Experimental Investigation of Optimum Process Parameters for Friction Stir Welding of Copper Plate

Wubalem Ayele Alito

A Thesis Submitted to the Department of Mechanical Design and Manufacturing Engineering
School of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Manufacturing Engineering

Office of Graduate Studies
Adama Science and Technology University

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CANDIDATE DECLARATION

I hereby declare that the work which is being presented in this thesis entitled "**Experimental Investigation of Optimum Process Parameters for Friction Stir Welding of Copper Plate**" In partial fulfillment of the requirement for the award of the Degree of Masters of Science in Manufacturing Engineering is my own work carried out September 2021 to June 2023 under the supervision and guidance of **Dr. Habtamu Beri,** Program of Mechanical Design and Manufacturing Engineering, Adama Science and Technology University, Adama, Ethiopia.

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

Submitted by: -

Wubalem Ayele Alito	____________	__________
Candidate	Signature	Date

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

Dr. Habtamu Beri	____________	____________
Advisor	Signature	Date

APPROVAL PAGE FOR THESIS

We, the undersigned, members of the Board of Reviewers of the thesis open defense by **Wubalem Ayele** have read and evaluated his thesis entitled "**An Experimental Investigation of Optimum Process Parameters for Friction Stir Welding of Copper Plate**" 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.

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ACKNOWLEDGMENT

I would like to thank and praise the Almighty God for all the blessing and patience he gives me to successfully complete this thesis. I would like to express my deepest gratitude to my advisor, Dr. Habtamu Beri, for his guidance, support, encouragement, and patience throughout my study at Adama Science and Technology University. I would also like to thank Dr. Moera Gutu, for helpful discussions, supports and suggestions. I would like to extend my sincere appreciation to the Manufacturing and Design program for their education and support. I am also thankful to the Ethiopian Air Force Machine shop workers for manufacturing tool material from the existing material and eagerly worked with me the experiments on the vertical milling machine. I would like to thank special thanks to Major Adane, Head of Mechanical Work Shops in Ethiopian Air Force. Special thanks to the Senior Warrant Officer Abiyot and Alemayehu, again 2nd Lt. Kristo and L/AC Debebe, for helping me in conducting the experiments on the vertical milling machine in the shops. My special thanks to all my immediate bosses Lieutenant Col. Kinfe, Head of Logistics Engineering Main, and Lieutenant Col. Tadele, Head of Engineering Solutions, ETAF, for their valuable advice and encouragement in the assessing and calling to the different sites for finding the raw copper plate for the experimental work. Many thanks go to my family for their support and love.

I would like to express my immense gratitude and profound thanks to all those who have helped me in different ways during the tenure of my MSc. work at Adama Science and Technology University. My sincere apologies, if I have inadvertently missed out a few names.

ABSTRACT

Conventional welding of copper and its alloys tends to degrade the mechanical strength at the welded area due to high thermal diffusivity and melting point. Friction stir welding (FSW) is an excellent alternative for joining of these materials against fusion joining. FSW is an emerging solid state joining process in which the material that is being welded does not melt and recast. This process uses a non-consumable tool to generate frictional heat in the abutting surfaces. In this thesis work the process parameters were optimized by using the Taguchi technique based on Taguchi's L_9 orthogonal array. The main objective of this experimental investigation is to optimize the process parameters of FSW for joining of 5 mm thick copper plate using a constant square tool pin profile and the variable process parameters of tool rotational speeds of (750, 950 and 1180) rpm, tool traverse speeds of (20, 30, 40) mm/min, and tool tilt angles of (1, 1.5 and 2) degrees. Mechanical and microstructure analysis has been performed to evaluate the characteristics of friction stir welded copper plates. The tensile properties of all the weld joints showed a relative correspondence to the variation of the hardness in the weld zone. Tensile strength and hardness of FSW joints have been predicted for the optimum FSW process parameters, and their percentage contribution to a better joint is calculated using the signal-to-noise ratio, means, and analysis of variance. Based on the study, the analysis of variance for tensile strength results shows that the tool tilt angle was the most influential FSW process parameter with a percentage of contribution of 42.37%. The analysis of variance for average hardness results shows that the tool rotational speed is the most influential parameter, with a percentage of contribution of 85.85%. The maximum tensile strength of welded joint was 129.489 MPa at the process parameters of 1180 rpm of the tool rotational speed, 20 mm/min of the welding speed, and 2 degrees of tool tilt angle. The maximum hardness of welded joint was 86.65HRB at 1180 rpm tool rotation, 20 mm/min weld speed and 2 degrees of tool tilt angle. From the experimental investigation it is found that the joints fabricated at a tool rotation speed of 1180 rpm, traverse speed of 20 mm/min, and tool tilt angle of 2 degrees resulted in better mechanical properties compared to other process parameters. From the experimental results the optimal microstructural arrangement of welded joint was obtained from the weld joints by using optimum process parameters of 1180 rpm of tool rotational speed, 20mm/min of the welding speed, and 2 degrees of tool tilt angle.

Key words: process parameters, friction stir welding, copper plate and backing plate.

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ACRONMYS

AS	Advancing Sides
RS	Retreating Side
ANOVA	Analysis of Variance
BP	Backing Plate
CNC	Computer Numerical Control
DRV	Dynamic Recovery
DRX	Dynamic Restoration
FS	Frictional Stir
FSP	Friction Stir Process
FSW	Frictional Stir Welding
HAZ	Heat-Affected Zone
IMC	Intermetallic composite
MSD	Mean Square Division
OA	Orthogonal Array
BM	Base Metal
TTA	Tool Tilt Angle
RPM	Rotation Per Minute
S/N	Sign to Noise Ratio
SEM	Scanning Electron Microscopy
E_n	Sample Number
SZ	Stir Zone
TMAZ	Thermo Mechanically Affected Zone
TWI	Welding Institute of Technology
UTM	Universal Tensile Testing Machine
UVR	Ultraviolet Radiation
TTS	Tool Transverse Speed
TRS	Tool Rotational Speed

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CHAPTER ONE
INTRODUCTION

1.1 Background of the Study

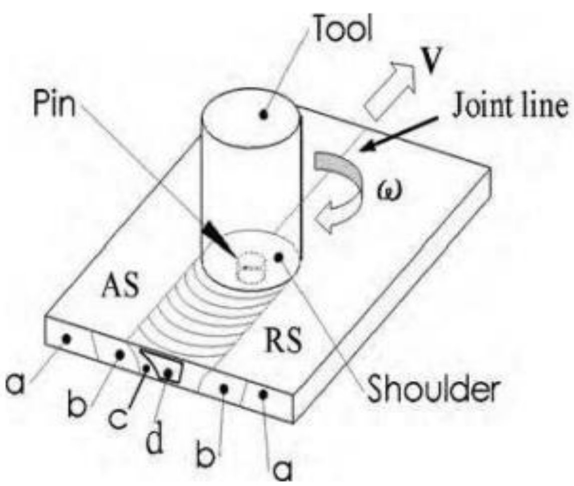
The Friction Stir Welding (FSW) technique was invented by The Welding Institute (TWI) in 1991. Since then, the material flow mechanism during welding and the microstructures of the welds have been discussed vigorously. The FSW process is executed while the materials are in a solid state, thus preventing many of the metallurgical problems that occur with conventional fusion welding, such as distortion, shrinkage, porosity and splatter. Furthermore, improved mechanical properties can also be achieved using this technique. Due to increasing demand for lightweight parts and environmental protection, applied this new welding technology to aluminum products in automotive and aerospace industries (Colligan et al., 2003). In particular, the FSW technique is used to easily weld 2000 and 7000 grade aluminum alloy sheets, which are traditionally difficult to weld with fusion welding (Kakimoto, 2005).

Few papers on the FSW process discussed the temperature history (such as the temperature range and other forming conditions for a successful FSW process) in a pure copper work piece, where the melting point and material properties of the copper are significantly different from those of aluminum alloys. In this paper, FSW experiments using pure C11000 copper will be discussed, along with the process control required for a successful FSW process. The Welding of copper is usually difficult by conventional fusion welding processes because the copper has the high thermal diffusivity, which is about 10 to 100 times higher than in many steels and nickel alloys. The heat input required is much higher than in almost any other material, and weld speeds are quiet low. To overcome these problems, the FSW which is one of the solid-state welding techniques is applied to the joining of copper. In this present study we explored the friction stir welding of copper. This study especially characterized and compared the microstructures of the copper base metal with those of the residual FSW zones using optical metallographic (OM) and transmission electron microscopy (TEM). Micro hardness profiles through the weld zone and corresponding tensile strength test data were also correlated with these microstructures. The basic concept of FSW is very simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint. The two primary functions of tools are heating of work piece and stirring/intermixing of material to produce the joint. The heating is accomplished by friction between the tool and the work piece. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in the generation of fine and equiaxed recrystallized grains (Danaf, 2013).

Heat generated by friction and deformation brings the material into a malleable state that promotes the forward displacement of the tool with the material flowing from the front to the back of the tool where it cools down, the weld is asymmetric since on one side of the weld, called the advancing side, the rotation of the tool is parallel to the advancing direction, while on the other side called the retreating side, the rotation is opposite to the direction of translation of the tool. The stirring of the tool minimizes the risk of having excessive local amounts of inclusions, resulting in a homogenous and void-free weld. Since the amount of heat supplied is smaller than during fusion welding, heat distortions are reduced and thereby the number of residual stresses (Ericsson & Sandstrom, 2003).

Friction stir welding (FSW) is a relatively new joining process that has been used for high production since 1996. Because melting does not occur and joining takes place below the melting temperature of the material, a high-quality weld is created. This characteristic greatly reduces the all effects of high heat input, including distortion, and eliminates solidification defects. Friction stir welding also is highly efficient, produces no fumes, and uses no filler material which makes this process environmentally comfortable (Kumar, 2016).

Friction stir welding was used commercially successfully from the early years of the 21st century and evolved into the world of metal joining in the aluminum industry. Friction stir welding is also considered the green welding technique because of its less energy consumption and lower heat generation during welding. Technically, the friction stir welding process is very simple and easy to understand. The metal pieces to be welded are fixed adjacent with a butting edge and a tool rotating to its central axis having a pin plunged up to the shoulder within the metal traveled along the abutting edge line of both metal pieces. The detailed process can be easily assessable from in Figure 1.1 below.



Key

a: Base Metal (BM)

b: Heat Affected Zone (HAZ)

c: Thermal-Mechanical Affected Zone (TMAZ)

Figure 1.1 Schematic diagram of the FSW (Mishra, 2017).

1.2 Application Areas of Copper and its Properties

Copper alloys is the most resourceful material with properties such as strength and conductivity of copper makes it suitable for many applications. Properties of copper are augmented with altering compositions and manufacturing methods. The alloying elements of copper are brass, bronze and gun metal (red brass). Hence copper alloys have good corrosion resistance, excellent heat conductivity, excellent electrical conductivity, good machinability and retention to electrical and mechanical properties at high temperatures. The copper is used in containment canisters for nuclear waste has been manufactured via a FSW process (Anderson et al., 1999). Copper is widely used in all electrical components due to its easy availability and high conductivity. All refrigeration and air-conditioning industries also use copper as a major component. Joining copper is a necessary action for its better use in the above-said industry (G. Singh et al., 2020). Copper is a mostly used industrial and functional metal for various thermal, electrical, and electronic applications that is, electronic packaging, electrical contacts, and resistance welding electrodes, air-conditioning, aerospace, automotive, and nuclear industries. This is because of good thermal and electrical conductivity, high plasticity, and excellent resistance to corrosion and oxidation (Arulmoni and Ranganath, 2014).

1.3 Statement of Problem

Copper and its alloys are frequently used in industrial applications because of their unique properties, such as high corrosion resistance, outstanding wear resistance, excellent thermal conductivity, and a good balance of strength and ductility. As a result, welding these materials is becoming increasingly important, particularly in the electrical, refrigeration, air-conditioning, aerospace, automotive, and nuclear industries. Because copper and its alloys have high thermal diffusivity, allowing more heat to be dissipated during fusion welding, it is impossible to perform weld joints using conventional fusion welding procedures. Other welding processes, such as resistance spot welding and bronzing, have significant distortion, solidification cracking, porosity, oxidation, lack of joint uniformity, and joint brittleness issues with copper and its alloys. Fumes, vapors, or smoke are also produced during fusion welding procedures, which can be hazardous to workers and the environment. As a result, the friction stir welding technique is a better welding method for joining copper and nonferrous metals in order to solve the problems mentioned above. Friction stir welding is a new technology for joining similar and dissimilar materials, particularly nonferrous metals and plastics. However, the primary issue with this technology is the investigation of optimal process parameters such as rotational speed, transverse or weld speed, and tool tilt angle. It is preferable to use the friction stir welding process to solve these issues.

1.4 The Objective of the Study

1.4.1 General Objectives

The general objective of this thesis work was investigation of optimum process parameters for friction stir welding of copper plate.

1.4.2 Specific Objective

The specific objectives of this thesis are:

1. To test the tensile strength of the welded joint
2. To test the micro-hardness of the welded joint.
3. To characterize the microstructure of the welded part.
4. To optimize the process parameters (tool tilt angle, tool rotational speed, and weld speed) for copper during frictional stir welding on a conventional vertical milling machine

1.5 Scope of the Study

The purpose of this thesis work is to perform friction stir welding on a copper plate of similar thickness (5mm) and to conduct experimental analysis of the microstructure, micro hardness, and tensile strength of weld joints by varying process parameters such as welding speed or transverse speed (mm/min), tool rotational speed (RPM), and tool tilting angle (degrees), and to determine the best combination of those process parameters on copper weld joint friction stir welded samples. Other factors that influence weld quality, such as manual feed depth, work piece material, and tool profile, were held constant. The friction stir welding for this research used conventional vertical milling machines in the Ethiopian Air Force Machine Workshop, Harar Meda.

1.6 The Limitation of the Study

The basic limitation of this thesis study is that it is difficult to adapt the techniques of friction stir welding to conventional milling machines. During this friction stir welding process, the limitation is the absence of force measurement tool and temperature control gauge readings on an integrated computer device. The initial cost of the FSW machine is too high. It is also less flexible than manual and arc welding processes. Some of the process's limitations are listed as follows:

- The need for large downforce and transverse forces means that clamping on the components to be joined is more extensive than for arc welding.

- Exit hole made by releasing the tool from the materials to be connected
- The use of frictional stir welding for overhead welding is impossible.
- Because no filler material is utilized in the process, gaps between the elements to be bonded must be minimized.

1.7 Expected Outcome of the Study

The study's expected outcome was to achieve the general and specific objectives listed above, as well as to gain access to the friction stir welding technique in local mechanical shops by demonstrating experimentally proven results for the manufacturing of copper joints. Furthermore, the FSW process may be the only way to obtain defect-free frictionally stir welded joints for copper and its alloys in a specific area of application.

1.8 Significance of the Study

Friction stir welding is a green technology due to its energy efficiency (low heat input), sustainable utilization of natural resources (less material waste, reduced material lead time, part count reduction, high weld quality, and performance, longer life cycle), reduced environmental impact (no shielding gases required, no fumes/splash/ozone produced, part cleaning requirements reduced, filler material addition not necessary) and process versatility (adaptable welding orientations and different thicknesses, microstructures, and compositions).

The important application of friction stir welding is in the aeronautical and aerospace industries, where the copper alloy is used as the primary material for their construction. The welding process enables manufacturers to completely replace the riveted joints and assemblies of lapped and abutted configurations that are used mainly for fuselage sections, propellant, and fuel tanks of commercial aircraft as well as space launch vehicles. Thus, the process allows the total elimination of the use of thousands of rivets. This has resulted in better quality, and stronger, unlike fusion welding, friction stir welding emits no polluting gases, making it a green joining method. Consumable filler rods and shielding gases are used in arc welding, which has an impact on the working environment. Friction stir welding can successfully join copper and its alloy metals with reasonable power consumption using a rotatable non-consumable tool pin. We can join with reduced energy consumption and no shielding gas, filler rod, or air pollution with this welding process. This technology will be a suitable alternative welding method, and it will be beneficial to the welding industry in general (Ethiopia). Friction stir welding, in general, has a number of advantages over traditional arc welding methods. These include:

- ❖ As a solid-state welding process, FSW is a largely defect-free joining method with no hot cracking, porosity, or solidification cracks.
- ❖ Due to the lower temperatures, there is a reduction in shrinkage and distortion in the material being joined.
- ❖ There are no filler materials, fluxes, or shielding gases required for copper or aluminum alloys. FSW is environmentally friendly as it produces no fumes, spatters, or UV radiation.

Table 1.1 Summary of key benefits of friction stir welding process (Sidhu & Chatha, 2012)

✓ Metallurgical Benefits	✓ Environmental Benefits	✓ Energy Benefits
✓ Solid phase process ✓ Low distortion of the workpiece ✓ Good dimensional stability and repeatability ✓ No loss of alloying elements ✓ Fine microstructure ✓ Absence of cracking	✓ No shielding gas required ✓ No surface cleaning required ✓ Eliminate grinding wastes ✓ Consumable materials saving, such as rugs, wire, or any other gases	✓ Improved materials use (e.g., joining different thicknesses) allows a reduction in weight ✓ Decreased fuel consumption in lightweight aircraft automotive and ship applications

1.9 Structure of the Thesis

The thesis is divided into five chapters. The first chapter provides a brief overview of the novel experimental investigation of optimal process parameters for friction stir welding of copper plate. Also, sections like the problem statement, significance, scope, limitations, objectives, and expected outcomes are included. Chapter two describes the general backgrounds about FSW processes; the idea and the principle of FSW processing, effect of process parameters of FSW and a detailed literature review are presented. Chapter three describes the general research design, material, tool design and manufacturing and experimental condition. In addition, the experimental setup and procedures as well as testing procedures are also explained in this chapter. Chapter four explains results and discussions obtained from experimental observations. Finally, summary of the thesis outcome is stipulated in the fifth chapter with the concluding remarks and provision of future works for further research directions.

CHAPTER TWO
LITERATURE REVIEWS

2.1 Introduction

According to the literature, extensive studies on the friction stir welding (FSW) of the aluminium and its alloys have been reported, but only a few investigations have been made until now on the optimization of friction stir welding of pure copper and its alloys. A brief review of some selected references on this topic was presented.

Lee and Jung (2004) probably the first researcher carried out research on FSW of copper. The experiment was conducted on 4 mm thick copper plates with the help of steel tool. It was observed that the size of grain in the nugget zone is very fine and equiaxed as compared to base metal. It is obvious from the study that the strength obtained by FSW is higher than that of electron beam welding.

Lee et al. (2004) conducted an investigation on hardness of friction stir welded copper sheets. They reported that hardness at edges of the weld was less than hardness of base metal, and in friction stir welding of copper unlike aluminum, TMAZ zone was not distinct. They also reported that hardness was almost constant up to middle of weld and after that sharply reduced until weld root.

Chen et al. (2006) observed that low tilt angle reduces the flow of materials during the process that results in formation of kissing bond like structure in stir zone while high tilt angle results in flashes. Tensile strength decreases owing to formation of kissing bond structure. FSW tool is one of the most vital elements of FSW setup as pin profile and shoulder profile regulate the amount of material stirred.

T.Shaktivel and J.Mukhopadhyay, (2007) conducted experiments on copper at constant tool rotational speed and welding speed. Mechanical and microstructural analysis has been performed to evaluate the characteristics of friction stir welded copper. Vickers hardness measurements were performed on cross section at mid thickness of the welded plate at a 300-gm load and 10 s dwell time. Similarly, the sectioned sample was prepared using standard metallographic procedure for microstructural investigation. The microstructure analyses were performed using optical microscope (OM) and scanning electron microscopy (SEM). From the analysis, it was found that, WN has extremely fine equiaxed grains compared to parent metal by replacing defected grains with defect free grains with frictional heat and plastic deformation, which results in higher hardness as compared to parent metal. The hardness of the WN was higher than the TMAZ, HAZ, and PM due to the presence of fine grains. The hardness values in the TMAZ were lower than in the WN but reverse was true as compared to the HAZ and parent metal. The HAZ exhibited lower hardness in the weld zone. Friction stir welding joint passes 85% weld efficiency as compared to the parent metal. The tensile fracture occurred in the HAZ at the advancing side of the weld due to the presence of few coarse grains. Similarly, the variations of the hardness values showed a relative correspondence to the fracture location.

Polar & Indacochea, (2009) studied Friction Stir Welding (FSW) of electrolytic high pitch copper plates by using a conventional CNC milling machine. The evolution of the welded microstructure was linked with process parameters employed in the investigation and rising temperatures during processing. A strong weld joint was obtained once the optimum process conditions were achieved. Microstructural examination and mechanical properties of the weldments were examined using optical and scanning electron microscopes. Low temperatures cause the metal to not plasticize efficiently during the early phases of FSW and when utilizing less-than-optimal welding conditions, resulting in defects such as large cavities, porosity, and poor bonding due to the absence of plasticized material. Cavities were detected in the weld's advancing zone, and the finest grains from the entire weld were found here. As the temperature grew, the voids decreased, and the grain size increased further along in the weld. In this situation, the usual weld nugget seen in friction stir welding of other metals was not present. The "stirred zone" of the weld showed dynamic recrystallization; because the strain rate in this region was the same in all three cases, the change in grain size was attributed to differences in process temperature.

Xue et al., (2010) conducted experiments under low heat input conditions, and defect-free friction stir welds of 5 mm thick pure copper plates were created. The microstructure and mechanical properties of the weld joints were studied. In which the stir zone (SZ) had equiaxed recrystallized grains that decreased in size when the heat input was reduced. The SZ had a significant percentage of high-angle grain boundaries that is greater than 15 deg which increased as the heat input increased (90.2% to 94.5 %). The percentage of twin boundaries fell as the heat input was reduced, and the number of twin lamellas decreased. The typical characteristics of the thermomechanical affected zone (TMAZ) were visible under very low heat input conditions. The grains in the heat-affected zone (HAZ) were slightly finer than those in the parent material (PM), however, the size of the grains varied slightly depending on the parameters. As the heat input increased, the hardness of the SZ increased, with the lowest hardness appearing at the HAZs where the welds failed. Under varied heat input circumstances, the ultimate tensile strength (UTS) was similar to that of the PM, but the yield strength (YS) and elongation were lower. As the lowest hardness value grew, the YS increased, and the elongation dropped because of improved strain localization.

Y.M. Hwang, P.L.Fan, and C.H.L (2010) investigated the mechanical properties of C11000 copper welded by FSW. The plates were taken with 60mm length 20mm width and 3.1mm thickness. The tool was made of SKH9 High Speed Steel. The tool had 3mm pin diameter, 12 mm shoulder diameter & 2.8mm pin length. The tool set on 1° angle. Two welded conditions were taken 1) Tool rotation Speed

800rpm & 900rpm. 2) Welding Speed 30mm/min & 50mm/min. The Experiment concluded that the hardness of the joint with a) rotation speed = 800rpm & welding speed = 30mm/min. b) rotation speed = 900rpm & welding speed = 50mm/min were found 55% & 70% of base metal respectively & the TS of weld was approx. 60% & 70% of base metal respectively. The approximate temperature for FSW of C11000 was between 460-530°C. Advancing side have higher temperature than retreating side. Hardness, Tensile Strength decreases offer FSW but elongation increases about 3 times.

Hwang et al. (2010) experimentally explored the thermal history of a work piece undergoing Friction Stir Welding involving butt joining with pure copper C11000. In the experiments, K-type thermocouples were used to record the temperature history at different locations on work piece. This data, combined with the preheating temperature, tool rotation speeds and tool moving speeds allowed parameters for a successful weld to be determined.

P. Xue, D.R.Ni, D.warg, B.L. Xiao, Z.Y. Ma (2011) studied the mechanical properties of FSW Al 1060 & pure copper (11000) pales of 5mm thickness with tool made of tool steel with 20mm shoulder diameter, 6mm pin dia. and 4.8mm pin length. The input parameter taken was tool rotation speed (400-1000rpm) and tool pin offset (0 - 3mm) & transverse speed taken constant at 100mm/min. The tensile & bending test was carried out. The experiment concluded that the maximum tensile strength & and sound bending properties obtained at 600rpm rotational speed & 2mm offset & sound weld was obtained when Cu is kept at advancing side.

Khodaverdizadeh et al. (2012) analyzed the work hardening behavior of FSW joints of pure copper alloys. The experiments were conducted at two different rotational speeds and constant feed rate and vice versa and it is evident that both factors influence the mechanical and metallurgical properties of copper joint. The grain size in SZ and HAZ decreases with increasing rotational speed and decreases in welding speed. Owing to this hardening capacity increases and stain hardening exponent decreases.

Lin et al. (2014) compared the properties of friction stir welded pure copper plates with TIG and it is observed that FSW of copper produced 13% more efficient weld than TIG.

Jabbari and Tutum, (2013) conducted in the pure copper plates with the thickness of 4mm in the constant traverse speed of 25 mm/min and five different rotation speeds. This research was aimed to find the optimum rotation speed for the friction stir welding of pure copper. According to this study, the mechanical properties like tensile strength and microhardness, microstructure of the friction stir weld joints were investigated. In this study the metallographic images were analysed and showed that the increasing of the rotation speed results in the increase of grain size in the nugget zone. Vickers hardness tests were conducted on the weld samples and the maximum hardness obtained in rotation speed of 900 rpm. Results of the tensile tests and their comparison with that of the base metal showed that the maximum strength and the minimum elongation are achieved again in this rotation speed. Yield strength and ultimate tensile strength increased with the decrease in grain size in the nugget region and the yield strength obeyed Hall-Petch relationship. Hence, the hardness values do not follow the relationship.

Heidarzadeh and Saeid, (2013) conducted experiments on friction stir welding of pure copper. According to this study, the mechanical properties of the friction stir welded joints were tested and investigated. In this study mathematical regression model was created with design expert software employing the response surface method with three parameters, five levels, and 20 runs. The three process parameters for this investigation were Rotational speed, welding speed, and axial force. Optical and scanning electron microscopes were used to evaluate the microstructural characterization and fractography of joints. The effect of welding parameters on the mechanical properties of friction stir welded joints was also fully investigated. The tensile strength of the joints increased up to a maximum value as welding parameters were increased. The percentage of elongation of the joints increased as rotating speed and axial force increased but dropped as welding speed increased. Furthermore, the toughness of the joints decreased as rotating speed and axial force increased but increased while welding speed increased.

Farrokhi et al., (2013) conducted experiments on stir welding of pure copper plates were on an air-conditioned environment. In this research, the defect-free FSW joints were performed at a rotation speed of 1600 RPM, and traverse speeds of 50mm/min, and 100 mm/min. In which microstructural and mechanical features of defect-free joints manufactured in air and under water were compared. The findings demonstrated that underwater friction stir welding can provide a finer microstructure. In both cases, the toughness of the welded joints was higher than the base metal. Furthermore, the joints welded in air and underwater are stronger than the base metal. The welding tool had a simple cylindrical pin with a diameter of 4 mm and a shoulder with a diameter of 12 mm which is made from H13 hot work steel. In the beginning, FSW was done in the air at 600, 800, 1000, 1250, and 1600 RPM and 50, 100, and 150 mm/min traverse speeds. The defect-free conditions were chosen, in which the macrostructure of the joints was void-free. Then, in defect-free conditions, underwater FSW was performed. The microstructural and mechanical properties of joints welded under both conditions were explored and compared, and temperatures at the bottom and middle of the plates were recorded using K-Type thermocouples during FSW.

Khodaverdizadeh et al., (2013) performed an experiment on the impact of tool pin profile on the microstructure and mechanical qualities of pure copper friction stir welded joints. At a constant rotation rate of 600 rpm and a traverse speed of 75 mm/min, two separate tools with threaded cylindrical and square pin profiles were used to construct the joints. During the FSW, four K-type thermocouples were used to record the temperature histories of the samples. Optical microscopy was used to assess the microstructural properties of the joints, and the resulting images were quantified using an image analysis technique. To characterize the mechanical properties of the joints, tension tests and Vickers hardness measurements were performed., In comparison to samples welded using a threaded cylindrical profile, the obtained results show that samples welded using a square pin profile had a finer recrystallized grain structure and higher mechanical properties. These results were attributed to the square pin profile's increased eccentricity with expanded and contract effects, which resulted in more plastic deformation and heat input into the joints.

Farrokhi et al., (2013) investigated the microstructural characterization of three different regions such as the nugget zone (NZ), the thermomechanical affected zone (TMAZ), and the heat affected zone (HAZ), which have been recognized in FSW joints. The tool used was a cylindrical pin tool. In addition to this Okamoto et al. fabricated a copper backing plate for cooling by FSW at a rotation speed of 1300 rev per a traverse speed of 170 mm per min. Lee and Jung welded a copper plate of 4mm thickness successfully at a tool rotation speed of1250 rev per min with a traverse speed of 61 mm per minute.

Suvarna et al., (2014) conducted experiments on friction stir welding for joining of 3 mm thick copper sheet using taper cylindrical tool pin profile. The defect free welds were obtained at a tool rotational speed of 900rpm and 1120 rpm and traverse speeds of 25, 31.5, 40 and 50 mm/min respectively. Mechanical and microstructure analysis has been performed to evaluate the characteristics of friction stir welded copper. The butted plates were clamped on a steel backing plate. The welding tool is tilted by 3 degrees of angle with reference to the welded plates and tool was rotated in the clockwise direction. The FSW joints were fabricated with taper cylindrical tool pin profile and are found to be defect free welds. The microstructural changes from the weld zone to the unaffected base metal were examined with optical microscopy. The microstructure of the friction stir welded copper joint consists of different zones such as (a) WZ (b) TMAZ (c) HAZ. Tensile test was conducted using computer controlled universal testing machine with a cross head speed of 0.5 mm/min. The charpy ‘V’ notch impact test was conducted at room temperature using pendulum type impact testing machine. Microhardness test was carried out using Vickers digital microhardness tester. The fractural morphology of the tensile and impact specimens of the fractured surface of the weld joints were studied using the scanning electron microscopy (SEM) to understand the mode of failure. According to this study, defect free welds were obtained at all the conditions such as tool rotation speed of 900rpm and 1120 rpm and weld speeds of 25, 31.5, 40 and 50 mm/min. The microstructure of the weld zone of FSWed joint at the condition of weld speed at 40 mm/min is observed to be having finer grains than that of the other weld conditions due to dynamic recrystallization. The joints made with tool rotation speed at 900rpm and weld speed of 40 mm/min resulted in good mechanical properties as compared with other weld conditions due to sufficient heat generation and proper mixing of the material in the weld zone.

Barenji, (2016) investigated the effect of heat input on microstructure and a mechanical property of friction stir welded pure copper was investigated. The 5 mm thick copper plates were used to perform friction stir welded joints at different traverse and rotational speeds. Also, the peak temperatures of the joints during friction stir welding were recorded using accurate thermocouples. In which, microstructure, hardness, and tensile properties of the joints were examined. The results showed that the outline of the stirred zone was observed at lower heat input conditions but disappeared when heat input increased. The thermomechanical affected zone was clearly characterized by elongated and recrystallized grains, respectively at lower and higher heat input conditions. Moreover, the lower heat input conditions caused finer grain sizes of the sire zone, and hence higher hardness and tensile strength. The joints welded at higher heat input conditions had more elongation and showed more ductile fracture mode defects that can result from conventional fusion welding. Accordingly, joints welded using FSW have revealed improved mechanical properties such as the ultimate tensile strength (UTS), tensile elongation (El), and hardness compared to the corresponding fusion welds. Therefore, it has been an effective joining or processing technique for a variety of different metals and alloys.

Azizi et al., (2016) investigated the joint made by friction stir welding of thick pure copper plate of 10mm. The rotation speed is taken constant 700rpm with discrete traverse speed of 50, 100, 150 & 200 mm/min. The tool was made of H13 steel with square pin profile. The tensile & hardness test were conducted. The microstructural features of the joints were examined by optical microscopy. The experiment shows that with increase in traverse speed, ultimate tensile strength and hardness increases to a maximum value then decreases. The value was maximum at traverse speed of 150 mm/min but the elongation decreases with increase in traverse speed.

Mehta et al., (2014) investigated effects of tilt angle on properties of dissimilar friction stir welding copper to aluminum was investigated. In this study, copper and aluminum 6061-T651 were welded by friction stir welding technology. Effects of tool tilt angle on mechanical and metallurgical properties were studied experimentally for dissimilar materials system. In this study, the tool tilt angle was varied from 0˚ to 4˚ with an interval of 1˚ while the other parameters such as rotational speed, welding speed, tool pin offset, of work piece material position were kept constant. Macrostructure analysis, tensile test, macro hardness measurement, scanning electron microscopy and energy dispersive x-ray spectrographic tests were performed to evaluate weld properties. The results of this study revealed that a defect free dissimilar copper-aluminum friction stir welding was achieved by tilt angles 2˚, 3˚ and 4˚. Maximum tensile strength was reported 117 MPa and macro hardness was reported 181 VH (in nugget zone) at the 4˚ tilt angle. Macro hardness was increased as tilt angle increases from 0˚ to 4˚. In addition to this, thermo-mechanically affected zone (at copper side) was found to be the weakest zone for dissimilar copper-aluminum friction stir welding system.

Pashazadeh et al., (2017) experimentally investigated the material flow and mechanical properties in friction stir welding of copper sheets. In this study, micrographs of friction stir welds on the copper alloy produced by a non-threaded tool pin. Also, tensile tests, hardness measurements, and microstructural evaluations were performed on the welded specimens.

Mishra et al., (2017) investigated the effect of FSW on room temperature tensile properties of C51000. The tensile specimens were machined from the nugget zone in two directions, parallel (longitudinal) and normal (transverse) to the weld. Longitudinal tensile specimens contained only fully recrystallized grains from the nugget zone, whereas transverse tensile specimens contained microstructures from all four zones, i.e., parent material, HAZ, TMAZ, and nugget zone. Summarizes the longitudinal tensile properties of nugget zone. As-welded samples show a reduction in yield and ultimate strengths in the weld nugget, while elongation was unaffected. Mahoney attributed the reduced strength to the reduction in pre-existing dislocations and the elimination of the very fine hardening precipitates.

Singh et al., (2020) conducted an experimental study by varying different FSW process parameters. The tool's rotational and traverse speeds were studied for parametric optimization with three distinct tool materials in these investigations. The grey relational technique was used to optimize tensile strength and impact strength. The findings show that parameters have a major impact on results. Finally, the gray relational technique was found to be a reliable method for optimizing a combined set of responses in a single try. The results show that the H13 tool material has a greater rotating speed and a lower traverse speed, which results in improved mechanical qualities. A microstructure study has been performed on scanning electron microscopy (SEM) and the change in grain size within the weld zone has been observed.

Tomasz et al., (2020) conducted experiments on friction stir welding of copper plates. According to this study, the mechanical properties of the friction stir welded joints were tested & investigated. This paper describes the influence of the friction stir welding travel speed on the mechanical properties of the butt joints of copper plates. The mechanical properties of the FSW joints were evaluated with respect to parameters of plates' material in the delivery state and after recrystallization annealing. The results of microhardness tests and fractographic analysis of tested joints are also presented. Base material samples and FSW butt joints were fabricated from 5 mm thick plates of high purity electrolytic copper (Cu-ETP R220) with a chemical composition containing more than 99.9% Cu, according to the EN 573-1 standard. The FSW welds were performed on a conventional Jafo CNC milling machine at a constant rotation speed ω = 580 rpm and at three different traverse speeds: V = 40, 60 and 80 mm/min.

The other FSW parameters were zero tilt angle, plunged depth of 0.3 mm, tool plunging speed of 2.5 mm/min and dwelling time of 5s. The good quality (defect-free) of the FSW joints produced in accordance with the above parameters was confirmed by visual observation and ultrasonic evaluation. The microstructure measurements were performed for base material and three FSW joint specimen (i.e., one specimen for considered travel speed) in accordance of ISO 6507-1. The metallographic investigation was conducted using optical microscope. In the area of tested FSW joints, a significant decrease in microhardness was observed relative to the base material property. The microhardness profiles determined for the cross-section of the joints had a W-type shape with a sudden decrease in microhardness in the HAZ and a tendency towards a slight increase in WN which, in the qualitative sense, correlated well with the average grain sizes observed in these zones. Tensile strength parameters of tested FSW joints were significantly lower than those of base material properties which was predominantly related to the loss of the cold-work hardening effect as a result of the recrystallization process in the HAZ. Resulting from the FSW process, the yield stress decreased on average by more than 60%, and ultimate stress fell by about 15%.

2.2 Principle of Operation of FSW

Friction stir welding (FSW) is a solid-state joining technique in which coalescence occurs owing to thermomechanical deformation of workpieces as the resulting temperature exceeds the solidus temperature of workpieces. The fundamental concept of FSW technique is depicted in Figure 2.1. It consists of a non-consumable rotating tool having a specially designed tool pin and shoulder. Tool pin is plunged into the faying faces of sheets or plates to be joined thus tool moves in the transverse direction along the length. The tool rotates in the clockwise direction and translates from front to back as shown in Figure 2.1. The left side where the direction of tool rotation is same of tool travel direction is termed as advancing side. It is opposite to the direction of metal flow. The side opposite to advancing side where rotation of tool is reverse of direction of tool travel is termed as retreating side. Owing to frictional heat between tool and workpiece, material around the pin is softened and a solid-state joint is produced without melting (Backer and Bolmsjo, 2014; Lui et al., 1997; Mishra and Mahoney 2008).

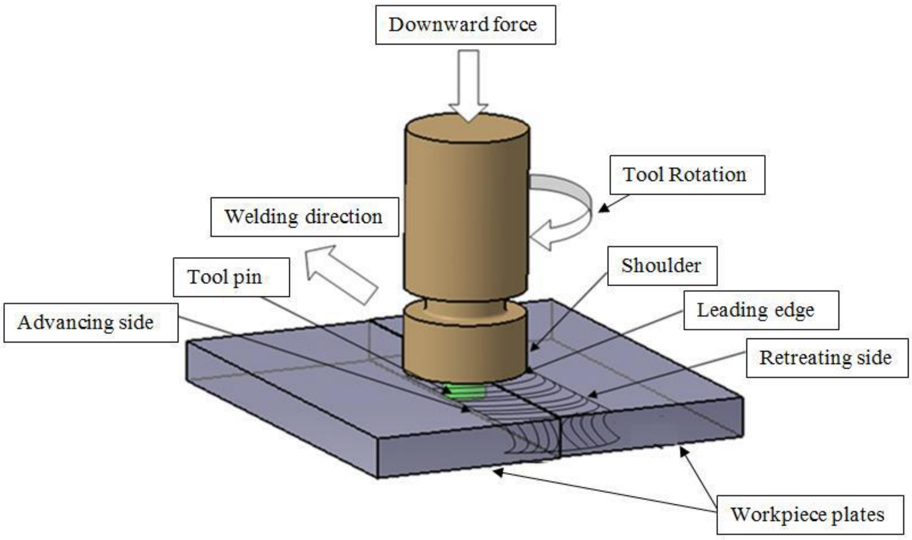


Figure 2.1 Principle of friction stir welding (Backer and Bolmsjo, 2014)

In FSW joints various microstructural regions can be observed as illustrated in Figure 2.2. The parent metal region is unaffected by heat as it is far away from the recrystallized zone and hence microstructural and mechanical properties of this region remains unaltered. The second region is heat-affected zone that is next to parent metal and is affected by heat but no plastic deformation takes place in this region; however, mechanical and microstructural property changes. The next region is thermo-mechanically affected zone that is very near to weld nugget and it is plastically deformed by means of tool. In this region material deforms without recrystallization. Next region is nugget zone or stir zone or fully recrystallized zone in which tool pin rotates and produces frictional heat; results in severe plastic deformation (Mahoney et al., 1998; McNelley et al., 2008).

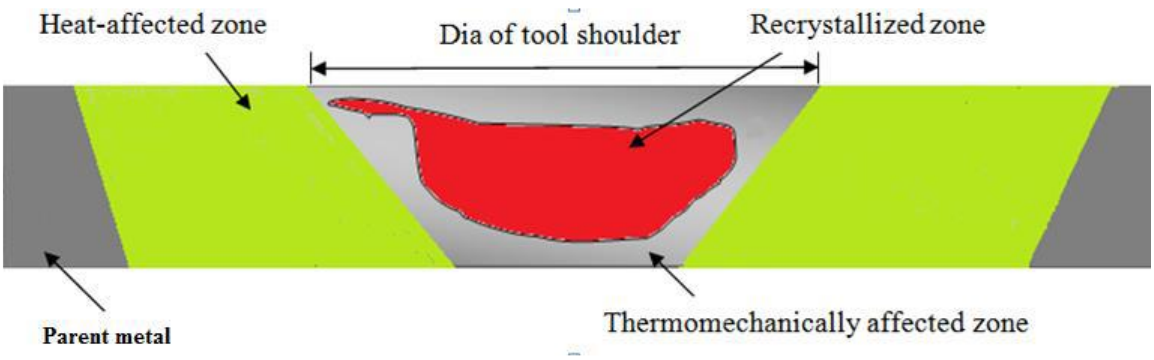


Figure 2.2. Microstructural regions of friction stir welding (Mahoney et al., 1998)

2.3 Phases of Friction Stir Welding

The FSW process consists of four phases: 1) plunging phase, 2) dwelling phase, 3) welding phase, and 4) exit or retract phase. The process starts with the first phase when the tool approaches the material, and then penetrates it in order to generate the initial amount of heat.

The second phase is characterized by the process of reaching the operating temperature necessary to start the welding process. This involves a constant pressure force to be present between the tool and the material, which creates the required mechanical (friction) energy. This process continues until the material's elastic modulus, i.e. the pressure force between the tool and the material, drops, which is a sign that the required temperature is reached, and the welding process can start.

The phase of welding (third phase) is realized through a complex thermo-mechanical process that involves the integrated action of thermal heating and plastic deformation. Realization of welding in the FSW processes involves mixing the "doughy" basic material of the work piece along the joint line. Given that the temperature generated this type of heating does not provide a complete diffusion, the basic materials of both pieces in the joint need to be mixed mechanically using the tool pin.

Mechanical work plays a key role in this process: it both affects the generation of thermal energy, ensures the mixing of base materials in their "doughy" phase in order to achieve a quality structure in the weld joint. In the last (fourth) phase, the tool exits the material (by vertical movement), completing thereby the welding cycle.

2.4 Process Parameters of FSW

FSW involves complex material movement and plastic deformation. Welding parameters, Tool geometry and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of material (Mishra & Ma, 2005).

Therefore, welding speed, the tool rotational speed, the tilt angle of the tool, and tool material are the main independent variables that are used to control the FSW process. During friction stir welding, process parameters play a significant role for the occurrence of welding and to control the weldment (Venu et al., 2019).

2.4.1 Tool rotation speed (TRS)

One of the crucial parameters that have significant impact on the quality of the weld in FSW is Tool Rotation Speed. The speed at which fixed tool rotates in vertical milling machine is referred to as tool rotation speed. Clockwise rotation can be viewed from above the tool, looking down onto the work piece. Vertical milling machine offers different tool rotation speeds ranging from very low level to quite high levels. Appropriate selection of the tool rotation speed is very much necessary to cause extensive plastic flow of the materials to be welded (Bikram et al., 2018).

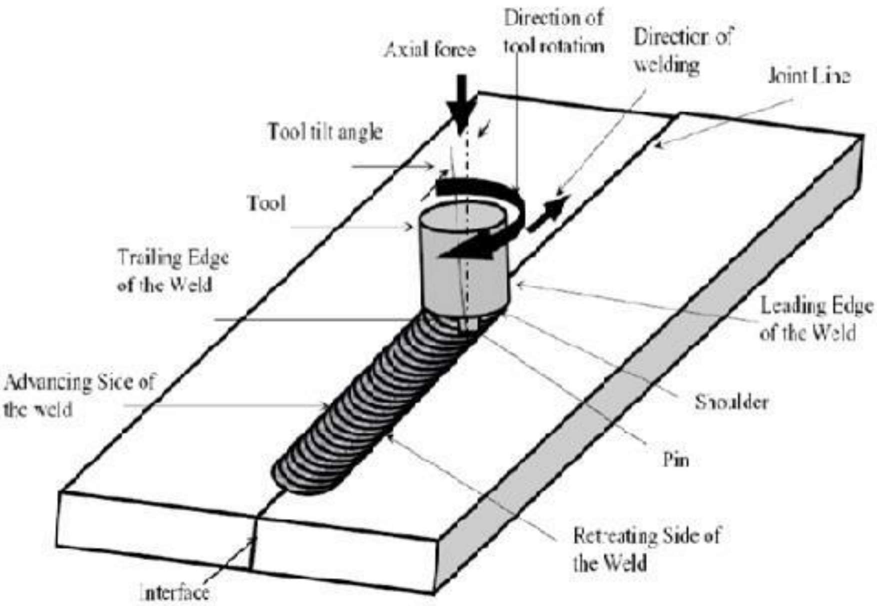


Figure 2.3 Process parameters in FSW (Bikram et al., 2018).

It explains the rotation of the tool like how past it rotates, whether it rotates in clockwise or anticlockwise direction. As the tool rotates from leading edge to tilting edge, material flows take place. For FSW, two parameters are very important: tool rotation rate (v, rpm) in clockwise or counter clockwise direction. The motion of the tool generates frictional heat within the work pieces, extruding the softened plasticized material around it and forging the same in place so as to form a solid-state joint.

2.4.2 Tool transverse speed

In vertical milling machine, tool is fixed but only rotates at its position and work pieces that are clamped on to fixture travels. By travelling feed/feed rate, we mean the speed with which work pieces that are clamped onto fixture travels or how quickly the tool travels through the interface. It may also be termed as welding speed i.e. speed at which welding occurs. The relation between travelling feed/feed rate and the generation of heat during welding is complex but it is generally said that raising the tool rotation speed and reducing the feed rate will result in increasing the temperature at weld surrounding which in turn leads to production of successful weld.

The tool traverse speed should be minimum in order to produce a successful weld and to produce required plastic flow. The welding speed depends on several factors, such as alloy type, rotational speed, penetration depth, and joint type. Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. During traversing, softened material from the leading edge moves to the trailing edge due to the tool rotation and the traverse movement of the tool, and this transferred material, are solidify in the trailing edge of the tool by the application of an axial force (Mishra & Ma, 2005).

2.4.1 Tool tilt angle

In addition to the tool rotation rate and traverse speed, another important process parameter is the angle of spindle or tool tilt with respect to the work piece surface. Tool should be tilted to enable a gradual increase of forging pressure. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin. The tool is usually characterized by a small tilt angle (θ), and as it is inserted into the sheets, the blanks material undergoes to a local backward extrusion process up to the tool shoulder. Further, the plunge depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders (Mishra, & Ma, 2005).
As the tool may in some circumstances be tilted through a small angle, part of the shoulder may be embedded deeper into work piece. This angle of tilt is referred to as "tilt angle'. Tilting the tool by 2-4 degrees, such that rear of the tool is lower than the front, has been found to assist the forging of the material at the rear of the tool (Bikram et al., 2018).

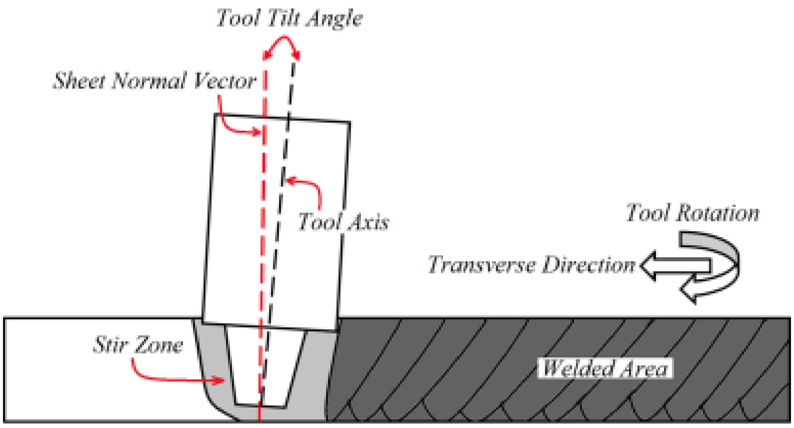


Figure 2.4. Friction stir welding tool tilt illustration (Elyasi et al., 2016).

2.5 Effects of Process Parameters on FSW

While several FSW process parameters have been shown to have minimal influence on the comparable and dissimilar material FSW, others are proven to be crucial in producing high-quality joints free of defects. Since the weld qualities (material flow and heat input in particular) are determined by the process parameters. Consequently, it would be crucial to focus on the aspects that have the biggest impact on these characteristics (Singh et al., 2020).
In friction stir process, the welding process parameters such as tool rotational speed, traverse (weld) speed, and tool tilt angle all play a part in determining the quality of the welds. In this research, the three process parameters are taken into account namely rotational speed, transverse

speed, and tool tilt angles. Major process parameters used to weld the two similar copper plates using FSW and their effects on the joint properties are discussed below.

2.5.1 Effect of Tool Rotational and Tool Traverse Speed on FSW process

Two critical factors for FSW are the tool traverse speed (n, mm/min) along the joint line and the tool rotation rate (v, rpm) in either a clockwise or counterclockwise orientation. In order to create a solid-state seamless junction, the tool's action creates frictional heat inside the work components, which extrudes the softened plasticized material surrounding it and forges it in place (Sidhu & Chatha, 2012). Welding speed is a speed at which the tool moves translationally along the weld line of the joint. It is one of the critical parameters which governs the heating of work pieces during the welding process. The amount of heat input is inversely proportional to the welding speed. In other words, low welding speed generates more heat during the FSW process than that high welding speed. The tool rotational speed is another critical process parameter that significantly affects the reaction temperature during dissimilar FSW. The turning motion of the tool around its axis affects the plastic deformation by influencing the frictional heat generation and provides sufficient axial force, which affects the material flow, the size of the nugget zone and most importantly, the IMCs formation.

The tool linear speed, v (mm/s), and rotating speed, ω (rpm) are possibly the most significant FSW process parameters since both parameters have a substantial influence on the material flow and heat input. Generally, the heat input is directly proportional to the rotational speed and inversely proportional to the traverse speed, both factors are interrelated as Heat Input $\propto \omega / v$. Therefore, both process parameters are important to produce a quality weld and higher ultimate tensile strength (UTS) hence these parameters need to be addressed properly by increasing rotational speed, the strained area becomes wider, and the position of the maximum strain region moves towards the advancing side (AS) from its initial retreating side (RS) of the weld. This indicates that the fracture position of the weld is also get affected by tool rotational speed (Taylor et al., 2014).

On account of the compounding effect of both process parameters, various researchers have reported the term revolutionary pitch (v/ω) which affects the weld quality. A higher revolutionary pitch value manifests fast welding (i.e., cold-welding), whereas a lower pitch value manifests slow welding (i.e., hot welding) Higher pitch ratios account for inadequate material flow and low peak temperature, whereas a too low value will cause adverse material flow and higher liquation which promotes IMC growth, both conditions detrimental to the weld quality Lower rotational speed leads to low-temperature generation in the nugget zone (NZ)and the volume fraction of coarse second phase (strengthening) particles While at higher rotational speed, second phase particles undergo more fragmentation and lead to particles separation in other section of the TMAZ (V. P. Singh et al., 2020).

2.5.2 Effect of Tool Tilt Angle on FSW process

Tool tilt angle is the position at which the FSW tool is placed relative to the work piece surface. 0^{o} or no tilt angle is referring to when the tool is perpendicular to the work piece. Applying an appropriate tilt angle during FSW of dissimilar materials is vital as it holds stirred material under the tool's shoulder and increases the forging action to obtain a uniform flow of material through the proper vertical and horizontal motion of the plasticized material (Mishra, & Ma, 2005).
Mehta et al., (2016) joined aluminum and copper using FSW by varying the tool angle to the work piece to investigate the effects of tilt angle on the Al-Cu joint properties. It was reported that the flash defect was reduced when the tilt angle was increased from 0^{o} to 4^{o}. Furthermore, at a higher tilt angle, the greater compressive force was exerted underneath the shoulder area. This allowed the tool to forge the stirred material downwards and stop it from spreading outside the shoulder diameter, resulting in a sound joint and better weld appearance. On top of that, a higher tilt angle also improved the hardness at the Al-Cu joint area, which is attributed to the formation of IMCs at the interface due to higher heat production in the stir zone. According to the previous research works, it is proven that tool tilt angle affects the joint's strength and integrity. Therefore, an optimal value of tilt angle must be selected to achieve the best weld results.

2.5.3 Effect of backing plate

The resultant weld quality and its properties are largely dependent on the thermal boundary condition at the bottom of the work pieces to be joined. For a given alloy type, tool geometry, and chosen process parameters (welding speed, rotational speed), these thermal boundary conditions are dictated by the back plate material used. This work aims to clarify the impacts of the root side thermal boundary condition on weld process variables and subsequent joint qualities by using backing plates constructed of materials with significantly different thermal diffusivity. Aluminum, stainless steel, mild steel, and siliceous coating were used as the backing plate (BP) materials for the 5-mm-thick AMr5 (AA 5056) welds. For a specific instance, the backing plate's material effects on elongation and tensile strength were determined (Zybin et al., 2018).

In the μ-FSW process, the correlation between heat loss and weldability was examined by varying the BP while maintaining the same welding speed and tool rotational speed. Figure 2.6 depicts the heat loss mechanism to the BP. When a BP has low thermal conductivity, heat is produced between the revolving tool and the base metal, little heat is transmitted to the BP, and there is minimal overall heat loss. In this instance, there is still a significant quantity of energy per unit volume in the weld region, which promotes good plastic flow of the molten metal and the production of an excellent weld joint. On the other hand, BPs with high thermal conductivity leads to significant heat loss, and weld joint defects may result from poor plastic flow (Alloys, 2020).

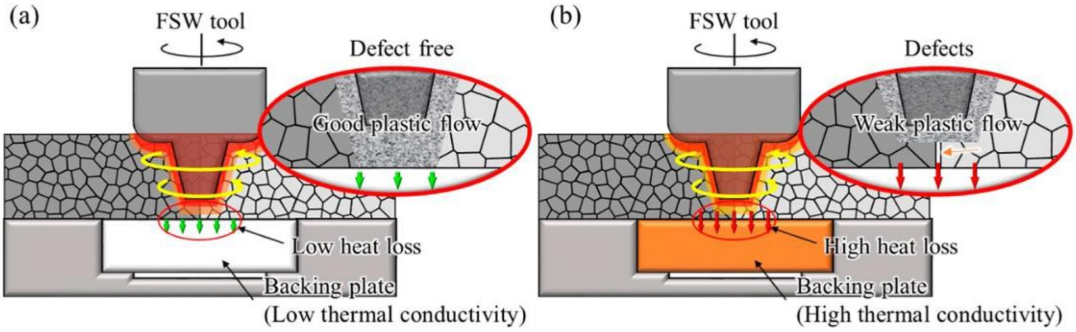


Figure 2.5 Mechanism of heat loss to the backing plate using (a) low thermal conductivity and (b) high thermal conductivity (Source: Alloys, 2020).

Three materials with different thermal conductivities were used as BPs under the same heat input conditions to understand the effect of heat loss on weldability. The thermal conductivity and density values of the cordierite ceramic, titanium alloy, and copper alloy materials are shown in Table 2.1.

Table 2.1 the thermal conductivity and density of backing plate materials (Alloys, 2020).

Backing Plate Material	**Thermal Conductivity (W/Mk)**	**Density (g/cm^3)**
Cordierite ceramic	2.3	2.3
Titanium alloy	4.48	15.6
Copper alloy	9.96	388

2.6 Response Measurement for Determining Weld Quality

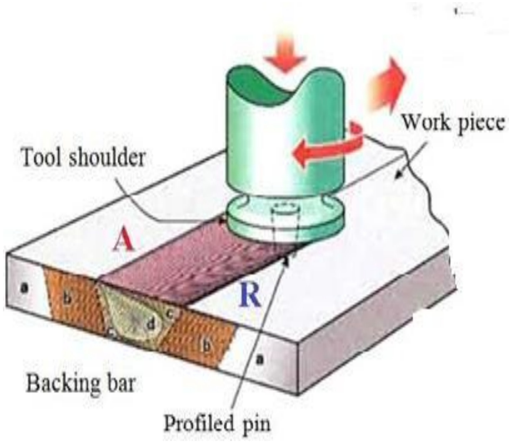
Because of its superior joint performance and mechanical qualities, FSW is widely used in a wide range of industries. To evaluate the quality of the welded joints, various microstructural and mechanical characterization investigations are required. These characterizations are required to comprehend the joint's in-service performance and failure behavior, as well as to correlate the effect of process parameters on the performance of the welded joint. Microstructural characterizations include the size, shape, morphology, and orientation of grains and precipitates. After mechanical testing, a fractured specimen is fractographically examined. Mechanical characterization includes, among other things, determining the joint's microhardness, tensile strength, elongation, impact strength, and fatigue strength (Khan et al., 2017).

2.6.1 Mechanical properties

The basic mechanical properties considered in FSW are weld joint microhardness and tensile strength. In general, hardness is defined as resistance to indentation and, in some cases, resistance to deformation. Hardness, particularly for metals, is a measure of their resistance to plastic deformation. There are various hardness measurement tests available, but the indentation hardness test is most commonly used in engineering applications for metal. A square-base diamond pyramid with a 136° included angle between opposite faces is used as an indenter in the Vickers hardness test. Diamond pyramid hardness (DPH) testing is commonly used (Khan et al., 2017).

2.6.2 Microstructure of FSW Joints

In general, in an FSW process, the joint material can be separated into four visually distinct microstructural zones based on how they are affected (Jafri et al., 2015). Figure 2.6 depicts how these zones are distinguished.



Key

A. Advancing side of the weld
R. Retreating side of the weld
a. Unaffected material
b. Heat affected zone (HAZ)
c. Thermomechanical affected zone (TMAZ)
d. Weld nugget or stir zone

Figure 2.6 Basic microstructural zones of friction stir wed joint (Jafri et al., 2015)

Base metal: This is material remote from the weld, which has not been deformed, and which, although it may have experienced a thermal cycle from the weld, is not affected by the heat in terms of microstructure or mechanical properties.

Heat affected zone (HAZ): In this region, which lies closer to the weld center, the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties. However, no plastic deformation occurred in this area.

Thermo-mechanically affected zone (TMAZ): The friction stir welding tool deformed the material in this region, and the heat from the process also had an effect on it. In the case of copper, sufficient plastic strain can be achieved without recrystallization in this region, and the recrystallized zone (weld nugget) and the TMAZ deformed zones are usually well separated.

Weld Nugget: The fully recrystallized area, also known as the stir zone, refers to the area previously occupied by the tool pin. In friction stir processing, where large amounts of material are processed, the term stir zone is commonly used (Kumar et al., 2015).

2.7 Applications of friction stir welding

Recently, FSW won attractive attention by manufacturing industries because of the ability that outperformed other welding technique such as tungsten inert gas (TIG) to weld aluminum. Besides, it has the ability to be adapted in advanced automation system such as robotic which is very predominant in aluminum components and panel fabrications of highly rated technology readiness level (Smith et al., 2003). This is due to its low distortion and its suitability to produce large welded products including prefabricated panels as well as tailored blanks and joints. These advantages are also shared in marine application when it is first commercially used for ship building in 1996 with the ability to joint thick panels, sandwiched, honeycomb panels and corrosion resistance material panels (Kallee et al., 2002). FSW is well favoured for performing butt joint in comparison to conventional arc welding application which also turns out to be significantly viable in terms of low labor cost and shorter welding cycle time (Delany et al., 2007). The other important application of friction stir welding is in aeronautical and aerospace industries where aluminium alloy is used as primary material for their construction. The welding process enables manufacturers to completely replace the riveted joints and assemblies of lapped and abutted configuration that are used mainly for fuselage sections, propellant and fuel tanks of commercial air craft as well as space launch vehicle (Arbegast, 2006). Thus, the process allows total elimination of the use of thousands of rivets. This has resulted in better quality, stronger and lighter joints at reduced assembly cost for aviation industry. Meanwhile in automotive application, FSW and its recently innovated process of friction stir spot welding (FSSW) are introduced to replace conventional resistive spot welding (RSW) in the transition when aluminium alloy application is ready and becoming ideal to be used for panels in passenger and commercial vehicle bodies. This has compelled car manufacturers to use the same concept not only for the body panels, but for other parts as well (Kallee et al., 2005).

Table 1.2 Summary of the Literatures: selection of FSW process parameters

S. N	Title	Author	Material	FSW Parameters	Method and Types of Tests	Findings/ Conclusions
1	Experimental investigation on the effect of welding parameters on friction stir welding of pure copper joints.	Heidarzadeh and Saeid, (2013)	Pure copper	Rotational speed, welding speed, and axial force.	Response surface method Tensile strength test Hardness Test microstructural characterization and fractography of joints	• The tensile strength of the joints increased up to a maximum value as welding parameters were increased. • The percentage of elongation of the joints increased as rotating speed and axial force increased but dropped as welding speed increased. • The toughness of the joints decreased as rotating speed and axial force increased but increased while welding speed increased.
2	Optimization of process parameters in conducted experiments on stir welding of pure copper plates were on an air-conditioned and in water environment	Farrokhi et al., (2013)	Pure copper	rotation speed, traverse speeds	Taguchi Method FSW microstructural and mechanical features	• The findings demonstrated that underwater friction stir welding can provide a finer microstructure. • The joints welded in air and underwater are stronger than the base metal.
3	Experimental investigation the impact of tool pin profile on the microstructure and mechanical qualities of pure copper friction stir welded joints	Khodaverdizadeh et al., (2013)	Pure copper	constant rotation rate of 600RPM, traverse speed of 75 mm/min & two separate tools with threaded cylindrical and square pin profiles	ANOVA tension tests and Vickers hardness measurements Hardness Optical microscopy was used to assess the microstructural properties of the joints	✓ Samples welded using a square pin profile had a finer recrystallized grain structure and higher mechanical properties. ✓ The square pin profile's increased eccentricity with expanded and contract effects, which resulted in more plastic deformation and heat input into the joints.

2.8 Research Gap

Several researchers have attempted to study the effects of process parameters such as tool geometry, heat inputs, clamping forces, temperature, tool tilt angles, and so on, on the microstructure and mechanical properties of FSW joints of a copper plate with the same or different thicknesses in the literature. Following a thorough study of the current literature, research gaps in friction stir welding of copper plates of similar thickness using the Taguchi methodology were identified. The majority of researches on friction stir welding improvements has focused on the effects of process parameters, but relatively few researches has been done to investigate the optimum process parameters for friction stir welding of copper plate. Additionally, on a 5mm copper plate, the combined effects of friction welding process parameters such as tool tilt angle, tool rotational speed (RPM), and welding speed or transverse speed (mm/min). So, this thesis work addresses the gaps identified in the above summary of literature reviews in order to achieve the specific objectives of this thesis work through practical work using Taguchi techniques.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

After a depth review of the literature, some guidance and experience on the proper workpiece material selection, process parameter management, study methodology, and FSW welding conditions are now available and using a vertical milling machine, an experiment were carried out using a proper selection of orthogonal arrays for an experimental plan, taking FSW welding process parameters such as tool rotating speed, tool traverse speed, and tool tilting angle for copper plate as the basis material.

3.2 Research Methodology

To meet the research objectives outlined in Chapter 1. The schematic diagram of the framework of the applied techniques is shown in figure 3.1.

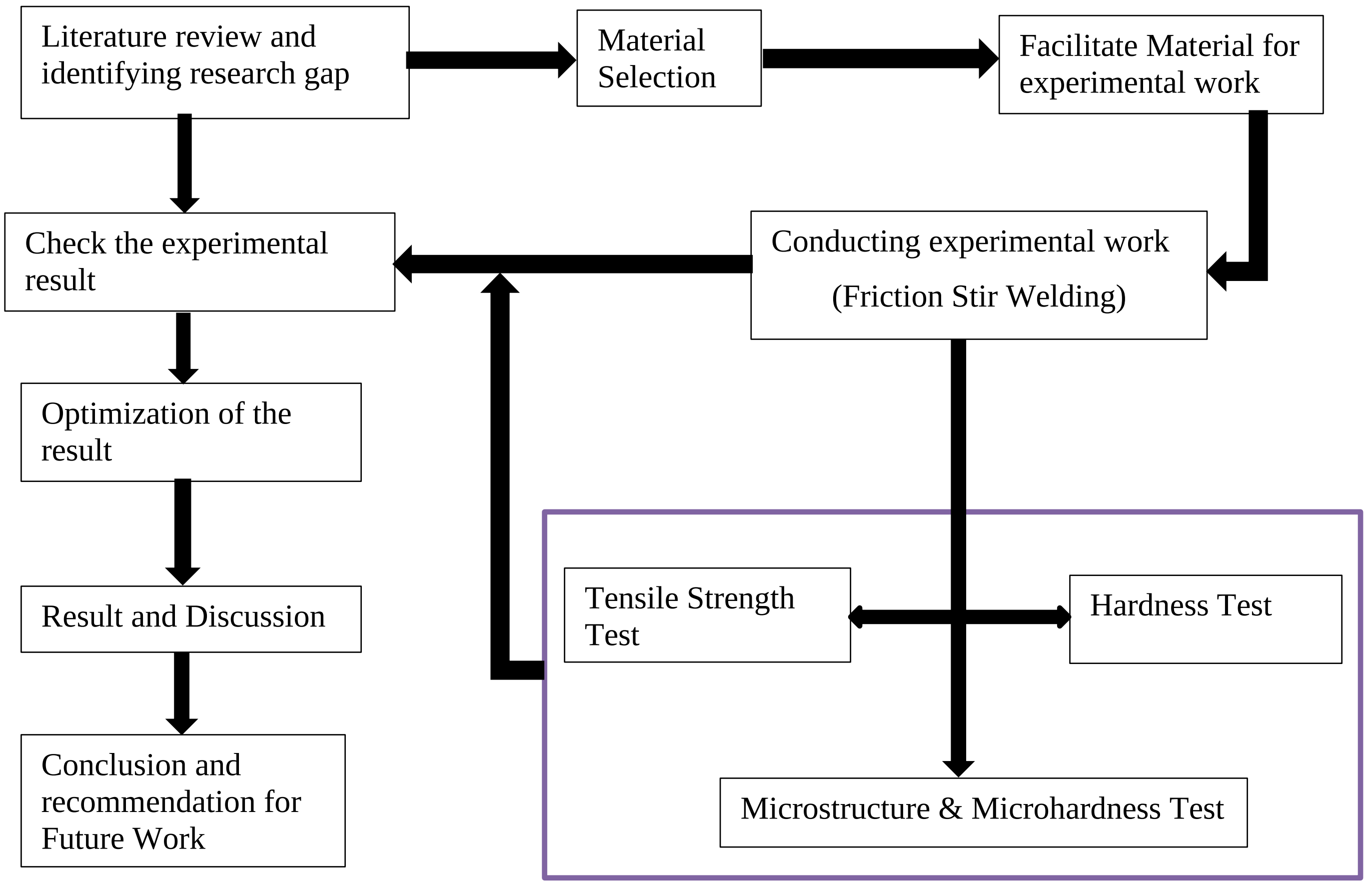


Figure 3.1 Flow chart for experimental work (research methodology)

3.3 Material Selection

3.3.1 Base Material: Sample preparation, composition and size specification

The base material employed in this thesis will be similar copper plates with a thickness of 5 mm. The chemical composition of copper plate was obtained by the **s**pectrometry testing machine. Table 3.1 lists the chemical compositions of copper plates which is used as a base metal for FSW.

Table 3.1 Chemical composition of copper plates

Symbol	Zn	Pb	Sn	Fe	Ni	Si	Al	P	Cu
Wt.%	0.010	0.011	0.010	0.005	0.004	0.005	0.002	0.020	**99.863** (Balance)

In this thesis work, a copper plate with a thickness of 5 mm was prepared to perform butt weld joints. The copper plate was cut out by using power hacksaw cutter in the dimensions of 100 mm × 40 mm as shown in Figure 3.1. After the cutting operation, each of the work piece surfaces was cleaned with a sponge to remove wax, oil, or dust.

Figure 3.2 Work piece material (a) Base material stock size, (b) Copper plate samples prepared for joint formation.

3.3.2 Welding Tool Preparation and Fabrication process

FSW is not possible without a non-consumable tool. The tool used in this thesis work FSW is with square pin in shape. The tool consists of two main parts i.e. a pin or probe and a shoulder. The function of a tool is mixing of the work piece material and heating by frictional heat and hence material selection of the tool is very important factor. The good tool material should feature following properties: good static and dynamic properties at welded temperature, good wear resistance, and machinability & fracture toughness and high hardness at elevated temperatures and should retain the hardness for an extended period.

The specifications and standards should be used to design the friction stir welding tool. The main considerations are shoulder diameter and pin diameter. Sevvel & Jaiganesh (2014) stated that the shoulder-to-pin diameter ratio is 3. Work piece thickness is one of the key deciding factors during tool design configuration. According to R. Singh et al. (2016), the length of the pin should be just a little bit less than the thickness of the work piece. Therefore, the thickness of the work piece is 5mm and the pin length is decided at 4.5mm. For this study, the square pin profiles were designed and fabricated as shown in Figures 3.3 (a) and (b) respectively. The material of the tool used to carry out welding was made up of high carbon steel (H13). A non-consumable H-13 tool steel with flat shoulder is chosen as tool material to fabricate the joints because of its high strength at elevated temperature, thermal fatigue resistance and low wear resistance. The diameter of the shoulder and pin used were 12 mm, 4 mm respectively and length of the pin is 4.5 mm. A square pin tool as depicted in figure 3.3 (b), were fabricated as per the need of the research study that includes critical process parameters related to welding tool.

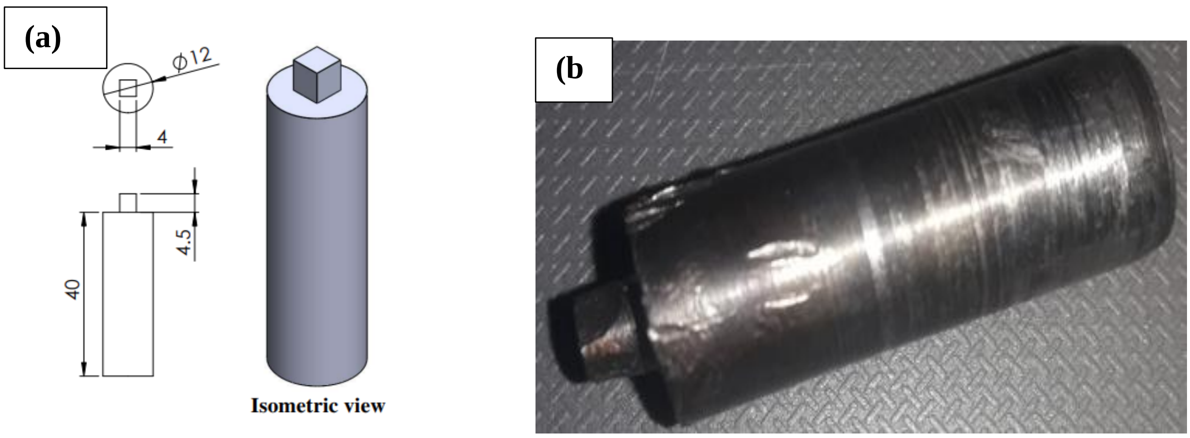


Figure 3-3 Tool specifications (a) Design of welding tool, (b) Fabricated square pin tool

3.3.3 Fabrication of the Backing plate material

The backing plate has a significant impact on the weld's quality and characteristics. The material used for the back plate determines the thermal boundary conditions at the bottom of the bonded work pieces. In this case, a significant amount of energy per unit volume remains in the weld zone, resulting in good plastic flow and the formation of an excellent weld connection. For this thesis work, cast iron was used as a backing plate at the base of the work pieces as depicted in figure 3.4 below.

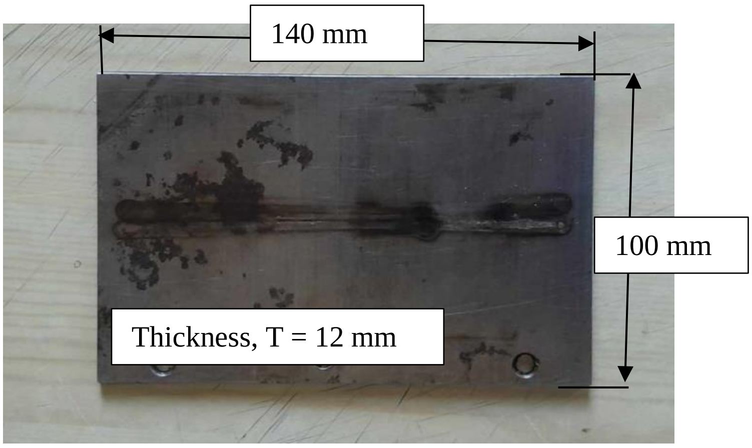


Figure 3.4 Fabricated backing plate for FSW

3.3.4 Machine specification for FSW

A Vertical Milling Machine has been used to carry out Friction Stir Welding process at Ethiopian Air Force (at Engineering Solutions Section), Machine Shop. Table 3.2 shows the size and working specifications of Vertical Milling Machine.

Table 3.2 The size and working specifications of Vertical Milling Machine

Specification	**Values**
Make	PACMILL-3KS
Spindle Position	Vertical
Number of Spindle Speeds	18
Range (rpm)	30 to 1500
Longitudinal Table Travel (mm)	950
Cross Table Travel (mm)	400
Tool Holder Diameter (mm)	50
Feed Range	Variable Auto Feed
Motor	3HP

3.4 Experimental Work

Experiments were conducted at the Ethiopian Air Force (Engineering Solutions Section), Machine shop/workshop on Conventional Vertical Milling machine as per DOE Taguchi by considering process parameters like tool rotational speed, welding speed and tool tilt angle at 3 levels which gives L9 Orthogonal array and analyze the output results based on ANOVA. Table 3.3 shows process parameters and their levels.

Table 3.3 Selected process parameters and their levels

S. No	Process parameter	Units	Levels		
			1	2	3
1	Tool Rotational Speed	rpm	750	950	1180
2	Tool traverse Speed	mm/min	20	30	40
3	Tool tilt angle	degrees (°)	1	1.5	2

3.4.1 Experimental Setup

In this thesis work the copper plates of 5 mm thickness were cut into the required size (100 mm x 40 mm) by power hacksaw cutter. The joint was obtained by butting the two plates and stirring them together with a rotating tool assembly by using conventional vertical milling machine. A non-consumable H-13 tool steel with flat shoulder is chosen as tool material to fabricate the joints because of its high strength at elevated temperature, thermal fatigue resistance and low wear resistance. The diameter of the shoulder and pin used were 12 mm, 4 mm respectively and length of the pin is 4.5 mm. The butted plates were clamped on a steel backing plate. The welding tool is tilted by 1°, 1.5°, 2° degrees of angle with reference to the welded plates and tool was rotated in the clockwise direction. A constant axial force is applied for all the joints.

Table 3.4 Experimental plan for FSW of copper plate (L9) OA

Experimental Run		Designation			Possible outputs combination	**Process Parameters**		
Sample Code	Sample No.	A	B	C		**Rotational speed (A)**	**Transverse speed (B)**	**Tool Tilt Angle (C)**
E_1	1 & 2	1	1	1	111	750	20	1
E_2	3 & 4	1	2	2	122	750	30	1.5
E_3	5 & 6	1	3	3	133	750	40	2
E_4	7 & 8	2	1	2	212	950	20	1.5
E_5	9 & 10	2	2	3	223	950	30	2
E_6	11 & 12	2	3	1	231	950	40	1
E_7	13 & 14	3	1	3	313	1180	20	2
E_8	15 & 16	3	2	1	321	1180	30	1
E_9	17 & 18	3	3	2	332	1180	40	1.5

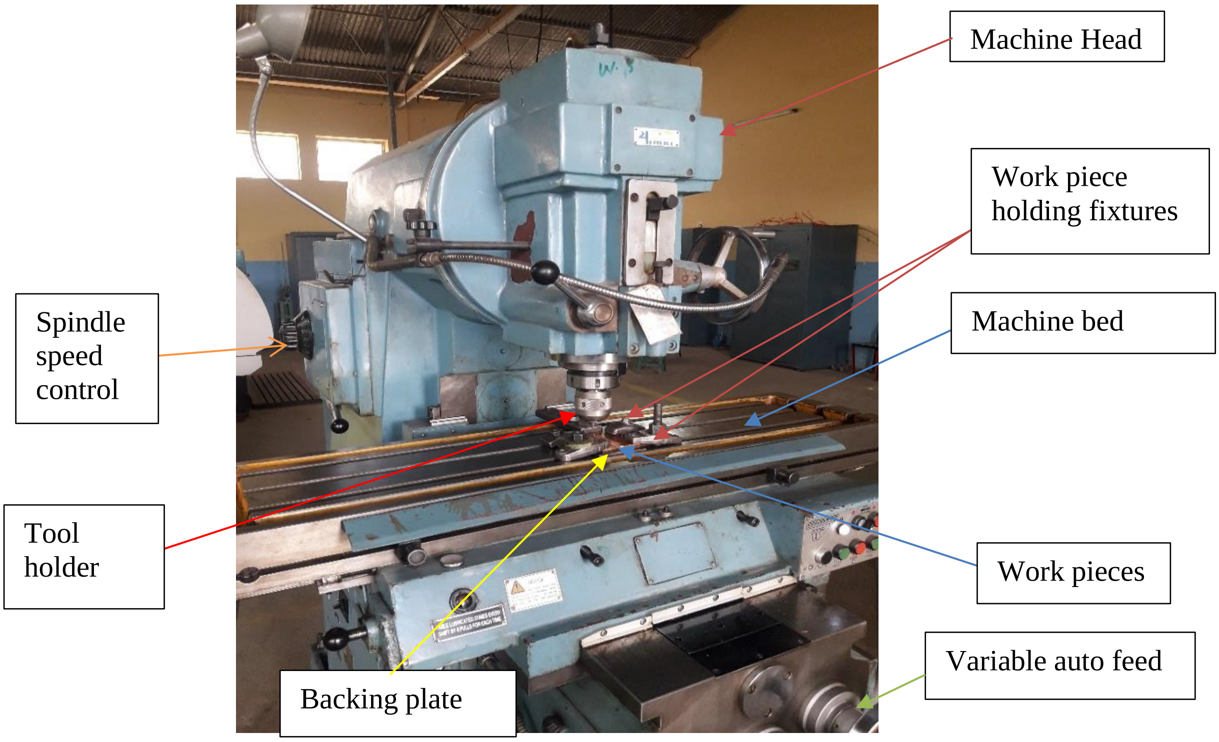


Figure 3.5 FSW experimental setup (at ETAF, Harar Meda)

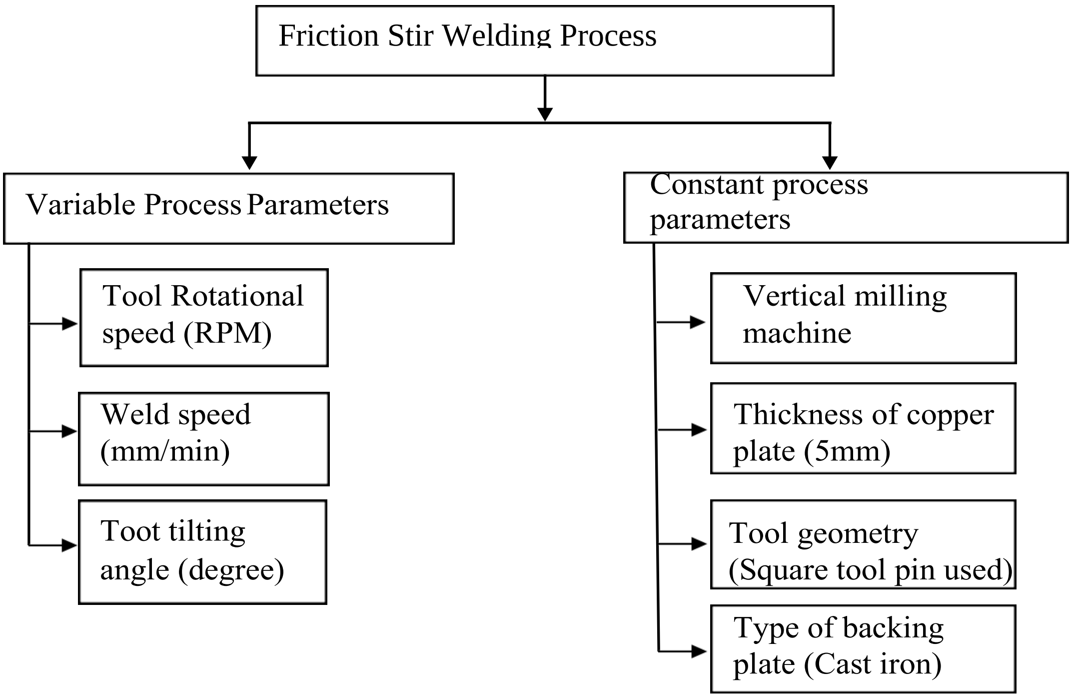


Figure 3.6 Variable and constant FSW process parameters

Schematic sketch of the weld joint and tool is as shown in Fig. 3.7 (a). The FSW joints were fabricated with square pin tool profile and are found to be defect free welds. The welded samples of the FSW joints with applied welding process parameters were shown in Fig. 3.7 (b) from (E1) to (E9).

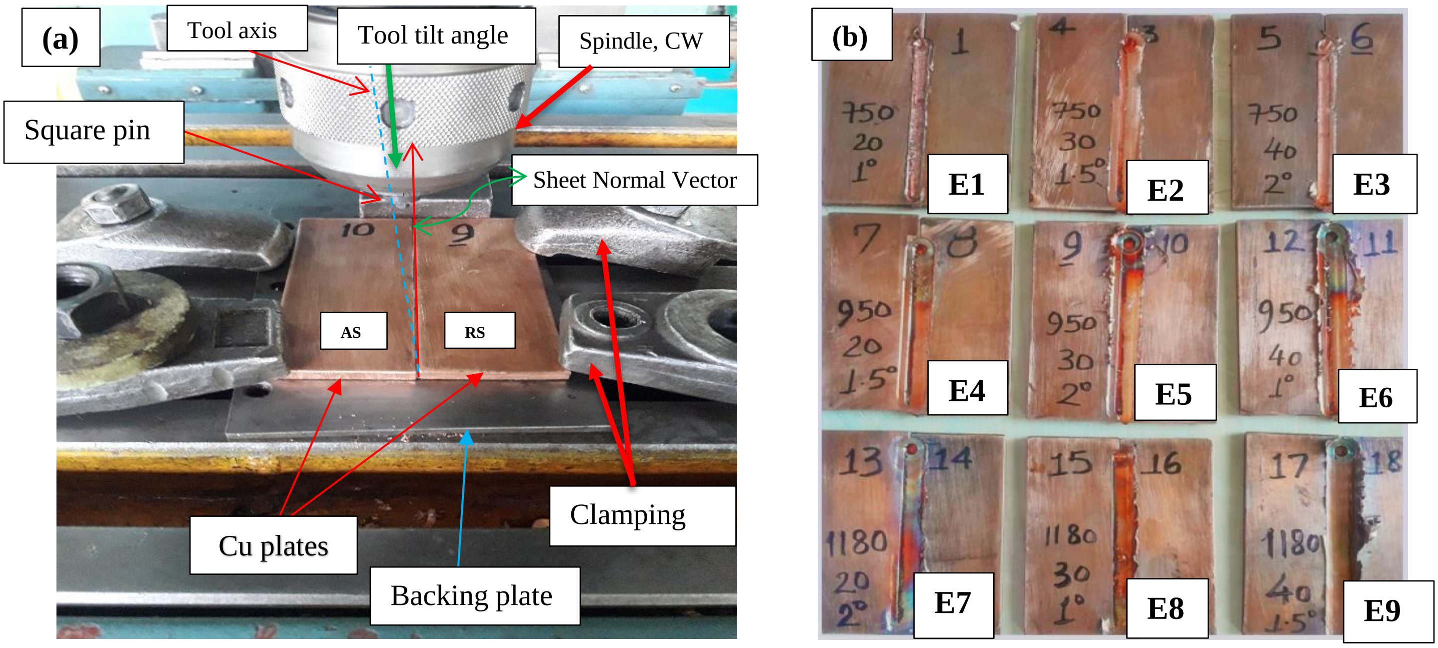


Figure 3.7 Schematic sketch of **(a)** weld joint and tool, **(b)** welded samples E_1, E_2, E_3, E_4, E_5, E_6, E_7, E_8, E_9.

3.4.2 Mechanical Property Test

3.4.2.1 Tensile Strength Testing

Tensile testing is a fundamental material science and engineering test in which a sample is subjected to a controlled tension until failure. Properties that are directly-measured via a tensile test are ultimate tensile strength, material toughness, maximum elongation, and reduction in area (Davis, 2004b).

For various testing, FSW-welded experimental specimens were created from welded copper plates and machined using ASTM to determine the necessary dimensions for studying their properties. The HUT 600 servo-hydraulic with a piston speed of 0.1-120mm/min with the max force of 600KN and EN 10002-1; exist at Ethiopian Technical University were used for tensile strength. UTM is quick, precise, and simple to use. It gets its name from the wide range of tests it can perform on various types of materials for example tension, flexural, compression, and shear tests.

From these measurements, the following properties can also be determined: Young's modulus, Poisson's ratio, yield strength, and strain hardening characteristics. Uniaxial tensile testing is the most used for obtaining the mechanical characteristics of isotropic materials. Some materials use biaxial tensile testing. The main difference between these testing machines is how the load is applied to the materials (Davis, 2004). The tensile properties for any base material are also applied as the same procedure and specimen preparation it is important that the tensile properties of the base metal, the weld metal, the bond between the base metal and weld metal, and the HAZ conform to the design considerations of the weldment. Where butt joints are used, the weld metal should usually develop the minimum tensile properties of the base metal (AWS committee, 2000).

3.4.2.2 Specimen preparation and test procedures for tensile strength

The preparation of test specimens depends on the purposes of testing and the governing test method or specification. A tensile specimen usually has a standardized sample cross-section. As shown in table 3.5 and figure 3.6. It has two shoulders and a gauge (section) in between. The shoulders and grip section are generally larger than the gauge section by 33% so they can be easily gripped (Davis, 2004b). The specimens prepared for testing were shown in figure 3.7.

Table 3.5 ASTM/E8 standard for tensile test specimen (Davis, 2004)

All values in inches (1 in = 25mm)	Plate type (1.5 in. wide)	Sheet type (0.5 in. wide)	Sub-size specimen (0.25 in. wide)
Gauge length	8.00 ± 0.01	2.00 ± 0.005	1.000 ± 0.003
Width	1.5 + 0.125–0.25	0.500 ± 0.010	0.250 ± 0.005
Thickness	0.188 ≤ T	0.005 ≤ T ≤ 0.75	0.005 ≤ T ≤ 0.25
Fillet radius (min.)	1	0.25	0.25
Overall length (min.)	18	8	4
Length of reduced section (min.)	9	2.25	1.25
Length of grip section (min.)	3	2	1.25
Width of grip section (approx.)	2	0.75	3⁄8

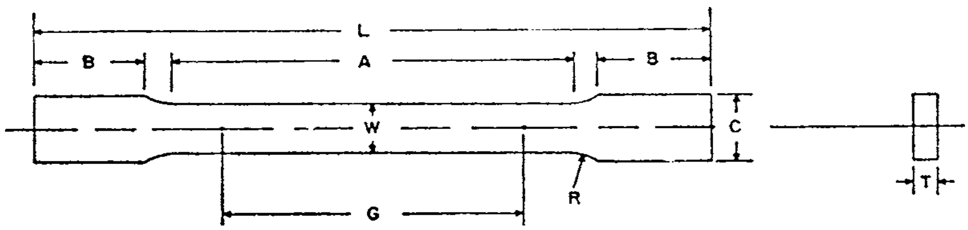


Figure 3.8 tensile test specimen standard dimension (Davis, 2004)

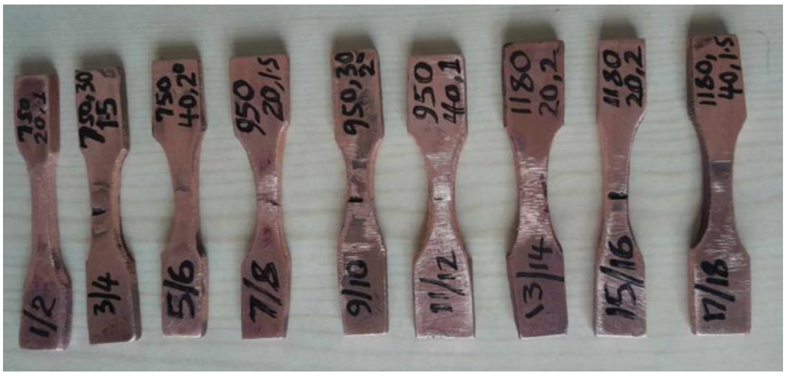


Figure 3-9 Specimen prepared for tensile strength test

The experimental procedure was carried out at Ethiopian Technical Institute using a HUT 600 servo-hydraulic Universal testing machine with a piston speed (strain rate) of 8mm/min as illustrated in figure 310 (a). After specimens were prepared and the UTM machine was set up properly the test process was performed by placing the test specimen in the testing machine and slowly extending it until it fractures as shown in figure 3.10 (b).

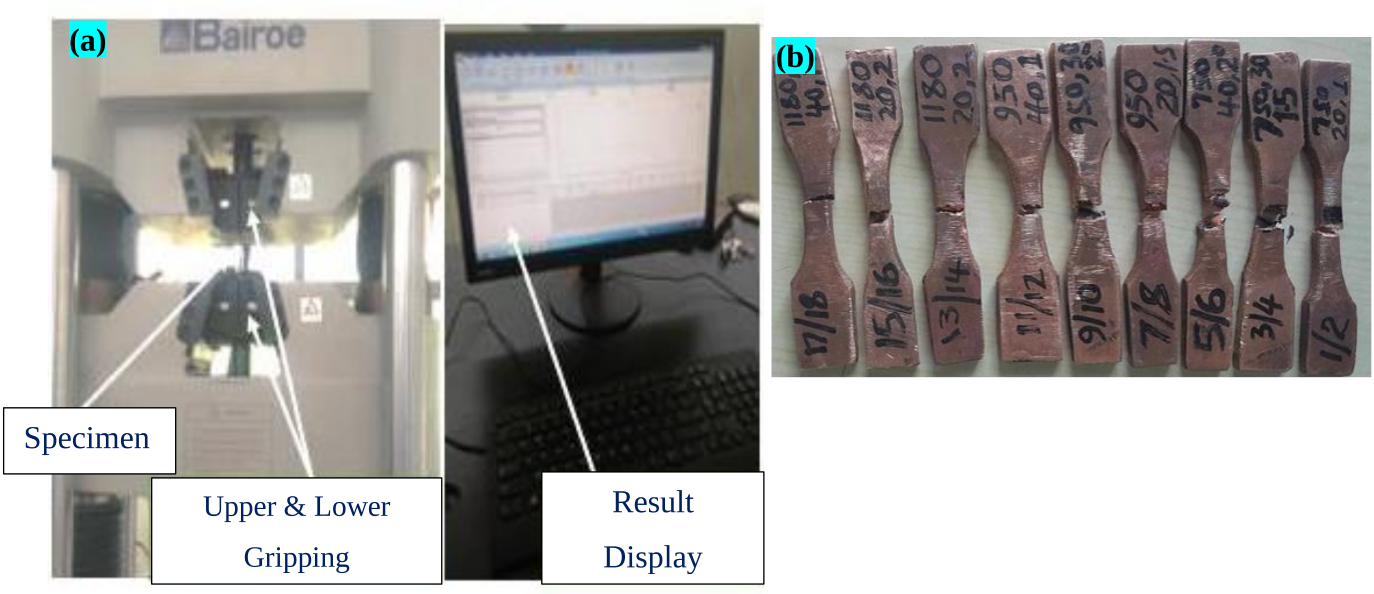


Figure 3.10 (a)Tensile test experimental set-up (at Ethiopian Technical Institute), (b) Specimens after the tensile test

3.4.2.3 Micro-structure and Micro-hardness Testing

The microstructure and micro-hardness of this study were computed at Defense Engineering College, materials lab using the optical microscopy Model: HUVITZ HR-300 series at the material science engineering laboratory.

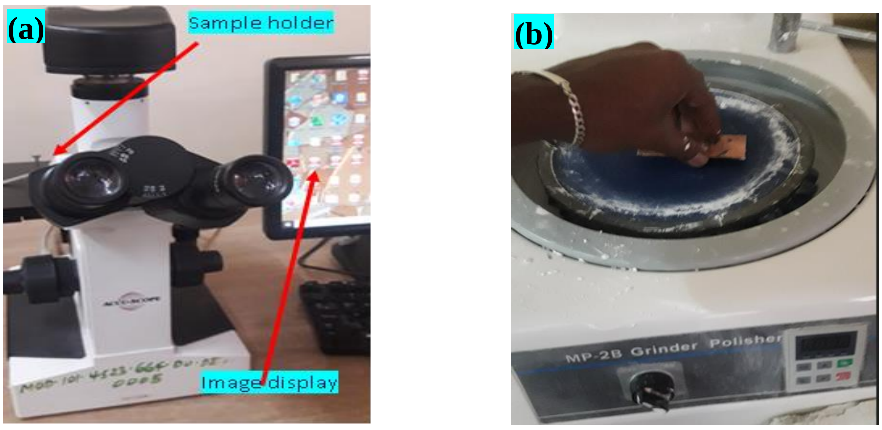


Figure 3-11 (a) Optical microscope and (b) Double disk polisher machine (DEC, Materials engineering laboratory)

For microstructural and micro-hardness testing the samples were sectioned using an abrasive cutter that has a coolant to protect the properties of the metal for testing, rough and fine polishing by using different grades of emery cloth as shown in Figure 3-11. Then the material was going for hot mounting. After mounting the sample then the specimens were ground using silicon carbide grit papers having #120-150-180-240-280-360-400-600-800-1200-2000 respectively. Furthermore, the samples were polished using a diamond suspension polishing agent using the double disk polishing machine as shown in figure 3.10 (b). Finally, the specimens were etched with the etchant solution consisting of cleaning and etching by 100 ml of aqueous solution that contains 5 gm of Ferric chloride, 96 ml of ethyl alcohol, and 2 ml of hydrochloric acid. Then the metallographic test was performed.

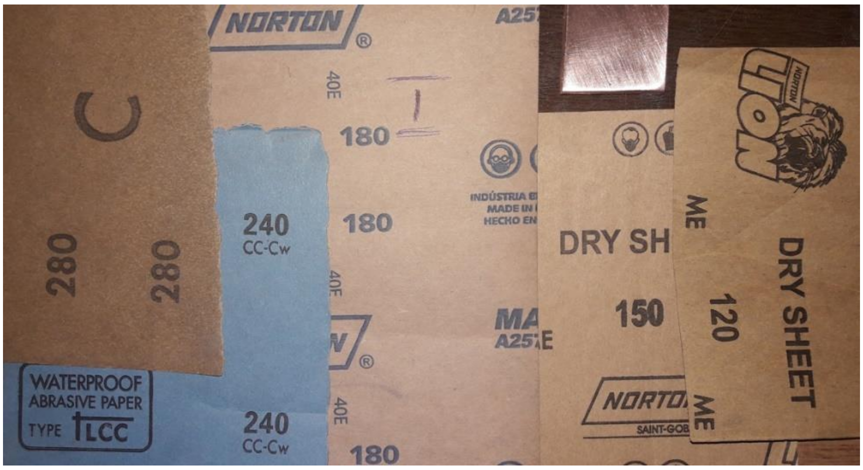


Figure 3-11 Types of silicon carbide grit papers with various grades

Micro-hardness testing using Rockwell hardness tester at the material engineering laboratory (DEC). For each test, a very small diamond indenter having pyramidal geometry is forced into the surface of the specimen. The resulting impression is observed under a microscope and measured; this measurement is then converted into a hardness number (William D. Callister, 2007).

3.5 Taguchi Method

Taguchi's, which is one of the Designs of Experiment (DOE) applications, is used to investigate the effect of a variety of parameters and their behavior by conducting a small number of experiments and evaluating their impact on certain behavior. It can determine the best conditions for the experiment at the same time, resulting in a superior outcome. According to Taguchi, there are three primary phases: planning, conducting, and analysis (Krishnaiah & Shahabudeen, 2012).

Three parameters will be evaluated in this process: tool rotational speed, welding speed, and tool tilt angle. The use of an orthogonal array is determined by the total degrees of freedom of the process parameters in the Taguchi DOE concept. The number of comparisons required to optimize each parameter (factor) with the selected levels is accounted for or defined as the degree of freedom. With three components and three levels of the experiment, Minitab 16 statistical software is used to develop the experimental design of process parameters and numerical analysis.

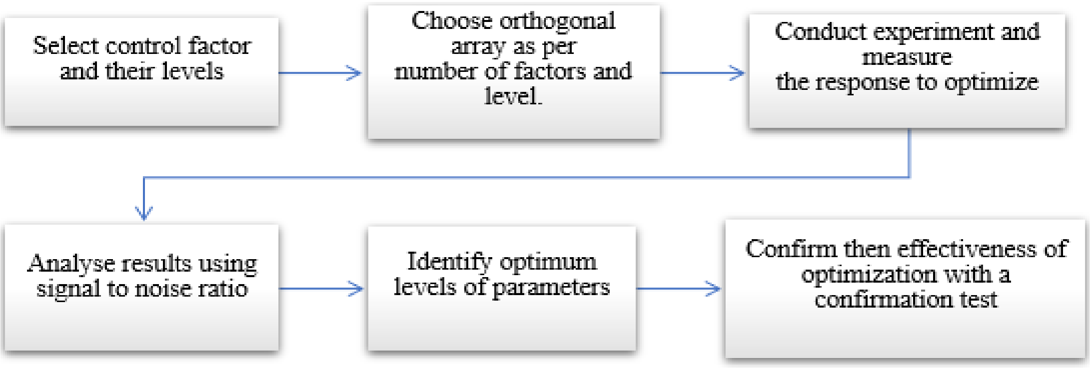


Figure 3-12 Design procedure of Taguchi methods

3.5.1 Orthogonal Array (OA)

Before choosing the orthogonal array, estimate the minimum number of experiments to execute based on the total number of degrees of freedom. The total degrees of freedom provided must be more than the number of experiments required to study the factors (Krishnaiah & Shahabudeen, 2012).

In this study, the number of layers of various factors was used to identify which orthogonal array to use. Three factors were chosen for the experiments, each having three levels.

$$DOF = P^* (L-1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1a)$$

Where, DOF= degree of freedom, P = number of factors and, L = number of levels.

DOF = 3(3– 1) = 6 (OA $\geq$ DOF, therefore OA has 9 experimental runs)

After calculating the Degree of Freedom (DOF), the number of experimental runs was chosen from an orthogonal array. The total number of orthogonal array (OA) experiments should be larger than or equal to the computed value, hence the L9 orthogonal array was chosen for the experiment design. This setup allows the testing of all three variables without having to run $27 = 3^3$. Nine different samples were manufactured with different parameters and at different levels. In the Taguchi method the response variation was studied using signal-to-noise ratio and minimizing by optimizing the responses parameter. The smaller is the better S/N ratio used for these responses.

3.5.2 Signal to noise ratio (S/N ratio)

The Taguchi technique emphasizes the value of evaluating response variation using the signal-to-noise ratio, which reduces the effect of uncontrollable parameter variation on quality characteristics. The desired value (mean) for the output characteristic is referred to as signal, while the undesired value (deviation, SD) is referred to as noise in the Taguchi method. As a result, the S / N ratio equals the average to SD ratio. Taguchi used the S / N ratio to assess the quality attribute that deviates from the desired value. There are numerous S / N ratios available depending on the type of characteristic; smaller is better, nominal is best, and larger is best (Karna & Sahai, 2012; Ross, 1996).

a) Larger the better (Maximization)
b) Smaller the better (Minimization)
c) Nominal the best

Taguchi method uses the S/N ratio to measure the deviation of the quality characteristic from the preferred value. The signal-to-noise ratio measures the sensitivity of the quality investigated to those uncontrollable factors (errors) in the experiment. A higher value of the S/N ratio is always desirable because a greater S/N ratio will result in less product variance around the target value. To perform S/N ratio analysis, mean square deviations (MSD) for the larger-the-better quality characteristic and S/N ratio were calculated from the following equation (3.1) and Equation (3.2).

$$\text{MSD} = \frac{1}{n}\sum_{i=0}^{n}\left(\frac{1}{yi^2}\right) \qquad (3.1)$$

Where *MSD* is mean square deviation; *n* is responses in the factor level combination and y_i is a particular mechanical property for i^{th} replicating the experiment.

For this thesis work, the objective is to maximize the quality of friction stir weld joint of 5mm thick copper plate depending on tensile strength and hardness of weld joints through optimum FSW process parameters, larger is better characteristic is used. The formula used for computing the S/N ratio is given in equation (3.2) below: The formula for the larger-is-better S/N ratio using base 10log is:

$$\frac{S}{N}\textbf{ Ratio }(\eta) = -10Log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{yi^2}\right)\right) = -Log_{10}(MSD) \quad (3.2)$$

Where *y* is responses for the given factor level combination and *n* is the number of responses in the factor level combination.

3.6 Single Objective Optimization Technique

These two quality characteristics such as tensile strength and hardness of friction stir welded joints were optimized individually through the Taguchi technique by using Minitab statistical software. In which S/N ratio; means and ANOVA table for both quality characteristics were analyzed concerning each process parameter which is necessary for the determination of optimized parameters. The higher value of the signal-to-noise ratio and mean values are always desirable (Larger is better) because the greater signal-to-noise ratio and means result in smaller product variance around the target value.

3.6.1 Analysis of Variance (ANOVA)

Minitab statistical software is used to calculate analysis of variance for the inquiry, as well as analysis of a response parameter for several experimental responses. The statistical approach of ANOVA is used to determine the influence of all control values. The percentage contributions of each control factor were utilized to measure the associated impacts on the performance characteristics in the analysis of variance. The significance level was set at 5%, which corresponded to a 95% level of confidence. The following formula was used to obtain the percentage contribution of each influential parameter from the analysis of variance (Krishnaiah & Shahabudeen, 2012). From analysis of variance Percentage contribution of each influential parameter was calculated by the following formula:

$$P\ (\%) = \frac{SSTR}{SST} * 100 \quad (3.3)$$

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

Analysis of variance (ANOVA) of the overall grade is done to show the significant parameters. If the P value for a factor becomes less than 0.05 then that factor is considered a significant factor at a 95% confidence level. In this thesis, ANOVA is done on MINITAB 22 software.

CHAPTER-4

RESULTS AND DISCUSSIONS

4.1 Introduction

During the friction stir welding process (FSW process), the effect of FSW process parameters on mechanical properties, welding joint shape, and microstructural properties of copper plate was investigated. The experimental data analysis is done based on two main quality factors; in which the first is the experimental data analysis for tensile strength values and the second is the experimental data analysis for hardness values. After the FSW welding process was completed, the FSW welded samples were gone through destructive testing, and the reaction parameters were measured. The outcome results for each experiment were discussed in this chapter in detail. The response results from an orthogonal array of experimental investigations were analyzed using Taguchi methods to identify the initial optimum process parameters of the FSW welding, and the most influential welding parameters on tensile strength, and hardness in graphical representation for the butt-welded joints of copper plate were identified by analysis of variance (ANOVA). The initial optimum parametric setting from Taguchi methods was used for Confidence Interval (CI) calculation for both tensile strength and hardness values.

4.2 Mechanical Properties of Welded Joints

The study focused on the investigation and parametric optimization of FSW welding settings when employing the Taguchi L9 orthogonal array to butt jointed welds of 5mm copper plates. Here under this topic, the effect of the process parameters on mechanical properties and its microstructure has been analyzed. Next, the response parameters from the test will be analyzed using the Taguchi technique, and the percentage contribution of parameters was identified using analysis of variance (ANOVA). Finally, the parameters are optimized to the optimum parametric setting using a single objective optimization technique. The FSW welding control parameters and levels utilized during FSW welding of copper plates are shown in table 4.1 below.

Table 4.1 Selected Process parameters and levels

S. No	Process parameter	Units	Levels		
			1	2	3
1	Tool Rotational Speed	rpm	750	950	1180
2	Tool traverse Speed	mm/min	20	30	40

3	Tool tilt angle	degrees (°)	1	1.5	2

4.2.1 Tensile Strength Result Analysis of Welded Joints

Tensile strength data were collected using a universal testing machine. The larger the performance qualities, the better the tensile strength (larger is the better). The tensile strength of the FSW copper joint is taken as the output characteristic as shown in Figure 4.2. To perform S/N ratio analysis, the mean square deviation (*MSD*) for the "the-larger-the-better" quality characteristic and S/N ratio is calculated by using by Equations (3.1) and Equation **(**3.2).

Table 4.2 Experimental result for Tensile strength

Experimental Run		**Process Parameters**			**Response Factor**	
Sample Code	Sample No.	Rotational speed (A)	Transverse speed (B)	Tool Tilt Angle (C)	Mean tensile strength (MPa)	Signal to noise ratio
E_1	1 & 2	750	20	1	112.29	41.0068
E_2	3 & 4	750	30	1.5	118.33	41.4618
E_3	5 & 6	750	40	2	123.42	41.8277
E_4	7 & 8	950	20	1.5	124.85	41.9277
E_5	9 & 10	950	30	2	116.86	41.3533
E_6	11 & 12	950	40	1	112.20	40.9998
E_7	13 & 14	1180	20	2	130.21	42.2928
E_8	15 & 16	1180	30	1	119.08	41.5167
E_9	17 & 18	1180	40	1.5	125.87	41.9984

From the calculated Signal-to-Noise ratio values the larger value equal to 42.2928, which is obtained at sample code E_7, is performed by a square tool pin with a higher tool rotational speed of 1180rpm, lower weld speed of 20mm/min, and with a higher values of tool tilt angle equal to 2 degrees. This experimental result for tensile strength and the calculated S/N ratios were similar to other studies as shown in the literatures reviews.

4.2.1.1 Mean Response Analysis for Tensile Strength

For every response characteristic, including mean and signal-to-noise ratio, a response table is computed. As indicated by equation (3-2), the response table can display which factors have the greatest influence on the response as well as the degree to which a given factor is linked to higher or lower response characteristic values. The following are the steps involved in making a response table:

1. Determine the selected response characteristic for the welding speed, tool tilt angle, and tool rotating speed at each level.
2. The disparities between the highest average response characteristic value and the lowest average response characteristic value for levels of that factor are then calculated to determine the delta values.
3. Rankings are assigned using the delta values, ranging from high to low. At the top of the ranking is the factor with the highest delta value.

It is crucial to determine the ranks and levels of means for each impacts process parameter mean calculation. Once the experimental test of mean values is calculated for each factor, level, and range (delta). Following are computations, delta = high UTS – low UTS ratio for each parameter is determined.

✓ **For Tool Rotational Speed,** the mean tensile strength was calculated as:

Level 1: Rotational Speed $= \frac{E1+E2+E3}{3} = \frac{112.29 + 118.33 + 123.42}{3} = 118.013.$

Level 2: Rotational Speed $= \frac{E4+E5+E6}{3} = \frac{124.85 + 116.86 + 112.20}{3} = 117.970$, Minimum.

Level 3: Rotational Speed $= \frac{E7+E8+E9}{3} = \frac{130.21 + 119.08 + 125.87}{3} = 125.0533$, Maximum.

Delta = Max. value – Min. Value = 125.0533– 117.970 = **7.0833.**

✓ **For Tool Traverse Speed**

Level 1: Weld Speed $= \frac{E1+E4+E7}{3} = \frac{112.29 + 124.85 + 130.21}{3} = 122.45$, Maximum.

Level 2: Weld Speed $= \frac{E2+E5+E8}{3} = \frac{118.33 + 116.86 + 119.08}{3} = 118.09$, Minimum

Level 3: Weld Speed $= \frac{E3+E6+E9}{3} = \frac{123.42 + 112.20 + 125.87}{3} = 120.4967.$

Delta = Max. value – Min. Value = 122.45 – 118.09 = **4.36.**

✓ **For Tool Tilt Angle**

Level 1: Degree $= \frac{E1+E6+E8}{3} = \frac{112.29 + 112.20 + 119.08}{3} = 111.523$, Minimum.

Level 2: Degree $= \frac{E2+E4+E9}{3} = \frac{118.33 + 124.85 + 125.87}{3} = 119.0167.$

Level 3: Degree $= \frac{E3+E5+E7}{3} = \frac{123.42 + 116.86 + 130.21}{3} = 123.4967$, Maximum.

Delta = Max. value – Min. Value = 123.497- 111.523 = **11.973.**

Table 4.3 Response Table for Means of tensile strength

Level	Process parameters		
	Tool rotational Speed (A)	Tool Traverse Speed (B)	Tool Tilt Angle (C)
1	118.0133	**122.450**	114.5233
2	117.970	118.090	123.0167
3	**125.0533**	120.4967	**123.4970**
Delta	7.0833	4.36	8.9734
Rank	**2**	**3**	**1**

Table (4.3) shows that tool tilting angle (C) has the highest value and is rated first, tool rotational speed (A) is ranked second, and tool traverse speed (B) has the lowest value when compared to other process parameters and is ranked third by Taguchi (means) analysis. These FSW welding settings **(A3B1C3**) were chosen for FSW welding of copper plate with a thickness of 5mm as the initial optimum process parametric setting.

Figure 4.1 shows the main effect plot for control factors for means of tensile strength value variations. The numerical value at the largest point in each graph of means of tensile strength represents the parameter's best value at that level. They also show the ideal conditions within the experimental conditions' range. When compared to other FSW welding factors, the tool tilt angle weight percentage is the most effective at increasing tensile strength, while the welding speed has the least effect. The Taguchi initial optimum process parameters setting was tool tilt angle at the third level (2 degree), tool rotational speed at the third level (1180 rpm), and tool traverse speed at the first level (20 mm/min).

Figure 4.1 Main effect plot for Means

4.2.1.2 Signal-to-Noise Ratio Analysis for Tensile Strength

Taguchi evaluated the quality attribute that differed from the desired value using the S/N ratio. As a result, the larger the tensile strength, the better the quality (Moera et al., 2022). To identify levels and ranks for means for each effects process parameter mean calculation is very important. Once the experimental test of mean values is calculated for each factor, level, and range (delta). ***Delta = high S/N ratio – low S/N ratio*** for each parameter is calculated after the following calculations.

- ✓ **For Tool Rotational Speed,** the S/N ratios was calculated as:

$$\text{Level 1: Rotational Speed } = \frac{E1+E2+E3}{3} = \frac{41.0068 + 41.4618 + 41.8277}{3} = 41.4321$$

$$\text{Level 2: Rotational Speed } = \frac{E4+E5+E6}{3} = \frac{41.9277 + 41.3533 + 40.9998}{3} = 41.4269\text{, Minimum.}$$

$$\text{Level 3: Rotational Speed } = \frac{E7+E8+E9}{3} = \frac{42.2928+41.5167+41.9984}{3} = 41.9359\text{, Maximum.}$$

Delta = Max. value – Min. Value = 41.9359– 41.4269 = **0.509.**

- ✓ **For Tool Traverse Speed**

$$\text{Level 1: Weld Speed } = \frac{E1+E4+E7}{3} = \frac{41.0068+41.9277+42.2928}{3} = 41.7424\text{, Maximum.}$$

$$\text{Level 2: Weld Speed } = \frac{E2+E5+E8}{3} = \frac{41.4618+41.3533+41.5167}{3} = 41.4439\text{, Minimum.}$$

Level 3: Weld Speed $= \frac{E3+E6+E9}{3} = \frac{41.8277+40.9998+41.9984}{3} = 41.6086.$

Delta = Max. value – Min. Value = 41.7424 – 41.4439 = **0.2985.**

✓ **For Tool Tilt Angle**

Level 1: Degree $= \frac{E1+E6+E8}{3} = \frac{41.0068+40.9998+41.5167}{3} = 41.1744, \text{Minimum}.$

Level 2: Degree $= \frac{E2+E4+E9}{3} = \frac{41.4618+41.9277+41.9984}{3} = 41.7959.$

Level 3: Degree $= \frac{E3+E5+E7}{3} = \frac{41.8218+41.3533+42.2928}{3} = 41.8246$, Maximum.

Delta = Max. value – Min. Value = 41.8246 – 41.1744 = **0.6502.**

Table 4.4 Response Table for Signal-to-Noise Ratios (Larger is better) of tensile strength

Level	Process parameters		
	Tool rotational Speed (A)	Tool Traverse Speed (B)	Tool Tilt Angle (C)
1	41.4321	**41.7424**	41.1744
2	41.4269	41.4439	41.7959
3	**41.9359**	41.6086	**41.8246**
Delta	0.509	0.2985	0.6502
Rank	**2**	**3**	**1**

Table 4.4 shows that the tool tilt angle has the biggest effect (Delta = 0.6502, rank = 1^{st}) followed by tool rotational speed (Delta = 0.509, rank = 2^{nd}), and tool traverse speed (Delta = 0.2985, rank = 3^{rd}) has the smallest effect on the (S/N) ratio. To get a higher tensile strength value, the controlling of tilt angle will be the first essential work as shown by the signal-to-noise ratio. According to the experimental result, the initial best parameter combination for increasing welded metal stiffness with the greater the better responsiveness of FSW welded copper plate is **A3B1C3**.

From Figure 4.2 the optimum level of FSW process parameters is obtained at rotational speed of 1180 rpm, welding speed of 20 mm/min and Tool tilt angle of 2°. From the analysis it's also set up that tool tilt angle is the utmost impacting parameter for tensile strength followed by rotational speed and welding speed

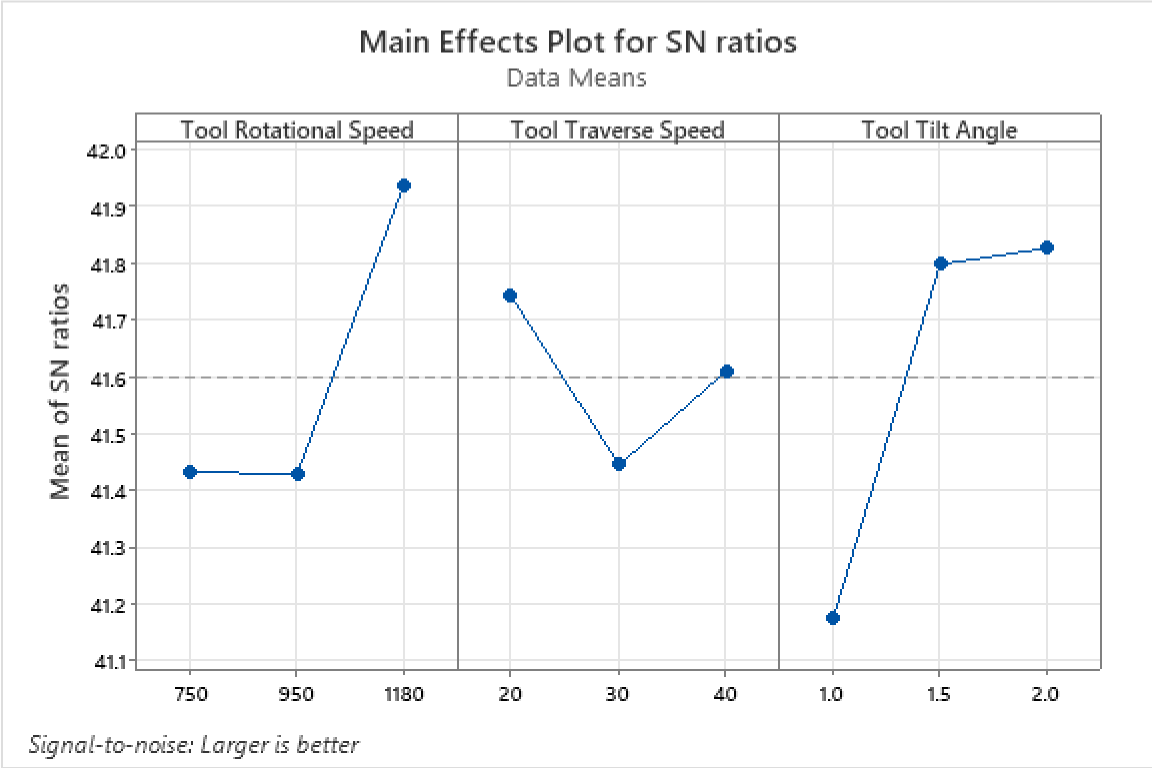


Figure 4.2 Main effect plot for S/N ratio of Tensile strength

4.2.1.3 Effect of FSW Process Parameters on Tensile Strength

Figure 4.2 shows how FSW process parameters affect FSW butt weld joint tensile strength, as well as the ideal values for each factor depending on their ranking. The optimal values for enhancing tensile strength, according to the analysis and primary effect plot graph for SN ratios, are tool tilt angle at level 3 (2 degree), the tool rotational speed at level 3 (1180 rpm), and tool traverse speed at level 1 (20 mm/min), with an initial process parametric setting of **A3B1C3**.

The tensile strength increases dramatically as the tool tilt angle increase from level one to level three, as shown in the graph below. The tensile strength increases drastically as the tool rotational speed is increased from level one to level three. However, as the tool traverse speed is increased from level one to level three, the material's tensile characteristics decrease slightly.

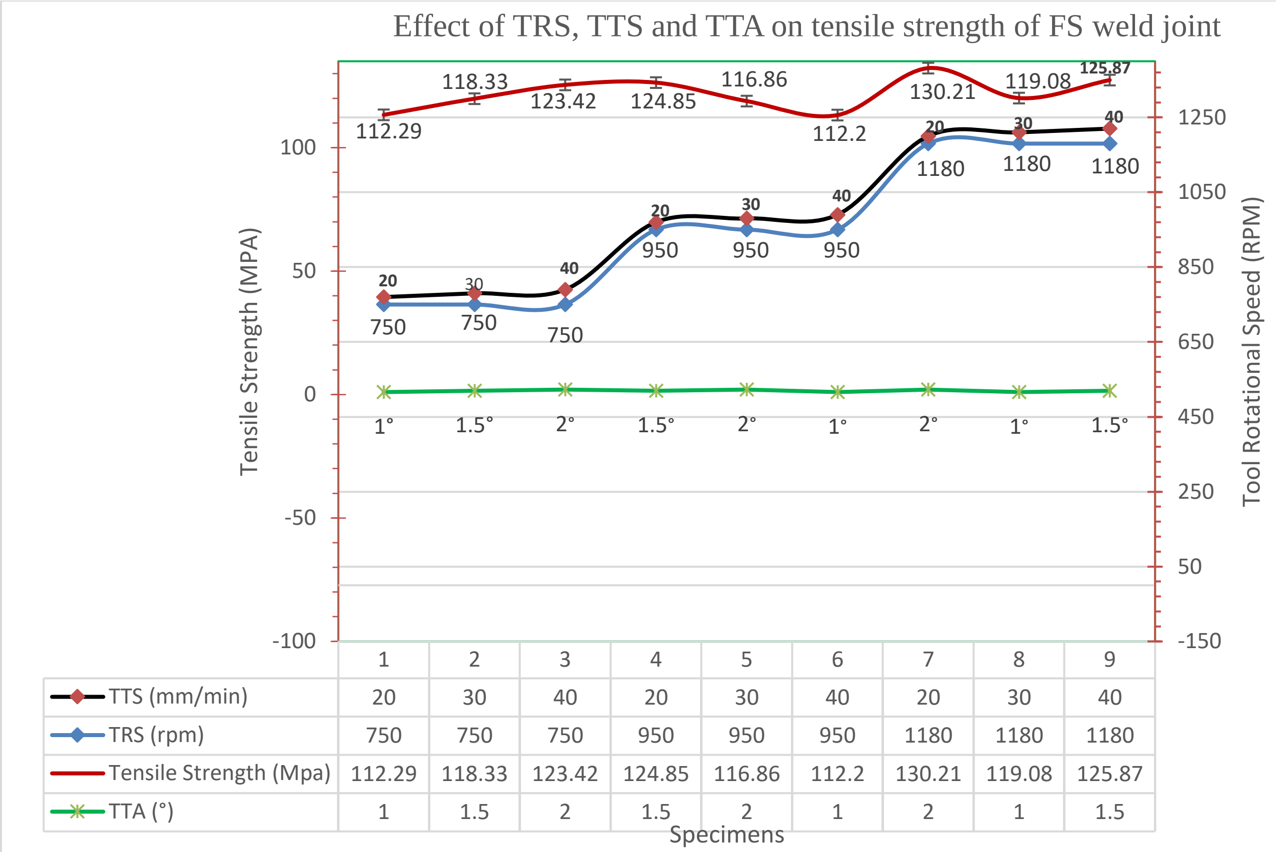


Figure 4.3 Effects of TRS, TTS and TTA on tensile strength of the FS weld joint

4.2.1.4 Analysis of Variance (ANOVA) for tensile strength

The most relevant characteristics (most significant parameters) that impact the tensile strength of FSW-welded copper plate are determined using analysis of variance (ANOVA), as shown in table 4.5. The S/N ratios of each component were used to compute their percentage contribution.

From the result of the ANOVA for tensile strength, the tool tilt angle shows a greater contribution of 42.37%, the tool rotational speed shows a 35.08% contribution, and the tool traverse speed has the lowest contribution of 17.08%. Here, the residual error was found to be 5.47%. The analysis of variance result for tensile strength is shown in Table 4.5 below.

Table 4.4 Analysis of Variance for S/N ratios

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
TRS	2	0.6610	35.08%	0.6610	0.33051	6.41	0.135
TTS	2	0.3217	17.08%	0.3217	0.16087	3.12	0.243
TTA	2	0.7984	42.37%	0.7984	0.39922	7.75	0.114
Error	2	0.1031	5.47%	0.1031	0.05154		
Total	8	1.8843	100.00%				

S = 0.231632%, **R-Sq** = 94.37%, **R-Sq(adj)** = 77.47%

Note: DF- Degrees of Freedom, Seq SS – Sequential Sum of Squares, Adj SS – Adjusted Sum of Squares, Adj MS – Adjusted Mean Square, F test of hypothesis, P value of hypothesis.

Additionally, when seeing the percentage contribution of each parameter, the tool tilt angle (42.37%) and tool rotational speed (35.08%) have a highly significant impact, while tool traverse speed (17.08%) has the least significant impact on the tensile strength of FS welded copper plate joints, as shown in figures 4.4 below.

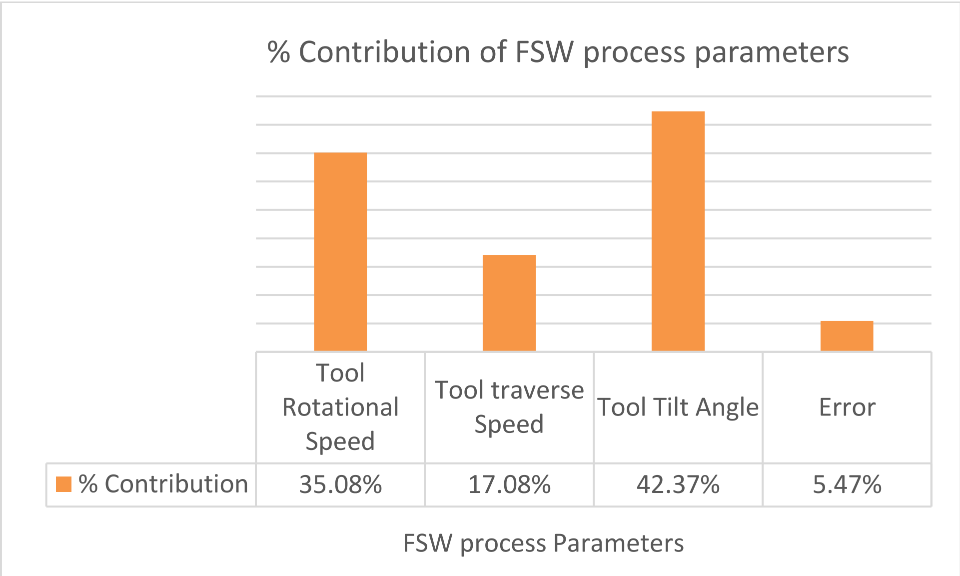


Figure 4.4 Percentage contribution of FSW process parameters on tensile strength

Table 4.5 Optimized weld tensile strength result obtained from ANOVA-Minitab statistical software

Taguchi Method			
Rotational speed (A)	Travel Speed (B)	Tool tilt angle (C)	UTS
1180 rpm	20 mm/min	2°	129.489 MPa

The predicted value of the tensile strength of the friction stir-welded joint for the optimum process parameter was calculated by using regression equation 4.3 obtained from Minitab software during the Taguchi analysis of the tensile strength of the friction stir-welded joints of copper plates.

Tensile strength = 93.7544 + 0.0167304 A - 0.0976667 B + 8.97333C...4.3

By using regression equation 4.3 obtained from the transformed response of tensile strength from Taguchi analysis, the predicted tensile strength of friction stir-welded joints was 129.489 MPa. The confirmed experimental value of the tensile strength of friction stirs welded joints obtained from this study at optimum process parameters was 130.21 MPa. The percent of error between the predicted and experimental values of this thesis work was 0.553%, which is less than 1%. The amount of error that is acceptable depends on the experiment, but for the agreement of many researchers, a margin error of 10% is generally considered acceptable error.

4.2.2 Hardness Test Result Analysis of FSW Copper Butt Joint

Rockwell and Vickers's hardness can be used to determine the material's hardness. From the weld center to HAZ and WZ, the specimens are tested with each test performed from the base metal, HAZ, and the weld zone, each at 3mm from the weld zone's centre. In each zone, three readings were recorded, and the average value was taken. For each trial experiment, Table 4.7 presents the measured average experimental results of hardness values. Larger hardness was projected to be the preferable option for better performance qualities (larger is better). Table 4.7 shows experimental data of the average hardness value of the samples of friction stir welded joints of the copper plate at HAZ, TMAZ, and SZ taken from both advancing and retracting sides based on the given process parameter.

4.2.2.1 Mean Response Analysis for Hardness of FSW Welded Joints

Tool rotational speed (A) at the third level has the higher value and is ranked first, followed by tool traverse speed (C) at the third level with a higher value, and tool tilt angle (C) at the second level with a medium value, which is ranked third, as revealed in tables 4.8. For FSW welding of copper plates with a thickness of 5mm, these welding settings (A3B3C2) were chosen as the initial parametric setting. For means of hardness value fluctuations, the main influence plot for control parameters is shown in Figures 4.5.

Table 4.6 Mean Experimental Data of hardness testing results of FSW weld joints

Sample code	Process Parameters			Average Hardness of joint weld (HRB)			
	TRS (A) (rpm)	TTS (B) (mm/min)	TTA (C) (degree)	HAZ Average	TMAZ Average	SZ Average	Mean
E_1	750	20	1.0	81.90	77.25	75.50	78.23
E_2	750	30	1.5	82.04	76.70	74.50	77.75
E_3	750	40	2.0	81.50	76.60	73.50	77.20
E_4	950	20	1.5	83.60	79.55	83.00	82.05
E_5	950	30	2.0	83.95	79.50	78.50	80.65
E_6	950	40	1.0	84.70	78.25	76.00	79.65

E_7	1180	20	2.0	85.05	82.45	79.90	82.47
E_8	1180	30	1.0	86.85	84.20	81.50	84.18
E_9	1180	40	1.5	87.10	84.35	88.50	86.65

Table 4.7 Response Table for Means of the Hardness at FSW welded joint zones

Welded Zones	Process Parameters			
	Levels	Tool Rotational Speed (A)	Tool Traverse Speed (B)	Tool Tilt Angle (C)
Heat affected Zone (HAZ)	1	81.81	84.20	84.18
	2	84.08	83.75	83.56
	3	**86.33**	**84.28**	**84.48**
	Delta	4.52	0.53	0.92
	Rank	**1**	**3**	**2**
Thermo-mechanical affected zone (TMAZ)	1	76.85	79.10	79.90
	2	79.10	80.13	**80.15**
	3	**83.67**	**80.38**	79.57
	Delta	6.82	1.28	0.58
	Rank	**1**	**2**	**3**
Stir zone (SZ)	1	74.50	76.47	77.67
	2	79.17	78.17	**80.17**
	3	**83.30**	**82.33**	79.13
	Delta	8.80	5.87	2.50
	Rank	**1**	**2**	**3**
Mean	1	76.08	77.97	79.07
	2	79.00	77.12	**79.63**
	3	**82.32**	**82.31**	78.69
	Delta	6.24	5.19	0.94
	Rank	**1**	**2**	**3**

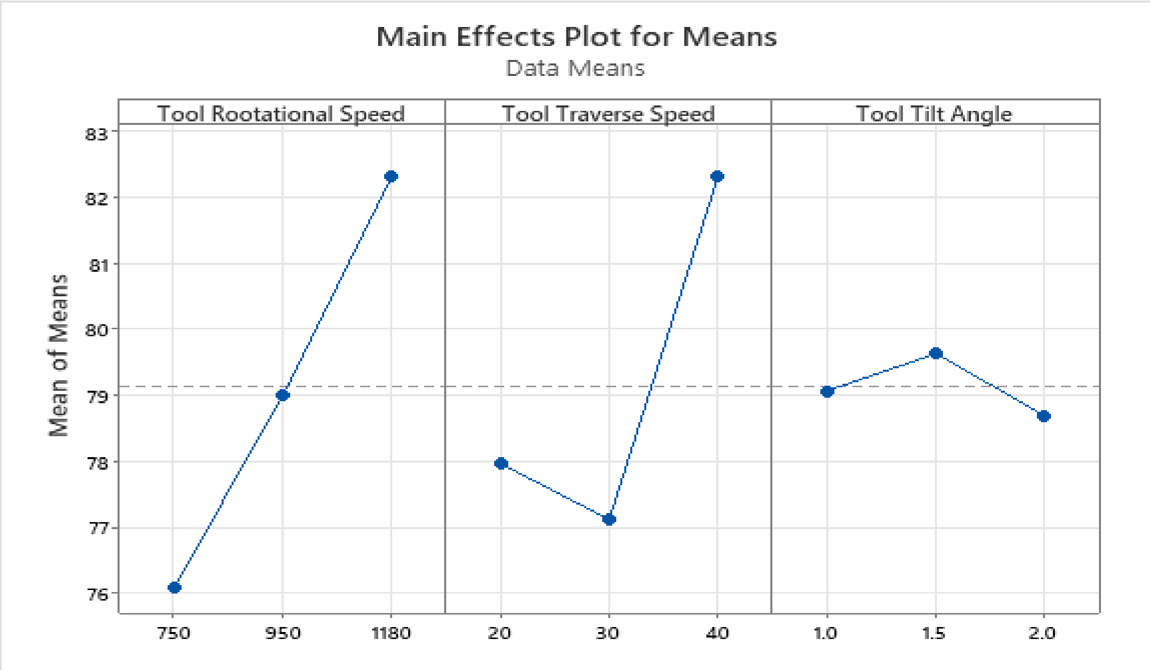


Figure 4.5 Main effect plot for means of mean hardness of FSW welded joint

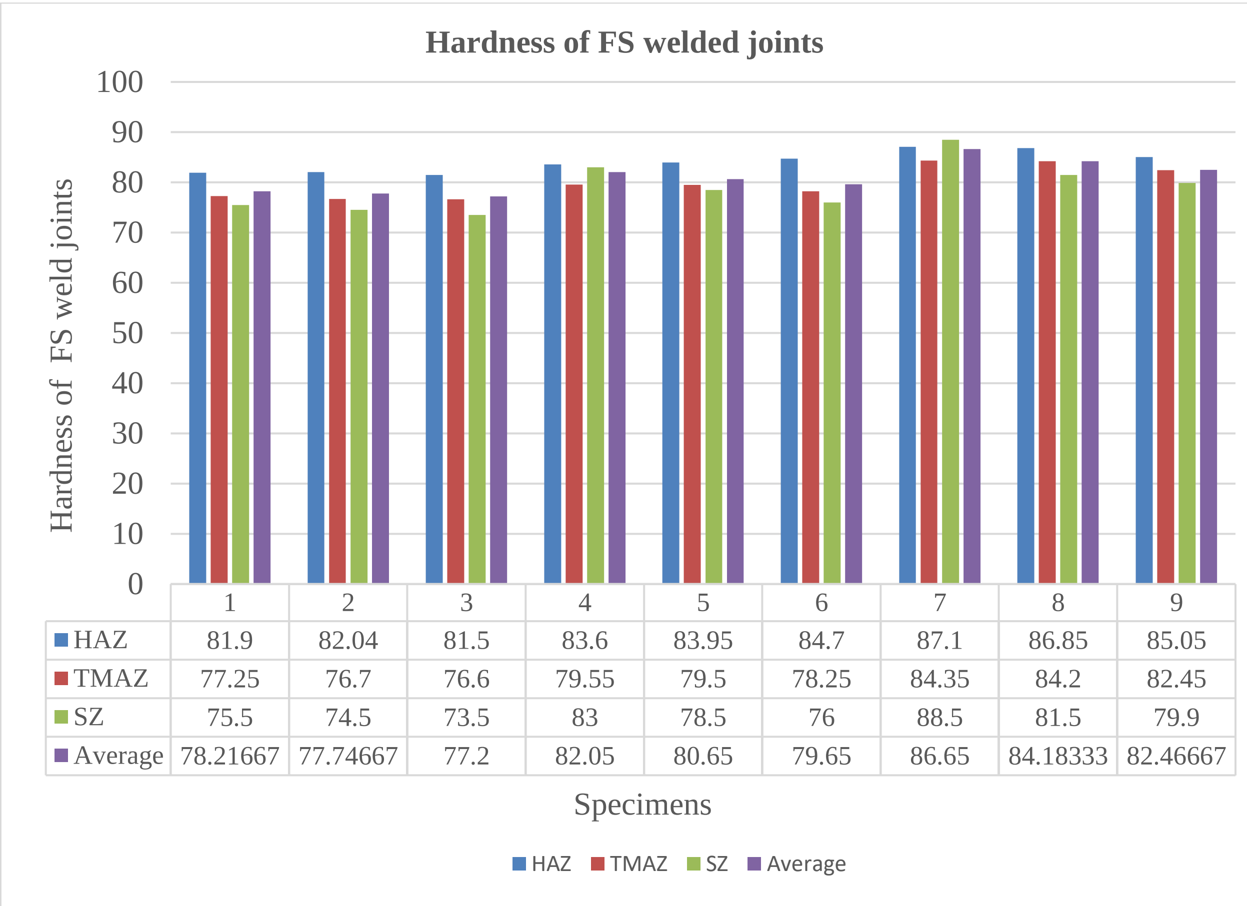


Figure 4.6 Hardness value of HAZ, TMAZ, SZ and Average

4.2.2.2 Signal-to-Noise Ratio Analysis for Hardness of FSW weld joint

Table 4.8 The S/N ratio of hardness at HAZ with process parameters

Sample code	Process Parameters			Response Factors	
	TRS (A) (rpm)	TTS (B) (mm/min)	TTA (C) (degree)	HAZ Average	S/N ratio
E_1	750	20	1.0	81.90	38.2657
E_2	750	30	1.5	82.04	38.2805
E_3	750	40	2.0	81.50	38.2232
E_4	950	20	1.5	83.60	38.4441
E_5	950	30	2.0	83.95	38.4804
E_6	950	40	1.0	84.70	38.5577
E_7	1180	20	2.0	85.05	38.5935
E_8	1180	30	1.0	86.85	38.7754
E_9	1180	40	1.5	87.10	38.8004

Table 4.9 The S/N ratio of hardness at TMAZ with process parameters

Sample code	Process Parameters			Response Factors	
	TRS (A) (rpm)	TTS (B) (mm/min)	TTA (C) (degree)	TMAZ Average	S/N ratio
E_1	750	20	1.0	77.25	37.7580
E_2	750	30	1.5	76.70	37.6959
E_3	750	40	2.0	76.60	37.6846
E_4	950	20	1.5	79.55	38.0128
E_5	950	30	2.0	79.50	38.0073
E_6	950	40	1.0	78.25	37.8697
E_7	1180	20	2.0	84.35	38.5217
E_8	1180	30	1.0	84.20	38.5062
E_9	1180	40	1.5	82.45	38.3238

Table 4.10 The S/N ratio of hardness at SZ with process parameters

Sample code	Process Parameters			Response Factors	
	TRS (A) (rpm)	TTS (B) (mm/min)	TTA (C) (degree)	SZ average	S/N ratio

E_1	750	20	1.0	75.50	37.5589
E_2	750	30	1.5	74.50	37.4431
E_3	750	40	2.0	73.50	37.3257
E_4	950	20	1.5	83.00	38.3816
E_5	950	30	2.0	78.50	37.8974
E_6	950	40	1.0	76.00	37.6163
E_7	1180	20	2.0	88.50	38.9389
E_8	1180	30	1.0	81.50	38.2232
E_9	1180	40	1.5	79.90	38.0509

Table 4.11 The S/N ratio of hardness at Average with process parameters

Sample code	Process Parameters			Response Factors	
	TRS (A) (rpm)	TTS (B) (mm/min)	TTA (C) (degree)	Mean hardness	S/N ratio for Average
E_1	750	20	1.0	78.23	37.8675
E_2	750	30	1.5	77.75	37.8140
E_3	750	40	2.0	77.20	37.7523
E_4	950	20	1.5	82.05	38.2816
E_5	950	30	2.0	80.65	38.1321
E_6	950	40	1.0	79.65	38.0237
E_7	1180	20	2.0	82.47	38.3259
E_8	1180	30	1.0	84.18	38.5042
E_9	1180	40	1.5	86.65	38.7554

Table 4.12 Response Table for S/N ratio of the Hardness at distinct friction stir welded zones

Welded zones	Process Parameters			
	Levels	Tool Rotational Speed (rpm)	Tool Traverse Speed (mm/min)	Tool Tilt Angle (degree)
	1	38.26	38.50	38.44
	2	38.49	38.46	**38.53**

Heat affected zone (HAZ)	3	**38.72**	**38.51**	38.50
	Delta	0.47	0.05	0.09
	Rank	**1**	**3**	**2**
Themo-mechanically affected zone (TMAZ)	1	37.71	37.96	38.04
	2	37.96	38.07	**38.07**
	3	**38.45**	**38.10**	38.01
	Delta	0.74	0.14	0.06
	Rank	**1**	**2**	**3**
Stir Zone (SZ)	1	37.44	37.66	37.80
	2	37.97	37.85	**38.05**
	3	**38.40**	**38.29**	37.96
	Delta	0.96	0.63	0.25
	Rank	**1**	**2**	**3**
Average	1	37.62	37.84	37.95
	2	37.95	37.74	**38.00**
	3	**38.30**	**38.30**	37.92
	Delta	0.68	0.56	0.09
	Rank	**1**	**2**	**3**

4.2.2.3 Effect of FSW Process Parameters on Hardness

Figure 4.7 depicts the effect of FSW process parameters on hardness as well as the ideal values based on their rank. According to the analysis and the primary effect plot graph for SN ratios, the optimal values for maximizing hardness are rotational speed at level 3 (1180 rpm), weld speed at level 3 (40 mm/min), and tool tilt angle at level 2 (1.5 degrees). From the graph below, it can be seen that when the rotational speed rises from level one to level three, the hardness rises dramatically. The harder the metal was at level four, the harder it was, as shown by L. S. Kumar et al. (2011). For the second influential process parameter, the hardness of the material diminishes as the weld speed drops from level one to level two. However, as the weld speed rate rises from level two to level three, the hardness rises as well. The tool tilt angle was the third influential parameter; as the tilt angle increased from level one to level two, the hardness increased from a lower value to a higher value. The hardness returns to fall down as the tilt angle goes from level two to level three.

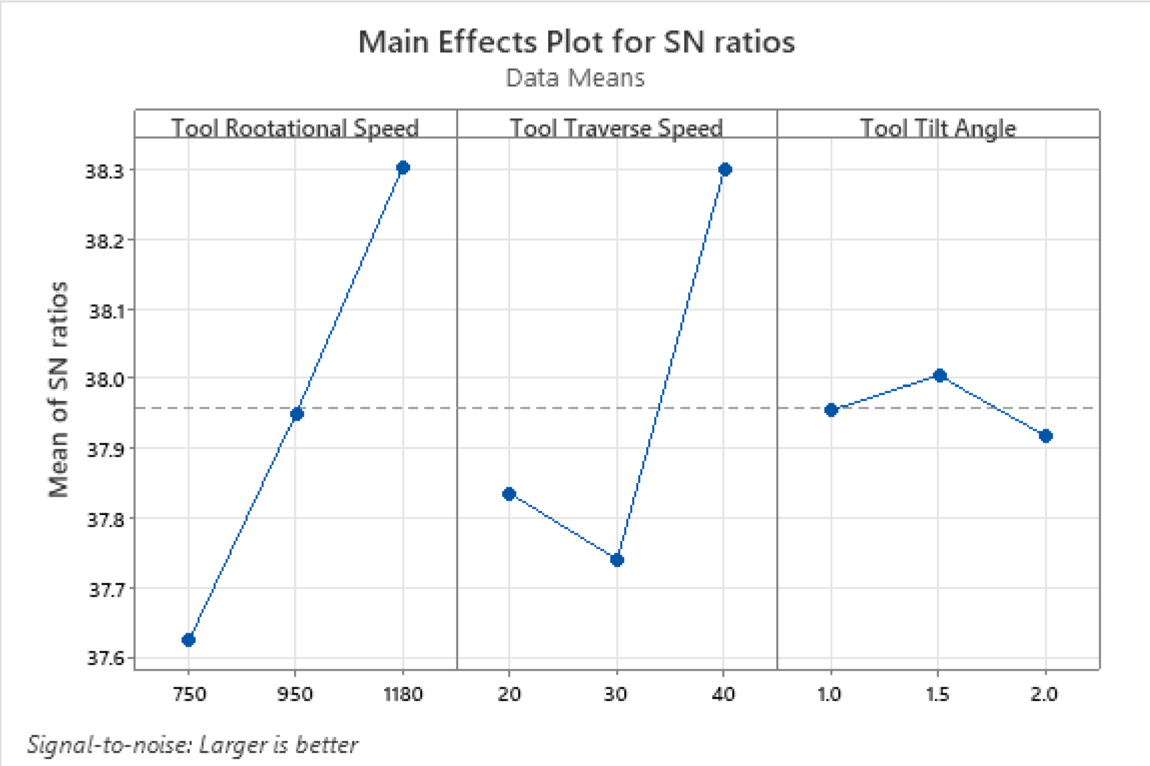
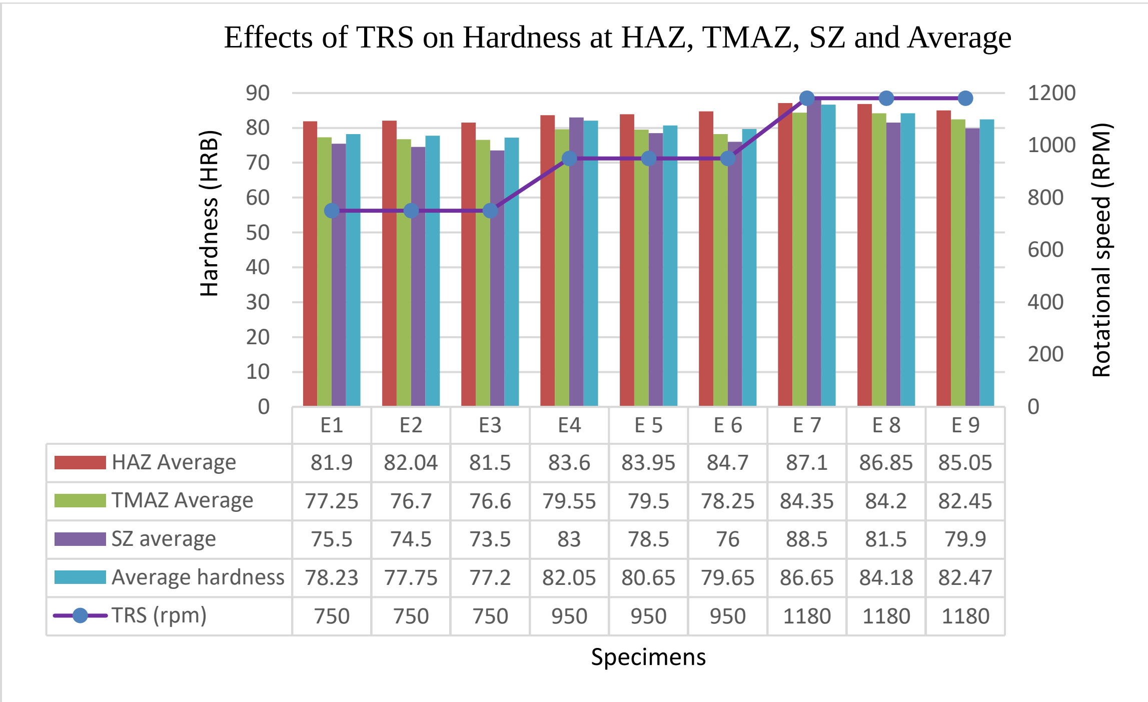


Figure: 4.7 Main Effect plot for S/N ratio for process parameters on the hardness of FS welded joints



	E1	E2	E3	E4	E 5	E 6	E 7	E 8	E 9
HAZ Average	81.9	82.04	81.5	83.6	83.95	84.7	87.1	86.85	85.05
TMAZ Average	77.25	76.7	76.6	79.55	79.5	78.25	84.35	84.2	82.45
SZ average	75.5	74.5	73.5	83	78.5	76	88.5	81.5	79.9
Average hardness	78.23	77.75	77.2	82.05	80.65	79.65	86.65	84.18	82.47
TRS (rpm)	750	750	750	950	950	950	1180	1180	1180

Figure 4.8 Effects of TRS on hardness at HAZ, TMAZ, SZ and Average

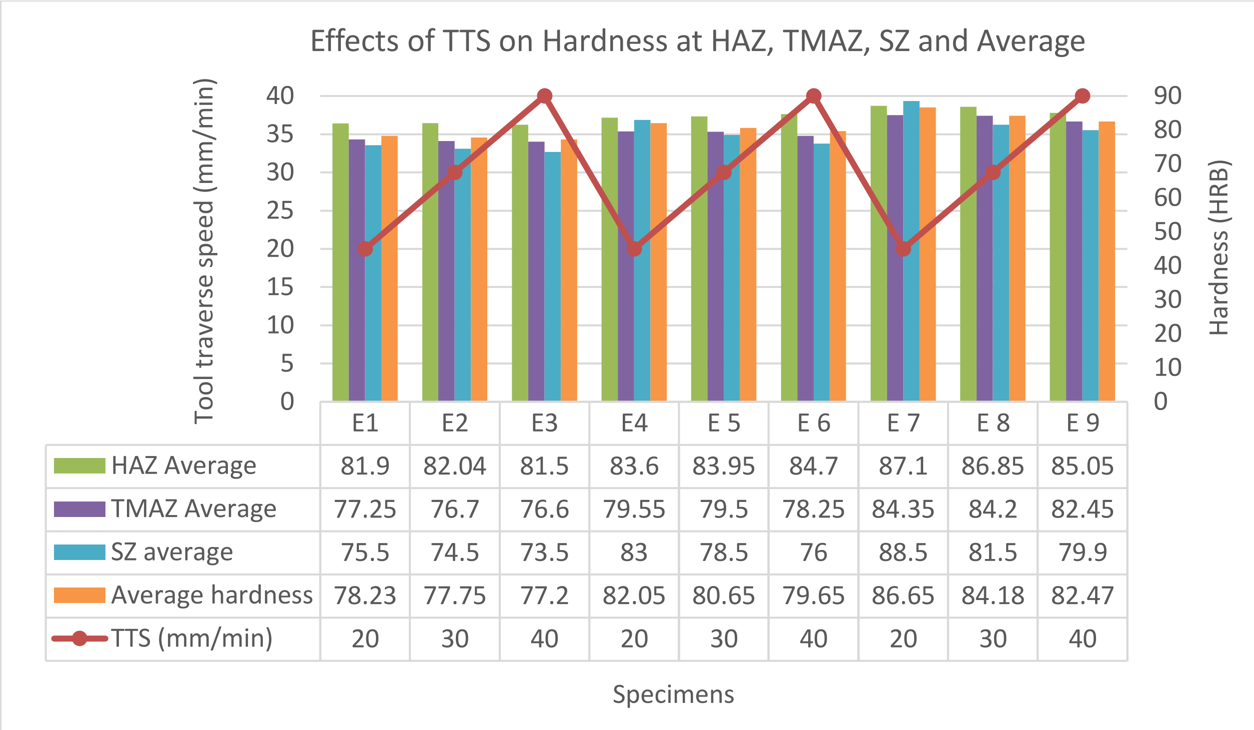


Figure 4.9 Effects of TTS on Hardness at HAZ, TMAZ, SZ and Average

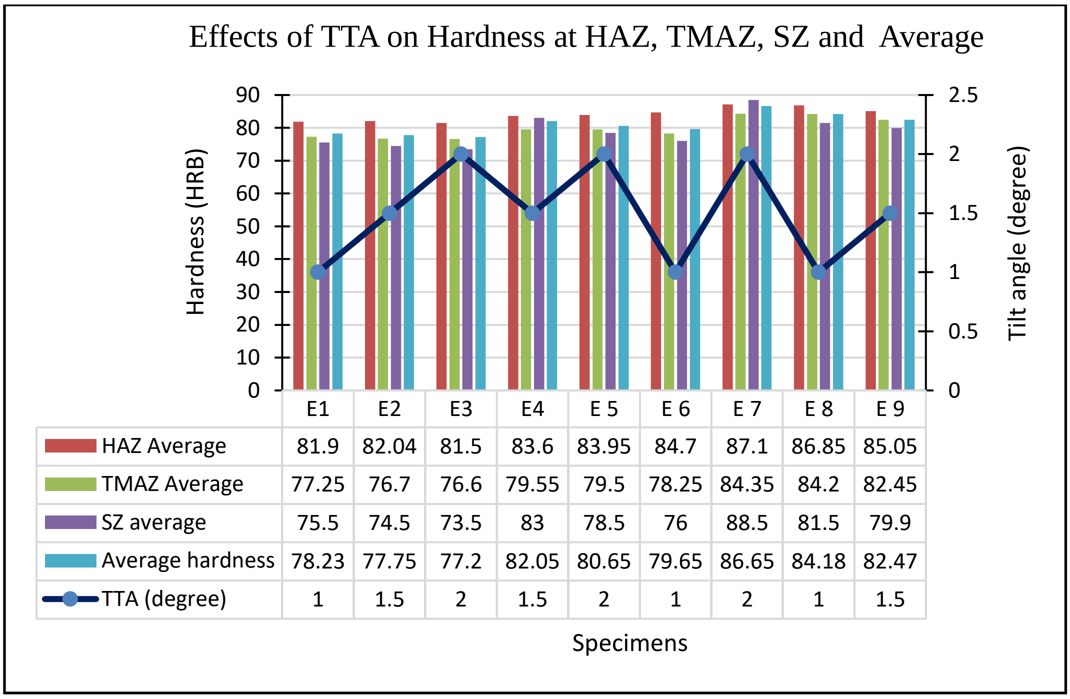


Figure 4.10 Effects of TTA on Hardness at HAZ, TMAZ, SZ and Average

4.2.2.4 Analysis of Variance (ANOVA)

Using analysis of variance (ANOVA), the most important characteristics (most significant parameters) that determine the hardness of FSW-welded copper plates are found and displayed in table 4.15. To determine the percentage contribution of each of the components, the study was conducted using their S/N ratios.

Table 4.15 Analysis of Variance for S/N ratio of stir zone

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Tool Rotational Speed	2	1.37804	65.75%	1.37804	0.68902	36.12	0.027
Tool Traverse Speed	2	0.59261	28.28%	0.59261	0.29630	15.53	0.060
Tool Tilt Angle	2	0.08695	4.15%	0.08695	0.04348	2.28	0.305
Error	2	0.03816	1.82%	0.03816	0.01908		
Total	8	2.09576	100.00%				

S = 0.138125%, **R-Sq** = 98.18%, **R-Sq (adj) =** 92.72%.

Table 4.16 Analysis of Variance for S/N ratio of TMAZ

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Tool Rotational Speed	2	0.834113	95.52%	0.834113	0.417056	298.40	0.003
Tool Traverse Speed	2	0.031364	3.59%	0.031364	0.015682	11.22	0.082
Tool Tilt Angle	2	0.004999	0.57%	0.004999	0.002499	1.79	0.359
Error	2	0.002795	0.32%	0.002795	0.001398		
Total	8	0.873270	100.00%				

S = 0.0373849%, **R-Sq** = 99.68%, **R-Sq (adj) =** 98.72%.

Table 4.17 Analysis of Variance for S/N ratio of HAZ

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Rotational Speed	2	0.326311	90.81%	0.834113	0.326311	21.74	0.044
Tool Traverse Speed	2	0.004887	1.36%	0.031364	0.004887	0.33	0.754
Tool Tilt Angle	2	0.013135	3.66%	0.004999	0.013135	0.88	0.533
Error	2	0.015011	4.18%	0.002795	0.015011		
Total	8	0.359344	100.00%				

S = 0.0866342%, **R-Sq** = 95.82%, **R-Sq (adj) =** 83.29%.

Table 4.18 Analysis of Variance for S/N ratios of Average hardness

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Tool Rotational Speed	2	0.76806	85.85%	0.76806	0.384032	65.95	0.015
Tool Traverse Speed	2	0.10462	11.69%	0.10462	0.052309	8.98	0.100
Tool Tilt Angle	2	0.01036	1.16%	0.01036	0.005182	0.89	0.529
Error	2	0.01165	1.30%	0.01165	0.005823		
Total	8	0.89469	100.00%				

S = 0.0763108, **R-Sq** = 98.70%, **R-Sq (adj)** = 94.79%.

Note: DF- Degrees of Freedom, Seq SS – Sequential Sum of Squares, Adj SS – Adjusted Sum of Squares, Adj MS – Adjusted Mean Square, F test of hypothesis, P value of hypothesis.

F-Value = 3.49 < F-ratio so the parameters were significant, and as shown in the percentage graph in figure 4-11, the rotational speed percentage contribution (85.85%), weld speed (11.69%), and tool tilt angle (1.16%) all have a significant impact on the hardness of FSW-welded copper plates with a thickness of 5mm. As a result, the tool rotational speed and tool weld speed have a highly significant impact on the hardness.

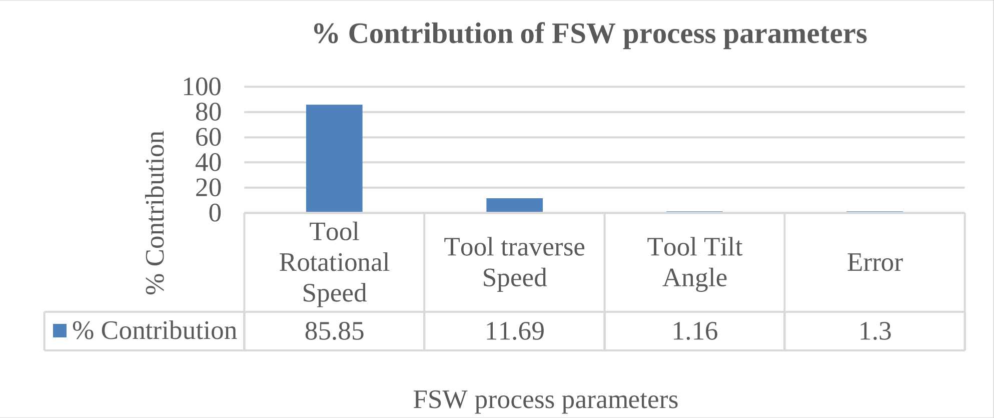


Figure 4.11 Percentage contribution of FSW process parameters on Average hardness

Table 4.19 Optimized hardness result obtained from ANOVA – Minitab 2022

Taguchi Method			
Tool Rotational Speed (RPM)	Tool Traverse Speed (mm/min)	Tool tilt angle (degrees)	Average hardness (HRB)
1180	40	1.5	86.65

Note: DOF- Degrees of Freedom, Seq SS – Sequential Sum of Squares, Adj SS – Adjusted Sum of Squares, Adj MS – Adjusted Mean Square, F test of hypothesis, P value of hypothesis.

The predicted value of the harness of friction stir welded joint for optimum process parameter was calculated by using regression equation 4.5 obtained from Minitab software during Taguchi analysis of hardness of friction stir welded joins of copper plate.

$$Hardness = 66.50 + 0.01560\ A + 0.0125\ B - 0.58\ C \qquad ....4.4$$

From calculation 4.4 the predicted hardness of friction stir welded joint of copper plate was 84.54 HRB. The confirmed experimental result of friction stir welded joint hardness obtained from this study at optimum process parameters was 86.65 HRB. The percent of error between predicted and experimental value of this thesis work was 2.44%. This error is still acceptable error, because approach to error less than 10% is generally considered acceptable error.

4.3 Microhardness Analysis of FSW Joints

Figure 4.12 depicts the differences in Vickers microhardness values as a function of distance from the weld center to the copper plates in sample 9. As seen in Figure 4.12 below with clockwise tool rotational direction, the micro hardness of FSW welded samples in advancing and retracting sides were taken starting from a weld center of which 7 mm distance for the thermomechanical affected zones (TMAZ) and from the weld center and 13 mm distance for the heat affected zones (HAZ).

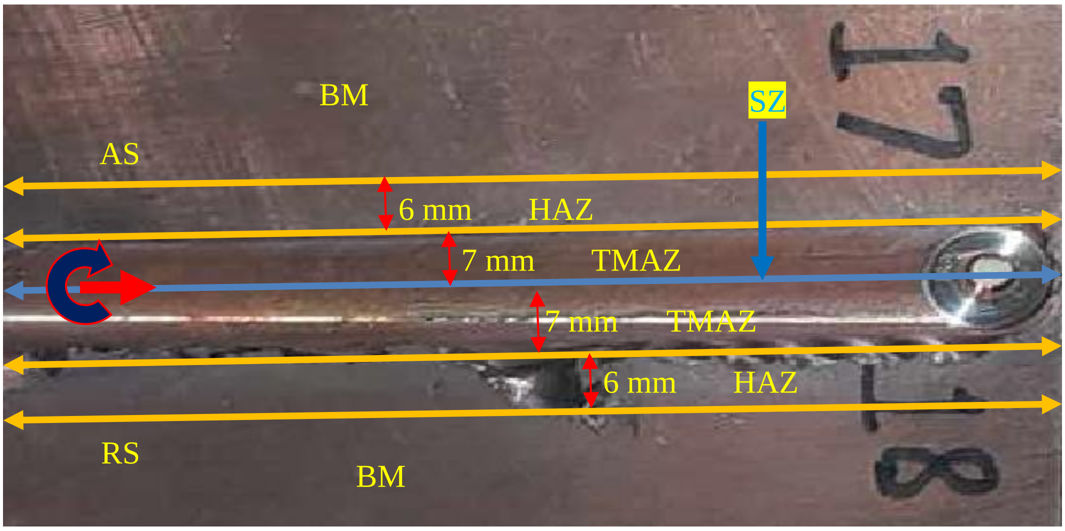


Figure 4.12 Basic sides of friction stir welded joints from welded center

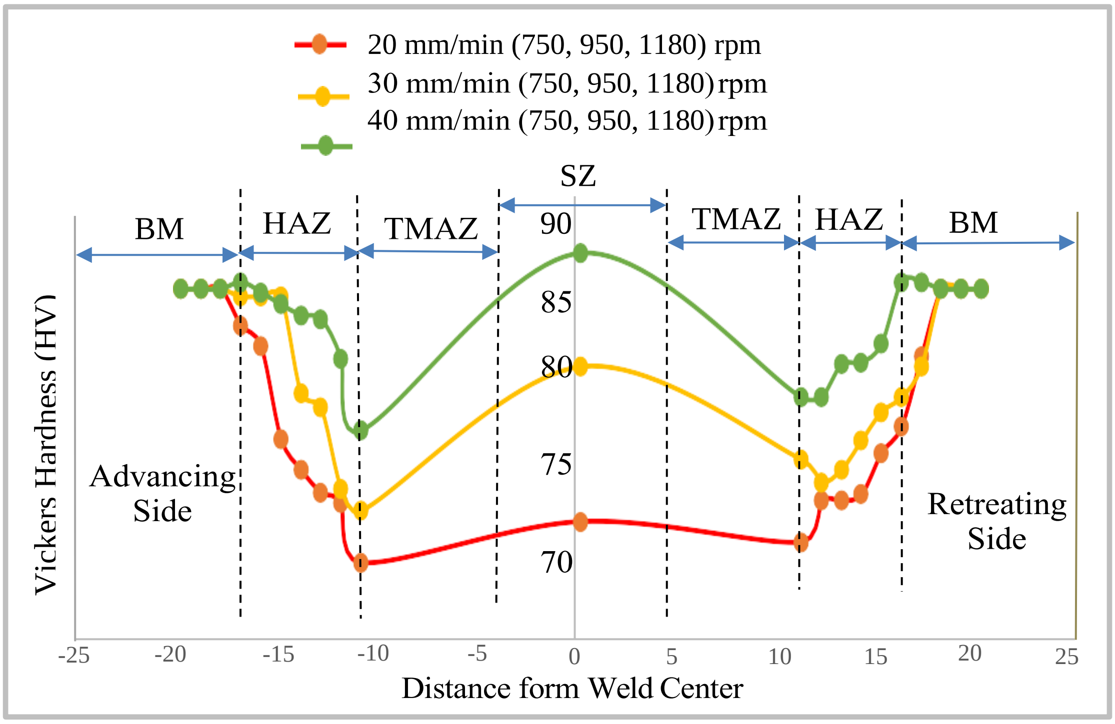


Figure 4.13 Micro-hardness graph for FS welded copper joints in the AS and RS at distinct traverse and rotational speeds

The microhardness profile over the weld line is illustrated in Figure 4.13. Higher average hardness combined with a more uniform distribution was seen in the TMAZ and SZ (the central region under the shoulder) due to the presence of fine and equiaxed grains. The HAZ has the lowest hardness, as would be expected given its exposure to heavy heat input. The approved friction stir-welded joint strength is exhibited by the hardness in the TMAZ and SZ, while being somewhat lower than the base metal. According to Salahi and Yapici (2015), who investigated the results, the advanced side had a lower hardness rating than the retreating side. Salahi and Yapici (2015) state that the data demonstrate that the FSW joints' advancing side has a lower hardness value than their retreating sides, and these findings are reliable. This is because the advancing side is producing more heat than the retreating side. The base metal has the same hardness value on both the retreating and advancing sides, as shown in Figure 4.13.

As shown in Figure 4.14, the hardness distributions were obtained across the advance and traverse cross-sections of the welded joints under different process parameters. In this experiment, the hardness of the welded joints decreased with the increase in rotational speeds and the decrease in weld speeds. This was due to lower welding speeds, and higher rotational speeds lead to more heat generation during friction stir welding. The higher heat input leads to an annealing softening effect, and the material becomes more ductile. But hardness was increased by increasing welding speed continuously, this was due to the formation of a lower heat input during friction stir welding.

The maximum hardness of 88.5 HRB was obtained in the nugget zone at sample tests produced by using higher tool rotational speed, higher weld speeds, and medium tool tilt angle. At high heat input conditions (lower weld speeds of 20 mm/min and 30 mm/min and higher rotational speeds of 950 rpm and 1180 rpm), the hardness of the SZ was lower than that of the BM because of the annealing softening effect. However, at low heat input condition (lower rotation speed of 750 rpm and a welding speed of 40 mm/min), the grain refinement effect was a dominant parameter, and therefore the hardness of the SZ was greater than that of the BM with the value of 88.50 HRB that is performed by the square tool at experiment number seven (E_9).

4.4 Microstructural Analysis of FS welded joint Samples

An optical microscope (Model: HUVITZ HR-300 series) was used to examine the microstructure of all FSW-welded samples and the base material. However, only one specimen was supplied with base materials: sample 7 (E7) chosen from FSW welded samples. These samples were selected for microstructural analysis based on the results of their tensile tests. Among these optical microscopic images of FSW-welded samples, the microstructural investigation was done on four distinct zones of sample 7 (the samples with the maximum UTS joint strength value). The microstructural investigations are done at the base metal as a reference and at the FSW-welded joints like HAZ, TMAZ, and SZ regions of the sample.

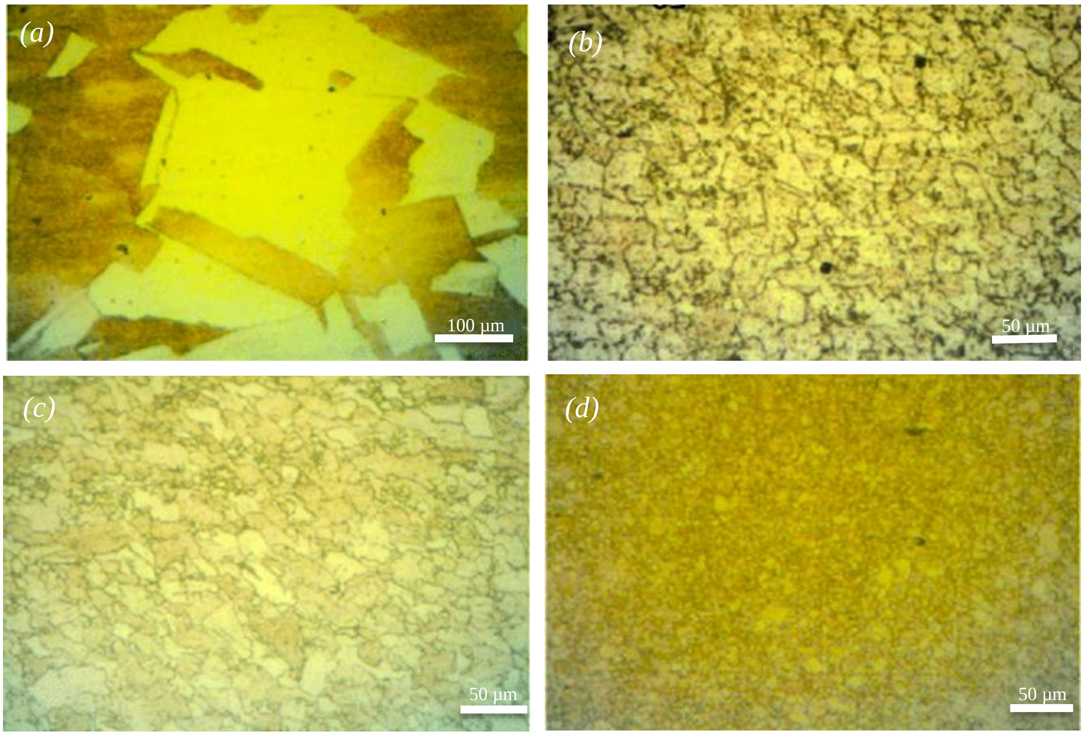


Figure 4.14 OM images of (a) Base metal, and OM images of FSW welded joints at distinct zones (b) HAZ, (c) TMAZ, and (d) SZ

The image consists of four separate optical microscopy images labeled (a), (b), (c), and (d). Each sub-image shows different microstructures of materials at various magnifications for BM and at the FSW weld joints with four distinct zones.

As can be seen from the images in figure 4.14 the BM microstructure is characterized by coarser grains or there are large, irregularly shaped crystal structures, it also has a network of large grain boundaries and the HAZ is by somewhat coarser equi-axed grain structure and complex network of cracks or grain boundaries is visible. The TMAZ is represented by elongated grains scattered along the flow lines. This is due to the frictional heat and shear stress passed on to the parent material during welding, while as well as the fact that the SZ of the FSW joints exhibits almost thin equiaxed grain structure. It appears more uniform in structure with no distinct features like cracks or grains visible. The FSW joints at SZ shows almost perfectly equiaxed grain structure. This is because dynamic restoration processes like dynamic recovery and recrystallization (DRV and DRX) are caused by the simultaneous presence of plastic deformation and heat during FSW. Therefore, the DRX phenomenon is responsible for the fine and equiaxed grains found in the microstructure of the SZ, according to a publication (Barenji, 2016). Dynamic recovery and recrystallization are two types of dynamic restoration phenomena that occur during hot deformation of metals and alloys.

The tool rotational speed and weld speed have greater impacts on welding heat input and could soften the material plastic flow, consequently affecting the microstructure and mechanical property of the welded joint. When increasing the welding speed and decreasing the rotational speed, the welding heat input is very low in which it cannot form enough heat between the rotating tool shoulder and base metal. Due to this effect, filling neither the cavity nor the hole-type defects can be created on the welded joints and consequently decreases the weld joint strength. The weld zone peak temperature and heat input increase with the increase in tool rotation speed and with a decrease in weld speed, which will improve the plastic flow of materials in the welding zone (SZ) to avoid the defects from the welded joint. When the tool rotation speed is increased to higher value and welding speed to the lower value, there are no typical friction stir welding defects in the weld joints. From previous literature based on microstructural characterizations, four distinct zones, namely, (BM), SZ, TMAZ, and HAZ, were identified in FSW joints by Khodaverdizadeh et al., (2013).

CHAPTER - 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research experimentally investigated and optimized the process parameters of FSW on copper plates with 5mm thickness as a base metal. The experimental results were analyzed using a Taguchi L9 orthogonal array and the signal-to-noise ratio method, and ANOVA was used to determine the influential effect of each FSW process parameter. As a result of the experimental findings, the following conclusions were drawn:

At the combinations of FS-welding conditions A3B1C3 (1180 rpm tool rotational speed, 20 mm/min tool traverse speed, and 2-degrees tool tilt angle), a maximum tensile strength of 130.21MPa was produced in a FS-weld of sample number 7 (E_7). The most significant characteristic of tensile strength was tool rotational speed, followed by tool traverse speed, and tool tilt angle is the least significant parameter according to ANOVA. The maximum hardness value of friction stir welded joint was equal to 86.65HRB obtained from FSW joins performed by using combined process parameters of tool rotational speed of 1180 rpm, tool traverse speed of 40 mm/min, and tool tilt angle of 1.5 degree.

As we understand from Taguchi analysis basically from values of signal to noise ratio (S/N ratios) and analysis of variance (ANOVA) the following conclusions are drawn from the present study.

- The tool tilt angle was the major factor, contributing to the effect of ultimate tensile strength of the FSW joints of the copper plate with 42.37% followed by tool rotational speed with percent contribution of 35.08% while tool traverse speed has the least effect at 17.08%.
- The optimum process parameters to get a good ultimate tensile strength of weld joint was found to be at the tool rotation speed of 1180 rpm, tool traverse speed of 20 mm/min, and at tool tilt angle of 2 degrees.
- The tool rotational speed was the major factor contributing to obtaining optimum hardness at the stir zone (SZ) with 65.75% followed by tool traverse speed with 28.28% while tool tilt angle has the least effect with 4.15%.
- The optimum parameters to obtain improved hardness at the weld zone are found to be tool rotation speed of 1180 rpm, welding speed of 40 mm/min, and tool tilt angle of 1.5 degrees.

- The tool rotational speed was the major factor contributing to obtaining optimum hardness at the heat affected zone (HAZ) with 90.81% followed by tool tilt angle with 3.66% while tool traverse speed has the least effect with 1.36%.
- The optimum parameters to obtain improved hardness at the heat affected zone are found to be tool rotation speed of 1180 rpm, welding speed of 40 mm/min, and tool tilt angle of 1.5 degrees.
- The tool rotational speed was the major factor contributing to obtaining improved hardness at TMAZ with 95.52% followed by the tool traverse speed with 3.59% while tool tilt angle has the least effect with 0.57%.
- The optimum parameters to obtain improved hardness at the thermo-mechanically affected zone are found to be tool rotation speed of 1180 rpm, welding speed of 40 mm/min, and tool tilt angle of 1.5 degrees.
- The tool rotational speed was the major factor contributing to gaining improved average hardness with 85.85% followed by tool traverse speed with 11.69% while tool tilt angle has the least effect with 1.16%.
- The optimum parameters to obtain improved average hardness were found to be tool rotational speed of 1180 rpm, welding speed of 40 mm/min, and tool tilt angle of 1.5 degree.

During microstructural characterization, the best and fine grain sizes were obtained from experiment (E_7) done by using process parameters namely, at higher condition of tool rotational speed at 1180 rpm, lower condition of weld speed at 20 mm/min and higher condition of tool tilt angle at 2 degrees. From microstructural characterization the best microstructural arrangement of welded joint with different grain sizes in the heat affected zone (HAZ), thermomechanical affected zone (TMAZ), and, stir zone (SZ) are also obtained. In which, the grain size in the stir zone is smaller than that of the other two zones.

5.2 Recommendations

This thesis work has been done on the same material with 5mm thickness of copper plate by considering variable process parameters of tool rotational speed, tool transverse speed and tool tilt angle. It is also required to investigate the friction stir welding process on different materials and with different thickness and different types of backing plate material for the capacity of heat dissipate between the workpiece and machine bed and also that affect the quality of weld joint hardness and tensile strength in friction stir welding process. The result of this thesis work can be improved and applied to manufacturing industries if further studies include the above-mentioned points.

5.3 Future Scope

This paper identifies, some areas on which further study can be done include: tool wear and tool life can be investigated for different tool shape and different work piece materials. Further different ferrous materials can be used as work piece with different tool material. From literature survey we noticed that much research has been done on different materials, but a very few research is done on copper plate with different material with a different thickness. This material can be investigated using different process parameters and with different optimization methods.

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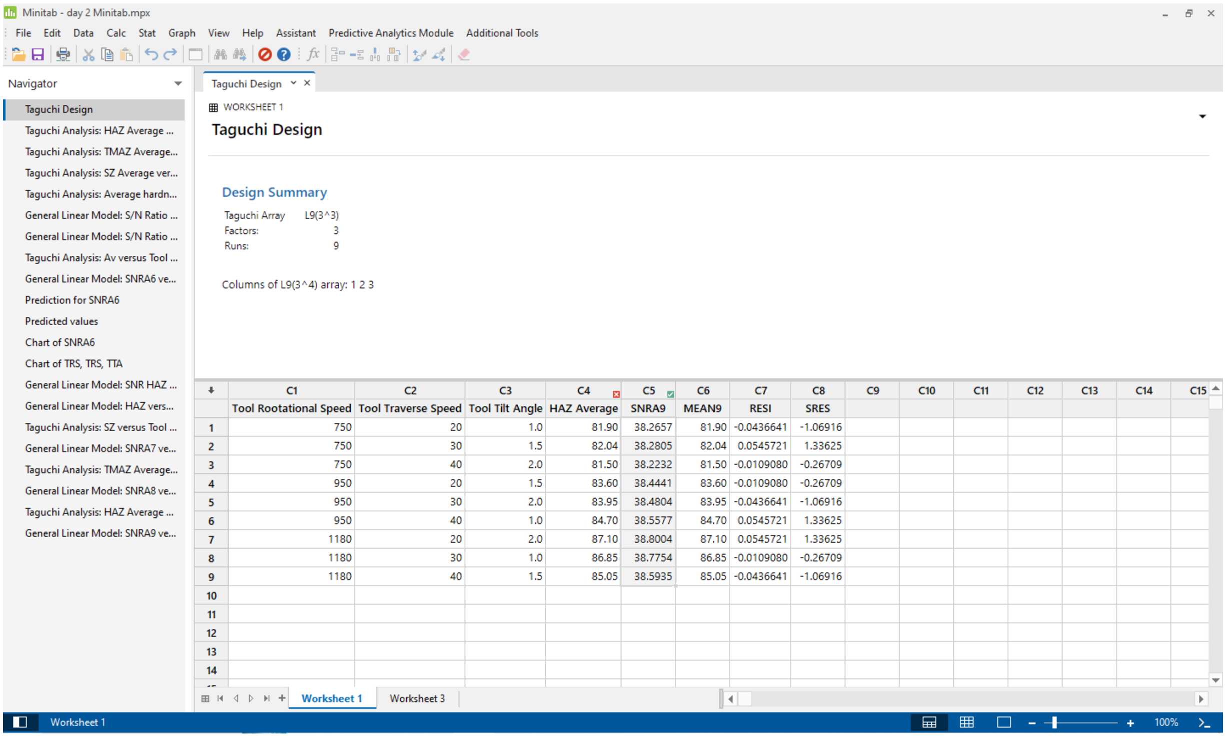
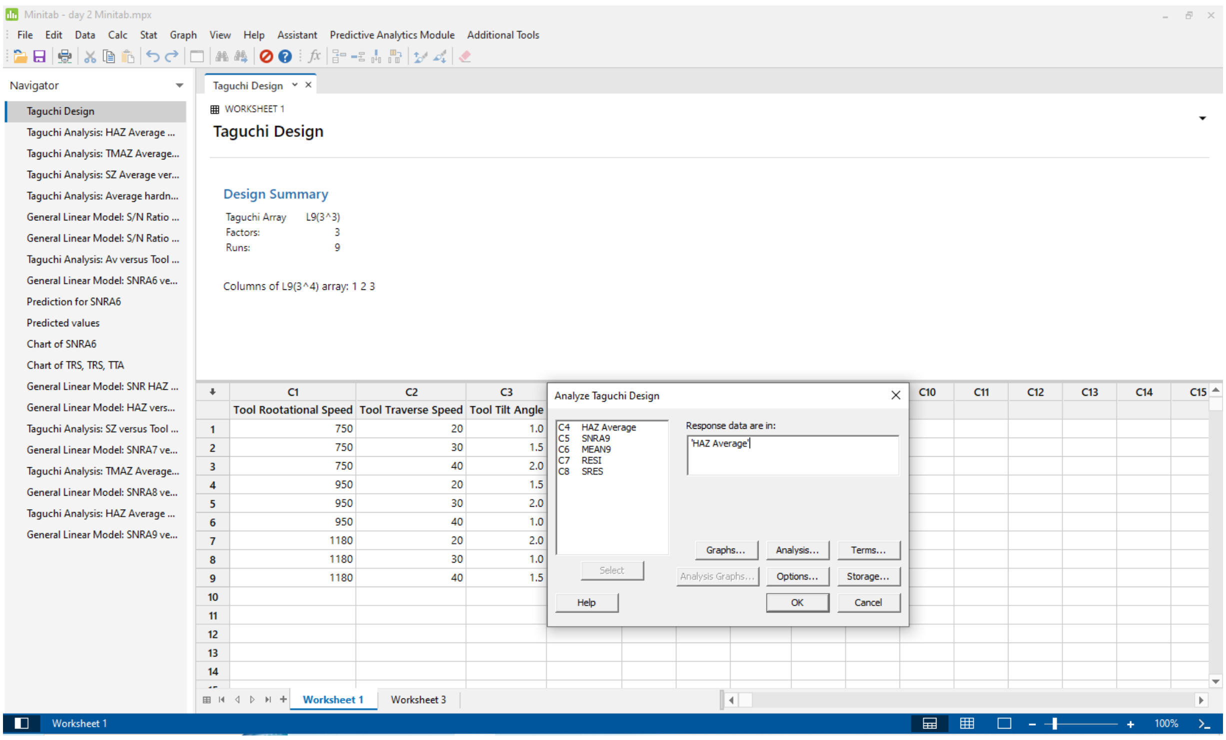
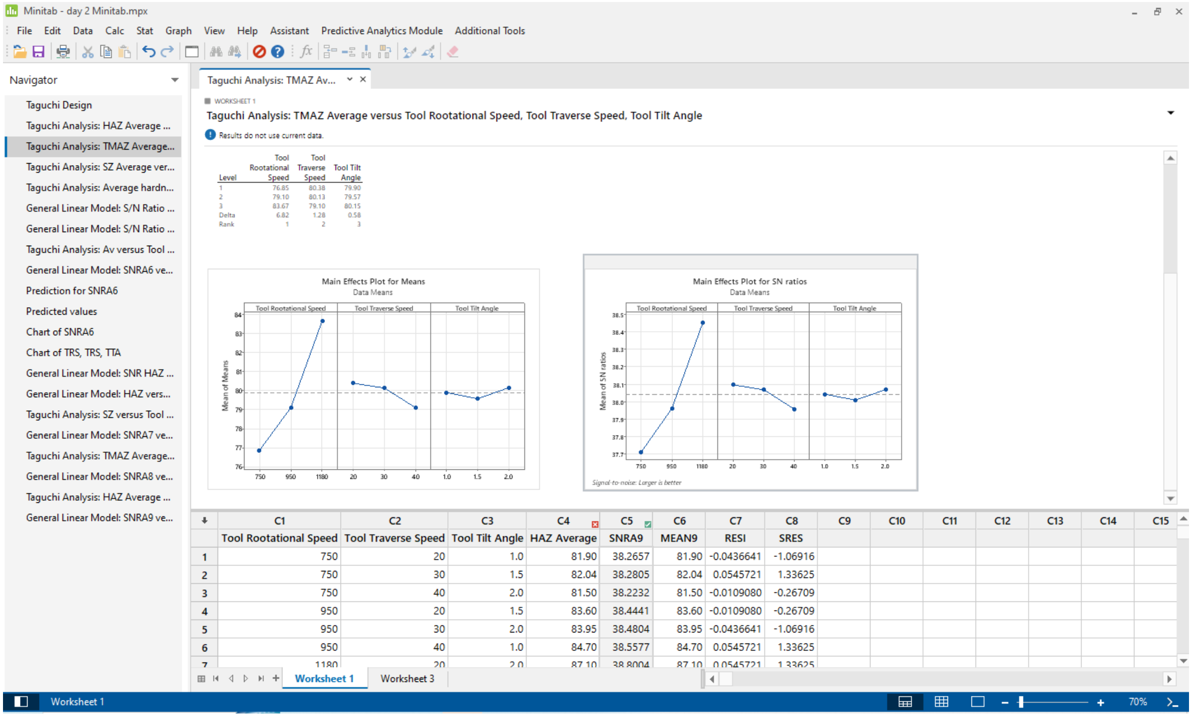
APPENDICES

Appendix 1: DOE Minitab Statistical software and Taguchi L9 orthogonal array design







Appendix A2 Coefficients for Transformed Response of tensile strength

Term	Coef	SE Coef	95% CI	T-Value	P-Value	VIF
Constant	1.0633	0.0772	(0.7310, 1.3955)	13.77	0.005	
TRS						
750	-0.200	0.109	(-0.670, 0.270)	-1.83	0.208	1.33
950	-0.186	0.109	(-0.656, 0.284)	-1.70	0.231	1.33
TTS						
20	0.228	0.109	(-0.242, 0.697)	2.08	0.173	1.33
30	-0.236	0.109	(-0.706, 0.234)	-2.16	0.163	1.33
TTA						
1.0	-0.419	0.109	(-0.889, 0.051)	-3.84	0.062	1.33
1.5	0.159	0.109	(-0.310, 0.629)	1.46	0.282	1.33