Characterization and optimization of process parameters on FS welded joints for AA 6023 – T6 aluminium alloy and pure copper

By

Firaol Faraja Wagari

A Thesis Submitted to Department of Mechanical Design and Manufacturing Engineering

School of Mechanical, Chemical and Materials Engineering

Office of Graduate Studies

Adama Science and Technology University

November, 2020

Adama, Ethiopia

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APPROVAL SHEET

We, the undersigned, members of the Board of Examiners of the final open defense by **Firaol Faraja Wagari** have read and evaluated his thesis entitled **"Characterization and optimization of process parameters on FS welded joints for AA 6023 – T6 aluminium alloy and pure copper"** and Examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirement of the degree of Master of Science in Manufacturing Engineering.

Name	Signature	Date
______________________ Name of student	__________	__________
______________________ Advisor	__________	__________
______________________ External Examiner	__________	__________
______________________ Internal Examiner	__________	__________
______________________ Chair person	__________	__________
______________________ Head of Department	__________	__________
______________________ School Dean	__________	__________
______________________ Post graduate Dean	__________	__________

DECLARATION

I hereby declare that the work which is being presented in this thesis entitled **"Characterization and optimization of process parameters on FS welded joints for AA 6023 – T6 aluminium alloy and pure copper."** In partial fulfillment of the requirements for the award of the degree of Masters of Science in Manufacturing Engineering is a realistic record work carried out by myself, that has not been submitted in any previous application for higher degree of any other universities, under the advising and supervisions of **Dr. Perumalla Janaki Ramulu**, Mechanical Design and Manufacturing Engineering Program, Adama Science and Technology University, Adama, Ethiopia.

The matter embodied in this thesis has spent more than one-year time duration to accomplish the whole work and all relevant resources of information used have been currently referred.

Firaol Faraja	______________	______________
Candidate	Signature	Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge and supervision. This research can be submitted for examination with my approval.

Dr. Perumalla Janaki Ramulu	______________	_______________
Advisor	Signature	Date

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ABSTRACT

Friction Stir Welding (FSW) is a solid-state welding process innovated and patented by Wayne Thomas in 1991, at London; the Welding Institute (TWI), used to join metals as well as non-metals in form of butt and lap weld joints. The fundamental concept of this joining process is done by non-consumable rotating tool consists of shoulder and pin by fixing the base materials on the bed of CVMM with a fixture and backing plates. The workpieces were joined together by heat, material movement, and forging action. FSW process has a wide industrial application like automobile, aerospace, marine and fabrication industries.

The aim of this thesis is to characterize mechanical properties and optimize the process parameters of AA 6023 – T6 – Cu dissimilar FS welded joints of 2mm thickness. For an adoption of FSW process on conventional vertical milling machines; FSW tool, backing plates and fixtures were designed. Optical microscope, tensile and hardness machines used to test microstructure, tensile strength and hardiness tests. The quantitative sampling approach is used and the results are taken from machines for 27 sampling size of 9 welded joints. The sound and defect free as well as good grain refinement of the weld joint is obtained at an optimum FSW process parameters for AA 6023–T6 aluminium alloy and pure Cu sheets are chosen at 1600 rpm rotational speed, 12.5mm/min transverse Speed and 2mm tool pin setoff. At an optimized combination of process parameters, the main effect plot for the S/N ratio and mean the Optimized Tensile Strength and hardness value has predicted as 170.40 MPa and 118.41 HV respectively.

***Keywords**: FSW process parameters, Taguchi method, microstructure, backing plates, fixture.*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

Symbols	Description
ASTM	American Society for Testing and Methods
AISI	American Iron and Steel Institute
D_p	Pin or probe diameter
D_p	pin diameters
D_S	shoulder diameter
*D*ps	Pin diameter at tip surface of the tool
*D*pt	Pin diameter at tip surface of the tool
HVN	Vickers Hardness number
t_p	Thickness of sheet metal
OPM	Optical microscope
SPR	shoulder-to-pin diameter ratio
AS	Advancing side
SEM	Scanning electron microscope
*L*p	Pin length
Ps	Shoulder surface profile
Psp	Pin surface profile
R_{sh}	tool shoulder radius
R_{psh}	tool pin radius at shoulder
R_{pt}	tool pin radius at tip
XRD	X-Ray diffraction
RPM	Revolution per minute
θ_{tp}	Tapered angle of the pin
UTM	Universal Testing Machine
GTAW	Gas tungsten arc welding
TEM	Transmission electron microscope

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Friction Stir Welding (FSW) is a solid-state welding process innovated and patented by Wayne Thomas in 1991, at London; the Welding Institute (TWI), for both butt and lap weld joints of metals and nonmetals along with plastics materials**.[1, 2]** These days joining of dissimilar materials, such as aluminium to steel (Al/Fe–C), or aluminium to copper (Al/Cu) is of great interest in engineering and design applications. Welding of such metals is remaining a solemn difficulty on the quality of the weld joints. In this sense, FSW is adopted solid phase welding process in which the pattern materials to be welded have unlike chemical and physical properties are joined each other without melting during welding process and enhance the mechanical properties of the welded joints. This led to use FSW for a wide range of alloys instead of using fusion welding process such as TIG and GTAW**.[3]**

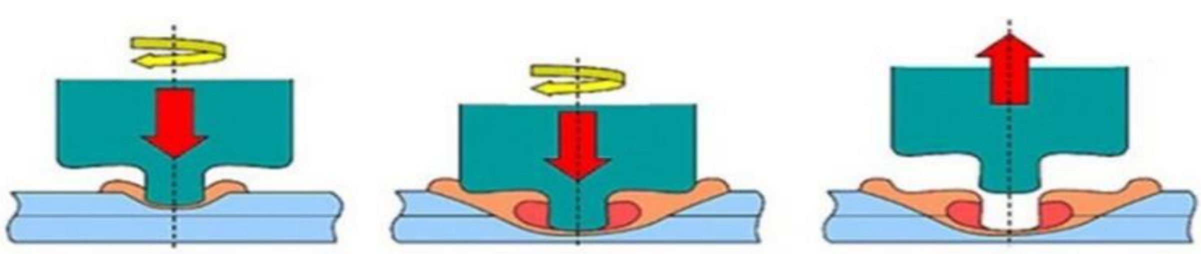
FSW process has many applications, but the welding machine used to perform its process is more expensive than different machines. The progression of using a Vertical Milling Machine as a FSW machine has been implemented with an equivalent performance. The position and the precision of the tool used are the basic issues in FSW processes. While the FSW tool is inserted or plunged in the workpiece there would be a pressure gap created in the workpiece. In order to control or avoid such gaps at the joint line during welding operations, fixtures should be used to fix the workpiece as and the backing plates together for the best joints.[**4**]

1.2 Friction stir welding process

In FSW process there is a non-consumable rotating tool that is prepared by designing the pin and shoulder that are used to create friction, stirring, mixing, and joining of material. Tool pin is plunged between adjoining surfaces of workpiece with appropriate rotational speed up to the shoulder makes an interaction with the workpiece surfaces. The contacting and rubbing action of the pin tool between workpiece yield a large amount of frictional and deformational heating which leads to the softening of workpiece materials. This softened material transported from front to back and top to bottom of the probe when the tool is moved along the weld route. This makes a solid-state joining system for friction stir welding. Contacting the shoulder to the workpiece increases the heat in workpiece and enlarges the zone of softened material, and limits the deformed material.[**5**]

A concurrent translation and rotational motion of the FSW tool does not generates a symmetric about the weld center line. This action is a one of the vital features of FSW process. During FSW there are two sides existed with respect to welding tool, due to this there is material flow paths. One is an advancing side (AS) of the weld which refers the welding tool rotates in the direction of its welding line relative to the workpiece, the material is forced to flow forward along the tool. The left one is retreating side (RS) that refers to the side of rotation and translation of the tool are in the contrary direction. The material on the other side is forced backwards along the tool.[**6**] The leading side of is in front of the tool and the trailing side of the tool is the rear of the weld tool. The top surface of the weld where the tool shoulder contact with the workpiece during a welding is known as a crown and the bottom surface of the weld is known as a root. The basic necessary conditions to be fulfilled in FSW process is shoulder pressure (F) has to be greater than internal pressure of plastic flow metal (P)**.[7]**

During the FSW process there are three main phases: the plunge phase, is the first step of FSW process in which the rotating welding tool is inserted or plunged into the weld joint and this work is typically implemented while the fixture surface and the backing plates are supporting the workpiece to withstand a specific downward axial force generated by the tool pin. Due to frictional heat and pressure of the tool pin, the workpiece is plastically deformed around the tool pin as the tool pin enters the workpiece which are prior to the start of linear welding phase. The plunge phase may be simplified by drilling a hole at the plunge position, reducing the heat and forces produced. The second phase is dwelling, is the main phase in which the heated and softened workpiece is adjacent to the tool deformed plastically, and solid – state bond is made between the surfaces of the upper and lower sheet, the weld joint is produced at this phase. The final phase is called termination - in which the tool is drawn out of the workpiece and protruded pin leaves a characteristic exit hole in the center of the weld joint.[**8**] A pictorial representation is shown in the Figure 1.1.

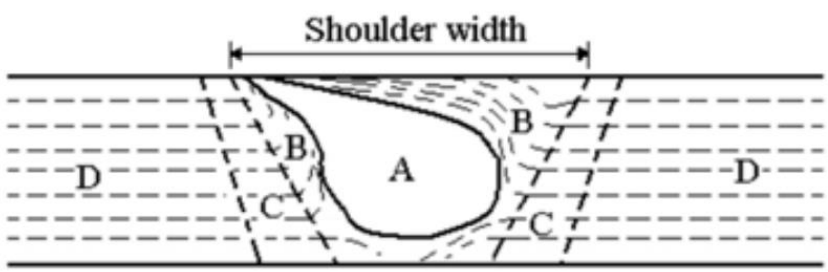


a) Plunge phase **b) dwelling** **c) termination**

Figure 1-1 Basic phases during FSW operation.[9]

1.3 Microstructure zones of the FSW joints

Friction Stir Welding can be considered as a hot-working process where a large amount of deformation is imparted to the workpiece through the rotating pin and shoulder. Based on a microstructural characterization of grains and precipitates normally there are four distinct welding zones for FSW process: the nugget zone or stir zone (NZ / SZ), the thermo mechanically-affected zone (TMAZ), and the heat-affected zone (HAZ) and base material (BM) as indicated in the Figure 1.2.[**1, 2, 9-11**]



A: Stirred zone; B: Thermo-mechanically zone (TMAZ); C: Heat affected zone; D: Base metal

Figure 1-2 An illustration of microstructural regions of friction stir welded material [10]

The properties of FSW joints can be characterized using optical micrographs, X-ray diffraction, and TEM. The shape, size, and distribution of precipitates in weld zones, and the strength and ductility of welds were seen to correlate directly with peak temperatures in weld nuggets and heat affected zones.

1.4 FSW process parameters

The mechanical properties and performance to control FSW joints are independent upon various process variables which includes the tool rotational speed, the transverse speed, the tilt angle of the tool, the downward force on the tool, tool geometry and design (shoulder and pin) and tool pin offset.[**12**] When the process parameter is properly used, defects can be minimized. Mechanical properties and these parameters are responsible for the temperature field, an amount of the heat generation rate, torque exerted by the tool, cooling rate, x-direction force and the power depend on these variables.[**13**] The speed of tool rotational (rpm), the transverse speed (mm/min) and depth of penetration are the basic process parameters in FSW.[**14, 15**]

1.5 Statement of the problem

The issues in the conventional welding technology like GTAW and MIG difficult to join either similar or dissimilar materials of non-ferrous without any defects (formation of brittle phases, porosity, poor surface welded structure, and cracking, etc.) had a critical phenomenon. For solving joining of non-ferrous materials FSW had been introduced in which metal will be joined without any melting point. Even for Al-Cu FS welding joints still critical problem found is defects such as: micro-voids, flash, cracks, and lamellar intercalated structure are existed. These defects are resulted while most of the researchers used not more than two FSW process parameters. In the FSW process, there are many process parameters in terms of tool configuration, tool position, operational parameters, and so on. Selection of exact and suitable process parameters to make proper joints is a challenge in FSW process. Industries required different welding joints profiles made by FSW process. Based on the existing research, the current problem joining of AA 6023 – T6 aluminium alloy and pure Copper through FSW considered introducing to the National applicable industries. The basic idea for selection of aluminium alloy and copper is high strength-to-weight ratio and high electron affinity. Hence, for this work depending upon scientific research and specification of FSW machine used, three process parameter settings such as: - rotational speed, transverse speed, and tool pin offset are selected before accomplishing FSW processes.

1.6 Objectives

1.6.1 General objective

The main objective of the thesis is to characterize the FS welded joints of AA 6023 – T6 aluminium alloy with pure copper and optimize its process parameters.

1.6.2 Specific objectives

The specific objectives of this thesis are to: -

- Design and fabricate fixtures, FS tool and backing plates for friction stir welding process setup which is simple to assemble onto convectional vertical milling machine.
- Conduct FSW experiment at different process parameters such as rotational speed, transverse speed, and tool pin offset at constant depth of penetration and tilting angle which affects welding quality and strength of the FSW material.

- Evaluate the microstructure for each welded joints.
- Evaluate the mechanical properties of FS welded joints using destructive testing such as hardness and tensile tests.
- Optimize the FSW process parameters based on the results of mechanical properties by design of experiments techniques.

1.7 Scope of the study

The main goal of this research work is to develop the basic understanding of friction stir welding process by joining Al 6026 T6 alloy and pure copper sheets that is performed on conventional vertical milling machine having straight butt-welding configuration. This research work is done at Adama Science and Technology University; which aims to provide know-how to make FS butt welded joints having of a defined length 203mm×120mm×thickness 2mm using different FSW process parameters such as rotational spindle speed, transverse speed, and tool pin offset. FSW process has shown to be a realistic technological solution to weld dissimilar Al-Cu joints.

1.8 Significance of the research

The significance of this thesis is to establish the scientific research by making FS welded joints for dissimilar materials of AA 6023 – T6 aluminium alloy and pure Copper under different process parameters and to expand the technology transfer for further research for the next generation. Additionally the combination FS welded joints have an application in different industries like ship buildings and marine industries to join parts such as sides and panels for decks, bulkheads, and floors; automotive and aerospace buildings on many parts such as fuselages, bus bars, wings, empennages, and fuel tanks for space vehicles, underground carriages, and building of container bodies; electrical industry for electrical connectors and electric motor housings, foil conductors of transformers, windings of the capacitors and condensers, heat exchangers tubes as well as in refrigeration.

1.9 Limitation of the study

While I am studied the friction stir welding of Al-Cu, I stayed a lot of periods to obtain the base materials AA 6023 – T6 aluminium alloy and pure Copper of 2mm thickness and D2 steel tool. An absence of these materials at a right time as well as a pandemic of COVID-19 was a constraint that extends my research work.

1.10 Outline of the thesis

This thesis is entitled Characterization and optimization of process parameters on FS welded joints for AA 6023 – T6 aluminium alloy and pure copper. This work embraced six chapters which are: introduction, literature review, working materials and methodology, data collection and analysis, results and discussions, lastly conclusion and recommendations. The first chapter of this paper begins with introduction which consists of the background of FSW, and its process parameters as well as FSW tools. Finally, the problem of the statement, an objective, scope and significance of the study is clearly shown in this chapter. Chapter two presents the FSW basics and shows the related literature review of dissimilar FSW done to realize this research. Chapter three gives detailed information on the working materials and methods. The fourth chapter presents data collections and analysis. It is distinguished that this chapter primarily focuses on aspects of joining between AA 6023 – T6 aluminium alloy and pure copper using FSW. Chapter five presents the results and discussions based on an investigated experiment. The final chapter of the paper presents the general summary by making a sound conclusions and recommendations as well as future scope.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter clarifies that friction stir welding is a joining process used to weld dissimilar materials without the melting point of the base metals and discusses some research of the dissimilar friction stir welding process done by researchers in recent years.

2.2 Material flow and Mechanism of Joining during Friction Stir Welding.

2.2.1 Material flow

The material flow during FSW of dissimilar materials is very complex mechanism. This happens due to material flow in FSW made by the rotational speed of the tool as well as the materials themselves have different properties which cause them to react differently to the forces from the tool it adds another layer of complexity on top. Somewhat a few researchers have stated how the materials have flowed in their research of dissimilar Al-Cu FSW.

Mishra et. al (2007) [**16**] identified the positioning and placement of base materials in joining of dissimilar Al –Cu FSW system considered as a significant factor that highly affecting FSW process parameter, material flow and quality of welding joint. The positioning and placement of the pattern material has a great impact on the butt and lap joint configurations in FSW processes. Material flow in the weld joint area was strongly affected by retreating and advancing sides. Other researchers [**17-20**] were also highly recommended, when the softer material was placed at the retreating side, the material was transported to the advancing side behind the probe easily, and the material flow increases in the nugget zone towards the advancing side. Therefore, for butt joint configuration of the FSW process, the position of the materials from the retreating side and advancing side should be Al and Cu respectively.

2.2.2 Mechanism of Joining during Friction Stir Welding

Friction stir welding can be deliberated as a metalworking process with five conventional zones. These zones involve preheat, initial deformation, extrusion, forging, and post heat/cool down, Figure 2.1 (a). For two reasons the temperature will rise at the head of the pin in the preheat zone. These reasons are the frictional heating due to the rotation of the tool and adiabatic heating due to the deformation of material. The heating rate and extent of preheat zone are governed by the transverse speed of the tool and the thermal properties of the workpiece. The initial deformation zone created as the tool moves forward.

This formation happens when the workpiece is heated above the critical temperature, and the stress exceeds the critical flow stress of the material. These two reasons of forming the deformation zone leads to the material flow. The material in the initial deformation zone is forced downwards into the extrusion zone and upwards into the shoulder area, as illustrated in Figure 2.1 (b). The extrusion zone location is around and at the end of the pin. In this region, where vortex flow patterns exist, a small amount of material is captured in the swirl pin specifically under the pin tip. The width of this zone is defined by the critical isotherm on both sides of the welding tool, where the temperature and the stress in this region are not be adequate to allow metal flow. When the material is in front of the welding tool and then is forced into the shoulder reservoir, it is called the forging zone. This process occurs when the pin or probe moves under hydrostatic pressure. The tool shoulder has two very important functions; applying a downward forging force and restricting the material flow in the cavity. The material beneath the tool shoulder is dragged into the joint zone; this dragged material starts from the retreating side and moves across the advancing side. The final zone is post heat/cool down zone which is located behind the forging zone. In this zone, the material can cool under either forced cooling or passive conditions. Finally, material flow can be influenced by the material type, and material temperature.

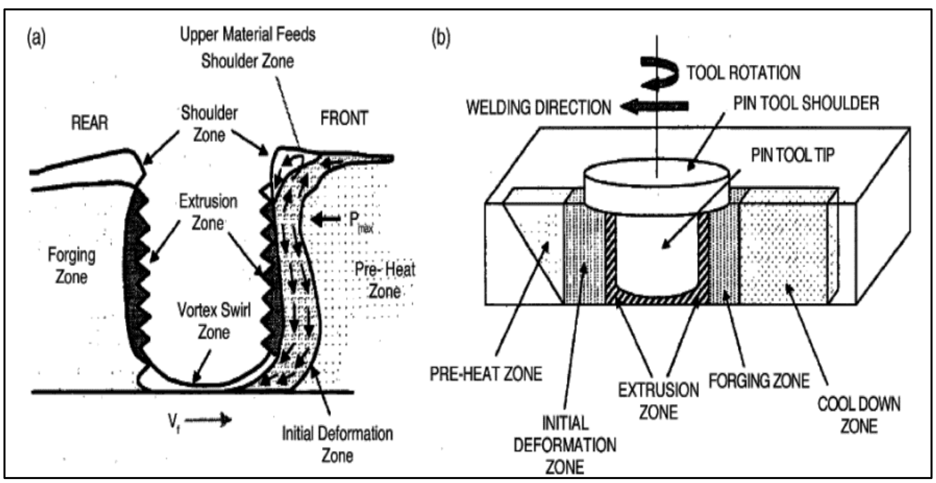


Figure 2-1 (a) Metal flow patterns and (b) metallurgical processing zones developed during friction stir welding [21]

In principle, friction stir welding is a technique in which two similar or dissimilar plates are to be welded in a required welding joint configuration (butt or lap) and fastened to stationary backing plate. The joining in the FSW process takes place by extrusion and forging of the metal at high strain rates.

2.3 Comparison between conventional welding and FSW

Nowadays there is some source for technical justification to use FSW process when compared to conventional welding methods. Many researchers have been justified the main distinctive points of FSW compared to: tungsten inert gas (TIG), GTAW processes. These includes: -

Kumar et al. (2014) [22] studied the comparison between conventional welding processes TIG, MIG and FSW depending on the heat input and welding joint efficiency for AA6061 aluminium alloy. The results of the study were established that, among three welding processes for FSW heat input 31% less as equated TIG welding and 51.2% less as equated to MIG welding as well as FSW joint efficiency is 19.4% and 35.5% greater when compared to TIG and MIG welded joints respectively. Heat –affected zone of TIG was wider than friction stir welding process. **Thakur et al. (2015) [23]** studied the comparison of experimental investigation of FSW and conventional fusion welding process tungsten inert gas (TIG) welded joints of AA 6063-T6 and the weld joint fabricated by FSW process have found to possess more the tensile strength and higher hardness with higher ductility than TIG weld joints. The weld joint efficiency for the FSW was approximately about 70% while 67% for TIG weld joint. Consequently, the dynamic recrystallization the microstructure of FSW joints were equiaxed grain structures and uniformly distributed very fine strengthening in the weld region. The XRD collected surface residual stresses measurements per location formed in both transverse and longitudinal directions and showed more value for TIG than FSW. **Balasubramanian et al. (2018) [24]** joined AA 6063 alloy in butt welding configuration by using conventional GTAW and FSW processes; in their studies they investigated tensile strength, impact strength and hardness of the weld joints produced by FSW process was high compared to GTAW joints as well as due to the stirring action of the tool FSW process produced very fine grain size of the weld joint than GTAW.

2.4 FSW Tool configuration

In FSW process the tool design and its geometry are very significant factor to producing sound welds. Hence, here the different types of tools used by researchers are listed hereafter.

Tomas *et al.* (2003) [25] established two new pin geometries of the tool for friction stir welding purpose: Flared-Triflute^{TM}, with the flute lands being flared out, and A-skew^{TM} with the pin axis being slightly inclined to the axis of machine spindle. From the result when equated to the conventional threaded pin, A-skew^{TM} and the Flared-Trifute^{TM} pins can enlarge welding region, shrink the upper plate thinning, enhance over 100% in transverse speed about 20% reduction in axial force and provide an orbital forging action at the root of the weld. **Zhao *et al.* (2006) [26]** studied the influence of tool pin geometry on material flow in friction stir welding process of Al 2014 alloy plates. The Cylindrical and Tapered Tool probes did not confirm effective mixing in the vertical direction leading to wormholes at the base of the thermo mechanical affected zone (TMAZ). At a Tapered Tools with threads were used, the welded joint obtained was free from defect welds. **Akinlabi *et al* (2010) [27]** studied the characterization of Dissimilar FSWs between 5754 Aluminium Alloy and C11000 Copper and successfully welded by using H13 tool steel and hardened to 52 HRC by employing the concave shoulder and threaded pin tool of geometric profile. **Aissani *et al.* (2010) [28]** designed a tri-flute type pin FSW tool. The geometry of the tool pin was conical threaded type. The FSW tool components that the researchers used was E24 mild steel. However, the pin and the shoulder material were fabricated from heat treated low alloyed – medium carbon steel 42CD4 steel. At the first test due to a bad selection of welding parameters defects were observed on an upper surface of the welding bond. The results gained not allowed giving sufficient efficiency. However, increasing the former transverse speed of the FSW more heat input was supplied by shoulder of the tool. This leads to two sheets AA2024-T4 and AA7075-T6 alloys were welded in excellent condition without any cracking, distortion or void.

Palanivel and Mathew (2011) [29] studied The Tensile behavior of friction stir welded dissimilar Aluminium of AA6351-T6 and AA5083-H111. The researchers investigated an experimental work using five different tools made of High Carbon High Chromium steel (HCHCr) having different pin profiles of: - Straight Square, Tapered Square, Straight Hexagon, Straight Octagon and Tapered Octagon without draft were used to weld the FSW joints. Among different pin profile of the tools the joint produced by the tapered octagon pin profiled tool had the lowest tensile strength. Higher transverse speed is associated with low heat inputs which results in fast cooling rates of the welding joint. In the tapered pin profiled tools, the same principle affects the material flow. Since the tapered square and tapered octagon pin profile sweeps less material when compared to that of the straight square pin tool, this joint exhibit less tensile properties. **Zhao *et al.* (2012) [30]** studied an experiment with three different types of tool pin profiles, threaded cylindrical, straight cylindrical, and taper cylindrical and determined that, the taper pin is extremely effective to attain high strength dissimilar Cu–Al FSW joint.

Cheepu et al. (2014) [31] studied the mechanical properties of friction stir welding joint between two dissimilar materials of pure titanium (Ti-6Al-4V) and stainless steel (304 SS). The tests, like the hardness test, tensile test, and bending test were conducted on the FSW joints. The welding joint was produced by inserting aluminium between titanium and stainless steel to prevent a formation of IMCs. However, TiAl and TiAl intermetallic compounds were produced that results decrease in microhardness strength of the welding joint. **Jawdat A *et al* (2014) [32]** joined the dissimilar FSW of pure copper and 6061 aluminium alloy sheets on a conventional vertical milling machine and investigated its surface morphology and mechanical properties of the butt joint welding configuration. The researchers arranged Aluminium in an advancing side and copper in retreating side as well as the tool used was high carbon steel having square pin that results in voids, poor surface quality, and cracks formed in copper side. **Sadeesh *et al* (2014)** [**33**] joined the dissimilar AA2024 (Al-Cu alloy) and AA6061 (Al-Mg-Si alloy) aluminium plates of 5mm thickness adopting friction stir welding (FSW) technique. The welding tool AISI H13 steel having different geometric profiles such as: cylindrical threaded pin, cylindrical pin, squared pin, tapered pin and stepped pin used. However, using cylindrical threaded pin and squared pin are found to be the best tool profiles that were produced welds without any defect at constant tilt angle of 2^{o} with process parameters of 28 mm/min and 710 rpm and 40 mm/min and 1000 rpm respectively. On other hand by using stepped pin, cylindrical, and tapered, under the same process parameters due to an absence of vertical motion of the material few macroscopic defects occurred.

Hasan *et al.* (2015) [34] studied fixtures and backing plates to join dissimilar materials of aluminium alloys of AA7075 – T6 and AA6061 –T6 rolled sheets by using FSW technique in butt configuration on vertical milling machine. In their study they were used a tool made of H13 steel having 12mm shoulder diameter with a surface profile of 8° concave, 4.2mm pin diameter with a tapered profile at 10°, the pin length was 2.7mm. The process parameters used during FSW operation were the rotational speed at 1000, 1100 and 1200 rpm; the transverse speed at 250, 300 and 350 mm/min and constant tilting angle at 3^{0} were used. **Padmanaban *et al.* (2015) [35]** studied dissimilar FSW joints between AA7075-T6 and AA2024-T3 alloys plates and an effect of tool, transverse speed and rotation speed on both tensile strength and microstructure. The experimental apparatus was conducted on a vertical milling machine. A tool designated was cylindrical threaded tool made of high-speed steel. Even though heat is generated at 900 rpm was not sufficient for rotational speed tool; at above 1200 rpm all the performed experiment to test the tensile strength of the specimens were failed due to an existence of micro voids and flash defect.

Yazdipour et al. (2016) [36] joined dissimilar butt friction stir welding of Al 5083-H321 and 316L stainless steel plates and studied the effect of the transverse speed, tool pin offset at constant rotational speed of 280 rpm. Due to uncomfortable selections of FSW process parameters they investigated the formation of the tunnel and void defect, continuous microcracks, $FeAl_3$ IMCs, and large steel fragments with a low strength. **Selamat *et al.* (2016) [10]** discussed on late innovation of similar and dissimilar FSW of aluminium alloys AA5083 and AA6061 particularly on butt welding joint by using H13 steel welding tool. The shape of this tool geometry was simple and cylindrical threaded in profile. **Sharma *et al.* (2016) [37]** studied tensile strength of dissimilar FSW alloys AA6061 and MgAZ31 joint by using HCHCr and H13 steel tools having different tool pin geometries. During the experiments have been performed the main process parameters taken were transverse speed and tool rotational speed; the tools used were HCHCr and H13 steel having different tool pin profiles such as Cylindrical Threaded Pin, Cylindrical Flute Pin, and Cylindrical Groove Pin was used.

Prasanna *et al* (2016) [38] studied an analogy of the microstructures and mechanical properties of FSW joint of Aluminium to Brass and Al6061 and pure copper plates in 4mm thickness on convectional vertical milling machine. In conducting the experiment H13 tool having a tapered shoulder and pin used and the result of the product was free from defects. **Mehta *et al.* (2016) [39]** studied effects of tool pin design on formation of defects in dissimilar friction stir welding of AA 6061 –T651 and electrolytic tough pitch Cu of 6.3mm that has a butt-welding joint configuration. The writers were used different tool steel of M2 grade having cylindrical and the polygonal pin profile designs such as triangular, square and hexagonal profiles. The dimension of pin diameter is 6mm, 8mm and 10 mm; however, in all polygon tool pin profiles there were an existed different type of defects like voids, pores, flash formation and cracks are formed due to insufficient pressure placed upon the workpiece and defect free was made by cylindrical tool pin.

Boumerzoug *et al.* (2017) [40] investigated the effect of traverse speed microstructural characteristics and metallurgical properties of friction stir welding of 6061-T6 aluminium alloy to ultra-low carbon steel using a constant rotational speed of the tool 1200 rpm and at different transverse speed of 100 mm/min, 200mm/min, and 400mm/min. The welding joint conducted was lap joint configuration and the tensile strength of the joint was investigated on universal tensile testing machine as well as microstructure observations and chemical analysis of the joint was performed by scanning electron and optical microscopy. The tool used to conduct FSW was made from quenched and tempered steel X40CrMoV5 having 50 HRC. The basic phenomenon formed in the welded joint was the grain refinement in the aluminium side. **Deore *et al.* (2017) [41]** suggested the selection of tool material for FSW process as the main and important task to identify the excellence of welding joint configuration. The choice of tool material depends up on its operational features such as fracture toughness, wear resistance, and operational temperature that governs the types of materials which can be fused or processed.

Beygi *et al.* (2018) [42] studied Influence of tool geometry on material flow and mechanical properties of friction stir welded Al-Cu bimetals; to investigate the FSW processes experimentally the authors have been used three dissimilar tool geometries having a profile of Pyramidal, Threaded Cylindrical, and Threaded Conical. Among the selected tool profiles Threaded Conical Tool afforded a best compromise between the different material flow regions during the process as well as maximum welding strength and a few defects was obtained.

2.5 Fixture and backing plates designs

Design of the fixture for FSW concerned always be overcome the high temperatures reached during the welding process; at high temperature the welded joints may permanently stuck to the backing plate. Therefore, the fixture should be withstanding the forces and rising temperature during welding process without distortion in shape. The prominent purpose to design and fabricate a fixture for FSW is to hold the workpiece at its position to prevent the specimens from vibration, bending, separating, sliding and that would affect the quality of the weld while welding operation is done as well as it supports the metal plates to be joined. **Zybin *et al.* (2018) [43]** studied an effect of backing plates materials made of siliceous coating, stainless steel, mild steel and aluminium in FSW process to control the thermal diffusivity and achieved the tensile strength and elongation for individual case of 5-mm-thick AA 5056 welding. The shape and size of the weld at stir / nugget zone for all cases are similar, but there are some differences particularly at the root region. For all backing plates free from any defect products were fabricated and using steel backing plate gives the best tensile strength and uniform elongation percentage.

According to **Celik *et al* (2016) [44]** the designed fixture should: -

1. have to be hold the workpiece securely without any gap between interface, to provide a comfortable locking during tightening and FSW operation
2. securely hold the workpiece to prevent the misalignment of the workpiece that could be result due to the motion of the FSW tool along the welding travel.
3. be quick acting so as to reduce the overall setup time (assemble and disassemble clamping systems)
4. be produce a sufficient frictional effect for proper holding purpose of plates and without causing any undesirable effects to the workpiece such as surface damage or distortion.
5. be an easy to operate manually to allow the fixture to be properly mounted over the bed of Vertical Milling Machine for welding operation.
6. be low-cost so that their application in small lot sizes is economical.

Baghel *et al.* (2012) [45] designed and developed the fixture for FSW process from stainless steel 304 by using Auto CAD software. At the time fixture design is concerned, the first problem always to be overcome is due to the high temperatures reached during the process; under such extreme conditions, the welded blanks are possible to remain stuck to the backing plate compromising both the integrity and the soundness of the joint of the fixture itself. The fixture should able to withstand the forces and increasing temperature during welding process without distortion in shape. To support the metal plates to be joined, the fixture is designed and fabricated using different machining processes.

Hasan *et al.* (2015) [34] designed a simplified clamping system and fixtures to join dissimilar materials of aluminium alloys of AA7075–T6 and AA6061–T6 rolled sheets by using FSW technique in butt configuration. The designed clamping system consists of backing plate, compound pressure bars, side plates and bolts and nuts. The results of the tests shown good materials mixing and high tensile strength, free from any weld defects, and smooth surface finish without gap creation between the welded specimens and geometric imperfection and an efficiency of the joint reached 82% with respect to the ultimate strength which was 252.1MPa was obtained at the rotational speed of 1100rpm and transverse speed of 300mm/min.

Mishra *et al.* (2017) [46] studied Fabrication and Vibration Analysis on Friction Stir Welding Fixture for Mass Production and, their study revealed that mild steel is the material used for manufacturing the fixture base plate, clamps, and stopper. The sound reasons they put on the selection of mild steel for a fixture is due to the material has high toughness and strength which is required to withstand unbalanced force and pressure during FSW operation.

The main purpose of the backing plate is to provide support to the workpiece [**39**]. The backing plate has to be unbending smooth surface and firmly secured the workpiece to the fixture in order to resist the vertical and transversal forces that can be lift and push the workpiece apart during the FSW process. The backing plate materials should be highly strong and tough to withstand unbalanced force and pressure during friction stir welding processes additionally it should be available in low cost to reduce the cost of FSW setup. Different researchers **[15, 47, 48]** in their studies commonly used the medium carbon steel and mild steel H13 for backing plate material.

2.6 Review on Process Parameters for FSW process

The selection of the critical process parameters to perform FSW experiment is main step that affect the performance of welded joints. These process parameters are classified into three main groups. The first group is the tooling related parameters which include: - shoulder and pin material, shoulder diameter, pin diameter, pin length, feature geometry of the tool, thread pitch etc. The second group is machine related parameters: spindle speed, transverse speed, tool tilt angle, plunge force or depth, etc. The third group is other parameters: anvil material and its size, workpiece size, workpiece properties, etc.[**10**] Different researchers have described an effect of welding parameters on mechanical properties of the joints which are made direct bonding between two materials.

2.6.1 FSW tool rotation speed

The rotational tool speed is the rotational frequency of the spindle of the machine that is measured in revolutions per minute (RPM). Basically in the FSW process the rotational speed of the tool is a significant process parameter used for two purposes: - firstly affects the plastic deformation by influencing the frictional heat; secondly it provides sufficient forging load of the tool which simultaneously influence the material flow, tool life, the welding quality, stir zone size, tool wear, microstructure and mechanical properties of the welding joint.[**1, 11, 21, 47**]

The tool material and its geometry are the key components of FSW tool. However, a basic tool of friction stir welding (FSW) is mainly composed of two components: a probe or pin and tool body or shoulder.**[21, 48]** A fundamental feature of these parts is pin geometry, shoulder diameter, shoulder surface angle, including its shape and size, and the nature of tool surfaces shown in Figure 2.2.**[25, 48]** The tool geometries determine the heating, forging pattern, and plastic flow of the plastic weld metal as well as the weld size, transverse speed and welding tool strength. The tool material decides the working temperature, welding tool strength, and the rate of frictional heat, at the final stage decides which materials can be friction stir welded.**[49]**

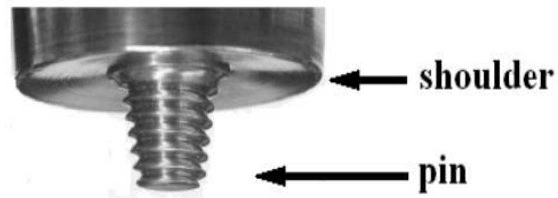


Figure 2-2 Parts of FSW tool profile [49]

2.6.2 FSW tool profile

2.6.2.1 Tool probe

The basic functions of the probe or pin in the friction stir welding process includes to generate frictional heating and plastic deformation to the faying surfaces of the workpiece and shearing the edges of the workpiece in front of it, and stirring and mixing the materials behind the tool as well as softens the materials in front the tool.[**47, 48**] The geometry of the tool probe is a profiled pin which rotates along an axis of the rotating component. It impacts the flow of material that is plastically deformed and affects welding properties. The cylindrical, Whorl and Triflute designs are suitable for butt welding.[**38**]

2.6.2.2 Tool Shoulder

The shoulder of FSW tool is a working surface of a tool which applies a large downward force to the workpiece surface; it generates and increases most of the heat through the friction on the regions of the workpiece, compelled to prevent or constrains the heated metal beneath the bottom shoulder surface, while both the shoulder and the tool pin affect the material flow. It causes plastic deformation under the bottom surface of the shoulder. [**47 38**]

2.6.3 FSW transverse speed

The traverse speed is the velocity through which tool travels along welding line of the joint. The movement of the transverse speed is a horizontal feed rate against the workpiece. Its unit is expressed in distance per time for milling (typically millimeters per minute or inches per minute). But for boring and turning operations it is can be expressed in distance per revolution (typically millimeters per revolution or inches per revolution).[**1, 15**] As the transverse speed increases, the heat transfer rate decreases between the workpiece and the weld zone. Therefore, the effect of the welding process will be observed in the smaller region of the welding edges. On the other hand, by increasing transverse speed, the process speed will increase and distortion will reduce. Also, with increasing transverse speed, the temperature gradient generated in different weld zones will decrease. When the transverse speed is changed, it should be noted that the transverse speed changes must be accompanied by changes in the rotation speed. Otherwise defects, such as cavity and porosity, are formed in the weld zone. For every transverse speed, there must be a particular rotation speed that generates flow material for welding purpose.

During FSW process is performed the correlation between the frictional heat input and the transverse speed is so complex. However, a sound weld joints will be achieved by increasing the rotational spindle speed or decreasing the transverse speed. In FSW the transverse speed has a vital role to achieve good quality of weld joints for dissimilar materials. It affects the metallurgical bonding and material mixing of materials as well as controls the heat generation by a tool upon the materials.[**21**]

2.6.4 Tilting angle and plunge depth

The tool tilt angle is defined as the angle between the pin or probe axis and the direction perpendicular to the workpiece. If the position of FSW tool is perpendicular to the workpiece it is said as zero or no tilt angle. In FSW process an appropriate tilt angle is used to safeguard the holding of stirred material under shoulder by the help of tool pin and provides a constant material flow by increasing the forging action to get proper material flow from top to bottom and front to back under FSW tool.[**1**] Often FSW tools tilted in the direction of welding line in order to enhance the material containment ability of the tool. When a tool tilted, the characterizing angle is referred to as the “tilt angle” which controls the weld appearance and makes it thin. The values of tilt angle vary from one material to another depending up on welding process parameters and base material properties.

Using an appropriate tilt angle safeguards that the shoulders hold the stirred material created by tool pin and transport it as it should be from the upper to bottom and to the back from the front under the FSW tool. Tool tilt angle also helps to increase the compression of an axial force and plastically deformed material under the FSW tool to achieve better weld joint strength.

Accordingly, the vertical material as well as horizontal flow inside the stir zone is influenced by tilt angle. Most of the time tool tilt angle is set at some small tilt angle typically from 1^o to 4^o to have a good welding appearance.**[20]** However, in another study the optimum tilt angle recommended for dissimilar FSW of AA6061−T651−Cu was from 2° to 4°.[**33**]

In FSW of pure Cu to AA2024 alloy using 2° tool tilt angle with higher axial plunge force provided a free flow to Cu particles in Al matrix; as a result, higher strength and good metallurgical bonding formed.[**1**]

The depth of penetration 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. Depth of penetration depends upon the thickness of the material to be welded. It is expressed in unit of millimeter (mm)**.[14, 25, 38]** Plunge depth is one of the important FSW process parameter to ensure both the downward pressure and maximum penetration of the tool into the materials just before plastic deformation formed. The plunge depth is dependent on the thickness of material being welded. 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. On the other hand, reduce the plunge depth compared to the nominal setting, which may result in flaws in the weld.[**38**]

2.6.5 Tool pin offset

In FSW the tool pin offset refers to FSW tool displacement from weld center line or tool pin axis toward the faying surface of base material. When FSW tool is positioned precisely at the center of weld joint line it is said to be no or zero tool pin offset.[**1**] In FSW process the tool pin offset is a distance which is located between the tool pin axis and the faying surface of the pattern material It is one of the most important aspect to achieve defect free in dissimilar FSW joint. The best value of tool pin offset selection is mainly depending upon the pattern material composition, thickness, tool design and process parameters.[**20, 39**]

Figure 2.3 shows the position of the workpiece and FSW tool for zero and 1mm pin offset towards Aluminium side.

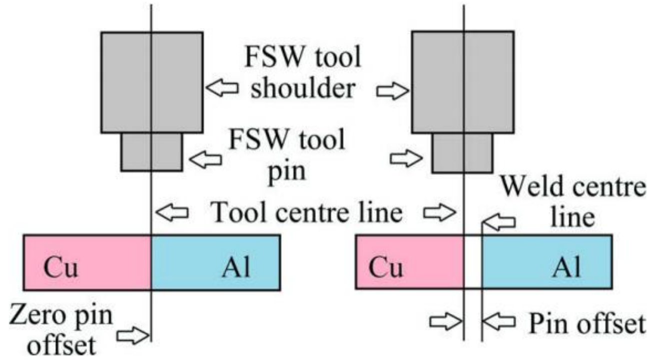


Figure 2-3 Schematic of tool workpiece position for pin offset [1, 19]

During dissimilar FSW processes tool pin offset served to optimally distribute the generated heat in the pattern materials to produce a sound welding joint. Hence the major temperature developed in FSW of Al and Cu is a function of tool pin offset.[**45**] To achieve a good quality of welding joint while FSW process of Al – Cu the tool pin offset suggested to use range was 1.5−2 mm.[**1,11**]

Table 2.1 Process parameters of FSW process [12]

Variable Process Parameters	**Major contribution and effect**
Tool Rotation Speed (rpm)	Frictional heat, "stirring", breaking of oxide layer breaking and mixing of material
Transverse speed (mm/min)	Weld appearance, material flow and heat control
Tilt angle of the machine (^{o})	Weld appearance, extrusion, thinning and forging action
Tool pin offset (mm)	Optimally distributes the thermal stresses for dissimilar welding
Forging force [kN]	Keeping contact of tool and workpiece generate frictional heat

2.7 Defects and failures of Al – Cu FS welded joint

The frictional heat produced in the workpiece while FSW process is done depends on the tool geometry and FSW process parameters.[**13**] During FSW, the choice of welding parameters like rotational and transverse speeds can be a vital issue to affect the result of FSW Al-Cu weld. Under intense pressure the rotational and transverse speeds govern the frictional heat and flow of the base materials during the process makes different Al-Cu phases. These phases are called intermetallic compounds (IMCs). An intermetallic compound is defined as solid phases containing two or more metallic elements, with optionally one or more non-metallic elements, whose crystal structure differs from that of the other constituents. The most frequently existed

IMCs are Cu_9Al_4 and $CuAl_2$.[**17, 31**] These IMCs are brittle and to achieve a sound FSW of Al-Cu joints it is important to avoid excess formation and keep them as a thin, uniform and continuous layer at the base material interface.[**41**]

Tan *et al.* (2013) [51] studied the joining of AA5A02 and pure Copper made of 3mm thickness sheet metals having butt weld joint configuration by FSW system and investigated too low frictional heat with high travel speeds cannot induce interfacial reaction between the Cu and Al, due to different in the nature and number of crystal lattices, the radius of atoms in the materials. They used transverse speed within a range of 20 – 40 mm/min; also studied microstructure of the welded joints that promote cavity defects and insufficient mixing at high transverse speeds. Lower transverse speeds promote less flash formation, good appearance and proper mixing. **Sahu *et al.* (2016) [52]** joined AA1050 alloy to a pure Cu 4mm thick sheet metals and they used the rotational speeds 600 – 2400 RPM. In their studies they found that increasing the rotational speed up to 1200 RPM resulted in better weld strength but once the rotational speed exceeded 1200 RPM the result of the strength started to decrease. Medium rotational speeds produce better welds. Higher transverse speeds lead to more flash formation and more material interaction.

Celik *et al* (2016) [44] studied FSW of AA1050 and pure copper 4mm thickness, which stated an increase of frictional heat when tool rotation speed is higher and lower transverse speed, this leads the weld zone grows more along with more material cutting, can be helpful for the weld properties. On the other hand, due to furthermore frictional heat increases the formation of IMCs happens which reduce the tensile strength and increase the brittleness of the weld. **Bhattacharya *et al.* (2017) [53]** studied the relationship between joint strength, welding forces, and frictional heat input for FS butt-welding of AA6063 and Pure Cu having 3mm thickness. They distinguished that when they increased the frictional heat in the FS butt-welding of the system the torque and an axial force decreased. In their study, it was also clearly observed that increasing the rotational speed of the tool from 800 RPM to 1000 RPM, therefore the frictional heat, enhanced the joint strength significantly. Better welds obtained with lower travel speeds. High transverse speeds produced less smooth material flow. The transverse speeds they used in their investigation are 20 and 40 mm/min; as well as a tensile strength joint efficiency was 86.5%.

2.8 Review on Al-Cu optimization

Optimization deals with acquiring process parameters that would be considered as an important to precise a range of values having long spam to certain value. It helps to reduce the process of manufacturing with so many process parameters having less efficiency or output. So precise value acquirement will reduce cost and improve its output parameters. The following are the part of optimized technique done in Friction stir welding.

Manisegaran et al. (2018) [54] joined flat butt joint FSW of 2mm thick A6061 and 1mm thick Copper on vertical conventional milling machine. The spindle speed and traverse speed are the main process parameters used to optimize tensile strength of the welded joints is Taguchi method. The spindle speed and traverse speed used varies from 500 – 1440 rpm and 30 – 90 mm/min respectively. High tensile strength of the weld joint is 188.23MPa at optimum process parameter of 500 rpm and 30 mm/min.

Panaskar et al. (2019) [55] joined AA6063-ETP Copper having both 3mm thickness using Taguchi Technique at optimal levels of the tool rotational speed 1000 rpm and 5 mm/min tool traverse speed respectively is 59.84% and 34.53 % to the tensile strength of welded joints which is compared to an average of tensile strength of AA6063-ETP Copper.

Acharya et al. (2019) 56] joined AA6061 aluminium alloy sheets with a thickness of 2.5 mm and commercial copper sheet having 98% copper of 3.0mm thickness. AA6063-ETP Copper having both 3mm thickness using and the process parameters in FSW is optimized using Taguchi Technique at optimal levels of the tool rotational speed 1000 rpm and 5 mm/min tool traverse speed respectively is 59.84% and 34.53 % to the tensile strength of welded joints which is compared to an average of tensile strength of AA6063-ETP Copper.

2.9 Summary of Literature and Gap

Many researchers were studied FSW of dissimilar pure copper and aluminium alloys. Successfully joined pure copper and aluminium alloys was obtained between:- (i) AA5754 and Cu11000, (ii) AA6061 and Cu110, (iii) AA6061 and AA2024, (iv) AA5A02 and Cu110, (v) AA1050 and Cu 110, (vi) Al7075 – T6 and AA6061 – T6, (vii) AA5083 and 6061 (viii) AA6061 and MgAAZ31 (ix) pure Al and copper (x) AA6351 – T6 and AA5083 – H111. It can be clearly seen from the literature, FSW of dissimilar materials were studied and the effects of process parameters and tool geometries on microstructural and mechanical properties of aluminium alloy and copper welding joint as well as other combination of dissimilar FSW were stated. From these studies, the gap identified is as follows.

- There is a research gap on FSW process of dissimilar AA6023 – T6 alloy and copper.
- Most of the researchers used two process parameters of FSW. This resulted the existence of defects, and crack during performing the FSW processes.
- Due to limited effects of process parameters of FSW experimental investigated for the mechanical properties was either on hardness or tensile strength testing only.
- Optimization of process parameters had not done on AA 6023- T6 aluminium alloy and pure Copper welded joints.

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1 Introduction

The tools for problem solving described through published research and one in particular chosen as a solution. The base materials, FSW tool, fixture and backing plate, and conventional vertical milling machine are the basic required materials and different equipment and machinery were used during performing FSW process.

FSW experiment was performed to investigate the microstructure as well as mechanical properties such as tensile strength and hardness of the dissimilar welded joints of AA 6023 – T6 aluminium alloy and pure copper. An effect of FSW process parameters were optimized by DoE particularly using Minitab software. Finally, an evaluation of the solution was made and results were presented.

3.2 Material properties

3.2.1 Selection of AA 6023 – T6 alloy and pure copper for FSW process

In this study an author selected AA 6023–T6 aluminium alloy and pure copper sheets which are dissimilar base materials used to joined in butt joint configuration by FSW process on convectional vertical milling machine (FU-281). The reason behind the selection of Al-alloy and Cu the combination for FSW process is due to owing a specific property such as: - high strength to weight ratio, low density, good corrosion resistance, high thermal and electrical conductivity, good mechanical properties, high electron affinity, and non-toxic. FSW of dissimilar materials of AA 6023–T6 aluminium alloy and copper that will be valuable for the wide-ranging applications in: transportation, marine industry, aerospace, construction industry, packaging and containers.
According to the European system, the AA 6023–T6 aluminium alloy is basic designations of wrought products in which AA 6023 indicate–aluminium –magnesium–silicon alloys and T6 stands for thermally treated. This identifies the alloys that are aged to produce a stable condition. T6– solution heat treated tempered condition. The chemical composition of AA 6023–T6 aluminium alloy used for this study is listed in Table 3.1.

Table 3.1 The nominal chemical compositions of AA 6023 – T6 aluminium alloy (w%)

Material	C	Cr	Mo	S	P	Si	V	W
AA 6023-T6 alloy sheet	1.61	11.50	0.43	0.014	0.018	0.25	0.16	0.077

Cu and its alloys have high electrical and thermal conductivity, good corrosion resistance, ductility and formability, which makes it vital in numerous applications, especially as a transporter of electricity and heat. Due to its high cost, it has been replaced by other lower cost metals such as Al in some applications. A pure copper has purity reaching 99.9 % with an oxygen percent estimated at 0.04%. Also, the electrical conductivity of this type of copper is very high, higher than any metal except for silver. The chemical composition for copper used in this research is shown in Table 3.2.

Table 3.2 The nominal chemical compositions of pure copper (w%)

Element	Cu	Fe	Bi	Sb	As	Pb	S
Copper	99.9	0.005	0.001	0.002	0.002	0.005	0.005

3.3 Tool material selection for FSW process

The selection of the tool material used for FSW process parameters is very important subject because it decides the quality of the welding joint by influencing heat generation.**[21]** Hence, the selected tool material for FSW process should have: - a high compressive yield strength to resist wear under hot operation, an excellent fracture toughness to resist a damage during plunging and dwelling, low coefficient of thermal expansion, good machinability and cheap in price and greater hardness than workpiece.**[24]**

There are many materials that can be used to manufacture friction stir welding tools [**60**].

Table 3.3 Tool materials and suitable weld metals

S.No	**Tool Material**	**Suitable weld material**
1	Tool steels	Al alloys, aluminium metal matrix composites and copper alloys
2	WC –Co	Aluminium alloys, mild steel
3	Ni-Alloys	Copper alloys
4	WC composite	Aluminium alloys, low alloy steel and magnesium alloys, Ti-alloys
5	W-alloys	Titanium alloys, stainless steel and copper alloys
6	PCBN	Copper alloys, stainless steels and nickel alloys

For this research work AISI D2 steel is selected as FSW tool due to it has an excellent wear and scratch resistance as well as high compression strength. The chemical composition of the D2 steel tool is clearly stated in the Table 3.6.

Table 3.4 Chemical compositions of AISI D2 steel

Elements	Cr	Si	Mn	C	P	S	Mo	Ni	Cu	Fe
Weight in %	15.30	0.42	0.37	1.51	0.05	0.02	1.34	0.1	0.1	Balanced

AISI D2 tool steel is the most widely used steel which is a high carbon–high chromium air hardening tool steel, very sensitive to heat treatment AISI D2 tool steels preheated very slowly upto 815ºC and then temperature increased upto 1010ºC. It is then held at 1010ºC for 20 to 45 minutes and quenched in air; it has hardness value of 55-62 HRC.

3.4 Selection equipment and machinery for FSW process

Table 3.5 Materials and equipment used for FSW of AA 6023 –T6 and pure Copper

S.No	Materials	Specification	Task of materials
1.	Aluminium alloy sheet	Aluminium alloy 6023-T6	Pattern material to be welded.
2.	Pure copper	Cu 110	Pattern material to be welded.
3.	D2 tool steel	Tapered geometry having 12mm shoulder diameter and 3.5mm pin diameter.	Generate heat, mechanically stirring and mixing plasticized material.
4.	Hexagonal headed bolt and nuts	50 mm length M18×2mm bolts	To adjust the backing plate up and down, also rigidly fixing side supporter on backing plate
5.	T bolt and nuts	21mm length M16×2mm bolts	To clamp the fixture on the milling machine table during an operation of FSW
6.	Backing plate	450mm×300mm×3mm plate	To hold workpiece in position during welding process
7.	Expandable collates	Having diameters of 10mm collates.	To hold FSW tool on conventional vertical milling machines
8.	Open box wrench	10mm, 18mm, and 27mm wrench	To tightening and opening the bolts
9	Phelonic Resins		Used to support specimen in mounting process
10	H_2O_2 and NH_4OH	5ml of H_2O_2 and 50ml of NH_4OH	Used as an etchant

The FSW process requires the suitable process parameter like rotation speed, travel speed, tilt angle and tool pin offset. Hence the machine preparation phase is the most crucial phase to achieve the best values for these process parameters. The convectional vertical milling machine (FU-281) was selected for FSW machine; for a basic specification sheet on this machine view appendix 1.

Table 3.6 Machinery used to perform FSW processes and sample test of the welded materials

S.No	Machinery	Model	Task of materials
1.	Universal milling machines	FU-281	To perform FSW welding process, slot and hole on the backing plate
2.	Shearing machine	Hydraulic shear	Cut the samples from AA 6023-T6 aluminium alloy and pure copper sheets as well as backing plates.
3.	Drilling machine	Universal drill TSAR-25	To make hole
4.	Grinder/ Polisher	RB 204 Metpol-II	Removes saw marks, level, clean and grinding little stock from sample surfaces
5	Lathe machine	Excel XL-420	Face turning, taper turning and groove on FSW tool
6	Abrasive cutter	RB 203 Abcut-M	Cut bulk samples
7.	Hot mounting press	RB 206 Metpress-A	Sample preparation
8.	Heat treatment machine		Heat treat FSW tool (D2 tool steel)
8.	Vickers hardness tester	HVS-50	Hardness test
9.	Tensile testing machine		Ultimate tensile strength test
10	Optical microscopy	Magnification 50x, 100x, 200x, 500x and 1000x	Microstructural test

3.5 Research methodology

For this particular research work an author is used a quantitative research sampling approach to test an objective of the paper by examining the relationship among process parameters of FSW. These control parameters, in turn, can be measured, normally on instruments, so that numbered data can be analyzed using statistical techniques or procedures. The last written report has a combination of structure containing of introduction, literature review, materials and methodology, results and discussion.

The sampling – method of the data collection which is statistically taken from different machines such tensile testing machine and hardness machine which has been shown the results of the tensile strength and Vickers hardness of the welded joints respectively. Additionally images of the microstructures of the welded joints are taken from metallurgical research optical microscope. For this research work the results taken from the listed machines depends on an orthogonal array of Taguchi method. The means of means and Signal-Noise ratio for both tensile and hardness tests are taken from Minitab17 software. An optimization of the FSW process parameters for AA 6023 – T6 Aluminium alloy and pure Copper is done by DoE particularly by Taguchi method and ANOVA.

3.6 FSW Procedure

To have an accurate result from the DoE welds it is important to have all welds made under the exact same circumstances so that no extra noise skews the results. A certain procedure was followed for each weld after the FSW tool was fixed. The complete assembly of FSW setup on the CVMM has shown in Figure 3.1. Friction Stir welds of AA 6023-T6 Aluminium alloy and pure copper sheets have 203mm x 120mm x 2mm dimension which is fabricated in the machine shop of ASTU, Ethiopia using a CVMM. The aluminium alloy sheet is placed at the retreating side and copper is placed in advancing side and the tool pin is plunged into it while the tool pin touches aluminium during the welding process.

For this work, the process parameters used for FSW were rotational speed of the spindle, transverse speed, and tool pin offset. An experimental work was conducted depending on the chosen welding parameters listed in Table 4.2. The microstructural investigations of the weld joints interfaces were identified by an optical microscope and the weld joints performance was evaluated by using tensile and hardness tests according to ASTM-E8 standard.

This complete procedure of FSW process is listed as follows: -

1. Select, design and fabricate the materials for tool, fixture and backing plates.
2. Select rolled sheets workpiece made of AA 6023-T6 aluminium alloy and pure Copper to be welded having the size of 102mmx120mmx2mm was cut by using shearing machine.
3. Locate all of the fabricated fixture and backing plates on the bed of the CVMM work bench and place the copper sheet at an advancing side and AA 6023 – T6 alloy sheet at retreating side with an appropriate position on the bottom backing plate and by keeping its position put the top backing plate on by considering straightness of the line of weld joint for FSW butt joint.
4. Clamp the workpiece on the fixtures using nuts and bolt system.
5. Set FSW process parameters such as: rotation speed (ω), transverse speed (v), tool pin offset (O_p) and tilt angle of the tool (A) on CVMM. Then insert the fabricated FSW tool into the spindle of the CVMM and tighten manually by using expandable collate material. Then run the machine at defined process parameters excluding transverse speed by keeping constant depth of cut upto it reached 1.9mm from one end of the workpiece and

stop a constant depth of cut as soon as the shoulder of tool touch the workpiece and continue for ten seconds it up to the tool generate sufficient heat before it begun a joining process of workpiece.

6. Start automatic transverse speed (v) to begun a joining process of the workpiece together up to it reaches 120mm weld length.
7. Cut the specimen according to the standard size for testing purpose.
8. Repeat the same procedure for other workpiece by considering all process parameters.

Figure 3-1 FSW setup on CVMM

CHAPTER FOUR

DATA COLLECTION AND ANALYSIS

4.1 FSW tool design and manufacturing

4.1.1 Design of the pin of the tool

In order to increase material flow between the within the workpiece the tip of tool and the bottom backing plate should not be touch each other during the FSW process. Most frequently the distance between the bottom of the welding workpiece and the tip of pin is 0.1~0.2 mm. However, depending upon the change of either plunging depth of tool or workpiece thickness the distance between tip tool pin and the bottom backing plate surface might change from this value. The longer distance may result in the appearance of root flaws because of the lack of enough material flow.[**60**] The flow velocity of the material in contact with the tool is the same as the linear velocity of the contact position of tool.[**61**].

The geometry and features of the tool material for FSW process has a great significance effect during the process. The tool design and geometry affect the heat input, force, and torque variations and plasticized material flow in FSW technology. Tool pin is responsible for plasticized material flow by stirring action in the joint area. Pin length highly affects the penetration level of plasticized material in stir or nugget zone. Pin diameter and its surface geometry affect the size of nugget zone, material flow and microstructure.[**52**] It is most important that the pin length should be less than the workpiece thickness to provide full closure to the bottom part of the joint.

Pin or probe diameter (D_p) also depend on the thickness of sheet metal.

$$D_P = 1.8t_p + 0.4\,mm \qquad (3.1)$$

Where, D_p represents pin diameters and t_p represents thickness of sheet metal.

4.1.1.1 Shape of Friction Stir Welding pin tool

The flat pin design is the most commonly used in the friction stir welding process due to an easy to manufacture it and can afford high forge force at plunging stage, and can reduce forge force and tool wear. Friction stir welding pin has two very common outer surface shapes, cylindrical and tapered. An author used a tapered pin tool for FSW purpose.

4.1.2 Design of the shoulder of tool

In FSW process, the dimension of the shoulder diameter and geometry or surface features affect the quality of weld and it is responsible for the maximum frictional heat generation. It has been found that the shoulder produces about 87% heat by rubbing action between the workpiece and the shoulder surface and the rest 13% heat is produced by a pin.[**1, 6**]

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

$$D_S = 2.26t_p + 7.48 \text{ mm} \quad (3.2)$$

Where, D_S represents shoulder diameter and t_p is thickness of sheet metal.

In FSW processes the shoulder-to-pin diameter ratio (SPR) defines the relationship between the dimensions of tool shoulder and probe or pin [**1].** The range of SPR for dissimilar FSW of Al−Cu varied from 2:1 to 5:1. When it is compared to similar FSW process this value is very high. The selection of SPR depends on the alloy type and the thickness of the workpiece **[13].**

FSW tool was fabricated at Metal Industry Development Institute, Addis Ababa city. The detail information of the designed tool specifications for this research work was shown in Table 3.7.

Table 4.1 Specification of designed FSW tool

Tool geometries	**Tool Material**	**Design Specifications of the tool**
Flat Tapered	D2 steel	Ps – Shoulder surface profile = flat; *D*s – Shoulder diameter =12mm Psp – Pin surface profile = tapered *D*ps – Pin diameter at shoulder surface of the pin=4mm *D*ps – Pin diameter at tip surface of the tool =3.5mm θ_{tp} – Tapered angle of the pin = 7.5^0 *L*p – Pin length=1.9mm *D*s/D*p* – Shoulder to pin diameter ratio=3

All dimensions are in mm.

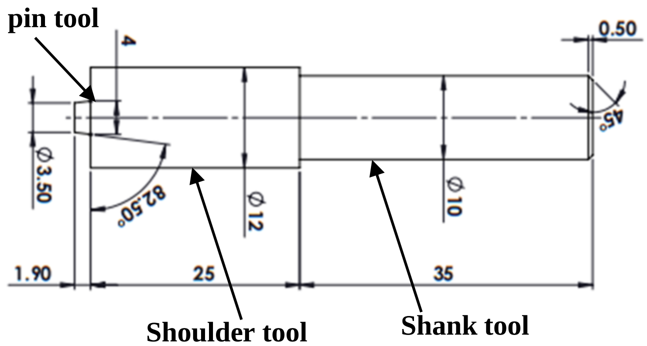


Figure 4-1 Designed tool for FSW

4.1.3 Manufacturing procedure of the FSW tool

In FSW process to achieve best quality of welding joints a manufacturing of a well desired FSW tool geometry has a great impact. The procedure to manufacture FSW tool was listed as follows: - cylindrical rod of AISI D2 tool steel having 13mm diameter was selected and cut at length of 70mm after placed on a power hacksaw cutting machine. After cutting operation was successfully done, the excess dimension of the material is removed from the surface of the workpiece by facing and turning operations was done by using the high carbon steel cutter to produce flat surfaces at the ends of the workpiece and reduce the diameter of the cylindrical workpiece on lathe machine. Depending up on the size and shape of the designed tool facing operation was performed by feeding tool perpendicular to the axis of rotation of the chuck at 0.5mm/min. Next to facing operation, rough surface turning operation is done at feeding the tool along the axis of rotation of the chuck is performed at 0.25mm/rev upto the get 12mm and 10mm diameters and length of 25mm and 35mm for one another respectively and continued the turning operation from the side of 12 mm diameter upto achieve 4 mm pin diameter and 1.9 mm pin length from the end of the faced side of the workpiece and taper turn operation was implemented from end of workpiece at taper angle of 82.5^0 upto the end side workpiece size reached 3.5 mm depending on designed drawing. Then the workpiece was taken away from the chuck of the lathe machine and inserted into itself by changing the previous position to make facing the end of the workpiece. Afterward the chambering operation was done at 0.5 *x* 45^0.

After tool manufacturing process completed, heat treatment was accomplished up to HRC-54 by using heat treatment machine. The tool heat treatment process done by heating the furnace up to 960°C and AISI D2 tool steel were inserted in the furnace and removed from inside after 45 minutes and quenched in air media below 65^{0}C. Then it was tempered at 200^{0}C for 50 minutes to reduce breakability of the material. Finally, surface finishing done by using cylindrical grinding operation to achieve the desired design.

4.2 Design and fabrication of fixtures and backing plate

4.2.1 Material selection for fixture

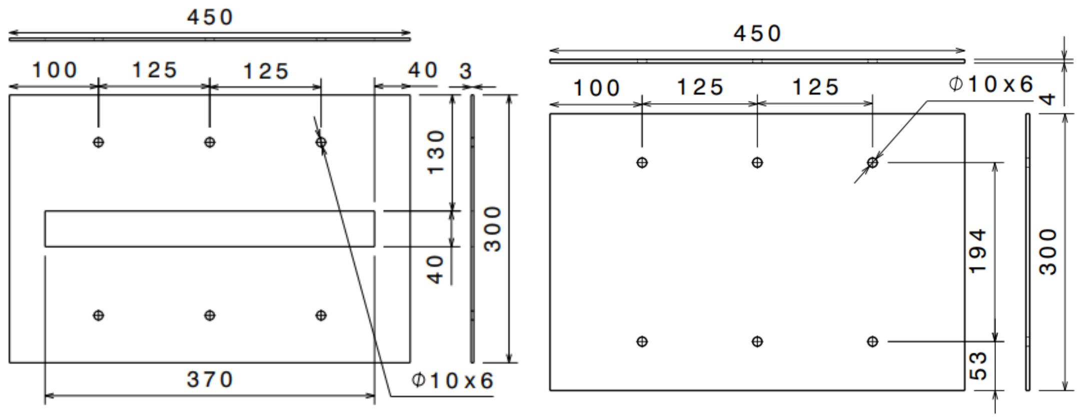
Different researchers [**34, 50, 52**] clearly shown that mild steel plate material used for manufacturing fixtures, bottom backing plate and top plate. The material preferred for fixture is AISI 1018 steel; this type of steel is known as mild/low carbon steel. It has a significant mechanical property like high toughness, high strength, high hardness, excellent ductility and weld ability. It is required to resist the downward force and pressure during friction stir welding.

4.2.2 Design of backing plate

For this research work an author selected and used a mild steel / low carbon steel AISI 1018 for bottom and top backing plates.

To achieve the safety and stability of the workpiece and sound FSW joint keeping the position workpiece should be constant; this is mainly ensured by putting workpiece between bottom and top backing plate. The bottom backing plate is also used to prevent wetting of workpiece material upon the top surface of fixture. The bottom backing plate and clamping system designed for FSW are used to support and hold the workpiece and top backing plates. Top backing plate is extremely affected by vertical force that comes from bolts of 18mm × 2mm to secure the workpiece unbendingly in right position during welding process.

Both the bottom and top backing plate in thesis was cut by using a hydraulic shearing machine (automatic sheet metal cutter) and the feature of the backing plate part is formed. The slot in the top backing plate is wider than the shoulder diameter of the tool to the insert the pin tool inside faying surface of the workpiece, which is used to guide the position of workpiece and make a loose-sliding fit; but after the desired position of workpiece is determined the workpiece has to be fixed between top and bottom backing plate by nuts and bolts. A multi-view drawing of fabricated product for top and bottom backing plates can be viewed in Figure 4.2.



(a) Top backing plate **(b) Bottom backing plate**

Figure 4-2 Backing plates

4.2.3 Design of the fixtures

The method of clamping the fixture for FSW setup and its effects on welding joint performance are well understood to assured the welding quality. An objective of designing of FSW fixtures is used to achieve the workpiece should not spread or be lifted during the process. In FSW a gap presence between specimens up to 33% of the workpiece thickness could be tolerated without the existence of weld flaws and does not affect the weld joint strength. It was illustrated that the possibility of defects could also be minimized by preventing any creation of gaps between the two butt plates.[**62**]

4.2.4 Components of the fixture

The fixture in this work is one of the main components, fabricated separately with all suitable features. These components include: - bottom supporter plate, side supporter plates, top supporter plates, side adjusters or spacers, and nut and bolt. After fabricating different parts of the clamping system separately, depending upon the design specification the bottom supporter plate, side supporter plates and top supporter plates were welded to form a single product.

4.2.4.1 The bottom support plates

The bottom supporter plate of the fixture has to be smooth surface with uniform thickness to make straight position of the workpiece and backing plates to make a comfortable system during FSW processes. The designed dimensions of this plate depends on the size of the slots on the bed of the milling machine to be fix securely to the slots of the milling machine by aligning six holes which are provided for the use of M18 × 2 mm bolts in order to withstand and resist the vertical forces that can be bend workpiece and backing plates which would affect the whole working systems during FSW process. After it is fixed upon the bed of the machine it used to support the workpiece, side adjuster, side supporter plates, both bottom and top backing plates as well as nuts and bolts. A multi-view drawing of fabricated product for bottom supporter plate was shown in Figure 4.3.

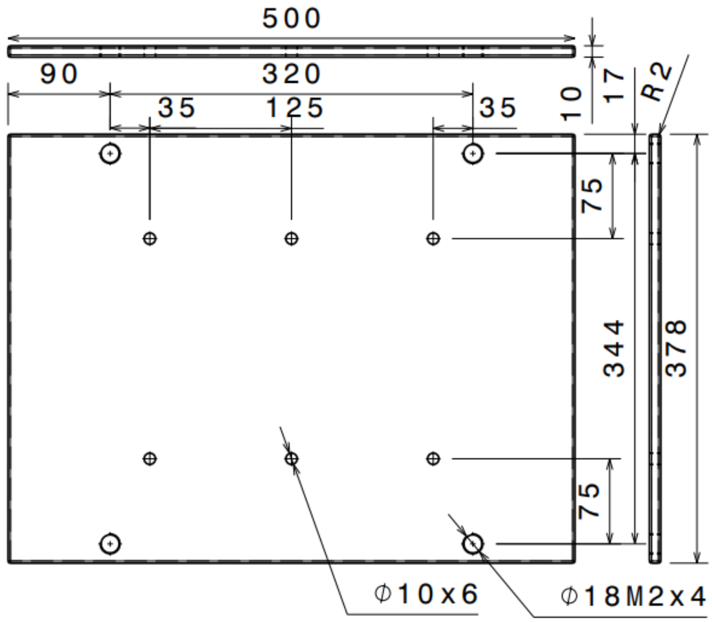


Figure 4-3 Bottom supporter plate

4.2.4.2 The side supporter plates

For this study there are two side supporter plates are used and some of its surface features of these supporters are provided with slots made by end milling machine tool. This is done to insert and slide the side adjuster plate through itself and used to hold the top supporter plate through which the clamping force is applied after the workpiece to be welded by FSW operation was properly located. Both side supporter plates were welded perpendicularly and in parallel upon the bottom supporter plate by using arc welding machine. A multi-view drawing of fabricated product for side supporter plate can be viewed in Figure 4.4.

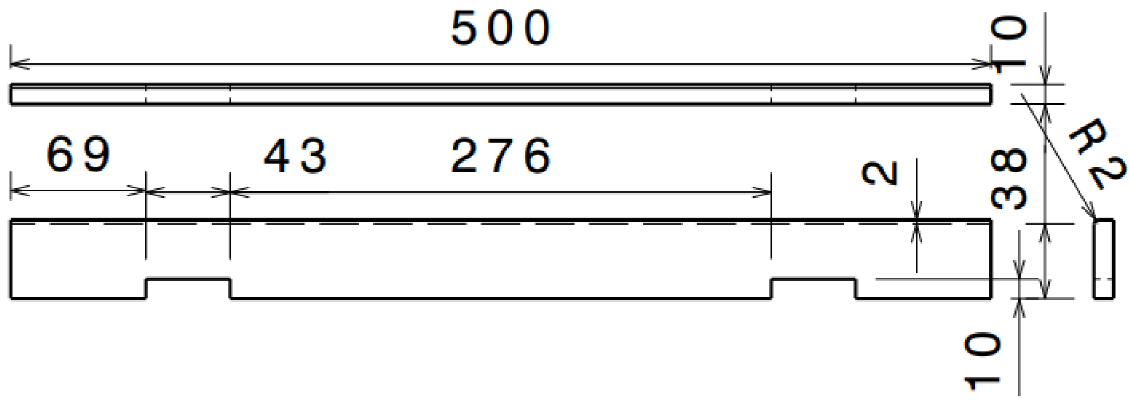


Figure 4-4 Side supporter plate

3.5.4.3 The bolt supporter plate

The bolt supporter plate is fixed upon the side supporter plate by using arc welding and it has to be withstand the vertical clamping forces applied manually by bolts of length 88mm M18 of 2mm pitch diameters and delivered through M18 threaded holes with 2 mm pitch on top backing plate through to fix 2mm thickness of AA 6023–T6 aluminium and pure Copper sheets with the bottom supporter plate. A multi-view drawing of fabricated product for bolt supporter plate can be viewed in Figure 4.5.

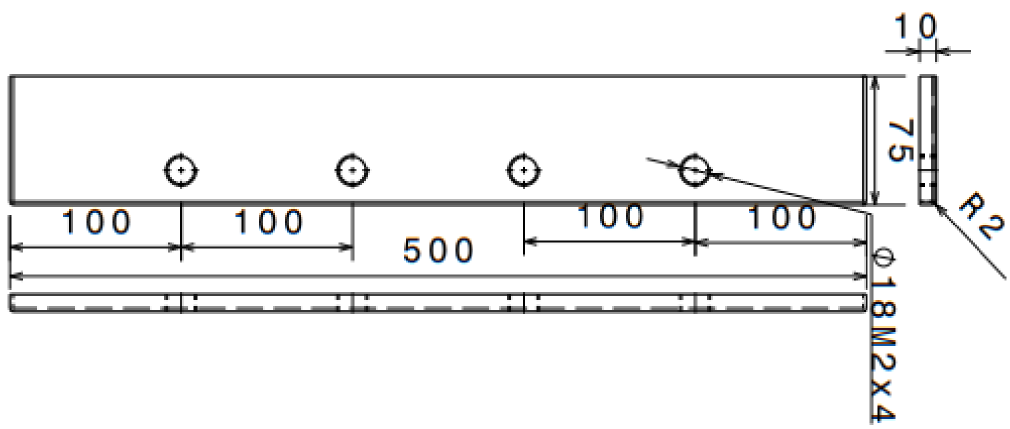


Figure 4-5 Bolt supporter plate

3.4.4.4 Nut and bolts

In this thesis work two different types of T–bolts and nuts are used. One type of bolts has of length 88mm M18 with 2mm pitch is used in order to safeguard every movement of workpiece that will produce in internal defects and crack during welding process, and nuts with another type of bolts having a length of 65mm with M10×2mm pitch was used to fix the fixture upon the CVMM bed.

3.4.5 Fixture manufacturing procedures

Before FSW process was performed on a convectional vertical milling machine, the fixture is designed and fabricated using different machining processes. In this work paper the major operations in manufacturing of the fixture was done at Yasin Ibrahim Manufacturing Industry and Haromsa Advanced manufacturing engineering industry in Adama town. The manufacturing procedures made after design of the fixture are listed as follows: -

1. **Cutting operation: -** at Yasin Ibrahim Manufacturing Industry cutting operation of the mild steel plate having 1000mm × 500mm × 10mm was performed by automatic hydraulic shearing machine into different dimensions 500mm × 380mm × 10mm for the bottom supporter plate of the fixture, 500mm × 75mm × 10mm for bolt supporter plates, 500mm × 38mm × 10mm for both right and left side supporter plates and 100mm × 45mm × 10mm for adjuster supporter plates.
2. **Milling operation: -** at Haromsa Advanced Manufacturing Industry different features of the fixture such as holes with different dimension, threaded part of holes, slots and welding of the assembled parts of the fixture according to design specifications was fabricated. The milling operations was performed on milling machine to produce a fillet on sharp edges, grooving the side supporter backing plate, drilling the fixture at the required position by using 15.5mm end mill cutter to made twelve holes; similarly, six holes on the fixture were produced by using an end mill cutter of 10mm diameter.
3. **Threading operation:** - this operation was performed on hand twist-drilling machine by using different size of drill bits. Twelve similar threads of 18 mm diameter with a pitch of 2 mm on 15.5mm diameter holes were produced by using a drill bit of 18mm diameter with a pitch of 2 mm.
4. **Surface finishing:** - surface grinder was used for removing the roughness and providing the desired tolerance. After performing all these operations finally fixture is produced.

4.3 Selection of Process Parameters for FSW

Based on the literature reviews, each of the friction welding process parameters such as rotational speed, transverse speed, tilt angle, plunge depth and tool pin offset have their own effect to obtain a joint geometry and efficiency.

The rotational speed of the tool of FSW results in the stirring and mixing of material around the rotating pin. During FSW of dissimilar Al–Cu the rotational speed should be curiously selected because the heat generated has a great impact on the welding joint. The low rotational speed not able produce a sufficient heat; so, it is not desirable select it during FSW process. Depending upon CVMM rotational speed specification and literature review [**38, 47, 59**] for this thesis work three different rotational speeds namely 1000rpm, 1250rpm, and 1600rpm are used.

For this research work to achieve better and sound welded joints three different transverse speeds selected are low in numerical values from CVMM which are 12.5mm/min, 16mm/min, and 20mm/min.

For this work while FSW of butt joint configuration an author selected 2^{o} tool tilt angle [**1, 28, 47**] at constant plunging depth of 1.9mm which is far from backing plate at 0.1mm; [**60**] a profile of the tool was made with flat shoulder of 12 mm in diameter and a tapered threaded pin of 4mm diameter at shoulder surface and 3.5 mm diameter at the tip of the pin and the length of pin used was 1.9 mm.

In this study an author used 1, 1.5 and 2mm at an advancing side of Copper.[**1,13,25**]

4.4 Performing Microstructural observation

The main phenomenon in observation of microstructure of the welding joint is used to provide information the grain size, features of grain boundary and structure, existence of IMCs, has a great impact upon its mechanical properties of the materials. An analysis of the microstructure observation results is used as a criterion for acceptance or rejection of the product. For this thesis work due unavailability of SEM and TEM only an optical microscope was selected for examinations microstructural test by magnifying the features of the specimen of the welding joints by 1000x. Therefore, to identify and evaluate the microstructure of the welding joint, it is mandatory to prepare a test specimen very curiously and properly. The different procedures in sample preparation from the welding joint for microstructural test include: -

- Selecting the sample of the materials
- Sectioning the specimen to avoid altering or destroying the structure of interest
- Mounting the specimen
- Grinding the specimen surface
- Polishing the sample and
- Chemical etching

4.4.1 Selecting the sample

To identify the microstructure evaluations the samples are selected from orthogonal array of DoE and to identify the grain structures on its transverse sections. As a result, it is important to provide the laboratory with information about the location or the rolling direction of the test specimen. For this paper work purpose 9 samples were selected to examine microstructures.

4.4.2 Sectioning the sample

Test samples of AA 6023-T6 aluminium and pure Copper having a weld bead at is center were carefully sectioned at a dimension 10×30×2mm to avoid the change or destruction of the structure of the welded joints. To prevent a change in microstructure of the specimen, a heat and mechanical damage cutting operation is performed by hacksaw. The specimen is sectioned at 15mm length away from both sides of faying surfaces of the welded joint.

4.4.3 Mounting the specimen

Once the test specimen is cut to an appropriate size, it is mounted on hot mounting press machine and the plastic material is used. Mounting operation involves putting the sample in a mold and surrounding it by the mounting material made of phenolic resins powder by using hot mounting machine. Phenolic resins powder used has comfortable with the sample with respect to hardness and abrasion resistance. The mounting of the specimen is used to facilitate the protection of the specimen edges and improve its rough shape to enable the grinding and polishing operation steps as well as used to guide the specimen while performing microstructure and hardness tests. This system automatically mounted using a hydraulic power package that automatically pressurized at 27.5GPa and heated the mold up to 250^0C for 300 seconds, took 300 seconds for holding time and 420 seconds for cooling hours using water as cooling of the media by using a solenoid valve. Finally, the mounted specimen is removed from the mold.

4.4.4 Grinding the specimen

Grinding operation of the specimen follows mounting operation to remove the surface damage that happened during the cutting of the sample step and used to provide a fine flat surface. Primarily a grinding operation is done by using a hand file and polished by different emery papers of 400 and 800 grit grade for rough surface of the specimens in one direction to remove burs and prepare the specimen for polishing operations.

4.4.5 Polishing the specimen

Polishing the specimen operation step removes the last thin layer of the deformed metal by using 1200 grit grade for fine polishing that is followed with 2000 grit grade for highly fine polishing papers. Then the final polishing operation of the specimens was polished by polisher (RB 204 Metpol-II, R and B Inc. Korea.) This polisher is driven by a motor having lubricated abrasive disk made of SiC paper and a diamond suspension liquid that were used for smooth and shiny surface finish. The disk rotates at 250 rpm of the grinder disk to give a last flat surface that is nearly free of the disturbed or deformed metal that has been introduced by the previous sample preparation steps.

4.4.6 Chemical etching

Chemical etching the specimen is the final step that might be used to show the microstructure of the test sample. This step is used to reveal features such as grain boundaries of the specimen. In order to enable identify the AA 6023-T6 and copper in the weld joint an appropriate reagent used was a solution of 5 ml H_2O_2 in 45 ml NH_4OH under holding time of 15 seconds. Transverse cross-sectioning of the weld joints was performed for microstructural analysis. Microstructure analysis was accomplished using Metallurgical Research Optical microscope 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 1000x. Figure 4.6 shows the mounted FSW joints for hardness and micro-structure observations.

Figure 4-6 Mounted FSW joints for Micro-structure and hardness

4.5 Optimization of FSW Process Parameters

In order to obtain confirm the results of tensile strength test and hardness from an experimental works, it is compulsory to design it statistically by using DoE. Hence, statistical DoE gives a clear answer to important questions with a valid, efficient and minimal cost. It also allows for the measurement of experimental error, quantification of effects and gives perception into interactions of variables. In this study the DoE used for best optimization is done by using the Taguchi method and ANOVA.

4.5.1 Taguchi Method

The key process parameters of a FSW system are studied and optimized in order to improve certain desired features. The process parameters for FSW are investigated using an orthogonal set of experiments and the desired output is taken as scalar functions to be optimized by the method. Taguchi method is selected due to it agrees for much smaller number of experiments which makes the method less expensive and more efficient than other DoE as well as allows to optimize an experiment in a fewer time.

The main implementation procedures of the Taguchi method can be written as follows:

- Identify the process parameters and their levels
- Select Taguchi orthogonal array matrix experiment
- Conduct experiment and measure the response to optimize
- Analyze an experiment results using signal to noise ratio and ANOVA

- Select the optimal levels of designed process parameters
- Predict the optimum levels of the process parameters and performance
- Verify the effectiveness of optimization with a confirmation test and plan the future action.

4.5.2 Selection of Orthogonal Array

Taguchi method of experiments is in the form of an orthogonal array matrix selected depending on the number of process parameters with their levels are the mandatory thing for optimization. At this moment, to conduct the experiments for FSW system three process parameters with three levels each the corresponding orthogonal array is the so called L_9 one. Taguchi test array is orthogonal it is possible to extract the effect of each FSW process parameter using only 9 tests. The process parameter levels giving the highest performance parameter results on average are identified and their average results are combined with the total means of each performance parameter in an algebraic model to calculate the optimum weld joints performance.

According to DoE the degree of Freedom (DOF) of FS welding operation can be calculated by the formula as given below.

$$\mathrm{DOE} = \mathrm{P}(\mathrm{L} - 1) \qquad (3.3)$$

Where, DOF= degree of freedom, P = number of factors and L = number of levels DOE = P (L-1) = L_9

4.5.3 Analysis of Variance (ANOVA)

ANOVA statistical analysis is the statistical technique used to further interpret the results from the experiments using the Signal-to-Noise ratios (S/N) of all process parameters output. ANOVA estimates the results whether the proportional contribution of the process parameters are statistically significance in difference or not in the desired characteristics. 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 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:

$$P(\%) = \left(\frac{SSTR - DOFxMSE}{SST}\right) x\, 100 \qquad (3.4)$$

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

4.5.4 Verification of experiment

A confirmatory experiment was done by suggested Taguchi method by considering the optimal desired setting of the process parameters with their levels to verify the results. Table 4.2 provides the orthogonal array of Taguchi method used for FSW process parameters with its levels. Total number of experiments of the orthogonal array should be greater than or equal to the total DoE required for the experiment.

Table 4.2 FSW process parameters with its value

Experiment number	Process parameters		
	Rotational tool speed (rpm)	**Transverse Speed (mm/min)**	**Tool pin offset (mm)**
1.	1000	12.5	1.0
2.	1000	16.0	1.5
3.	1000	20.0	2.0
4.	1250	12.5	1.5
5.	1250	16.0	2.0
6.	1250	20.0	1.0
7.	1600	12.5	2.0
8.	1600	16.0	1.0
9.	1600	20.0	1.5

4.6 Mechanical strength testing for FSW joint

Weld joint efficiency (η), is a criterion to identify the acceptable weld joint and it is expressed as the ratio of weld tensile strength to the workpiece tensile strength. The welded joint performance made of AA 6023–T6 aluminium alloy and pure Copper obtained by dividing UTS of welded joints derived from experiment.

4.6.1 Hardness test

The hardness of any material defined as the capacity of a material to resist indentation or scratching plastic deformation marked on the surface with an indenter under specified force. For this work Vickers hardness testing machine (HV05) is selected and used to characterize the hardness of welded joints of both AA 6023-T6 aluminium alloy and pure Copper. Vickers hardness test uses a square based diamond pyramid indenter with an angle of 136^{o} between an opposite face at vertex, which is pressed into the surface of the test specimen using a prescribed force of 10 kgf (kilogram of force) to produce a pyramidal indentation as shown in Figure 4.7.

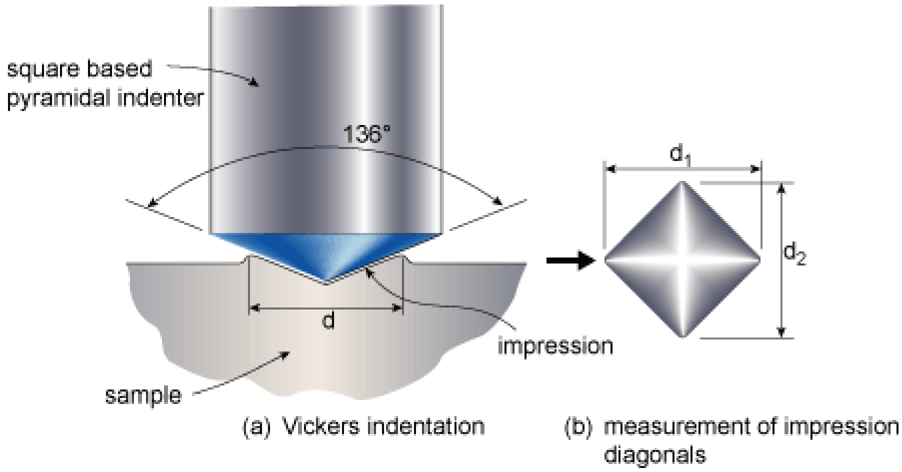


Figure 4-7 Vickers hardness test

The Hardness Vickers number is determined by the diamond indents into the specimen of AA 6023 –T6 aluminium alloy and pure Cu which is calculated by the formula:

$$HV = P = \frac{Constant\ x\ test\ force}{surface\ area\ of\ indentation} = \frac{0.102x2F(sin\frac{136^2}{2})}{d^2} \qquad (3.5)$$

Where VHN is Vickers hardness number, P is pressure, F is the force of the indentation and d is an average distance between both opposite corners of the indentation.

The hardness sample tests of the AA 6023-T6 alloy and pure Cu specimens mounted, grinded and polished according to the standard measurement. Using a Vickers hardness machine tester HVS – 50, microhardness measurements implemented at load test of 10kgf is pressed upon the surface of the specimen by an indenter under holding time of 10 seconds by far away at 2mm gap between indentations to offer a sufficient hardness measurement across the weld over the long range. To differentiate the distance from the center of weld joint toward AA 6023-T6 aluminium alloy and pure Copper negative and positive signs are used. For each welded joints the hardness values are taken by an averaging five data points. The collected data of Vickers hardness taken from HVS – 50 machine is shown in Table 4.3 below.

Table 4.3 Hardess values

Weld number	Distance from the center of weld joint [mm]	Vickers Hardness number reading under 10kgf				
		Trial 1	**Trial 2**	**Trial 3**	**Average of the trials**	**Average trials at weld joint**
1	-10	48.9	47.7	47.6	48.07	
	-8	50.8	50.2	53.8	51.6	
	-6	51.1	51.6	54.3	52.33	
	-4	52.2	52.5	72.1	59	**92.98**
	-2	81.1	88.6	90.1	86.6	
	0	131.2	114.5	96.1	114	
	2	110.1	119.6	115.2	115	
	4	86.6	92.9	92	90.5	
	6	97.2	89	92.2	92.8	
	8	92.5	88.1	90	90.2	
	10	88.6	84.7	89.1	87.5	
	12	89.5	83.3	86.2	86.33	

Weld number	Distance from the center of weld joint	Vickers Hardness number under 10 kgf				
		Trial 1	**Trial 2**	**Trial 3**	**Average of the trials**	**Average trials at weld joint**
2	-10	51.6	51.5	49.1	50.74	
	-8	53.7	53.9	50.4	52.67	
	-6	59.4	54.5	50.9	54.9	
	-4	89	60.6	52.2	67.37	**94.65**
	-2	97.9	124.3	82	101.4	
	0	115.2	116.2	131.2	120.87	
	2	91.3	109	112.9	104.4	
	4	88.3	87	92.5	89.3	
	6	84.5	85.7	86.2	85.47	
	8	82.2	83.7	82	82.63	
	10	79.3	81.5	79.3	80.03	
	12	75.5	85.1	75.5	78.8	

Weld number	Distance from the center of weld joint	Vickers Hardness number under 10 kgf				
		Trial 1	**Trial 2**	**Trial 3**	**Average of the trials**	**Average trials at weld joint**
3	-10	51.8	46.8	51.6	50.1	
	-8	51.4	48.5	53.2	51	
	-6	55.1	48.8	54.3	52.73	
	-4	72.1	51	72.1	65.1	**91.14**
	-2	90.1	56.8	96.1	81	
	0	96.4	124.3	108.2	107.63	
	2	95.4	112.3	97.5	101.73	
	4	97.2	106.2	91.5	98.3	
	6	92.7	119.6	89.5	100.6	
	8	87	99	88.1	93.4	
	10	89.5	90.1	84.5	88	
	12	88.1	91.5	83.3	87.7	

Weld number	Distance from the center of weld joint	Vickers Hardness number under 10 kgf				
		Trial 1	**Trial 2**	**Trial 3**	**Average of the trials**	**Average trials at weld joint**
4	-10	47	47	51.1	48.4	
	-8	50	50.8	53.8	51.34	
	-6	51.8	54.3	55.1	53.37	
	-4	52.5	83.3	75.3	70.37	**96.95**
	-2	86.4	96.1	92.5	91.67	
	0	109.2	119.6	106.2	111.67	
	2	114.5	97.2	114.5	108.73	
	4	108.2	90.1	97.2	98.5	
	6	89	87	99	91.67	
	8	86	86	93.9	88.63	
	10	84.5	84.5	92.5	87.12	
	12	83.3	82.2	89.5	85	

Weld number	Distance from the center of weld joint	Vickers Hardness number under 10 kgf				
		Trial 1	Trial 2	Trial 3	Average of the trials	Average trials at weld joint
5	-10	47.6	53.1	50.4	50.37	
	-8	53.9	56.1	53.2	54.4	
	-6	71	60.6	60.3	64	
	-4	72.5	75.3	75.89	74.56	**101.57**
	-2	87	89	98.4	91.5	
	0	88.6	120.3	119.6	109.5	
	2	147.4	123.2	134.6	135.07	
	4	111	88.3	92.5	97.27	
	6	99.5	88.1	92.6	93.4	
	8	95.4	86.4	90.1	90.63	
	10	93.9	83.5	84.5	87.3	
	12	92.9	81.5	82.2	85.53	

Weld number	Distance from the center of weld joint	Vickers Hardness number under 10 kgf				
		Trial 1	Trial 2	Trial 3	Average of the trials	Average trials at weld joint
6	-10	50.4	47.1	49.6	49	
	-8	51.5	50.2	50.9	50.9	
	-6	54.5	51.4	53.8	53.2	
	-4	61.3	53.2	54	56.2	**82.15**
	-2	63.4	60.3	60.6	61.43	
	0	82.8	83.3	83.3	83.1	
	2	89.9	98.4	110.1	99.5	
	4	110.1	112.9	99.2	107.4	
	6	116.2	111	92.7	106.6	
	8	85.7	93.9	89.5	89.7	
	10	83.7	87.9	88.1	86.57	
	12	82	90.1	86.4	86.2	

Weld number	Distance from the center of weld joint	Vickers Hardness number under 10 kgf				
		Trial 1	Trial 2	Trial 3	Average of the trials	Average trials at weld joint
7	-10	49.8	50.8	53.7	51.43	
	-8	53.2	52.7	55.1	53.7	
	-6	51.8	53.1	59.4	54.8	
	-4	50.5	75.3	91	72.3	**118.44**
	-2	135.3	107.1	115.2	119.2	
	0	143.2	113.2	147.4	134.6	
	2	134.1	114.8	138.5	129.13	
	4	124.6	166.8	119.6	137	
	6	90.6	95.4	99	95	
	8	89	92.2	95.4	92.2	
	10	89.2	88.6	92.2	90	
	12	81.9	82.2	90.1	84.7	

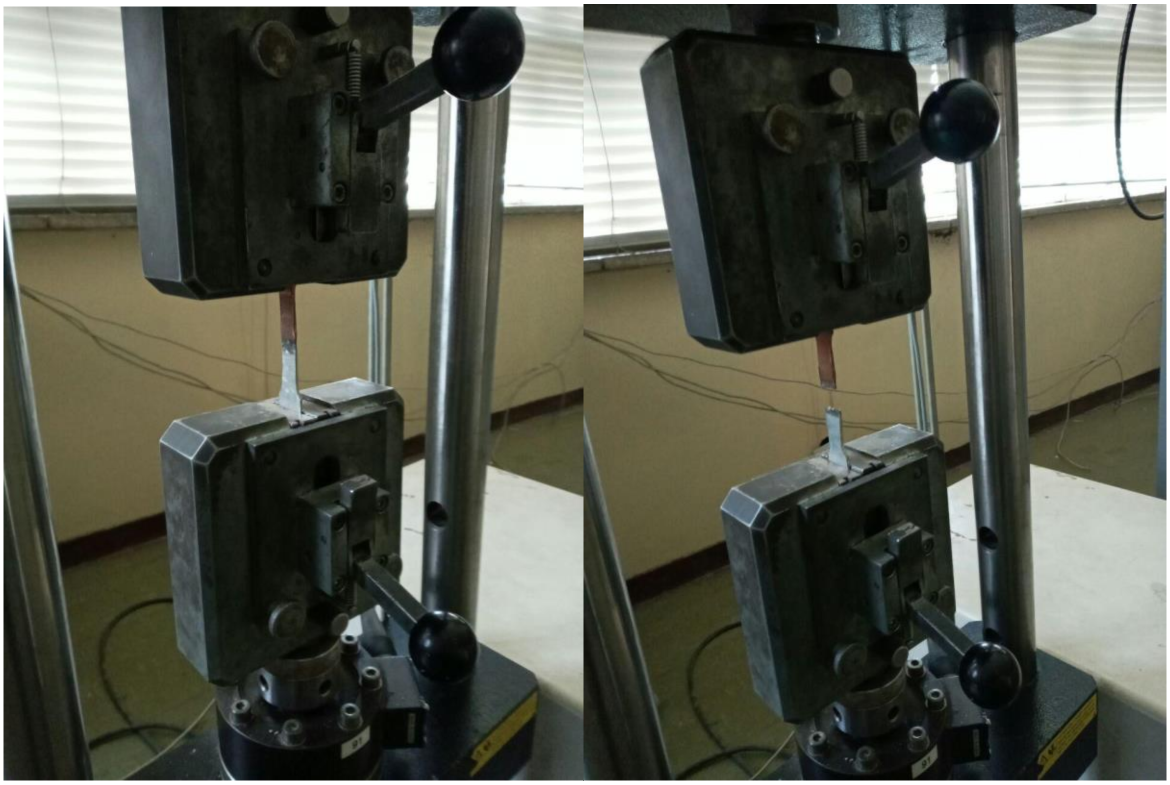
Weld number	Distance from the center of weld joint	Vickers Hardness number under 10 kgf				
		Trial 1	Trial 2	Trial 3	Average of the trials	Average trials at weld joint
8	-10	50.5	51.5	51.1	51.03	
	-8	49.6	52.3	53.8	51.9	
	-6	51	53.8	54.3	53.03	
	-4	57	82.4	56.8	65.4	**101.12**
	-2	60.6	88.6	60.6	69.93	
	0	124.3	123.2	114.8	120.8	
	2	158.5	92.5	158.5	136.5	
	4	130	88.3	120.3	112.9	
	6	98.7	87.5	98.7	95	
	8	95.9	87.9	93.9	92.6	
	10	88.8	85.7	92.7	89.1	
	12	82.6	85.3	90.1	86	

Weld number	Distance from the center of weld joint	Vickers Hardness number under 10 kgf				
		Trial 1	Trial 2	Trial 3	Average of the trials	Average trials at weld joint
9	-10	49.5	49.1	52.7	50.43	
	-8	51.4	50.9	53.2	51.83	
	-6	54.3	52.9	59.4	55.53	
	-4	83.3	76.9	76.9	74.03	**101.17**
	-2	96.1	103	119.6	106.23	
	0	96.3	120.3	115.2	110.6	
	2	112.3	92.5	106.2	103.7	
	4	111.3	92.9	98.4	100.9	
	6	87.5	87.9	92.2	89.2	
	8	87.2	86.2	90.6	88	
	10	87	85.1	87.5	86.53	
	12	86.2	83.5	85.5	85.1	

4.6.2 Tensile Test

Tensile testing is a destructive test process of the specimen that is used to identify the mechanical behavior of a material such as the ultimate tensile strength, yield strength, and its ductility under tension load at a constant rate until fracture. A tensile testing machine used a tension force up to the specimen is broken to confirm the ultimate tensile strength or load that the material can withstand and its elongation. Figure 4.8 provides universal testing machine setups before and after fracture of AA 6023 – T6 aluminium and pure copper welded joint specimen.

In this thesis work, tensile testing specimen measured in transverse to the welding direction. In order to assess the weld joints performance, the specimens were cut perpendicular to the welding line to evaluate an ultimate tensile strength. The necessary dimension of the specimen for the tensile testing in the transverse direction of the welding was prepared depends on both American Society for Testing of Materials (ASTM E8) standards and capacity of the machine. The standard specimens were prepared from the welded sheets having 203mm × 20mm × 2 mm dimension by cut up using a hacksaw and then by considering a fracture at neck which is located at a middle of the specimens, three tensile specimens were fabricated for each trial to estimate the tensile strength of the weld joints. Figure 4.9 is provided the tensile testing specimens made at orthogonal array of different FSW process parameter.



(A) **(B)**

Figure 4-8 UTM setup before (A) and after (B) Fracture of the Specimen

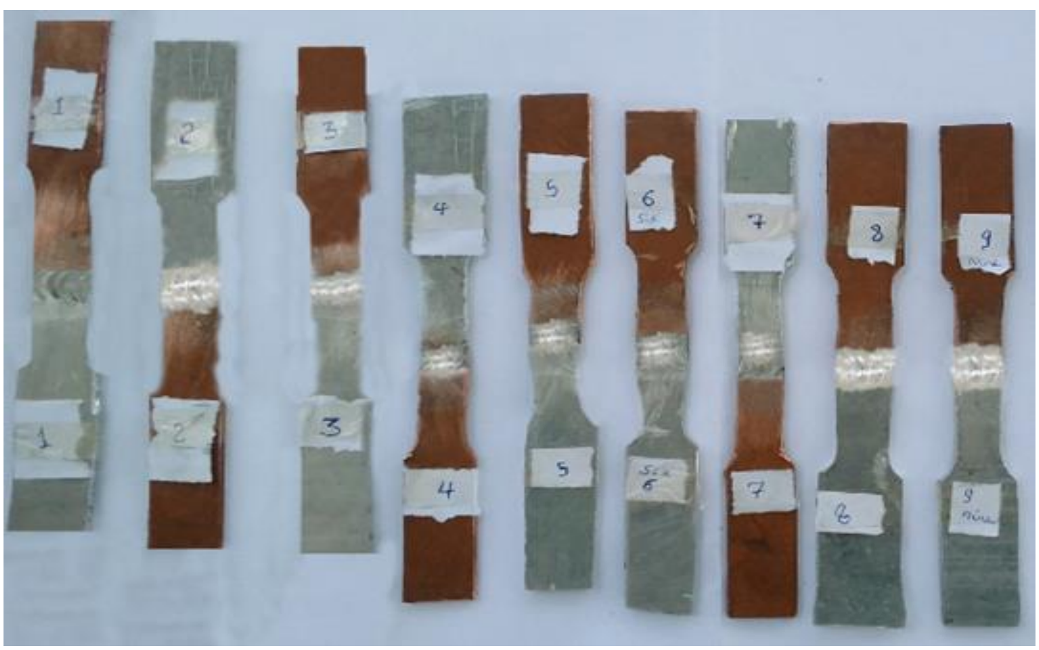


Figure 4-9 Tensile specimens of FSW joints made by different process parameters

CHAPTER FIVE

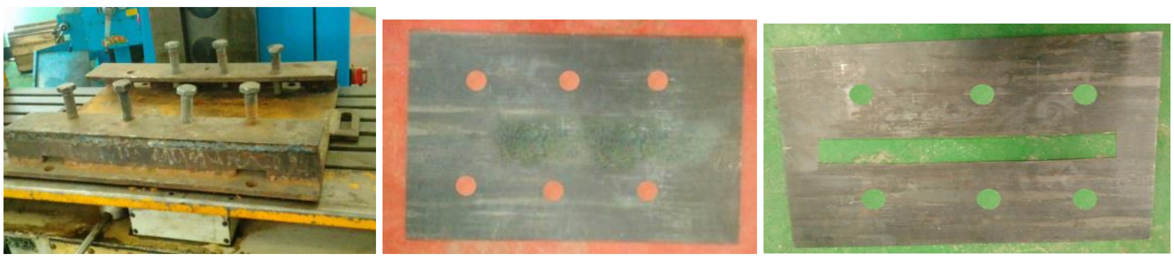
RESULTS AND DISCUSSION

5.1 Manufactured tool, backing plate and fixture for FSW of AA 6023-T6 and Cu 110 sheets

The FSW tool design is the maximum operative process parameter in the FSW welding to enhance the welding quality by producing the force and torque encountered during joining; affecting the heat input and plasticized material flow. Hence, for FSW of dissimilar AA 6023-T6 aluminium alloy and pure Copper sheets the simple FSW tool is designed and cost–effective tool material used is as AISI D2 tool steel. The tool is tempered and quenched conditions as well as hardened up to 58HRC. The Figure 5.1 shows the D2 steel of FSW tool with shoulder and pin of 12mm and 3.5mm diameters respectively.

Figure 5-1 FSW tool after welding operation

The backing plate is manufactured from 4 and 3mm-thick mild steel plate as shown in Figure 5.2. During the design and manufacturing, the main feature has been considered such as vibration controlling during the FSW process.



(A) **(B)** **(C)**

Figure 5-2 Fixture on bed of CVVM (A) Top backing plate (B) and bottom backing plates (C) after FSW performed on CVMM

5.2 AA 6023–T6 aluminium– pure Copper welded joint

Figure 4.3 shows the illustrative welding structure of weld joints of AA6023 and pure copper with its process parameters. In Figure 5.3 (a – f, i) the welded joints produced have different surface structure which resulted to the formation of defects which are discussed in next section and Figure (g and h) are indicating the FSW joints defect free made with process parameters combination of (1600, 12.5 and 2.0; 1600, 16.0 and 1.0) respectively which was shown in Table 4.2. The quality of the surface structure of the welded joint is used to identify the rejections of the welds with an agreement of the microstructures of the weld joints at different FSW process parameters.

a) 1000 rpm, 12.5mm/min and 1mm (weld 1)

b) 1000 rpm, 16mm/min and 1.5mm (weld 2)

c) 1250 rpm, 20mm/min and 2mm (weld 3)

d) 1250 rpm, 12.5mm/min and 1.5mm (weld 4)

e) 1250 rpm, 16mm/min and 2mm (weld 5)

f) 1600 rpm, 20mm/min and 1mm (weld 6)

g) 1600 rpm, 12.5mm/min and 2mm (weld 7)

h) 1600 rpm, 16mm/min and 1mm (weld 8)

i) 1600 rpm, 20mm/min and 1.5mm (weld 9)

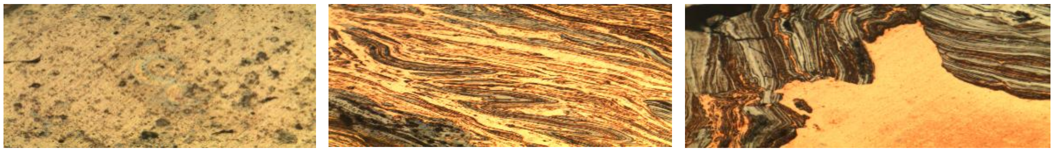
Figure 5-3 AA 6023 – T6 – pure Copper FSW joints with corresponding process parameters

5.3 Microstructural results at selected process parameters

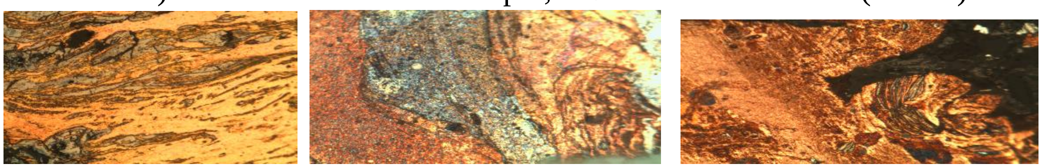
The results of microstructure of the welded joints of AA 6023–T6 aluminium alloy and copper is used to identify the different zones in the welded joints. In the scientific phenomenon, the microstructure of Al/Cu FSW is affected by the nature and number of crystal lattices, the radius of the atoms in materials.[**57**] Even if the grain size of the welded joint is not measured, its grain structure is varied at different locations. During FSW process of AA 6023–T6 aluminium alloy and pure Copper, high plastic deformation is formed and high amounts of strain energy is stored in welding joints both materials to join one to another. The results of the microstructure for all FSW process parameters is identified depending on an orthogonal array of Taguchi method discussed to identify the welding quality to accept or reject the welded joints which is listed as follows:-

For the first process parameters combinations small micro-voids, non-uniform material flow, and lamellar intercalated structure defect (fluid like morphology of both AA 6023 – T6 aluminium alloy in swirl and vortex structure without melting point) is created at low rotational speed, low transverse speed and low tool pin offset which produced formation of low frictional heat input produced which is difficult to stir and mix parent materials uniformly with each other easily as shown in (Figure 5.4 (a). For the second process parameters combinations similar defect is formed with an additional defect of tunnel at low rotational speed, medium transverse speed and medium tool pin offset which resulted low frictional heat input which is difficult to refined and join the materials easily at weld joints as shown in Figure 5.4 (b). For the third process parameters combinations deformed pure copper grain structure is shown in Figure 5.4 (c) caused by low rotational speed, high transverse speed and tool pin offset. For the fourth process parameters combinations non-uniform mixing of AA 6023 –T6 and pure Copper and laminar intercalated structure is formed by medium rotational speed, low transverse speed and medium tool pin offset as shown in Figure 5.4 (d) which is resulted in brittleness of new AA 6026-T6 – Copper formation during FSW processes. For the fifth process parameters combinations deformed AA 6023-T6 grain structure as well as micro-voids is formed due to tough mixing of Cu particles with aluminium matrix as shown in Figure 5.4 (e) which is resulted by medium rotational speed and transverse speed as well as high tool pin offset. For the sixth process parameters combinations lamellar intercalated structure, interface and internal discontinuity of material flow is created due to low frictional heat input generated at low rotational speed, low transverse speed and tool pin offset as shown in Figure 5.4 (f). For the seventh process parameters combinations is the best microstructure formed due to high rotational speed and tool pin offset as well as low transverse speed which is more suitable to stir and mix the deformed materials within the welded joint shown in Figure 5.4 (g). Therefore dynamic crystallization of the material flow leads to a good grain structure at welded joint. For the eighth process parameters combinations microstructure and the material flow in welded joint is good due to high rotational speed and medium transverse speed and low tool pin offset shown in Figure 5.4 (h). For the ninth process parameters combinations a crack and lamellar intercalated structure is created at weld joint due to high rotational speed which is created by excessive formation of flash as shown in Figure 5.4 (i). For each weld joint at three different position of the weld joint 1000x magnification is taken.

Generally as it is clearly seen from Figure 5.4 except weld 7 and 8 in all welded joints different types of defects are created. However, welded joints produced at FSW process parameters of number 7 and 8 are defect free and sound welds. Different microstructures are formed due selection of different values of FSW process parameters.

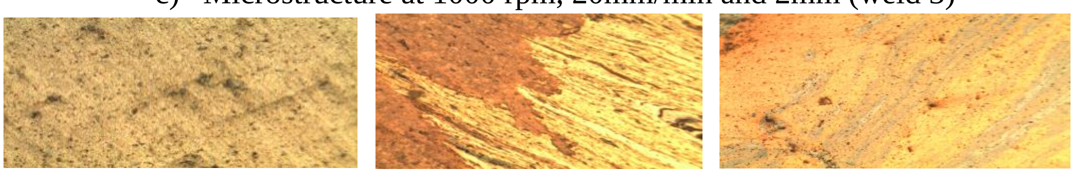


a) Microstructure at 1000 rpm, 12.5mm/min and 1mm (weld 1)

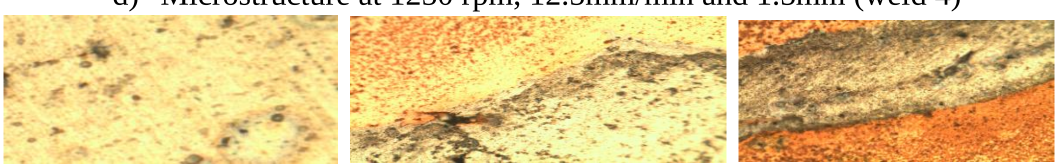


b) Microstructure at 1000 rpm, 16mm/min and 1.5mm (weld 2)

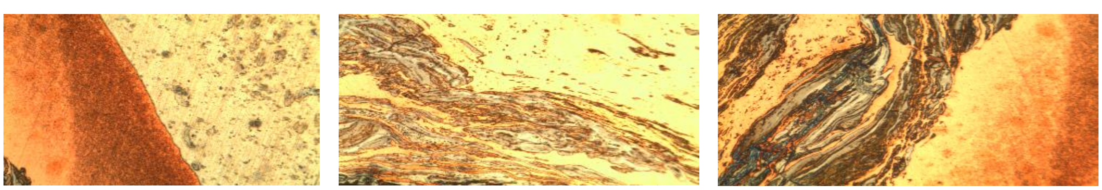
c) Microstructure at 1000 rpm, 20mm/min and 2mm (weld 3)



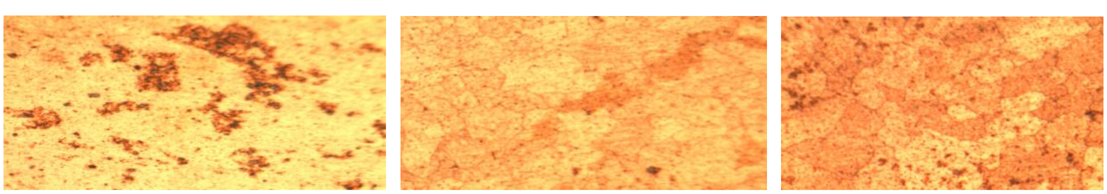
d) Microstructure at 1250 rpm, 12.5mm/min and 1.5mm (weld 4)



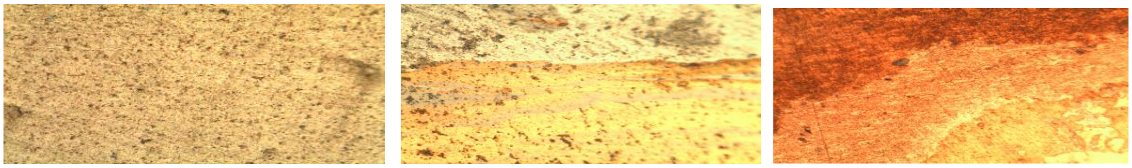
e) Microstructure at 1250 rpm, 16mm/min and 2mm (weld 5)



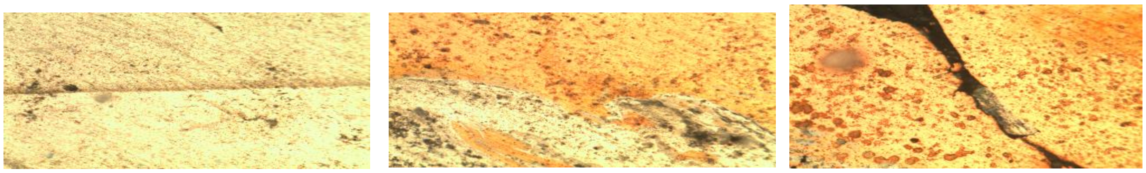
f) Microstructure at 1250 rpm, 20mm/min and 1mm (weld 6)



g) Microstructure at 1600 rpm, 12.5mm/min and 2mm (weld 7)



h) Microstructure at 1600 rpm, 16mm/min and 1mm (weld 8)



i) Microstructure at 1600 rpm, 20mm/min and 1.5mm (weld 9)

Figure 5-4 Microstructure of FSW joints corresponding with process parameters

5.4 Tensile test result

Table 5.1 illustrates the outcomes of tensile strength test of FS welded joints depending on orthogonal array of DoE.

Table 5.1 Experimental results of mean value tensile strength value for weld joints

Sam-ple no	ω (rpm)	V (mm/min)	Tool pin offset (mm)	Tensile Strength (MPa)			Average UTS (MPa)	Weld Performance (%)	S/N Ratios
				Trial 1	Trial 2	Trial 3			
Base material					AA 6023 – T6		210		
					Pure Copper		355		
1.	1000	12.5	1.0	114.6	124.8	120.6	120.00	43.24	41.5836
2.	1000	16.0	1.5	108.80	116.76	112.21	113.00	40.72	41.0616
3.	1000	20.0	2.0	106.36	100.33	108.3	105.00	37.84	40.4238
4.	1250	12.5	1.5	121.2	119.8	131	124.00	44.68	41.8684
5.	1250	16.0	2.0	135.00	124.45	130.45	130.00	46.85	42.2789
6.	1250	20.0	1.0	105.68	99.25	98.8	101.24	36.48	40.1070
7.	1600	12.5	2.0	166.15	172.1	173.2	170.40	61.41	44.6294
8.	1600	16.0	1.0	136.29	130.79	134.98	134.00	48.29	42.5421
9.	1600	20.0	1.5	138.02	140	142	140.00	50.45	42.9226

At low transverse speed and high rotational speed up to certain value high frictional heat input is produced which results in good material flow and welding appearance in FS welded joints as well as it increases the UTS. On the contrary to this, when both rotational speed and transverse speed increases the material flow of the weld joint is insufficient that results brittleness properties of the material which leads presences of defects; that is confirmed with the results of preceding studies in literature.[**53 – 59]**

5.4.1 Analysis of Mean for tensile strength

The average main value of tensile value for each factor i.e. rotational speed (A), welding speed (B), and tool pin offset (C) calculated from three trials for each experiments and their main effect plot is shown in Table 5.2. Since the mean of means for Table 5.2 is tensile strength the unit is MPa.

Table 5.2 Response table for main effects plot for larger is better

Level	Rotational speed	Transverse speed	Tool pin offset
	Symbol		
	A	**B**	**C**
1.	112.7	**138.1**	118.4
2.	118.4	125.7	125.7
3.	**148.1**	115.4	**135.1**
Delta	35.5	22.7	16.7
Rank	1	2	3

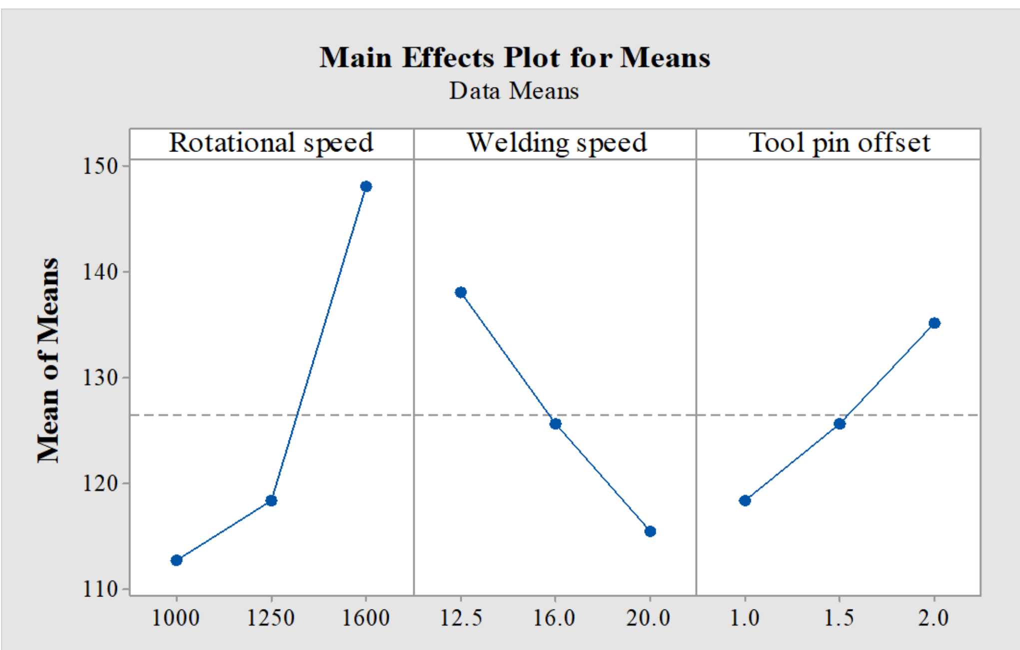


Figure 5-5 Mean of means result obtained for tensile test using Minitab software

The graph of Figure 5.5 shows an effect of FSW process parameters upon tensile strength. Effects of each process parameters: - rotational speed, transverse speed and tool pin offset on the mean of means on UTS are clearly shown graphically. Its explanation is discussed as follows:-

The primary factor which mainly affects the mean of means of UTS is rotational speed and its numerical values are 1000RPM, 1250RPM and 1600RPM. At lower and medium tool rotational speed of 1000RPM and 1250RPM respectively, the generated fictional heat at the weld zone is not adequate to strain the plasticized material. This results in poor merging of material flow and formation of defects like: micro-voids, non-uniform material flow, lamellar intercalated, interface and deformed AA 6023 – T6 aluminium alloy and Cu grain structures. An existence of these defects in the welded joints resulted in lower tensile strength. At high tool rotational speed of 1600RPM, the generated fictional heat at the weld zone is adequate for stirring and dispersing the plasticized material around the tool pin. These yields a sufficient plasticized material flow with fine dynamic recrystallized grains and make homogenous material which is defect free and sound welded joints. When rotational speed of the tool is increased to1600RPM, UTS at the weld zone also increases.

The secondary factor which mainly affects the mean of means of UTS is transverse speed and it numerical values are 12.5mm/min, 16mm/min and 20mm/min. At lower transverse speed of 12.5mm/min, the pin and shoulder of the tool contact time the parent materials take a long time. As a result, the rotating tool generates a sufficient frictional heat softly and transportation of an adequate plasticized material flow and good merging of materials with fine grains is formed which results defect free welded joints and high tensile strengths. An increasing of transverse speed results in decreasing of UTS. As transverse speed increases to 16mm/min and 20mm/min, the pin and shoulder of the tool contact time to the parent materials decreases. For this reason without obtaining the desired plasticized material flow extra turbulence flow of the parent materials is formed under an action of tool. This produced an excessive flash and cracks. Reduction of frictional heat produced by high transverse results insufficient plasticized material flow from Copper side to AA 6023 – T6 aluminium side. As a result the tensile strength of welded joints across the weld zone is decreased.

The tertiary factor which mainly affects the mean of means of UTS is tool pin offset and it numerical values are 1mm/min, 1.5mm/min and 2mm/min. The hardness of AA 6023 – T6 aluminium is less than that of pure Copper; for this reason tool pin offset is fixed in copper side to plasticize the materials under an action of pin and shoulder of the tool and the refined material flow of AA 6023 – T6 and Copper are homogeneously mixed to each other. Furthermore, when the pin offset was smaller, more Copper was stirred into the nugget zone. As a result, the AA 6023 – T6 aluminium alloy easily transported to Copper create strong bond. In case of this thesis work the tensile strength increases with the tool pin offset values. This is resulted due to increasing of tool pin offset toward an advancing side produces the homogenous stirred particles that could be easily dispersed in welding zones. In contrary to this, as tool pin offset decreases inhomogeneity of material is formed which leads different defects like: lamellar intercalated, voids, flash. Due to combination of nonferrous material for FSW in all welded joints very low tensile strength were found.

The control process parameters main effect plot for means of tensile strength variations is as shown in the Figure 5.5. The result taken from the above data shows means as lager is better is selected for tensile strength output.

$$\text{Delta} = \text{maximum mean} - \text{minimum mean} \qquad (5.1)$$

Table 5.2 and Figure 5.5 show that the factor with the highest effect on the mean is rotational speed weight (Delta=35.5, Rank=1). The factor with the least effect on the mean is tool pin offset (Delta=16.7, Rank = 3). The plot of an effect of means is necessarily useful for adjusting the mean on better value. From Table 5.2 is clearly seen that optimal parameter combination on larger-the-better character is **A3B1C3** are the possible parameter combinations for increasing the tensile strength of weld joint.

5.4.1.1 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 gained predicted value of the responses (tensile strength) the equation 5.2 is used.

$$y_{opt} = m + \sum_{i}^{n} (m_i - m) \qquad (5.2)$$

Where m = Average performance mean ratio value for tensile strength, m_i = optimum level of mean value for each process parameters, n is number of process parameters.

$$y_{opt} = 126.4 + (148.1 - 126.4) + (138.1 - 126.4) + (135.1 - 126.4)$$

$$y_{opt} = 168.5 \ (predicted\ mean\ value\ for\ tensile\ strength)$$

5.4.1.2 Analysis of S/N Ratios for tensile strength

The tensile strength result obtained experimentally is found and to optimize the UTS of the weld joint Taguchi method S/N ratio to measure its variation. In this particular thesis work, the response variables are larger-the-better. Table 5.3 presents the calculations of S/N Ratios for tensile strength results using the Minitab 17 design of experiments.

Table 5.3 Response Table for Signal to Noise Ratios Larger Is Better

Level	**Rotational speed**	**Transverse speed**	**Tool pin offset**
	Symbol		
	A	**B**	**C**
1.	41.02	**42.69**	41.41
2.	41.42	41.96	41.41
3.	**43.36**	41.15	**42.44**
Delta	2.34	1.54	1.03
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 5.3.

$$Delta = \left(Maximum\frac{S}{N}\ Ratio - minimum\frac{S}{N}\ ratio\right) \qquad (5.3)$$

From the tensile strength results and main effects plot for the signal-to-noise (S/N) ratios the rotational speed weight has the greatest effect (Delta = 2.34, Rank = 1). The factor with the minimum effect on S/N ratio is tool pin offset (Delta = 1.03, Rank = 3). Table 4.3 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 major effect plot for the tensile strength of S/N ratio is shown in the Figure 5.6.

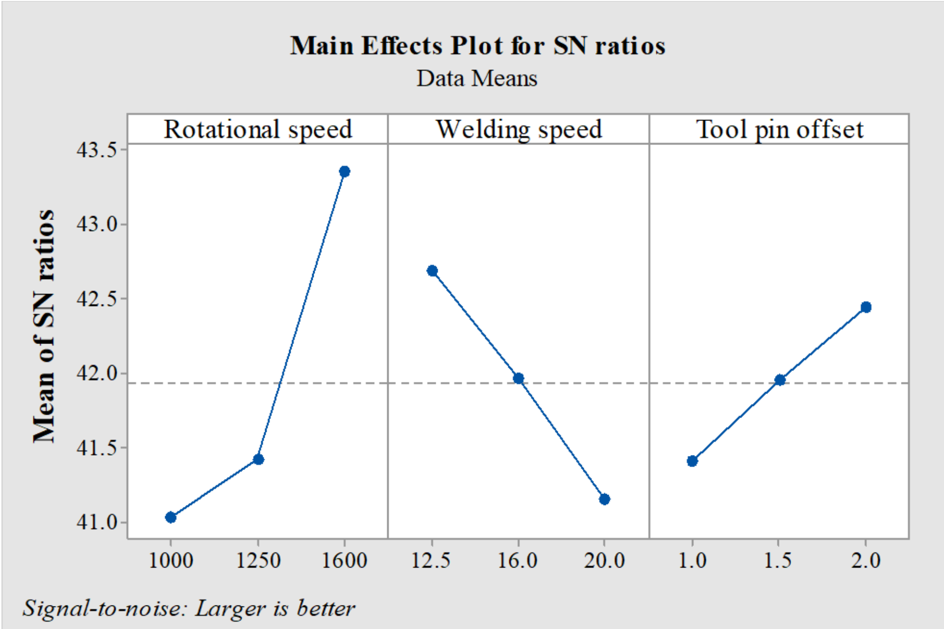


Figure 5-6 Tensile strength main effects plot for S/N ratio

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 operative process parameter of FSW to enhance the tensile strength is the rotational speed weight high percentage when compared to other factors.

5.4.1.3 Predict the Performance at Optimal Levels of the S/N result

For predicting the optimum response, three factors of parameters 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 5.2 is used.

$$y_{opt} = m + \sum_{i}^{n} (m_i - m) \qquad (5.4)$$

Where m = Average performance S/N ratio value for tensile strength, m_i = optimum level of S/N ratio value for each process parameters, n is number of process parameters.

$$y_{opt} = 41.93 + (43.36 - 41.63) + (42.69 - 41.63) + (42.44 - 41.63)$$

$$y_{opt} = 44.63 \; (predicted\ S/N\ value\ for\ tensile\ strength)$$

5.4.2 Analysis of Variance (ANOVA) for tensile strength 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 which is shown in Table 5.4.

Table 5.4 Analysis of Variance for tensile strength value

Source	DF	SST	MSE	F-Value	P-Value	Percent contribution	Significance (α =0.05)
Rotational speed	2	2174.2	1087.09	15.96	0.059	61.96%	Highly significant
Transverse speed	2	776.7	388.37	5.70	0.149	22.14%	Significant
Pin tool offset	2	421.8	210.89	3.10	0.244	12.02%	Significant
Error	2	136.2	68.11			3.88%	
Total	Total	3508.9				100%	

Table 5.4 presents tensile strength value percentage contribution variation of factors A, B, and C. It is seen that both rotational speed and transverse speed factor has statistical and physical significances on the tensile strength value of weld joint during rotational speed at 95% confidence level. From the Table 5.4, it is clearly shown that the rotational speed weight percentage (61.96%), transverse speed (22.14%), and tool pin offset (3.88%) have significant influence on weld joint of FSW of AA 6023-T6 alloy and pure Copper sheets.

5.4.3 Determining the Optimum Condition for tensile value

From above discussion rotational speed weight percentage optimum level value 1600rpm, transverse speed optimum level value 12.5mm/min, and tool pin offset optimum level value 2mm make the response S/N ratio values highest. An optimum FSW process parameter gained from the DoE setting selected for tensile strength value and experimental results is used to identify the optimum process parameters as illustrated in Table 5.5.

Table 5.5 Optimum process parameters setting levels and their values

Controllable factors	Selected value	Level of the selected value	Rank of affecting the response
Rotational speed	3	1600	1
Transverse speed	1	12.5	2
Tool pin offset	3	2	3

5.5 Hardness test result

The results of hardness for each welded joints is taken from the computer after diamond indenter is dwelling out. Hence the result of hardness on AA 6023 – T6 aluminium alloy side is less than pure Copper side. However the hardness at welded joints are harder than the hardness of both parent materials; this is happened due to grain refinement and plastic deformation of materials. Table 5.6 illustrates the outcomes of mean value of hardness test of FS welded joints depending on orthogonal array of DoE. The result of mean value of hardness at weld joint is provided in Table 5.6.

Table 5.6 Experimental result for mean value of hardness

Sample no	ω (rpm)	V (mm/min)	Tool pin offset (mm)	Hardness			Average HV (for 10kgf)	Weld Perfor-mance	S/N Ratios
				Trial 1	Trial 2	Trial 3			
Base material				AA 6026-T6			54.00		
				C110			116.00		
1.	1000	12.5	1.0	92.24	93.62	93.09	92.98	109.4	39.40
2.	1000	16.0	1.5	96.34	99.42	94.2	94.65	11.35	39.52
3.	1000	20.0	2.0	90.24	90.12	93.05	91.14	107.22	39.19
4.	1250	12.5	1.5	94.16	97.26	96.96	96.95	114.06	39.73
5.	1250	16.0	2.0	101.3	99.22	104.19	101.57	119.49	40.14
6.	1250	20.0	1.0	81.5	81.62	83.32	82.15	96.64	38.29
7.	1600	12.5	2.0	117.54	115.44	122.34	118.41	139.31	41.47
8.	1600	16.0	1.0	106.08	95	102.29	101.12	118.96	40.10
9.	1600	20.0	1.5	99.86	97.12	103.52	100.17	117.85	40.01

An average of micro-hardness tests of FS welded joints of AA 6023 T6 aluminium alloy and pure Copper under each process parameters is shown graphically in Figure 5.7. From the graph it is clearly shown the optimum process parameters of FSW are shown for weld 7.

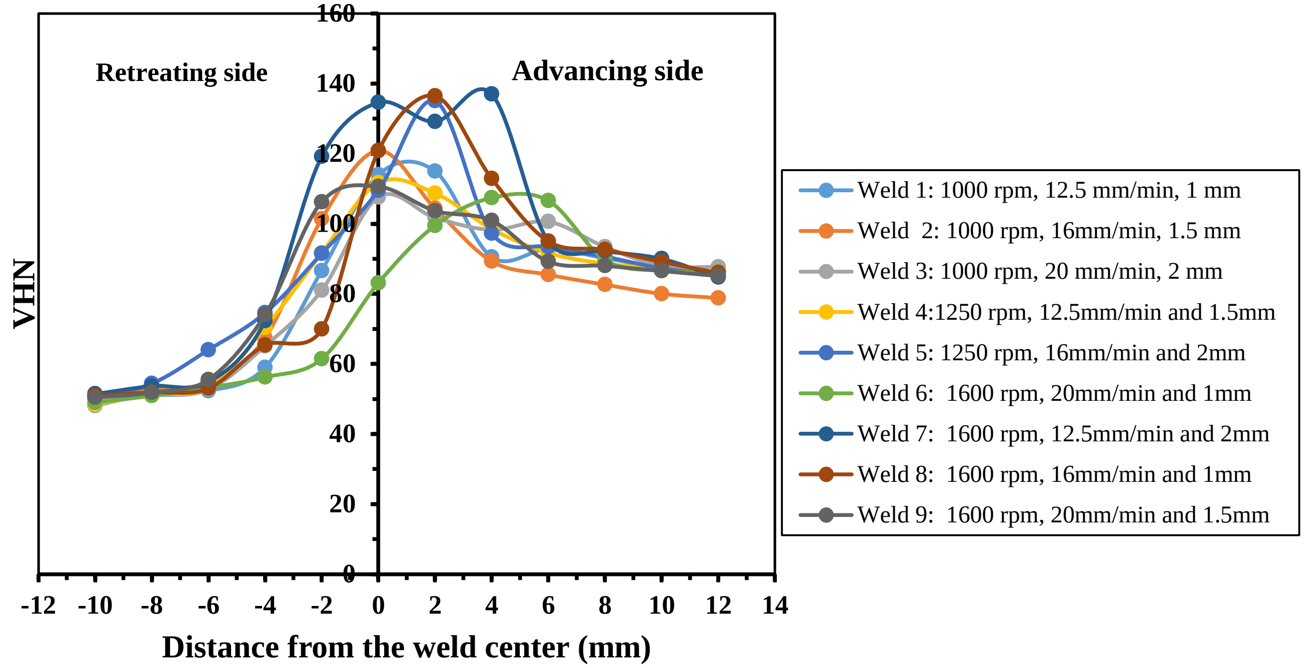


Figure 5-7 Microhardness distribution

From Figure 5.7 it was clearly observed that the results of micro-hardness profile of the FS welded butt joints of the AA 6023 – T6 aluminium and pure copper is harder than the parent materials. This is resulted due to an inhomogeneous distribution of hardness values created from strain hardening by stirring of the pin and shoulder tool previously occupied by these regions while FSW is under operation. The higher value of hardness may be resulted due to formation of intermetallic compounds which is harmful to the welding strength of the welded joints and leads it to brittle in nature. However for this research work the hardness test results are acceptable.

5.5.1 Analysis of Mean for Hardness

It is obvious that FSW the process parameters particularly rotational speed, transverse speed, and tool pin offset has a decisive influence on hardness of the FS weld joints as it is shown in Table 5.6. Taguchi method uses means of means for hardness as given in Table 5.7, for each factor i.e. Rotational speed (A), Transverse speed (B), and Tool pin offset (C) at each level. This table is used to select the optimum process parameters of FSW.

Table 5.7 Response table for means main effects plot for larger is better

Level	Rotational speed	Transverse speed	Tool pin offset
1.	92.92	**102.78**	92.08
2.	93.56	99.11	97.26
3.	**106.57**	91.15	**103.71**
Delta	13.64	11.63	11.62
Rank	1	2	3

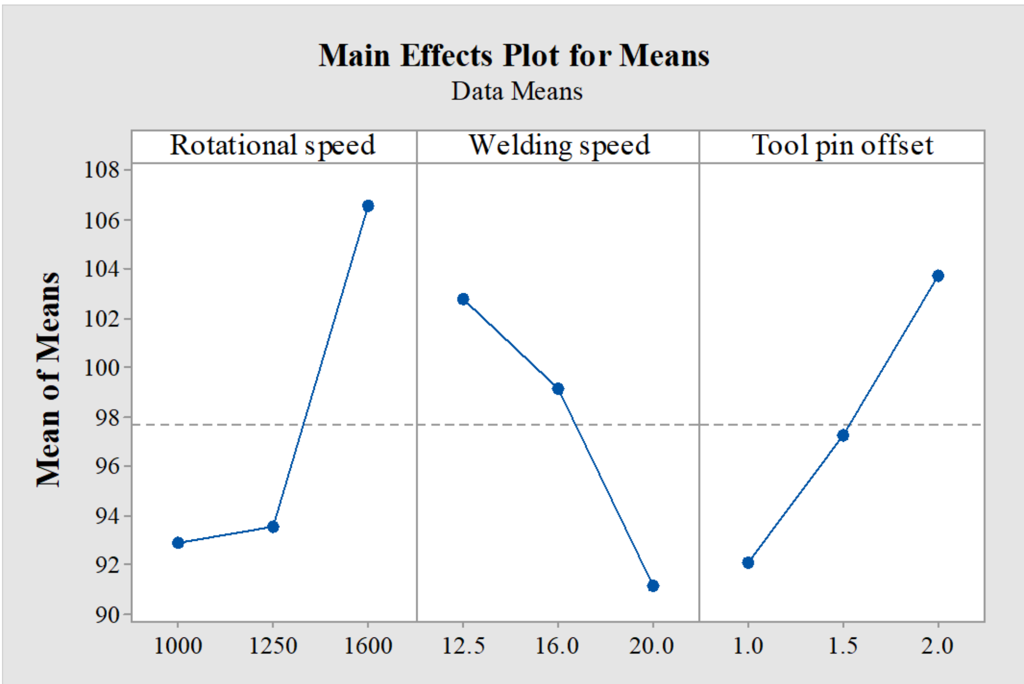


Figure 5-8 Mean of means result obtained for hardness using Minitab software

The control factors main effect plot for means of hardness value variations is as shown in the Figure 5.8. The result taken from the above data shows means as lager is better is selected for hardness value output.

$$Delta = Maximum\ hardness\ mean - minimum\ hardness\ mean \qquad (5.5)$$

Table 5.7 and Figure 5.8 show that the factor with the greatest effect on the mean is rotational speed weight (Delta =13.64, Rank = 1). The factor with the least effect on the mean is tool pin offset (Delta = 11.62, Rank = 3). The plot of this mean is mainly necessary 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.

5.5.1.1 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 obtain the forecasted value of the responses of hardness value equation 5.6 is used.

$$y_{opt} = m + \sum_{i}^{n}(m_i - m) \qquad (5.6)$$

Where m = Average performance mean value for hardness, m_i = optimum level of mean value for each process parameters, n is number of process parameters.

$$y_{opt} = 97.68 + (106.57 - 97.68) + (102.78 - 97.68) + (103.71 - 97.68)$$

$$y_{opt} = 117.7\ (predict\ mean\ value\ for\ hardness\ value).$$

5.5.1.2 Analysis of S/N Ratios for hardness

The hardness result obtained by using process parameters defined in orthogonal array; however, Taguchi method is used S/N ratio measures these variations. Table 5.8 presents the calculations of S/N Ratios for hardness results using the Minitab 17 design of experiments.

Table 5.8 Hardness response table for S/N ratio

Level	Rotational speed	Transverse speed	Tool pin offset
	A	**B**	**C**
1.	39.36	40.19	39.25
2.	39.39	39.92	39.76
3.	**40.53**	39.17	**40.27**
Delta	1.16	1.02	1.01
Rank	1	2	3

For each experiment an average of S/N value is calculated for each factor and level as shown in Table 5.8.

$$\text{Delta} = \left(\text{maximum hardness}\frac{\text{S}}{\text{N}}\text{ratio} - \text{minimum hardness}\frac{\text{S}}{\text{N}}\text{ratio}\right) \qquad (5.7)$$

By Looking at the hardness table and main effects plot for the signal-to-noise (S/N) ratios weight rotational speed have the greatest effect (Delta = 1.26, Rank = 1). The factor with the least effect on S/N ratio is the tool pin offset (Delta = 0.24, 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 hardness of weld joint. The control factors main effect plot for the hardness of S/N ratio is shown in the Figure 4.7.

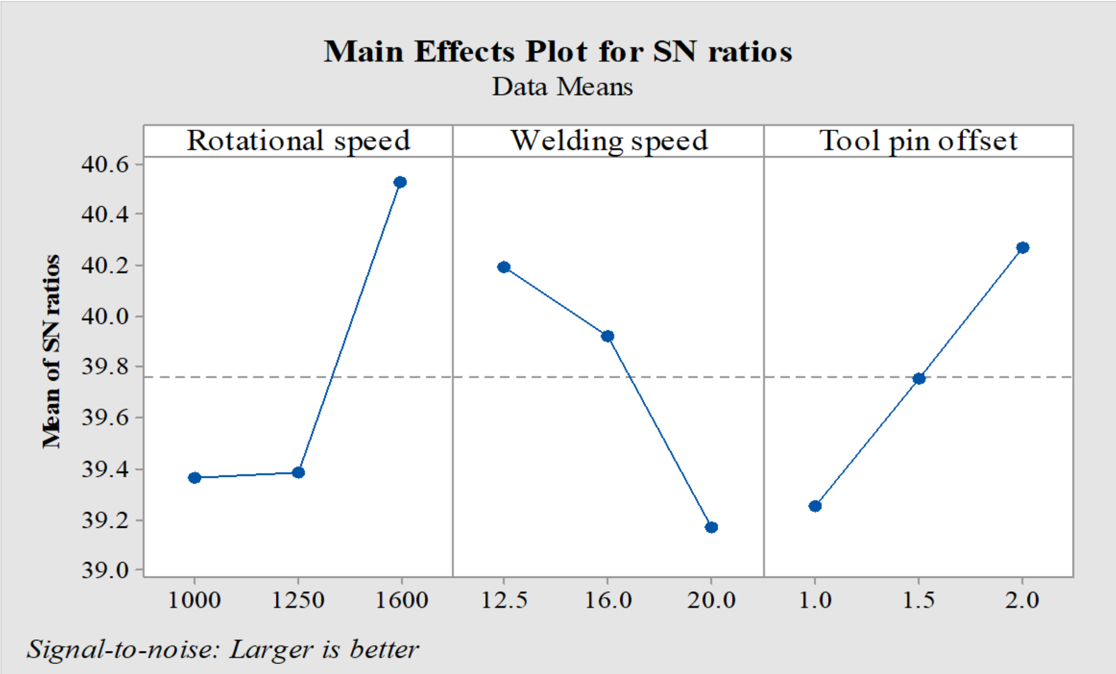


Figure 5-9 Hardness main effects plot for S/N ratio

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 hardness is the rotational speed weight high percentage when compared to other factors.

5.5.1.3 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. To find out predicted values of the response (tensile strength) equation 4.2 was used:

$$y_{opt} = m + \sum_{i}^{n} (m_i - m) \qquad (5.8)$$

Where m = Average performance S/N ratio value for hardness, m_i = optimum level of S/N ratio value for each process parameters, n is number of process parameters.

$$y_{opt} = 42.5 + (42.92 - 42.5) + (42.59 - 42.5) + (43.13 - 42.5)$$

$$y_{opt} = 43.64\ (predict\ S/N\ value\ for\ hardness\ value).$$

5.5.2 Analysis of Variance (ANOVA) for hardness value

ANOVA results DOF = degree of freedom, SST = Sum of squares, MSE = Mean square error and F = F- Ratio calculated by using Minitab 17 software were shown in Table 5.9.

Table 5.9 Analysis of Variance for hardness value

Source	DF	SST	MSE	F	P	Percent contribution	Significance (α =0.05)
Rotational speed	2	355.802	177.901	48.08	0.020	45.70%	Highly significant
Transverse speed	2	211.985	105.993	28.65	0.034	27.22%	Significant
Pin tool offset	2	203.468	101.734	27.50	0.035	26.13%	Significant
Residual error	2	7.400	3.700			0.95%	
Total	8	778.655				100%	

Table 4.9 presents hardness value percentage contribution variation of factors A, B, and C. It is seen that rotational speed factor has statistical and physical significances on the hardness value of weld joint during rotational speed at 95% confidence level. From the Table 5.9 it is clearly shown that the rotational speed weight percentage (45.70%), transverse speed (27.22%), and tool pin offset (26.13%) have significant influence on weld joint of FSW of AA 6023-T6 alloy and pure copper sheets.

5.5.3 Determining the Optimum Condition

From the above discussion rotational speed optimum level value1600 rpm, transverse speed weight percentage optimum level value 12.5 mm/min, and tool pin offset of 2 mm make the response S/N ratio values highest. Therefore, the optimum processing parameters signal to noise (S/N) ratio is selected. Table 5.10 presents the optimum parameters setting selected for hardness obtained from the design of experiment and experimental results.

Table 5.10 Optimum parameters setting levels and their values

Controllable factors	Level selected	Value of the level	Rank of affecting the response
Rotational speed	3	1600	1
Transverse speed	1	12.5	2
Tool pin offset	3	2	3

5.5.4 Verification of experimental result

After an optimum combination of process parameters and their levels was obtained, the predicted result and experimental result is confirmed. For this study an optimum combination of FSW process parameters and their levels coincidently match with one of the experiments in the orthogonal array, this led an Author to leave additional experimental work for confirmation test purpose. An optimum combination of parameters and their levels **(A3B1C3**) have a correspondent to an experiment of the orthogonal array of the trail condition (sample number 7) which is at 1600 rpm Rotational Speed, 12.5 mm/min Transverse speed and 2 mm tool pin offset of the experiment. Thus, the mean is calculated by averaging the response values of this trial and the Optimized parameters hardness value has been observed as 118.41 HV and the performance of weld joint is 139.31 % related to parent material and the Optimized Tensile Strength has been attained 170.40 MPa that is 61.41 % of the parent material tensile strength. Table 5.11 presents the confirmation experiment and predicted results comparison for both tensile strength and hardness.

Table 5.11 Comparison between predicted and experimental confirmation

	Combination	Tensile strength (MPa)		Hardness (HV)	
		Mean	S/N ratio	Mean	S/N ratio
Predicted	A3B1C3	168.5	44.63	117.7	43.64
Experiment	A3B1C3	170.40	44.6294	118.41	41.47

The results of validation experiment mean and S/N obtained from the experiment were compared with the predicted mean and S/N results as shown in Table 5.11 for both hardness and tensile strength. It can be seen from the table that the difference between experimental results and the predicted results are less than both tensile strength and hardness. 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 hardness and tensile strength are highly correlated with the predicted results.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

FSW process of 2mm thickness for both AA-6023-T6 Aluminium alloy and pure Copper is successful joined upon CVMM. Succeeding specific conclusions are drawn from this research: -

Different process parameters like rotational tool speed, transverse speed, and tool pin offset were used to identify the welded joint strength of AA 60623-T6 alloy and pure Copper made by FSW depends on as optimized for friction stir welding of AA 60623-T6 alloy and pure Copper and their effects on microstructure property, hardness and tensile strength were discussed. The most optimum of FSW process parameters for welding AA 6023 – T6 aluminium alloy and pure Copper sheets are chosen as at **1600 rpm** rotational speed**, 12.5** mm/min transverse speed and **2** mm tool pin setoff were a sound and defect free weld. At this optimum combination of process parameters, the main effect plot for the S/N ratio and mean the Optimized Tensile Strength and hardness value has been predicted as **170.40** MPa and **118.41 HV** respectively. The result shows:-

- Fine grain refinement in the weld joint and defect free produced at optimized parameters of 1600 rpm rotational speed, 12.5 mm/min transverse speed and 2 mm tool pin offset.
- For weld joint strength performance value, the rotational speed weight percentage (61.41 %), transverse speed (22.14 %) and tool pin offset (12.02%) have significant influence on weld joint of FSW of AA 6023-T6 alloy sheet. The Optimized Tensile Strength is shown as 170.40 MPa that is **61.41** % of base material. By comparing strength of parent material the fabricated welded joints of AA 6023 – T6 alloy and pure Copper dissimilar friction stir butt joint configuration has small tensile strength due to formation of a new grain structures under FSW process parameters which leads to a formation of less brittle material property.
- For welded joint hardness performance value the rotational speed weight percentage (45.70 %), transverse speed (27.22 %) and tool pin offset (26.13 %) have significant influence on weld joint of FSW of AA 6023 T6. The Optimized hardness value has been noted as **118.41** HV that is **139.31** % of base metal hardness.

- Defects like micro-voids, lamellar intercalated structure, deformed grain structure of pure Copper and AA 6023 – T6 Aluminium alloy is generated in welded joints.

6.2 Recommendations

Depending on the result and discussions as well as conclusion of this study the following recommendations are drawn: -

- ❖ An experimental investigation in this study was restricted to dissimilar nonferrous material (AA 6023-T6 alloy sheet to pure Copper sheet). However dissimilar material AA 6023 – T6 Aluminium alloy and metals also could be tried and analyzed.
- ❖ Due to high strength and toughness is required to with stand high compressive force mild steel is best to use for FSW backing plate and due to high hot working AISI D2 tool steel is also used as FSW tool for mass production during friction stir welding process.

6.3 Future scope

- ❖ In this study, the limited FSW parameters were employed. Further studies are needed to evaluate the effects of welding parameters on the welding joint properties to establish the better optimal weld parameters and reduce created defects.
- ❖ Further research work is to be incorporating an automation of FSW process as well as temperature and force measurements used during FSW process.
- ❖ More investigation is needed on welding joint of different thickness of base material and microstructural test of welded joint in longitudinal weld joint.

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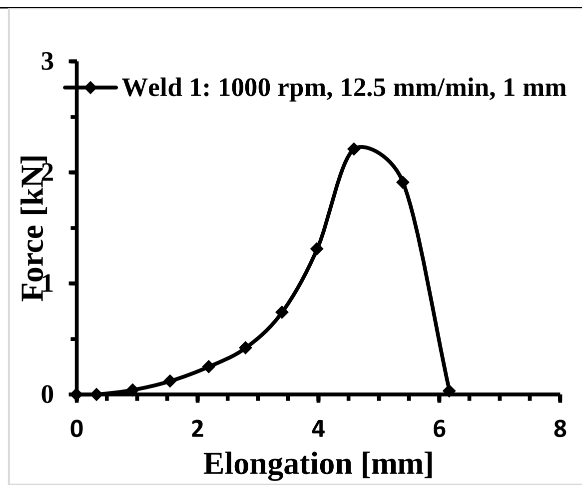
APPENDICES

Appendix 1: Specification of CVMM code F-281

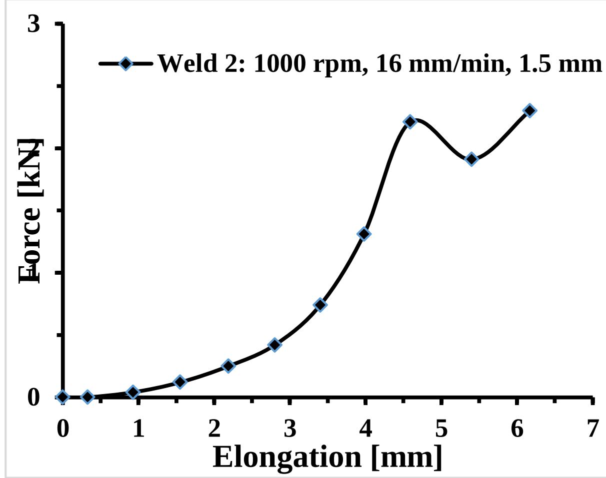
S.No	Spindle description	Units	Maximum
1	Main driven range normally	RPM	40 - 2000
2	Motor power	Kw	5.5
	Minimum torque	Nm	26.27
3	Maximum torque	Nm	1313.7
4	Feed motor power	Kw	1.5
5	Feed motor rotational speed	RPM	920
Feed range			
6	Vertical	mm/min	5.2-262
7	Horizontal	mm/min	12.5-630
8	Transverse	mm/min	12.5-630
9	Gear transmission ratio	-	1:1

Appendix 2: The result of tensile strength tests

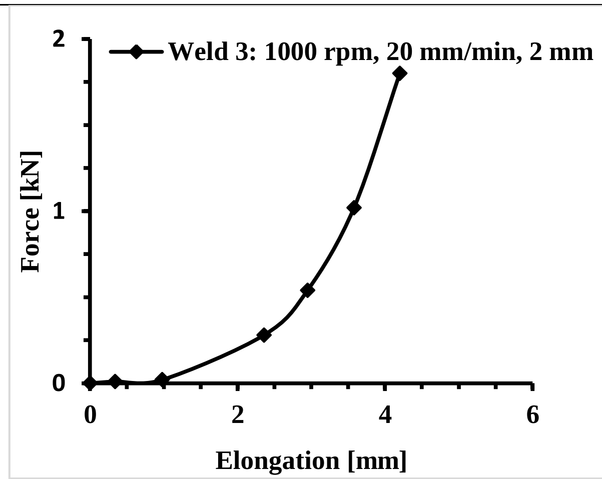
S.N	F [kN]	dL [mm]
1	0	0
2	0.33	0
3	0.93	0.04
4	1.55	0.12
5	2.19	0.25
6	2.8	0.42
7	3.4	0.74
8	3.98	1.31
9	4.59	2.21
10	5.4	1.91
11	6.17	0.03



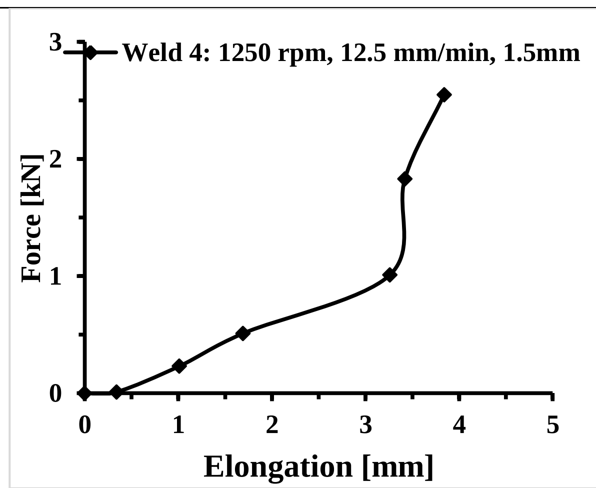
S.N	F [kN]	dL [mm]
1	0	0
2	0.33	0
3	0.93	0.04
4	1.55	0.12
5	2.19	0.25
6	2.8	0.42
7	3.4	0.74
8	3.98	1.31
9	4.59	2.21
10	5.4	1.91
11	6.17	2.3



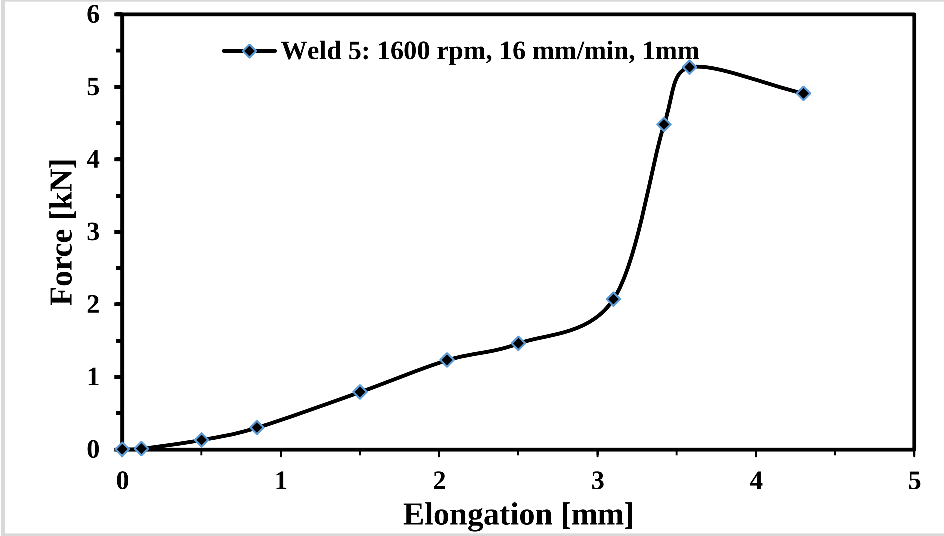
S.N	F [kN]	dL [mm]
1	0	0
2	0.34	0.01
3	0.98	0.02
4	2.36	0.28
5	2.95	0.54
6	3.58	1.02
7	4.2	1.8



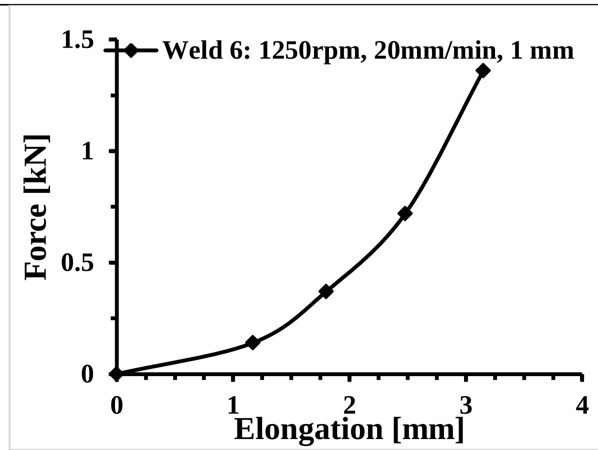
S.N	F [kN]	dL [mm]
1	0	0
2	0.34	0.01
3	1.01	0.23
4	1.69	0.51
5	3.26	1.01
6	3.42	1.83
7	3.84	2.55



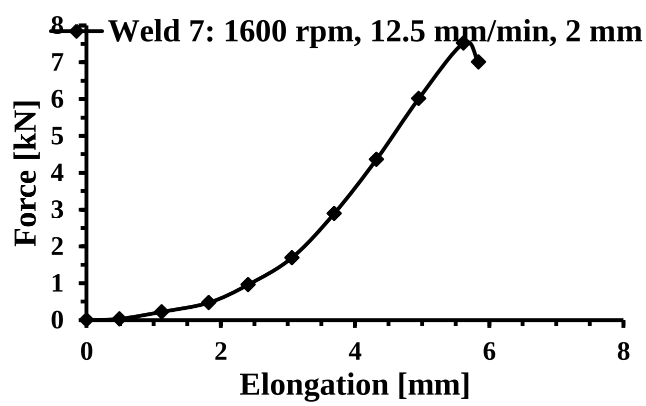
S.N	F [kN]	dL [mm]
1	0	0
2	0.12	0.01
3	0.5	0.13
4	0.85	0.3
5	1.5	0.79
6	2.05	1.23
7	2.5	1.46
8	3.1	2.07
9	3.42	4.48
10	3.58	5.27
11	4.3	4.91



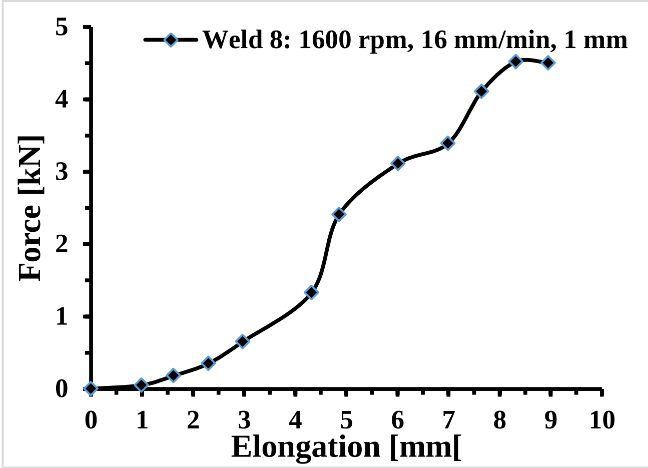
S.N	F [kN]	dL [mm]
1	0	0
2	1.17	0.14
3	1.8	0.37
4	2.48	0.72
5	3.15	1.36



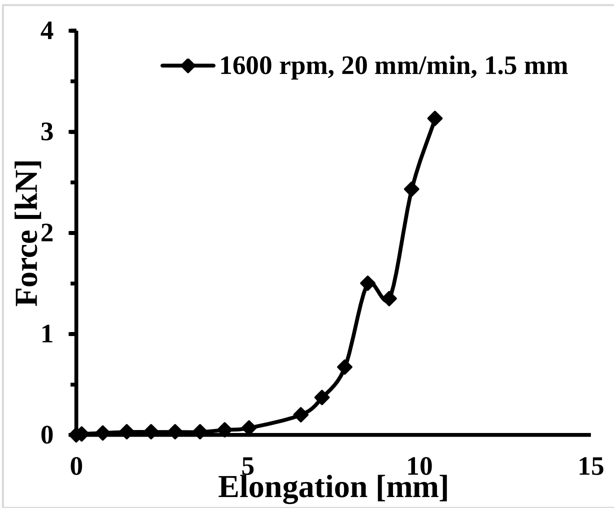
S.N	F [kN]	dL [mm]
1	0	0
2	0.49	0.03
3	1.12	0.22
4	1.82	0.47
5	2.41	0.96
6	3.06	1.69
7	3.69	2.89
8	4.32	4.36
9	4.95	6.01
10	5.62	7.52
11	5.84	7.01



S.N	F [kN]	dL [mm]
1	0	0
2	0.99	0.05
3	1.62	0.18
4	2.3	0.35
5	2.97	0.65
6	4.32	1.33
7	4.86	2.41
8	6.37	3.11
9	6.99	3.39
10	7.65	4.11
11	8.32	4.52
12	8.95	4.5



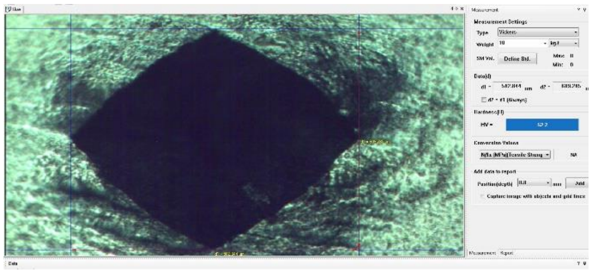
S.N	F [kN]	dL [mm]
1	0	0
2	0.16	0.01
3	0.78	0.02
4	1.48	0.03
5	2.19	0.03
6	2.89	0.03
7	3.61	0.03
8	4.33	0.05
9	5.04	0.07
10	6.55	0.2
11	7.17	0.37
12	7.83	0.67
13	8.5	1.5
14	9.13	1.35
15	9.78	2.43
16	10.46	3.13

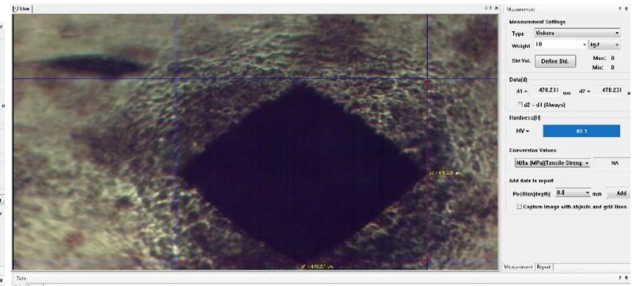


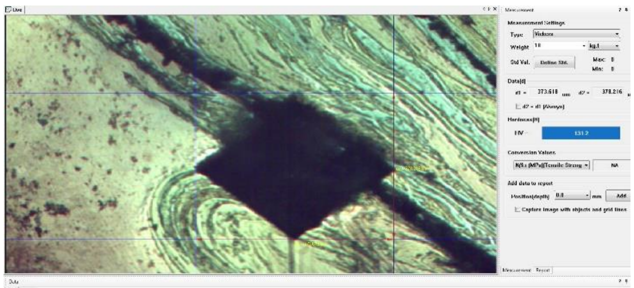
Force- Elongation graphs for weld joints under process parameters

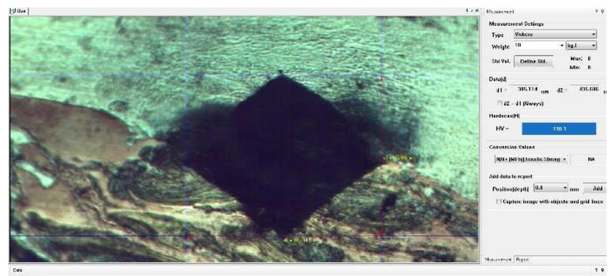
Appendix 3: results of hardness tests for each sample at specified process parameters

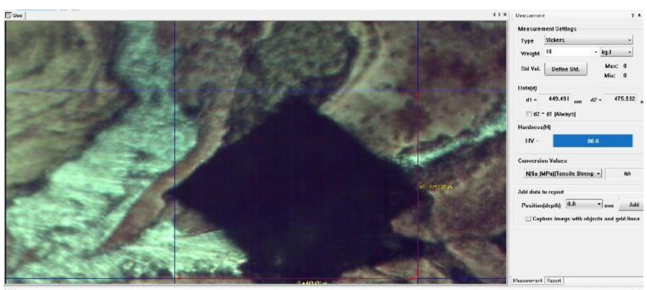
1. 1000 rpm, 12.5mm/min and 1mm (weld 1)



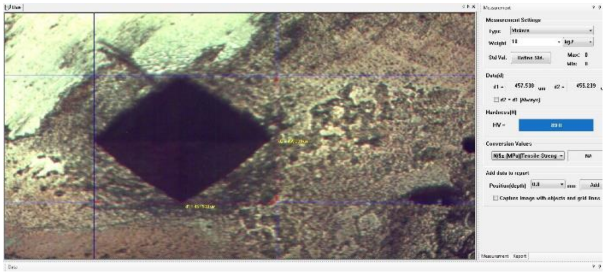


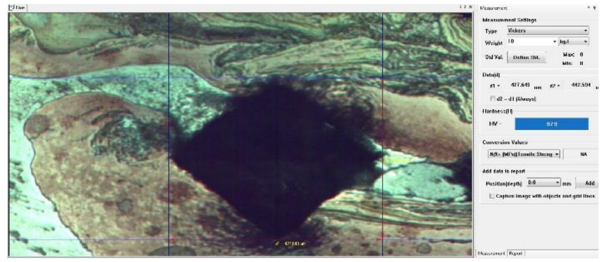


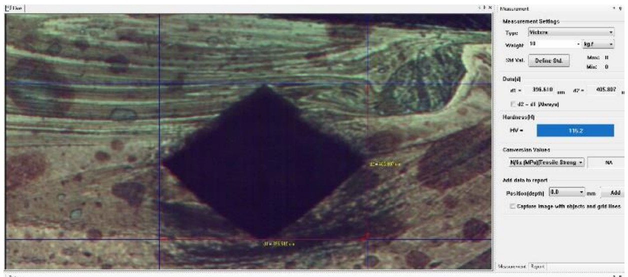


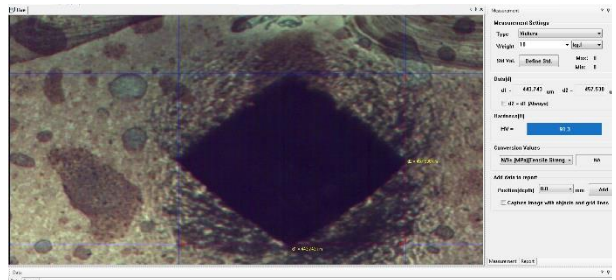


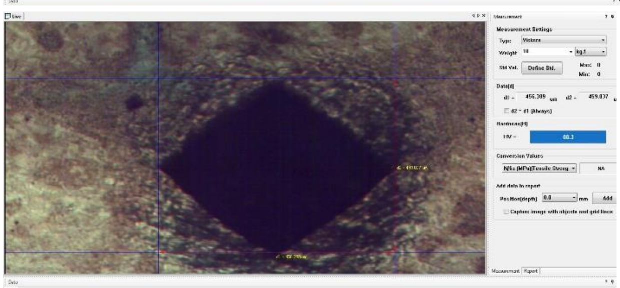
2. 1000 rpm, 16mm/min and 1.5mm (weld 2)



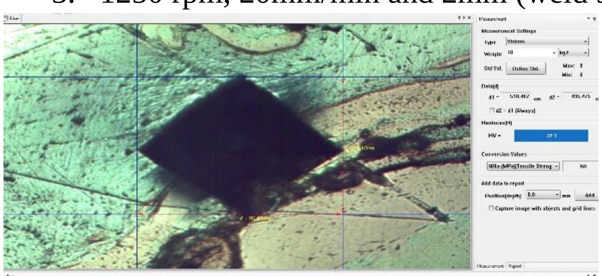


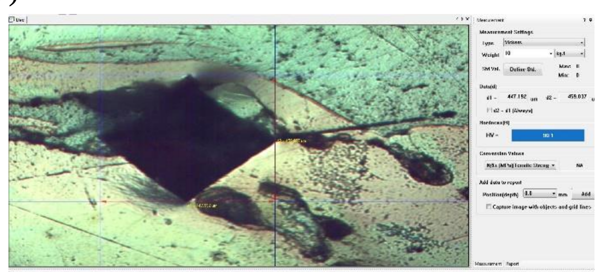


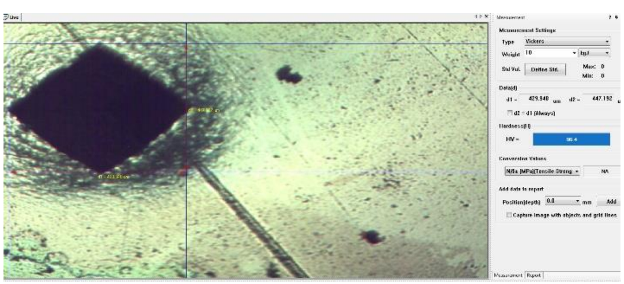


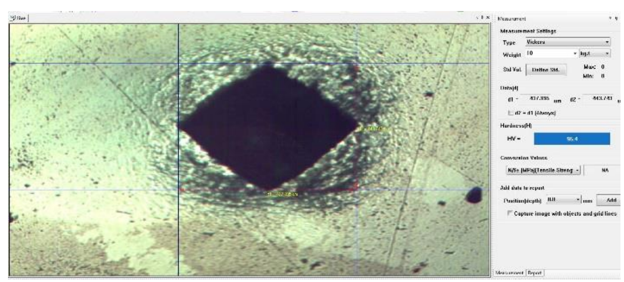


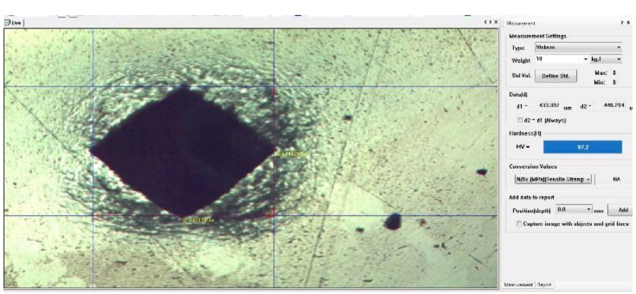
3. 1250 rpm, 20mm/min and 2mm (weld 3)



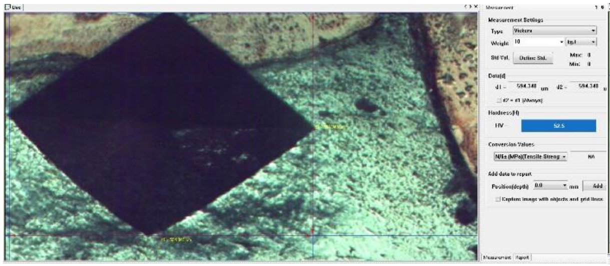


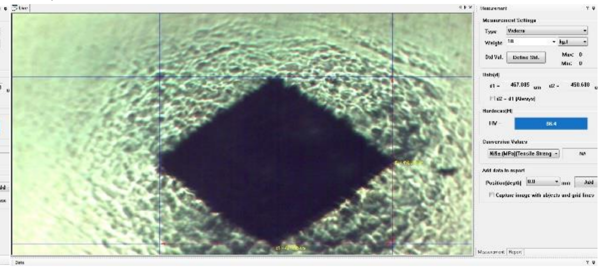


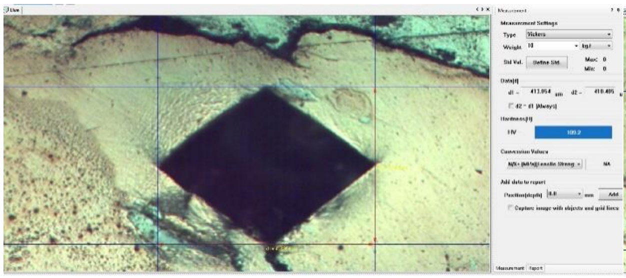


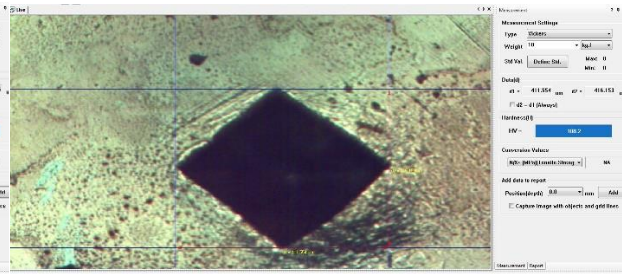


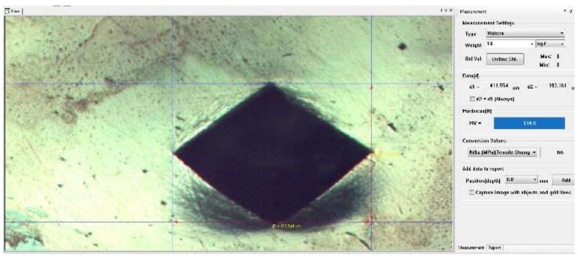
4. 1250 rpm, 12.5mm/min and 1.5mm (weld 4)



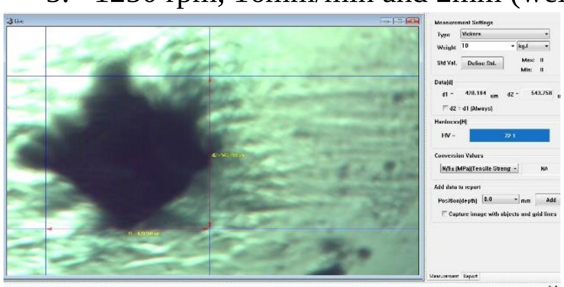


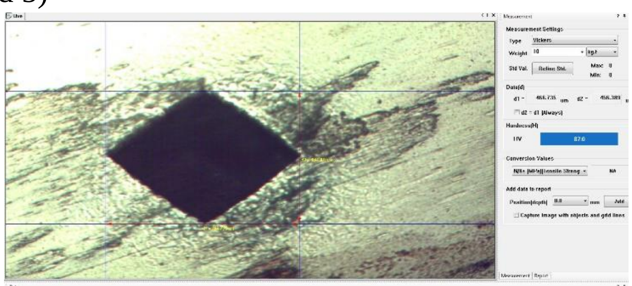


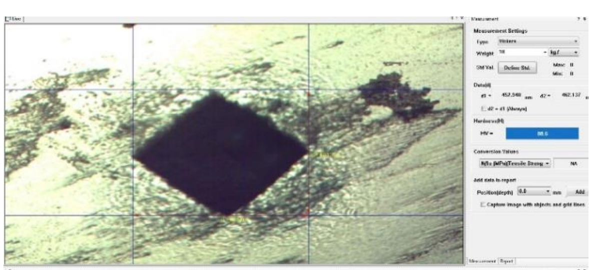


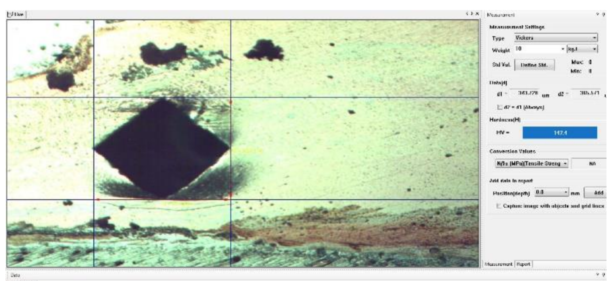


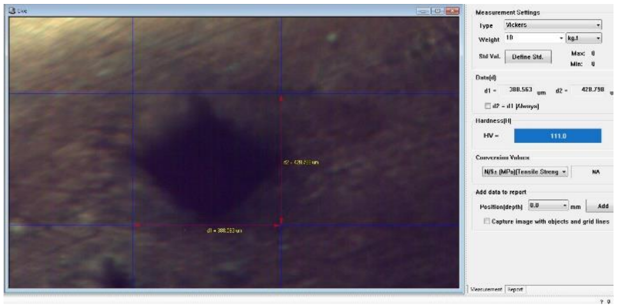
5. 1250 rpm, 16mm/min and 2mm (weld 5)



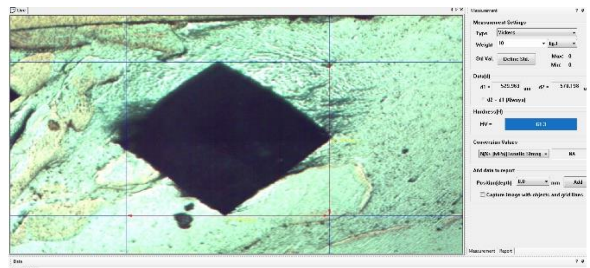


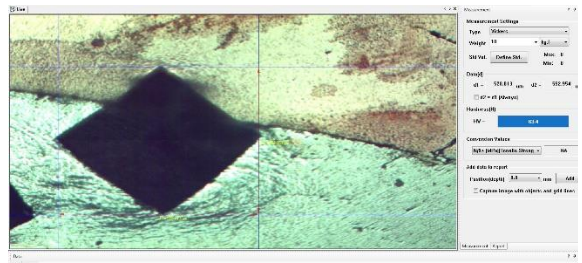


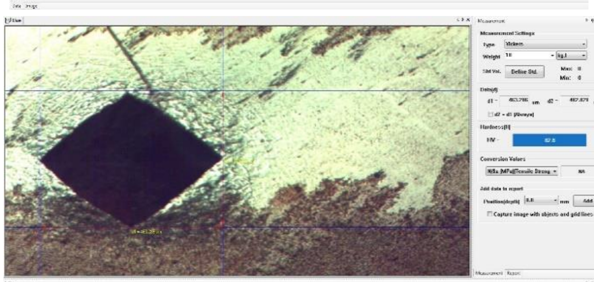


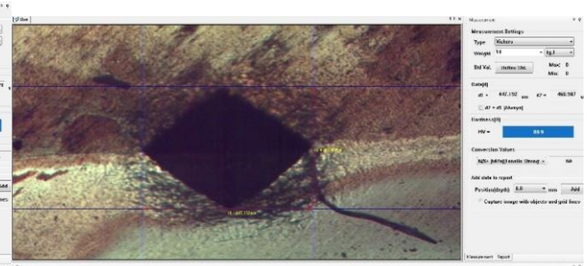


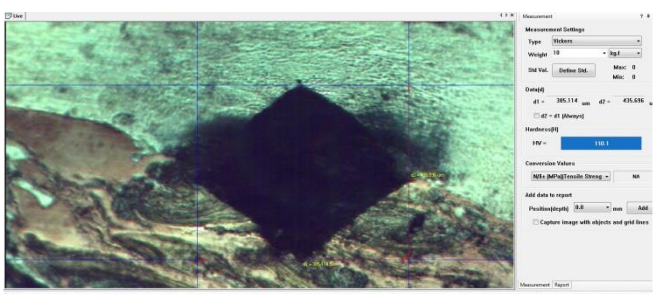
6. 1600 rpm, 20mm/min and 1mm (weld 6)



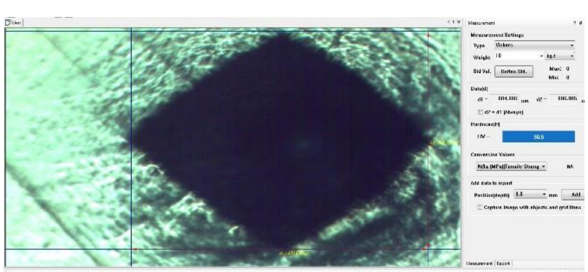


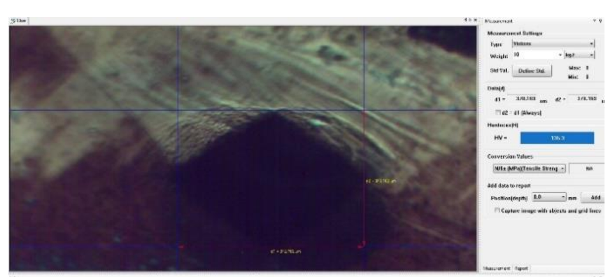


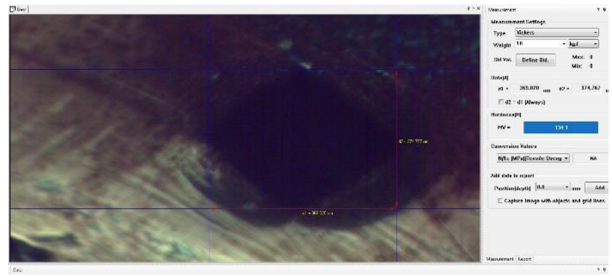


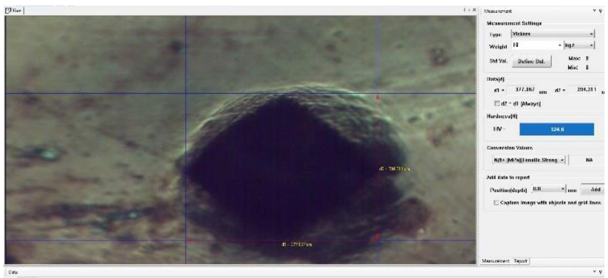


7. 1600 rpm, 12.5mm/min and 2mm (weld 7)

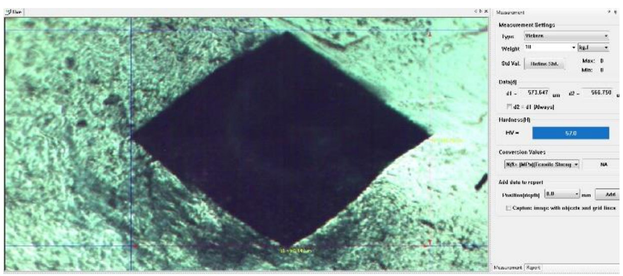


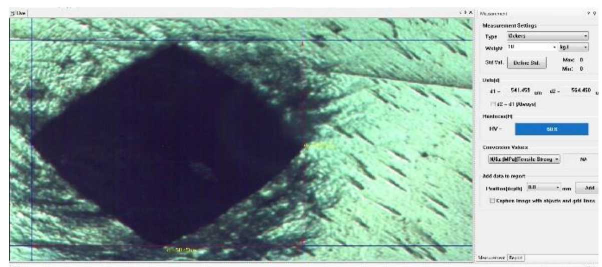


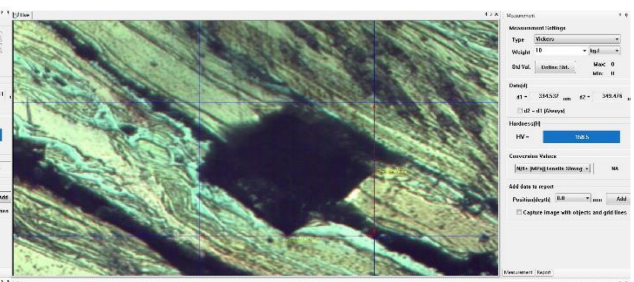


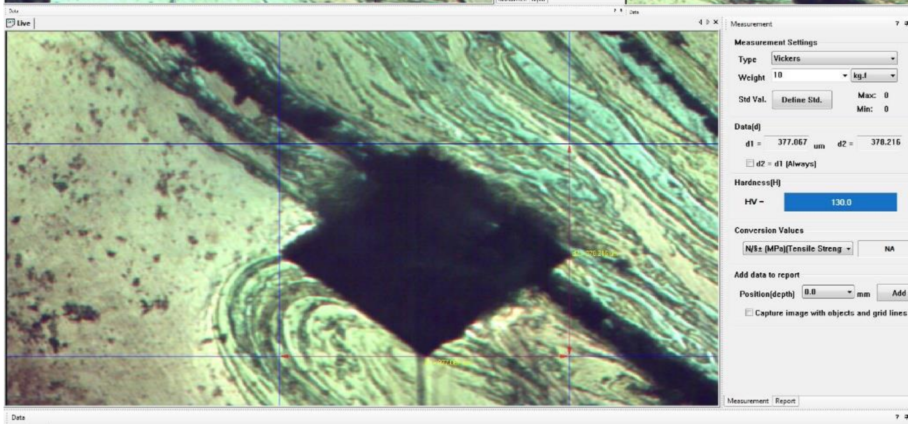


8. 1600 rpm, 16mm/min and 1mm (weld 8)









9. 1600 rpm, 20mm/min and 1.5mm (weld 9)