Experimental Investigation of Aluminum Alloy and Polymer Joints Made by Friction Stir Welding Process

Redwan Kedir Hassen

A Thesis Submitted to

The department of Mechanical Design and Manufacturing Engineering

School of Mechanical, Chemical and Materials Engineering

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

Office of Graduate Studies
Adama Science and Technology University

October, 2021

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled "**Experimental Investigation of Aluminum Alloy and Polymer Joints Made by Friction Stir Welding Process**" 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.

Redwan Kedir Hassen	_______________	___________
Name of the student	Signature	Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Experimental Investigation of Aluminum Alloy and Polymer Joints Made by Friction Stir Welding Process**" prepared under my guidance by **Redwan Kedir** submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Manufacturing Engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Perumalla Janaki Ramulu (PhD)	______________	____________
Advisor	Signature	Date

APPROVAL PAGE

I, the advisor of the thesis entitled "**Experimental Investigation of Aluminum Alloy and Polymer Joints Made by Friction Stir Welding Process**" and developed by **Redwan Kedir**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Perumalla Janaki Ramulu (PhD)	___________	________
Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Redwan Kedir have read and evaluated the thesis entitled "**Experimental Investigation of Aluminum Alloy and Polymer Joints Made by Friction Stir Welding Process**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Manufacturing Engineering.

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LIST OF ACRONYMS

A	Tilt Angel
Al	Aluminum
AS	Advancing Side
BM	Base Metal
D	Shoulder diameter
EPMA	Electron Probe Microscopic Analyzer
EDS	Energy Dispersive Spectroscopy
f	Number of Parameters
FSW	Friction Stir Welding
FSLW	Friction Stir Lap Welding
HAZ	Heat Affected Zone
HDPE	High Density Polyethylene
HRF	Rockwell Hardness scale
L	Number of Levels
N	Number of Experiments
NZ	Nugget Zone
PCBN	Polycrystalline Cubic Boron Nitride
P	Pin diameters
PP	Polypropylene
PMMA	Poly (Methyl Methacrylate) Acrylic
R	Rotational Speed

RPM	Revolution Per Minute
RS	Retreating Side
SEM	Scanning Electron Microscopy
SS	Stainless Steel
SZ	Stir Zone
T	Travel Speed
t	Thickness of plates
TEM	Transmission Electron Microscopy
TMAZ	Thermo-Mechanically Affected Zone
TWI	The Welding Institute
UTS	Ultimate Tensile Strength
VHN	Vickers Hardness Number
WC	Tungsten Carbide
WC-Co	Tungsten Carbide-Cobalt
XRD	X-Ray Diffraction

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ABSTRACT

Friction Stir Welding (FSW) is a solid-state welding process innovated and patented by Wayne Thomas in 1991, at London; the Welding Institute (TWI), used to join metals as well as non-metals in form of butt and lap weld joints. The fundamental concept of this joining process is done by non-consumable rotating tool consists of shoulder and pin by fixing the base materials on the bed of Convectional milling machine with a fixture and backing plates. The workpieces were joined together by heat, material movement, and forging action. FSW process has a wide industrial application like automobile, aerospace, marine and fabrication industries. This thesis was aimed to join aluminum alloy with high density polyethylene (HDPE) having of different thermal properties and thickness of 3mm each by the process of FSW. FSW process parameters such as rotational spindle speed, welding speed were variables and by keeping tilt angle, depth of penetration and pin offset as constant. To join the materials different FSW process parameters were selected depends on the previous researchers works. The parameters selected were welding speed of (850, 1000 and 1250) RPM, tool speed (40, 50 63) and by taking 2.5^0 tilt angle and 1mm off set distance from the center to aluminum side. FSW tool were designed and fabricated as shoulder diameter 16mm, pin probe diameter 2.5mm and probe length or plunge depth of 2.8 mm. All the joints were butt joints. From the result the reduction of pin length is 0.3 mm (reduced from 2.8 mm to 2.5 mm length) and the diameter of the pin/probe increased by 0.5 mm (increased from 3.5 mm to 4.0 mm) is observed. The joint formed by process parameter rotational speed of 1250RPM has highly grain size of aluminum and polymer mixture and the cause for that was higher speed of rotation. The most higher hardness joints were created with higher parameter values of 1250rpm and 40mm/min which is 83.4 hardness value. And from the tensile experiment the highest tensile strength joint was get 1.96 MPa which is 8.5% of the polymer parent material which is by 1250 RPM and 50 mm/min. From the study rotational speed has great effect on weld joint more than that of welding speed.

Keywords: *Friction stir welding (FSW); dissimilar material; aluminum; HDPE polymer; hardness value; process parameter.*

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Welding, a fabrication or sculptural process that joins materials, has a history as far back as the Bronze Age, where gold circular boxes estimated to be formed by pressure welding some 2000 years ago, have been recovered. The people in the Eastern Mediterranean area, especially the Egyptians, learned to weld pieces of iron together 3000 years ago. They left behind many tools and weapons, and also items of iron and bronze that exhibit forging, and forge welding operations have been recovered from the pyramids of Egypt. During the Middle Ages, many items of iron were produced that have been welded by hammering. One of the largest welds from this period is the Iron Pillar of Delhi in India, which was established nearly 1700 years ago. It was not until the 19th century that professional welding, as known today, was invented *Asadi et al. (2014).*

Friction stir welding process is solid-state joining that uses a non-consumable tool (i.e., harder than the material being welded) to join two facings of materials without melting *S. Malophery et al. (2016).* Wayne Thomas at The Welding Institute (TWI Cambridge, UK) patented the friction stir welding process in December 1991 as shown in Figure (1.1). This method can improve the joint mechanical properties, such as the strength, because the brittle compounds at the interface are minimized. Localized heating will generate because friction and plastic deformation between the tool (i.e., pin and shoulder) and the workpieces occurs. That friction and plastic deformation results in mixing and stirring the materials around the pin from the front to the back. The heat generated by friction leads to the softening of the metals, especially near the friction stir welding tool *Asadi et al. (2014).* That means mechanical energy is converted into thermal energy at the contact areas, without needing heat from other sources. The primary role of the friction stir welding tool is to heat the workpieces, and then induce the materials to flow and constraint beneath the shoulder. The materials that move around the pin can be very complicated and different from one tool to another, because of the various geometrical features of the tools. Simply, the friction stir welding concept is a particular design of a tool which consists of shank, shoulder, and pin. The pin can be inserted into a butt joint or even lap joint and then rotating forward along the joint line *Jung (2004)*. There are some advantages of friction stir welding tool, these advantages include heating the surfaces of the workpieces, creating plastic deformation, stirring and mixing the materials around the pin to produce the joint, flow the material, and restricting the heat beneath the shoulder. Friction stir welding has many more characteristics than traditional welding; these characteristics include energy-efficiency, no waste of the materials, environmentally-friendliness, good mechanical properties, little pollution, and versatile joining techniques between similar and dissimilar materials that are difficult to fusion weld.

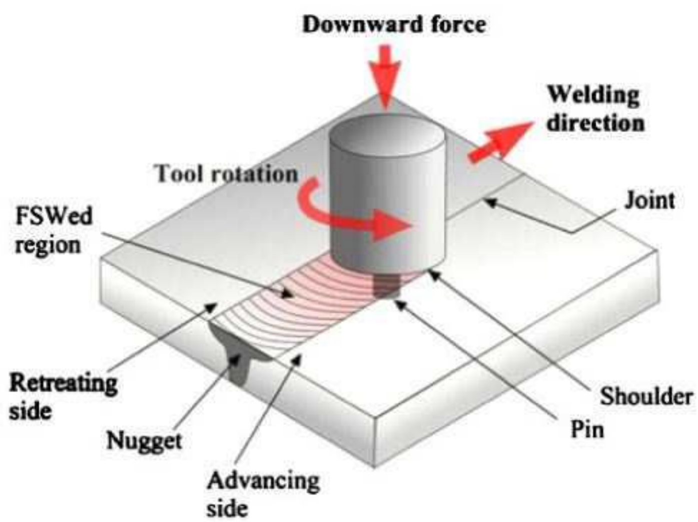

Figure 1. 1 Schematic drawing shows the principle of friction stir welding process; *S. Malophery et al. (2016)*.

1.2 Friction stir welding process

Thaoma et al. (1991) and C. Hofmann Douglas (2007), since it is invented it has been used extensively in many applications areas such as automobile, aircraft, maritime, railway and aerospace industries. FSW technique has numerous advantages over traditional welding practices. FSW joints possess sufficiently high strength, approximately equal to the strength of original material. Considerable weight reduction is possible by the implementation of this technique. It is possible to join alloys that cannot be welded feasibly with the help of fusion welding methods. FSW is executed at a temperature beneath the base metal’s melting point. So, all anomalies pertaining to re-solidification of welded material, like porosity, brittleness and crack generation can be avoided *C. Hofmann*

Douglas (2007). As the FSW process is carried out at lower temperatures, it doesn't experience much distortion and residual stresses. This technique also imparts great dimensional stability. Unlike the conventional welding processes, FSW doesn't require any filler material or shielding gas. Due to innumerable such qualities and advantages of FSW over conventional joining processes, it has become a rapidly emerging solidstate joining method. In the FSW technique, a tool with a shoulder and a profiled pin is rotated and slowly plunged into the joint line between two rigidly clamped substrates on a backing plate support. In Figure 1.2 a cylindrical tool pin profile, a schematic illustration of FSW, and a designed fixture for clamping the plates, are presented. The tool shoulder is in firm contact to the top surface of the workpiece with the load applied. The heat needed for softening the material is generated by friction and plastic deformation. The frictional heat is generated between the welding tool (shoulder and pin) and the workpieces. The tool shoulder experiences larger amounts of heat than the pin surface. However, the deformation or stirring is generated by rotation of the tool pin, thus leading to generation of additional heat.

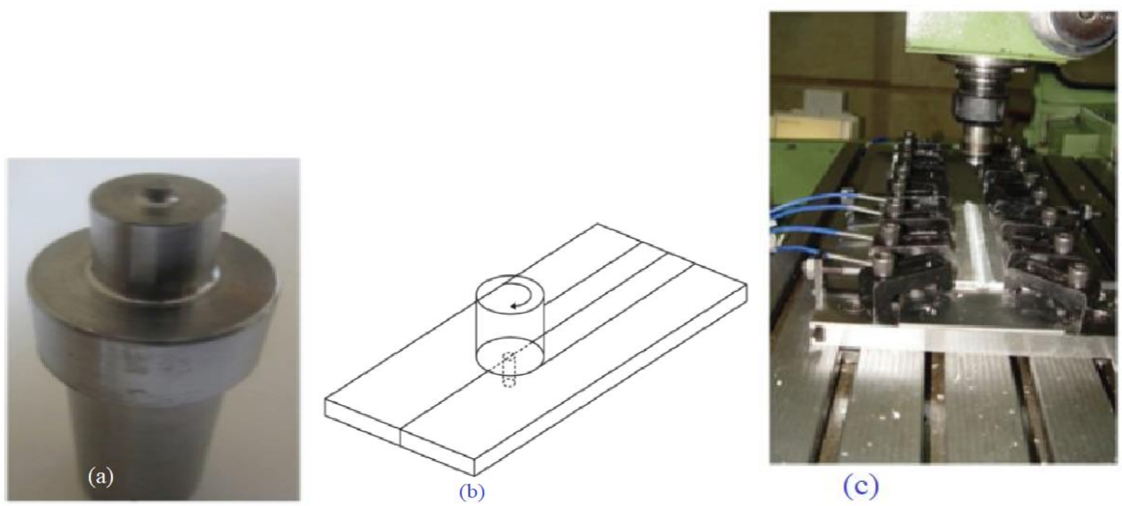

Figure 1. 2 Friction stir welding (a) tool, (b) schematic of FSW process and (c) set- up of FSW showing; *Asadi et al. (2014).*

The plasticized material around the pin experiences severe plastic deformation and a material flow from the front of the tool to the trailing edge, where it is forged into the joint. Consequently, this results in a solid-state bond between two plates. The velocities of two symmetrical points on the advancing side (AS) and retreating side (RS) are not the same, due to the combination of rotational and traverse motions of the tool. This actually leads to asymmetry in heat transfer and material flow of the two sides of the weld. In fact, in the AS, the direction of tool rotational speed and traverse speed are the same, which is different in the RS *Asadi et al. (2014).*

1.3 Joining of dissimilar materials

Dissimilar metal joining in general has great potential in practical applications to replace riveted joints leading to huge cost and weight saving, while friction stir welding (FSW), in particular being a solid state welding process, is of great advantage with respect to producing better joint integrity. Over the past few years, the manufacturing industry has developed an interest in joining dissimilar materials, but the differences in the mechanical and thermal properties of such materials make this difficult. Furthermore, the successful welding of dissimilar metals is a challenge due to the differences in the physical, chemical and metallurgical properties of the base materials (BM) used, and finding the optimum process parameter window continues to be the basic prerequisite.

FSW of dissimilar joints presents enormous challenges when compared to the welding of similar materials; this is due to the difference in the chemical, mechanical, physical and thermal properties of the metals being joined. Against this background, apart from the optimization of the operating process parameters, research studies have proved that FSW of dissimilar materials with good joint integrities are better achieved when the tool pin is offset and when the material with the high melting temperature is placed on the advancing side (AS) during the welding procedure *Cho et al. (2014)*.

1.4 Friction stir tools

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.

Therefore, the FSW tool is undoubtedly crucial to the achievement of the FSW process, being essential for improving both the welded joint's mechanical performance and the maximum possible welding speed during the technological process *Asadi et al. (2014).* In recent years, new geometrical features have been developed concerning FSW tool design *Fuller C.B (2007).* Owing to the various tools features, the material movement around the probe can be extremely complex and considerably different from one tool to the next *Zhang et al. (2012).*

1.4.1 Tool geometry

Regarding tool geometry, there are three types of FSW tools: fixed, adjustable and self-reacting. The fixed probe tool corresponds to a single component comprising the shoulder and the probe. Due to its fixed probe length, this kind of tool can only be used to weld workpieces/components with a specific and constant thickness *Fuller C.B (2007).* In adjustable tools, the shoulder and the probe are independent components, allowing adjustments in the probe length and making up different configurations of shoulder/probe facilitating the welding of a large number of varied components *Ding and Oelgoetz (1999).*

a. Tool shoulders

Tool shoulders are designed to promote frictional heating of the surface and subsurface regions of the workpiece that is to be welded. The tool shoulder is responsible for the majority of the deformational and frictional heating in the welding of thin metal sheets *Mishra and Mahoney (2007).*

b. Shoulder features

The shoulder can also contain some geometric features that increase the material friction. These features can be scrolls, ridges, knurling, grooves or concentric circles and can be embedded into any tool shoulder profile such as concave, flat or convex ones. Scrolls are the most commonly-used shoulder features *Asadi et al. (2014)*. Scrolls and concentric circles are another two types of shoulder feature that have been presented in the literature *Zhang et al. (2012).*

c. Tool probes

The tool probe has the ability to produce deformational and frictional heating. This component is designed in such a way as to disrupt the contacting surfaces of the components to be welded, to shear the material in its front and to move the material behind the tool. The depth of deformation and tool welding speed are mainly controlled by the tool probe as well as its geometry influencing the flow of plasticized material and affecting the performance of the welded joints *Asadi et al. (2014).*

1.4.2 Tool materials

The production of a good FSW joint requires the proper tool material to be selected for the desired application. New challenges have emerged with the requirement of welding materials, such as metal matrix composites, titanium or steel *Mishra and Mahoney (2007)*. It is important to have a FSW tool that keeps its dimensional stability, and does not lose its features or fractures during the welding process *Fuller C.B (2007).* It is desirable that the tool material has:

- *Good mechanical strength*: at room temperature and, mainly, at elevated temperatures. The welding process is carried out around 70 to 90% of the material melting point, so it is important that the tool material has sufficient strength at this temperature, otherwise it will failure *Mishra and Mahoney (2007)*.
- *Good wear resistance*: despite some potentially undesirable effects on the microstructure of the welded joint, significant tool wear increases the cost of the FSW process *Rai et al. (2011).*
- *No reactivity with the workpiece material*: the formation of undesirable phases during the welding process, if the tool and workpiece material reaction can lead to tool material degradation *Cam (2011).*
- *Good fracture toughness*: it is mandatory that the tool resists the damage carried out during the plunge and dwell periods *Zhang et al (2012)*. As well as difficulties in tool production leading to increase in cost, it is often desirable to sacrifice some durability for an acceptable tool price.
- *Low coefficient of thermal expansion*: during the welding process the workpiece temperature field depends on the tool material's thermal conductivity. The appropriate value of thermal conductivity depends on the process variables, the workpiece material and some other tool material properties *Rai et al. (2011)*. The

coefficient of thermal expansion may affect the thermal stresses in the tool *Cam (2011).*

- *Good machinability*: A good machinability is important in order to facilitate the manufacture of complex features on the shoulder and probe surfaces *Fuller C.B (2007).*

1.4.3 Tool material selection

Weld quality and tool wear are two important considerations in the selection of tool material, the properties of which may affect the weld quality by influencing heat generation and dissipation. The weld microstructure may also be affected because of interaction with eroded tool material. Apart from the potentially undesirable effects on the weld microstructure, significant tool wear increases the processing cost of FSW. Temperatures in the workpiece depend on the material properties of tool, such as thermal conductivity, for a given workpiece and processing parameters *Asadi et al. (2014).*

1.4.4 FSW parameters

Process parameters are an important aspect of process optimization and therefore need critical examination. Following subsections present the detailed description of FSW parameters.

➢ *Tool geometry*: Tool geometry is one of the most dominant characteristics of process optimization. It is very vital in governing material flow, as it regulates the traverse rate of the FSW tool.

➢ *Joint design:* Butt, as well as lap weld joints, are one of the most conventional joint configurations generally been used in FSW.

➢ *Welding parameters:* Tool rotational speed (N), measured in rpm in clockwise or counter-clockwise sense, as well as tool traverse speed (v), conventionally measured in mm/min across the weld joint in the welding direction are the most significant process parameters of FSW process

1.5 Problem statement

In the recent studies showed that fusion welding has emissions and smokes, this can cause environment to pollute and warm. And nowadays environmental pollution and global warming is burning issue, so that finding an option that are environmentally friendly manufacturing possibilities. For this reason, friction stir welding is one of the best materials joining mechanism.

Aerospace, vehicle and shipping industries are finding less weight and corrosion resistance materials, so that they are searching for combination of metal alloy and fiber-based polymer materials. For replacing of the exterior and interior parts of vehicle is polymer with aluminum is main choice. Weight in vehicle increases fuel consumption, so the need to decrease the weight, by replacing some parts of the vehicle like dashboard, bumper and inside of the door by lightweight materials. For this reason, polymer and aluminum alloy dissimilar materials will replace by availability, cost and high weight to strength ratio.

1.6 Objective

1.6.1 General objectives

The general objective of the thesis is to experimental investigation of aluminum alloy and polymer joints made by friction stir welding process.

1.6.2 Specific objectives

The specific objectives are to:

- Develop the necessary experimental conditions to set process parameters in-terms of welding speed, and tool speed for joining Al-HDPE by keeping tool tilt angle, shoulder diameter, pin profile as constant.
- Analyze the FSW systems and process parameters rotational speed, welding speed and tilting angle on weld performance.
- Study impact of the welding parameters and rotational speed.
- Evaluate the mechanical properties of dissimilar joints formed by FSW.

1.7 Scope of the study and limitation

The scope of this study to weld 2mm thickness dissimilar materials which is aluminum and HDPE polymer by using conventional milling machine and study the main FSW process parameters such as tool rotational speed and welding speed and mechanical properties of the joint formed by the process. The joint configuration used in this thesis is limited to butt joint configuration and also limited to only experimental investigation of mechanical properties of the joint formed by the two dissimilar materials.

1.8 Significance of the research

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

1.9 Outline of the thesis

This thesis work contains five chapters, which are: introduction, literature review, experimental work and methodology, results and discussions and lastly conclusion and recommendations. **Chapter one** begins with introduction which consists of the background of FSW, and its process parameters as well as FSW tools. Finally, the problem of the statement, an objective, scope and significance of the study is clearly shown in this chapter. **Chapter two** presents literature review of dissimilar FSW, literature on process parameter of FSW and literature on FSW tool geometry. **Chapter three** gives detailed information on the working materials, specifications and experimental procedures used and optimizing the FSW parameters. aluminum alloy and pure copper using FSW. **Chapter four** explains the results found from lab results i.e. hardness, microstructure and tensile of the joints formed by FSW of Al and HDPE. **Chapter five** which is the final chapter of the paper presents the general summary by making a sound conclusions and recommendations as well as future scope.

CHAPTER TWO

LITERATURE REVIEW

2.1 Frictions stir welding

FSW technique is one of the most suitable joining methods, which accounts for the considerable development efforts. Given the recent increase in industrial demand for lightweight design structures, novel joining methods are required to tackle new challenges, such as multi material joining. Even though the FSW technique was originally developed for joining aluminum alloys, the method presently being studied to weld other materials such as polymers, metallic materials, copper, and even joining dissimilar materials. One of the major obstacles to broader industrial implementation of FSW has been the affordability and suitability of FSW machines. The actual FSW machine can reach the price around one million US dollar *Lohwasser et al (2010*)**.** This is not favorable for the small industries, university laboratory or any personnel to invest this amount of money for expensive FSW machine.

2.2 Dissimilar materials joining through FSW process

Husseyin et al. (2005) studied that FSW could be used the joining of dissimilar Al alloy and stainless steel, from their observation showed that seven different zones of the microstructure in the welding were parent stainless steel, HAZ and TMAZ on the stainless steel on advancing side of weld, parent stainless steel, weld nugget, TMAZ and HAZ on the Al alloy at retreating side of weld and parent Al alloy. And also from microstructure showed that the hardness of the weld nugget showed variable values due to the presence of the fine or coarse dispersed stainless steel particles on the weld nugget.

Mukuna et al. (2013) reviewed that Friction Stir Welding (FSW) a solid-state welding process used for welding similar and dissimilar materials. Due to the process produces sound welds and does not have common problems such as solidification and liquefaction cracking associated with the fusion welding techniques it was widely used. The FSW of Aluminium and its alloys had been commercialized and recent interest was focused on joining dissimilar materials. The paper reviewed that the state of FSW between aluminium and copper were discussed on resulting weld microstructure, mechanical testing and the tools employed to produce the welds and also gave recommendation on future research in the field of study.

Khodabakhshi et al. (2014) investigated the microstructure-property characterization of a friction-stir welded joint between AA5059 aluminum alloy and high density polyethylene by using different joint designs and welding parameters, and from the investigation defect free FSW weld with good appearance was obtained by using butt joint configuration, AA5059 on the advancing side, pin offset of 1.4 mm, rotational speed of 710 rpm and traverse velocity of 63 mm/min. and also they showed that the microstructural features of the FSW joint cross-section contain entrapped aluminum fragments in a consolidated polymer matrix. From tensile test, fracture was performed from mixed zone/AA5059 interface and indicated much higher tensile strength on the SZ than that of the AA5059/HDPE interface attributed to aluminum surface wettability.

Ziacongo et al. (2014) reviewed friction stir welding were a relatively was a new solid-state joining technique which was widely adopted on different industry fields to join different metallic alloys that are hard to weld by conventional fusion welding. Friction stir welding was a highly complex process comprising several highly coupled physical phenomena, the complex geometry of some kinds of joints and their three-dimensional nature make it was difficult to develop an overall system of governing equations for theoretical analyzing the behavior of the friction stir welded joints. The paper reviewed that the latest developments on the numerical analysis, microstructures welded joints the properties of friction stir welded structures. And also, numerical issues such as materials flow modeling, meshing procedure and failure criteria were discussed.

Joon-Tae et al. (2015) investigated that Al-Li alloys played a significant role on the aerospace components due to their exceptional strength and stiffness-to-density ratios and were most competitive or superior to a composite based design in an aircraft or space launcher. On aerospace vehicle requires very large sheets, which size was not available commercially, the known fusion welding of Al-Li alloys was difficult due to the low melting temperature of element Li and causes porosity, cracking and low joint efficiency. Therefore, another solid-state joining process needed, like friction stir welding, it was generally appropriate for joining of Al-Li alloys, and from experimental investigation provided that influence of rotating and welding speed on microstructure, mechanical properties, and joint quality. In addition, recommended valuable information about processing window which results in a successful friction welded joining of those alloys.

Khodabakahshi et al. (2016) studied the mechanism and interface characterization during dissimilar friction stir welding of butt-dissimilar joint between an Al–Mg alloy and an amorphous HDPE produced by FSW. From the result showed that joint design and FSW parameters possess an impact influence on the formation of different defects inside the dissimilar stirred zone. From the study low-temperature severe plastic deformation during FSW process and subsequently dynamic recrystallization mechanism lead to formation of a nano-sized grain structure within the Al-chips during emerging and consolidation processes. On the other hand, from microscopic observations, suggested that the joining was accomplished by a mixed regime of surface mechanical interlocking and direct adhesion between the metallic Al-chips and consolidated polymeric layers by interface chemical reaction attributing to formation of alumina phase.

Francesco et al. (2017) investigated that the mechanical behavior and morphology of friction assisted joints made by aluminum and PVC sheets to know the influence of the main process parameters, and result showed that the maximum shear strength (16 MPa) was reached (that was 75% of the shear strength of the base material) by the employment of the maximum plunging load with an interaction time of 20 sec. Higher dwell time resulted on development of material degradation with consequent reduction in the joints strength. the success and strength of these joints mainly depends on the dimension of the joined area, the quality of the penetration of the teeth produced on the aluminum throughout the softened PVC substrate and the degradation of the polymer.

C.L. Yang et al. (2018) studied heat, mass transfer and material mixing in friction stir welding of dissimilar aluminum 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.

Chirag et al. (2018) investigated the mechanical Properties of dissimilar joint of Al Alloy (AA-6061) to PMMA (Acrylic) by taking different parameters of tool rotation speed 500 to 1000 rpm and traverse feed were 31.5 to 50 mm min^{-1} and get from 1000 rpm and 40 mm min^{-1} yielded a highest tensile strength of 7.076 MPa. The result showed that lowest tensile strength was observed 1.034 MPa was attained at 710 rpm and 50 mm/min because of less heat concentration on weld, which was resulted on chipping out of PMMA and poor mechanical interlocking. And from the test micro hardness near the weld was high (112 $VH_{0.098}$ and 16 $VH_{0.024}$) and decreased towards the parent material for both PMMA and AA 6061 respectively.

Hossain et al. (2018) investigated the joining of thermoplastics through welding offers numerous advantages over mechanical joining. The FSW was eliminating the use of costly fasteners and has only a limited effect on the strength of the parts being joined, and the process does not require the introduction of holes, loading pins, and the associated stress concentrations. The study was investigated to create butt joints of unreinforced polyphenylene sulfide (PPS) and short carbon fiber (CF)- reinforced polyetheretherketone (PEEK) plates. And also, they discussed the process parameters and tool traverse speed on the significant influence on the tensile strength of the joint.

Motajib et al. (2018) investigated the joint strength of reinforcement dissimilar joints of Polypropylene and Acrylonitrile Butadiene Styrene by incorporation of copper powder to the weld zone in order to know effects of process parameters such as rotational and traverse speeds and the heater temperature on the mechanical properties and the macrostructure of the joints. The investigation result showed that rotational and traverse speeds and heater temperature of 1600 rpm, 16 mm/min and 80 ◦C, offered the best mechanical properties of the joint; and from the condition, reinforced welded joint with strength equal to 91.2% of Polypropylene and hardness equal to 94.1% of Polypropylene was obtained. From the results they concluded that adding the copper powder to the joint increased the tensile strength and hardness of the joint.

Prabhu et al. (2018) studied friction stir welding (FSW) to join aluminum matrix composites (AMCs). They performed the solid-state welding of FSW process well below the melting temperature of the material, eliminates the detrimental effects of conventional fusion welding process. Their work gave an outline for friction stir welding technique used to join AMCs by investigated effect of process variables on the microstructure and mechanical properties of the joints, behavior of reinforcing materials during welding, effect of tool profiles on the joint strength were discussed. And gave few improvements and direction for future research.

The work presented by *Yongxian et al. (2018)* hybrid joint was achieved with a sufficient mixture of 6061-T6 aluminum (Al) alloy and polyether ether ketone (PEEK) via friction stir lap welding (FSLW) by a tapered thread pin with the triple facets. By seriously taking the process parameters the mechanical interlocking and adhesive bonding attributed to the high-quality joining. From the results they stated that increasing welding speed resulted on the reduction of the adhesion area and the decrease on the size of the Al anchor, deteriorating the mechanical interlocking.

Zhang et al. (2018) investigated that the use of carbon fiber-reinforced polymer (CFRP) in aviation, automobile, marine and offshore is increases sharply. Due to those reasons the joining technology of CFRP-metal was one of the key problems urgently to be solved as they stated. They investigated by joining carbon fiber-reinforced polymer and metal with different processes. The implementation processes and joining material by using a type of adhesive bonding, bolt connection, riveting, welding, z-pin (pin inserts), and joining (such as self-pierce riveting, hot riveting, mechanical clinching, friction welding) by plastic deformation, were summarized.

Chattopadhyaya et al. (2019) joined Al alloy and commercially pure copper alloys successfully using Friction stir welding (FSW). They used different weld parameter such as, tool rotational speed of 1400 and 2000 rpm and the traverse speed of 40 and 63 mm/min. In addition, mechanical tests and FESEM tests were implemented to study the joint strength and microstructural property. And from their result highest joint strength of weld was observed to 91% of Al parent metal, the fine-grained microstructure was observed on the WN and a large amount of Cu parent metal existed with different shapes in the elongated on weld nugget.

2.3 Process parameter of FSW

Livia et al. (2016) investigated that the Friction Stir Welding (FSW) process in order to evaluate the influence of process parameters on the mechanical properties of aluminum plates (AA5754-H111). On their studies two process parameters were considered for tests: the welding tool rotation speed and the welding tool traverse speed. The quality of joints was evaluated by means of destructive and non-destructive tests. The presence of defects and the ultimate tensile strength (UTS) were investigated for each combination of the process parameters.

Anajal et al. (2018) studied the effect of process parameters such as tool rotational and traverse speeds on mechanical and microstructural properties of FSW between Al alloy and PC plates, showed that the maximum tensile strength obtained were at 500 rpm tool rotation speed and 40 mm min^{-1} feed. An Al alloy was highly influenced by welding parameters and peak temperatures. Tensile strength of the welded joints was lower compared with those of the base material PC it was due to owing to thermal degradation by the tool stirring and frictional heat that softened the material at the joint interface.

As *Yongxian et al. (2018)* reviewed that during FSW of thermoplastic polymers and metal, the key factors influencing joint formation and quality was separated into three categories: equipment parameters, welding tool parameters and material properties. The processing variables of FSW are shown in Figure. 2.1

Welding tool and equipment parameters are mainly dependent on mechanical properties of polymers, such as yield strength, ductility and hardness, which play significant influences on plastic deformation. Thermal properties of material primarily affect welding peak temperature and thermal transfer. For the materials with a high thermal conductivity which easily results in the amounts of heat loss, high heat input is necessary to guarantee sufficient heat input, obtaining sound joint *Xu N. et al. (2014).* Oppositely, thermal conductivity of polymer is lower than Al alloys, which is difficult to transfer heat to preheat the materials at the front of the rotational tool. Therefore, higher heat input is also required to attain sound joint.

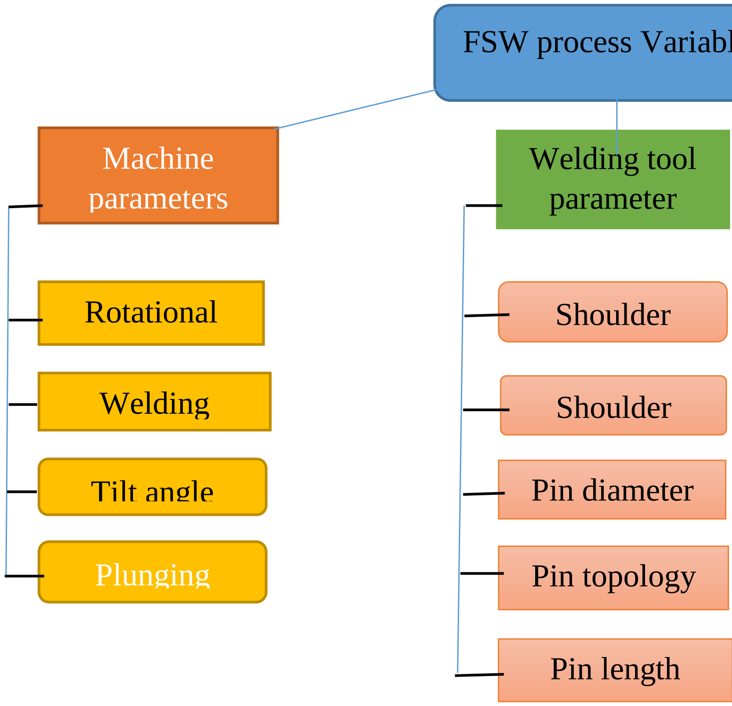

Figure 2. 1 Process parameters; *Yongxian et al. (2018).*

2.4 Tool geometry effects on FSW joints

Motajib et al. (2018) studied that the effects of tool geometry on dissimilar friction stir welding of polyethylene-polypropylene by took four different pin profiles, including threaded cylindrical, squared, triangular and straight cylindrical to showed the effects on microstructure and the mechanical properties of the joint formed, from the result the tool with threaded cylindrical pin provides the better mechanical properties for the welded joints versus the tools with squared, triangle and straight cylindrical pin shapes, respectively. And also the interaction effects of welding variables, including rotational speed and traverse speed were also studied, resulted that low traverse speed of 8 mm/min, the fluidity of the stir zone was increased and consequently a non-uniform layered microstructure was obtained.

Rishikesh et al. (2019) reviewed that friction stir welding (FSW) was developed as an alternative to conventional fusion-based welding. Their work provided an overview on the recent research on Friction Stir Welding (FSW). The work was summarized that the prominent research work on the field with due emphasis on the methodology involved, workpiece materials, tool design and material, workpiece sizes as well as the typical process parameters were involved. In addition, brief account of the numerical analysis of the FSW process was included.

2.5 Summary and literature gap

Many researchers done their researches on dissimilar materials joining by using friction stir welding (FSW). But most of the researcher done their researches on by joining of metal with other metals; that means aluminum with steel, aluminum with copper and aluminum with titanium alloys so there is a gap in joining of metal with plastics. In order to fill this gap, this work will focus on joining of dissimilar materials that means metal with plastic, this means aluminum alloy with high polyethylene and this material used for different application area in transportation industries like aerospace industries, shipping industries, vehicle industries and railway industries.

CHAPTER THREE

METHODOLOGY AND MATERIALS

3.1 Introduction

This Chapter highlights the materials used and methodology followed to investigate the friction stir welding process of to join aluminum with HDPE polymer by using conventional milling machine. The general procedures of pre-welding, welding, and post-welding process of experimental works are shown by the flow chart Fig 3.1.

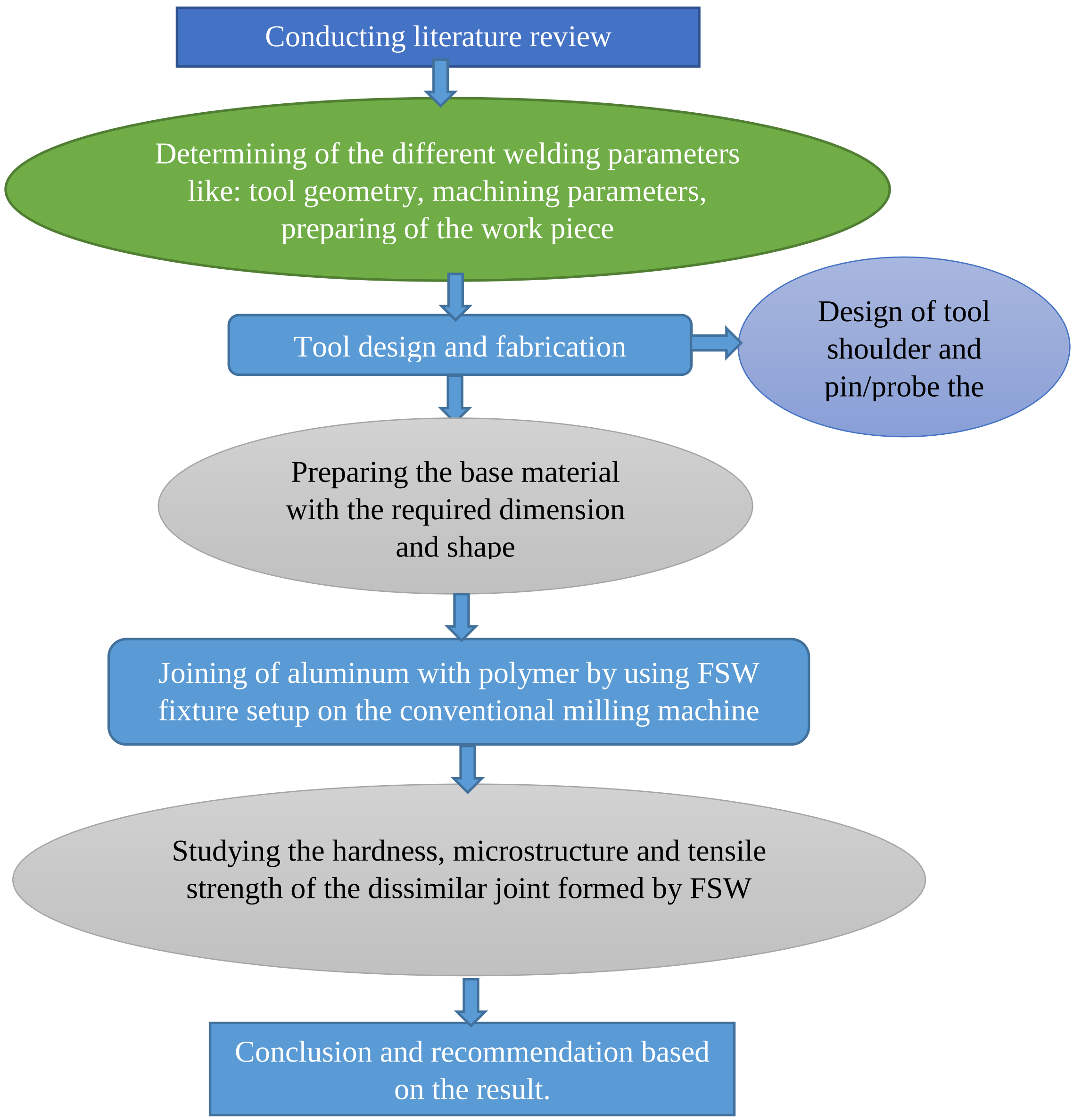

Figure 3. 1 Flow chart of thesis methodology

3.2 Materials and Equipment

The materials that are used to perform this FSW process are listed below on the Table 3.1, Table 3.2 and Table 3.3 respectively.

Table 3. 1 Materials used to perform FSW process of dissimilar material joining

S. No.	Materials	Purpose	Specification
1	Aluminum alloy sheet	Base material to be weld	Aluminum alloy 6023 3mm thickness
2.	Polymer plate	Base material to be weld	HDPE Polymer 3mm thickness.
3.	Backing plate	Holding the bottom part of the base material during welding process	$150mm \times 15omm \times 2mm$ Mild steel
4.	D2 steel tool	To perform the welding by generating heat during the process and plasticized materials.	16mm shoulder diameter, 2.8mm probe length and 3.5mm (inner) and 5mm (outer) pin/probe diameter
5.	Expandable collate	To hold FSW tool during welding.	With collates diameter of 14mm
6.	Clamp	To hold and fix the workpiece with the backing plate during welding.	

Table 3. 1 Specification of the conventional milling machine

S. No.	Spindle description	Units	Range
1.	Main spindle rotation.	RPM	40-2000
2.	Motor power	kW	5.5
3.	Maximum torque.	Nm	1313.7
4.	Minimum torque.	Nm	26.27
5.	Feed motor power.	kW	1.5
6.	Feed motor rotational speed.	RPM	920
Feed range			
7.	Horizontal (Traverse speed)	mm/min	12.5- 630
8	Vertical (plunge)	mm/min	5.2-262
9.	Gear ratio		1:1

Table 3. 2 Machines used to prepare sample and mechanical experiment

S. No.	**Machines**	**Purpose**	**Specification**
1.	Milling machine	To perform the FSW welding process	FU-281
2.	Shearing machine	To cut the plates	Hydraulic shear
3.	Heat treatment machine	To heat treat the FSW tool	Fours negate 44550-montoir.
4.	Vickers hardness tester	Hardness test	HVS-50
5.	Lathe machine	To prepare FSW tool profile	Excel XL-420

3.2.1 Aluminum alloy

Aluminum alloys are increasingly being used in a broad spectrum of load-bearing applications such as lightweight structures, light rail, bridge decks, marine crafts, vehicle industries and offshore platforms. For this thesis selected 6023 aluminum is used due to wide application area and easily performable. 6000 series rolled plate and sheet, High-strength structural members, (Al-Si-Mg) extrusions, forgings, vehicles, rolling stock, marine tubing and piping applications, architectural applications.

In the European system the prefix 'AW' denotes a wrought product. For the wrought alloys this is followed by the four-digit number which uniquely identifies the alloy. The first digit indicates the main alloying element, with numbers 1 to 9 being used, from that AW 1XXX is for pure aluminum, and AW 6XXX alloy indicate aluminum–magnesium–silicon alloys. Beneficial effects on mechanical properties and the aluminum producers attempt to eliminate this from their products. The raw material available in market by the size of 1.5meter by 0.75meter and hydraulic shearing machine was used to cut as desired size.

Table 3. 3 Physical and mechanical properties of aluminum alloys 6023

Properties	Amount
Ultimate tensile strength (MPa)	360
Yield tensile strength (MPa)	300
Elongation at break (%)	11
Modulus of elasticity (GPa)	69.4
Bulk modulus (MPa)	160
Poisons ratio	0.33
Shear modulus (GPa)	81.0
Density (g/cm^3)	0.0028
Specific gravity	7.75

3.2.2 Polymer

High-density polyethylene or polyethylene high-density is a thermoplastic polymer produced from the monomer ethylene. It is sometimes called "alkathene" or "polythene" when used for HDPE pipes. HDPE is known for its high strength-to-density ratio. The density of HDPE can range from 930 to 970 kg/m^3. Although the density of HDPE is only marginally higher than that of low-density polyethylene, HDPE has little branching, giving it stronger intermolecular forces and tensile strength (38 MPa versus 21 MPa) than LDPE.

The difference in strength exceeds the difference in density, giving HDPE a higher specific strength. It is also harder and more opaque and can withstand somewhat higher temperatures (120°C/248°F for short periods). High-density polyethylene, unlike polypropylene, cannot withstand normally required autoclaving conditions. The lack of branching is ensured by an appropriate choice of catalyst (e.g., Ziegler–Natta catalysts) and reaction conditions.

HDPE is resistant to many different solvents so it cannot be glued. Pipe joints must be made by welding. The physical properties of HDPE can vary depending on the molding process that is used to manufacture a specific sample; to some degree a determining factor are the international standardized testing methods employed to identify these properties for a specific process. For example, in rotational molding, to identify the environmental stress crack resistance of a sample, the notched constant tensile load test (NCTL) is put to use. In particular, high-density polyethylene (HDPE), also used in sectors, such as aeronautical, nautical and rail ones, is one of the plastics with more uses in the automotive industry like batteries, different kinds of tanks (oil, brake fluid, washer fluid, etc.), interior linings, bumpers, seats, storage inner compartments, trims, etc. Other materials used are ABS or polypropylene. Nowadays it used combined with other materials, plastics can decrease the weight of many parts of cars up to 70 %. *Cho et al. (2014) and Yongxian et al. (2018).*

Table 3. 4 Properties HDPE polymer

Properties	**Amount**
Temperature of crystallization	111.9 °C
Melting point	130.8 °C
Specific heat (solid)	1.9 kJ/kg °C
Specific heat capacity	1330 to 2400 J/kg-K
Latent heat of fusion	178.6 kJ/kg
Thermal conductivity	0.44 W/m°C
Crystallinity	60%
Density	0.95 g/cm^3
Young’s modules	600-1500 MPa

3.2.3 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.

3.2.4 D2 tool steel (tool material)

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. The mechanical properties of D2 are very sensitive to heat treatment. It is widely used for the production of shear blades, planer blades and industrial cutting tools; sometimes used for knife blades. The mechanical and physical properties of D2 tool steel listed below in Table 3.4.

Table 3. 5 Mechanical and physical properties of D2 steel

Properties	Units	Quantities
Ultimate tensile strength	MPa	1917
Yield tensile strength	MPa	1476
Hardness Vickers	HV	748
Modulus of elasticity	GPa	210
Elongation at break	%	1
Bulk modulus	MPa	160
Poisons ratio	-	0.3
Shear modulus	GPa	81.0

Density	kg/m^3	7.75
Thermal conductivity	w/m k	25.4

3.3 Tool design and fabrication

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 *Asadi et al. (2014)*.

The thermo- mechanical deformation and the workpiece frictional heating, essential for friction stirring, are influenced by the FSW tool design *Mishra et al. (2007)*. The shoulder is responsible for generating most of the heat during the process, applying a downward pressure on the workpiece surface, constraining the plasticized material around the probe and preventing the escape of the plasticized material from the workpiece joint line. However, the rotating probe mainly drags along, plasticizes and mixes the adjacent material presents in the stir zone (SZ), creating a welded joint without the need of fusion *Zhang et al. (2012)*.

In Friction stir welding, the tool geometry plays a fundamental role to obtain suited microstructures in the weld and the heat affected zone. Tool geometries contribute major role to obtain a quality weld joints. TWI has developed different type of tool specially designed to increase the penetration depth and thus considered the thickness of the plates that can be successfully welded. There are three types of FSW tools: fixed, adjustable and self- reacting. During the tool design especial attention needed to tool geometry and material selection such as; Tool shoulders, Shoulder features, Tool probes *Asadi et al. (2014)*.

3.3.1 Tool shoulders

The shoulder of the tool flat surface responsible for generating frictional heat during welding process. Shoulder diameter (D) also depends on the thickness of sheet metal.

$$D = 2.2\,t + 7.3\,mm \quad (3.1)$$

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

3.3.2 Tool probe

The tool probe is designed as tapered surface and threaded has the ability to produce deformational and frictional heating. The depth of deformation and tool welding speed are mainly controlled by the tool probe as well as its geometry influencing the flow of plasticized material and affecting the performance of the welded joints. Pin or probe diameter (P) also depend on the thickness of sheet metal.

$$P = 0.8t + 2.2\,mm \tag{3.2}$$

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

Figure 3.2 shows that the FSW tool design by using CATIA V5 cad software in order to fabricate it and all the dimensions described mm.

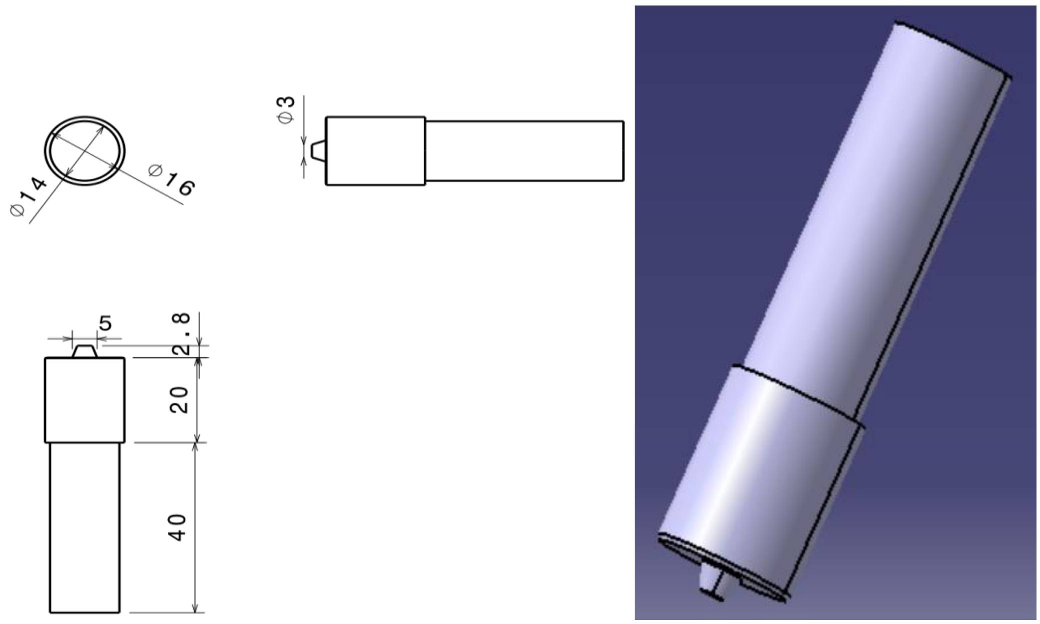

Figure 3. 2 Tool design and modeling

Below Figure 3.3 showed that the fabricated FSW D2 tool based on the designed specification.

Figure 3. 3 D2 steel tool material

Table 3. 6 Specification of the FSW tool used

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	3.5mm
5	Pin (probe) length	2.8mm

3.3.3 Heat treatment to tool material

Heat treatment process is deferent from the other manufacturing process by performed at high temperature oppression. First the furnace was heated up to 940°C and D2 tool steel were inserted in the furnace. Then after 40 minutes of stay in furnace they are removed off and quenched with oil media then tempered at 400°C to minimize brittleness of the material.

3.4 Conventional milling machine

Milling machine used to produce product by process of machining using rotary cutters to remove material by advancing a cutter into a workpiece. This may be done varying direction on one or several axes, cutter head speed, and pressure. It is one of the most commonly used processes for machining custom parts to precise tolerances. In this thesis conventional milling machine show in Figure 3. 4 was used to weld the two different materials i.e. aluminum and high-density polyethylene 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 as shown in Figure 3. 5.

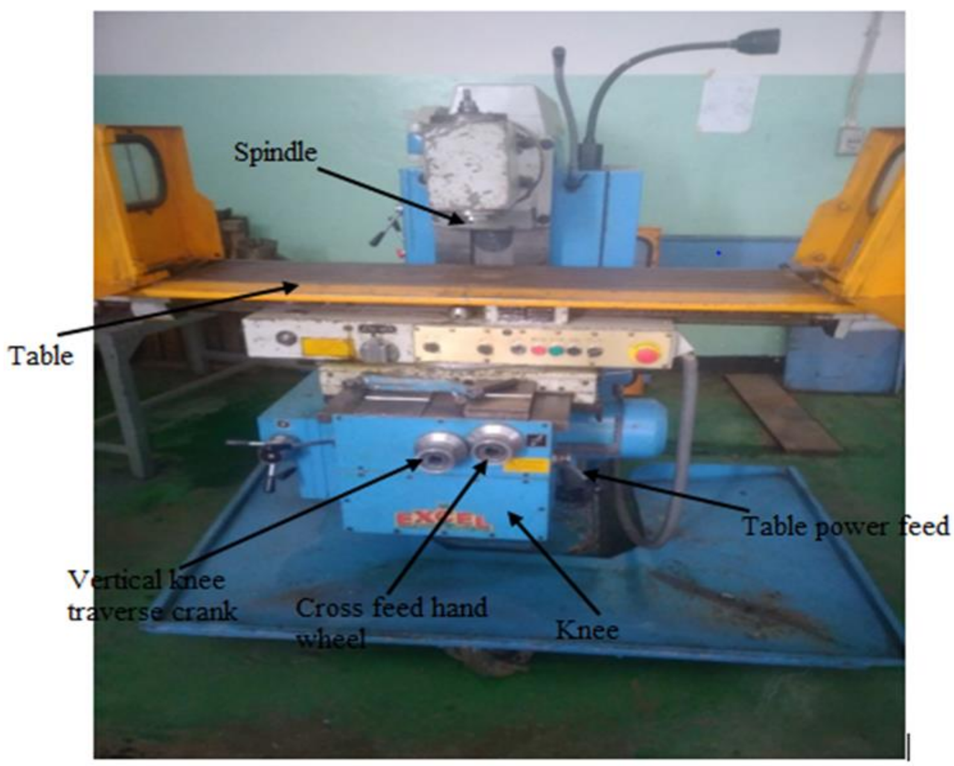

Figure 3. 4 Conventional milling machine

Figure 3. 5 Expandable collates

This expandable collate shown Figure 3.5 used to hold the tool during welding and it will have attached to conventional milling machine.

3.5 Welding and experimental procedure

In this work for joining trials, the materials were cut in the plate size, each having dimensions 140×50×3mm of AA6023 and HDPE sheets. The backing plate of 8mm thickness was placed at the bottom of the sheets. During the experiment, the plate of AA 6023 was always placed at the advancing side while HDPE plate was on retreating side to enhance mechanical interlocking. A tool of D2 steel having shoulder diameter of 16mm and heat treated to increase strength. The pin probe having diameter of 5mm at shoulder side and 3.5mm at the tip of probe was provided in the tool along with threads on it. The plunge depth was kept constant at 2.8 mm and tool tilt angle was set 2.5˚ for all the experiments. The tool rotation speed and traverse feed were taken as 850, 1000, 1250 rpm and 40, 50, 63 mm/min respectively. The profile micro-hardness was measured by using Vickers micro-hardness tester HVS-50 machines.

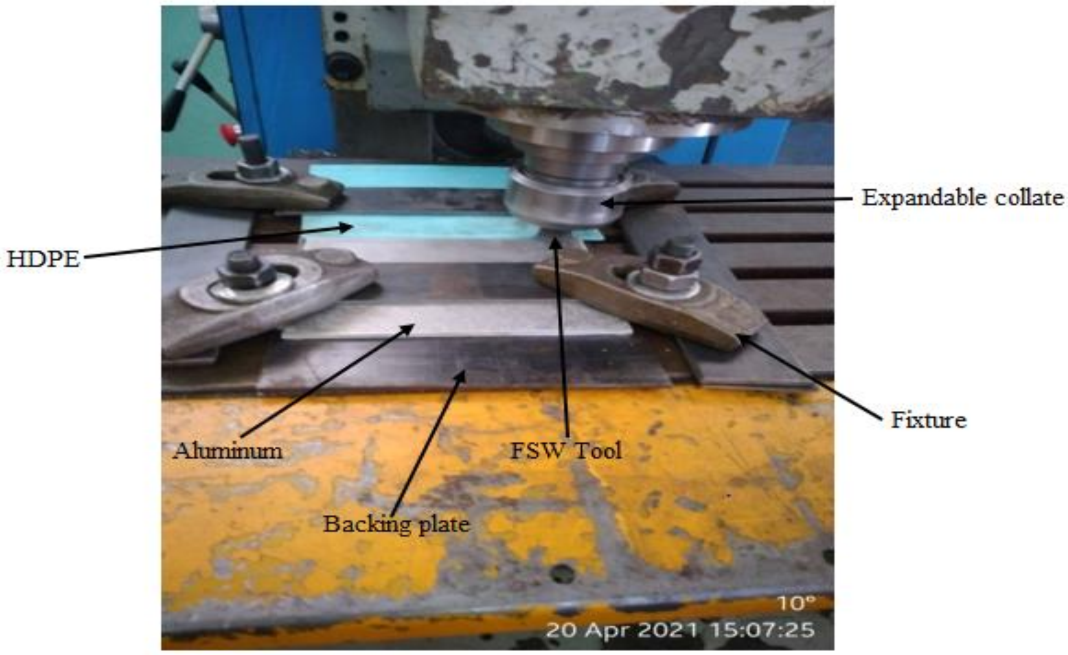

Figure 3. 6 Machine setup for welding process

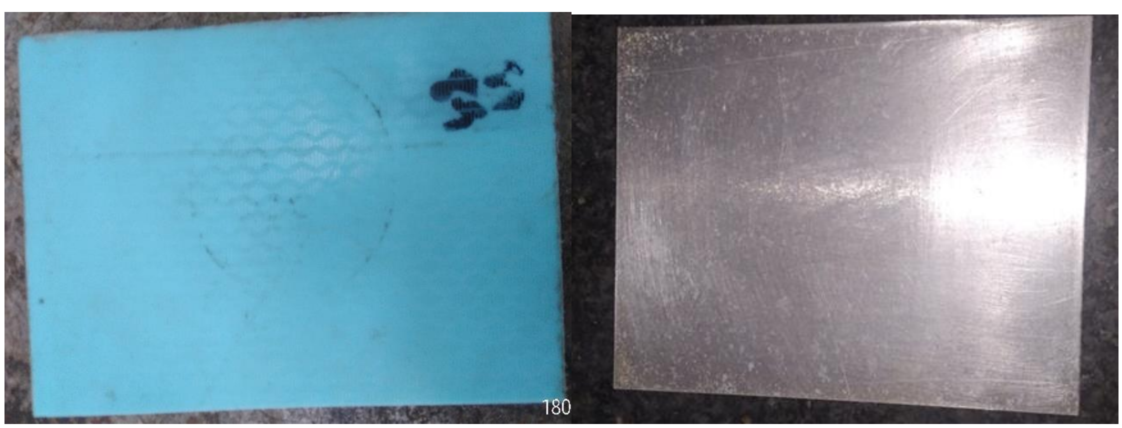

Figure 3. 7 Workpiece material samples (a) polymer (b) Aluminum alloy

3.6 FSW process parameters

Welding tool and equipment parameters are mainly dependent on mechanical properties of polymers, such as yield strength, ductility and hardness, which play significant influences on plastic deformation.

3.6.1 Tool rotational speed

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 850rpm, 1000rpm and 1250rpm.

3.6.2 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 defect because of not enough time to make stirring and mixing of the two material. For this thesis three different welding speed were selected depends on previous researches i.e. 40 mm/min, 50 mm/min, and 63 mm/min.

3.7 Design of the experiment

The design of experiment is based on full factorial by using Minitab software method. The parameters are 850, 1000 and 1250 tool rotational speed (RPM), 40 50 63 traverse speed or welding speed (mm/s), tilt angle (2.5^0) and 1mm offset of tool material from the center. In this design by taking tilt angle and offset as constant and the two parameters i.e. rotational speed and traverse speed as variable. So from this the experiment has 9 runs i.e. 9 samples were prepared and experimented.

3.7.1 Taguchi Technique

The Taguchi method was developed by Genichi Taguchi. He developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. Optimization of process parameters is the key step in the Taguchi method for achieving high quality without increasing cost. Here, to conduct the experiments 2 factors (parameters) each at 3 levels were selected.

Taguchi determines the minimum number of experiments to be conducted in the overall experiment based on the formula below.

$$N = L^f \quad (3.3)$$

Where:

N= Number of experiments to be conducted

f =Number of parameters

L=Number of levels

Thus using Minitab 18 by L9 orthogonal array the selected the order to make the further experiments were shown in Table 3.8

Table 3. 7 Experiment layouts of Taguchi L9

No. of experiments	Rotational speed (RPM)	Welding speed (mm/min)
1	850	40
2	850	50
3	850	63
4	1000	40
5	1000	50
6	1000	63
7	1250	40
8	1250	50
9	1250	63

Figure 3. 8 FSW joins made by a) 800RPM and 40mm/min b)800RPM and 50mm/min

Figure 3. 9 FSW joins mad by a) 100RPM and 40mm/min b)1000RPM and 50mm/min

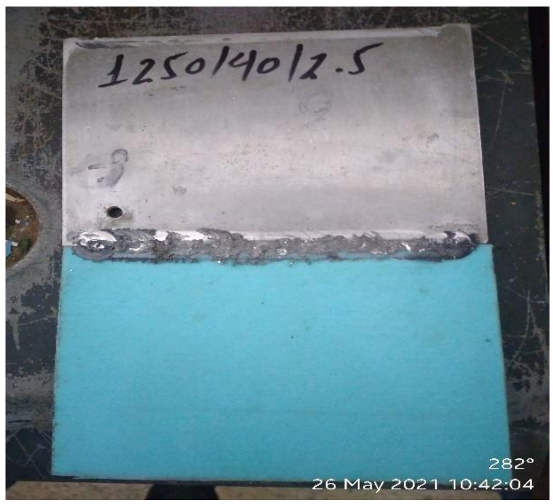

Figure 3. 10 FSW join made by 1250RPM and 40 mm/min

Figure 3. 11 FSW joints on top surface

3.8 Hardness Test

The application of hardness testing enables to evaluate a material's properties, such as strength, ductility and wear resistance, and so helps determine whether a material or material treatment is suitable for the purpose required. Hardness is the properties of material that allows resisting a plastic deformation, usually measured by penetration. The value of this property was the result of defined dimension procedures, thus depending on the hardness value methods used; the hardness value will be different. There are many methods to determine the hardness value of materials, among those Brinell, Vicker and Rockwell hardness tests frequently used. In this experiment Vicker hardness was used to determine the sample extruded qualities.

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 100 kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation. The Figure 3.14 below shows the Vickers hardness machine used to the hardness of samples.

Figure 3. 12 Vickers hardness testing machine

3.9 Microstructure Observation

Microstructure observation is used to determining grain size and, shape, and distribution of various phases and inclusions was important as these effects of the mechanical properties of the metal. This process follows some procedures in order observe the structures. The specimen preparation of sample to examine microstructure was cutting of specimen, grinding, polishing, etching, and observing microstructure by optical microscopy. For this thesis the microstructure observation is mounting done for only Alminum parent material because of the temperature effect the mounting temperature is almost equal to the melting point temperature of the polymer HDPE.

3.9.1 Cut Specimen from the Sample

Before microstructure observation the sample must be prepared as specimen accurately to the required testing size. For this work ten sample were selected to examine microstructures which is nine from welded sample and one sample from normal sheet metal were selected to examine microstructure for each test.

3.9.2 Grinding of Specimen

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

3.9.3 Polishing of specimen

In this step of specimen preparation, the specialized liquid spray on the surface of polishing cloth was diamond suspension liquid is used as spray form. In each of the polishing step, the specimen is washed with water and dried using pressurized compressor. The process continued up to four times until the specimen is free from any scratch and shine surface is obtained.

Figure 3. 13 Sample cut Al alloy for hardness test

Figure 3. 14 Specimens prepared for hardness test

Figure 3. 15 Microstructure observation setup

3.10 Tensile Strength Test

Tensile strength is the measurement of the force required to pull something such as rope, wire, or a structural beam to the point where it breaks. The tensile strength of a material is the maximum amount of tensile stress obtained before failure. The specimen used for the tensile test is the flat type. During the tests, a uniaxial load is applied through both ends of the sample. The dimension of the specimen is (85 x 40 x 3) mm. The specimen that are prepared to test tensile strength shown on the Figure 3.16.

The specimen is tested under a universal testing machine (UTM). Then the samples are left to brake till the ultimate tensile strength occurs. The stress-strain curve is plotted, for the determination of ultimate tensile strength (UTS). It is plotted from the data generated directly from the machine for the tensile test. Typical points of interest when testing a material include ultimate tensile strength or peak stress, offset yield strength that represents a point just beyond the onset of permanent deformation, and the rupture or fracture point where the specimen separates into pieces. Figure 3.16 shows the specimens that were prepared for tensile test. The machine that is used to determine the tensile strength of the specimen showed in Figure 3.17 below.

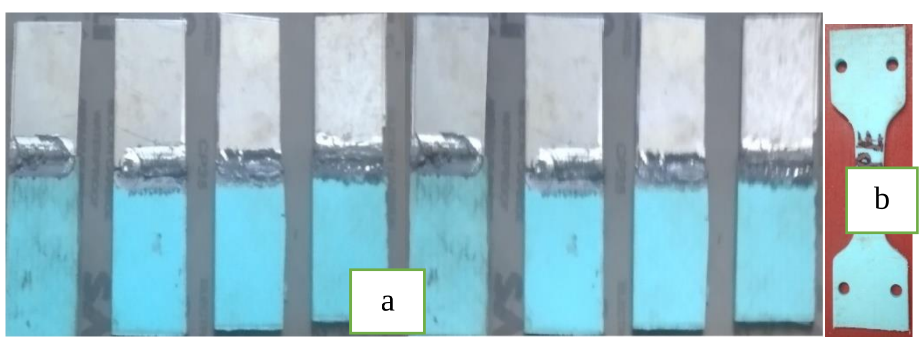

Figure 3. 16 specimens prepared for tensile test a) joints b) polymer

Figure 3. 17 machine setup for tensile test

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter includes the results of the trial and joint performance analysis by mechanical testing of hardness test. The joints characteristics were investigated by Vickers hardness tests analysis.

4.1 Manufactured tool for FSW

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

Figure 4. 1 a) Bottom view FSW tool after welding b) Front view of FSW tool after welding.

The figure 4.1 shows the FSW tool (D2 steel of FSW tool) after welding completely 9 samples (150mm length). The result shows the pin of tool worn out due to friction between the tool and the workpiece during welding. The reduction of pin length is 0.3 mm (reduced from 2.8 mm to 2.5 mm length) and the diameter of the pin/probe increased by 0.5 mm (increased from 3.5 mm to 4.0 mm).

4.2 FSW joints

The joints formed with different process parameter combination of welding speed, rotational, 1 mm offset distance from the center to aluminum side and 2.5^0 tilt angle. The first trial was done with the parameter of 850RPM and 40mm/min welding speed show not equally mixed of polymer with aluminum and this mostly due to lower rotational speed that is not enough to plasticize the aluminum. On the second and third trials almost similar defects observed. On the other joints which are form by the parameter of 1000 RPM, and 40 mm/min welding speed. In this trial the chips on the aluminum parent material formed with high grain size and this due to higher rotational speed that cause the polymeric material to over plasticize. The joint formed by process parameter rotational speed of 1250RPM has highly grain size of aluminum and polymer mixture and the cause for that was higher speed of rotation. Figure 4.1 to 4.9 shows the FSW joints of Al-HDPE at various process parameters and Figure 4.10 indicating the welded joints with zones.

Figure 4. 2 Joints formed by 850RPM and 40mm/min

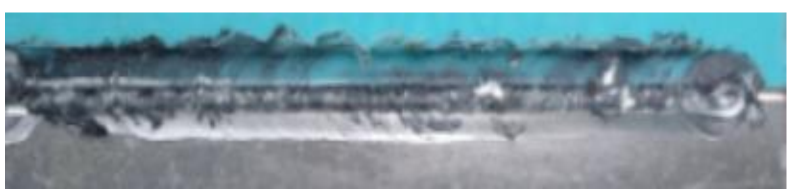

Figure 4. 3 Joints formed by 850RPM and 50mm/min

Figure 4. 4 Joint formed by 850RPM and 63mm/min

Figure 4. 5 Joint formed by 1000RPM and 40mm/min

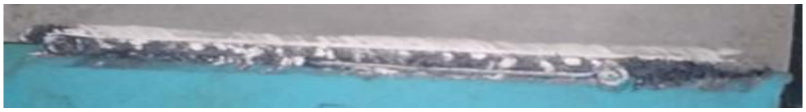

Figure 4. 6 Joint formed by 1000RPM and 50mm/min

Figure 4. 7 Joint formed by 1000RPM and 63mm/min

Figure 4. 8 Joint formed by 1250RPM and 40mm/min

Figure 4. 9 Joint formed by 1250 RPM and 50mm/min

Figure 4. 10 Joint formed by 1250RPM and 63mm/min

Figure 4. 11 Thickness side image of joint

4.3 Hardness test result.

FSW involves complex material flow under intensive plastic deformation. This is dependent on several process parameters, which result in highly modified microstructures. Several studies correlate the resultant microstructures with hardness profiles and use the hardness profile data as an initial evaluation of variation in mechanical properties.

Table 4. 1 Experimental result for mean value of hardness value

Sample no.	Rotational speed	Welding speed	Hardness values on			
			Parent material (Aluminum)		116.8	
			Parent material (Polymer)		66.8	
			Aluminum	Joint	polymer	Mean value
1	850	40	62.1	33.1	66.7	53.9
2	850	50	54.3	57.7	64.7	58.9
3	850	63	61.9	66.3	60.7	62.9
4	1000	40	52.5	37.0	31.4	40.3
5	1000	50	56.8	28.9	70.1	51.9
6	1000	63	58.4	33.4	32.4	41.4
7	1250	40	113.5	74.0	62.8	83.4
8	1250	50	123.9	51.2	30.3	68.4
9	1250	63	124.3	76.8	35.0	78.7

4.3.1 Analysis of Mean for Hardness

The average main value of hardness value for each factor i.e. Rotational speed and Welding speed calculated using the Minitab 18 design of experiments. Table 4.1 presents the experimental results of Vickers hardness test for each specimen and their mean values. In this study each Vickers hardness trial value is the average of three trial reading.

The hardness values are taken at three different regions for each sample i.e. at the center of the joint, 1mm from the center of joint to aluminum side and 1mm from the center of joint to polymer side for each combination of parameters the hardness value taken at three regions of welded area like at the side of Aluminum, at the center of the joint and at the side of polymer in order to know the harder area found for each sample. From the result it shows that harder values observed at the side of aluminum region. From the study it shows that when the parameter values increase the hardness value also increase. The hardness value that obtained from the is listed below the Table 4.1

The mean value of hardness value by using larger is better for each factor i.e. Rotational speed and Welding speed at each level are obtained and the result is listed in response table 4.2

Table 4. 2 Response table for main effects plot for larger is better

Level	Rotational speed	Welding speed
1	58.57	59.20
2	44.53	59.73
3	**76.83**	**61.00**
Delta	32.30	1.80
Rank	1	2

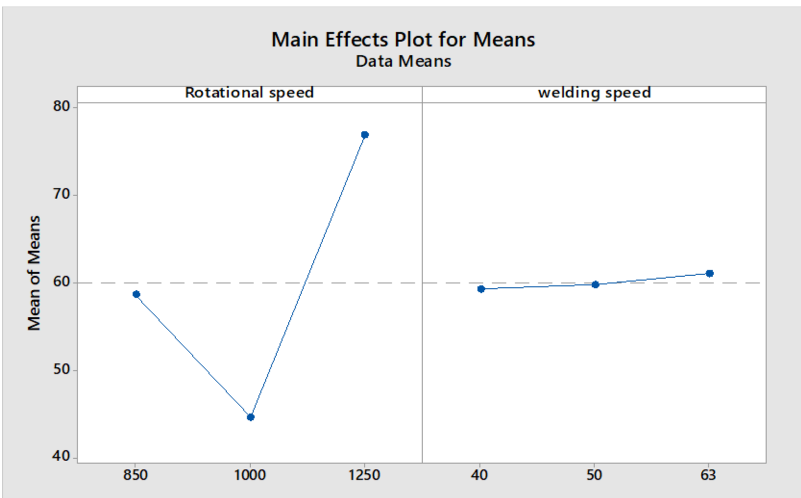

Figure 4. 12 Main effects plot using Minitab software

The control factors main effect plot for means of hardness value variations is as shown in the Figure 4.12 The result taken from the above data shows means as lager is better is selected for hardness value output.

Delta = (maximum mean – minimum mean). 4.1

Table 4.2 and Figure 4.12 show that the factor with the greatest effect on the mean from table 4.1 is welding speed weight (Delta 32.30 =, Rank = 1). The factor with the least effect on the mean is welding speed (Delta = 1.8, Rank = 2).

4.3.2 Analysis of S/N Ratios for Hardness

The Taguchi method uses S/N ratio to measure the variations of the hardness value in experimental design. The equations for calculating the signal to noise ratios are based on the characteristics of the response variables being reported. In this thesis, the response variables are larger-the-better. Table 4.3 presents the calculations of S/N Ratios for hardness value results using the Minitab 18 design of experiments.

Table 4. 3 Signal to Noise Ratios by Minitab18 for Larger is better

Level	Rotational speed	Welding speed
1	35.34	35.05
2	32.92	**35.47**
3	**37.68**	35.41
Delta	4.76	0.42
Rank	1	2

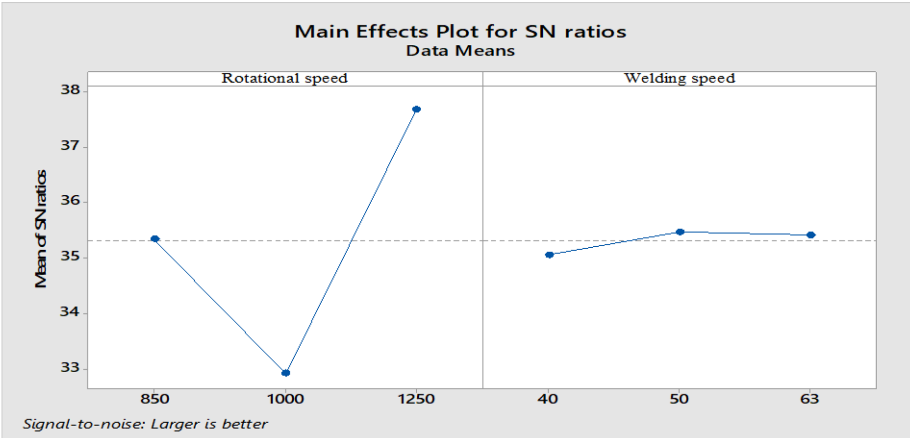

Figure 4. 13 Main effects for S/N plot using Minitab software

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

Delta = (maximum S/N – minimum S/N)

Table 4.3 and Figure 4.13 show that the factor with the greatest effect on the S/N from table 4.3 is welding speed weight (Delta 4.76 = Rank = 1). The factor with the least effect on the S/N is welding speed (Delta = 0.42, Rank = 2). Since main effect plots for S/N is helpful for adjusting the S/N on better value.

The figure 4.14 shows the hardness each sample and the parent materials.

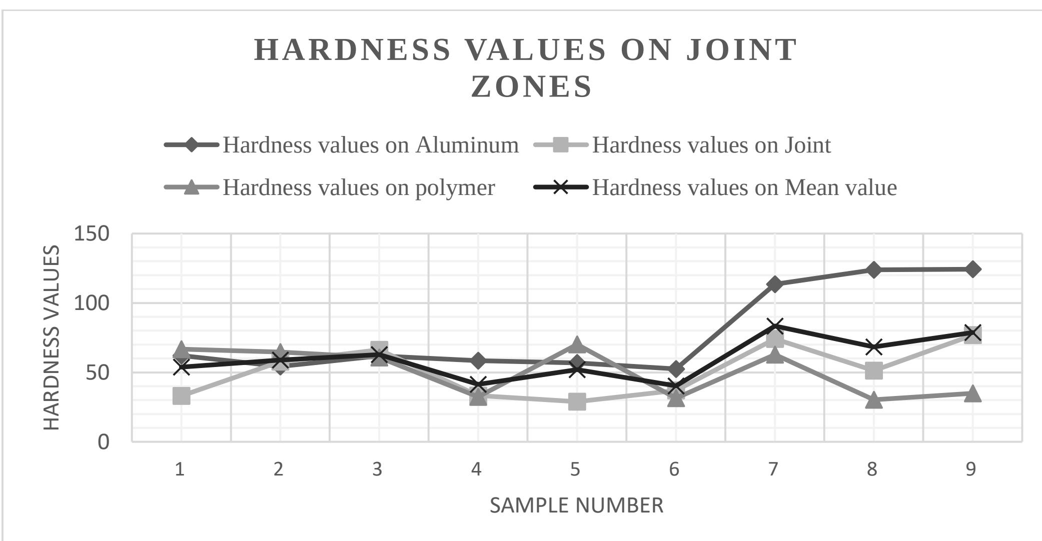

Figure 4. 14 Harness value chart

4.4 Microstructure observation

Microstructures determine the mechanical, physical, and chemical properties of materials. For example, the strength and hardness of materials are determined by the number of phases and their grain sizes.

From the microstructural investigations shows that the stir zone (SZ) formed with the relatively large size aluminum fragments entrapped through melted and re-solidified HDPE matrix. The presence of fragments with different sizes at SZ is related to non-uniform temperature distributions and material flow in advancing and retreating sides. And also showed that larger size of aluminum fragments at the retreating side is due to lower temperatures which resulted in a more coarse cutting action by the tool, rather than stirring of viscous material that occurs at higher temperatures.

The microstructure of the weld consisting of aluminum chips surrounded by polymeric HDPE matrix. The direction of molten polymeric flow is controlled by threaded pin to flow in vertical direction near the pin towards the shoulder. From the structure also seen that the effects of tool travel speed on the joint formation. It can be seen that low travel speed results in fine aluminum chip weldment compared with higher travel speed.

By the of FSW, the localized heating is accomplished between the tool and work-pieces that soften the material around the pin and the combination of tool rotation and it leads to the movement of material from one parent material to the other and due to this aluminum–polymer interlocking was produced.

4.5 Tensile strength

After doing tensile testing operation on prepared specimen the result of the tensile strength on different combination of parameters the data was recorded and organized to calculate the signal to noise ratio of each sample. The input experimental values were measured using universal tensile testing machine as described in chapter 3. The tensile strength for the HDPE polymer material from the test was 23.91MPa, and from the tensile test of the sample the highest tensile strength was get 1.96 MPa which is 8.5% of the polymer parent material. The tensile results from the UTM machine and S/N ratio for tensile strength listed below Table in table 4.4.

Table 4. 4 tensile result and S/N ratio for tensile result

Ex. No	Tool rotational speed (RPM)	Welding speed (mm/min)	Tensile strength (MPa)	S/N ratio of tensile strength
1	850	40	1.39	2.86030
2	850	50	1.41	2.98438
3	850	63	1.45	3.22736
4	1000	40	1.60	4.08240
5	1000	50	1.70	4.60898
6	1000	63	1.75	4.86076
7	1250	40	1.80	5.10545
8	1250	50	1.96	5.84512
9	1250	63	1.89	5.52924

4.5.1 Analysis of S/N Ratios for tensile strength

The Taguchi method uses S/N ratio to measure the variations of the tensile strength in experimental design. In this thesis, the response variables are larger-the-better. Therefore, larger-the-better characteristic was used and S/N equation for this characteristic is given in equation. Table 4.5 presents the calculations of S/N Ratios for tensile strength results using the Minitab 18 design of experiments.

Table 4. 5 Response Table for Signal to Noise Ratios for Larger is better

Level	Rotational speed	Welding speed
1	0.7057	1.4295
2	2.0039	1.6097
3	**2.2338**	1.9042
Delta	1.5281	0.4748
Rank	1	2

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

By Looking at the tensile strength table and main effects plot for the signal-to-noise (S/N) ratios the rotational speed weight have the greatest effect (Delta = 1.52, Rank = 1). The factor with the least effect on S/N ratio is welding speed (Delta = 0.47, Rank = 2). Table 4.5 and Figure 4.15 shows the main effects of welded joints based on the tensile test strength.

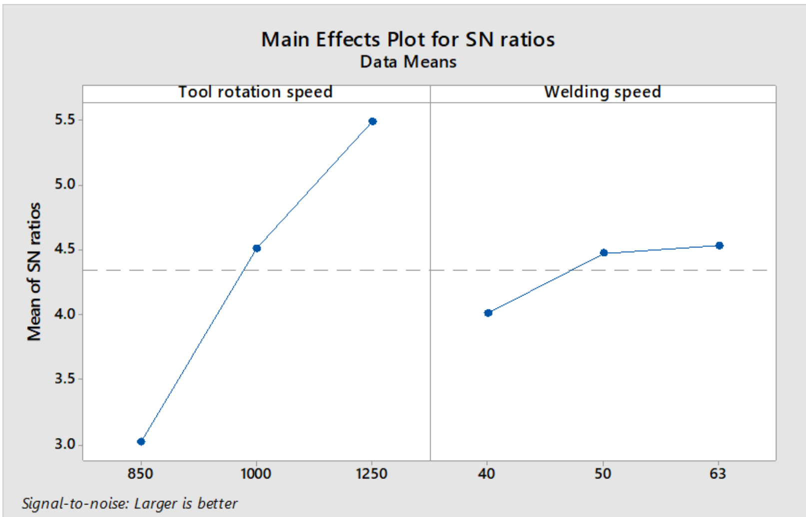

Figure 4. 15 Main effect plot for S/N of tensile strength

4.5.2 Analysis of Mean for tensile strength test

The average main value of tensile strength for each factor i.e. Rotational speed and Welding speed and calculated using the Minitab 18 design of experiments. Table 4.4 presents the experimental results of UTS machines for each specimen and their mean values. The control factors main effect plot for means of tensile strength variations is as shown in the Figure 4.15 The result taken from the above data shows means as lager is better is selected for tensile strength output.

Delta = (maximum mean – minimum mean).

Table 4.6 and Figure 4.16 show that the factor with the greatest effect on the mean is rotational speed weight (Delta 0.467 =, Rank = 1). The factor with the least effect on the mean is welding speed (Delta = 0.100, Rank = 2). Since main effect plots for means is helpful for adjusting the mean on better value.

Table 4. 6 Response Table for Means for larger is better

Level	Tool rotation speed	Welding speed
1	1.417	1.597
2	1.683	1.690
3	**1.883**	1.697
Delta	0.467	0.100
Rank	1	2

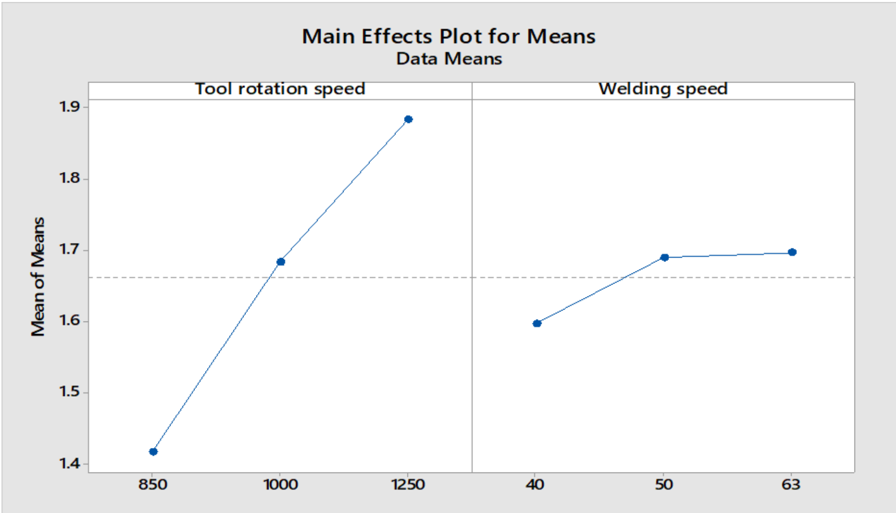

Figure 4. 16Main effects plot for Means of tensile strength

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Friction stir welding was used to join aluminum alloy sheets to HDPE polymer. A range of different welding parameters were studied including, rotational speed of (850, 1000, 1250) rpm, traverse speed of (40, 50, 63) mm/min with tilt angle of 2.5^0 to get quality joints. The joints were created by friction stir welding with the tool contacting on the Aluminum side and polymer side by offset 1mm to the side of Aluminum. Friction stir welding was successfully implemented to weld aluminum alloy and HDPE plates with less strength.

- The tool threaded profile has a great role to mix and material flow from the Aluminum side to polymer on the welded joints.
- The most higher hardness joints were created with higher parameter values of 1250rpm and 40mm/min.
- There were different defects found on the joints like porosity, surface roughness, flash formation due to insufficient material flow.
- The most tensile strength joint gained by the parameter of 1250 RPM & 50 mm/min.

5.2 Recommendation

- ✓ This work investigation was limited to dissimilar material of aluminum alloy and HDPE polymer. However, it can apply for other metallic material and polymers.
- ✓ Also, this work only performed for butt welding configuration it can be applied for lap welding and T-welding.
- ✓ In this work it was investigated only experimental analysis but it is also possible to performs simulation of the analysis to determine the material flow and other effects.

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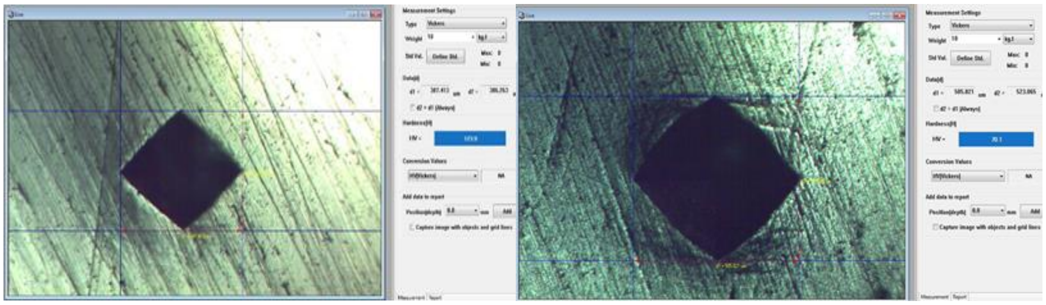
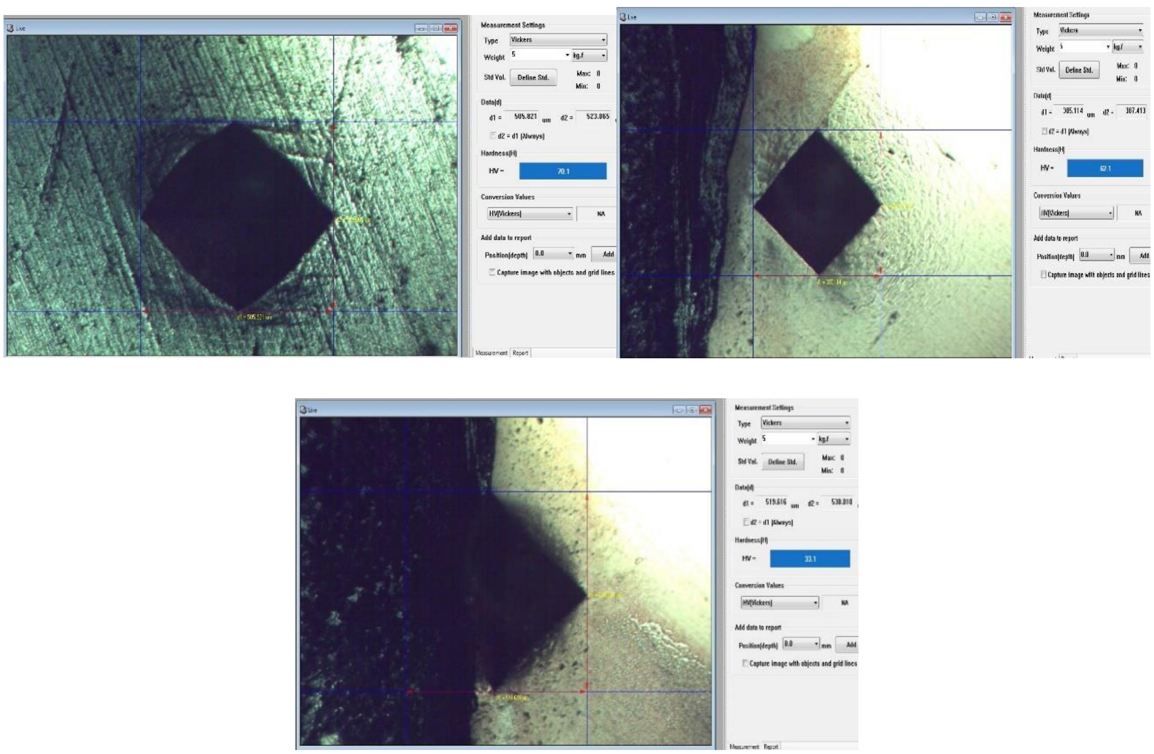
APPENDIX

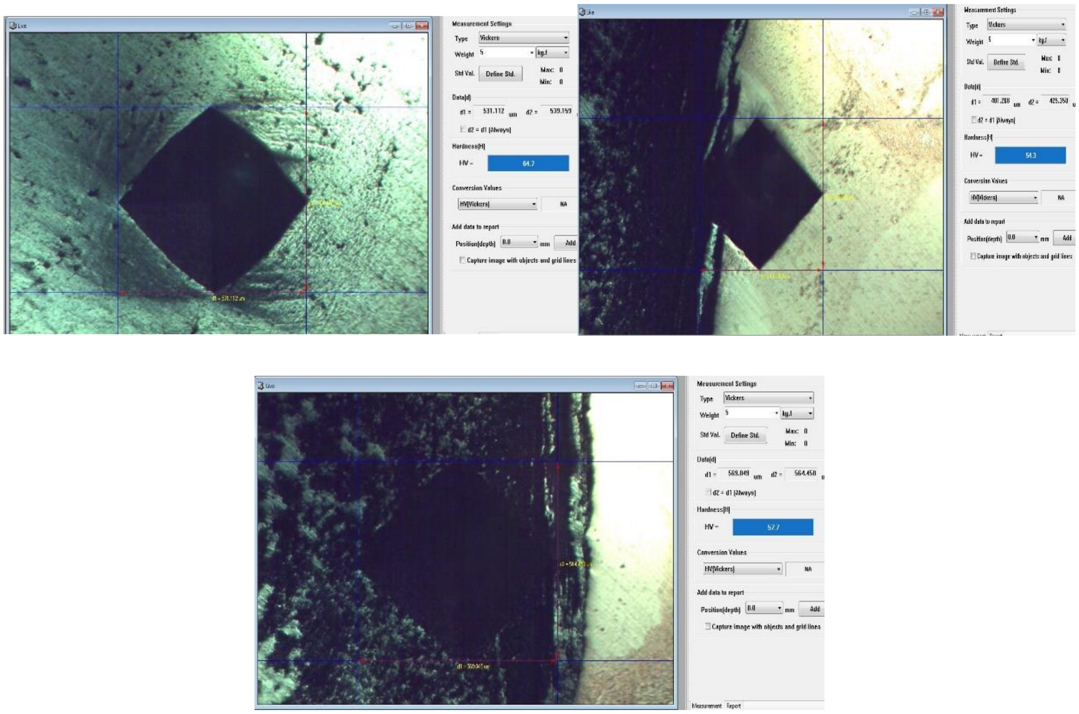
Appendix 1: hardness test results



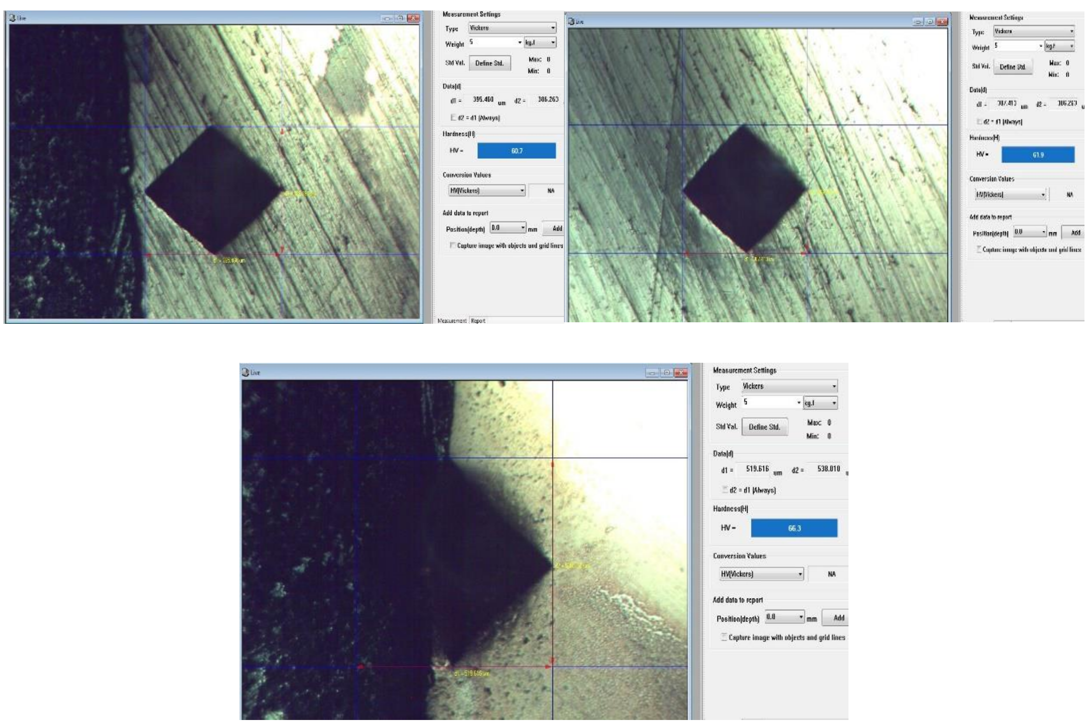
The hardness values of base materials of Aluminum and HDPE respectively



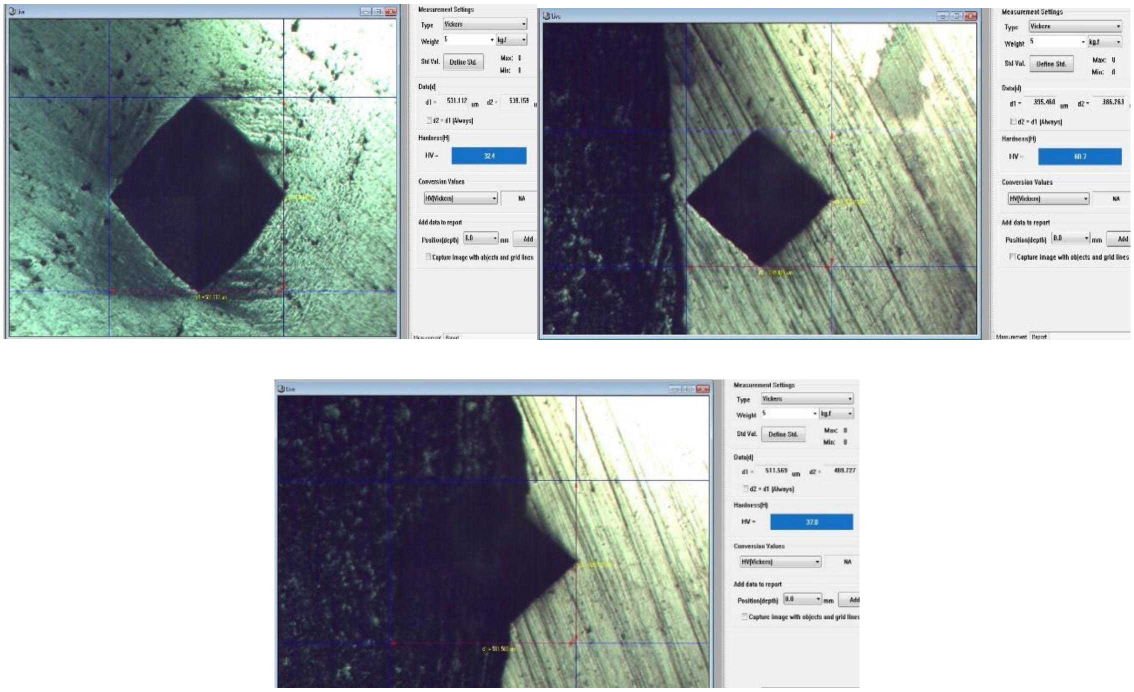
The hardness values of the welded sample 1 i.e. 850 RPM, 40 mm/min, 2.5^0



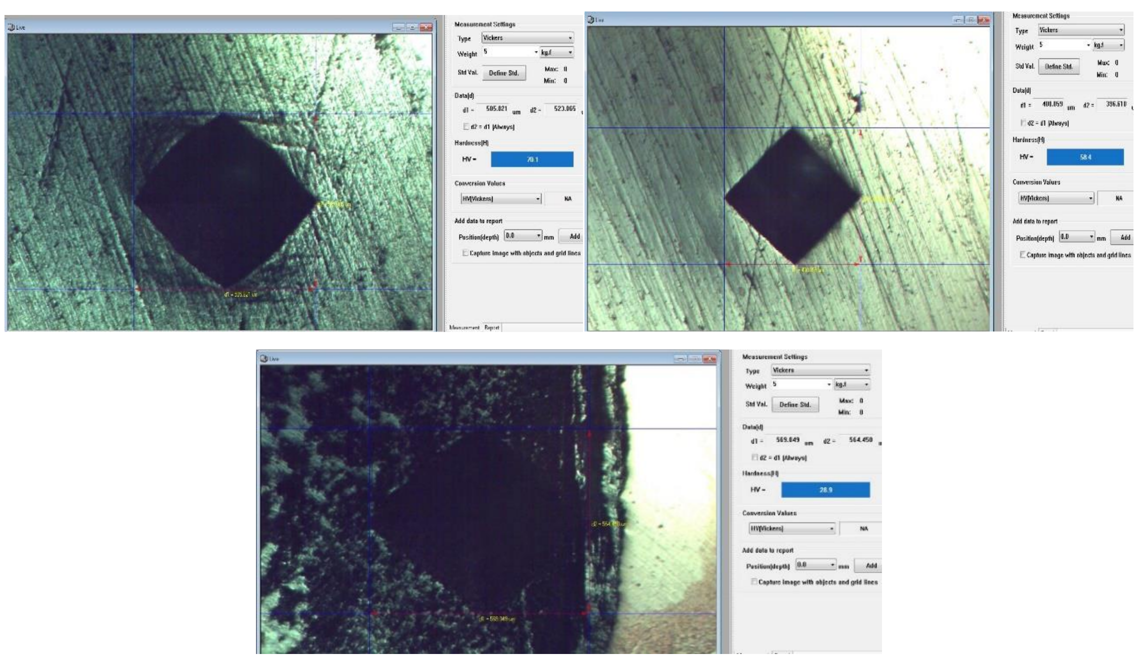
The hardness values of the welded sample 2 i.e. 850 RPM, 50 mm/min, 2.5^0



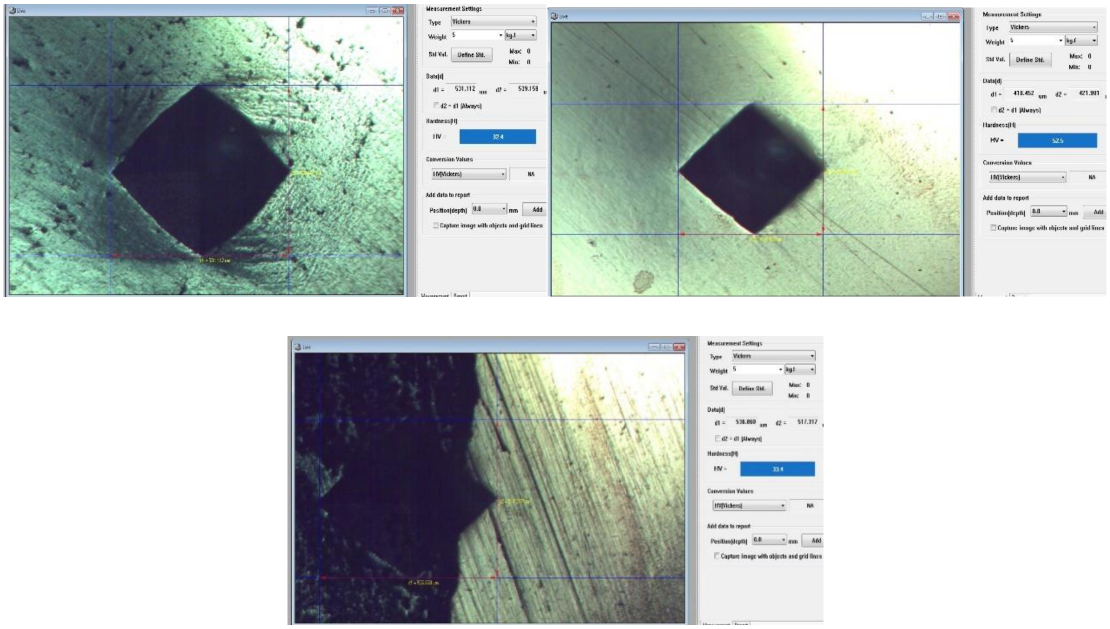
The hardness values of the welded sample 3 i.e. 850 RPM, 63mm/min, 2.5^0



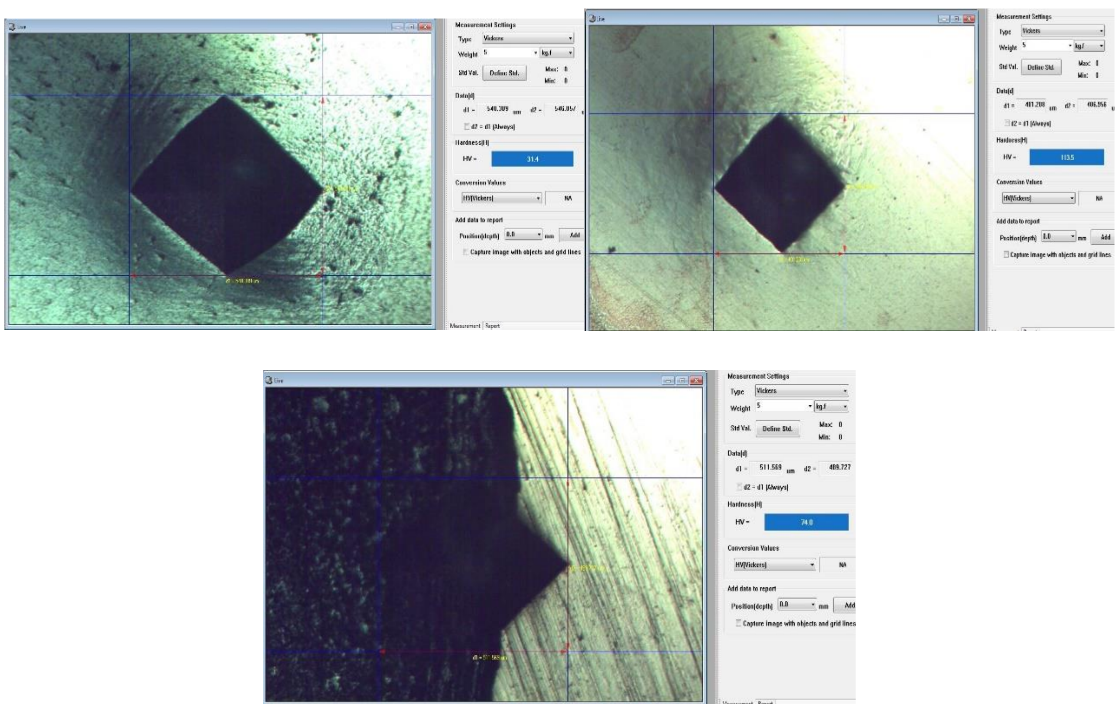
The hardness values of welded sample 4 i.e. 1000 RPM, 40 mm/min, 2.5 ^{0}



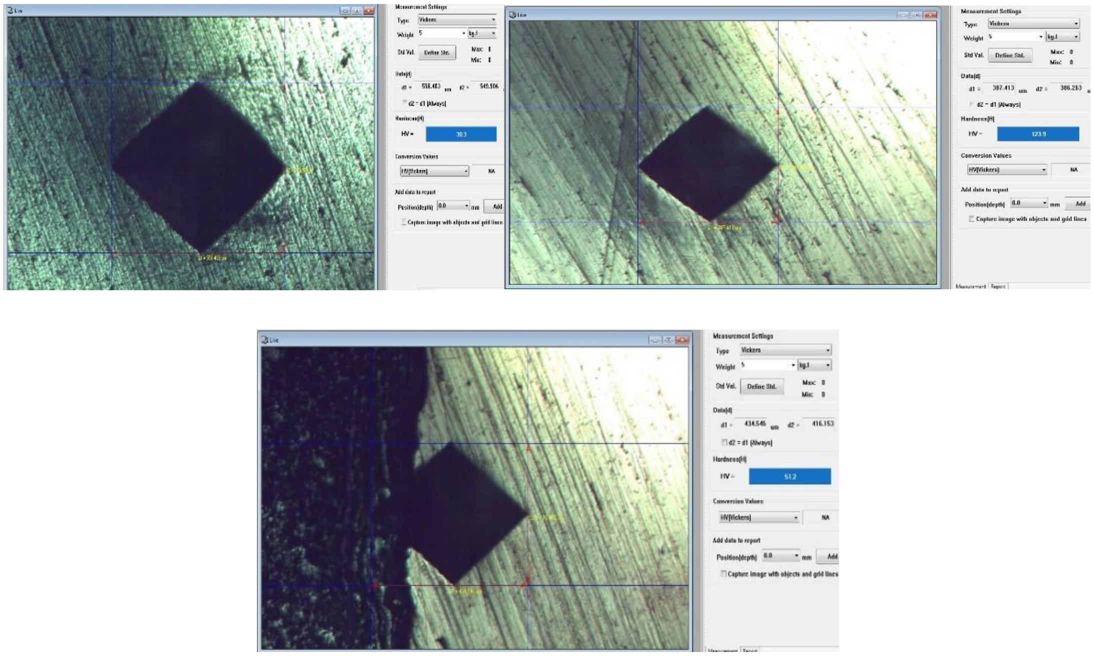
The hardness values of welded joint sample 5 i.e 1000 RPM, 50 mm/min, 2.5^{0}



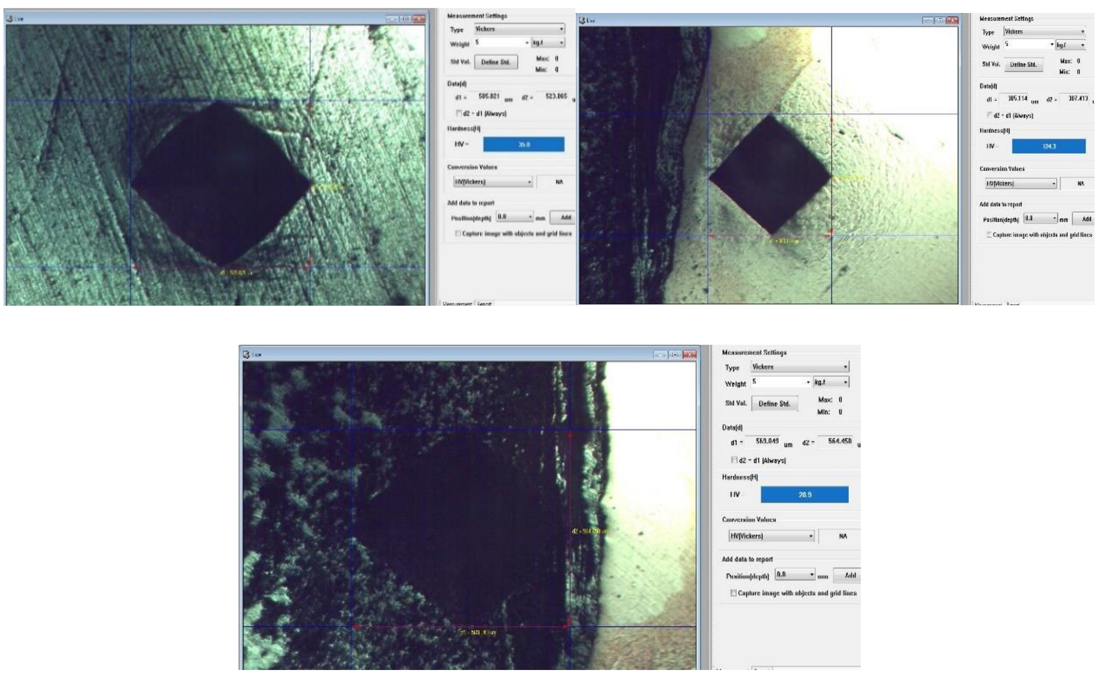
The hardness values of the welded joint sample 6 i.e. 1000 RPM, 63 mm/min, 2.5^0



The hardness values of the welded joint sample 7 i.e. 1250 RPM, 50 mm/min, 2.5^0

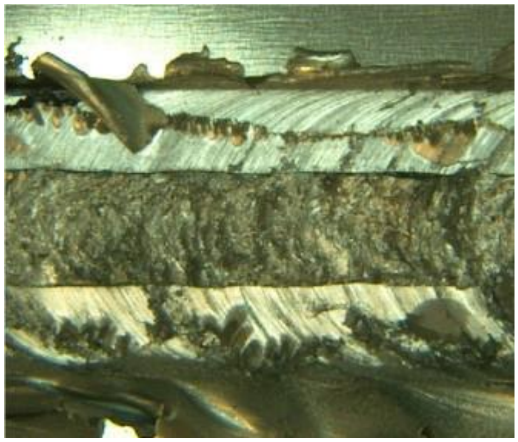


The hardness values of hweded joint sample 8 i.e. 1250 RPM, 50 mm/min, 2.5^0



The hardness values of welded joint sample 9 i.e. 1250 RPM, 63 mm/min, 2.5^0

Appendix 2: Result of microstructures



Microstrcture observation of joint 1 i.e. 850 RPM, 40 mm/min, 2.5^0

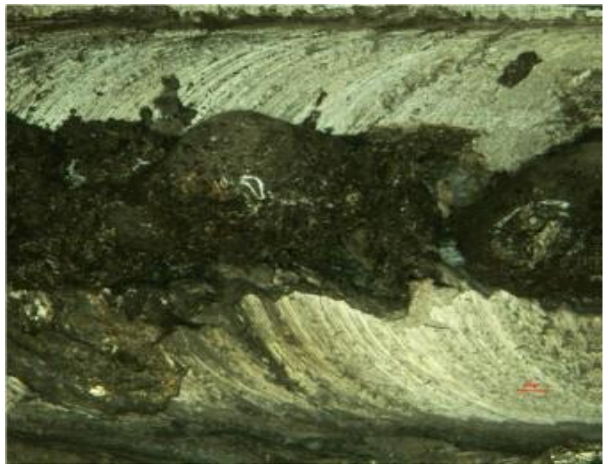
Microstructure observation of joint 2 i.e. 850 RPM, 50 mm/min, 2.5^0

Microstructure observation of joint 3 i.e. 850 RPM, 63 mm/min

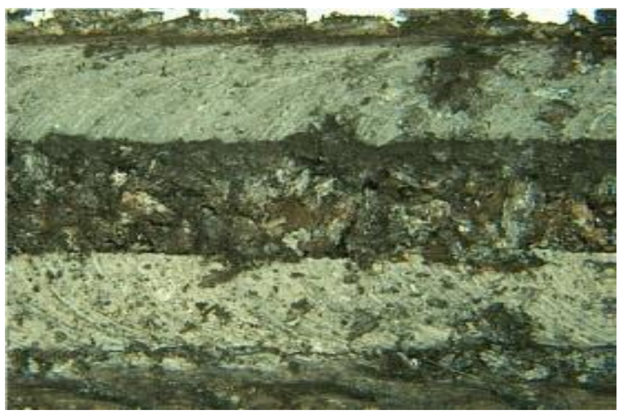
Microstructure observation of joint 4 i.e 1000 RPM, 40 mm/min, 2.5^0

Microstructure observation of joint 5 i.e. 1000 RPM, 50 mm/min, 2.5^0

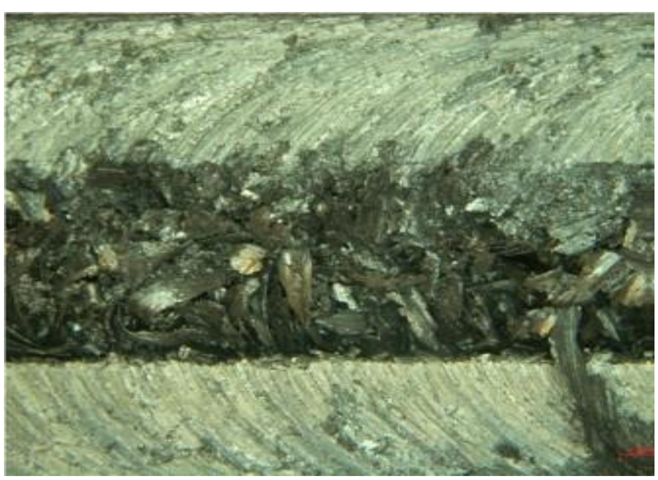
Microstructure observation of joint 6 i.e. 1000 RPM, 63mm/min 2.5^0



Microstructure observation of joint 7 i.e. 1250 RPM, 40mm/min, 2.5^0

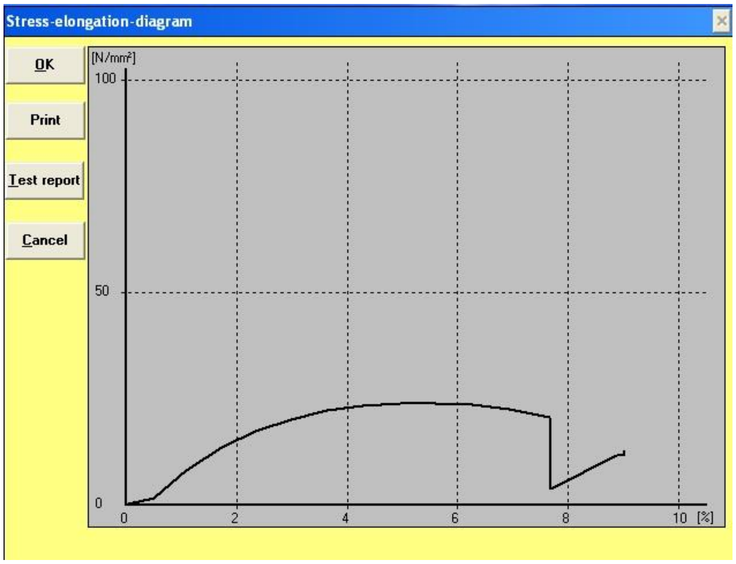


Microstrucre observation of joint 8 i.e. 1250 RPM, 50 mm/min, 2.5^0

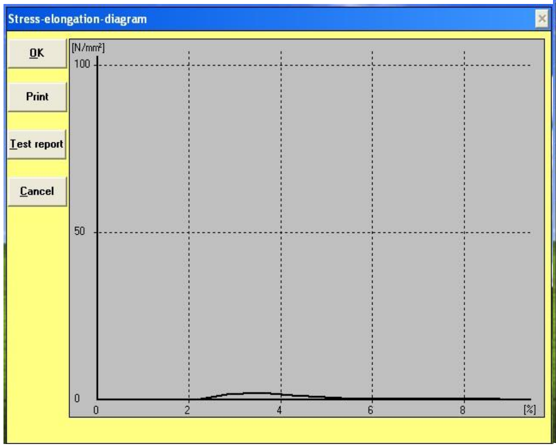


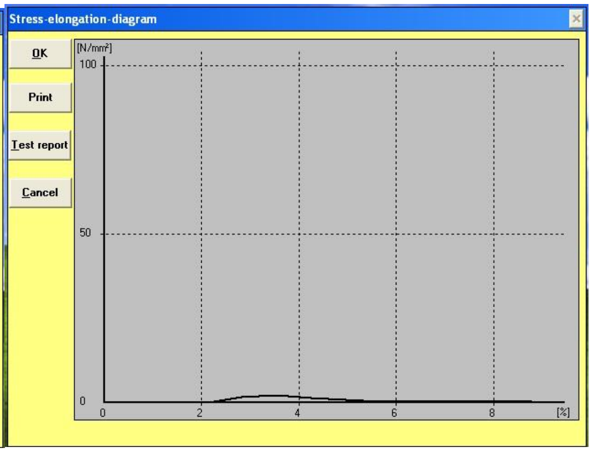
Microstructure observation of joint 9 i.e 1250 RPM, 63 mm/min, 2.5^0

Appendix 3: Result of Tensile test

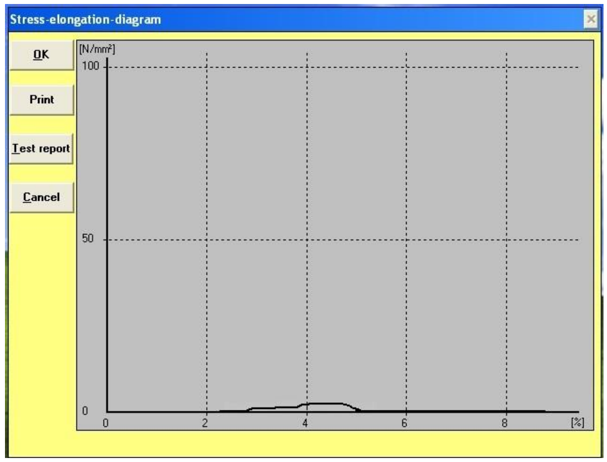


Stress-Strain graph for parent polymer material

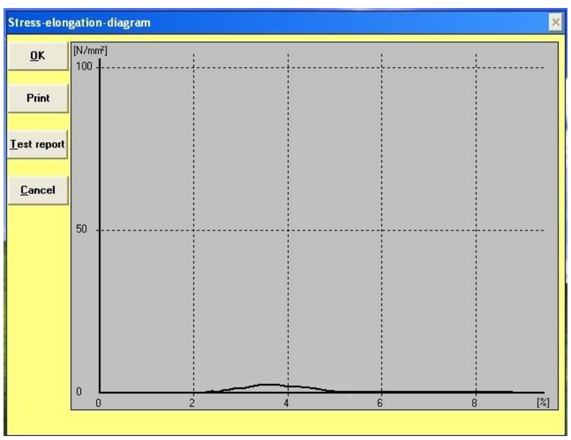




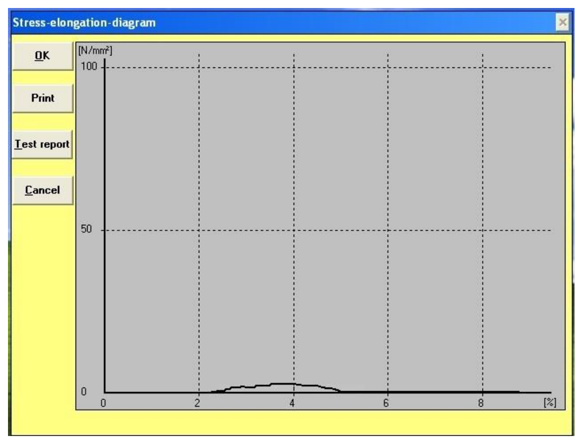
Stress-Strain graph for 850 RPM & 40 mm/min   Stress-Strain graph for 850 RPM & 50 mm/min



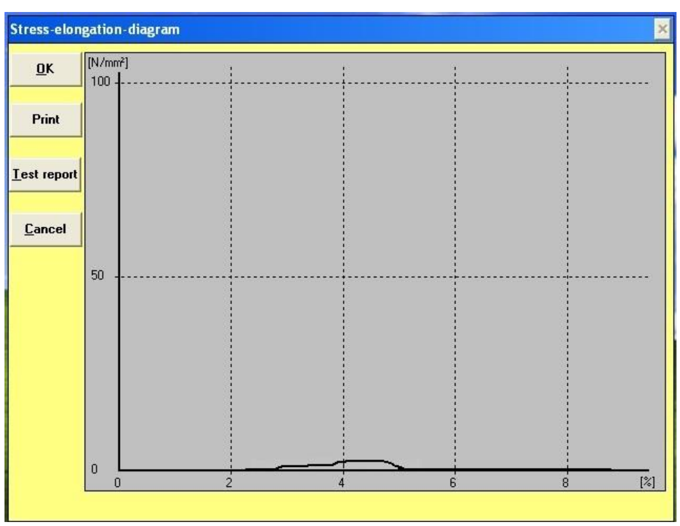
Stress-Strain graph for 850 RPM & 63 mm/min



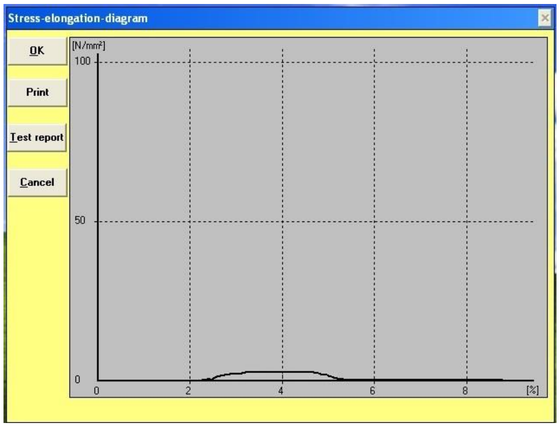
Stress-Strain graph for 1000 RPM & 50 mm/min

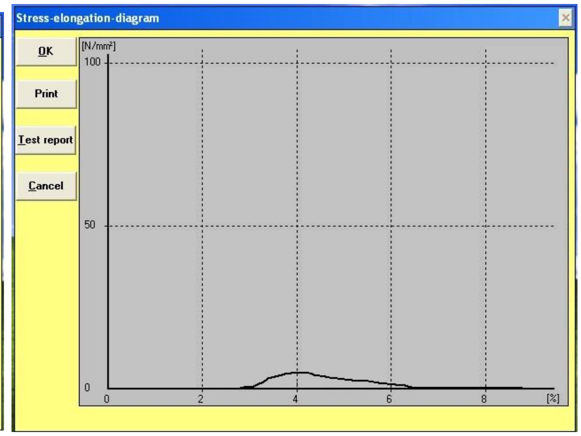


Stress-Strain graph 1000 RPM & 50 mm/min

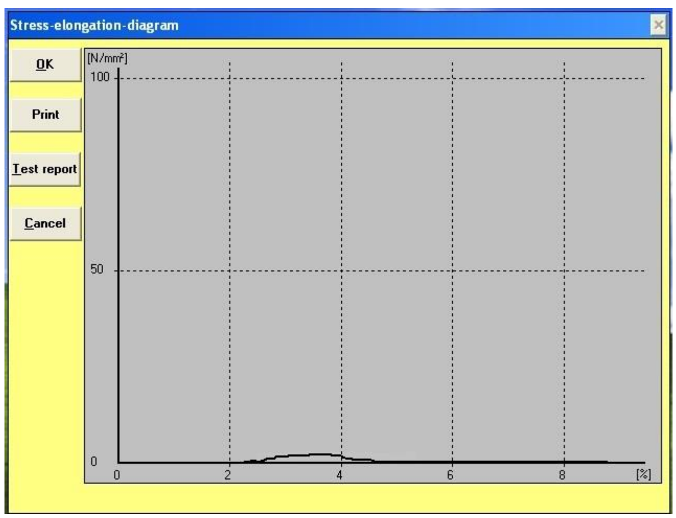


Stress-Strain graph for 1000 RPM & 63 mm/min

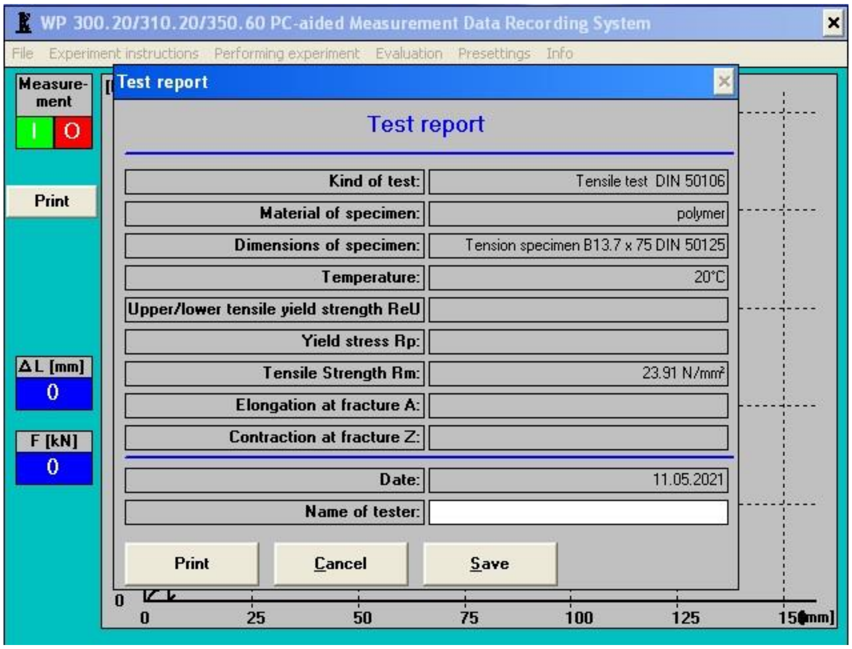


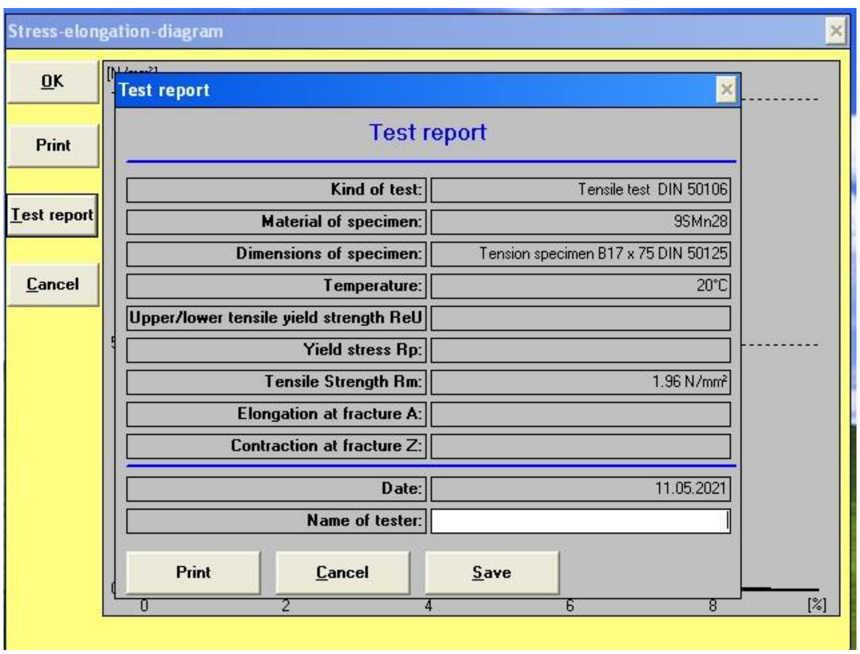


Stress-Strain graph of 1250 RPM & 50 mm/min   Stress-Strain graph of 1250 RPM & 50 mm/min



Stress-Strain graph of 1250 RPM & 63 mm/min


WP 300.20/310.20/350.60 PC-aided Measurement Data Recording System
File
Experiment instructions
Performing experiment
Evaluation
Presettings
Info
Measure-ment
I
O
Print
ΔL [mm]
0
F [kN]
0
Test report
Test report
Kind of test:
Tensile test DIN 50106
Material of specimen:
polymer
Dimensions of specimen:
Tension specimen B13.7 x 75 DIN 50125
Temperature:
20°C
Upper/lower tensile yield strength ReU
Yield stress Rp:
Tensile Strength Rm:
23.91 N/mm²
Elongation at fracture A:
Contraction at fracture Z:
Date:
11.05.2021
Name of tester:
Print
Cancel
Save
0
25
50
75
100
125
150 [mm]


Stress-elongation-diagram
OK
Print
Test report
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Test report
Test report
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Tensile test DIN 50106
Material of specimen:
9SMn28
Dimensions of specimen:
Tension specimen B17 x 75 DIN 50125
Temperature:
20°C
Upper/lower tensile yield strength ReU
Yield stress Rp:
Tensile Strength Rm:
1.96 N/mm²
Elongation at fracture A:
Contraction at fracture Z:
Date:
11.05.2021
Name of tester:
Print
Cancel
Save
0
2
4
6
8
[%]