

Experimental investigation and optimization of FSW process parameter of dissimilar metal with zinc particle



Asrat Agegnhew Agena

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

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

Office of Graduate Studies
Adama Science and Technology University

February, 2024
Adama, Ethiopia

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DECLARATION

I declare that this thesis proposal entitled “Experimental investigation and optimization of FSW process parameter of dissimilar metal with zinc particle” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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ACKNOWLEDGMENT

Above all, I would like to extend my special thanks to the almighty God for all the blessing and patience he give me to successfully complete this thesis. I have had faced a lot challenges for finishing this thesis. I have met a variety of good heart people in the face of adversity. And it was only because of GOD that I was able to have this experience and learn these life lessons. So, first and foremost, I'd like to express my gratitude to the almighty GOD for his unending blessings and lessons in my life. Dr. G.M. Sayeed Ahmed my thesis advisor, deserve special thanks for his advice, support, and understanding throughout the thesis.

Furthermore, I want to thank Mr. Biftu and Mr. yared for providing me with excellent advice and important recommendations and direction during my studies whenever I needed it and for making me feel hopeful about finishing this thesis. I also owe a debt of gratitude to Mr. Gezahign, Mr Yonas and Dr. Tewodros for their relentless advice, suggestion, and support during working at the Center of Excellence for Engineering and MIDI. Furthermore, Mr. Leta deserves my gratitude for his support and advice during working at SEM assessment at Adama Science and Technology University (ASTU).

My heartfelt thanks and affection go out to my one and only Mr. Michael W. for his unwavering support and understanding. I thank you so much and appreciate you for all those restless days and sleepless nights you spent supporting me. You've been my inspiration throughout this, and I'm confident you'll be my pillar for the rest of my life.

Finally, I would like to acknowledge all my families and friends, for their love, encouragement, appreciation, and endless support which made me stronger each day.

Thank you all

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ACRONYMS

ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BM	Base Metal
DOE	Design of Experiment
FSW	Friction Stir Welding
HAZ	Heat affected zone
HV	Vickers Hardness
OA	Orthogonal Array
OM	Optical Microscope
PSA	Particle Size Analyser
S/N	Signal to Noise Ratio
SST	Total sum of squares
SEM	Scanning electron microscope
SZ	Stir zone
TMHAZ	Thermo Mechanical Heat affected zone
TS	Tensile strength
UTM	Universal testing machine
UTS	Ultimate tensile strength

ABBREVIATIONS

b	width
d	diameter
et.al.	And others
L	Length
t	Thickness

ABSTRACT

Friction stir welding (FSW) is a solid-state joining process developed at The Welding Institute (TWI) in 1991. FSW works by using a non-consumable tool, which is rotated and plunged into the interface of two workpieces. The objective of this research was the experimental investigation and optimization of FSW process parameters for dissimilar metals with zinc particles. Mechanical properties such as hardness and tensile strength were analysed, and microstructural analysis of the joint was conducted using an optical microscope and SEM. In this research, the experiment was conducted to determine the effects of process parameters (travel speed, rotational speed, and zinc particle weight percentage) on mechanical properties, hardness, and tensile strength. Design of experiments was conducted to quantify and optimize the effects of process parameters on hardness and tensile strength. Designs were prepared based on the Taguchi L9 orthogonal array, and the significance of process parameters on the response was identified by analysis of variance (ANOVA). The results showed that hardness and tensile strength increased with increasing rotational speed and zinc particle weight percentage, and decreased with increasing travel speed. Hardness and tensile strength were highly affected by rotational speed and travel speed. The maximum Vickers hardness was 138 HV, and the maximum tensile strength was 186 Mpa. Predicted optimum parameters for hardness and tensile strength were recorded at a travel speed of 45 m/s, rotational speed of 1200 rpm, and zinc particle weight percentage of 20 %.

Key words: Friction Stir Welding, Brass, Aluminum, Zinc particle, Mechanical properties and Microstructure

CHAPTER ONE

INTRODUCTION

1.1. Background of Friction Stir Welding (FSW)

Friction Stir Welding was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminum alloys (Thomas et al., 1991). A rotating tool consisting of a pin and shoulder plunges into the workpiece, generating heat through both friction and plastic deformation, as it creates weld seam. FSW is a more energy efficient technique as compared to electrical arc based and laser joining operations owing to the solid-state process nature, which requires significantly less power (Mishra and Ma, 2005).

FSW is considered to be the most significant development in the area of metal joining in past few decades. The process is also regarded as a “green” technique, due to its energy efficiency, environment friendliness, and versatility it does not involve use of any filler material or cover gas or flux during welding. The process has been commercially used to join high-strength aerospace aluminum alloys and other metallic alloys that are difficult to weld by conventional fusion welding techniques. Further, FSW overcomes the common problems associated with fusion welding such as cracking, porosity, and alteration of alloy chemistry. A schematic of the process is shown in Figure: 1.1.

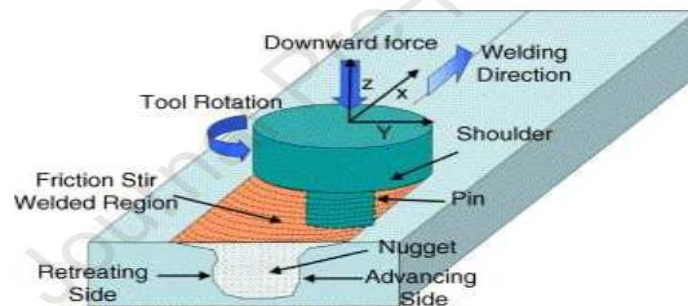


Figure 1.1: Schematic illustration of FSW (Raja et al., 2020)

During FSW a specially designed, no consumable tool, which has two components namely a pin and a shoulder, is used. The tool is made to rotate at high speed and a downward force is applied to the tool so that the pin plunges into the base material and the shoulder just touches the surface. As the tool rotates, large frictional heat is generated at the tool workpiece interface that takes the temperature of the material to a range where it becomes plastic. The tool is then made to traverse at a desired speed. As the tool moves forward the plasticized material flows around the pin and is consolidated by the forward movement of the shoulder leaving

behind a processed zone. The plasticized material flows in a complex way around the tool from one side to another due to the simultaneous rotational and linear motion of the tool. The side in which the tangential velocity of the tool surface is parallel to the traverse direction is defined as advancing side and the other side is defined as the retreating side.

During FSW, the material flows in a complex pattern around the tool from the advancing side (AS) to the retreating side (RS), where the AS indicates the side at which the rotational direction and the welding direction are the same, while the RS denotes the side at which the rotational direction is reverse to the welding direction. The heat generated by a rotating tool changes the material in the vicinity of the tool from a hard solid state into a soft “plastic-like” state. The material undergoes extensive plastic deformation following quite complex paths around the tool, depending on the tool geometry, process parameters, and material to be welded.

1.1.1. Steps involved in Friction Stir Welding

- Rotating tool prior to contact with the plate
- Tool pin makes contact with the plate, creating heat
- Shoulder makes contact, restricting further penetration while expanding the hot zone
- Plate moves relative to the rotating tool, creating a fully recrystallized, fine grain microstructure

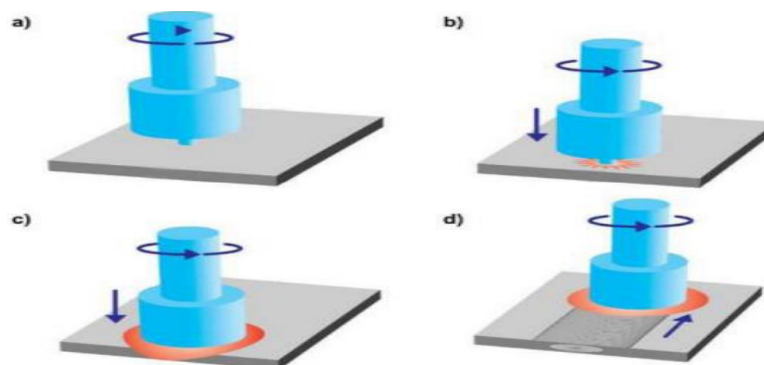


Figure 1.2: Steps involved in FSW

FSW is a thermo mechanical process which involves severe plastic deformation of the material at elevated temperatures, typically greater than $0.5T_m$. Temperatures as high as $0.9T_m$ have been reported during FSW and since there are no evidences of melting it are considered as a solid-state process. The process was originally subjected to aluminium alloys and other soft metals such as magnesium. However, in the recent past it has been successfully applied

to a variety of materials including copper, brass, iron, steel and high entropy alloys even hard to deform hexagonal close pack metals and low ductility alloys are processed by this technique since the deformation occurs at elevated temperature.

FSW has attracted a special attention of the aerospace and automotive industries, due to the potential weight reduction and cost saving, along with the favourable retention of properties. It shows a great potential in manufacturing sectors, particularly in the ship, bridge, wagon building, aerospace, defence, marine, aircraft, automotive and railway industries. FSW of dissimilar metals has prompted considerable scientific and technological interest because of the difficulties and challenges of ensuring the reliability and structural integrity of joints of such lightweight alloys using traditional fusion welding processes. This technique can be used to produce a variety of forms of welds, including butt, lap, corner, T, spot, fillet, and hem joints as well as to weld hollow objects, such as tanks and tubes/pipes. Recently, near-net shape manufacturing of large titanium parts has been accomplished by combining FSW with superplastic forming (SPF).

The beauty of the process is that it does not change the shape and size of the base material and can be carried out selectively on a part of an engineering component for site specific property enhancement, without affecting the properties in the rest of the material.



Figure 1.3: Application of FSW in various industries (Raja et al., 2020)

Aluminium-brass joints present some interest, particularly for thermal and electrical applications. Although these intermetallic compounds (IMCs) ensure metallurgical bonding between the materials, which is detrimental to the mechanical and functional performances of the Al-brass joints, the formation of IMCs is promoted in the liquid state due to the significant diffusion of the elements. This is why many studies have focused on solid-state welding of such materials, among which friction stir welding (FSW) is prominent.

This paper thus aims

- ✚ To investigate the behaviour and the role of Zn during welding.
- ✚ To consider the consequences of the changes of microstructure due to Zn on the joint mechanical performances.

1.1.2. Formation of different weld zones during FSW

Friction heating and the plastic deformation generated by rotating and stirring effect of FSW tool forms different zones termed as the base material (BM), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and stir zone (SZ) which is frequently termed as the nugget zone (NZ). Each weld zone exhibits distinct microstructural characteristics that determine the quality and properties of the welded joint. As shown in Figure 1.4, TMAZ is located in between the HAZ and SZ (Kumar et al., 2020).



Figure 1.4: Weld zones (Kumar al., 2020)

Stir zone (SZ)

Most severely deformed and being dynamically re-crystallized zone is the stir zone, which carries the lowest hardness value among the rest of the weld zones despite equiaxed grain structure.

Heat affected zone (HAZ)

HAZ is known as the weakest zone as the materials in this zone are thermally affected and therefore, for enhancement in the mechanical properties of this zone, FSW is conducted under water to control temperature levels.

Thermo-mechanically affected zone (TMAZ)

The materials in the TMAZ are plastically deformed and being thermally affected as well, whereas in HAZ materials are not plastically deformed. Recrystallization and elongation of grain structure which is accountable for the improvement in the tensile strength of the joint were observed to be initiated in the TMAZ

1.1.3. Process Parameters

The various process parameters that influence friction stir welding are listed below:

- Tool material
- Tool pin profile
- Tool rotational speed in rpm
- Tool traverse speed in mm/min

Tool rotational speed causes stirring and mixing of material around the rotating pin while the translation of the FSW tool shifts the stirred material from the front to the rear side of the pin. The term traverse feed is defined as the rate of travel of the tool along the welding direction, or with respect to the length of the workpiece.

Effect of Process Parameters:

Rotation speed and traverse speed of the tool are the two most important process parameters which significantly affect the microstructure and hence, the mechanical properties of the processed material.

The ratio of tool rotation speed to the traverse speed (ω/v ratio) decides the heat input into the material. As the rotation speed of the tool is increased the material stirring (deformation) becomes more intense and more frictional heat is generated at the tool plate interface, and hence the temperature of the workpiece increases. At the same time as the traverse speed decreases, the tool stays in an area for longer time and consequently that volume experiences more heat. Therefore, the heat input into the material is directly proportional to ratio of rotational to traverse speed and hence, the ratio decides the final grain size in the stir zone.

A higher ω/v ratio will result in increased heat input, leading to the formation of coarse grains in the stir zone (SZ), while a lower ratio will promote the development of finer grains. However, there is a minimum ω/v ratio for a given material. Below this threshold, the heat generated by friction and stirring may not be sufficient to soften and plasticize the material, potentially resulting in discontinuous flow around the rotating tool and the formation of defects. This minimum ratio also determines the smallest achievable grain size in a material. It is important to note that excessively low ratios may also increase the risk of tool breakage, as the material may not reach a soft enough state to flow adequately. One method to achieve a finer

grain size is by cooling the plate behind the tool, which helps prevent the growth of dynamically recrystallized grains.

1.2. Problem statement

In recent decades, there has been increasing attention towards replacing traditional welding techniques and heavier metals due to their environmental impact and high manufacturing costs, particularly in aerospace, automotive, and marine applications. Friction Stir Welding (FSW) offers a promising solution for welding dissimilar metals, leveraging their advantageous properties. Literature reviews have highlighted that incorporating reinforcement in FSW can address these challenges effectively. Studies have shown that using zinc particles as reinforcement can enhance mechanical properties and refine grain structures. Reinforcement materials are utilized in welding to modify the chemical and physical properties of metal matrix composites (MMC), thereby improving their mechanical behavior. However, certain limitations are encountered in welding dissimilar metals, such as improper distribution and mixing of reinforcement particles, resulting in lower mechanical strength compared to the base metal. This phenomenon diminishes the interfacial bonding between aluminum (AL) and brass joints, adversely affecting mechanical properties. To mitigate these issues, researchers are focusing on properly selecting process parameters, ensuring uniform distribution of reinforcement particles throughout the joint, and designing appropriate tools. These strategies are expected to alleviate the aforementioned challenges and enhance welding performance.

This study aims to address this gap by leveraging a unique opportunity to introduce new welding techniques in Ethiopia. Specifically, the study focuses on welding dissimilar metals using zinc particle reinforcement to enhance strength for various engineering applications. By adopting advanced welding methods like FSW with reinforcement, Ethiopia can capitalize on its mineral wealth to produce high-quality structural materials tailored to specific industry needs.

1.3. RESEARCH QUESTION

Regarding all the above-mentioned facts among FSW of dissimilar metal and from the problem statement, the following research questions are raised.

- i. What are the effects of Zinc particle in FSW joint?

- ii. What is the effect of FSW process parameter on physical and mechanical properties of Al- brass joint?
- iii. What does the morphology of Al-Brass joint looks like after welding?
- iv. At what condition the FSW process parameter effect on the welded joint is low and high?

1.4. Objectives

1.4.1. General objective

The main objective of this work is “to experimentally investigate and optimize the friction stir welding process parameters for dissimilar metals with zinc particles”.

1.4.2. Specific Objectives

The specific objectives of welding dissimilar metal materials by FSW can be:

- ✚ Testing the mechanical properties of FSW materials, including tensile strength and hardness.
- ✚ Characterizing the morphology of welded joints using optical microscopy (OM) and scanning electron microscopy (SEM).
- ✚ Optimizing the process parameters and studying their effects on the physical and mechanical properties of welded joints using Taguchi experimental design.
- ✚ Understanding the impact of cracks on the microstructure evolution of FSW materials using DIGIMIZER software.

1.5. Scope of study

In order to achieve the objectives specified the following scopes were settled: -

- ✚ Gathering base materials that use for welding samples.
- ✚ The welding of dissimilar metal was conducted by using FSW technique.
- ✚ Physical and mechanical properties of samples are identified by using convection testing machine. The study was limited to the evaluation of physical and mechanical properties namely, tensile strength and hardness

- ✚ The micro structural analysis of these welded dissimilar materials was carried out using Optical Microscope (OM) and Scanning Electron Microscope (SEM)
- ✚ To study the influences of process parameters such as Rotational speed, Travel speed and Zinc particle Wt. % by using Taguchi experimental design on Minitab software.

1.6. Challenges

Limitations of Friction Stir Welding:

The limitation faced during FSW of dissimilar metal with Zn particle is in this study, the FSW machine is not available in Ethiopia due to that was less difficult to control the parameters and factors which affect mechanical and physical properties of welded samples under FSW technique.

- If suitable values of the process parameters are not selected during FSW, certain process defects may develop such as tunnel defects, pinholes, voids, etc. due to poor material flow and consolidation.
- Friction Stir Welding can be performed on metals, plates and sheets only up to a depth of 50 mm.
- It is a local machining process; a large processed region cannot be obtained in a single pass.
- Exit hole left when the tool is withdrawn.
- Large down forces are required, with heavy-duty clamping necessary to hold the plates.

1.7. Significance of the study

This study underscores the significance of MMC (Metal Matrix Composite) materials in addressing the evolving needs of the manufacturing industries, particularly in sectors such as automotive components. MMCs offer a compelling combination of properties including enhanced strength, stiffness, and lower density compared to conventional materials like steel. These attributes contribute to improved performance and sustainability, aligning with the growing emphasis on environmental responsibility and energy efficiency. The advantages of MMCs outlined in the study, such as lower embedded energy compared to steel, cost-effectiveness, and ease of manufacturing and welding, make them highly appealing for various applications. Furthermore, the study highlights the potential of MMC materials to enable the adoption of new production technologies and materials, facilitating innovation and pro-

gress in the manufacturing sector. Importantly, the study emphasizes the role of MMC materials in supporting green development initiatives without sacrificing material performance. With the increasing demand for lightweight materials to reduce energy consumption, MMCs emerge as a promising solution to meet these needs effectively.

1.8. Research motivation

In recent decades, there has been a growing emphasis on replacing traditional welding techniques and heavier metals due to their environmental impact and high manufacturing requirements. Surface quality plays a crucial role in determining product quality across various industries, meeting functional requirements. In welding, the quality of the weld significantly influences the mechanical and microstructural properties of welded metals. Friction Stir Welding (FSW) offers advantages over fusion welding, being suitable for various materials and environmentally friendly. Ethiopia boasts diverse welding sectors with significant potential for structural materials across various applications. However, there's a lack of investigation into the performance and application of FSW techniques within Ethiopia's welding sector, primarily due to limited awareness about this welding process and the unavailability of Friction Stir Welding machines. Thus, this work is motivated by the need to address these gaps.

1.9. Thesis layout

This thesis entitled as Experimental investigation and optimization of FSW process parameter of dissimilar metal with zinc particle has five chapters;

Chapter 1 Presents the background and application of friction stir welding in brief. Explain introduction of friction stir welding dissimilar metals welding techniques, research questions, objectives, the problem statement, the significance of the study, and scopes of the study.

Chapter 2 Presents related literature works on friction stir welding, summary and find out research gap on welding metals is described.

Chapter 3 Focuses on the methodology, experimental procedure, equipment used and materials used to achieve the objective of this thesis work.

Chapter 4 Presents result and discussion of major findings of this experimental work.

Chapter 5 Discussed or summarize the study, conclude from overall study, recommendation and future research directions.

CHAPTER TWO

LITERATURE REVIEW

Literatures

A review of available literature is to provide background information on the issues to be considered in this thesis. The review is focused on the various aspects of the welding dissimilar metal by FSW with a special reference. This chapter contains review of existing research reports:

- ✚ Review on types of particle and particle size
- ✚ Review on types of types of cooling
- ✚ Review on welding parameter
- ✚ Review on tool wear
- ✚ On Taguchi Method

At the end of this chapter a research gap in the earlier investigations are presented.

2.1.1. Review on types of particle and particle size

Friction stir welding (FSW) is a solid-state welding process that can be enhanced through the addition of particles to the weld zone. These particles serve various purposes, including strengthening the weld, modifying microstructure, and introducing desirable properties to the joint. The types of particles and their sizes play critical roles in determining the characteristics and performance of the welded joints.

In their study, Shafique et al. (2021) investigated the structural and mechanical properties of friction stir welded Al₂O₃ and SiC reinforced Al 7075 alloys. They achieved a sound weld using a revolution speed of 1600 RPM and a transverse speed of 17 mm/min. The inclusion of Al₂O₃ and SiC particles in the welded joint led to a notable increase in hardness, approximately 10 to 12% higher than that of joints without particles. This enhancement in hardness was attributed to the higher thermal conductivities of the added ceramic particles and the precipitation strengthening mechanism

In their study, Ioannis et al. (2020) focused on surface modification and hardening of Aluminium Alloys AA5083 using the friction stir process, with Cu reinforcement in the form of a strip with a thick-

ness of 0.8mm. The process parameters included a rotational speed of 1000 rpm combined with a transverse speed of 13 mm/min. The addition of Cu reinforcement significantly impacted the macro hardness of the AA5083 alloy. The distribution of the reinforcement strip inside the aluminum alloy resulted in a substantial increase in macro hardness, from 77 HV to 138 HV, within the Cu-reinforced stir zone.

The study conducted by Karpasand et al. (2020) investigated the impact of powder addition method and volume fraction of reinforcement on the tribological behavior of Al7075 with B4C reinforcement in the surface composite produced by friction stir processing (FSP). B4C powders were incorporated into prepared grooves with widths of 1 mm and 2 mm on the surface of Al7075 alloy using two different methods. In the first method, the B4C powders were added prior to four consecutive passes in one stage, while in the second method, the powder addition occurred in two stages: before the first pass and after the second one. Microstructural evaluations revealed that increasing the volume fraction of reinforcement led to a significant reduction in the matrix grain size. Additionally, it was observed that in the first method, the reinforcement exhibited a more homogeneous and uniform distribution in the samples processed through four consecutive passes.

In their study, Nosko et al. (2019) investigated the effects of powder particle size on the weldability, microstructure, and mechanical properties of Al-Al₂O₃ nanocomposites fabricated by friction-stir welding (FSW). They used different particle sizes of Al₂O₃ (9µm, 63µm, and 250µm) as reinforcement for making butt joints with aluminum alloy. The researchers observed that reducing the particle size of aluminum oxide from 250µm to 9µm resulted in grain refinement in the welded joints. The joint quality was evaluated through macro cross-sectional studies, revealing that defects at the weld root increased with higher traversal speeds. However, defect-free friction stir welds with homogeneous cross-sections were achieved for all powder sizes using specific FSW parameters ($w = 1200$ rpm and $v = 300$ mm/min). Additionally, at higher speeds (600 mm/min), a wineglass profile was observed.

In their study, Kar et al. (2018) investigated the impact of a zinc interlayer on the microstructure evolution and mechanical properties in the dissimilar friction stir welding of aluminum to titanium. The presence of zinc particles was found to enhance the flowability of the aluminum nugget zone, leading to improved homogeneity in the distribution of fine titanium particles. This alteration in the phase evolution effectively limited the formation of the conventional Al₃Ti intermetallic phase. Additionally, the distribution of titanium depended on the

size of the particle reinforcement, with fine particle reinforcement being distributed more homogeneously.

In their study, Moradi et al. (2018) investigated the effects of micro and nano silicon carbide (SiC) reinforcement on the properties of dissimilar metal friction stir welding (FSW) between AA6061 and AA2024. The researchers used two different sizes of SiC particles along the joint line, varying groove widths, and tool offsets during the welding process. They found that joints made using specific parameters, including a rotational speed of 800 rev min⁻¹, traveling speed of 31.5 mm min⁻¹, groove width of 0.3 mm, and tool offset of 0.5 mm, exhibited the most homogeneous distribution of particles for both micro and nano SiC particles.

In their study, Bahrami et al. (2015) investigated the effect of nano-SiC reinforcement on Al 7075 alloy via friction stir welding (FSW) and concluded that a 20% volume fraction of SiC nanoparticles improved the mechanical properties of the welded joint compared to a SiC-free joint. The researchers emphasized that the mechanical properties of the welded joint are influenced by factors such as grain size, reinforcement dispersion, and the bonding quality between the matrix and reinforcement materials. During tensile testing, fractures occurred differently for the SiC-free joint and the SiC-reinforced joint. The SiC-free joint fractured at the stir zone (SZ), while the SiC-reinforced joint fractured from the base metal. Additionally, the SiC-reinforced specimens exhibited ductile fracture morphologies, indicating better toughness, while the SiC-free specimen showed a quasi-cleavage fracture mode, confirming its moderate percent elongation.

Karthikeyan¹ and Mahadevan, (2014) they studied mechanical property evaluation of friction stir welding of Al 6351 alloy with addition of SiC reinforcement particle in the surface of butt joint. The process parameters are SiC particle size (wt. %), axial load, welding speed and rotational speed at three levels selected. The responses are Tensile strength, Brinell hardness and Impact strength. The optimized welding parameters range for good quality friction stir welded joint of Al 6351 was found to be at 1.5 wt. % of SiC particles, 2 KN of axial load, 1000 RPM of tool rotational speed and 29 mm/min of welding speed. Among the chosen parameter reinforcement particle size (wt. %) and axial load is found to be the influencing factors in determining the mechanical properties. Because of the pinning action of the added SiC particles, the mechanical properties are improved in annealed condition too.

Devaraju Aruri et al. (2013) in his work on Wear and mechanical properties of 6061-T6 aluminum alloy surface hybrid composites [(SiC + Gr) and (SiC + Al₂O₃)] fabricated by friction

stir processing, he concluded that Microhardness increases due to presence and pinning effect of hard SiC and Al₂O₃ particles. Low wear rate was exhibited in the Al–SiC/Gr surface hybrid composite due to mechanically mixed layer generated between the composite pin and steel disk surfaces which contained fractured SiC and Gr. The presence of SiC particles serves as load bearing elements and Gr particles acted as solid lubricant. Tensile properties are decreased as compared to the base material due to the presence of reinforcement particles which make the matrix brittle.

As reported by Gandra et al. (2011) coarse particles make a weaker particle-substrate bond, which hinders the material movement trace generated by the tool stirring, and leads to the particle agglomeration. However, due to stronger bond in case of fine powder particles, they follow the material trace left by the tool and leads to more homogeneous distribution. Additionally, as the number of the holes available for B₄C powder reinforcement and weight of the powder were kept constant, the volume fraction of B₄C particles remained constant. Hence, decreasing the size of B₄C particles by ~ 50% increases the number of particles enormously for interaction with the tool and substrate thereby, which may lead to a more uniform distribution of the particles comparatively.

Mishra et al.(2005) initiated an innovative application of FSW known as friction stir processing (FSP) method to enhance microstructure and mechanical features of the workpiece. Their work comprises using of FSP method to produce metal matrix composite (MMC). They placed reinforcement particles at the upper surface of AA5083 alloy and after that FSP method applied at that surface. They observed an enormous improvement of mechanical strength and micro hardness (almost double as compared to the base metal). Their findings opened a new window of opportunity to fabricate MMC using FSP for improved not only mechanical and microstructural properties but also for enhanced super plasticity.

2.1.2. Review on types of cooling

Friction stir welding (FSW) is a solid-state joining process that generates heat through friction between a rotating tool and the workpiece material. Effective cooling mechanisms are essential to manage heat generation and maintain stable welding conditions, ensuring high-quality welds.

Nan et al. (2020) investigated on the effect of cooling medium liquid CO₂ on the properties of friction stir welding (FSW) AZ31B magnesium. They found that ultrafine grains with high dislocation density were obtained in the top region of the weld due to liquid CO₂ cooling. The peak temperature and the high temperature exposure time in the weld surface region were remarkably reduced compared with those of the bottom region. The top region showed the higher strength and elongation compared with the bottom region, and the welding efficiency reached 93%.

Prasad et al., (2021) studied on the Mechanism of microstructure evolution and grain growth in friction stir welding of AA6061-T6 and AISI304 in air and water media. Grain size depends on rate of cooling of the weld region. They conducting FSW experiments in two different media i.e. air and water. The FSW sample yields finer microstructure in water medium the weld regions than air medium. Grain growth was observed after coalescences of subgrains. Results have shown higher grain growth for FSW in air medium. Results have also shown transformations of Goss {110} <100> and B{110} textured grains of base aluminium into Copper {112}, E{111} and F {111} dominated textured grains at the stir zone (SZ). Water medium produced relatively highly shear textured grains than air medium at SZ.

Aghajani et al., (2021) investigated on the Effects of Rapid Cooling on Properties of AA3003 aluminium and A441 AISI steel Friction Stir Welded Joint. Three different cooling mediums including, forced water, forced CO₂ and forced air were employed, and also non-cooled sample was processed for comparison. The highest and the lowest cooling rate belong to CO₂ and non-cooled sample. The best and the poorest macrograph without any segregation at interface belong to the water-cooled and CO₂ cooled FSW sample. The CO₂ cooling FSW sample exhibits the smallest grain size due to the suppression of grain growth during dynamic recrystallization (DRX). Fracture observation indicates that there is a semi-ductile fracture in the water cooling sample and CO₂ cooling sample exhibits more brittle fracture. Hardness evaluation reveals that the higher the cooling rate formed, the higher the hardness in stir zone, and hardness changes in the aluminium side were higher than the steel side.

Iwaszko and Kudła et al.,(2021) investigated on Microstructure, hardness, and wear resistance of AZ91 magnesium alloy produced by friction stir processing with air-cooling. The cooling was carried out using a jet cooling nozzle, generating a stream of cold air and enabling intensive cooling of the friction stir processed (FSPed) zone. The process parameters were tool rotational speed of 500 rpm and travel speed of 30 mm/min. In the samples modi-

fied with the jet cooling nozzle, greater grain refinement was obtained than in the case of naturally cooled material. The average grain size in the surface part of the stirring zone was 1.4 μm and 9 μm in the samples with air-cooling and with natural cooling, respectively. Both the naturally cooled specimen and air-cooled specimen were characterized by a distinctly higher hardness than the base material. Slightly higher wear resistance and high energy efficiency was found in jet cooling nozzle when compare to the naturally cooled sample.

Patel et al., (2019) investigated that Hybrid friction stir processing with active cooling approach to enhance superplastic behaviour of AA7075 aluminium alloy. They are FSP at different cooling medium such as compressed air, water, and CO_2 to study the effect of variety of cooling rate during the process. Among the hybrid FSP samples, CO_2 cooling sample was produced at the lowest processing temperature. The microstructures of all the samples were characterized by fine equiaxed grain in the stir zone (SZ). grain size Reduction in hybrid FSP samples was found due to higher cooling rate, which prevented the coarsening of grains in the SZ. Grain refinement Improvement was observed in the order of normal (4.12 mm), compressed air (3 mm), water (2.64 mm), CO_2 (1.96 mm) FSP samples. All FSP samples obtained the superplastic elongation. The highest elongation of 572% was achieved for CO_2 cooling sample due to the finest grained microstructure produced at the lowest heat input during FSP.

Yang et al. (2018) studied heat, mass transfer and material mixing in friction stir welding of dissimilar aluminium and magnesium alloys by developing a computational fluid dynamics model and, considered the stress reduction caused by the recrystallization around the tool. The result showed that the local turbulence was a key factor influencing the formation of the severe intercalated zone and the mixing zone and the widening of the mixing zone on trailing side.

Zhang et al. (2014) observed the formation of Al_3Ti phase after 4-pass FSP in air when processing the sintered billets composed of Al and Ti mixed powder by FSP. Ti particles reacted with the Al and formed Al_3Ti after 4-pass FSP in air when the sintered Al-Ti billets subjected to FSP. The absence of Al-Ti IMCs here can mainly be ascribed to the forced water cooling. In 2012 he also Reported that compared with FSP in air and water, FSP in water not only significantly reduced the peak temperature, but also greatly shortened the thermal exposure duration. Therefore, it can be preliminarily considered that the forced water cooling has a signif-

icant inhibitory effect on the Al/Ti interface diffusion reaction. The detailed Al/Ti interfacial microstructure was further improved.

2.1.3. Review on welding process parameter

The parameters such as axial force, rotational speed, transverse speed, and the design of the tool, define the structural and mechanical characteristics of the friction stir welded joints. These process parameters are held reasonable for the weld defect phenomenon as well.

Sabry et al., (2019) investigated on effect of tool rotational speed on FSW T-joint of aluminium alloy (AA6063-T6). The rotational speed of the tool during FSW influences heat generation as an influence of the friction at the surface of the specimen, significantly affecting plastic deformation, material flow, and the grain structure of the material at the weld zone. Tool rotational speed was the most influencing factor for the attainment of high tensile strength along with the tensile elongation. Maintaining ideal travel speed at constant, T-joint of aluminium alloy (AA6063-T6) was subjected to FSW, revealing the direct proportionality of tensile strength with the tool rotational speed spanning 1000–1800 rpm. Increasing tool rotational speed with increased axial force resulted in a joint with high hardness number.

Saader et al., (2019). Investigated on the FSW of AA6092/SiC composite plate. At three different tool rotational speed 1000 rpm, 1500 rpm, 2000 rpm, they got different nugget zone particle size. They found that at 1500 rpm higher amount of fine particle size present in the nugget zone, which subsequently leads to higher tensile strength, elongation and ductile mode fracture.

Ravi et al. (2018) explored the impact of tool rotational speed on the mechanical and metallurgical characteristics of the weld joints. With a tool rotating at 1000 rpm, higher mechanical qualities were seen in the joint that was welded. Examined the impact of the process parameter on friction stir welded Al-B₄C on mechanical and microstructural characteristics as a function of rotational speed MMCs. suggests using a moderate tool speed (RPM) to accomplish single pass welds free of defects. Microstructure studied revealed fine re-crystallized equiaxed grains in the weld nugget due to frictional heating and extensive plastic deformation.

L et al. (2016) investigated on the effect increasing welding speeds on 7050-T7451 aluminium alloy. When the welding speeds increased the transverse tensile properties of 7050-T7451 aluminium alloy plates which reduced grain size in the SZ and TMAZ. Increasing speed of tool rotation with high axial pressure allows avoiding weld zone defects such as void, crack-

ing, or distortion with further improvement in the strength of friction stir weld joint whereas, decreasing welding speeds results in the widening of the nugget zone reducing the hardness number of friction stir welded joint.

Kuma et al. (2016) found no simple correlation between the temperature and the input power or heat. Although the heat input is commonly considered in fusion welding, it is a poor indicator of the temperature of the material surrounding an FSW tool, at least for the joining of thin plates of aluminium. It is likely that when the traverse speed is reduced, much of the additional heat is conducted into the backing plate, as evidenced by the observed correlation between the heat input and the backing plate temperature as well as through the tool. The down force in FSW provides intimate thermal contact between work piece and backing plate, but this contact evolves with position during the welding process, requiring complex calibration.

Jannet et.al. (2015) compared the mechanical properties of friction stir welded joints of AA 6061 T6 and AA 5083 produced with four different rotation speeds with that of welds produced using fusion welding. They concluded that the FSW joints had higher tensile strengths than fusion welding due to the narrow width of heat affected zone in FSW than in fusion welding and improvement in microstructure due to higher degree of plastic deformation by the mechanical stirring action of the rotating tool in the case of FSW.

Donatus et al. (2015) examined the corrosion in dissimilar friction stir welds of AA5083-O and AA6082-T6 alloys for two different tool traverse speeds. Corrosion was seen as more in the friction stir weld done at a traverse speed of 400 mm/min than done at 300 mm/min, due to the higher tool rotation rate for a unit length and for a slower welding speed (300 mm/min) which gave a better mix of materials and less zonal heterogeneities.

Narayana Yuvaraj et al. (2015) in his work on Fabrication of Al5083/B₄C surface composite by friction stir processing and its tribological characterization, he concluded that The microstructure in the FSPed specimens with nano B₄C particles three passes exhibits fine grain size, higher hard-ness (124.8 Hv), ultimate strength (360 MPa) and wear rate(0.00327 mg/m) in comparison to the base material hard-ness (82 Hv), ultimate strength (310 MPa) and wear rate(0.0057 mg/m).

M. Mosallae et al. (2014) in his study on improvement of structural and mechanical properties of Al-1100 Alloy via friction stir processing; he concluded that FSP causes grain refine-

ment and a slight decreasing of precipitates size. The effect of tool rotation rate and traverse speed on the grain size of the SZ is twofold, i.e., increasing of these parameters causes grain refinement at first, and thereafter causes grain growth. The optimal FSP condition for Al-1100 alloy is 720 rpm tool rotation rate and 20 mm/min traverse speed. This FSP condition results in improving of tensile strength and elongation up to 22 and 8% of those of base metal, respectively.

2.1.4. Review on tool wear

Stirring action of the tool at high operating temperature and process forces, under which the tool experiences extreme conditions of wear and deformation. During FSW the tool is subjected to wear due to diffusion across the tool–BM interface and deformation. The wear and deformation are critical as they affect joint properties, tool life, and process cost. The wear and deformation also degrade the surface quality and affect the joint properties with inclusions of tool material. Among the various mechanisms that affect the tool wear and degradation, abrasion, adhesion, and oxidation at high temperatures are common. The tool life is critical, based on which the selection of material and geometry of tool is done. The selection of tool material is made based on mechanical, physical, chemical, and thermal properties of the BM, and process temperature and forces.

Akeem et al (2017). Reported the wear analysis of coated (AlCrN using cathodic arc physical vapour deposition (PVD) coating) and uncoated tool alloy steel 4140 grade during FSW of AA6061-T6. The authors demonstrated that the AlCrN coating improved the wear resistance in comparison to uncoated alloy. They also found that the micro particles and micro defects in cathodic arc PVD coating affected the corrosion and surface morphology of coating, which led to its failure, pitting corrosion, and sticking of BM.

Adesina et al (2017) the impact of tool wear on joint properties has also been investigated for friction stir welds. He employed H13 tool steel tool to weld AA6092/17.5 Sicp composite and investigated the effect of tool wear on joint properties (by varying tool rotational speed from 1000 r/min, 1500 r/min, and 2000 r/min).

M. Azizieh et al.(2017) in his work on Fabrication of Al/Al₂Cu in situ nanocomposite via friction stir processing; he concluded that the pin diameter has a higher effect on the particle distribution and microhardness than the number of FSP passes and rotation-to-travel speed ratio. Owing to the formation of intermetallic nanoparticles and dispersion through the Al

matrix, the Vickers microhardness of the prepared in situ nanocomposite was increased by 57% in comparison with the base metal. Irregular morphology of the interface between Cu and the Al matrix is attributed to the local melting and therefore, rapid reaction of Cu with the base metal.

Hasan et al. (2015) demonstrated the impact of tool degradation by comparing tools with unworn and worn tool geometries. The authors demonstrated that the worn tool leads to lower material stirring and higher strain rates. It has been noted that the tool life significantly depends on the prevalent flow stresses and process temperatures during welding.

2.1.4. Review on backing plate design

A review on backing plate design in friction stir welding (FSW) reveals its crucial role in ensuring stable and efficient welding operations. Backing plates serve multiple functions, including providing support to the workpiece, facilitating heat dissipation, and enhancing tool movement.

Rosales et al. studied the effect of backing plate in friction stir butt welding of 4-mm-thick 6013-T6 and 3.2-mm-thick 2024-T351 aluminum alloy plates. Three backing plate materials were considered in their study: steel, copper, and ceramic. While, defect free welds were obtained with steel backing plate, tunnel defects and excess flash formation were observed with copper and ceramic backing plates, respectively.

Upadhyay and Reynolds investigated the effects of forge axis force and backing plate thermal diffusivity on friction stir butt welding of 4.2-mm-thick 6056-T451 aluminum alloy plates. Three millimeter thick aluminum alloy 2099, tool steel, Al₆XN (Allegheny Ludlum super austenitic stainless steel), Ti-6-4, and ceramic floor tile were used as backing plates. It was found that peak, mid-section, stir zone temperatures for ceramic backing plate were about 40, 35, and 25°C higher than that for aluminum, steel, and Al₆XN backing plates, respectively. Stir zone temperatures were found to be sensitive to forge axis force, tool rpm, welding speed, and backing plate material. While tunnel defects were found for peak, mid-section, stir zone temperatures of around 360-400°C, excess flash formation was observed when mid-section temperatures exceeded around 450°C.

Recently, Zhang et al. observed the effect of backing plates on friction stir butt welding of 3.2-mm-thick 2024-T3 aluminium alloy sheets at 600 rpm and 200 mm/min welding speed for copper, medium carbon steel, and granite backing plates. Steel backing plate was seen to

give the highest joint efficiency of about 90 %, while granite and copper backing plates resulted in significantly lower joint efficiencies. While the presence of a tunnel defect was responsible for the loss of weld strength for copper backing plate, softening in HAZ could be responsible for loss of weld strength for granite backing plate. Separately,

As observed by Soundararajan et al. friction stir lap welding does not produce good quality welds with the same ease as friction stir butt welding. In addition to factors that influence quality of friction stir butt welds, clamping arrangement, sheet positioning, and pin height play an important role in FSW in lap configuration.

Buffa et al. show that shorter pins (significantly smaller than the combined thickness of the two sheets welded in lap configuration) with sheet placement and clamping as shown in Fig. result in better quality lap welds. Failure of friction stir lap welds, under monotonic or cyclic loading, is seen to be strongly influenced by hook and cold lap defects that form at the interface between stir/thermo-mechanically affected zone and the HAZs.

Yazdanian et al. observed that the height of hook and cold lap defects, which directly influence the lap shear strength, increased with increasing tool rotational speed and decreasing welding speed. In this work, friction stir welds were obtained using 6063-T4 aluminum alloy plates. 6063-T4 is a medium strength, naturally aged Al-Mg-Si alloy with good post weld formability characteristics and resistance to stress corrosion cracking.

2.1.5. Review on FSW optimizing parameter by using Taguchi method

Taguchi method is a numerical tool and is simple, economical and resourceful for various applications. It is an efficient method of analysis for the evaluation of the maximum number of parameters using a minimum number of experimental tests in an unbiased way Rao et al., (2008). The outcome of Taguchi method can also be associated with the statistical level of confidence. With respect to the Design of experiments (DOE), Taguchi's parameter design is one of the major and noteworthy tools for robust designing that also has a very simple and systematic methodology based on performance, the quality of the product and overall cost for the design optimization.

V. G. Patel and M. K. Patel (2014): This paper provides a comprehensive review of studies that have employed the Taguchi method for optimizing FSW process parameters. It discusses various factors considered in the optimization process, such as tool rotational speed, traverse

speed, axial force, tool geometry, and material properties. The review also highlights the effectiveness of the Taguchi method in improving weld quality and efficiency.

N. Arunbalaji and S. Murugan (2016): While not exclusively focused on the Taguchi method, this review paper provides a comprehensive overview of optimization techniques used in FSW, including Taguchi-based approaches. It discusses the significance of process parameters such as rotational speed, traverse speed, tilt angle, and tool geometry in FSW optimization. The review also examines the challenges associated with FSW parameter optimization and suggests directions for future research

N. Yedla, S. R. Poluri, and K. Ramachandra Reddy (2017): This review paper summarizes recent research efforts aimed at optimizing FSW parameters using the Taguchi method. It discusses the application of Taguchi-based experimental design techniques for determining the optimal combination of process parameters to achieve desired weld characteristics. The paper also evaluates the strengths and limitations of the Taguchi method in the context of FSW optimization.

2.2. Research gap

There is a significant opportunity to explore FSW materials by combining dissimilar metals with and without zinc particle reinforcement. Optimizing parameters and characterizing the mechanical properties of FSW materials remain areas requiring investigation. FSW, with optimized input parameters, holds potential for various application areas, as previous studies have demonstrated its suitability for use in ships, automotive, and aircraft applications.

Key input parameters such as zinc particle size, rotational speed, and transverse speed require analysis and optimization. Lower interfacial temperatures can influence fusion and material flow in the weld zone. Improper material flow can lead to anisotropic weld properties, making it challenging to assess the quality and durability of welded joints. Other potential causes of undesirable weld defects include insufficient friction time, dissolution of reinforcement particles, and distorted grain structures.

Welding dissimilar metals with varying physical and mechanical properties presents its own set of challenges. To address these issues, the development of a Taguchi technique for joining dissimilar materials is essential for regulating process parameters and minimizing defects."

CHAPTER THREE

MATERIALS AND METHODS

3.1. Introduction

In this section, different materials and machines that are used for welding of dissimilar metal material was discussed. The materials included in this section are Aluminium, Brass, D2 tool steel and zinc particle has been discussed. Machines and instruments were discussed with supporting photographs and schematic diagrams.

Welding and experimental procedure in this work for joining trials, the materials will cut in the plate size, each having dimensions $110 \times 75 \times 2$ mm shown in figure 3.1 of 6061 Aluminium and CZ108 Brass sheets. The backing plate of 5 mm thickness was placed at the bottom of the sheets. During the experiment, the plate of 6061 Aluminium was always placed at the retreating side while CZ108 Brass plate was on advancing side to enhance mechanical interlocking. A tool of D2 steel having shoulder diameter of 16 mm and heat treated to increase strength. The FSW parameters will be selected based on an experimental design incorporating an L9 orthogonal array test matrix with strength selected as the response factor. The parameters used in the operation are Zinc particle Wt. %, rotational speed, and transverse speed will be taken as (10, 15, 20 gram), (800, 1000, 1200 rpm) and (45, 55, 65 mm/min) respectively. The profile micro hardness was measured by using Vickers micro-hardness tester machines. Microstructural characterizations were carried in optical and scanning electron microscopy studies. For microscopy observations, samples were initially cut, mechanically polished and finally chemically etched. Scanning electron microscopy (SEM) studies aimed at investigating the fracture mechanisms and Zn particle distribution. Digimizer software was used for analysing crack size.

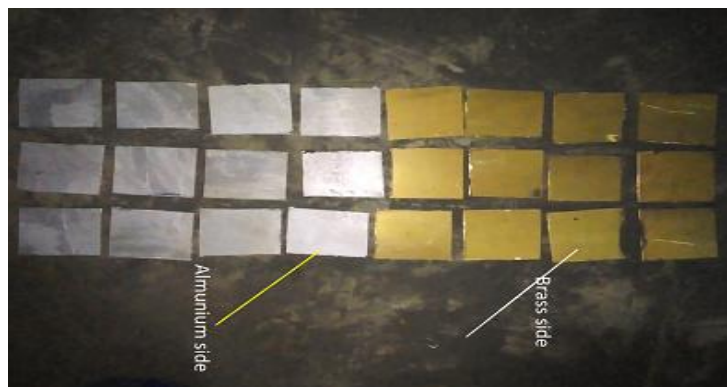


Figure 3.1: Base metal AA 6061 and Brass



Figure 3.2: shearing machine picture



Figure 3.3: FSW welded sample picture

3.1.1. Experimental Procedure

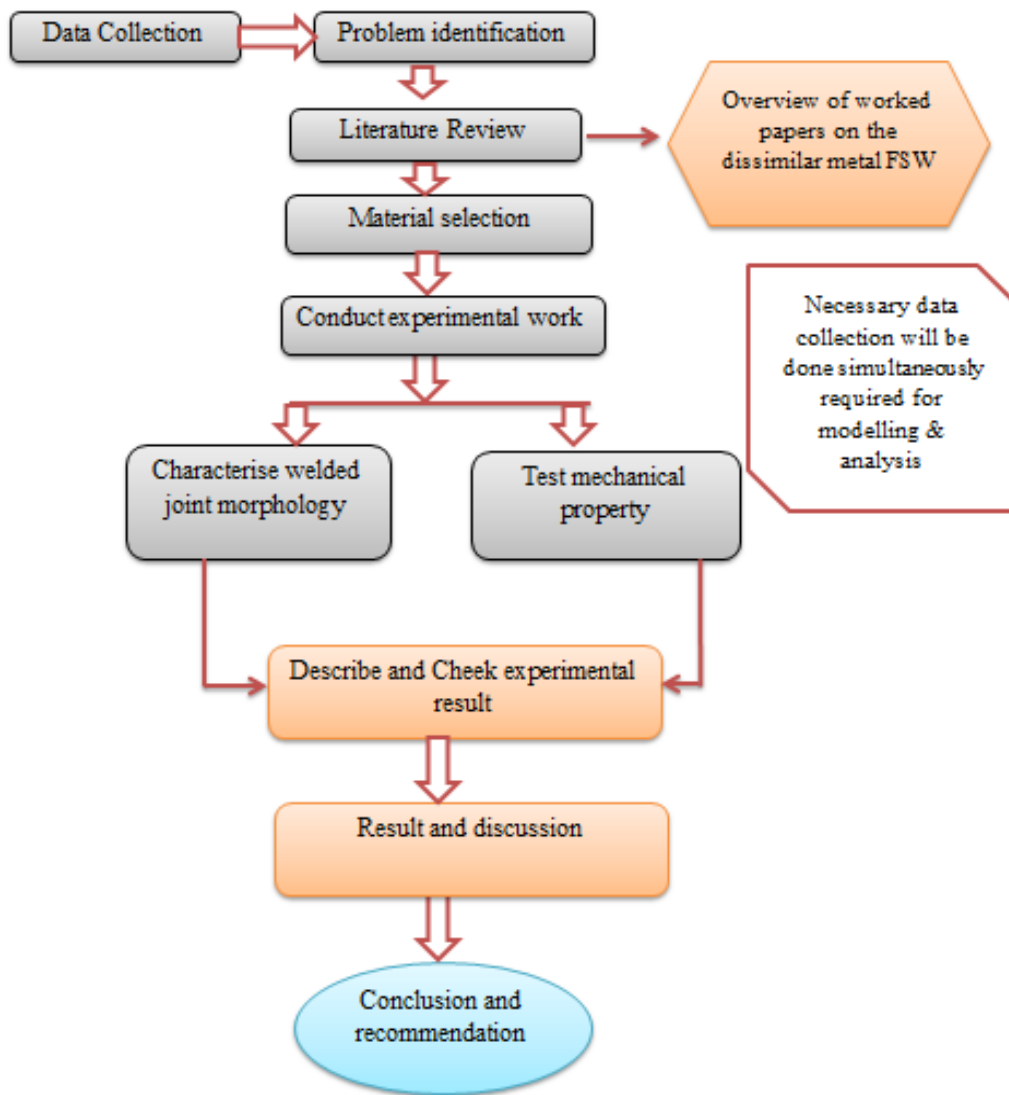


Figure 3.4: Experimental procedure

3.1.2. Materials and Composition

3.1.2.1. 6061 Aluminum

The 6061 aluminium is 6xxx aluminium alloys, which entails those mixtures which use magnesium and silicone as the primary alloying element. The nominal composition is listed below. The melting point is 588°C (1090°F). 6061 aluminium alloy is heat treatable, easily formed weld-able and good at resisting corrosion. The chemical composition and mechanical properties of AA 6061 are listed in table 3.1 and table 3.2.

Table 3.1: Chemical Composition of Aluminium 6061:

Elements	Si	Mg	Mn	Zn	Cr	Cu	Fe	Ti	Al
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Wt%	0.56	0.799	0.0818	0.015	0.5	0.24	0.31	0.0132	balance
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Table 3.2: Mechanical properties of Aluminium 6061:

Properties	Metric
Tensile strength	310 Mpa
Elastic modulus	68.9 GPa
Poisson's ratio	0.33
Elongation	12-17%
Hardness, Vickers	107

3.1.2.2. Brass

Brasses are alloy of copper and zinc. They may also contain small amounts of other alloying elements to impart advantageous properties. Brasses have high corrosion resistance and high tensile strength. Brass alloy CZ108 is a high purity cold forming brass. It is used when severe bending or riveting properties are required. The nominal composition, physical and mechanical properties of type Brass alloy CZ108 is listed in table 3.3. and 3.4.

Table 3.3: Chemical Composition of brass alloy CZ108:

Element	Cu	Zn	Pb	Al	others
Wt. %	62.57	37	0.101	0.0964	0.2326

Table 3.4: Mechanical properties of brass alloy CZ108:

Property	Value
Density	8.44Kg/m ³
Melting point	916 ⁰ c
Tensile strength	300-550 Mpa
Elongation A50mm	38-3%
Hardness Vickers	55-180HV

3.1.2.3. Bottom backing plate

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

steel (iron containing a small percentage of carbon, strong and tough but not readily tempered), also known as plain-carbon steel and low-carbon steel, is now the most common form of steel because its price is relatively low while it provides material properties that are acceptable for many application areas. The material used for backing plate are discussed by Ahmed et al. (2018) the- literature given the common backing plates used in the literature include medium carbon steel and mild steel.

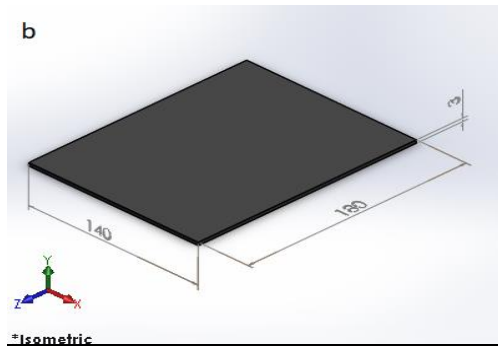


Figure 3.5: Back plate

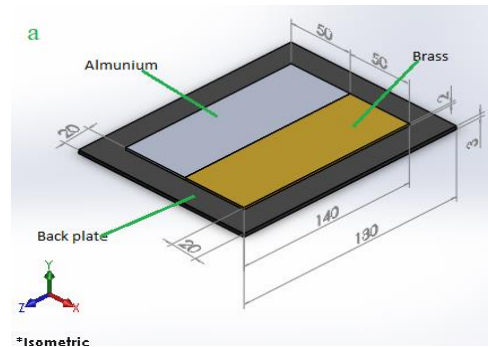


Figure 3.6: Assembly image

3.1.2.4. Zinc Particles:

zinc (Zn), chemical element, a low-melting metal of Group 12 (IIb, or zinc group) of the periodic table, that is essential to life and is one of the most widely used metals. The Zinc Dust is a pure metal powder, which is grey in color and is produced by condensation of purified zinc vapors. Zinc is of considerable commercial importance. Zinc is used as a reducing agent in chemical processes, mainly in the form of powder or granules. And it is widely used in the galvanization industry. The chemical composition and mechanical properties of Zinc particle are listed in table 3.5.

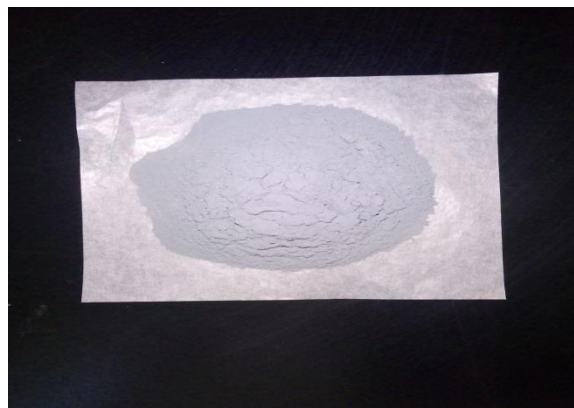


Figure 3.7: Zinc powder.

Table 3.5: chemical composition of zinc particle

Elements	Zn	Pb	Sn	Cu	Fe	Cd
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Wt. %	99%	0.005%	0.001%	0.005%	0.005%	0.05%
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Figure 3.8: zinc metal powder

Table 3.5: Properties of Zinc:

properties	Value
Atomic number	30
Atomic mass	65.38 u
Oxidation state	+2
Density	7.14 gm/cm ³
Melting point	419.5 °C
Boiling point	907 °C
Crystal Structure	Hexagonal
Molecular Weight	65.38 g/mole

3.1.3. Tool Design and Manufacturing:

3.1.3.1. Tool material:

Cold-work tool steels include the high-carbon, high-chromium steels or group D steels. This material is widely available, easily machinable and affordable in cost, due to this reasons the material is very applicable in wide manufacturing industries. D2 is very wear resistant but not as tough as lower alloyed steels. It is widely used for the production of shear blades, planer blades and industrial cutting tools. The density and melting point is $7.7 \times 1000 \text{ kg/m}^3$ and 1421°C The composition, mechanical and physical properties of D2 tool steel listed below in Table 3.6 and Table 3.7. D2 steel is an air hardening, high- carbon, and high- chromium tool

steel. It has high wear and abrasion resistance properties. It is heat treatable and will offer hardness in the range of 55- 62 HRC and good for short term operations. D2 is an air-hardening, high carbon, high chromium tool steel with extremely high wear resisting properties.

Table 3.6: Chemical composition of D2 tool steels.

Elements	Cr	C	Mo	Mn	Si	V	Ni	S	P	Co
Wt. %	11.36	1.58	0.61	0.32	0.014	0.13	0.15	0.014	0.02	0.167

Table 3.7: Mechanical properties of D2 tool steel.

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

3.1.3.2. Tool Design:

Pin/probe of tool

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

$$T = 0.8t + 2.2 \text{ mm} \quad (3.1)$$

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

Shoulder of tool

The shoulder of tool is the cylindrical surface responsible for generating the frictional heat. Shoulder diameter (D) also depends on the thickness of sheet metal.

$$D = 2.2 t + 7.3 \text{ mm} \quad (3.2)$$

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

Tool modelling

The FSW tool design by using CATIA V5 cad software in order to fabricate it and all the dimensions described mm. The tools with circular taper tool pin geometry namely were designed the geometry of FSW tool is shown in figure 3.9.

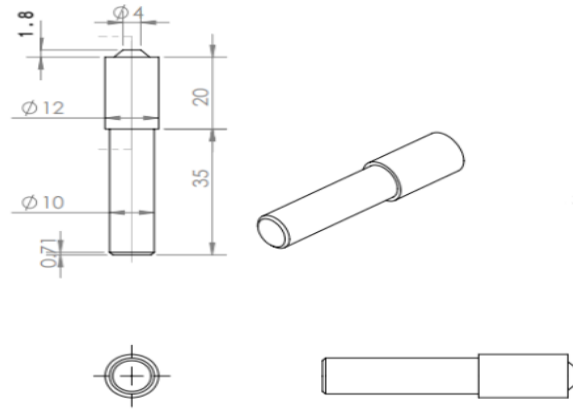


Figure 3.9: Circular tapered pin tool (All dimensions are in mm).

Table 3.8: Tool geometry depends on sheet metal thickness (Ramnath et a. (2018))

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

3.1.3.3. Tools Manufacturing:

Tools are manufactured on Lathe machine. A groove is made on the base of tool pin as shown in the figure 3.10; this will act as a clearance between the workpiece and tool shoulder and helps in mixing and binding the zinc particles with the base metal.



Figure 3.10: tool manufacturing process

The use of a non- consumable tool is mandatory during the FSW process. The pin, or probe, and the shoulder are its main components. Three main purposes are provided by the tool, namely heating the workpiece, stirring and moving the plasticized material in order to produce the welded joint and controlling the processed material under the tool shoulder (Besharati et al., 2014).

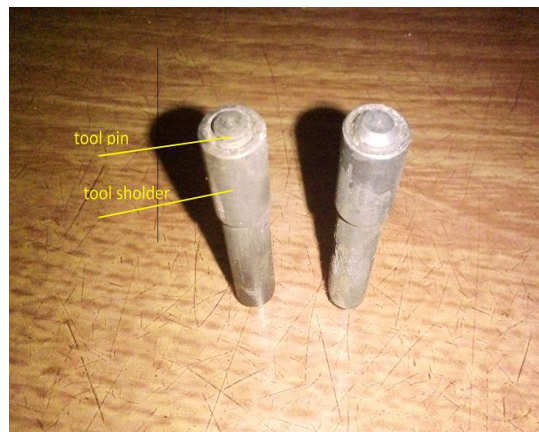


Figure 3.11: Tool profiles after manufacturing.

Table 3.8: Tool material measurements

S. No.	Tool description	Specification of tapered pin tool
1	Tool material	Heat treated D2 Steel tool
2	Tool shoulder diameter	16mm chamfered 0.5mm all round
3	Pin inner diameter	5mm
4	Pin outer diameter	3.5
5	Pin (probe) length	1.8mm

3.1.4. Tools and equipment

Milling machine

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



Figure 3.12: Milling machine

Spectrometers

Spectrometers are devices that are used to measure the spectra of samples. Typically, they measure the electromagnetic radiation intensity as a function of the wavelength of the radiation. There are many types of spectrometers designed to measure different types of spectra and to yield different types of information about their material samples. For example, a spectrophotometer measures ultraviolet, visible and near infrared light that is either reflected from or transmitted through a sample. APMI-MASTER Smart OES analyzer, which is made in Germany, spectrometer measures the light scattered from machine to the sample that has absorbed light at a different wavelength.



Figure 3.13: Spectrometers

Lath machine

Lath machines typically referred to as Turning machine, can be found in a variety of sizes and designs. While most lathes are horizontal turning machines and vertical machines are sometimes used, typically for large diameter work pieces. In this paper horizontal lath was used for manufacturing FSW tool.



Figure 3.14: Lath machine

Hardness tester

The purpose of the hardness test is to determine the suitability of a material for a given application, conformance to a specification, standard, or particular treatment to which the material has been subjected (heat treatment, thermal process). The three most commonly used are the Brinell test, the Vicker's Diamond test, and the Rockwell test. All three methods involve indentation of the material. The hardness is calculated by measuring the force applied and comparing this to some geometrical aspect of the indentation such as the surface area or depth.



Figure 3.15: Hardness tester

3.1.5. FSW proses parameter

Welding tool and equipment parameters are mainly dependent on mechanical properties of aluminium, brass, such as yield strength, ductility and hardness, which play significant influences on plastic deformation. And the selected process parameters are rotational speed, transverse speed and zinc particle Wt. %.

Tool rotational speed Experimental investigation and optimization of FSW process parameter of dissimilar metal with Zinc particle During FSW the quality of the joint mainly depends on the rotational speed of the tool results in the stirring and mixing of material around the rotating pin. For, these research three different rotational speeds were used 800rpm, 1000rpm and 1200rpm.

Traverse or welding speed In order to get a good quality of FSW welded joint welding speed has a great effect on the joints formed. In some cases, if higher welding has more defects because of not enough time to make stirring and mixing of the two materials. For this thesis three different welding speed was selected depends on previous researches 45 mm/min, 55 mm/min, and 65 mm/min.

Zinc particle Wt. %

In order to get a good quality of FSW joint reinforcement Wt. % has a great effect on the joints formed. In some case, if higher amount of reinforcement has more defects because of not enough time to dissolve and mixing of the two materials. For this thesis three different reinforcement composition was selected depends on previous researches 10 gram, 15 gram and 20 gram.

Table 3.9: Three levels with three factors.

Traverse Speed	Rotational Speed	Zinc particle Wt. %
(mm/min)	(rpm)	(Grams)
45	800	10
55	1000	15
65	1200	20

3.2. Taguchi Method

3.2.1. Taguchi Philosophy of Quality Engineering

Taguchi have been popular with both academic as well as industrial research and development. In what is termed as “off-line quality control” Taguchi advocates robust design to reduce variation from target value by making performance characteristics insensitive to noise factor. The characteristics features of Taguchi philosophy is the definition of quality as a loss function and reduction of variation from target in terms of a measure termed as signal to noise ratio.

3.2.2. Perspective of Taguchi Method:

Taguchi method can be broadly characterised under five categories

- Designing an experiment
- Robust design
- Orthogonal array
- Signal to noise ratio
- Quality loss function

Design of Experiments (DoE):

The design of an experiment involves the following steps

- Selection of independent variables
- Selection of number of level settings for each independent variable
- Selection of orthogonal array

- Assigning the independent variables to each column
- Conducting the experiments
- Analysing the data
- Inference

Robust Design:

A main cause of poor yield in manufacturing processes is the manufacturing variation. These manufacturing variations include variation in temperature or humidity, variation in raw materials, and drift of process parameters. These sources of noise / variation are the variables that are impossible or expensive to control.

The objective of the robust design is to find the controllable process parameter settings for which noise or variation has a minimal effect on the product's or processes functional characteristics. It is to be noted that the aim is not to find the parameter settings for the uncontrollable noise variables, but the controllable design variables. To attain this objective, the control parameters, also known as inner array variables, are systematically varied as stipulated by the inner orthogonal array. For each experiment of the inner array, a series of new experiments are conducted by varying the level settings of the uncontrollable noise variables. The level combinations of noise variables are done using the outer orthogonal array.

However, when the functional characteristics are not affected by the external noises, there is no need to conduct the experiments using the outer orthogonal arrays. This is true in case of experiments which are conducted using the computer simulation as the repeatability of a computer simulated experiments is very high.

Typical Orthogonal Array:

While there are many standard orthogonal arrays available, each of the arrays is meant for a specific number of independent design variables and levels. For example, if one wants to conduct an experiment to understand the influence of 3 different independent variables with each variable having 3 set values (level values), then an L9 orthogonal array might be the right choice. The L9 orthogonal array is meant for understanding the effect of 3 independent factors each having 3 factor level values. This array assumes that there is no interaction between any two factors. While in many cases, no interaction model assumption is valid, there

are some cases where there is a clear evidence of interaction. A typical case of interaction would be the interaction between the material properties and temperature.

Table 3.9: Layout of L_9 orthogonal array.

$L_9(3^3)$ Orthogonal array				
Experiment #	Independent Variables			Performance
	Variable 1	Variable 2	Variable 3	Parameter Value
1	1	1	1	p1
2	1	2	2	p2
3	1	3	3	p3
4	2	1	2	p4
5	2	2	3	p5
6	2	3	1	p6
7	3	1	3	p7
8	3	2	1	p8
9	3	3	2	p9

The Table 3.9 shows an L_9 orthogonal array. There are totally 9 experiments to be conducted and each experiment is based on the combination of level values as shown in the table 3.11. For example, the third experiment is conducted by keeping the independent design variable 1 at level 1, variable 2 at level 3 and variable 3 at level 3.

Signal to Noise Ratio:

In Taguchi designs, a measure of robustness used to identify control factors that reduce variability in a product or process by minimizing the effects of uncontrollable factors (noise factors). Control factors are those design and process parameters that can be controlled. Noise factors cannot be controlled during production or product use, but can be controlled during experimentation. Higher values of the signal-to-noise ratio (S/N) identify control factor settings that minimize the effects of the noise factors.

Taguchi experiments often use a 2-step optimization process. In step 1 use the signal-to-noise ratio to identify those control factors that reduce variability. In step 2, identify control factors that move the mean to target and have a small or no effect on the signal-to-noise ratio. The signal-to-noise ratio measures how the response varies relative to the nominal or target value under different noise conditions.

Taguchi design analysis signal to noise ratio.

Table 3.10: Taguchi design analysis signal to noise ratio.

Signal-to-noise ratio	Goal of the experiment	Data characteristics	Signal-to-noise ratio formulas (S/N)
Larger is better	Maximize the response	Positive	$S/N =$
	Target the response and you want to base the signal-to-noise ratio on standard deviations only	Positive, zero, or negative	$S/N = -10 \times \log_{10}(\sigma^2)$
Nominal is best	Target the response and you want to base the signal-to-noise ratio on means and standard deviations	Non-negative with an "absolute zero" in which the standard deviation is zero when the mean is zero	$S/N = -10 \times \log_{10}\left(\frac{\bar{y}^2}{\sigma^2}\right)$
Nominal is best (default)			
Smaller is better	Minimize the response	Non-negative with a target value of zero	$S/N = -10 \times \log_{10}\left[\sum\left(\frac{y^2}{n}\right)\right]$

Quality loss function:

Taguchi's approach differed from the traditional one of manufacturing a product within a specification based on tolerances equally spaced around a target value. He developed a concept of quality loss occurring as soon as there is a deviation away from the target value, and worked in terms of quality loss rather than just quality. He defined quality loss as: 'the loss imparted to society from the time the product is shipped', and this related the loss to society as a whole. Thus, it included both company costs such as reworking, scrapping and mainte-

nance, and any loss to the customer through poor product performance and lowered reliability.

A loss function curve can be calibrated by using information from the customer. Taguchi associates a simple, quadratic loss function with deviations from the target. Thus:

- The smaller the performance variation, the better the quality of the product.
- The larger the deviation from the target value, the larger the loss to society.
- A loss will occur even when the product is within the specification allowed, though it is minimal when the product is on target.

After the design engineer has determined the costs of parts being manufactured out of specification, this information can be used to justify expenditure on quality improvement, enabling decisions to be made on firm cost and quality grounds. Thus, the 'quality gain' from changing a design might sometimes be estimated as not worthwhile, though ensuring that a product is produced at a quality level acceptable to the customer remains an important consideration.

Table 3.11: The L9 orthogonal array (OA) and its level of control factors

Experiment #	L ₉ (3 ³) Orthogonal array		
	Travel speed(mm/min)	Rotational speed(rpm)	Zinc particle Wt. %
1	45	800	10
2	45	1000	15
3	45	1200	20
4	55	800	15
5	55	1000	20
6	55	1200	10
7	65	800	20
8	65	1000	10
9	65	1200	15

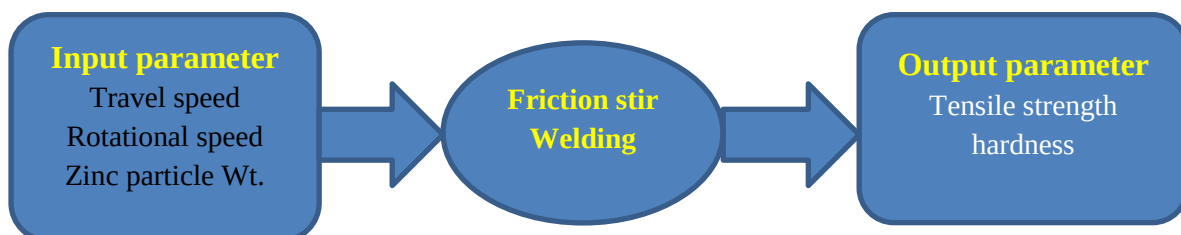


Figure 3.16: input and output of FSW

3.2.3. Steps in Taguchi Methodology:

Step-1:

- Identify the main function, side effects, and failure mode.

Step-2:

- Identify the noise factors, testing conditions, and quality characteristics.

Step-3:

- Identify the objective function to be optimized.

Step-4:

- Identify the control factors and their levels.

Step-5:

- Select the orthogonal array matrix experiment.

Step-6:

- Conduct the matrix experiment.

Step-7:

- Analyse the data, predict the optimum levels and performance.

Step-8:

- Perform the verification experiment and plan the future action.

3.3. Mechanical characterization

3.3.1. Hardness test

Hardness tests are extensively used to characterize a certain material and to identify if it is appropriate for its intended purpose. All hardness tests involve the utilization of a particularly shaped indenter that is harder than the material under testing. The indenter is pressed onto the test surface with the use of a certain amount of force. The size of the depth of the indent is measured in order to determine the hardness value.

Hardness tests are beneficial because:

- The hardness test is easy to conduct.
- Results can be obtained within 30 seconds.
- Tests are relatively cost effective.
- Finished components can be subjected to testing without being damaged.

- Any shape and surface size can be subjected to testing.

The major applications of hardness tests are to verify the type of heat treatment to be used on a part and to identify if a material possesses the required properties for its intended use. This makes hardness tests beneficial in variety applications. The five most common hardness scales are: Knoop, Vickers, Rockwell, Brinell and Shore. In this experiment Vickers's hardness test was used to measure the sample extrudes qualities. Vickers hardness test was measured to determine the hardness of a material, calculated from the size of an impress produces under load by a pyramid shaped diamond indenter. The samples are prepared for each test, 10 mm × 10 mm × 2mm specimen was cut at the cross section for microstructural study and macro-hardness. Before macro hardness measurement welded sample passed through different sample preparation steps these are mounted and grinded with 400, 800, 1200 and 2000 grit size sand paper and then polished by diamond suspension and finally etched at acidic solution. Macro-hardness was measured with Vickers micro-hardness tester HVS-50 machines just after microstructural test by using both 5Kgf and 10Kgf. After that, the diamond was pressed on the surface of material at measuring range up to approximately 10 Kgf (kilogram force) and the size of the impression was measured with the help of a calibrated microscope. The Vickers hardness number (HV) was calculated using the following formula:

$HV = \text{constant} \times \text{test force} / \text{surface area of indentation.}$

$$= 0.102 \times 2F \left(\frac{\sin 136^\circ / 2}{d_1 d_2} \right) \quad (3.3)$$

Where; F is indentation forces and $d_1 d_2$ is represents indentation area.



Figure 3.17: Macro hardness test of sample

3.3.2. Tensile Strength

A tensile tester, also known as a pull tester or universal testing machine (UTM), is an electromechanical test system that applies a tensile (pull) force to a material to determine the tensile strength and deformation behaviour until break. It is used to find out how strong a material is and also how much it can be stretched before it breaks. This test method is used to determine yield strength, ultimate tensile strength, and ductility, strain hardening characteristics, Young's modulus and Poisson's ratio.

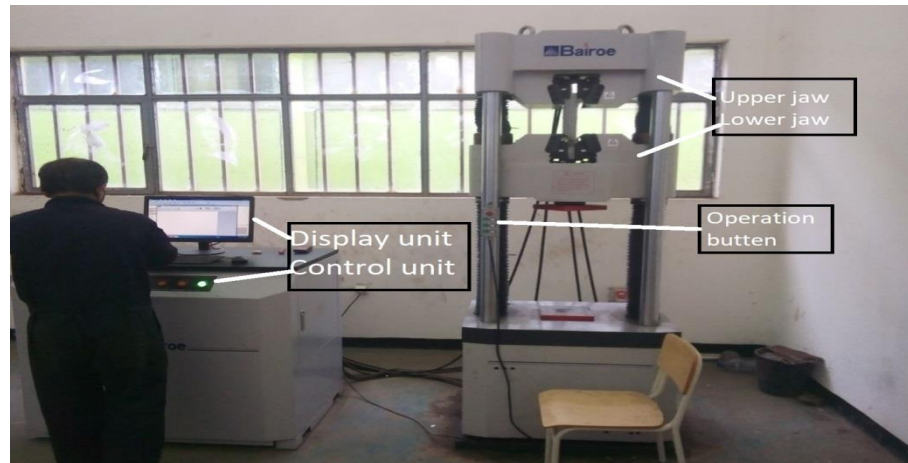


Figure 3.18: tensile testing machine parts

The tests were performed on the universal testing machine HUT-1000 series of microchip controlled Electro-hydraulic servo universal testing machines at Ethiopian Technical University material testing lab, Addis Ababa, Ethiopia as shown in (Figure 3.14). At a crosshead speed of 10 mm/min and the results were used to calculate the tensile strength of welded joint samples. The dimension of the specimens was 200 mm $\times$ 20 mm $\times$ 2 mm with a shape of dog bone type as shown in the Figure 3.19, and a uniaxial load was applied through both the ends. The ASTM standard test method for tensile properties of non-ferrous welded joint was conducted with UTM according to (ASTM E8) standard.

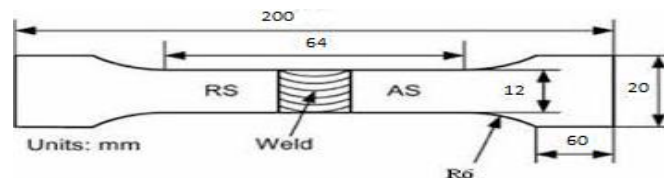




Figure 3.19: Tensile test specimen standard dimension (Davis, 2004)

3.4. Microstructural Analysis

3.4.1. OM (Optical Microscope)

By using OM (Optical Microscope) analysis, the qualitative information on the distribution of particles and morphology of hybrid composite specimen after polishing process can be observed. The microstructure analysis of the examined composites indicated that the mechanical properties were related to the proportion of particle in the welded joint. They were affected by defects (voids, holes, pores, cracks) in the structure. Voids and pores were formed during production incomplete dissolution of the particle in the welded joint.

Sample Preparation:

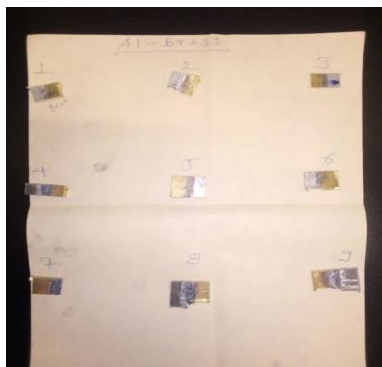


Figure 3.20: prepared sample for hardness test

From nine samples for each test, 10 mm × 10 mm × 2 mm specimen were cut at the cross section for microstructural study and macro-hardness measurement from each sample. Before macro hardness measurement welded sample mounted and grinded with 400, 800, 1200 and 2000 grit size sand paper and polished by diamond suspension. Macro-hardness was measured with Vickers micro-hardness tester HVS-50 figure 3.20 machines just after microstructural test by using 10Kgf.



Figure 3.21: Prepared samples for microstructure and hardness test

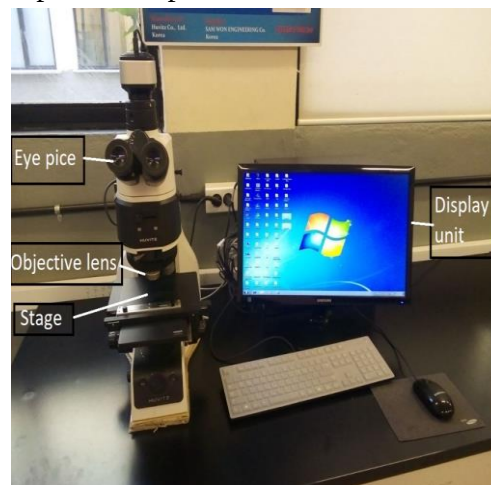


Figure 3.22: Optical microscope parts

3.4.2. Scanning Electron Microscope (SEM):

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that contain information about the surface topography and composition of the sample. The electron beam is scanned in a raster scan pattern, and the position of the beam is combined with the intensity of the detected signal to produce an image. In the most common SEM mode, secondary electrons emitted by atoms excited by the electron beam are detected using an Everhart-Thornley detector. SEM can achieve resolution better than 1 nanometre.

Sample Preparation:

SEM samples have to be small enough to fit on the specimen stage, and may need special preparation to increase their electrical conductivity and to stabilize them, so that they can withstand the high vacuum conditions and the high energy beam of electrons. Samples are generally mounted rigidly on a specimen holder or stub using a conductive adhesive.

Small sample pieces of size 10mm cubes are prepared by wire cut from the friction Stir welded plates as shown in the figure 3.23.



Figure 3.23: Scanning Electron Microscope in ASTU Biology Department.

3.4.3. Spectrophotometry

Spectrophotometry can be an extension of any of the foregoing types of spectroscopy. It is a term that refers to the quantitative analysis of spectra to compare the relative absorption or emission of different wavelengths of light. Spectrophotometry is the quantitative measurement of how much a chemical substance absorbs light by passing a beam of light through the sample using a spectrophotometer. By measuring the intensity of light detected, this method can be used to determine the concentration of solute in the sample

3.4.4. PSA (Particle size analyser)

With the laser diffraction technology of the PSA series you can determine the particle size and particle size distribution of both liquid dispersions and dry powders from the nanometre up to the millimetre range. The knowledge of the material's particle size and size distribution is essential for product development and quality control as these two parameters have an impact on the process ability as well as the properties of the final product.

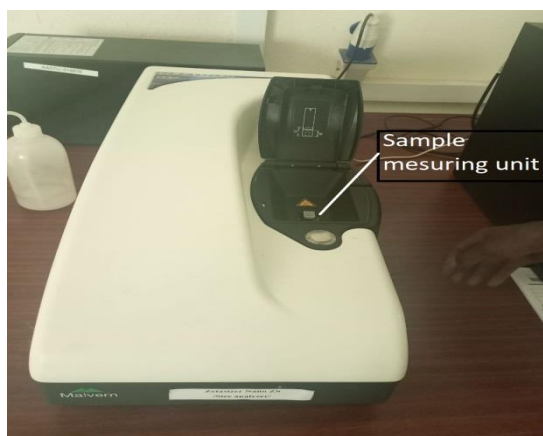


Figure 3.24: Particle size analyser

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Manufactured FSW tool for Dissimilar joint

In FSW, heat is produced as a result of the tool rubbing against the workpiece and the material deforming plastically. At the welding temperature, the tool material should be strong, tough, and hard wearing. Improvements in tool design have been shown to cause substantial improvements in productivity and quality. The tool contains different parts from them tool pin profile has a remarkable effect on the rubbing and the most effect on the plastic deformation. In this thesis work D2 tool steel was used to successfully to weld the dissimilar Brass and AA 6061 joint. FSW D2 tool manufactured through different operations such as: cutting, grooving, chamfering, facing, turning and heat treatment operation are using.

The figure 4.1 blow shows the FSW tool (D2 steel of FSW tool) after welding completely 18 AA 6061-brass samples (80 X 210 mm). The result shows the tip of tool (pin) of tool worn out due to friction between the tool and the workpieces during welding. The reduction of pin length for AA-Brass 0.7(reduced from 1.8 to 1.1) the diameter of the pin/probe for AA-Brass dissimilar joint increased by 3.1 mm (increased from 3.8 to 6.9).The diameter of AA-Brass joint is highly increased due to melting point temperature and hardness of Brass is high when compared to AA so that it requires more friction.



Figure 4.1: FSW tool after welding

4.2. Backing plate manufactured

A backing plate is a metal plate attached to the backside of a weld to prevent molten metal from dripping through the open root of a weld joint. It helps to ensure that 100% of the base metal's thickness was successfully weld defect free weld joint of AA 6061-Brass alloy sheet within optimized parameters fused by the weld (full penetration). Imam et al. (2015) studied effects of backing plate on macrostructure (heat affected and weld stirred zones) and weld mechanical properties were obtained for each of the cases. Due to the presence of back plate defect free welds could be obtained. It is manufactured by different process such as; cutting operations, grinding operation, drilling operations, thread operation and welding operation are used. Backing plate rigidly secured on milling machine table by the nuts bolts of length 21 mm M16 with 2 mm pitch thread to protect the movement of blank during welding process. Figure 4.2 shows the manufactured backing plate.



Figure 4.2: manufactured back plate

4.3. Analysis of Vickers Hardness test

Hardness is a material's resistance to deformation, indentation, or scratching. A material's resistance to deformation, indentation, or scratching is measured by its hardness. The Hardness testing's main objective of Hardness testing's is to measure a material's resistance to plastic deformation. The welded joint is significantly impacted by the materials' hardness. During the hardness test, a sample was loaded with 10 kgf. Two testes are followed for each sample, and then the average value was calculated. The Table below lists all the experimental data.

The average main value of hardness value for each factor i.e. Travel Speed (A), Rotational Speed (B), and Zinc particle Wt. % (C) calculated using the Minitab 22 design of experiments. The results obtained during hardness test on welded specimen of different process parameter are summarized in Table 4.1. It can be noted from the graph that the hardness of joint increases with increases in rotational speed and travel speed. Thus, the rotational speed and

travel speed helped in increasing the hardness of the welded joint hardness. (Ravi et al. (2018)) studied effect of tool rotational speed on mechanical and metallurgical properties of the weld joints. Observed better mechanical properties joint welded with 1000 rpm of tool rotational speed. Table 4.1 shows the separate signal to noise ratio of each sample in the design experiment. The largest values of the S/N ratios were indicated in sample number three and the lowest value in sample number seven with S/N ratios of 42.823 and 41.43 respectively. Those are respective highest and lowest S/N ratio value.

Table 4.1: Micro Hardness Vickers table for Aluminium brass joint

Exp. Run	Travel speed	Rotational Speed	Zinc Particle Wt. %	Hardness			S/N ratio
				Trial 1	Trial 2	Average	
1	45	800	10	127.1	135.9	130.25	42.2956
2	45	1000	15	125.0	121.0	133.95	42.5389
3	45	1200	20	134.3	142.5	138.40	42.8227
4	55	800	15	121.0	114.8	123.00	41.7981
5	55	1000	20	135.1	132.8	127.10	42.0829
6	55	1200	10	132.1	129.2	131.50	42.3785
7	65	800	20	127.8	126.4	117.90	41.4303
8	65	1000	10	130.6	129.9	127.10	42.0829
9	65	1200	15	123	124.3	130.65	42.3222
Average performance mean value						128.49	42.17

The mean value of hardness value for each factor i.e. Travel Speed (A), Rotational Speed (B), and Zinc particle Wt. % (C) at each level are obtained and the result is listed in response table 4.2. The main effect plot for means of hardness value variations during welding is as shown in the Figure 4.4. The result taken from the above Table 4.2 data shows means as larger is better is selected for hardness value.

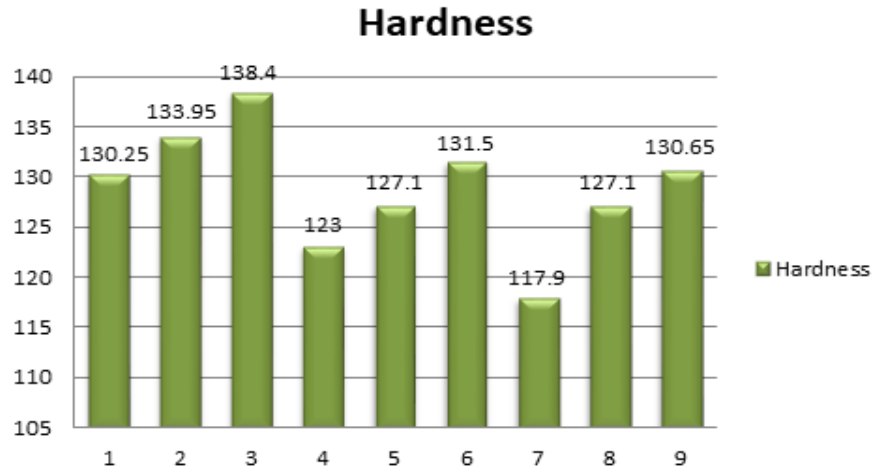


Figure 4.3: Hardness result graph

Table 4.2: Response table for main effect plot

Level	Traverse Speed (mm/min)	Rotational Speed (rpm)	Zinc particle Wt. % (Grams)
1	134.2	123.7	127.8
2	127.1	129.4	129.2
3	125.2	133.5	129.6
Delta	9	9.8	1.8
Rank	2	1	3

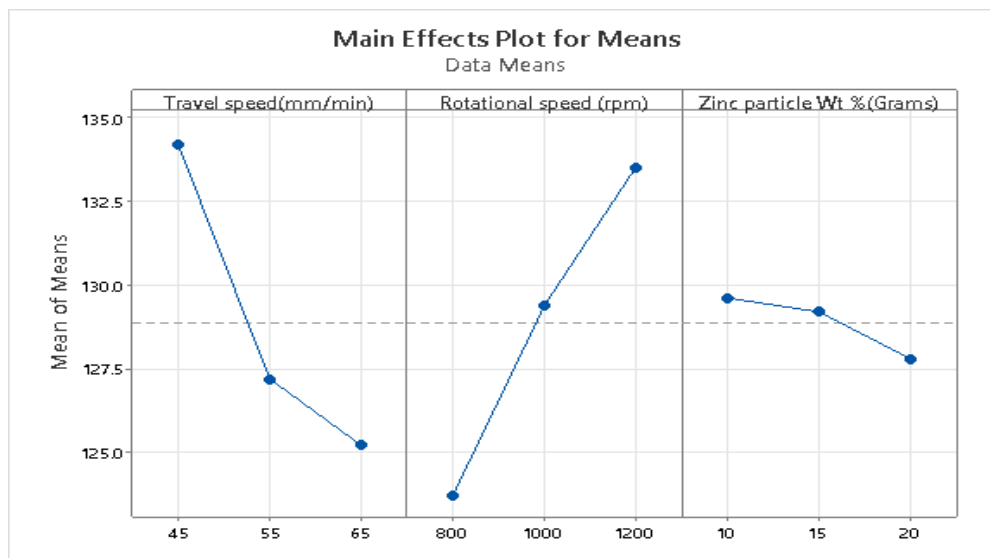


Figure 4.4 Main effect plot for means

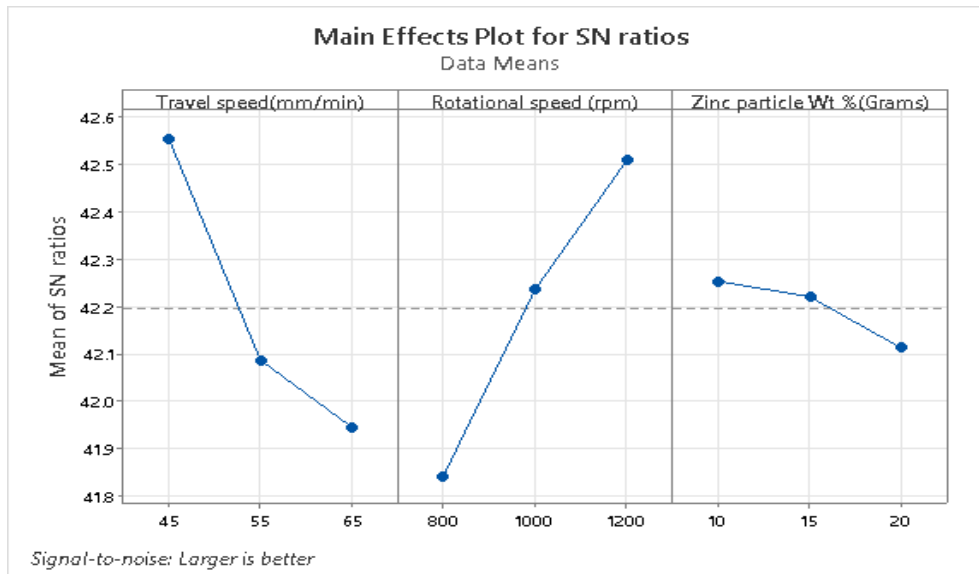


Figure 4.5 Main effect plots for SN ratios

Figure 4.4 shows the main effect plot for the control variables, which reveals that the means of hardness value variations. The conclusion drawn from the mentioned data is that larger is better hardness values are preferred.

Delta = (maximum mean – minimum mean).

Table 4.2 and Figure 4.4 demonstrate that Zinc particle weight percentage (Delta 1.8 =, Rank = 3) has the less impact on the mean from the table 4.2. Rotational Speed (Delta = 9.8, Rank = 1), the factor with the large impact on the mean, is the most important. Since means' primary effect plots can be used to change the mean's value, they are useful. Any parameter levels that result in specimens with better hardness values, such as **A1B3C3**, will be considered as a better parameter combination for better hardness values.

Predict the Performance at Optimal Levels the mean value

Three factors of parameter elements are chosen based on their mean values in order to predict the best response. The optimum levels of parameters mean value for hardness value are **A1B3C3**. The following equation is used to determine the predicted value of the responses (hardness value):

$$Y_{opt} = m + (mA1 - m) + (mB3 - m) + (mC1 - m) \quad (4.1)$$

$$Y_{opt} \text{ Hardness} = 128.86 + (134.2 - 128.86) + (133.5 - 128.86) + (129.6 - 128.86)$$

$$=124+5.34+4.64+0.74$$

$H_{opt}=134.72$ (predict mean value for hardness value) Where, m = Average performance mean value for tensile strength, $mA1$ = optimum level value for parameter A, $mB3$ = optimum level value for parameter B, $mC3$ = optimum level value for parameter C, H_{opt} = hardness at optimum level value.

Analysis of Variance (ANOVA) for hardness value

ANOVA results DOF = degree of freedom, SSTR = Sum of squares, MSE = Mean square error and F = F- Ratio calculated by using Minitab 22 software were shown in table 4.3.

Table 4.3: Analysis of Variance for hardness value

Source	DOF	SST	SSSTR	MSE	F	P	% contribution	Significance e ($\alpha=0.05$)
Travel speed	2	0.6056	0.6058	0.3029	21.68	0.044	45.29%	Significant
Rotational speed	2	0.6736	0.6736	0.3368	24.11	0.040	50.27%	Significant
Zinc	2	0.0324	0.3237	0.0162	1.16	0.463	2.43%	Insignificant
Particle Wt. %								
Residual error	2	0.0279	0.0279	0.0138			2.01%	
Total	8	1.3397					100%	
S=0.1182		R-Sq=97.91%		R-Sq(adj)=91.66%				

The analysis of variance (ANOVA) also shows that rotational speed and travel speed are significant factors affecting the hardness ($P < 0.05$), while Zinc particle Wt. % has almost no significance ($P>0.05$). Table 4.3 presents hardness value percentage contribution variation of factors A, B, and C. It is observed that factor Zinc Particle Wt. % has statistical and physical insignificances on the hardness value of weld joint. Both rotational speed and welding speed factor has statistical and physical significant on the hardness value at 95% confidence level. From the table 4.3 and figure 4.6 it is clearly observed that the rotational speed weight percentage (50.27 %), Travel speed (45.29 %) and Zinc Particle Wt. % (2.43 %) have significant influence on weld joint of FSW of AA 6061 with Brass alloy sheet. Therefore, controlling the rotational speed for welding AA and Brass joint will help to get good hardness.

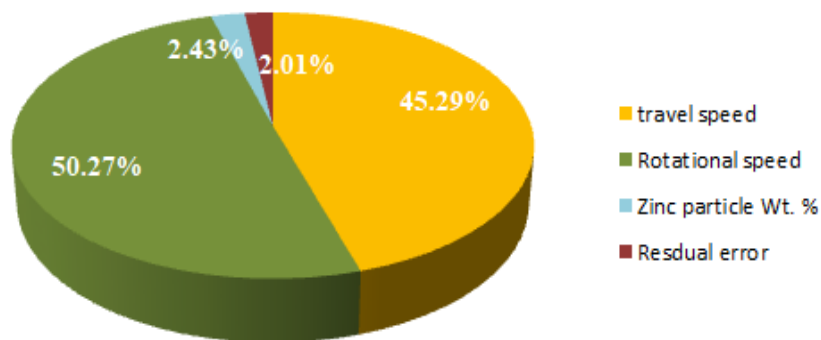


Figure 4.6: Percentage Contribution of welding parameters on hardness.

Determining the Optimum Condition for hardness value

From above discussion travel speed optimum level value 45 mm/min, Rotational speed weight percentage optimum level value 1200 rpm, and Zinc Particle Wt. % 20 % make the response S/N ratio values highest. Therefore, the optimum processing parameters signal to noise (S/N) ratio is selected. Table 4.4 and figure 4.7 presents the optimum parameters setting selected for hardness value obtained from the design of experiment and experimental results.

Table 4.4: Optimum parameters setting levels and their values

Controllable factors	Level selected	Value of the level	Rank of affecting the response
Travel speed	1	45	3
Rotational speed	3	1200	2
Zinc Particle Wt. %	3	20	1

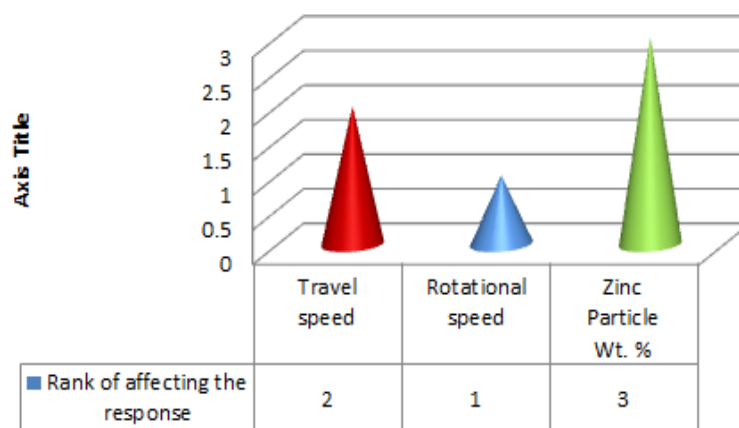


Figure 4.7: Rank of affecting response on hardness.

4.4. Tensile test result

A sample in the shape of a dog bone was tested for tensile strength using a universal testing machine. The experimental data in Table 4.7 were transformed to S/N ratios in order to analyse Taguchi's L9 OA utilizing the design of experiment. The impact of changing the process parameters, including rotational speed, travel speed, and zinc particle Wt. %, on the responses of mechanical characteristics was examined. The larger better-quality characteristic was chosen to explore the influence of factors on the response because higher values of mechanical characteristics were desired. The individual signal to noise ratio for each sample in the design experiment is shown in Table 4.7. The S/N ratios showed the highest values in sample number nine with S/N ratios of 44.7609 and the lowest value in sample number five with S/N ratios of 43.8625.

Table 4.7: Tensile table for Aluminium brass joint					
Exp. Run	Travel speed	Rotational Speed	Zinc Particle Wt. %	Tensile strength	S/N ratio
Base metals			Brass	256	
			Aluminium	106	
1	45	800	10	165	44.3497
2	45	1000	15	173	44.7609
3	45	1200	20	186	45.3903
4	55	800	15	157	43.9180
5	55	1000	20	159	44.0279
6	55	1200	10	166	44.4022
7	65	800	20	156	43.8625
8	65	1000	10	157	43.9180
9	65	1200	15	166	44.4022

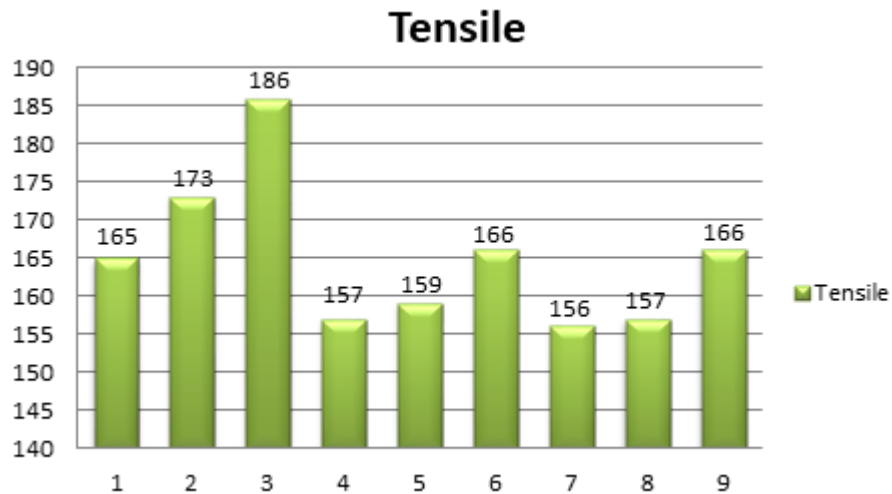


Figure 4.8: Tensile for each Experimental Run.

The mean value of tensile strength for each factor i.e. Travel Speed (A), Rotational Speed ((B), and Zinc particle Wt. % at each level are obtained and the result is listed in the main effect response table.

Table 4.8: Response table for main effect plot.

Level	Traverse Speed (mm/min)	Rotational Speed (rpm)	Zinc particle Wt. % (Grams)
1	174.7	159.3	162.7
2	160.7	163.0	165.3
3	159.0	172.7	167.0
Delta	15.0	13.3	4.3
Rank	1	2	3

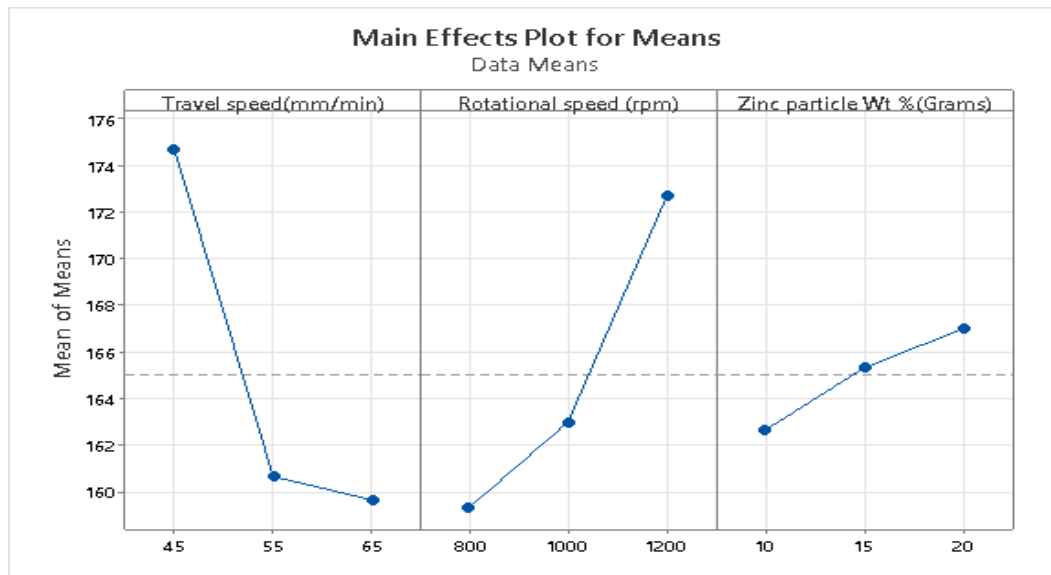


Figure 4.9: Main effect plot for Means

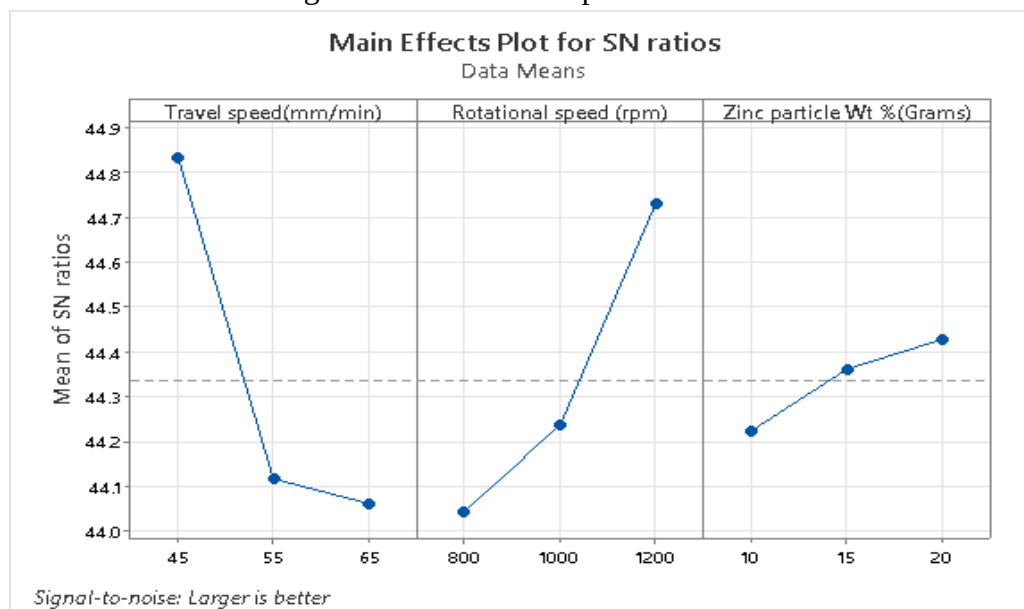


Figure 4.10: Main effect plot for SN ratios.

The control factors main effect plot for means of tensile strength value variations is as shown in the Figure 4.9. The result taken from the above data shows means as larger is better is selected for tensile strength value output.

Delta = (maximum mean – minimum mean).

Table 4.8 and Figure 4.9 show that the factor with the greatest effect on the mean from table is Travel speed (Delta 15.0 =, Rank = 1). The factor with the least effect on the mean is Zinc particle Wt. % (Delta = 2.43, Rank = 3). Since main effect plots for means is helpful for adjusting the mean on better value. Those parameter levels with better hardness value of speci-

mens that means **A1B3C3** will be taken as a possible parameter combination for better values.

Predict the Performance at Optimal Levels the mean value

For predicting the optimum response, three factors of parameters are selected by mean value. **A1B3C3** is the optimum levels of parameters mean value for hardness value. To find out predicted value of the responses (tensile strength value) the following equation is used:

$$Y_{op} = m + (mA1 - m) + (mB3 - m) + (mC3 - m) \quad 4.2$$

$$\text{Tensile strength} = 165 + (174.7 - 165) + (172.7 - 165) + (167 - 165)$$

$$T = 165 + 9.7 + 7.7 + 2$$

$$T_{opt} = 184.4 \text{ (predict mean value for hardness value).}$$

Where, m = Average performance mean value for tensile strength, $mA1$ = optimum level value for parameter A, $mB3$ = optimum level value for parameter B, $mC3$ = optimum level value for parameter C, T_{opt} = tensile strength at optimum level value.

Analysis of Variance (ANOVA) for Tensile strength value

ANOVA results DOF = degree of freedom, SSTR = Sum of squares, MSE = Mean square error and F = F- Ratio calculated by using Minitab 22 software were shown in table.

Table 4.9: Analysis of Variance for tensile strength value

Source	DOF	SST	SSSTR	MSE	F	P	% contri- bution	Significance e ($\alpha=0.05$)
Travel speed	2	1.1151	1.1151	0.5576	33.45	0.029	56.62%	significant
Rotational speed	2	0.7564	0.7564	0.3782	22.69	0.042	38.41%	significant
Zinc	2	0.0647	0.0647	0.0323	1.94	0.340	3.285%	Insignificant
Particle Wt. %								
Residual error	2	0.0333	0.0333	0.0167			1.691%	
Total	8	1.9695						
S=0.1291	R-Sq. =98.31%		R-Sq. (<i>adj</i>) =93.23%					

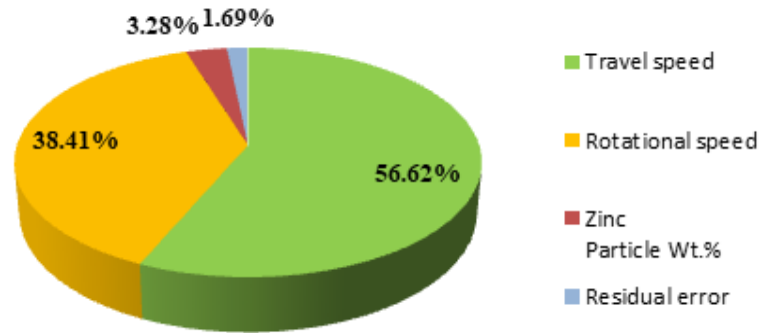


Figure 4.11: Percentage Contribution of welding parameters on tensile strength. The analysis of variance (ANOVA) also shows that rotational speed and travel speed are significant factors affecting the tensile strength ($P < 0.05$), while Zinc particle Wt. % has almost no significance ($P > 0.05$). Table 4.9 presents tensile strength value percentage contribution variation of factors A, B, and C. First travel speed, secondly rotational speed and thirdly Zinc particle Wt. % has statistical effect on the tensile strength value. From the table 4.9 it is clearly observed that the Travel speed (56.62 %), rotational speed weight percentage (38.41 %) and Zinc Particle Wt. % (3.285 %) have influence on weld joint of FSW of AA 6061 with Brass alloy sheet. Therefore, controlling the Travel speed for welding AA and Brass joint will help to get good Tensile strength.

Determining the Optimum Condition for tensile strength value

From above discussion travel speed optimum level value 45 mm/min, Rotational speed 1200 rpm, and Zinc Particle Wt. % 20 % make the response S/N ratio values highest. Therefore, the optimum processing parameters signal to noise (S/N) ratio is selected. Table 4.10 and figure 4.12 presents the optimum parameters setting selected for tensile strength value obtained from the design of experiment and experimental results.

Table 4.10: Optimum parameters setting levels and their values.

Controllable factors	Level selected	Value of the level	Rank of affecting the response
Travel speed	2	45	1
Rotational speed	3	1200	2
Zinc ParticleWt. %	1	20	3

Rank of affecting the response on tensile strength

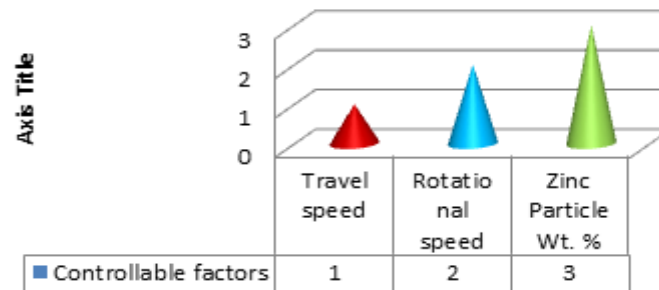


Figure 4.12: Rank of affecting response on Tensile strength.



Figure 4.13: Sample prepared for tensile test.

The amount of intermetallic compounds, the cold welding conditions (travel speed and rotational speed), which were performed at low rotational and medium or high travel speeds, and the zinc particle weight percentage were likely the three factors that had the greatest impact on the joint's tensile behavior. As the tool's rotational speed (or travel speed) is increased, frictional heat generation rises, causing the materials to be stirred and mixed more (see Figure 4.14), thus increasing the tensile strength (Soundararajan et al., 2007). Consequently, there is an increase in the development of the fine-grained size zone (nugget).

At the interface between the aluminum alloy and brass, a subsequent increase in rotational speed led to an abundance of intermetallic compounds (a larger intermetallic compound region; see s1), which decreased the tensile strength. Several authors suggested that the intermetallic compounds are responsible for the preferential development of cracks in the tensile strength test (Shojaeefard et al., 2013). They indicated that the intermetallic compound region

should mainly contain aluminum, brass, and Al₂Cu, Al₄Cu₉, and CuZn phases.

Furthermore, the tensile behavior of welds is examined. Results show that carrying out the welding procedure at a rotational speed of 1000 rpm, 55 m/min, and 10% zinc particle weight percentage is accompanied by a low ultimate tensile strength of 156 MPa for the joint, in addition to a brittle behavior. However, results of tensile tests indicate that at an optimum point, the ultimate strength of the joint will reach 80% of the aluminum tensile strength. As shown in Table 4.9, the weld fabricated by a rotational speed, travel speed, and zinc particle weight percentage of 1200 rpm, 45 m/min, and 20% possesses a maximum ultimate tensile strength of 186 MPa. In fact, these optimum parameters provide proper material flow resulting from a suitable temperature, along with sufficient forging force at the interface. Additionally, the weld has fewer defects and perfect mechanical bonding at the interface. Also, what makes this bond so strong is the narrow continuous intermetallic layer at the interface.

4.5. Microstructural Observation

Current research indicates that FSW joints exhibit symmetrical physical and mechanical characteristics. These are the result of the welding material's advancing and retreating sides being at different temperatures (Rao et al., 2013). Microstructure analysis involves examining the crystal structure using a microscope. In this study, one specimen was taken from each welding process parameter, and then microstructure observations were made in the welded zone (BM, HAZ, TMAZ, and SZ) on both the advancing and retreating sides (Mishra et al., 2005), as shown in Figure 4.14.

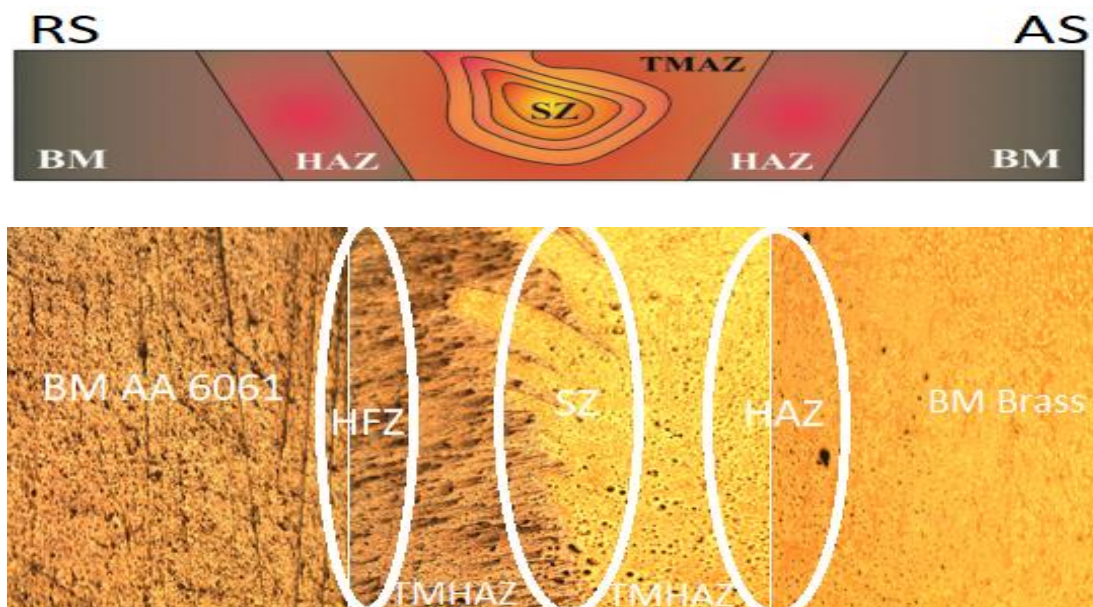


Figure 4.14: Microstructure BM, HAZ, TMHAZ and SZ analysis for sample 3. As shown in Fig. 4.14, optical microscopic investigations in the current work have identified four unique zones in all joints on both the aluminum and brass sides: (1) base metal or parent material (BM), (2) heat-affected zone (HAZ), (3) thermo-mechanically affected zone (TMHAZ), and (4) stir zone (SZ). The stir zone is composed of fine-grained dynamically recrystallized material and experiences the highest strain rates and temperatures. These factors contribute to continuous dynamic recrystallization and precipitate dissolution. Consequently, the large grains in the BM undergo dynamic recrystallization in the stirred zone, attributed to high plastic deformations and temperatures, resulting in coarser grains in the TMHAZ and finer grains in the stirred zone. The structure of the TMHAZ is noticeably distorted, with grains produced by dynamic recrystallization interfaced on each side of the nugget zone. Typical micrographs of TMHAZ associated with the brass and aluminum sides are shown in Fig. 2a, while the microstructure in the HAZ is depicted in Fig. 2d. The HAZ remains unaffected by mechanical effects, with absent plastic deformation. Thus, modification of the initial grain structure in the HAZ is solely attributed to the thermal cycle induced by frictional heat (Shojaefard et al., 2013).

Three key features of this region that need to be studied are weld defects, scattering particles, and microstructure. According to Fig. 4.15, a tool rotating fast or slowly will cause more weld defects. Weld defects such as tunneling defects, wormholes, and macroscopic cracks usually arise from improper material flow in the stir zone (Nandan et al., 2008).

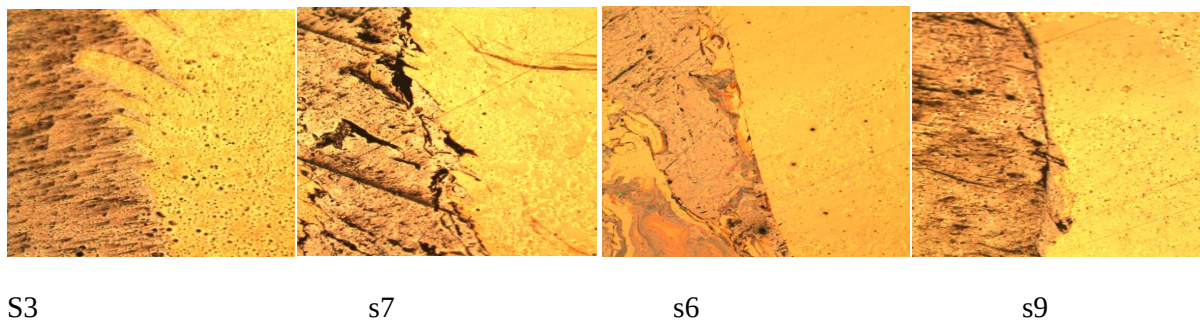


Figure 4.15: different samples microstructural results.

Additionally, as shown in Fig. S7, in this scenario, aluminum adheres to the tool and the pin erodes more. This effect facilitates the development of large defects in the nuggets. However, results from Fig. S3 indicate that a moderate material flow is achieved in the stir zone at a rotation speed of 1200 rpm, resulting in a defect-free stir zone. The formation of onion rings at this rotation speed confirms the establishment of a proper material pattern (Fig. 4.15 S3). Moreover, it is observed that by reducing the rotation speed to a moderate rate, the size of

scattered particles in the stir zone significantly decreases. As shown in Fig. 4.15 S9, a composite structure is formed by fine brass particles dispersed across an aluminum matrix at a rotational speed of 1000 rpm. Due to their modest size, these particles do not produce interface discontinuities.

Slow rotation (800 rpm) prevents the joint area from reaching a suitable temperature due to insufficient heat generation. Consequently, the stir zone cannot be appropriately plasticized, resulting in defects, especially macro cracks along the upper surface of the weld, as shown in figures S7 and S9. Additionally, excessive heat from high-speed rotation (1200 rpm) overly plasticizes the stir zone, decreasing the yield strength of brass near the interface. Low viscosity in the nugget zone leads to greater turbulence, resulting in weld defects, particularly tunnel defects. Softening of brass near the interface causes large brass fragments to form in the stir zone, accompanied by sharp angles that cannot be perfectly filled by plasticized aluminum, leading to adjacent weld defects, as seen in S7 and S6.

Furthermore, grain growth in brass is not as intense as in aluminum due to its higher melting point, resulting in a lower grain growth temperature and less heat exposure.

The grain shape in the base metal area of AA6061 appears slightly dark due to strain hardening treatment processes during manufacturing. After cold working, these grains become flat, with the elongation direction aligned with the rolling direction. The microstructure of base metals AA6061 and brass is generally dark, with slight lightness, indicating the presence of the aluminum-brass phase, while the light color represents the AL-brass phase

4.5.1. Influence of Pin Profiles and Preheat Temperature at HAZ

The microstructural changes in the HAZ region can be observed in Figure S3, which compares the grain sizes in each of the FSW specimens, particularly in the HAZ retreating side (RS) and the HAZ advancing side (AS) welds. These images illustrate that when there is a greater variation in the preheating temperature, the grain size in the HAZ RS and AS areas increases. This phenomenon occurs because a larger heat input results in a slower cooling rate.

The influence of pin profiles and preheat temperature at the TMAZ depicts the microstructural changes in the TMAZ area on the RS and AS sides. It shows that the areas affected by the tool mixing have a flat and elongated microstructure, which is used by the tool to weld the

nugget area. The grain size in this zone appears smaller than in the HAZ area (Patel et al., 2016).

4.5.2. Influence of Pin Profiles and Preheat Temperature at Weld Nugget

In Figure 4.14, the microstructure in the weld nugget (stir zone) is depicted. Compared to the grain size between the HAZ and TMAZ, the grain size becomes finer and denser in the weld nugget because it is deformed by the pin tool during the welding process. The weld nugget area undergoes plastic deformation due to stirring from the FSW tool, leading to grains being refined through dynamic recrystallization. Consequently, the grain size becomes finer than in the HAZ and TMAZ regions. This demonstrates that changes in the grain size of the microstructure during the welding process are closely linked to the heat behavior and plastic deformation occurring during welding.

Preheating softens the materials and enhances material flow in the stir zone, reducing welding speed and improving efficiency. Verma et al. (2019) reported an 8% increase in joint strength with preheating compared to conventional FSW. As the preheat temperature rises, the welding temperature spreads more uniformly over the tool, resulting in a slower cooling rate. A coarser grain size can be achieved when the cooling rate is slower. Muhayat et al. (2021) indicated that some extra grain development occurred because the maximum temperature of the stir zone increased as the rotation speed of the tool increased.

4.5.3. Macro examination of aluminum (6061)-brass interface by using DIGIMIZER

Identification of crack growth and fractured surfaces at welded joints is crucial. However, with different metals and surface topologies, determining the crack length of an open fractured surface using non-destructive testing (NDT), thermal imaging, etc., can be challenging. In such cases, it is often easier to determine critical crack lengths and cracked areas using image segmentation techniques.

Based on friction welding tests conducted, specific surface cracks were identified based on the crack length and scratched surface area. These cracks are represented by varying color intensities such as black, red, green, and blue. The study concludes that in Figures a and l, there is a strong color contrast between the welded areas. Figures display a screenshot of the different colored intensities provided by color regions generated using the DIGIMIZER software.

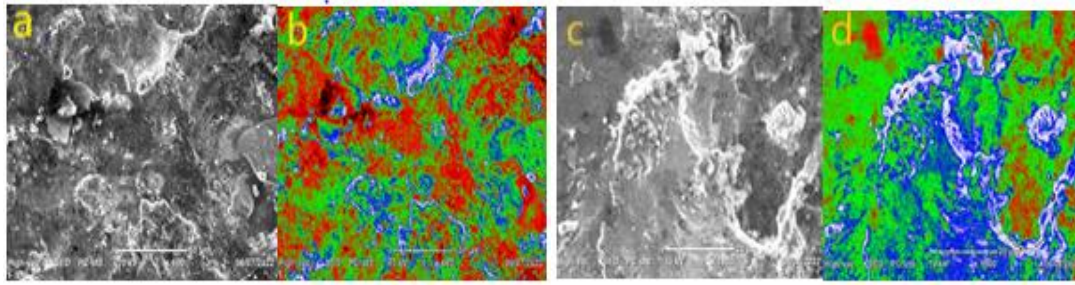


Figure 4.16 SEM and digmizer image for S1 (a and b) and S3 (c and d). When compared to other colour intensities the crack length was found to be less Px for s4 and s3. The surface crack is represented by area of blackness, which contains fewer micro cracks. For s1 the crack length was 66.2503 and the crack area was 1317.127 Px, as seen in figure 4.16 b. The most surface of the welded interface may be seen in the region was red colour, where for s3 in figure 4.16 d the longest crack measured was 25.5226 and crack area was 171.682 Px, was found the most surface of the welded interface seen in the region was blue colour. The dark peak zone, denoted by the coloured intensity region, is believed to be the location of the surface cracks.

Table 4.11 degmizer crack area description for sample 1 result

Tool	Measure	N	Mean	SD	Min	Max
Area	Area	8	425.2926	440.6995	52.025	1317.127
	Perimeter	8	98.0243	66.9183	32.011	212.374
	Length	8	34.4163	20.9161	13.156	66.290

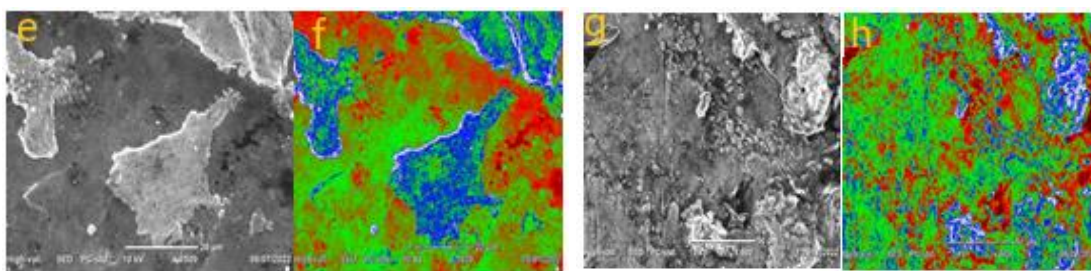


Figure 4.17: SEM and digmizer image for S4 (e and f) and S6 (g and h). At the close vicinity of edges, in these samples, a few numbers of cracks are identified when compared to the other samples of the welded joint with high green-colored intensities. Due to the smallest crack length being 25.5226 and crack area 117.682 seen in Figure 4.17f, green color intensity is discovered to be greater when compared to other colour intensities, indicating that less heat energy was supplied. Figure 4.17f and h display various colored intensities. Based on statistical evaluations of the fragmented surface's parts, the typical shade of blue

intensities is less, which is a measure of the good quality of the weld. The maximum for s6 crack length of 59.9974 and crack area 1257.428 px was discovered. A maximum broken surface area of 1724.734 Px2 was discovered

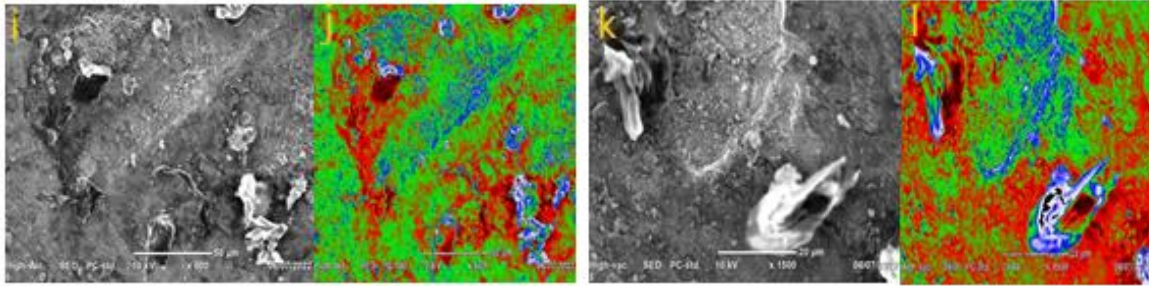


Figure 4.18: SEM and digmizer image for S8 (i and j) and S7 (k and l).

The surface of the previous samples contains a lot of green and colorful patches, which show fewer cracks on the surface. The crack width was extracted based on black color intensities, as depicted in Figure 4.18j and l, which contained a significant amount of fragmentation compared to the other sample's crack length and crack area for sample 8 (90.446 and 3030.51) and sample 7 (117.956 and 4187.445) Px. The last sample had the highest average surface crack length and crack area

Table 4.12: degmizer crack area description for sample 7 result

Tool	Measure	N	Mean	SD	Min	Max
Area	Area	11	1514.4801	1085.3835	440.009	4187.445
	Perimeter	11	200.7943	92.5680	88.954	380.547
	Length	11	70.7134	24.8484	28.827	117.956

It was discovered that there are many pores on the metallic surface as a result of different process parameters acting on the weld, which causes various surface cracks and the occurrence of different weldings are provided by the DIGIMIZER software. When compared to other welded regions, the red-colored intensities were higher in figures b, j, and l. Figure l illustrates the greatest crack length and crack area, which is based on statistical measurements. Tables 4.11 and 4.12 present various mean results. Using statistical measurements of the segments at the broken surface, all figures provide information regarding the various intensities at the welded zones. Experimental validation was done to ensure that the process settings produced the best results, and it was verified that the maximal welded zone crack had an area and length of 4187.445 and 117.956 Px. A minimum welded area and length crack of 171.682 and 25.522 Px was discovered.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

This chapter presents the summary and conclusion derived from the study, which optimized the process parameters and mechanical properties of dissimilar metals in FSW of Aluminum and Brass. It also provides recommendations and the scope for future work that can be pursued by manufacturing engineering scholars.

5.1. Conclusion

The current study focused on FSW welding of dissimilar metals using zinc particles as reinforcement on a CNC milling machine with a D2 tool steel welding tool. FSW tools, backing plate, and the clamping system were manufactured for this purpose. The main welding parameters studied were travel speed, rotational speed, and zinc particle weight percentage. The effect of these parameters on hardness and tensile strength was studied using an L9 Taguchi orthogonal array design. Selection of welding parameters was based on knowledge from the literature, recommendation's and experience. The role of each factor was identified through analysis of variance (ANOVA) for each response. Based on the results, the following conclusions were drawn:

- ✚ The optimum combination of parameters obtained from the main effect plot for the signal-to-noise (S/N) ratio and mean resulted in the best combination for tensile strength and hardness at 1200 rpm rotational speed, 45 mm/min welding speed, and 20% zinc particle weight percentage. The optimized tensile strength and hardness values were predicted as 186 MPa and 138.4 HV, respectively.
- ✚ Higher values of tensile strength were observed at 186 MPa. Analysis of variance indicates that travel speed, contributing 56.62%, had the highest influence on the tensile strength of the welded joint, followed by rotational speed at 38.41%, and then zinc particle weight percentage at 3.28%. Therefore, travel speed was the most significant factor affecting tensile strength.
- ✚ Higher values of hardness were observed at 138.4 MPa. Analysis of variance indicates that zinc particle weight percentage, contributing 73.3%, had the highest influence on the hardness of the welded joint, followed by rotational speed at 14.46%, and then travel speed at 8.54%. Therefore, the amount of zinc particle weight percentage was the most significant factor affecting hardness.

- ✚ According to optical microscopic investigations, three distinct zones were identified: the stirred (nugget) zone, the thermomechanically affected zone (TMAZ), and the heat-affected zone (HAZ). FSW resulted in defect-free weld joints and grain boundary refinement in the stirred zone.
- ✚ According to SEM outcomes, fragment defects were accompanied by the formation of other defects, including tunneling defects and voids in their vicinity. Although tunneling and void defects are directly observable through SEM images, this study indicates that the occurrence of coarse and continuous fragments of brass in SEM images can be interpreted as reliable evidence of defect formation

5.2. Recommendation

Based on the results and conclusions found from this study, the following recommendations are made;

- ✚ This investigation was limited to dissimilar nonferrous materials (AA 6061 and Brass). However, other dissimilar materials could be explored and analysed.
- ✚ The study could be extended by using other reinforcements (such as SiC, Cu, etc.).
- ✚ The Further extension of the study could involve exploring various parameters and their effects on different mechanical properties.
- ✚ H13 tool is recommended for mass production of friction stir welding operation, as it is a hot working tool steel.

5.3. Futures work

- ✚ Study the effects of tool wear on joints on different mechanical and microstructural properties, as well as types of tool wear.
- ✚ Only three welding parameters were studied in this research: travel speed, rotational speed, and zinc particle weight percentage. Further research should incorporate other parameters such as temperature measurements, tilt angle, and measurement of the forces acting during the process.
- ✚ More investigation is needed on welding different thicknesses of workpieces to test the joints between the base metal and the backing plate.
- ✚ The present study can be further extended by employing different optimization techniques, such as multi-response optimization and response surface methodology, with various processing parameters.

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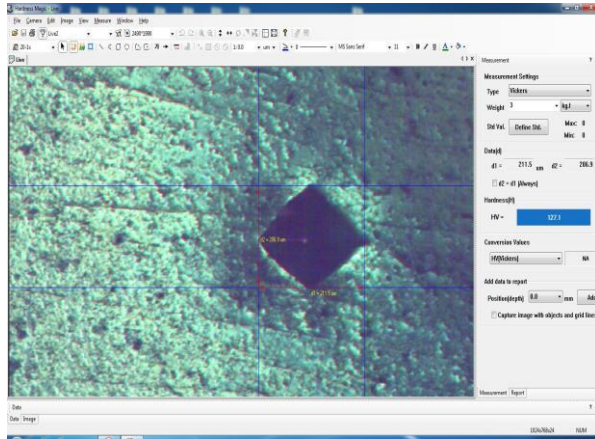
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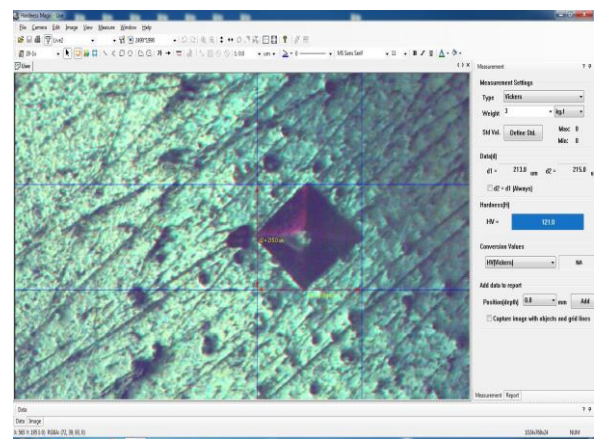
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APPENDESIC

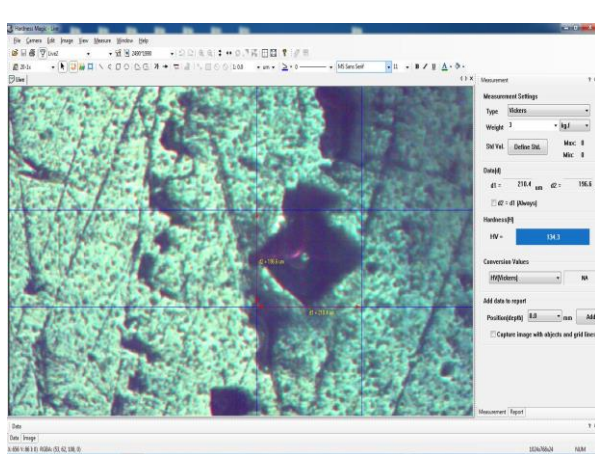
Appendix 1: Vickers Hardness data



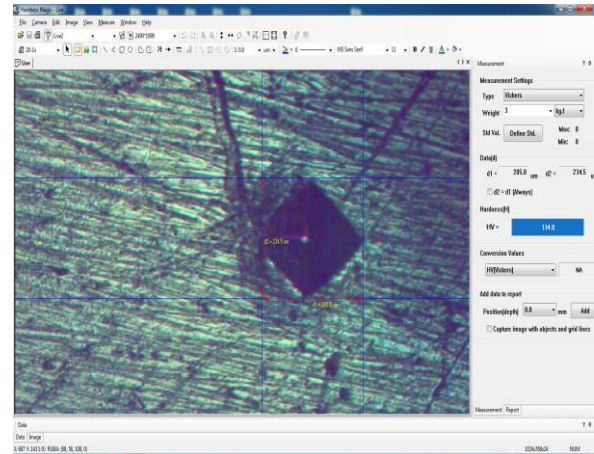
Vickers Hardness Value for sample 1



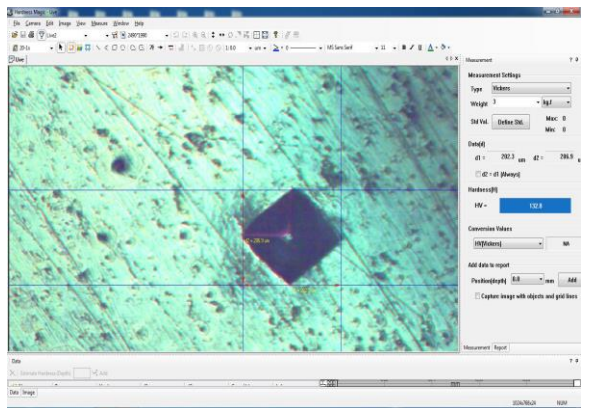
Vickers Hardness Value for sample 2



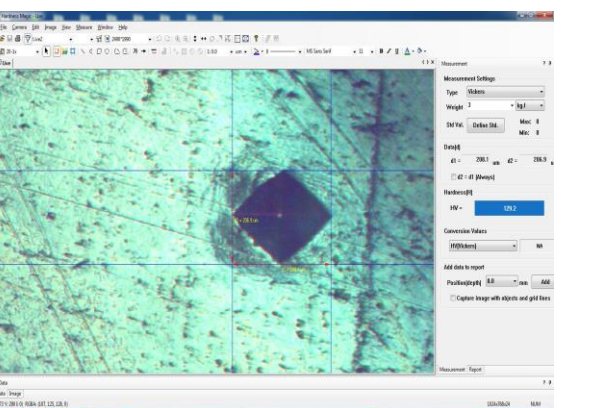
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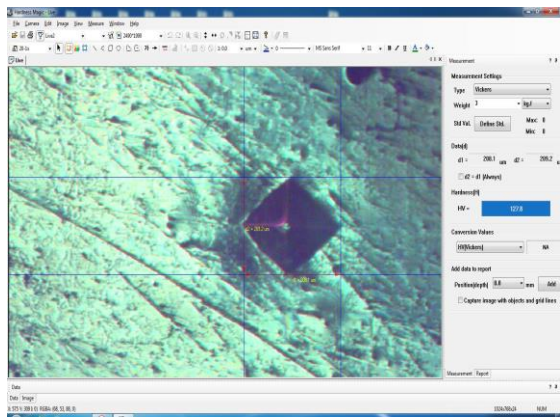
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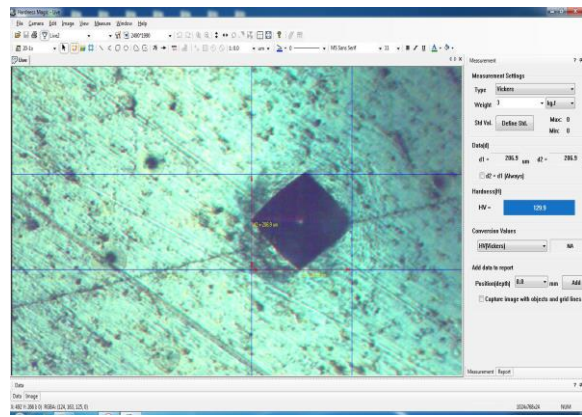
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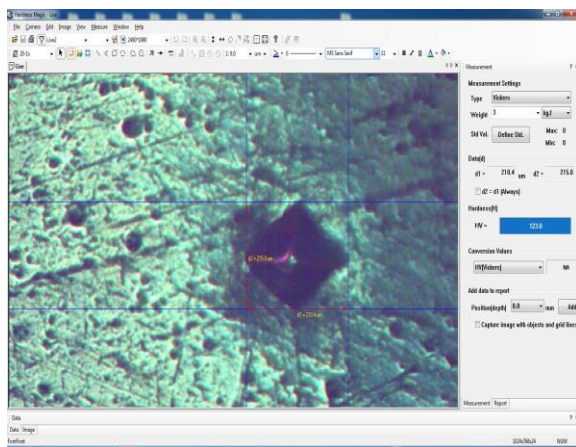
Vickers Hardness Value for sample 6



Vickers Hardness Value for sample 7

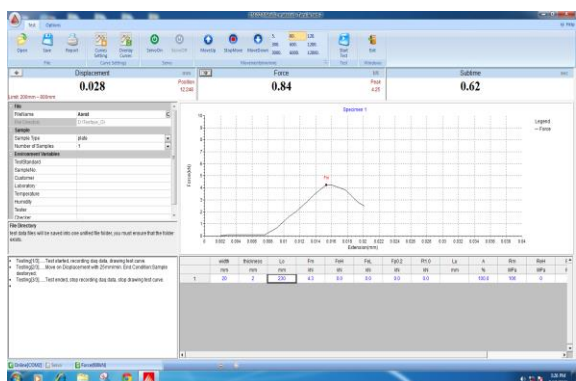


Vickers Hardness Value for sample 8

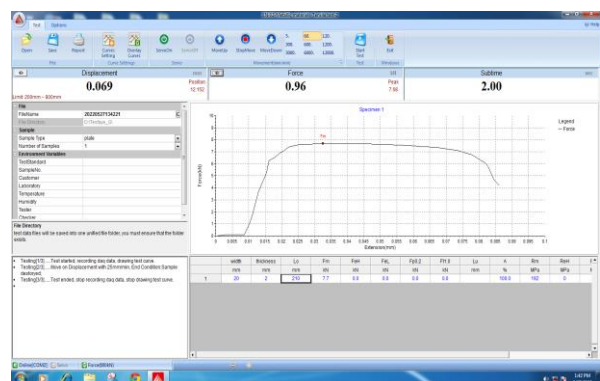


Vickers Hardness Value for sample 9

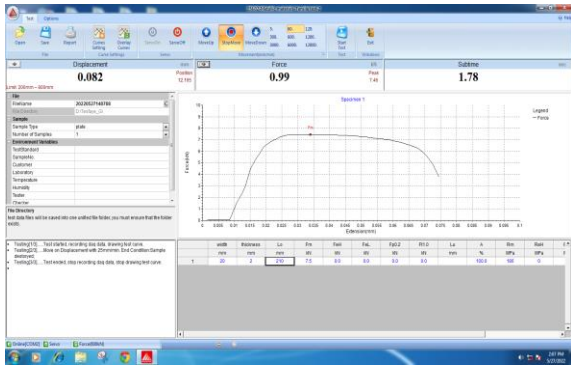
Appendix 2: Tensile strength data



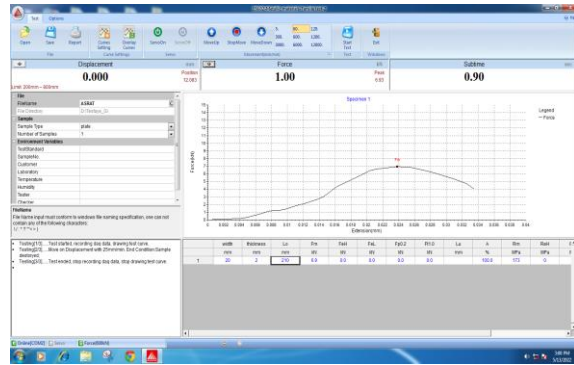
Tensile strength Value for base metal brass



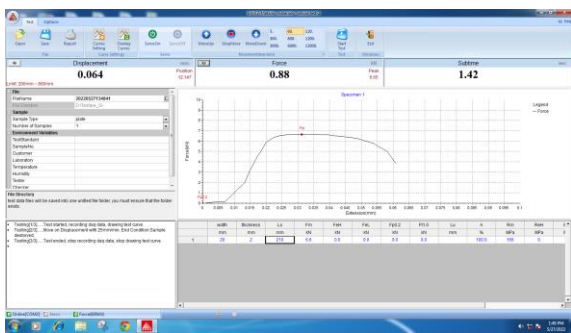
Tensile strength Value for base metal AA 6061



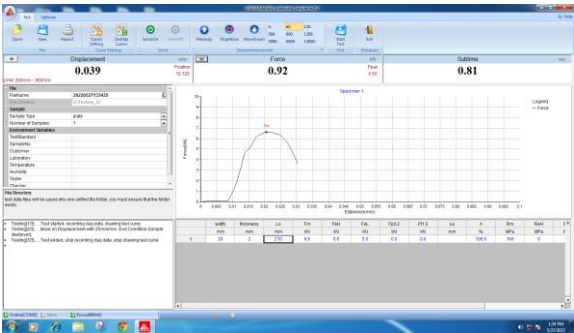
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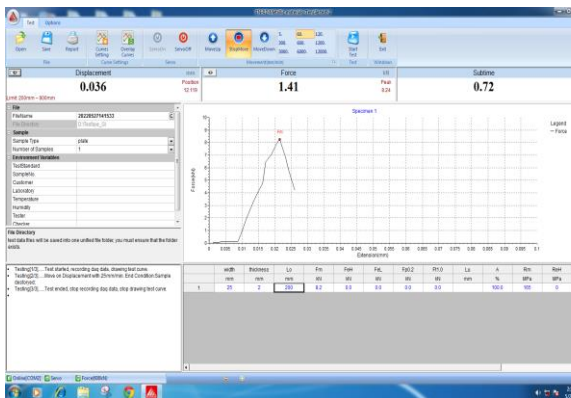
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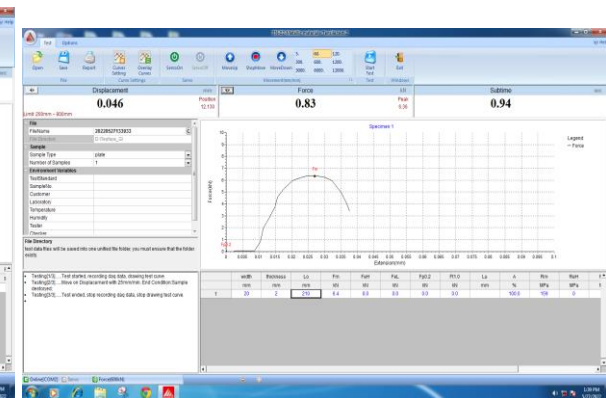
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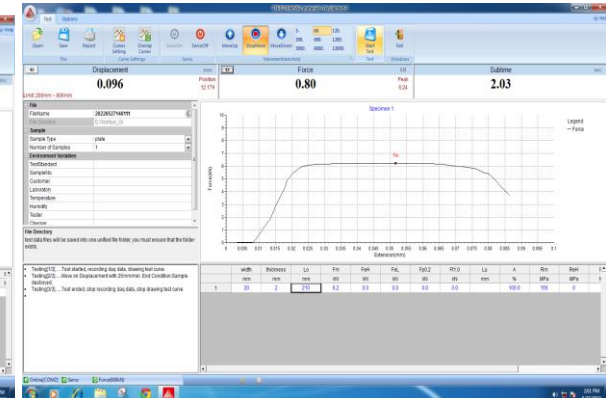
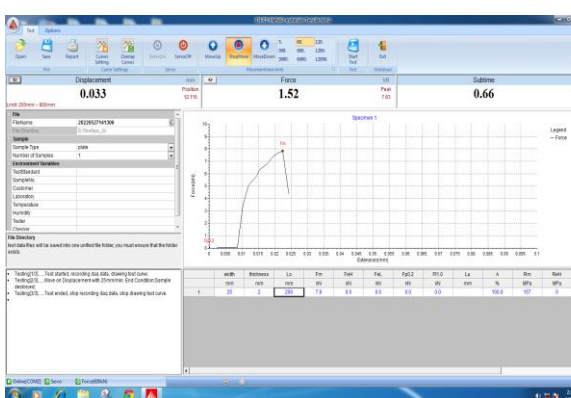
Tensile strength Value for sample 4



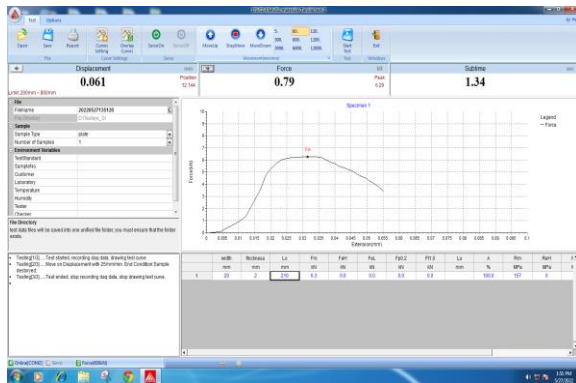
Tensile strength Value for sample 5



Tensile strength Value for sample 6



Tensile strength Value for sample 7



Tensile strength Value for sample 8



Tensile strength Value for sample 9

Appendix 3: PSA result

Size Distribution Report by Intensity v2.2



Sample Details

Sample Name: zink ASRAT 2

SOP Name: CNC.sop

General Notes:

File Name: Nano material.dts

Record Number: 506

Material RI: 1.59

Material Absorbance: 0.010

Dispersant Name: Water

Dispersant RI: 1.330

Viscosity (cP): 0.8872

Measurement Date and Time: Monday, May 23, 2022 2:36:0...

System

Temperature (°C): 25.0

Count Rate (kcps): 27.7

Cell Description: Disposable sizing cuvette

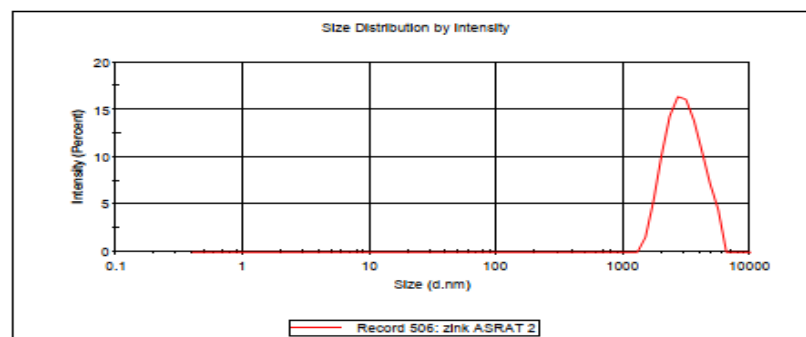
Duration Used (s): 180

Measurement Position (mm): 0.85

Attenuator: 11

Results

	Size (d.nm):	% Intensity:	St Dev (d.nm)
Z-Average (d.nm): 2823	Peak 1: 3108	100.0	1008
Pdl: 0.207	Peak 2: 0.000	0.0	0.000
Intercept: 0.483	Peak 3: 0.000	0.0	0.000
Result quality: Refer to quality report			



Size Distribution Report by Intensity

v2.2



Sample Details

Sample Name: zink Asrat

SOP Name: CNC.sop

General Notes:

File Name: Nano material.dts	Dispersant Name: Water
Record Number: 505	Dispersant RI: 1.330
Material RI: 1.59	Viscosity (cP): 0.8872
Material Absorption: 0.010	Measurement Date and Time: Monday, May 23, 2022 3:09:5...

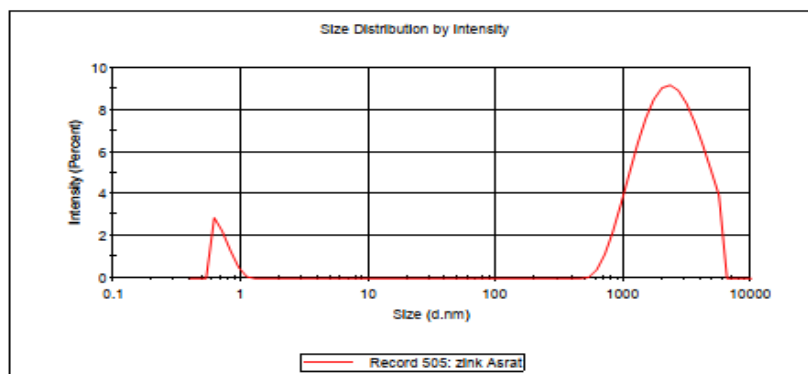
System

Temperature (°C): 25.0	Duration Used (s): 240
Count Rate (kcps): 129.0	Measurement Position (mm): 0.85
Cell Description: Disposable sizing cuvette	Attenuator: 11

Results

	Size (d.nm):	% Intensity:	St Dev (d.nm):
Z-Average (d.nm): 1941	Peak 1: 2513	93.0	1262
Pdl: 0.194	Peak 2: 0.7232	7.0	0.1126
Intercept: 0.134	Peak 3: 0.000	0.0	0.000

Result quality : **Good**



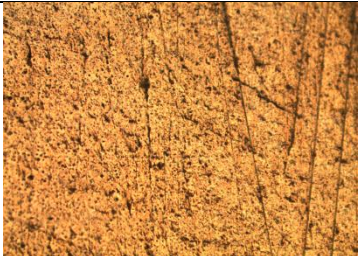
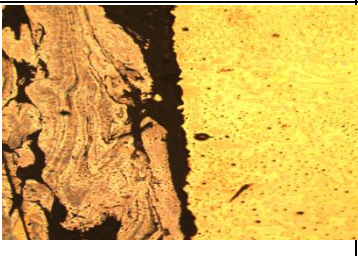
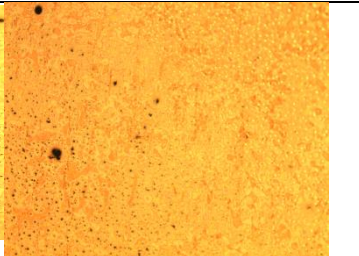
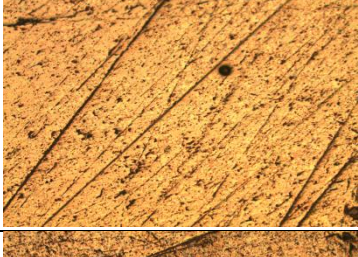
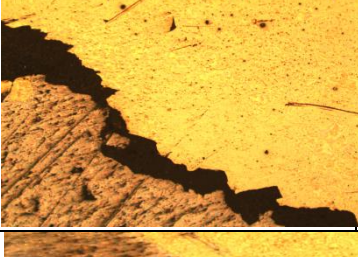
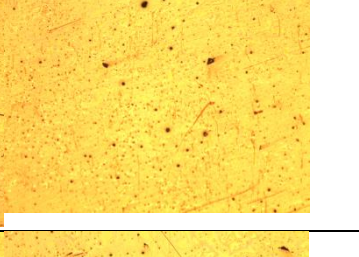
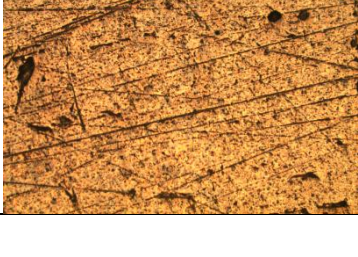
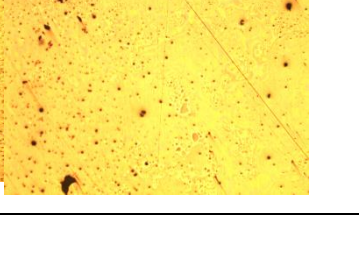
Appendix 4: Zinc particle Wt. %

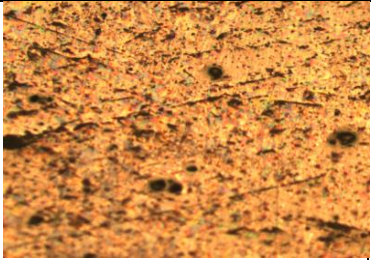
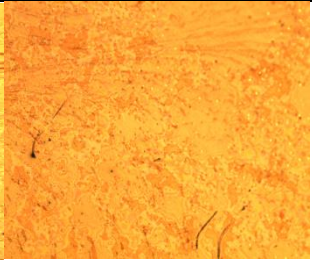
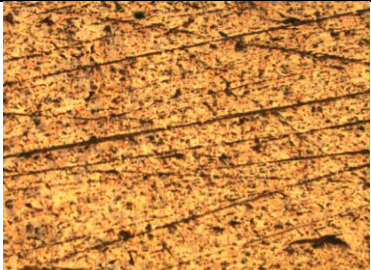
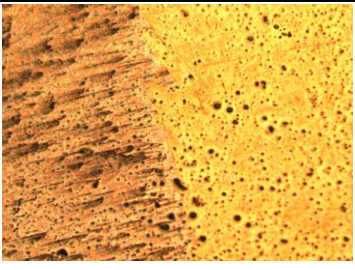
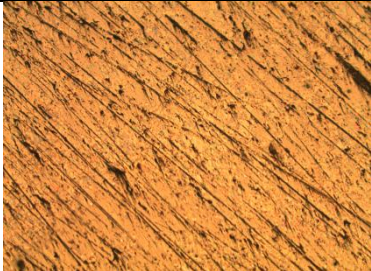
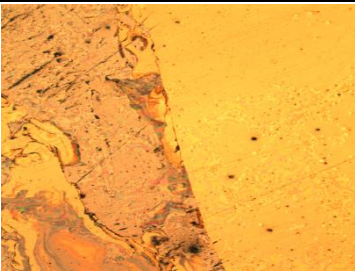
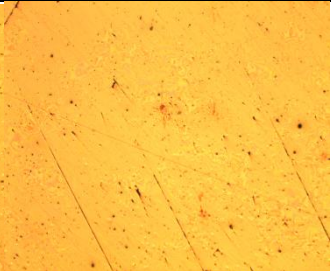
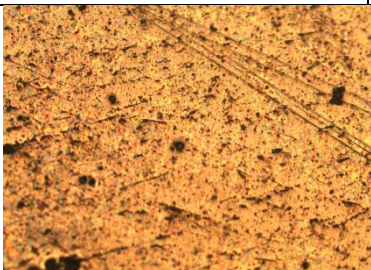
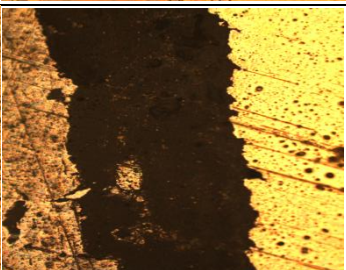
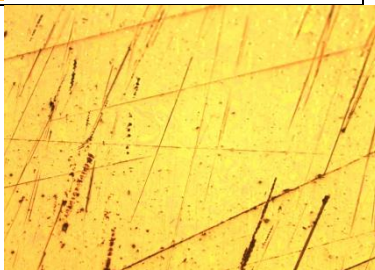
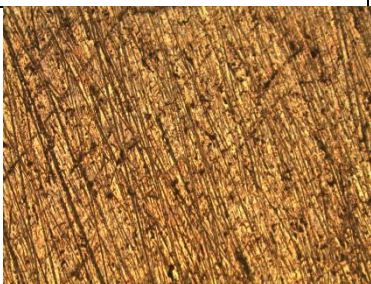
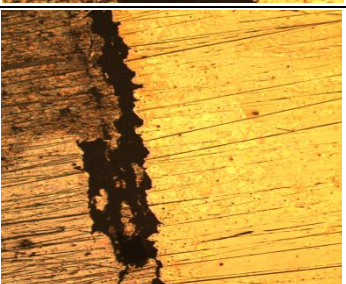
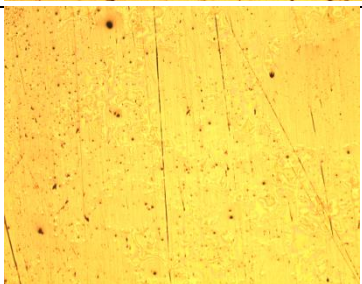
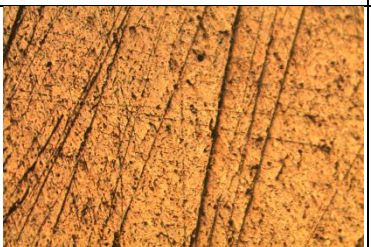
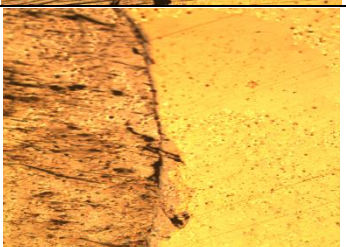
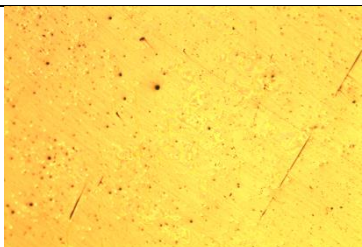


Figure of Zinc particle 10, 15 and 20 gram Wt. %

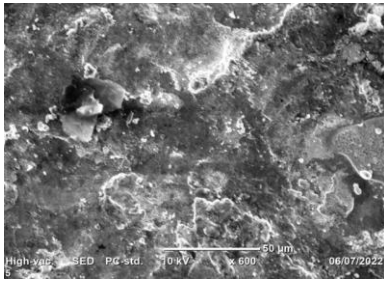
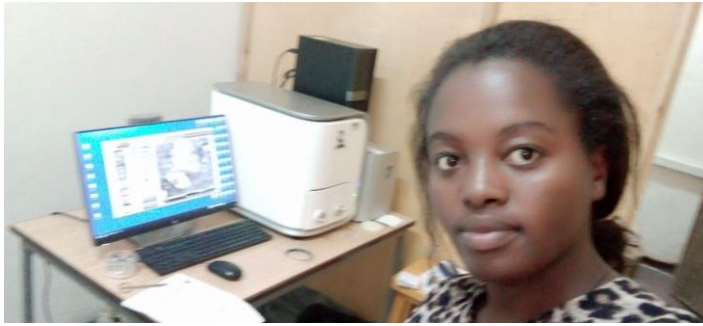
Appendix 5: Optical Microscope images

Table of different parts of welded joint morphology Base metal Brass, FSW Zone and Base Metal Aluminium

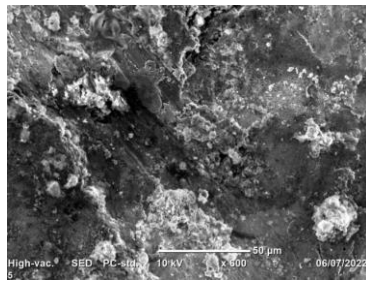
Sam- ple No	Base metal Almunium	FSW Zone	Base Metal Brass
1			
2			
3			

4			
5			
6			
7			
8			
9			

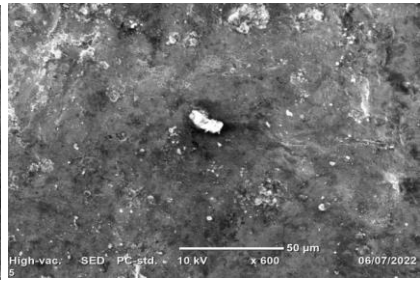
Appendix 6: SEM images



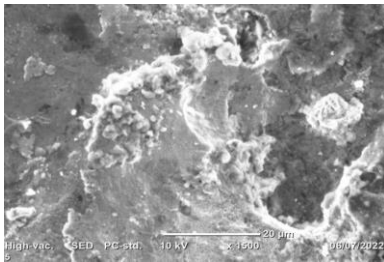
S1



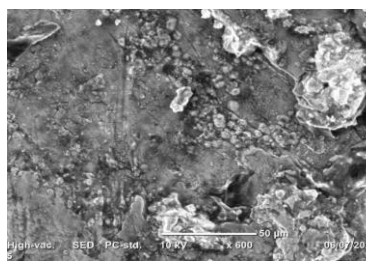
S2



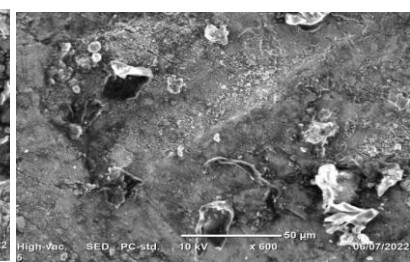
S3



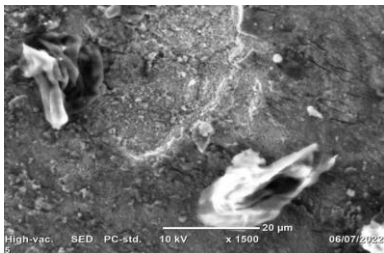
S4



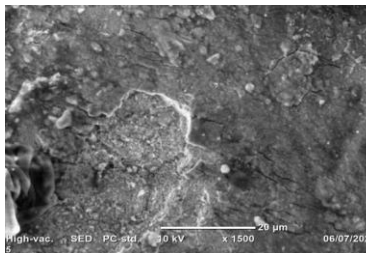
S5



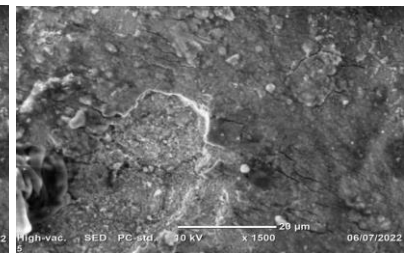
S6



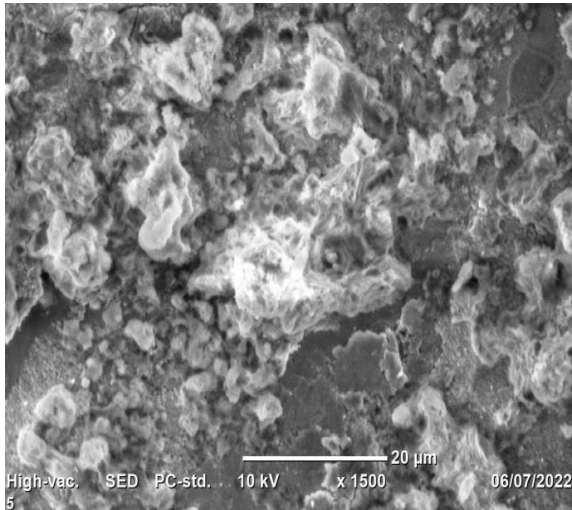
S7



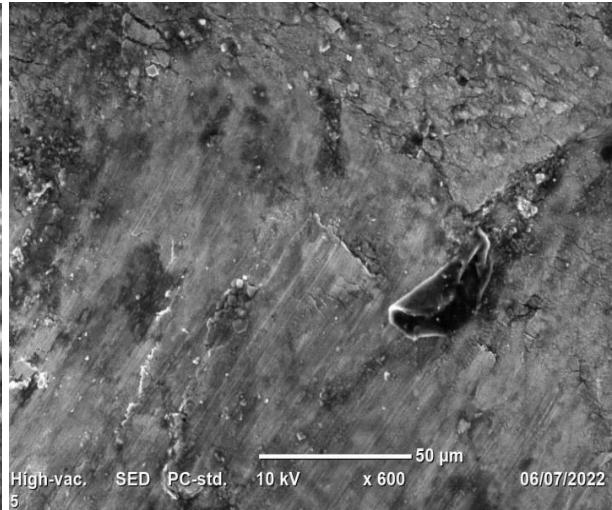
s8



S9

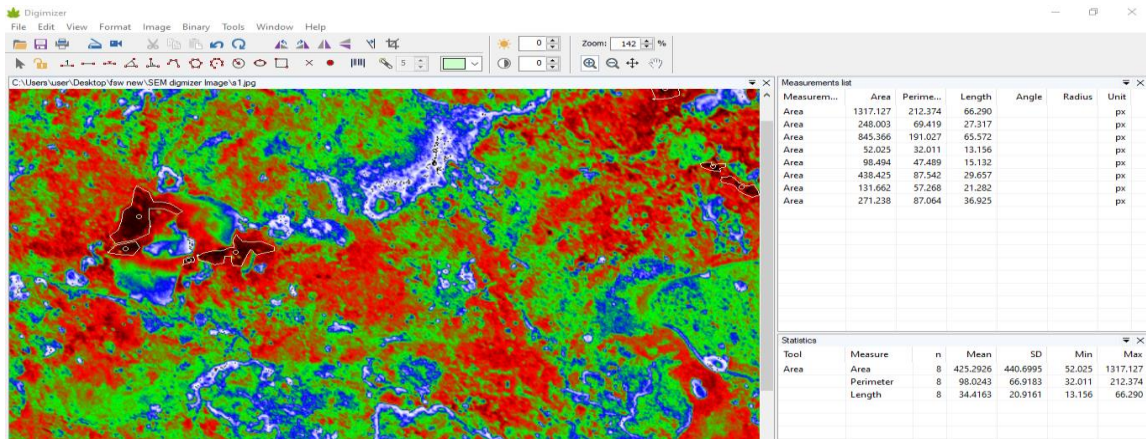


B S5



B S8

Appendix 7: Digmizer results and taguchi



Minitab - Untitled

File Edit Data Calc Stat Graph View Help Assistant Predictive Analytics Module Additional Tools

Navigator

- Taguchi Design
- Taguchi Analysis: Hardness vers...
- Taguchi Analysis: Hardness vers...
- Taguchi Analysis: Hardness vers...
- Taguchi Analysis: Hardness vers...
- Taguchi Analysis: Hardness vers...

Taguchi Design

WORKSHEET 1

Taguchi Design

Design Summary

Taguchi Array L9(3⁴)

Factors: 3

Runs: 9

Columns of L9(3⁴) array: 1 2 3

	C1	C2	C3	C4
	Travel speed	ritational speed	Zinc particle Wt. %	Hardness
1	45	800	10	130.25
2	45	1000	15	133.95
3	45	1200	20	138.40
4	55	800	15	123.00
5	55	1000	20	127.10
6	55	1200	10	131.50
7	65	800	20	117.90
8	65	1000	10	127.10
9	65	1200	15	130.65

