (DOE) Taguchi method is commonly used because it is a problem–solving tool which can improve the performance of the product, process design and system. Design of experiment is a technique of defining and investigating all possible conditions involving multiple factors, parameters, and variables in an experiment. To observe the most influential process parameters in the tensile strength and hardness value of weld joint namely rotational speed, welding speed and tilting angle at three levels were considered in case of this thesis.

3.2.5.2 Selection of orthogonal array and Column Assignment

The selection of a particular orthogonal array was based on the number of levels of various factors. Here, to conduct the experiments 3 factors each at 3 levels were selected. Now the Degree of Freedom (DOF) of welding operation can be calculated by the formula as given below.

$$DOF = P*(L - 1) \tag{3.3}$$

Where, P = number of factors

L = number of levels

DOF = 3(3 – 1) = $L_{9,}$ However, total number of experiments of the orthogonal array (OA) should be greater than or equal to the total DOF required for the experiment. Thus, L9 orthogonal array was selected to make the further experiments were shown in Table 3.10.

3.2.5.3 Data Analysis and Optimal setting:

The optimal setting of factors is obtained by drawing main effect. The data obtained is analyzed by raw data of the S/N data (Signal to Noise Ratio) and ANOVA. For S/N data analysis, the conversion of raw data to S/N data is based on the maximizing the value of tensile strength and hardness value was selected as larger is the better type of characteristic. Nine different FSW welding joint were manufactured with different parameters and at different levels. In the Taguchi method the response variation was studied using signal-to-noise ratio and maximizing by optimizing the responses parameter. The larger is the better S/N ratio used for these responses.

3.2.6 Analysis of variance (ANOVA)

The purpose of the analysis of variance (ANOVA) was to find which parameters significantly affect the quality characteristic. ANOVA is the statistical technique used to find the influence of all control parameters. In the analysis of variance, the percentage contributions of each control factor were used to measure the corresponding effects on the performance characteristics. The significance level of 5 %, i.e. for 95 % level of confidence was considered in this analysis. ANOVA results indicate whether there is statistically significance in difference or not in output characteristics. ANOVA analysis involves when α values is below 0.05 is significant and above 0.05 is not significant. From analysis of variance Percentage contribution of each influential parameter was calculated by the following formula:

$$P (\%) = \left(\frac{SSTR - DOF \times MSE}{SST}\right) \times 100 \tag{3.4}$$

Where, P: Percentage contribution of individual factor, SSTR (Adj SS): Sum of squares or treatment sum of squares, DOF: Degree of freedom, MSE (Adj MS): Mean square Error and SST: Total sum of squares.

3.2.7 Confirmatory Experiment:

Taguchi suggested that if the optimal setting is not among the trials of the experiments, then confirmatory experiment should be done to verify the results. A confirmatory experiment is done considering the predicted optimal setting of the factors to verify the results. In these work three parameters (i.e. rotational speed, welding speed, and tilting angle) are selected as input parameters or independent variable. To get optimum parameters by fixing three factors with three levels (i.e. rotational speed (1250, 1600 and 2000 rpm), welding speed (12.5, 25 and 50 mm/min) and tilting angle (1, 2 and 3 degree)). The layout of experiment was given by Taguchi method is listed in the table 3.10 and optimizing method of the parameters was done by both Taguchi method and ANOVA method by using MINITAB 17.

Table 3.10 Experiment layout of Taguchi L9

No. of experiments	Revolution Per Minute	Welding Speed	Tilting Angle
1	1250	12.5	1
2	1250	25.0	2
3	1250	50.0	3
4	1600	12.5	2
5	1600	25.0	3
6	1600	50.0	1
7	2000	12.5	3
8	2000	25.0	1
9	2000	50.0	2

3.2.8 Friction Stir Welding of aluminum alloy 6023 T6

To test the developed fixture's feasibility 2 mm thickness sheets of aluminum alloy 6023-T6 were friction stir welded. The sheets were cut by hydraulic shear machine specification is given in the figure 3.11 into a dimension of 50 mm × 100 mm, 100 mm × 100 mm, 100 mm × 150 mm, 100 mm × 300 mm, 100 mm × 500 mm . Tool steel D2 was used as the tool material that table 3.6 list the chemical composition of the work material and Table 3.7 gives some of its important mechanical and thermal properties. FSW tool depend on workpiece material and thickness. The welding tool with shoulder diameter of 11.7 mm and cylindrical pin with 3.8 mm was using for aluminum alloy sheet of thickness 2 mm. The detailed tool geometry and its image are shown in Fig. 3.9. The welding tool was prepared by turning of D2 tool steel on conventional lathe and heat treated according to standard specification of D2 tool steel heat treated in *Addis Ababa metal development industry*. Welding was performed parallel to the rolling direction of sheets on universal milling machine (model: FU- 281) in *Adama Science and Technology University*. Finally, the welding of AA 6023 T6 performed by combination of parameters set on table 3.10 on FSW welding setup.

3.2.9 Microstructure Observation

Determining grain size and, shape, and distribution of various phases and inclusions was important as these effects of the mechanical properties of the metal. The microstructure would expose the mechanical and thermal treatment of the metal, and it may be possible to predict its behavior under a given sets of conditions. The specimen preparation of sample to examine microstructure was cutting of specimen, grinding, polishing, etching, and observing microstructure by optical microscopy. The procedure of specimen preparation metallographic test was as follows.

3.2.9.1 Cut Specimen from the Sample

The first step of any microstructural test is to; cut the specimen from the sample accurately to the required testing size. For this work ten sample were selected to examine microstructures which is nine from welded sample and one sample from normal sheet metal were selected to examine microstructure for each test. Then one-centimeter length specimen was cut from each sample by using consumable high speed rotating disc abrasive cutter.

3.2.9.2 Mounting Specimen for Microstructural test

The second step of specimen preparation was mounting specimen for microstructural. Specimens cut from each sample were fixed in a holder to be handled easily during polishing, which is necessary to examine microstructure. The mounting operation was done by RB 206 Metpress-A machine using two cup MC-PRC/phenolic resin conductive powder. The maximum heating temperature was 250 ^{0}C and took 1020 seconds/17 minutes (i.e. 300 sec for heating time, 300 sec holding time, and 420 sec for cooling time) for each sample. The machine consists of upper ram, lower ram, heating part and cooled by water controlled by solenoid valve. A small piece of specimen increased in to a 32 mm diameter pellet before grinding and polishing as shown in fig. 3.12.

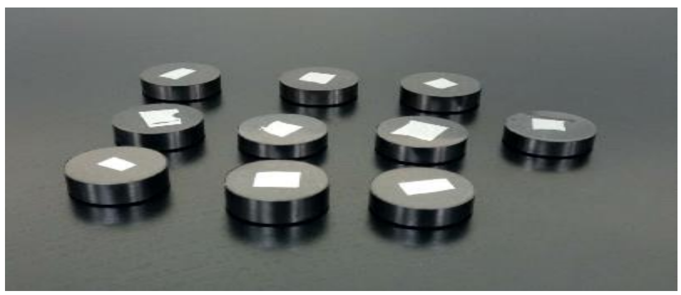


Figure 3.11 Samples of mounted specimen

3.2.9.3 Grinding of Specimen

After a mounting operation, two grinding process were applied on each specimen. The first one was a rough grinding using silicon carbide paper and second one intermediate grinding process using RB 204 Metpol-II machine. The specimen was grinded by the same method and procedure. Firstly, the specimen grinded by 400 grit size silicon carbide paper for about two minute. Again grinded by the following carbide papers 800, 1200 and 2000 grit size respectively. After each step of grinding dust particle is washed by water and removed by compressor. The rough grinding of sample was continued until the surface in flat and free from nicks, burrs, etc.

3.2.9.4 Polishing of specimen

The success of fine polishing depends largely upon the care that was worked during a previous grinding operation step. The final approximation to a flat scratch-free surface was obtained by using of the wet rotating wheel covered with a special cloth that charged with carefully sized abrasive particles. In this step of specimen preparation, the specialized liquid spray on the surface of polishing cloth was diamond suspension liquid is used as spray form. Ten specimens of sample of each test polished four times before the etching. In each of the polishing step, the specimen is washed with water and dried using pressurized compressor. The process continued up to four times until the specimen is free from any scratch and shine surface is obtained.

3.2.9.5 Etching

Etching was the final step of specimen preparation to make the sample visible to many structural characteristics of the metal. This was accomplished by using an appropriate reagent which subjects the polished surface to chemical action**.** All samples were etched by 25 ml hydrochloric acid, 25 ml nitric acid, 25 ml methanol, and one droplet hydrogen fluoride combination. The duration of time of each sample etching was 30 second.

Then the shine surface of specimen put on the table of optical microscopy and examines its microstructure properties. The optical microscopy was having five magnification ranges which are 50×, 100×, 200×, 500×, and 1000×. The scanning area covers 104 mm × 102 mm. Microstructural properties observed by 20 micrometer label.

3.2.10 Hardness Test

Hardness is the properties of material that allows resisting a plastic deformation, usually measured by penetration. It was not a fundamental property of the material. The value of this property was the result of a defined dimension procedure, thus depending on the hardness method used; the hardness value will be different. All hardness tests contain the use of a specifically shaped indenter, significantly harder than the test sample. This indenter is pressed into the external surface of the sample using a specific force. Either the size or depth of the indent is measured to determinate a hardness value. Hardness measurements were extensively used for the superiority control of materials because they are rapid and considered to be non-destructive tests when the marks or indentations produced by the test are in low stress areas. There are many methods to determine the hardness, among those Brinell, Vickers and Rockwell hardness tests are frequently used. In this experiment Vickers's hardness test was used to measure the sample extrudes qualities. Vickers hardness test was measured to determine the hardness of a material, calculated from the size of an impress produces under load by a pyramid shaped diamond indenter. The diamond was pressed on the surface of material at measuring range up to approximately 10 Kgf (kilogram force) and the size of the impression was measured with the help of a calibrated microscope. The Vickers hardness number (HV) was calculated using the following formula:

HV = constant * test force/surface area of indentation.

$= 0.102*2F\ (\sin 136^0/2)/d_1d_2$ (3.5)

Where; F is indentation forces and d_1d_2 is represents indentation area. The Vickers hardness should be reported like 400 HV/10, which means a Vickers hardness of 400, was obtained using a 10kg force. Very accurate readings can be observed in this test, which is one of the main advantages of the Vickers hardness test and just single type of indenter is used for each and every type of metals or surface treatments. From ten samples for each test, 10 mm × 10 mm × 2 mm specimen were cut at the cross section for microstructural study and macro-hardness measurement from each sample. Before macro hardness measurement welded sample mounted and grinded with 400, 800, 1200 and 2000 grit size sand paper and polished by diamond suspension. Macro-hardness was measured with Vickers micro-hardness tester HVS-50 machines just after microstructural test by using both 5Kgf and 10Kgf.

Figure 3.12 Macro hardness test of sample

3.2.11 Tensile test

Tensile testing is one of the most fundamental tests for engineering, and provides valuable information about a material and its associated properties. The samples dimension were 200 mm × 50 mm × 2 mm used depend on standard and machine capacity. The samples were already machined to the proper dimensions required for the test, according to ASTM E8 standards. Three samples of each experiment were tested in the Kinston load frame, and the data gathered into an Excel spreadsheet. The purpose of this experiment was to gather information about each experiment result to get optimum UTS, so that important mechanical properties could be determined.

Each specimen was measured with the calipers to determine the diameter of the cross section. A gage length was determined (typically 50.00 mm) and scribed into the specimen so that the distance between the two marks could be measured after the tensile test was completed. The load cell was zeroed to ensure that the software only measured the tensile load applied to the specimen. The specimen was loaded into the jaws of the Instron load frame so that it was equally spaced between the two clamps. The axial and transverse extensometers were attached to the reduced gage section of the specimen, ensuring that the axial extensometer was set correctly when attaching it to the gage and that the transverse extensometer was across the complete diameter of the specimen. This precaution results in better data and prevents damage to the extensometers.

(a) Tensile test specimens (b) **Tensile test machine**

Figure 3.13 Tensile test specimen and typical Instron load frame used for tensile testing

CHAPTER FOUR

4 Results and Discussion

4.1 Manufactured backing plate

Backing plate designed for FSW provide to support work pieces and manufactured by different process such as; cutting operations, milling operations, drilling operations, thread operation and welding operation are used. Backing plate rigidly secured on milling machine table by the T-nuts bolts of length 21 mm M16 with 2 mm pitch thread to protect the movement of blank during welding process. Figure 4.1 shows the manufactured backing plate. Manufactured backing plate was successfully weld defect free weld joint of AA 6023-T6 alloy sheet within optimized parameters.

a) Backing plate after FSW performed **b) Backing plate secured on milling machine during FSW**

Figure 4.1 FSW setup on conventional milling machine

4.2 Manufactured tool for FSW of AA sheet

The design of the tool is a critical factor, as a good tool can improve both the quality of the weld and the maximal possible welding speed. It is desirable that the tool material be sufficiently strong, tough, and hard wearing at the welding temperature. Improvements in tool design have been shown to cause substantial improvements in productivity and quality. FSW D2 tool manufactured through different operations such as: cutting, turning and heat treatment operation are using. In this thesis work D2 tool steel successfully weld the AA 6023-T6.

a) Bottom view FSW tool after welding

b) Front view of FSW tool after welding

Figure 4.2 FSW tool after welding

The figure 4-2 shows the FSW tool (D2 steel of FSW tool) after welding completely 40 samples (4 m length). The result shows the pin of tool worn out due to friction between the tool and the workpiece during welding. The reduction of pin length is 1 mm (reduced from 1.8 mm to 0.8 mm length) and the diameter of the pin/probe increased by 2.3 mm (increased from 3.8 mm to 6.1 mm).

4.3 Welded Samples at selected welding parameters

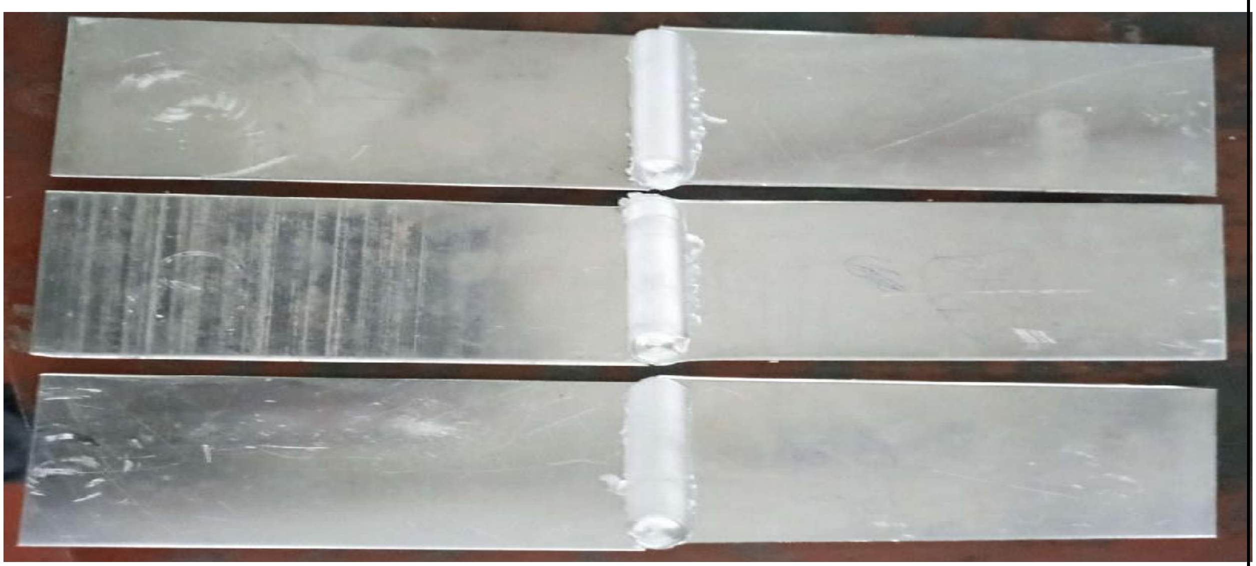


Figure 4.3 welded sample of aluminum alloy 6023 T6 at different parameters

The above figure 4-3 shows the welded specimens at different combination of welding parameters set by Taguchi orthogonal array. AA 6023 T6 welded by FSW on conventional vertical milling machines while comparing the weld joint tensile strength and hardness value improved as the rotational speed increased and decreasing the welding speed.

4.4 Microstructural Test Result

The microstructures of four regions of welding zone are (i) Parent Material, (ii) Nugget, (iii) Heat Affected Zone (HAZ), and (iv) Thermo-Mechanically Affected Zone (TMAZ).

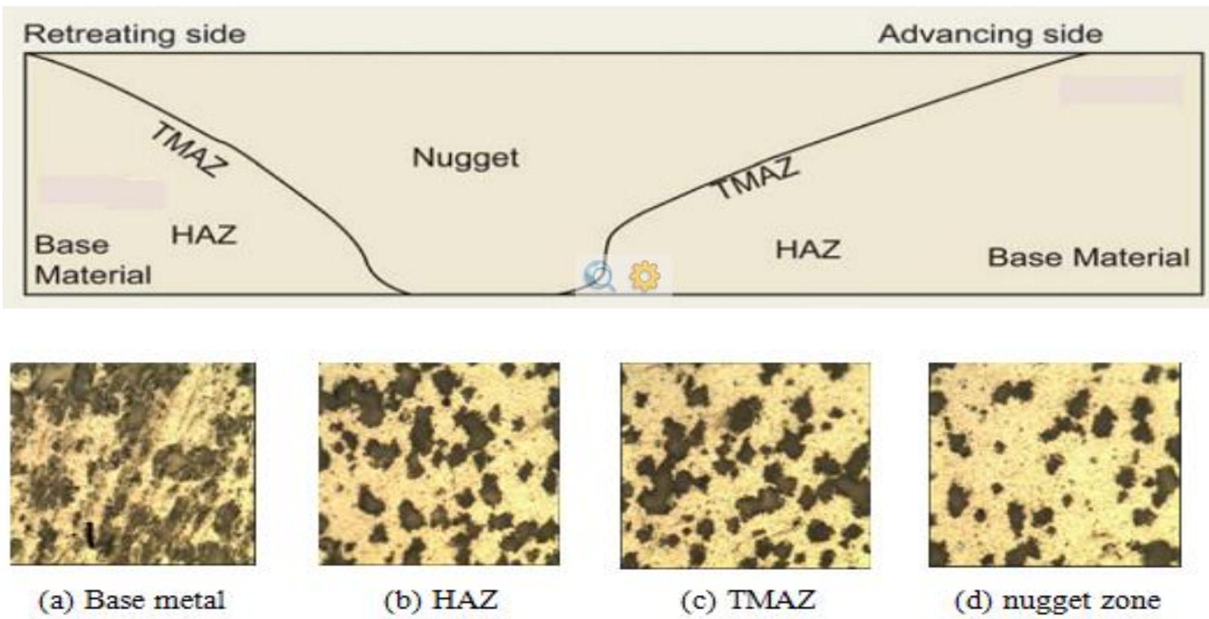


Figure 4.4 Microstructure of FSW in each welding zone

The above figure shows there is grain refinement in the weld joint, as well as defect free friction stir weld joint at optimized parameters of 2000 rpm rotational speed, 12.5 mm/min welding speed and 3˚ tilting angle.

4.5 Hardness test result

Hardness is the resistance of a material to deformation, indentation or scratching. The basic goal of hardness testing is to quantify the resistance of a material to plastic deformation. The hardness of materials has a significant effect on the weld joint. Load used during hardiness test was 98.07

N (10 kgf) on three trails on a sample. For each test, three reputations are followed and an average value was taken. All the experimental data is tabulated in the Table 4.1.

4.5.1 Analysis of Mean for Hardness

The average main value of hardness value for each factor i.e. Rotational speeed (A), Welding speed ((B), and Tilting angle (C) calculated using the Minitab 17 design of experiments. Table 4.1 presents the experimental results of Vickers hardness test for each specimen and their mean values. In this study each Vickers hardness trial value is the average of three trial reading.

Table 4.1 Experimental result for mean value of hardness value

Experiment No.	**Rotational speed (rpm)**	**Welding Speed (mm/min)**	**Tilting Angle (degree)**	**Hardness Value (HV)**			**Avg. HV (for 10 kgf)**	**Weld Performance HV (%)**	**S/N Ratios**
				Trial 1	**Trial 2**	**Trial 3**			
Base Metal							**54.03**		
1	1250	12.5	1	48.7	49.0	48.2	48.63	90.00	35.7034
2	1250	25	2	46.2	50.1	49.8	48.70	90.14	35.6000
3	1250	50	3	49.6	48.2	46.4	46.07	85.26	35.1473
4	1600	12.5	2	55.2	51.7	48.6	51.83	95.93	36.1707
5	1600	25	3	50.7	50.9	49.7	50.43	93.34	36.0193
6	1600	50	1	47.1	47.4	48.2	47.57	88.04	35.3959
7	2000	12.5	3	52.2	54.3	54.4	53.63	99.26	36.4375
8	2000	25	1	51.8	51.3	51.4	51.50	95.32	36.1153
9	2000	50	2	49.3	49.0	47.7	48.67	90.08	35.7107
Average performance mean value							49.66	91.93	35.811

The mean value of hardness vlue for each factor i.e. Rotational speeed (A), Welding speed ((B), and Tilting angle (C) at each level are obtained and the result is listed in response table 4.2.

Table 4.2 Response table for main effects plot for larger is better

Level	Rotational speed	Welding speed	Tilting angle
	Symbol		
1	68.13	**73.21**	70.18
2	71.19	71.57	70.89
3	**73.08**	67.62	**71.33**
Delta	4.94	5.60	1.16
Rank	2	1	3

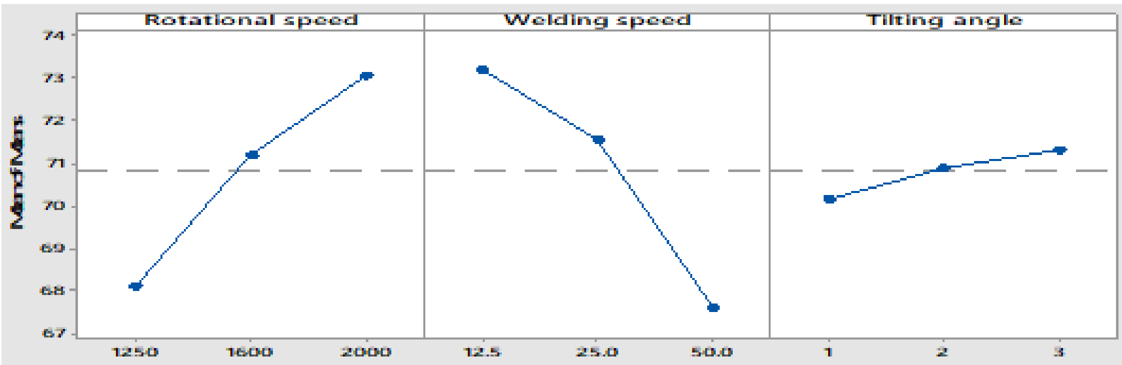


Figure 4.5 Result obtained using Minitab software

The control factors main effect plot for means of hardness value variations is as shown in the Figure 4.5. The result taken from the above data shows means as lager is better is selected for hardness value output.

Delta = (maximum mean – minimum mean). 4.1

Table 4.2 and Figure 4.5 show that the factor with the greatest effect on the mean from table 4.1 is welding speed weight (Delta 5.60 =, Rank = 1). The factor with the least effect on the mean is tilting angle (Delta = 1.16, Rank = 3). Since main effect plots for means is helpful for adjusting the mean on better value. Those parameter levels with better hardness value of specimens that means **A3B1C3** will be taken as a possible parameter combination for better values.

4.5.1.1 Predict the Performance at Optimal Levels the mean value

For predicting the optimum response, three factors of parameters are selected by mean value. **A3B1C3** is the optimum levels of parameters mean value for hardness value. To find out predicted value of the responses (hardness value) the following equation is used:

$$Yopt = m + (mA3 - m) + (mB1 - m) + (mC3 - m) \quad 4.2$$

Where, m = Average performance mean value for tensile strength, $mA3$ = optimum level value for parameter A, $mB1$= optimum level value for parameter B, $mC3$= optimum level value for parameter C.

$Yopt$=70.80 + (73.08-70.80) + (73.21-70.80) + (71.33-70.80) =70.80 +5.22

$Yopt$=76.02 (predict mean value for hardness value).

4.5.1.2 Analysis of S/N Ratios for tensile strength

The Taguchi method uses S/N ratio to measure the variations of the hardness value in experimental design. The equations for calculating the signal to noise ratios are based on the characteristics of the response variables being reported. In this thesis, the response variables are larger-the-better. Table 4.3 presents the calculations of S/N Ratios for hardness value results using the Minitab 17 design of experiments.

Table 4.3 Response Table for Signal to Noise Ratios Larger Is Better

Level	Rotational speed	Welding speed	Tilting angle
	Symbol		
	A	B	C
1	35.48	**36.10**	35.74
2	35.86	35.91	35.83
3	**36.09**	35.42	**35.87**
Delta	0.60	0.69	0.13
Rank	2	1	3

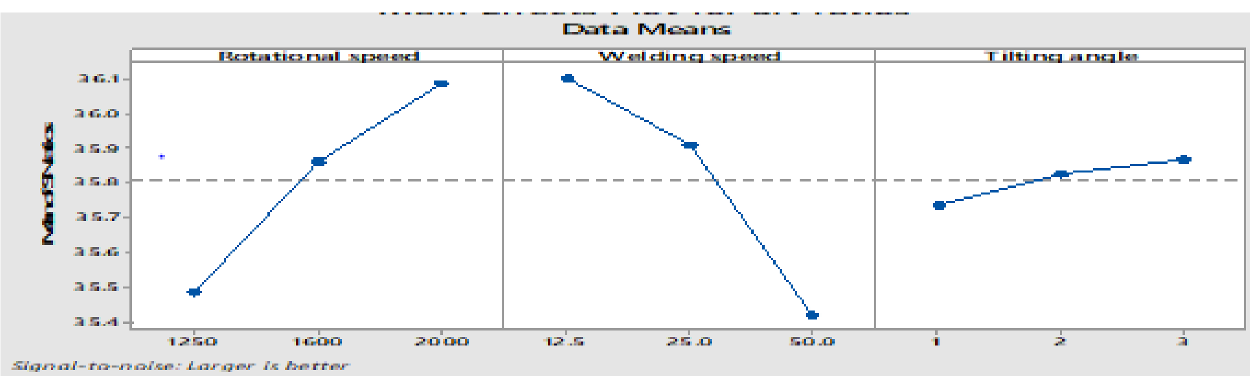


Figure 4.6 Result of main effects plot for means

The control factors main effect plot for S/N ratios of hardness value of weld joint variations is as shown in the Figure 4.6.

Delta = (maximum S/N – minimum S/N)

Table 4.3 and Figure 4.6 show that the factor with the greatest effect on the S/N from table 4.3 is welding speed weight (Delta 0.69 = Rank = 1). The factor with the least effect on the S/N is tilting angle (Delta = 0.13, Rank = 3). Since main effect plots for S/N is helpful for adjusting the S/N on better value. Those parameter levels with better hardness value of specimens that means **A3B1C3** will be taken as a possible parameter combination for better values.

4.5.1.3 Predict the Performance at Optimal Levels the S/N Result

For predicting the optimum response approximately, three factors of parameters are selected by large S/N ratio value. **A3B1C3** is the optimum levels of parameters S/N ratio value for hardness value. To find out predicted values of the response (hardness value) equation 4.2 was used:

$Yopt = m + (m\text{A3} - m) + (m\text{B1} - m) + (m\text{C3} - m)$

= 35.81+ (36.09-35.81) + (36.10-35.81) + (35.87-35.81) = 35.81+0.54

= 36.85 (predicted S/N for hardness value)

4.5.2 Analysis of Variance (ANOVA) for hardness value

ANOVA results DOF = degree of freedom, SSTR = Sum of squares, MSE = Mean square error and F = F- Ratio calculated by using Minitab 17 software were shown in table 4.4.

Table 4.4 Analysis of Variance for hardness value

Source	DF	SST	SSSTR	MSE	F	P	Percent contribution	Significance (α=0.05)
Rotational speed	2	0.55932	0.55932	0.29766	25.62	0.038	41.17 %	Significant
Welding speed	2	0.75111	0.75111	0.37555	34.41	0.028	55.28 %	Significant
Tilting angle	2	0.02643	0.02643	0.01322	1.21	0.452	1.94 %	Insignificant
Residual error	2	0.02118	0.02118	0.01091			1.56 %	
Total	8	1.35869					100 %	

Table 4.4 presents hardness value percentage contribution variation of factors A, B, and C. It is observed that both rotational speed and welding speed factor has statistical and physical significances on the hardness value of weld joint during rotational speed at 95% confidence level. From the table 4.3 it is clearly observed that the rotational speed weight percentage (41.17 %), welding speed (55.28 %) and tilting angle (1.94 %) have significant influence on weld joint of FSW of AA 6023-T6 alloy sheet.

4.5.3 Determining the Optimum Condition for hardness value

From above discussion welding speed weight percentage optimum level value 2000 rpm, welding speed optimum level value 12.5 mm/min, and tilting angle optimum level value 3˚ make the response S/N ratio values highest. Therefore, the optimum processing parameters signal to noise (S/N) ratio is selected. Table 4.5 presents the optimum parameters setting selected for hardness value obtained from the design of experiment and experimental results.

Table 4.5 Optimum parameters setting levels and their values

Controllable factors	Level selected	Value of the level	Rank of affecting the response
Rotational speed	3	2000	2
Welding speed	1	12.5	1
Tilting angle	3	3	3

4.6 Tensile test result

4.6.1 Analysis of Mean for tensile strength test

The average main value of tensile strength for each factor i.e. Rotational speeed (A), Welding speed ((B), and Tilting angle (C) calculated using the Minitab 17 design of experiments. Table 4.1 presents the experimental results of UTS machines for each specimen and their mean values. In this study each UTS machines trial value is the average of three trial reading.

Table 4.6 Experimental result for mean value of tensile strength

Experiment No.	**Rotational speed (rpm)**	**Welding Speed (mm/min)**	**Tilting Angle (°)**	**Tensile Strength (MPa)**			**Avg. UT (MPa)**	**Weld Performance**	**S/N ratios**
				Trial 1	**Trial 2**	**Trial 3**		**Strength (%)**	
Base Metal							**210**		
1	1250	12.5	1	178.3	165.8	163.7	169.26	80.60	41.3412
2	1250	25	2	167.0	164.5	133.7	155.07	73.84	40.5802
3	1250	50	3	165.5	188.7	152.0	168.74	80.35	41.3138
4	1600	12.5	2	162.0	156.0	153.3	157.10	74.81	40.6937
5	1600	25	3	150.0	135.0	174.0	153.00	72.86	40.4639
6	1600	50	1	152.5	139.5	142.0	144.67	68.89	39.9769
7	2000	12.5	3	204.5	178.7	200.8	194.67	92.70	42.5563
8	2000	25	1	178.5	178.0	179.5	178.70	85.10	41.8126
9	2000	50	2	204.5	153.0	178.4	178.64	85.07	41.8086
Average performance mean value							166.65	79.36	41.17

The mean value of tensile strength for each factor i.e. Rotational speeed (A), Welding speed (B), and Tilting angle (C) at each level are obtained and the result is listed in response table 4.7.

Table 4.7 Response table for main effects plot for larger is better

Level	Rotational speed	Welding speed	Tilting angle
	Symbol		
	A	B	C
1	128.1	**135.5**	127.9
2	118.1	126.4	127.5
3	**143.4**	127.8	**134.1**
Delta	25.3	8.9	6.7
Rank	1	2	3

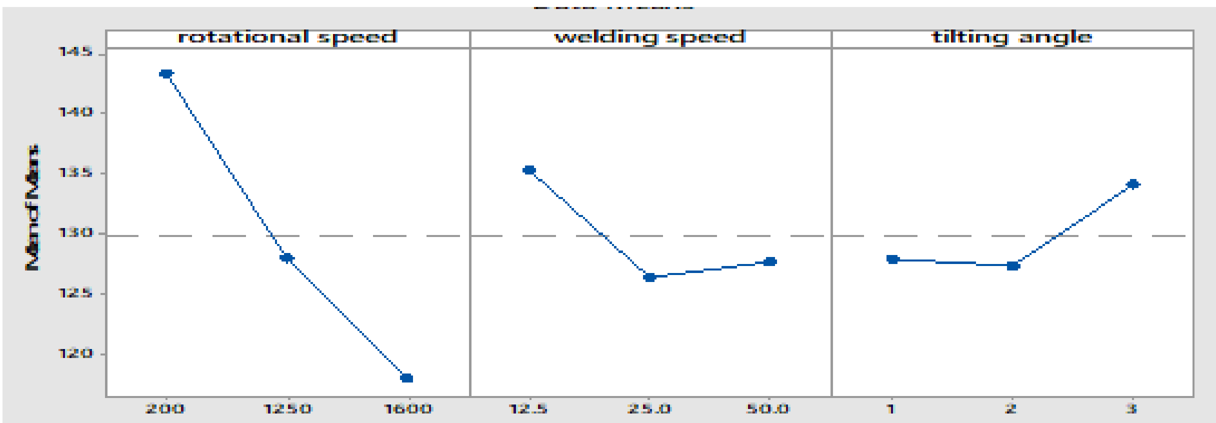


Figure 4.7 Result obtained using Minitab software

The control factors main effect plot for means of tensile strength variations is as shown in the Figure 4.7. The result taken from the above data shows means as lager is better is selected for tensile strength output.

Delta = (maximum mean – minimum mean).

Table 4.7 and Figure 4.7 show that the factor with the greatest effect on the mean is rotational speed weight (Delta 25.3 =, Rank = 1). The factor with the least effect on the mean is tilting angle (Delta = 6.7, Rank = 3). Since main effect plots for means is helpful for adjusting the mean on better value. Those parameter levels with better hardness value of specimens that means **A3B1C3** will be taken as a possible parameter combination for better values.

4.6.1.1 Predict the Performance at Optimal Levels the mean value

For predicting the optimum response, three factors of parameters are selected by mean value. A3B1C3 is the optimum levels of parameters mean value for tensile strength. To find out predicted value of the responses (tensile strength) the equation 4.2 is used:

$Yopt = m + (mA3 - m) + (mB1 - m) + (mC3 - m)$

$Yopt$=129.849 + (143.4-129.849) + (135.5-129.849) + (134.1-129.849) =129.849 +23.453

$Yopt$=153.302 (predict mean value for tensile strength).

4.6.1.2 Analysis of S/N Ratios for tensile strength

The Taguchi method uses S/N ratio to measure the variations of the tensile strength in experimental design. In this thesis, the response variables are larger-the-better. Therefore, larger-the-better characteristic was used and S/N equation for this characteristic is given in equation. Table 4.8 presents the calculations of S/N Ratios for tensile strength results using the Minitab 17 design of experiments.

Table 4.8 Tensile strength response table for S/N ratio

Level	Rotational speed	Welding speed	Tilting angle
	Symbol		
	A	**B**	**C**
1	41.08	**41.53**	41.04
2	40.38	40.95	41.03
3	**42.06**	41.03	**41.44**
Delta	1.60	0.50	0.42
Rank	1	2	3

After calculating the S/N ratio for each experiment, the average S/N value is calculated for each factor and level as shown in Table 4.8.

Delta = (maximum S/N ratio – minimum S/N ratio).

By Looking at the tensile strength table and main effects plot for the signal-to-noise (S/N) ratios the rotational speed weight have the greatest effect (Delta = 1.60, Rank = 1). The factor with the least effect on S/N ratio is tilting angle (Delta = 0.42, Rank = 3). Table 4.8 shows that optimal parameter combination on larger-the-better character is **A3B1C3** are the possible parameter combinations for increasing the tensile strength of weld joint. The control factors main effect plot for the tensile strength of S/N ratio is shown in the Figure 4.7.

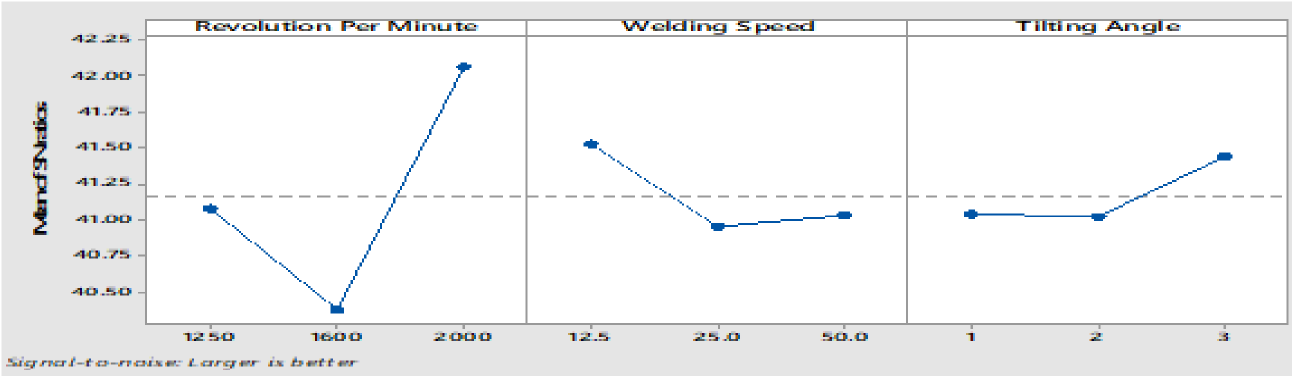


Figure 4.8 Tensile strength main effects plot for S/N ratio

The numerical value of the maximum point in each graph shows the best value of that particular parameter. They also indicate the optimum conditions in the range of the experimental conditions. The most effective parameter to enhance the tensile strength is the rotational speed weight high percentage when compared to other factors.

4.6.1.3 Predict the Performance at Optimal Levels the S/N Result

For predicting the optimum response approximately, three factors of parameters are selected by large S/N ratio value. **A3B1C3** is the optimum levels of parameters S/N ratio value for tensile strength. To find out predicted values of the response (tensile strength) equation 4.2 was used:

$Yopt = m + (m\text{A3} - m) + (m\text{B1} - m) + (m\text{C3} - m)$

= 41.17+ (42.06-41.17) + (41.53-41.17) + (41.44-41.17) = 4.995+1.52

= 42.69 (predicted S/N for tensile strength)

4.6.2 Analysis of Variance (ANOVA) for Tensile Strength

ANOVA results DOF = degree of freedom, SSTR = Sum of squares, MSE = Mean square error and F = F- Ratio calculated by using Minitab 17 software were shown in table 4.9.

Table 4.9 Analysis of Variance for tensile strength

Source	DF	SST	SSSTR	MSE	F	P	Percent contribution	Significance (α=0.05)
Rotational speed	2	353.26	353.26	176.633	83.84	**0.012**	80.68 %	Significant
Welding speed	2	50.185	50.185	25.093	11.91	0.077	11.46 %	Insignificant
Tilting angle	2	30.218	30.218	15.109	7.17	0.122	6.9 %	Insignificant
Residual error	2	4.213	4.213	2.107			0.96 %	
Total	8	437.88					100 %	

Table 4.9 shows tensile strength percentage contribution variation of factors A, B, and C. It is observed that rotational speed factor has statistical and physical significances on the tensile strength of weld joint during rotational speed at 95% confidence level. From the Table 4.9 it is clearly observed that the rotational speed weight percentage (80.68%), welding speed (11.46 %) and tilting angle (6.9 %) have significant influence on weld joint of FSW of AA 6023-T6 alloy sheet.

4.6.2.1 Determining the Optimum Condition

From above discussion rotational speed weight percentage optimum level value 2000 rpm, welding speed optimum level value 12.5 mm/min, and tilting angle optimum level value 3˚ make the response S/N ratio values highest. Therefore, the optimum processing parameters signal to noise (S/N) ratio is selected. Table 4.10 presents the optimum parameters setting selected for tensile strength obtained from the design of experiment and experimental results.

Table 4.10 Optimum parameters setting levels and their values

Controllable factors	Level selected	Value of the level	Rank of affecting the response
Rotational speed	3	2000	1
Welding speed	1	12.5	2
Tilting angle	3	3	3

4.6.2.2 Confirmation Test

Once the optimal combination of process parameters and their levels was obtained, the final step was to verify the predicted result against experimental result. If the optimal combination of parameters and their levels coincidently match with one of the experiments in the OA, then no confirmation test is required. By considering this, Confirmation test was not required in this case study because the optimum combination of parameters and their levels **(A3B1C3**) have a correspondent to an experiment of the orthogonal array of the trail condition (trial 7) of the experiment. The obtained optimal factor combination is one of the trial conditions (Trial 7) of the experiment. Thus, the mean is calculated by averaging the response values of that trial.

The Optimum combination of parameters obtained from above at 2000 rpm Rotational Speed, 12.5 mm/min Welding Speed and 3˚ tilting angle and the Optimized parameters hardness value has been observed as 53.63 HV and the performance of weld joint is **96.26** % related to base metal and the Optimized Tensile Strength has been obtained 194.67 MPa that is **92.70** % of the base material tensile strength. Table 4.11 presents the confirmation experiment and predicted results comparison for both tensile strength and hardness.

Table 4.11 Comparison between predicted and experimental confirmation

	Combination	Tensile strength (MPa)		Hardness (HV)	
		Mean	S/N ratio	Mean	S/N ratio
Predicted	A3B1C3	153.302	42.69	76.02	36.85
Experiment	A3B1C3	151.685	42.5563	76.445	36.4375

The results of confirmation experiment mean and S/N obtained from the experiment were then compared with the predicted mean and S/N results as shown in Table 4.11 for both tensile strength and hardness. It can be seen from this table that the difference between experimental results and the predicted results are very small. The values of predicted by using Taguchi approach is approximately near to the value which is experimentally obtained. These verify that the experimental results of both tensile strength and hardness are strongly correlated with the predicted results.

Aditya and Abhijit Datta (2015) [16] optimized parameters for maximum tensile strength for aluminum alloys and get maximum welding performance of **78 %** base material in this work welding strength performance is increased to **92.70 %** and a weld joint hardness value performance is **99.26** %.

CHAPTER FIVE

5 CONCLUSIONS

5.1 Conclusions

The actual FSW machine price is very expensive, it around one million US dollar**.** This is not favorable for the small industries, university laboratory or any personnel to invest this amount of money for expensive FSW machine. A vertical milling machine is successfully reconfigured and utilized to produce friction stir welding of aluminum alloy 6023-T6 alloy sheet. FSW tools, backing plate and the clamping system are manufactured for this work. Friction Stir Welding has a grain refining effect in the Stir Zone of aluminum alloy 6023-T6 alloy sheet. Mechanical properties are also improved compared to the base material. FSW has performed under appropriate process conditions, joining of aluminum alloy 6023-T6 alloy sheet without defects attained and due to the homogeneous microstructure in the joints. The Optimum combination of parameters obtained from the main effect plot for the S/N ratio and mean with the best combination at **2000 rpm** Rotational **Speed, 12.5** mm/min Welding Speed and **3**˚ tilting angle and the Optimized Tensile Strength and hardness value has been predicted as **194.67** MPa and **53.63 HV** respectively. The result shows:

- Grain refinement in the weld joint, as well as minimizing of welds joint defects at optimized parameters of 2000 rpm rotational speed, 12.5 mm/min welding speed and 3˚ tilting angle.
- FSW is done with defect free weld joint and grain boundary refinement in stirred zone.
- For welded joint hardness performance value the rotational speed weight percentage (41.17 %), welding speed (55.28 %) and tilting angle (1.94 %) have significant influence on weld joint of FSW of AA 6023 T6. The Optimized hardness value has been noted as **53.63** HV that is **99.26** % of base metal hardness.
- For weld joint strength performance value, the rotational speed weight percentage (80.68 %), welding speed (11.46 %) and tilting angle (6.9%) have significant influence on weld joint of FSW of AA 6023-T6 alloy sheet. The Optimized Tensile Strength is shown as 194.67 MPa that is **92.70** % of base material.

5.2 Recommendation

Based on the results and conclusion found from this study, the following recommendations drawn:

- Mild steel is the best material for FSW backing plate, since mild steel has high strength and toughness which is required to with stand unbalanced force and pressure during friction stir welding.
- This work investigation was limited to similar nonferrous material (AA 6023-T6 alloy sheet). However dissimilar material mild steel and AA 6023-T6 also could be tried and analyzed.
- H13 tool is recommended for mass production of friction stir welding operation, since this tool is hot working tool steel.

5.3 Futures work

- Further research work is to be incorporate temperature measurements and measurement of the forces acting during the process.
- Welding different thickness of workpiece to test the backing plate.
- More investigation is needed on mechanical and microstructural test of welded joint in longitudinal weld joint.
- Automation the FSW process is also the future work of this thesis.

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APPENDIX

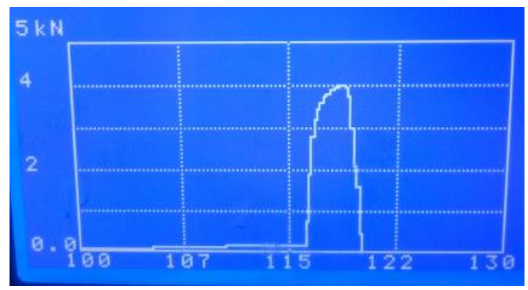
Appendix 1: tensile test result

a) Tensile strength

b) Stress strain curve

Tensile test result of aluminum alloy 6023 T6 at 1250 rpm, 12.5 mm/min and 1˚

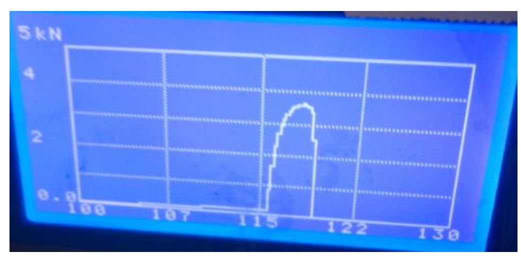
a) Tensile strength



b) Stress strain curve

Tensile test result of aluminum alloy 6023 T6 at 1250 rpm, 25 mm/min and 2˚

a) Tensile strength



b) Stress strain curve

Tensile test result of aluminum alloy 6023 T6 at 1250 rpm, 50 mm/min and 3˚

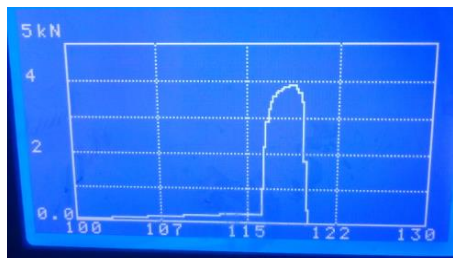
a) Tensile strength

b) Stress strain curve

Tensile test result of aluminum alloy 6023 T6 at 1600 rpm, 12.5 mm/min and 2˚

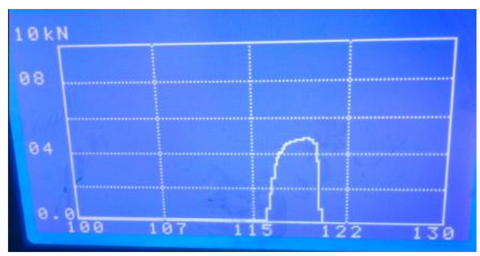
a) Tensile strength b) Stress strain curve

Tensile test result of aluminum alloy 6023 T6 at 1600 rpm, 25mm/min and 3˚



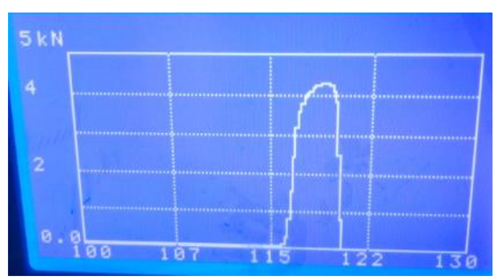
a) Tensile strength b) Stress strain curve

Tensile test result of aluminum alloy 6023 T6 at 1600 rpm, 50 mm/min and 1˚



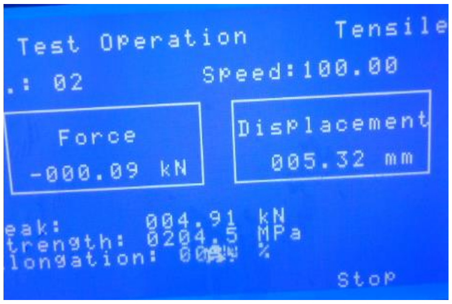
a) Tensile strength b) Stress strain curve

Tensile test result of aluminum alloy 6023 T6 at 2000 rpm, 12.5 mm/min and 3˚

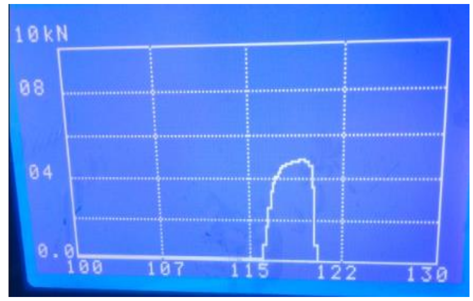


a) Tensile strength b) Stress strain curve

Tensile test result of aluminum alloy 6023 T6 at 2000 rpm, 25 mm/min and 1˚



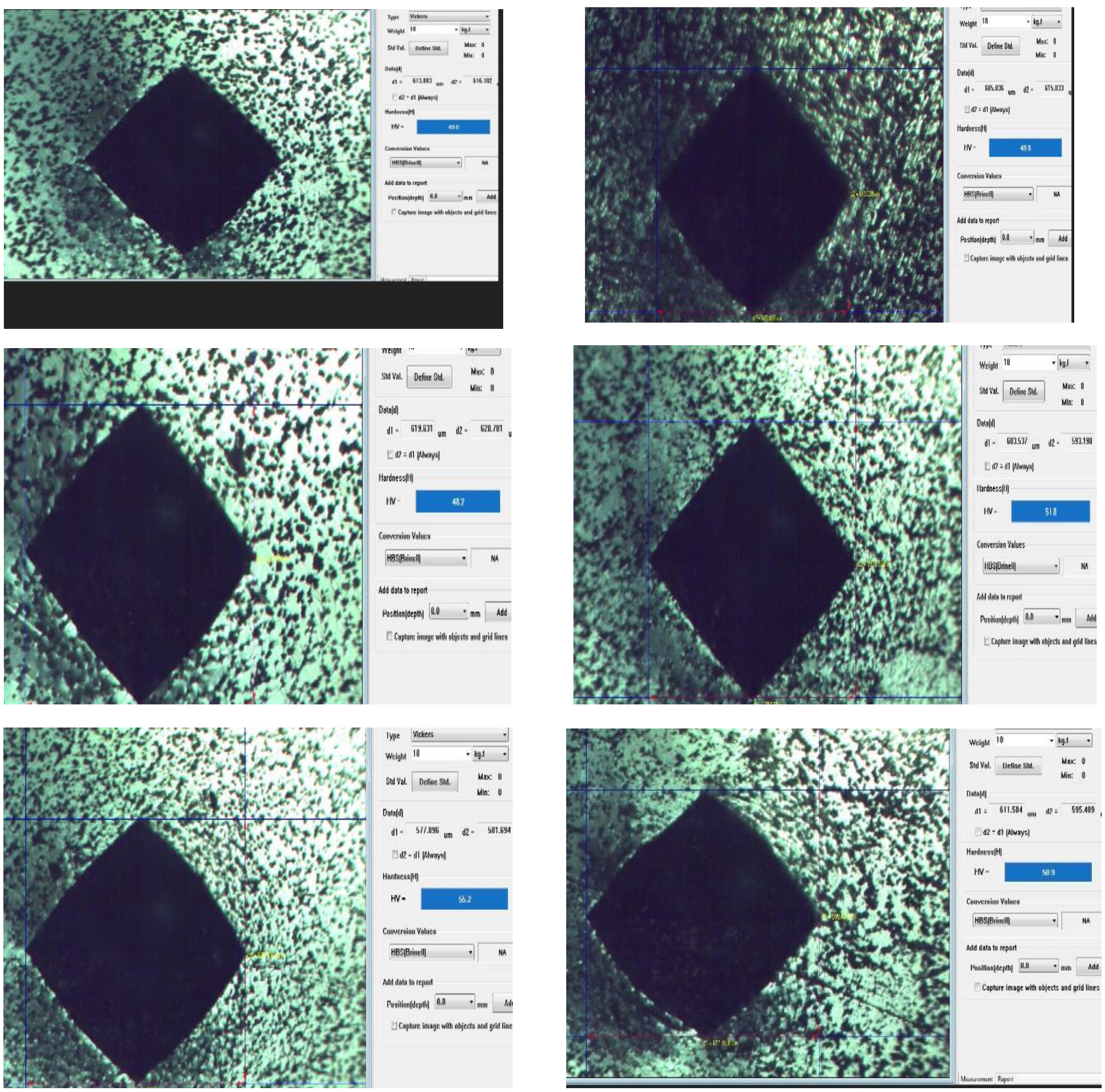
a) Tensile strength



b) Stress strain curve

Tensile test result of aluminum alloy 6023 T6 at 2000 rpm, 50mm/min, and 2˚

Appendix 2: result of hardness test



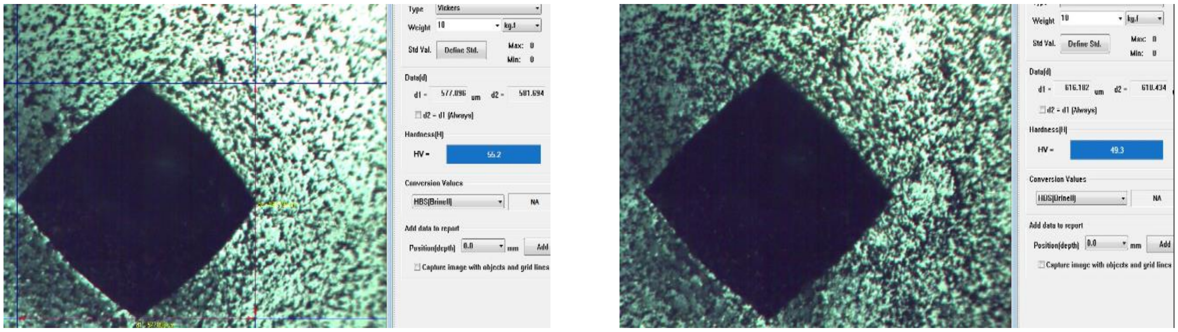
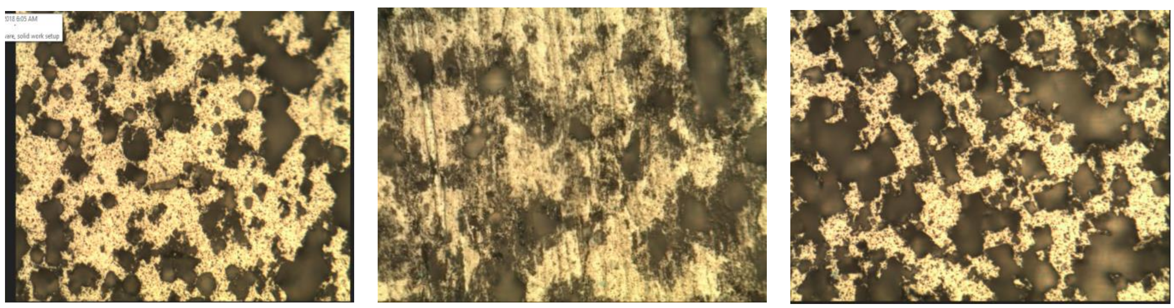
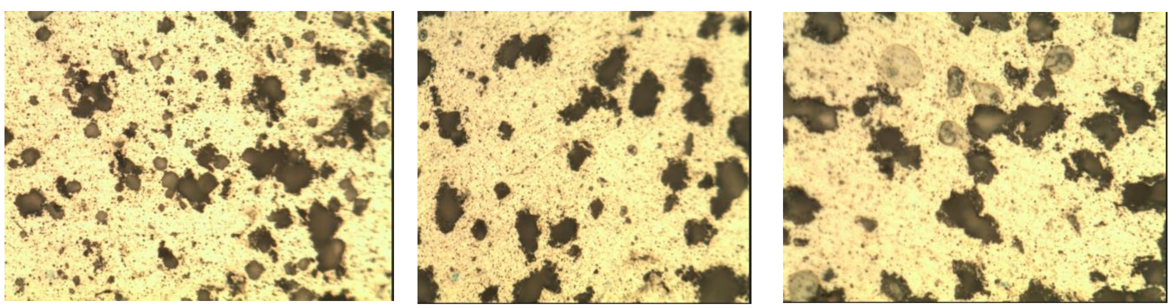


Figure: Hardness test result of aluminum alloy 6023 T6

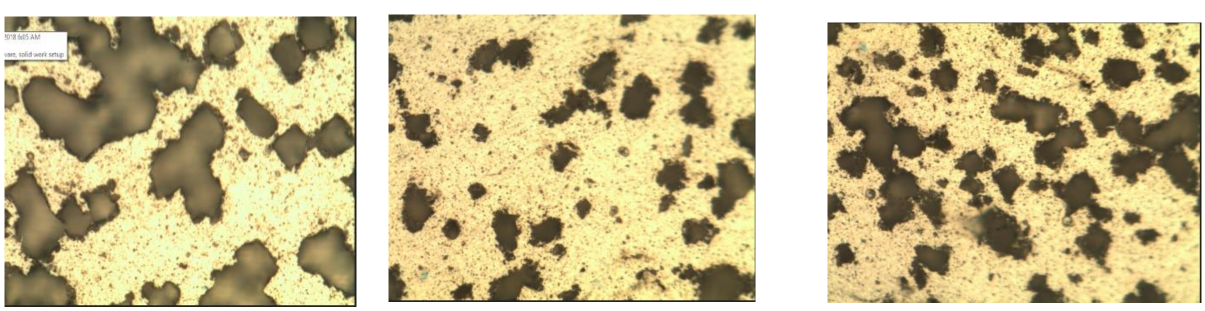
Appendix 3: result of microstructures



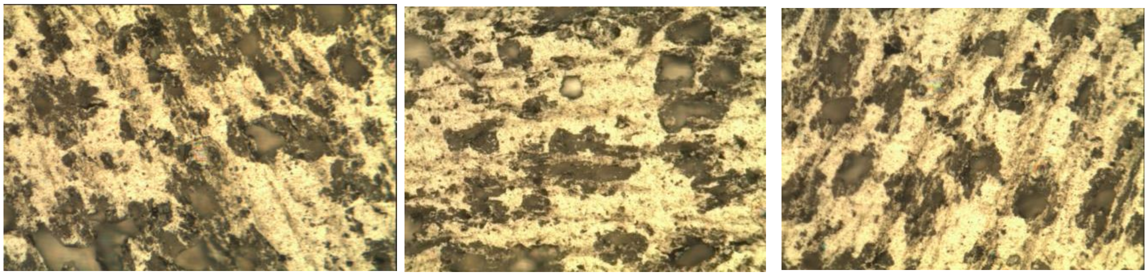
a) Microstructures at 1250 rpm



b) Microstructures at 1600 rpm



c) Microstructures at 2000 rpm



d) Microstructures of base metal

Microstructures result of aluminum alloy 6023 T6

Appendix 4: Taguchi Out Put

Taguchi Analysis: Average HV, welding perf versus Rotational speed, welding speed, tilting angle

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotational speed	2	0.55932	0.55932	0.27966	25.62	0.038
Welding speed	2	0.75111	0.75111	0.37555	34.41	0.028
Tilting angle	2	0.02643	0.02643	0.01322	1.21	0.452
Residual Error	2	0.02183	0.02183	0.01091		
Total	8	1.35869				

Linear Model Analysis: Means versus Rotational speed, Welding speed, Tilting angle

Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotational speed	2	37.339	37.339	18.6696	21.33	0.045
Welding speed	2	49.692	49.692	24.8458	28.39	0.034
Tilting angle	2	2.039	2.039	1.0194	1.16	0.462
Residual Error	2	1.751	1.751	0.8753		
Total	8	90.820				

Response Table for Signal to Noise Ratios
Larger is better

Level	Rotational speed	Welding speed	Tilting angle
1	35.48	36.10	35.74
2	35.86	35.91	35.83
3	36.09	35.42	35.87
Delta	0.60	0.69	0.13
Rank	2	1	3

Response Table for Means

Level	Rotational speed	Welding speed	Tilting angle
1	68.13	73.21	70.18
2	71.19	71.57	70.89
3	73.08	67.62	71.33
Delta	4.94	5.60	1.16
Rank	2	1	3

Taguchi Analysis: TS, Wp versus rotational speed, welding speed, tilting angle

Analysis of Variance for Means ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
rotational speed	2	4.27775	4.27775	2.13888	48.59	0.020
welding speed	2	0.58808	0.58808	0.29404	6.68	0.130
tilting angle	2	0.33517	0.33517	0.16759	3.81	0.208
Residual Error	2	0.08804	0.08804	0.04402		
Total	8	5.28905				

Linear Model Analysis: Means versus rotational speed, welding speed, tilting angle

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
rotational speed	2	971.10	971.10	485.548	91.09	0.011
welding speed	2	137.83	137.83	68.914	12.93	0.072
tilting angle	2	82.62	82.62	41.311	7.75	0.114
Residual Error	2	10.66	10.66	5.331		
Total	8	1202.21				

Response Table for Signal to Noise Ratios
Larger is better

Level	rotational speed	welding speed	tilting angle
1	42.06	41.53	41.04
2	41.08	40.95	41.03
3	40.38	41.03	41.44
Delta	1.68	0.58	0.42
Rank	1	2	3

Response Table for Means

Level	rotational speed	welding speed	tilting angle
1	143.4	135.3	127.9
2	128.1	126.4	127.5
3	118.1	127.8	134.1
Delta	25.3	8.9	6.7
Rank	1	2	3