MICROSTRUCTURE AND MATERIAL FLOW INVESTIGATION OF DISSIMILAR FRICTION STIR WELDED PLATES

by

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Dissertation submitted in partial fulfillment

of the requirements of the

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CERTIFICATION OF APPROVAL

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Approved:

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TRONOH, PERAK

September 2013

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Muhammad Syukri Bin Norashid

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Given this opportunity, I would like to acknowledge those who have been helping me, either directly or indirectly, in continue working on the project – starting from preliminary research, to the development phase and until the completion phase of this Final Year Project in Universiti Teknologi PETRONAS.

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ABSTRACT

The Friction Stir Welding (FSW) was first invented on December 1991 by Wayne Thomas in The Welding Institute (TWI), Cambridge, United Kingdom. Friction Stir Welding has been initially developed for welding aluminium alloys, but several recent studies show that it should be also successfully applied to other materials, such as metal-matrix composites. The concept of the FSW is that a non-consumable rotating tool with a specific designed pin and shoulder is inserted between the edges of metal plates to be joined. Then the welding tool will be stirred traversely along the line of joint. The tool which acted as a heating of workpiece and movement of material to produce the joint will produced the plastic deformation of workpiece. However, for dissimilar metal plates which specifically aluminium and metal-matrix composites (MMC), there are only a few studies about dissimilar plates between AA1100 and 6092/ SiC/ 25p (T6). Therefore, this project is done to study the movement of SiC in the weld zone. Before the microstructure analysis is done, there are many steps to be done first which are the completion of the welding tool, FSW process and surface preparation. After that, microstructure analysis is done and the results shows that at lower travel speed, the material flow for SiC is well mixed and enter the opposite side of the metal plates. However, there are worm holes produced after the welding which is mainly because of the advancing and retreating side as well as thickness error of the metal plates. Based on this project, by analysing the microstructure the characteristics and properties of the joint produced by friction stir welding (FSW) can be determined. Therefore, this project will help the FSW industry by providing additional information about joining AA1100-6092/ SiC/ 25p (MMC).

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ABBREVIATIONS AND NOMENCLATURES

FSW	Friction Stir Welding
TWI	The Welding Institute
MMC	Metal Matrix Composite
OM	Optical Microscope
EDX	Energy Dispersive X-ray Spectrometry
AWS	American Welding Society
IIW	International Institute of Welding
HAZ	Heat Affected Zone
TMAZ	Thermomechanically Affected Zone
CNC	Computer Numerical Control
SiC	Silicon Carbide
Al	Aluminium
Si	Silicon
C	Carbon
O	Oxide
S	Sulphur
Mn	Manganese
Zn	Zinc

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

The Friction Stir Welding (FSW) was first invented on December 1991 by Wayne Thomas in The Welding Institute (TWI), Cambridge, United Kingdom. This joining technique is energy efficient, environment friendly, and less welding defect. In addition, it can be used to join high-strength aluminum alloys and other metallic alloys that are hard and even impossible to be welded by conventional fusion welding. Friction Stir Welding has been initially developed for welding aluminium alloys, but several recent studies show that it should be also successfully applied to other materials, such as particles reinforced aluminium based composites [1]. In this case, wear damage of the welding tool occurs frequently during welding, due to the abrasive action of the ceramic reinforcement. However, the joining by FSW process can avoids the formation of shrinkages, porosity as well as the aggregation of the ceramic reinforcement in the welded zone and also reduces the thermal stresses.

The concept of the FSW is that a non-consumable rotating tool with a specific designed pin and shoulder is inserted between the edges of metal plates to be joined. Then the welding tool will be stirred transversely along the line of joint. The tool which acted as a heating of workpiece and movement of material to produce the joint will produced the plastic deformation of workpiece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin [2]. As a result of this heating and flow of material process, a joint is produced in solid state. Because of various geometrical features of the tool, the material movement around the pin can be quite complex [3]. FSW process will make the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains [4]. Good mechanical properties will be produced if the grain boundaries of the microstructure is fine.

Aluminium matrix composites, reinforced with ceramic particles, can be welded by fusion processes and solid state joint processes [5]. However, the traditional fusion welding techniques will be critical when applied to these materials. This is because the typical welding problems of aluminium alloys which are high thermal expansion and conductivity, high solubility of gases in the molten state, solidification shrinkages and cracking presence of oxide inclusions [2]. Furthermore, with the presence of the ceramic reinforcement there are additional problems that will make the welding more difficult which are high viscosity of the melted composites, undesired interfacial chemical reactions between the ceramic reinforcement and the molten matrix alloy, different thermal expansion coefficients between the matrix and the ceramic reinforcement, and segregation of particles during solidification. Hence, the purpose of this project is to study and investigate the microstructure of the joint between two different parent material which are aluminium and metal-matrix composites (MMC).

1.2 PROBLEM STATEMENT

The friction stir process (FSW) provide better quality of welding and environmentally friendly compared to conventional fusion welding. However, for dissimilar metal plates which specifically aluminium and metal-matrix composites (MMC), there are still improvement need to be done because FSW will result deleterious reactions between both parent materials when attempting of joining them. Furthermore, there are only a few studies about dissimilar plates between Aluminium 1100 and Aluminium 6092 reinforced with 25% SiC (T6). Therefore, the movement of SiC in the weld zone is unclear and need to be investigated.

1.3 OBJECTIVES

The objectives of this project are:

a) To investigate the microstructure of weld zone of dissimilar plates.
b) To investigate the movement of Silicon Carbide (SiC) particles in the weld zone.

1.4 SCOPE OF STUDY

Table 1: Scope of study for this project.

Item	Description
Welding Tool	H13 Tool Steel (Grade 2344) with tapered pin.
Machine Type	1. Bridgeport Romi Power Path 15. 2. CNC milling machine VMC 2216XV. 3. Linear Hack Saw Machine KP-280. 4. Abrasive Cutter. 5. Auto Mounting Press SIMPLIMET 1000.
Welding Focus	Butt weld joint.
Workpiece Material	1. Aluminium 1100. 2. Aluminium 6092 reinforced with 25% Silicon Carbide (6092 / SiC/ 25p).
Parameter (FSW)	1. Rotational speed: 1200 rpm. 2. Travel speed: a) 25 mm/min. b) 30 mm/min. c) 35 mm/min.
Analysis	1) Microstructures study using Optical Microscope (OM) with three different parameters. 2) Visual inspection for the material flow. 3) Energy Dispersive X-ray Spectrometry (EDX) for both parent materials to check the element percentage.

The scope for this project is by using tapered H13 tool steel (Gr 2344) welding tool which was fabricated using Bridgeport Romi Power Path 15. Then the welding tool was involved in hardening process by heat treatment in the furnace. The workpieces material used for this project are AA1100 and 6092/ SiC / 25p (T6) MMC. The plates will be joined as butt weld joint using CNC milling machine VMC 2216XV. Then the analysis will be conducted by using optical microscope (OM) for three different parameters; 25mm/min, 30 mm/min and 35mm/min.

CHAPTER 2

LITERATURE REVIEW

The rapid and successful industrialisation of FSW across a range of fields has generated significant interest in standardisation of the process, particularly for safety critical applications [8]. The current status of standardisation activities in the field of FSW is as follows:

1. **American Welding Society (AWS) standard on Friction Stir Welding (FSW)**
   AWS publishes codes on multiple aspects of welding and materials joining. The code books or journal are made to specific letters and numbers for reference, and many welders will refer to a specific combination of code letter or number when referring to the code book. In the book, the different welding methodologies, inspection methods, and metals are published under different codes. As an example, for fiction stir welding (FSW), AWS had published the standard which the code is D17.3M:2010. The book describes about the 'Specification of Friction Stir Welding of Aluminium Alloys for Aerospace Applications' [8].

2. **International Institue of Welding (IIW) standard on Friction Stir Welding (FSW)**
   This Institute has established the Technical Commissions, and each one of them covered a relatively broad subject of welding science and technology. Under some of them, there are a number of Technical Sub-commissions which specify more aspects for welding specification. A total of five ISO standards and updates for friction stir welding (FSW) have been published under the direct responsibility of IIW [9] .

3 **Registration of Friction Stir Welding (FSW**)
   Prior to the publication of friction stir welding (FSW) standards, various certification agencies (including Lloyds Register, DNV, Germanischer Lloyd) have issued insurance approvals for FSW users for the production of specific components [8]. These agencies have been certified for standard welding code requirements. This approach involves the development and verification of welding procedures, followed by qualification testing which are visual

appearance, bend tests, tensile tests, macro sections, hardness tests, corrosion tests, and quality control.

The difficulty of making high-strength, fatigue and fracture resistant welds in aerospace aluminum alloys, such as highly alloyed 2XXX and 7XXX series, has long inhibited the wide use of welding for joining aerospace structures [1]. These aluminum alloys are considered as non-weldable for fusion welding processes because of the poor solidification microstructure and porosity in the fusion zone. These factors make the joining of these alloys are impossible and unattractive.

Table 2: Different between fusion welding processes and FSW.

Fusion Welding Processes	**Friction Stir Welding (FSW)**
Hot cracking and porosity	No hot cracking and porosity
High residual stresses and distortions	Low residual stresses and distortions
Oxide removal is required	Oxide removal is optional
Some of aluminium alloys are difficult to weld	Most metal that fusion welding process cannot be welded can be welded by FSW
Produced fume and slag that are not safe	Safe and environment friendly

There are also research and development done for dissimilar metal plates. One of them is the welding of aluminium metal matrix composites. However, fusion welding of aluminum metal matrix composites (Al-MMC's) is difficult due to the deleterious reactions between reinforcing hard particles and liquid aluminum [10]. The different in melting points for both material also has been found problematic to join them together. When the both material have melting point with high margin, the material will liquefies but will not produced a proper weld seam.

However, some research for dissimilar metal plates had successfully being presented. Yoshikawa established a joining criterion for lap welding of dissimilar aluminium and stainless steel [11] and Fukumoto et al achieved good weld joint efficiency in dissimilar joints between normal carbon steel (S45C) and 6063 aluminium alloy [12]. Other successful dissimilar joining using the FSW process include Aluminium and Brass by Esmaeili et al [13], Aluminium and Titanium by Wei et al [14]; Aluminium and Magnesium by Yan et al [15] and Magnesium and Titanium by Aonuma and Nakata [16]. Successful welds of aluminium and copper with good joint integrities have also been reported by Akinlabi [17]. These studies showed that a lot of potential exists to successfully join dissimilar materials using the Friction Stir Welding (FSW).

The deleterious reaction between dissimilar plates are also can affect the material flow for both plates. Based on the study done by Yan et al.[15], the dissimilar plates used were 5052 aluminum alloy and AZ31 magnesium alloy. The results showed that the layer thickness of the onion ring was uneven since the two alloys had different flow abilities as shown in Fig. 1a. However, the microstructure of the stir zone is greatly refined.

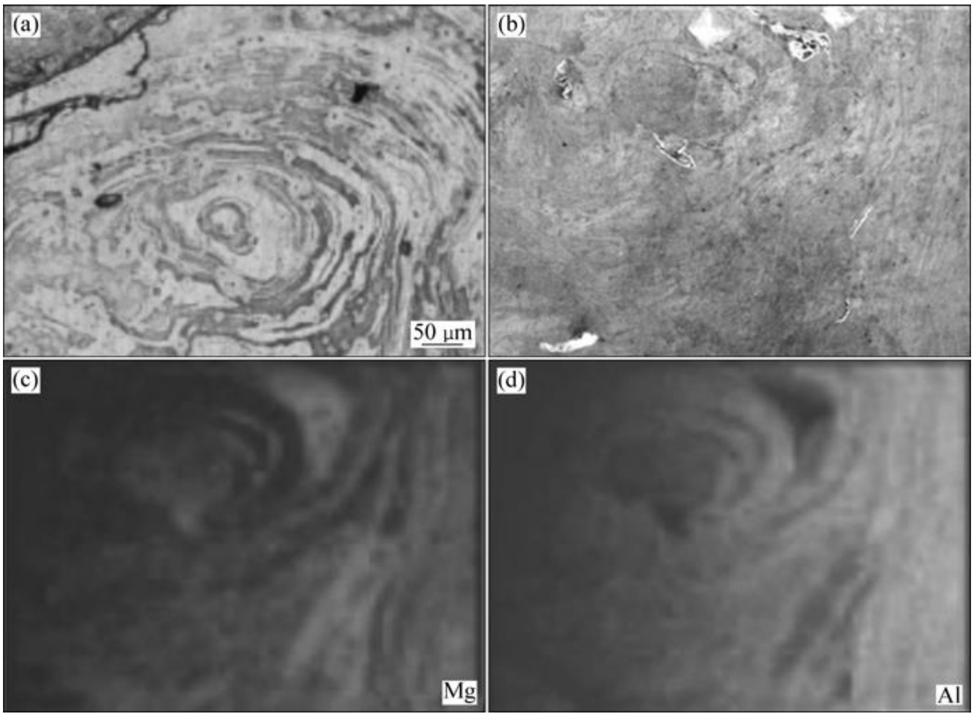


Figure 1: (a) Optical microstructure in the welding region (b) EDS maps of Mg (c) EDS maps of Al (d) distribution in onion ring. [15]

The parameters used for FSW is also important and can affect the characteristic of the microstructure and material flow in the weld zone. According to Tan et al.(2013), insufficient material flow is caused by insufficient heat input. Fig. 2 shows surface appearances and cross sections of Al/Cu joints produced at different traverse speeds. At traverse speed of 40 mm/min, the boundary of Al and Cu plates could be seen from the surface appearance shown in Fig. 2a. Cavity defect was observed in the cross-sectional macrograph indicating incomplete mixing between Al and Cu. While at the lower welding speed of 20 mm/min, a good appearance with few flash was observed in Fig. 2c. The proper mixing occurred and void-free joint was obtained shown from cross section in Fig. 2d.

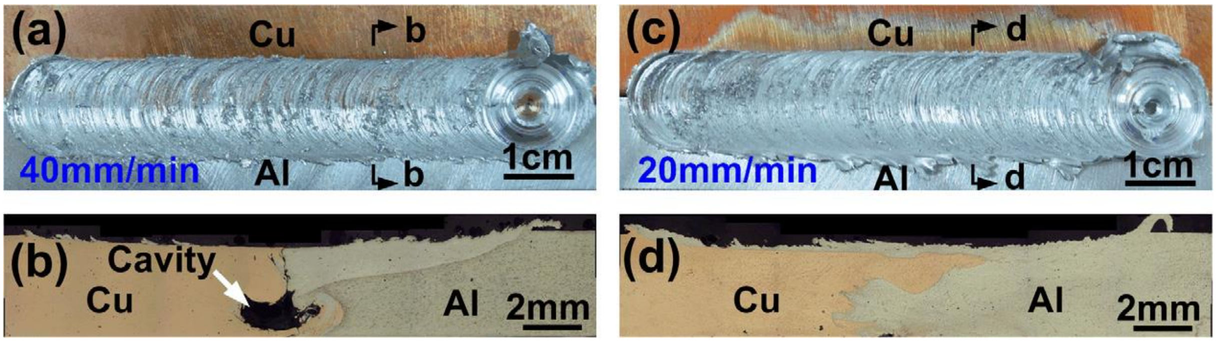


Figure 2 : Weld appearances and cross sections of friction stir welded joints at different transverses speeds: (a, b) 40 mm/min, (c, d) 20 mm/min. [12]

In this project, the dissimilar metal plates that are used are between aluminium alloys and metal matrix composites. The difficulty of fusion welding of aluminum metal matrix composites (Al-MMC’s) can be eliminated by doing Friction Stir Welding (FSW) as there is no melting during welding process and problems associated with liquid-solid reactions are not to be worried about. In this solid state welding technique a rotating tool, cylindrical in shape with a pin of smaller diameter extending from the tool shoulder, is translated along the joint line and produces, during its path, frictional heating and also plastic deformation of the material, due to a stirring effect around the pin.

According to D. Storjohan (2005), FSW of Al-MMC’s produced a homogeneous microstructure with a uniform hardness profile when compared to fusion welded Al-MMC’s. Figure 3 showed the microstructure of the parent material for 2124/SiC MMC and 6061/Al2O3 MMC. When compare to Figure 4, which are microstructure of the friction stirred weld plate, the microstructure showed very little difference to the parent material.

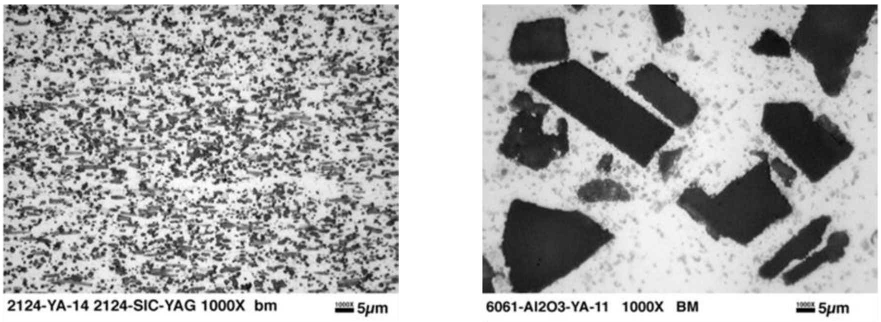
(a)  (b)

Fig. 3 : Micrographs of base metal region from (a) 2124/SiC MMC and (b) 6061/Al2O3 MMC

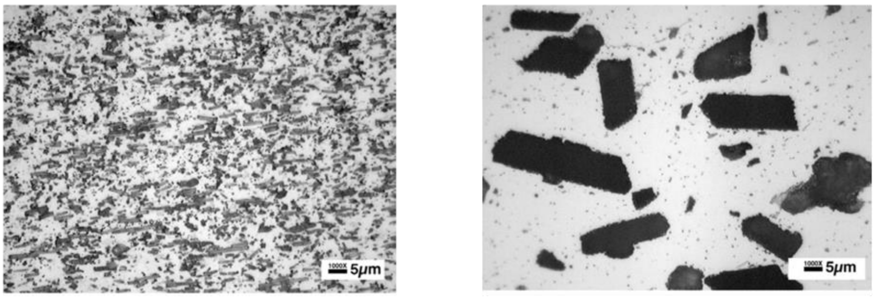
(a)  (b)

Fig. 4 : Micrographs of friction stirred weld metal region from (a) 2124/SiC MMC and (b) 6061/Al2O3 MMC

The solid-state nature of the Friction Stir Welding (FSW) results in a highly characteristic microstructure. The microstructure can be broken up into the following zones which are thermomechanically affected zone (TMAZ), heat affected zone (HAZ), stir zone and flow arm zone. The thermomechanically affected zone (TMAZ), which is adjacent to the weld nugget, has been plastically deformed and thermally affected. In this region, the strain and temperature are lower and the effect of welding on the microstructure is small. TMAZ will exhibits the elongated grains of alumium alloy matrix and the SiC particle free regions of the composite.

The heat affected zone (HAZ) region is subjected to a thermal cycle but is not deformed during welding. The temperatures for this region during welding are lower than in the TMAZ but may still have a significant effect if the microstructure is thermally unstable. In fact, in age-hardened aluminium alloys this region commonly exhibits the poorest mechanical properties [18]. This region will exhibit a similar microstructure both at the retreating and advancing sides as the base composite. Friction stir welding (FSW) of Al-MMC's produced a homogeneous microstructure with a uniform hardness profile when compared to fusion welded Al-MMC's.

The *stir zone* is a region of heavily deformed material occured at the location of the pin during welding process. The grains within the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material [19]. The features of the stir zone is the common occurrence of several concentric rings which has been referred to as an "onion-ring" structure [20].

The *flow arm zone* is on the upper surface of the weld and consists of material that is dragged by the shoulder from the retreating side of the weld, around the rear of the tool, and deposited on the advancing side.

The design of the tool is a critical factor as a good tool can improve both the quality of the weld and the maximum possible welding speed [21] . The welding tool has two primary functions which are localized heating and material flow [1]. There are many types of the welding tools such as Tri-flute type tool, A-skew type tool, straight pin head, tapered pin head, and threaded pin head. The welding tool must have strong, durable, hard and high melting point so that it can resist to wear, withand the strong abrasion of the material and affect the welding seam of the joint.

CHAPTER 3

METHODOLOGY

3.1 PROJECT METHODOLOGY

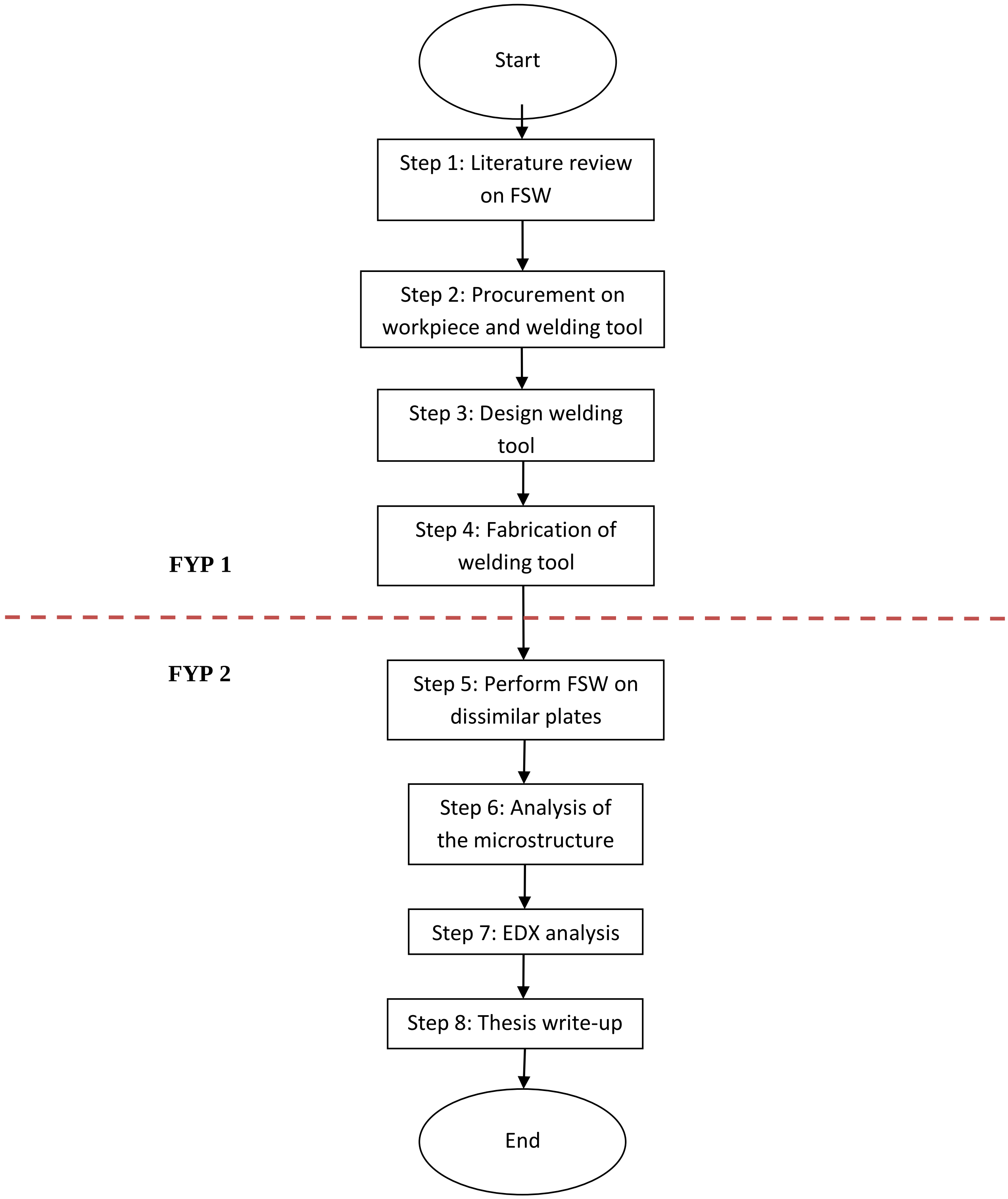


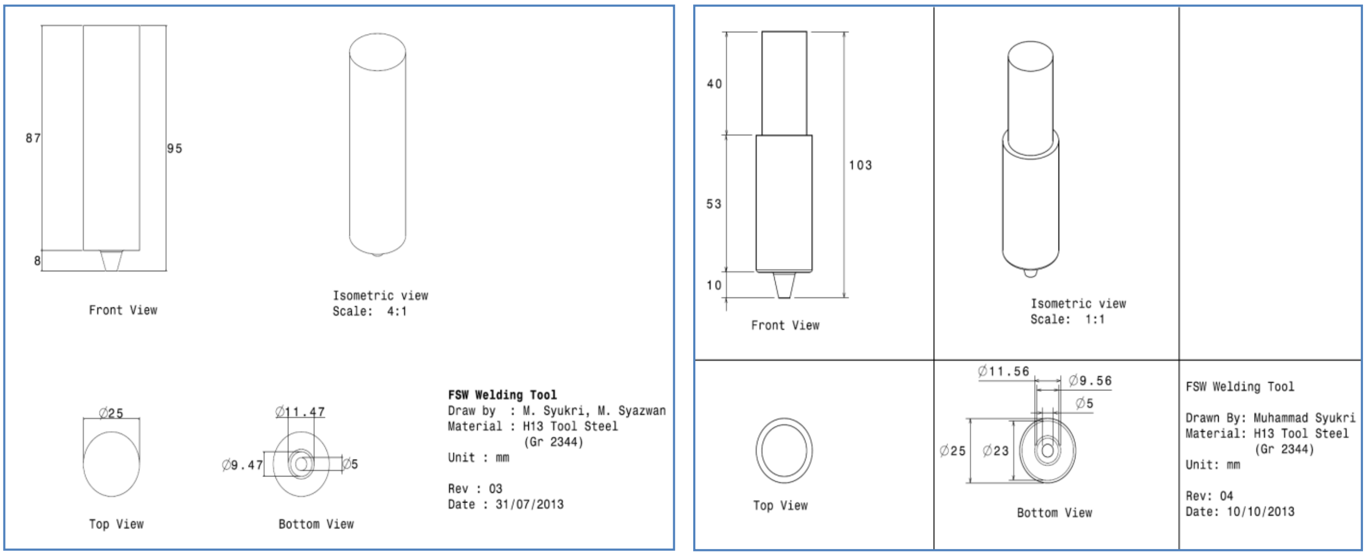
Figure 5: The flow process of the methodology.

3.2 FABRICATION OF WELDING TOOL

The welding tool needs to be fabricated first in order to proceed with the welding process. The steps of the fabrication of the welding are tool is design, fabricate and heat treatment.

Firstly, the welding tool have been designed with suitable dimensions and geometry based on the researches in literature review and discussions with supervisor. Then the detail of the design was given to lab technician for fabrication process. The detail of the tool will be as specified in Figure 6.

However, due to technical errors occured, the design of the tool steel have been changed as the diameter of the tool steel was too big for the clamping process in the milling machine. Thus the design of the tool steel has been modified by using the same CNC Lathe machine. Based on the figures shown below, the diameter on the upper part of the welding tool has been decreased to 20mm from 25mm.



(a) (b)

Figure 6 : (a) Detail design of welding tool; and (b) Detail design of the modified welding tool.

After the designing process, the fabrication process can be proceeding with the aid from the lab technicians. Firstly, the tool was fabricated from the raw H13 Tool Steel at Block N using Bridgeport Romi Power Path 15. The coding was done by technician assistant who is in charge of the machine.

Figure 7 : Machine (Bridgeport Romi Power Path 15) used for fabrication.

Then, the fabrication process for hardening was conducted at Block 17 by using the CARBOLITE heat treatment furnace. The steps for hardening are as follows; (1) preheat at 750℃ for two hours,(2) dwelling at 1010℃ for one hour and (3) cooling by air quench. Then the oxide layer on material need have been removed by using sand paper.

(a) (b)

Figure 8 : (a) Tool steel after fabrication and, (b) tool steel after hardening process.

3.3 PROCESS OF THE FSW

The FSW have been conducted at Block N by using CNC milling machine VMC 2216XV as shown in Figure 9. The machine was conducted by a technician who was in charge of this equipment.

Figure 9: CNC milling machine used for welding.

The process of FSW using the CNC milling machine is described as follows:

1. Two aluminum plates are placed together and clamped on the jig with bolts and nuts.
2. The jig is clamped to the Bridgeport Milling Machine with an inclined angle of 3°.
3. Proceed with the welding process by coding and adjustment on the milling machine.

The parameters used for the welding process are very important as the results can be analysed by the manipulative and constant variables. The manupulative variable in this project is the travel speed of the welding tool while the constant variables are the spindle speed (rpm), plunge feed rate (mm/min), depth of plunge, dwell time, inclination angle and metal plates side. The details of parameters are as shown below:

Table 3: Parameters used for welding.

Parameters	Sample 1	Sample 2	Sample 3
Plunge feed rate (mm/min)	10	10	10
Spindle speed (rpm)	1200	1200	1200
Travel speed (mm/min)	25	30	35
Depth of plunge (mm)	10	10	10
Dwell time (s)	10	10	10
Inclination angle (°)	3	3	3
Metal plates side	Advancing: MMC Retreating: AA1100	Advancing: MMC Retreating: AA1100	Advancing: MMC Retreating: AA1100

Figure 10: One of the samples after FSW.

3.4 SURFACE PREPARATION FOR MICROSTRUCTURE ANALYSIS

Before the microstructure analysis, there are several steps need to be done first which are :

a) Cutting
b) Mounting
c) Grinding
d) Polishing
e) Etching

3.4.1 Cutting

After the welding process, the workpiece have to cut off so that the size of the samples can be fitted into the mounting machine. Firstly, the machine was cut by using the Linear Hack Saw Machine KP-280. Then the cutting process was followed by using Abrasive Cutter.

Figure 11: Linear Hack Saw Machine KP-280 used for cutting the workpiece.

Figure 12: Abrasive cutter used for sectioning the workpiece.

The section of the cutting process is as shown below:

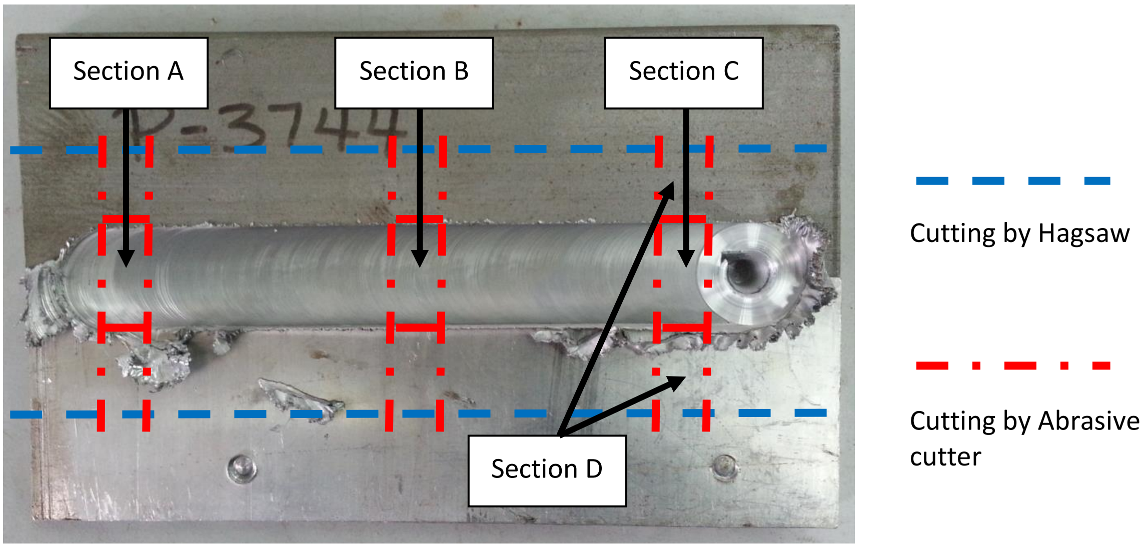


Figure 13: Cutting section of workpiece.

The reason of the cutting method using two equipments is because the original size of the workpiece which is 120mm x 200mm x 12mm does not fit in the abrasive cutter. Therefore the workpiece have to be cut first by using the hacksaw so that the workpiece can be insert into the abrasice cutter.

The workpiece have been cut into three sections which are located at the start, middle and end point of the weldment area. These sections will be taken for analysis of:

i. Section A and C – Visual analysis of the material flow.
ii. Section B and D – Microstructure analysis by Optical Microscope (OM).

The sections of the workpiece contain all welding regions for microstructure analysis. The regions included the weld nugget, thermomechanically heat affected zone (TMAZ), and heat affected zone (HAZ). However, there is no base metal region as the size for the mounting machine is not enough to be mounted with the base metal region. Thus, the section for base metal analysis is separated into section D which include the MMC and aluminium 1100.

3.4.2 Mounting

The mounting process is required so that the sample is easier to hold and labeled. The mounting process have been done by using SIMPLIMET 1000 Auto Mounting machine as shown in Figure 14 at Block 17.

Figure 14: SIMPLIMET 1000 Auto Mounting Press machine.

The steps of the mounting process are as follow:

1. The surface is cleaned by the reagant.
2. The sample is placed with the surface analysis at the bottom.
3. The black Phenolic Compression Powders is poured on top of the sample.
4. Press the 'START' button and the machine will automatically pressurize and heating the mounting powder.
5. The sample is being cooled by water and ready to be analysed or grinding.

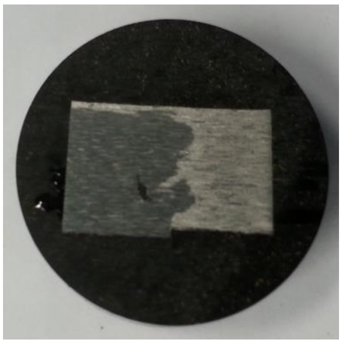
Figure 15: One of the samples that have been mounted.

3.4.3 Grinding

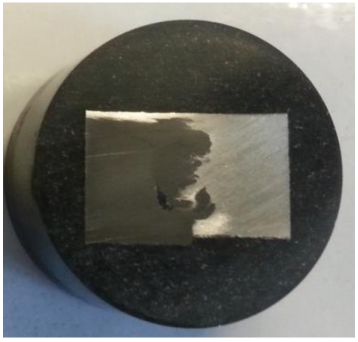
The grinding process is done to reduce the scratches and damaged layers from the cutting process. It is done by applying light pressure at the samples on the rotating disc which covered by Silicon Carbide (SiC) paper with various grades. There are many grades available for the SiC paper which are 180, 240, 320, 400, 600, 800, 1200 and 2400 grits. The lower the grits the rougher the sand paper as the number indicates grains per square inch. The details of the sand paper used are shown in the Table 4 below:

Table 4: Grade of SiC used for grinding.

Grade	**Lubricant**	**Abrasive**	**Rotational speed (rpm)**
180	Water	SiC	240
240	Water	SiC	240
320	Water	SiC	240
400	Water	SiC	240
600	Water	SiC	240
800	Water	SiC	240
1200	Water	SiC	240
2400	Water	SiC	240



(a)



(b)

Figure 16: (a) The sample before grinding and (b) the sample after grinding with 1200 grits.

3.4.4 Polishing

The polishing process is done by using the same machine with grinding which is METASERV 2000 at Block 17. However, soft cloth was used instead of abrasive paper. The soft cloth will be used by combining the micro-particles called the diamond and Metadi fluid as a lubricant.

The polishing process contains two types of grades which are coarser polish and finer polish. The coarser polish has bigger diameter which is 6 microns and could remove the remaining scratches after the grinding process. The finer polish has smaller diameter which is 1 microns and this is done purposely to produce smoother surface until mirror-like surface is produced.

3.4.5 Etching

The last stage of the surface preparation is the etching. This is done purposely to reveal the microstructure which could not be seen without etching such as grain boundaries, twins and second phase particles. The samples are etched by swabbing a cotton tip dipped in etchant, or immersing the sample with the etchant. This step is quite complicated as the sample can be not well etched either lack of etching time or too much etching time. If the sample does not reveal the microstructure because of lack of etching time, the etching process can be repeated without grinding and polishing again. However if the sample is over etched, the sample required grinding and polishing to remove the surface that have been attacked by chemical.

There are many reagents used for etching process depending on the material or metal used. Keller’s reagent is one of the effective reagents used for the aluminium alloys. The Keller’s reagent is a mixture of:

(a) 190 ml of distilled water (H_2O)
(b) 3 ml of hydrochlouric acid (HCl)
(c) 5 ml of nitric acid (HNO_3)
(d) 2 ml of hydroflouric acid (HF)

The procedures in etching are as follows:

1. Keller's reagent is mixed.
2. Reagent is applied on the surface of the samples by using cotton swab or immersing about 15 to 25 seconds.
3. Sample is washed with running distilled water and followed with alcohol after the reaction can be seen.
4. Sample is dried by using Struer Drybox-2.
5. The sample is checked with optical microscope.
6. Repeat step 2 to 4 if the microstructure still can't be seen.

Figure 17: Apparatus used for etching.

Figure 18: The samples are being dried by Struer Drybox-2.

3.5 MICROSTRUCTURE ANALYSIS

The microstructure analysis contained two parts which are analysis using Optical Microscope (OM) and Energy Dispersive X-ray Spectrometry (EDX).

3.5.1 Optical Microscope (OM)

The OM is a common equipment used for microstructure examination. It has several magnifications which are 50x, 100x, and 500x. The surface of the sample have to be flat otherwise the view could not be focused and blurred. The OM is connected with the computer so the view can be captured immediately into the computer. The OM used for this project is Leica DM LM Optical Microscope as shown in the Figure 19.

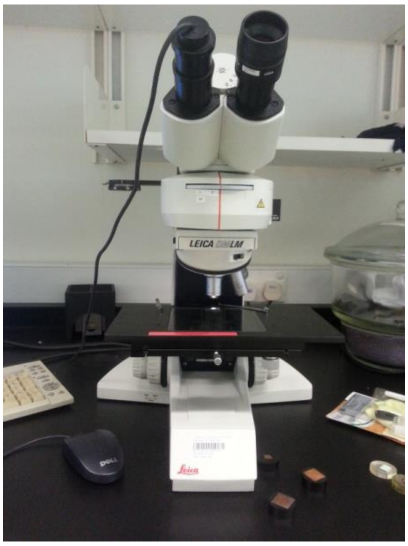


Figure 19: OM used for microstructure analysis.

3.5.2 Energy Dispersive X-Ray Spectrometry (EDX)

The EDX analysis will be done at Block P. EDX is a elemental analysis by using X-Ray as its source and the number and energy of the X-rays emitted from a specimen can be measured by an energy-dispersive spectrometer. The results will be summarize in weight percentage at the point where the X-ray is emitted.

3.6 LIST OF TOOLS AND EQUIPMENTS REQUIRED

Table 5: List of tools and equipments required during final year project.

No	Tool / Equipment	Function
1	Aluminium plates (MMC and AA1100)	- main materials that will be welded and analysed.
2	H13 tool steel	- welding tool used for FSW.
3	CNC Lathe Bridgeport Romi Power Path 15 machine	- to fabricate welding tool.
4	CARBOLITE heat treatment furnace	- for hardening the welding tool.
5	CNC milling machine VMC 2216XV	- for FSW process.
6	Jig	- for clamping the workpiece.
7	Linear Hack Saw Machine KP-280	- to make workpiece fit in abrasive cutter.
8	Abrasive Cutter	- for sectioning the workpiece.
9	SIMPLIMET 1000 Auto Mounting machine	- to mount the sample that have been sectioned.
10	METASERV 2000	- for grinding and polishing the samples.
11	SiC paper	- abrasive paper used for grinding.
12	Diamond and Metadi fluid	- lubricant used for polishing.
13	Struer Drybox-2	- used to dry the sample before and after etching.
14	Leica DM LM Optical Microscope	- used for analysis of microstructure.

3.7 GANTT CHART AND KEY MILESTONE

3.7.1 Gantt chart for FYP I

Table 6: Gantt chart for FYP I.

Detail	W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 9	W 10	W 11	W 12	W 13	W 14
Literature review on FSW														
Procurement of workpiece and welding tool														
Design the welding tool														
Fabrication of welding tool														
Hardening process of welding tool														
Trial run														

3.7.2 Gantt chart for FYP II

Table 7: Gantt chart for FYP II.

Detail	W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 9	W 10	W 11	W 12	W 13	W 14
Perform FSW on dissimilar plates														
Surface preparation														
Microscopy analysis														
Thesis writing														

3.7.3 Key Milestone

Table 8: Key Milestones.

Number	Milestone	Date
1	Completion of Welding Tool	23th August 2013
2	Completion of Friction Stir Welding	4th October 2013
3	Surface Preparation Completion	1st November 2013
4	Experimentation and Data Gathering	29th November 2013
5	Final Report Writing	27th December 2013

CHAPTER 4

RESULT AND DISCUSSION

4.1 TOOL STEEL

One of the results obtained are the fabrication completion of the welding tool and the procurement of the workpiece material. The fabrication of the welding tool have been done by Bridgeport Romi Power Path 15 and furnace for heat treatment. The Figure 20 below showed the tool steel after fabrication and hardening process.

(b) (b)

Figure 20: (a) Tool steel after fabrication and, (b) tool steel after hardening process.

The hardening process have been done by preheating at 750 °C for two hours. The two hours preheating is done to ensure that the whole material have the same material either inner part or outer part of the material. Lack of time for preheating will affect the characteristics of the material and resulting different prediction from the expected result.

Then, the material will be heated rapidly from preheat to high heat at 1010 °C and dwelling for one hour. Based on the physical properties of H13 Tool Steel, heating at 1010 °C will make the material reached at austenizing condition which will make the material have the maximum hardness, resistance to thermal fatigue cracking and wear use. Therefore, these characteristics are important to ensure the quality of the welding tool as well as FSW.

After the dwelling process, the material will be air quenched for one night. There are many different method to cool the material, however the reason air quench was chosen is because the material will become less brittle and high hardness and toughness. There are one more method to make the material more hardness and toughness which is by water quench, however the material also become brittle as the the material is rapidly cooled. So the brittle material is not suitable for the application of FSW as the force used at the welding tool during FSW is high enough to break the tool steel.

Due to technical error, the welding tool have to be modified. However, the modification of the tool steel does not affect the hardness of the material. This is because the hardening process done was deep and already covered for the whole tool steel. Thus, the welding process have been carried on after the fabrication.

4.2 FSW OF DISSIMILIAR PLATES

The welding activities have been done at Block N by using CNC milling machine VMC 2216XV. There are three samples which are AA1100-AA6092 reinforced with 25% Silicon Carbide for travel speed of 25mm/min, 30mm/min, and 35mm/min. The welding were successfully done however, there are worm tunnels that can be seen by visual inspection located in the weldments for all samples. The worm tunnel is caused by lack of material flow during welding process.

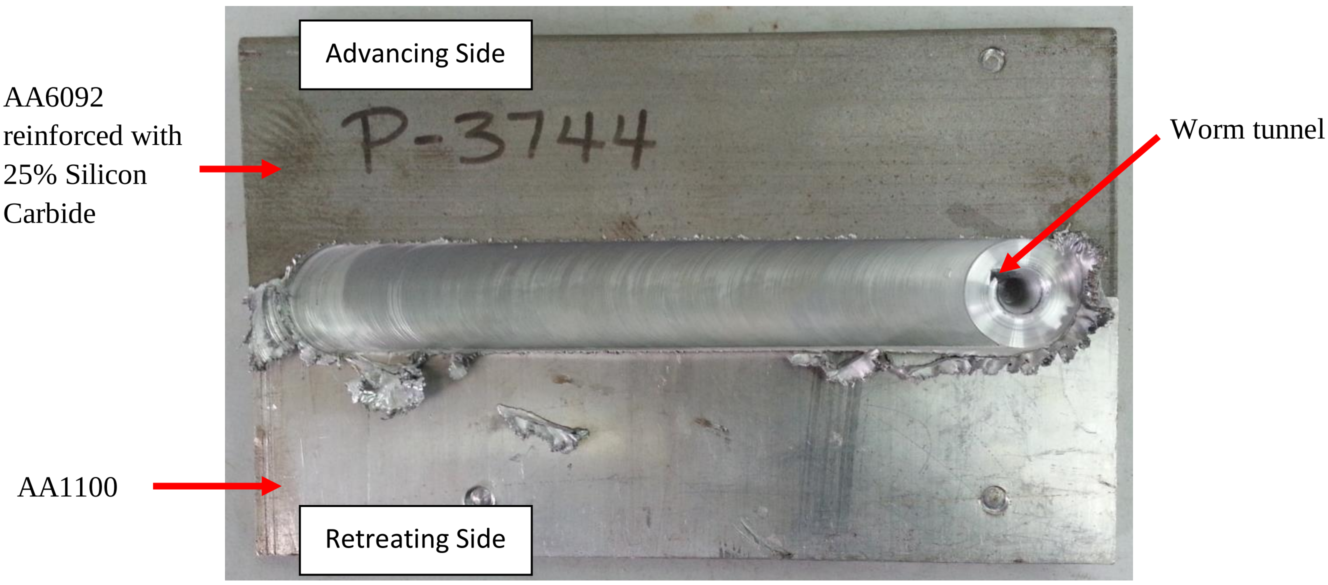


Figure 21: Figure of the completed FSW.

However, based on Figure 12, the first sample which is for travel speed of 35 mm/min, the worm tunnel is the smallest compared to the other samples. This is because of the late finding for the thickness effect. There are differences about 1mm of thickness for both aluminium plates. Thus, 1mm metal plate was used to increase the height of one plate so that the contact between welding tool and metal plates are the same. However, for samples of 25 mm/min and 30 mm/min, the 1mm metal plate was placed too far from the weldment and caused the sample bend resulted from the high force applied during welding. So, the contact area between welding tool and metal plates are not the same and caused the lack of heat produced during welding and incomplete material flow.

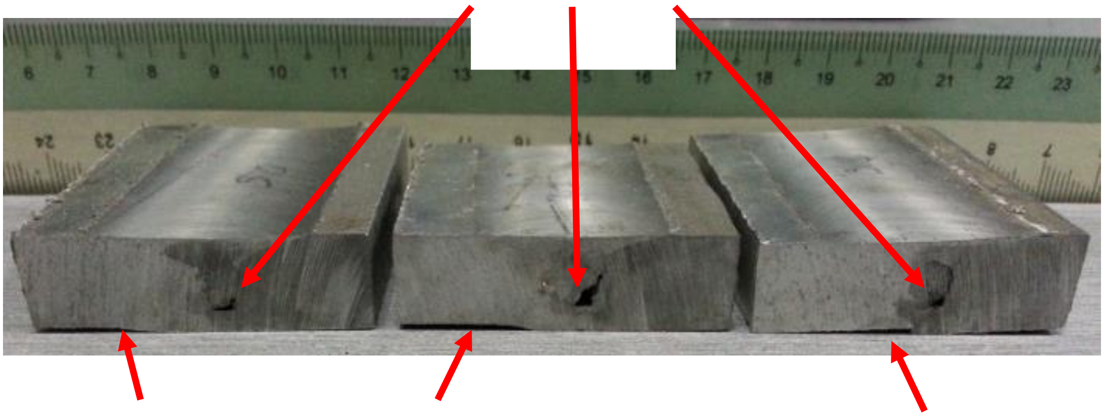


Figure 22: Middle cross section of the sample (from left; 25 mm/min, 30 mm/min, 35 mm/min).

4.3 VISUAL ANALYSIS OF THE WELDMENT

The results of visual analysis for start, middle, and end point of welding are shown on the Table 9 until Table 11.

Table 9: Results of visual analysis for start point of welding (Section A).

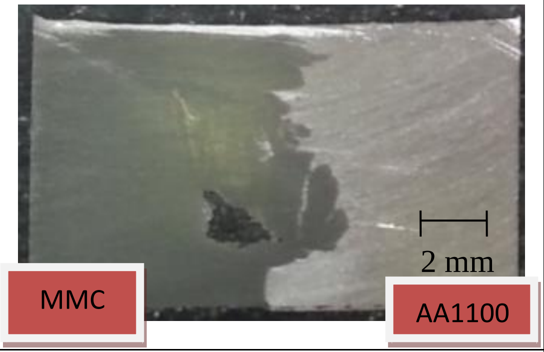
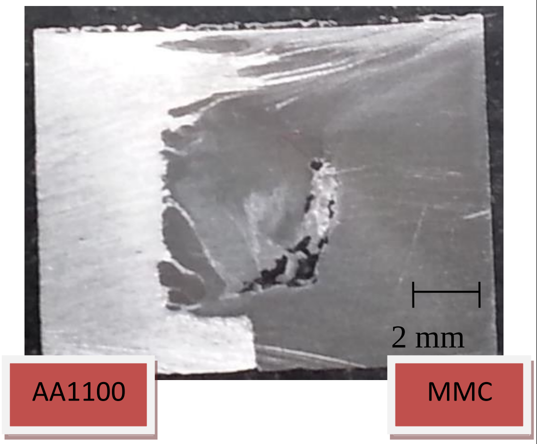
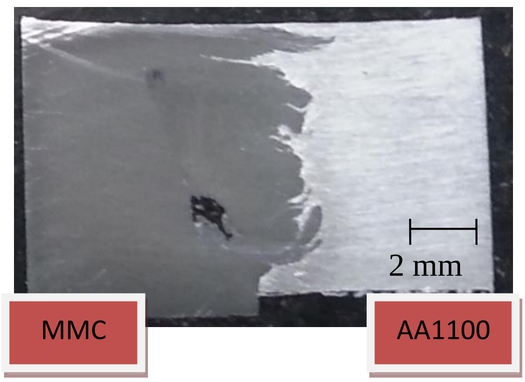
Parameter	Figure	Description
25 mm/min		Based on the observation, the material flow is well mixed and a portion of MMC is mixed with the portion of AA1100 at the centre of the weldment.
30 mm/min		The material flow for SiC is moderately mixed and produced a boundary between MMC and AA1100 at TMAZ region. However at the top of the weldment, the material flow is well mixed.
35 mm/min		The material is not well mixed compared to the other parameter as this parameter have highest travel speed. The material produced boundaries at the weld nugget and TMAZ region.

Table 10: Results of visual analysis for middle point of welding (Section B).

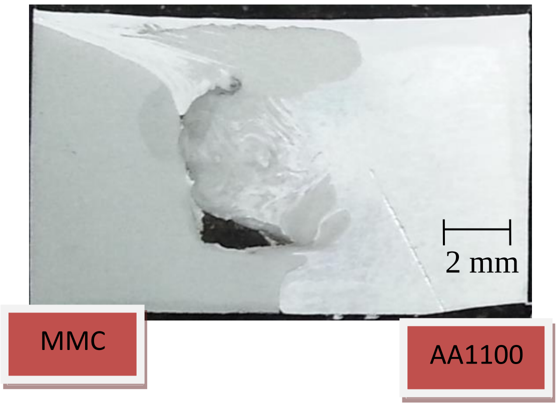
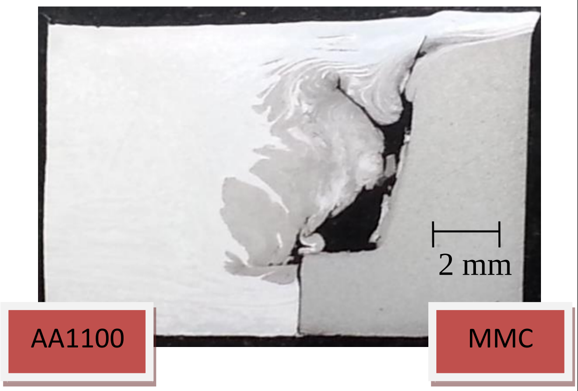
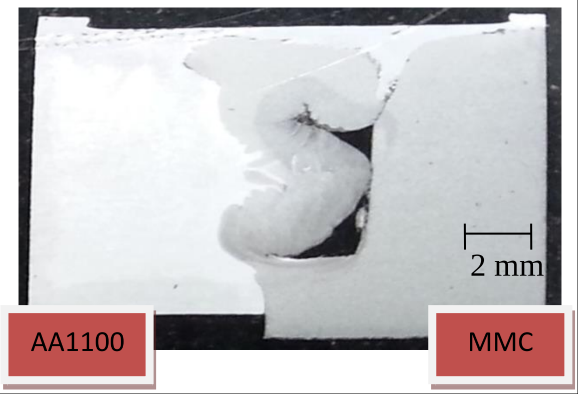
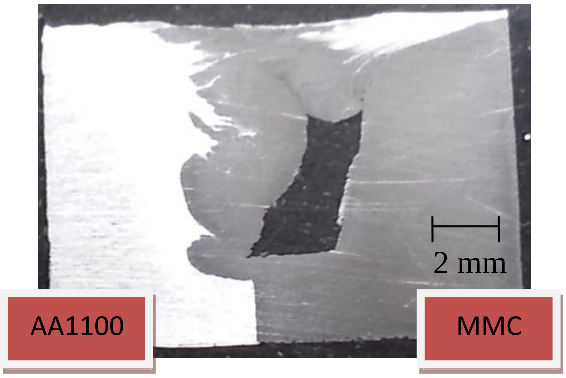
Parameter	Figure	Description
25 mm/min		The material flow is very well mixed at the top and centre of the weldment. Note the fine and furry-like portion at the centreof the weld nugget and TMAZ region. There is also a portion of AA1100 at the top left of the weldment.
30 mm/min		The material is well mixed and produced biggest worm hole. The MMC material mixed at the centre of the weldment. Note the fine portion at the top of weld nugget region.
35 mm/min		The material is moderately mixed but the portion is less fine compared to the others. There is boundaries observed but the MMC material still enter the AA1100 material region.

Table 11: Results of visual analysis for end point of welding (Section C).

Parameter	Figure	Description
25 mm/min		The AA1100 have entered the MMC portion in the weld nugget region. However the mixing does not occured very well compared to other point of welding.
30 mm/min		The material mixed together and a portion of AA1100 can be seen on top of the weld nugget region. There is also a slight boundary between AA1100 and MMC.
35 mm/min		The material flow is well mixed and less boundary can be seen compared to 30 mm/min welding parameter. The worm hole for this parameter also is the smallest.

Based on the observation, the material flow is best mixed at lower travel speed which is at 25 mm/min. This is also supported in the literature review that the insufficient material flow is caused by insufficient heat input (Tan et al, 2013). The slower the speed, the more heat is produced as the time stirred on the metal plates is longer.

The MMC material have mixed and enter the region AA1100 more than the AA1100 entered the MMC region. One of the reasons of this case is the advancing and retreating side during welding. The MMC is located at the advancing and AA1100 located at the retreating side. Therefore, the volume of MMC particles moved towards opposite plates is more than the movement of AA1100 particles.

The results are supported by the research made by Tilman U. Seidel entitled 'Material Flow in Friction Stir Welding: Experiment and Fluid Mechanics based Process Model'. The research made to study the material flow for aluminium alloy. Based on Figure 23, the blue colour which is from advancing side is mixed and moved more towards opposite plates more than the retreating side towards advancing side.

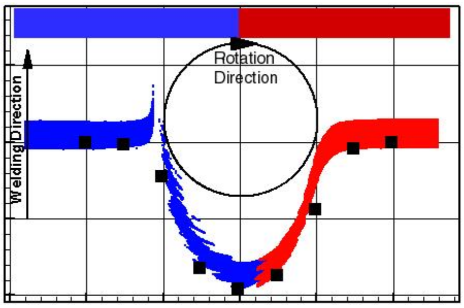


Figure 23: The simulation of material flow during FSW. Blue is from advancing side and red is from retreating side.[22]

Note that all the worm holes are at advancing side of the material which is MMC. This is because the material advancing is moved more to the retreating side, but the material from retreating side moved less to the advancing side. This is because of the material bend due to thickness error and also based on the theoretical diagram from Figure 23 which stated that retreating side flows and moved less to the advancing side.

Theoretically, slower travel speed gives smaller worm hole due to complete material flow and sufficient heat input. However, in this project the observation is different from the theory due to thickness error during FSW. At starting point, product at 35 mm/min gives smallest worm hole, product of 25 mm/min is the smallest worm hole at middle point and product of 35 mm/min is the smallest worm hole for ending point.

4.4 ANALYSIS OF THE MICROSTRUCTURE

The analysis will be done by using Leica DM LM Optical Microscope (OM) at Block 17. The welding region analysed by OM are based on Figure 24. The figures of microstructure taken are unetch weld nugget region, one base metal region and four welding regions. The results are shown on Table 12 until Table 18.

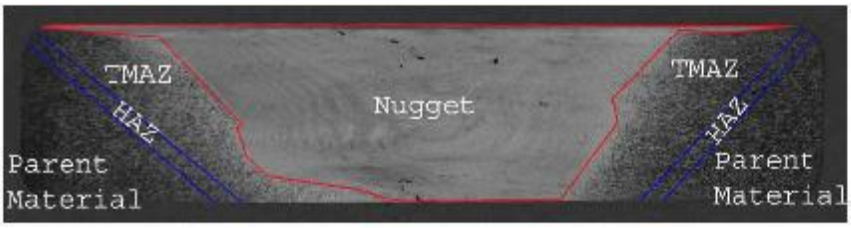


Figure 24: The welding region for FSW.

Table 12: Microstructure results for unetch weld nugget region.

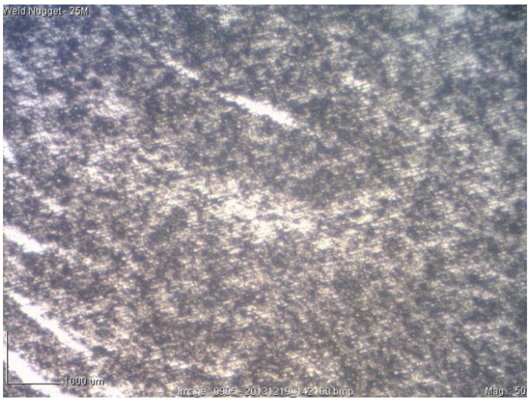
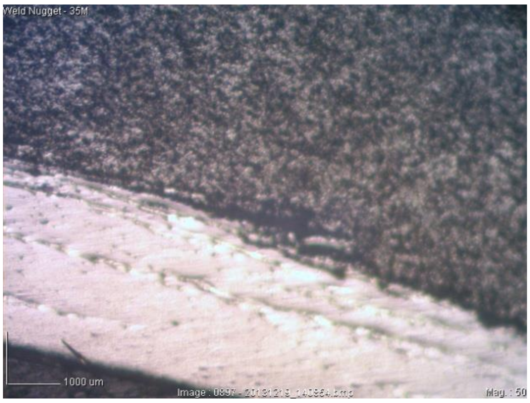
Parameter	Figure (50x magnification)	Description
25 mm/min	 1000μm	The material for MMC and AA1100 are well mixed and no boundaries can be seen in the region. The dark colour indicate the precipitate and SiC from MMC and lighter colour indicate the aluminium alloy from AA1100.
30 mm/min	 1000 μm	The are less boundaries between MMC and AA1100 however the material still mixed well. There are portion of MMC which is dark in colour mixed in the AA1100 material which can be seen in dark spot at bottom left of the figure.
35 mm/min	 1000 μm	There are boundaries between MMC and AA1100. The darker colour is the MMC and lighter colour is the AA1100. The material does not mixed very well.

Table 13: Microstructure results for base metal.

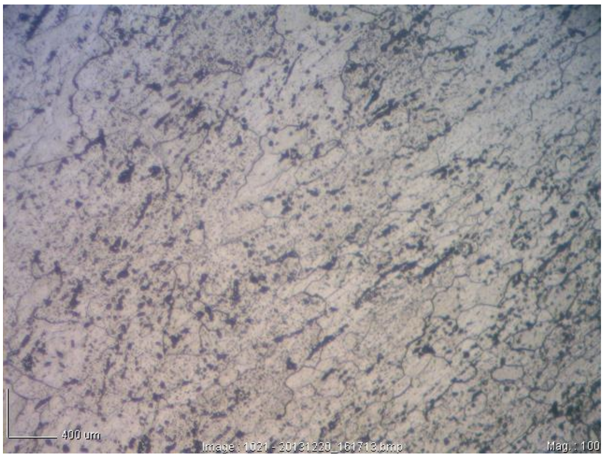
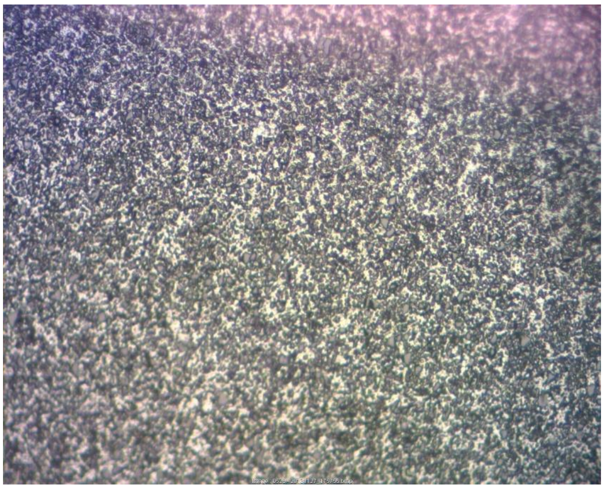
Material	Figure (100x magnification)	Description
AA1100	 400 µm	The figure shows that the AA1100 material that have been etched. The black spot indicate the effect of the etching as the etchant is acidic and corrosive. Thus the material have been eroded. The grain boundary also can be seen in the microstructure.
MMC	 400 µm	The material of MMC contain Silicon Carbide (SiC) and aluminium alloy. Based on the figure shown, the dark spot is the SiC and precipitate while the lighter colour is the aluminium alloy. These materials have been reinforced to become metal-matrix-composite (MMC).

Table 14: Microstructure results for weld nugget region.

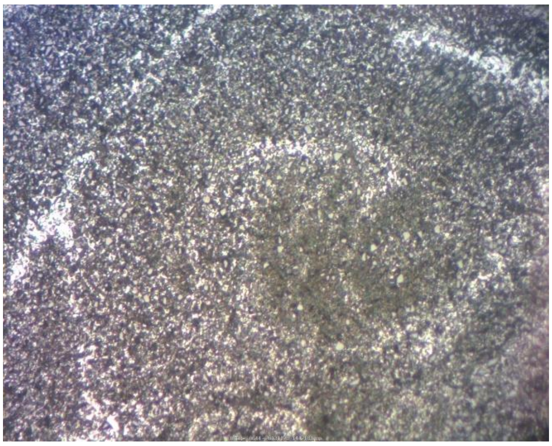
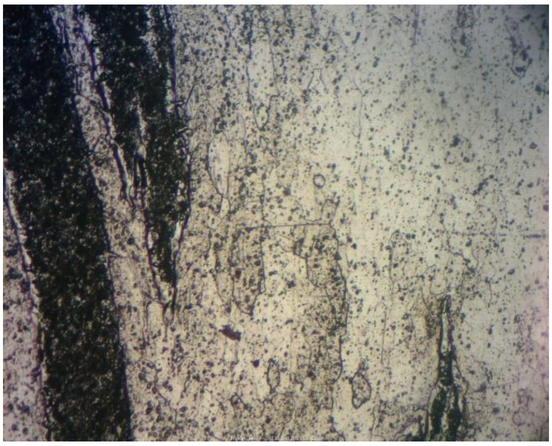
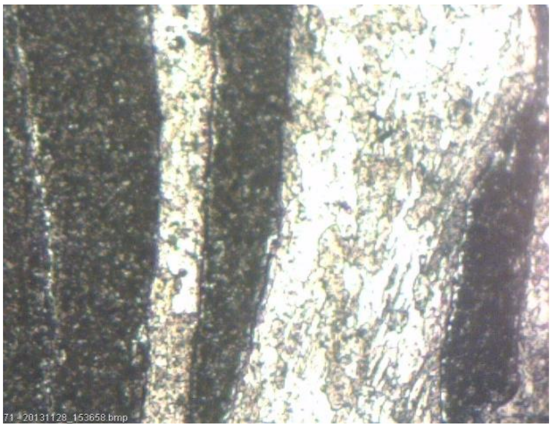
Parameter	Figure (100x Magnification)	Description
25 mm/min	 400 µm	The figure shows that there is no boundaries between MMC and AA1100 and the material is mixed well. The SiC is mixed with the Al material and form a spiral shape of Al material.
30 mm/min	 400 µm	The boundaries can be seen between MMC and AA1100. The graind boundaries produced is small especially at the boundary of SiC material. This is because the temperature is highest at this region during welding process.
35 mm/min	 400 µm	The figure shows that the grain boundaries produced is small and SiC material is well mixed with Al alloy. There are boundaries between MMC and AA1100.

Table 15: Microstructure results for TMAZ at retreating side.

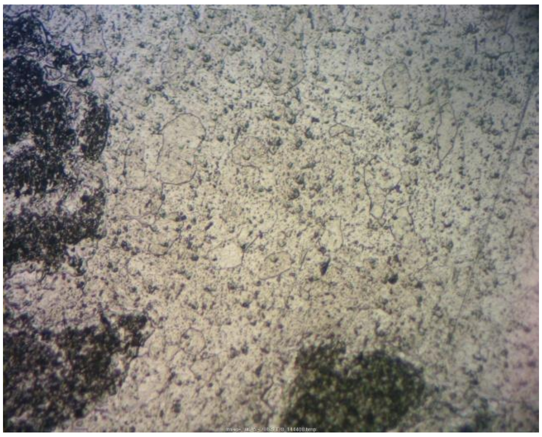
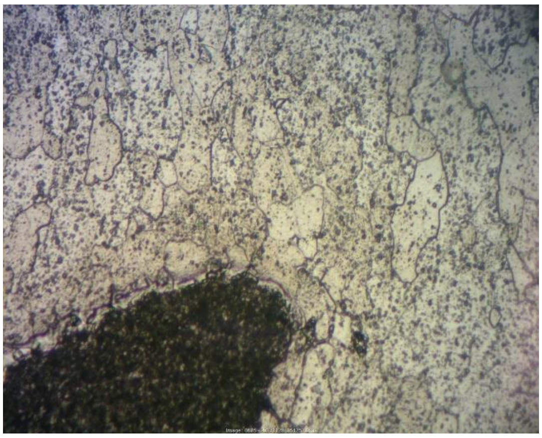
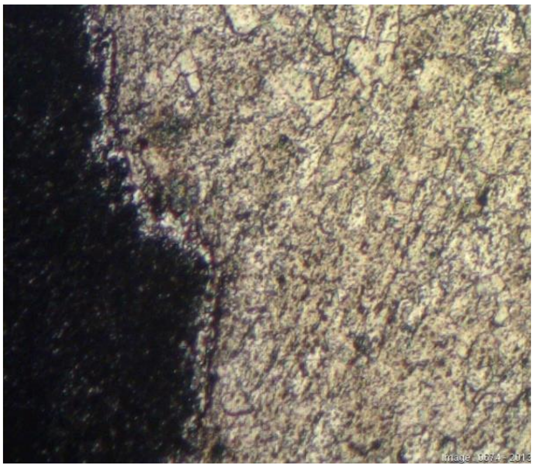
Parameter	Figure (100x Magnification)	Description
25 mm/min	 400 µm	There are boundaries but the material mixed very well as the AA1100 materials mixed with the MMC materials and formed a spiral shape at the top left of the figure. The grain boundaries also can be seen and the size is slightly bigger compared to the weld nugget region.
30 mm/min	 400 µm	There are boundaries between MMC and AA1100. The grain boundaries produced is bigger than TMAZ at 25 mm/min. This is due to the faster travel speed and less heat produced.
35 mm/min	 400 µm	There are also boundaries between MMC and AA1100 for this parameter. The grain boundaries also bigger than the others.

Table 16: Microstructure results for TMAZ at advancing side.

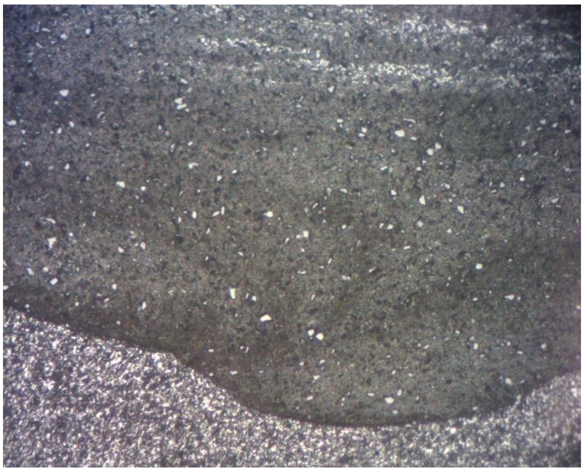
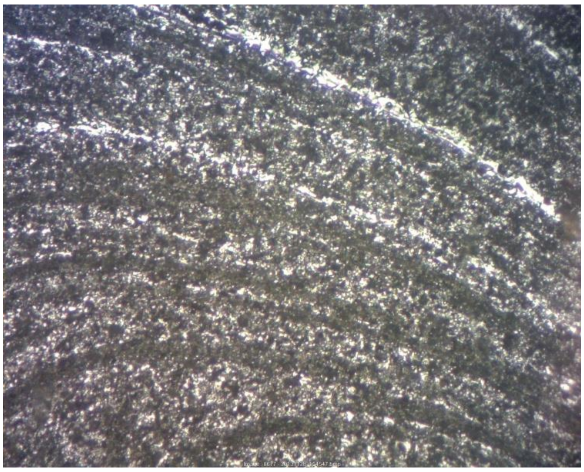
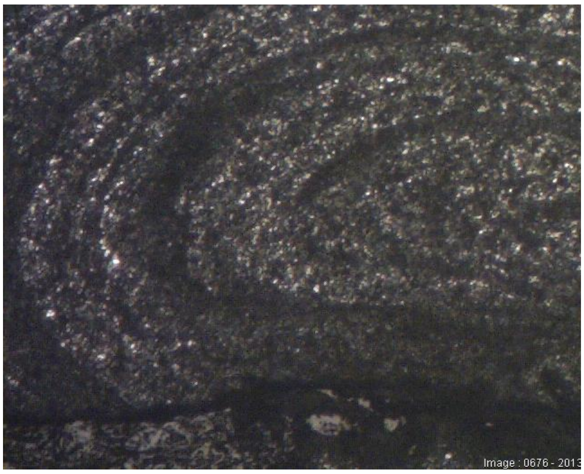
Parameter	Figure (100x Magnification)	Description
25 mm/min	 400 µm	The material is mixed very well and no spiral is produced as it is completely mixed. Note the boundaries of darker colour is the mixed material while lighter colour is the MMC.
30 mm/min	 400 µm	The material is mixed and there is no boundaries between MMC and AA1100. The lighter colour is the Al alloys particle while darker colour is the SiC particles. Note the spiral shape produced at this region.
35 mm/min	 400 µm	The material is mixed but there is boundaries as shown at the bottom of the figure. The welding region produced spiral shape of Al and Sic after welding.

Table 17: Microstructure results of HAZ at retreating side (AA1100).

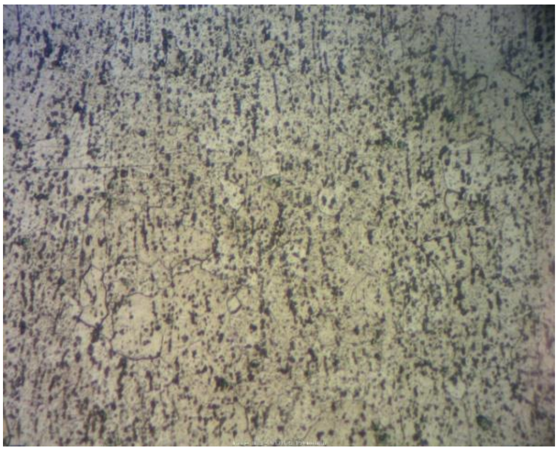
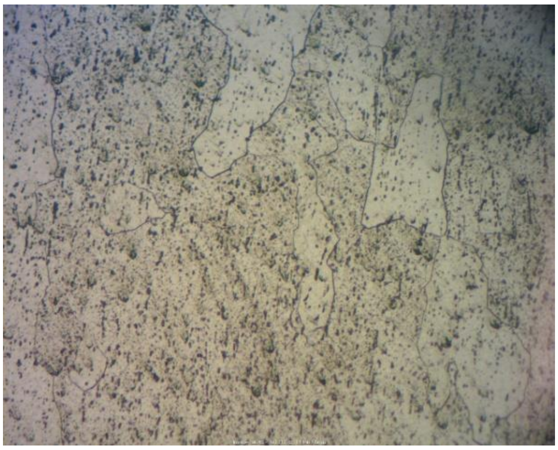
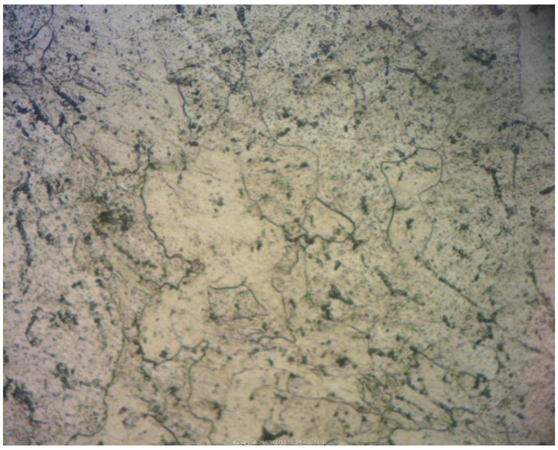
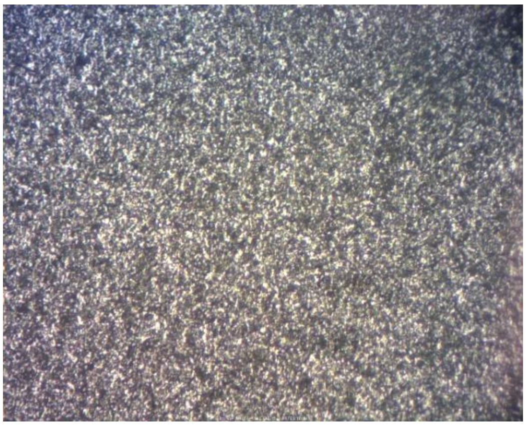
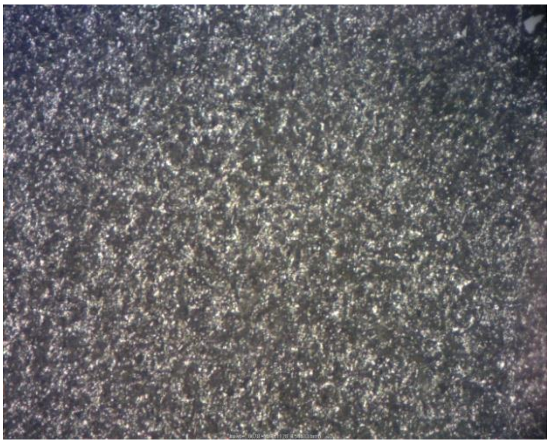
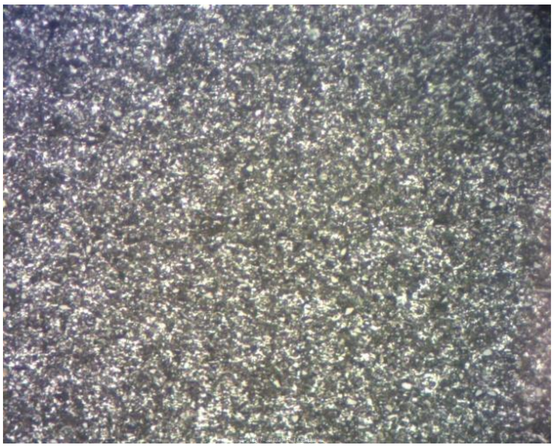
Parameter	**Figure (100x Magnification)**	**Description**
25 mm/min	 400 µm	The graind boundaries produced for this parameter is the smallest. This is because the heat input at this parameter is the highest effected by the slowest travel speed.
30 mm/min	 400 µm	The grain boundaries is slightly bigger compared to the travel speed of 25 mm/min.
35 mm/min	 400 µm	The graind boundaries at this parameter is the biggest as the travel speed for this sample is the highest.

Table 18: Microstructure results of HAZ at advancing side (MMC).

Parameter	Figure (100x Magnification)	Description
25 mm/min	 400 µm	The figure show the intensity of the black and white spot is at the highest compared to the other parameter. The spots are considered the grain boundaries in this type of material as it is the reinforced metal with composites.
30 mm/min	 400 µm	The grain boundaries is moderately small and the intensity is slightly lower compared to the parameter of 25 mm/min.
35 mm/min	 400 µm	The grain boundaries is the biggest compared to the other parameters. This is because the heat input for this parameter is the lowest compared to the other parameters.

Based on the results shown, the material flow for SiC is well mixed with the Al particles in the weld nugget and TMAZ region. This is because of the effect of the advancing side for the SiC in the MMC and also the low speed of the travel speed. The advancing side affected the material flow of SiC by making the volume of MMC's materials moved and mixed with the material from retreating side more than the opposite particles movement. The low speed affected the movement of the SiC particles by producing more heat input and more stirring rate at one point.

The grain boundaries at slower travel speed also smaller compared to the faster travel speed. This is mainly because of the heat input produced at slower travel speed. The stirring pin shoulder which act as a heating mechanism has made the samples deform and easy to stirred due to high temperature. Thus by increasing the time stirred at one point, the material of the sample could be easily stirred and have smaller grain boundaries.

Theoretically, smaller grain boundaries or dislocations in the material gives the material stronger and harder by resisting the movement of the dislocations in the microstructure. However, this theory cannot be proved yet as the hardness and strength of the joint will not be mechanically tested in this project.

4.5 ENERGY DISPERSIVE X-RAY SPECTROMETRY (EDX) ANALYSIS

4.5.1 Aluminium Alloy 1100

Table 19: Element percentage in AA1100.

Element	Weight (%)	Atomic (%)
C	16.91	30.14
O	7.32	9.80
Al	74.92	59.45
Si	0.52	0.40
S	0.32	0.22
Totals	100.00	100.00

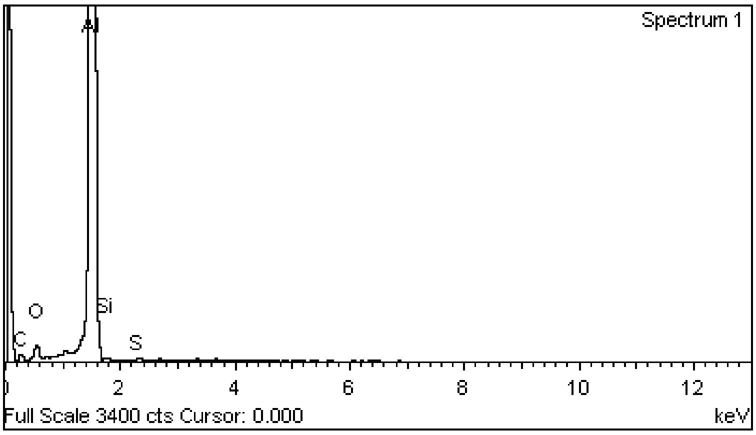


Figure 25: Graph of element percentage for AA1100.

Based on the Table 19, there are five type of elements exist in the AA1100 which are carbon (C), oxide (O), aluminium (Al), silicon (Si), and sulphur (S). However, based on the journal or theoretically for AA1100, the material that should be in the material are zinc (Zn), copper (Cu), and mangenese (Mn) while sulphur should not be in the material. The weight percentage also differ from the theory in which the Al percentage should be minimum of 99 percent (%). However, in this analysis the reading shows the weight percentage of Al equal to 74.92 percent (%).

4.5.2 Aluminium 6092/ SiC/ 25p (MMC)

Table 20: Element percentage for MMC.

Element	Weight (%)	Atomic (%)
C	15.93	27.19
O	18.13	23.23
Al	48.29	36.69
Si	17.64	12.88
Totals	100.00	100.00

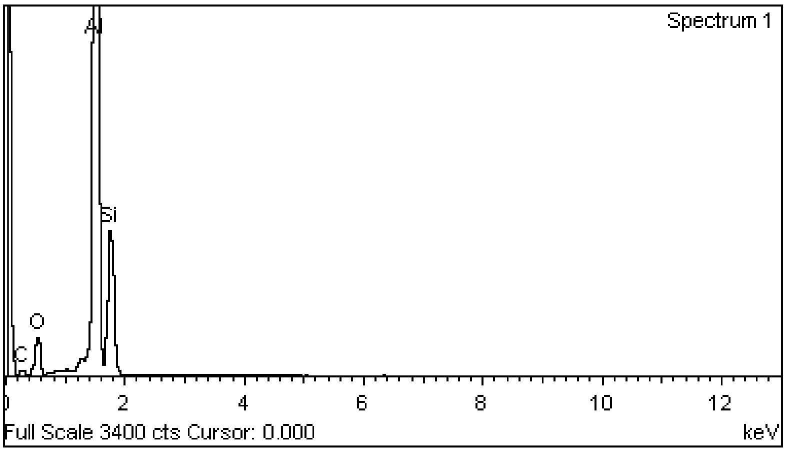


Figure 26: Graph of element percentage for MMC.

Based on the Table 20, there are four types of element detected by EDX analysis which are carbon (C), oxide (O), aluminium (Al), and silicon (Si). The total combination of Si and C should be 25 percent (%) as indicate in the material mill cert. However, in this analysis the result showed a total of 33.57 percent (%).

There are errors may be occuring during EDX analysis that give different results to the material mill certificate. This is mainly because of the material itself which are containing dirts and oxide layer or corrosion. Thus the EDX analysis will show the different elements existed such as oxide.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSION

As a conclusion, the material movement of SiC in the welding region is observed to be well refined at lower travel speed. The SiC and Al materials have been well mixed and there is fewer boundaries observed between those two materials. This is because of the sufficient heat input due to lower speed of the welding tool. Besides that, the materials from advancing side also have flow more and enter the retreating side’s material compared to retreating side enter the advancing side’s material.

Furthermore, the grain boundaries also smaller at lower travel speed as it has sufficient heat input. The visual and microstructure analysis were done to proof this hypothesis and also based on the results obtained.

The material properties for slower travel speed are harder as the grain boundaries at this parameter are small. Thus the dislocation or grain boundaries resist the movement of the material which make it stronger and harder. However, the worm hole need to be minimized as it can affect the material and joint properties by reducing the maximum stress that can be applied to the welding joint.

Therefore, the project done can help the research and development for FSW industries by providing informations about the results of FSW for AA1100 and 6092/ SiC/ 25p MMC.

5.2 RECOMMENDATION

The recommendation for this project is that to test the hardness of the welding tool before and after the hardening process. This is to ensure that there are increase in hardness of the welding tool. Therefore the quality of the welding process can be ensured and proof that the increase of hardness after the heat treatment.

Furthermore, the metal plates to be joined also must be same in thickness so that the probabilities of producing defect after FSW can be reduced. If plate is used for increasing the height, make sure the increasing plate is placed near the weldment so that the sample will not bend after FSW. However it is better to modify the thickness by using the milling machine.

The microstructure analysis also can be done for more details such as more tests conducted and increase the manipulative variables so that the results obtained become more accurate. As an example, future research can be done and compare the effects of the advancing and retreating side for both materials.

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