Microstructural Study of Friction Stir Welded Dissimilar Materials: 6061 Aluminum Alloy to Pure Copper

By

Siti Nabihah binti Shamsuddin

FINAL YEAR PROJECT REPORT

Submitted to the Mechanical Engineering Department Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Mechanical Engineering)

MAY 2011

Universiti Teknologi PETRONAS
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31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved:

Dr. Mokhtar Awang
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2011

CERTIFICATION 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.

....

(SITI NABIHAH BINTI SHAMSUDDIN)

ABBREVIATIONS AND NOMENCLATURES

AISI – American Iron and Steel Institute	**HCl** – hydrochloric acid
Al – aluminum	**HF** – hydrogen flouride
CRT – cathode ray tube	**HNO_3** – nitric acide
Cu – copper	**HT** – heat treatment
D – plunge depth or the penetration of the pin of the welding tool (mm)	**N** – spindle speed (rev/min)
EDX – energy dispersed x-ray	**OM** – optical microscope
FeCl – ferric chloride	**S** – move feed rate (mm/min)
FESEM – field emission scanning electron microscope	**SEM** - scanning electron microscope
FSW – friction stir welding	**SiC** – silicon carbide
FYP – Final Year Project	**TMAZ** – thermo-mechanically affected zone
H_2O - water	**TWI** – The Welding Institute
HAZ – heat-affected zone	**UTP** – Universiti Teknologi Petronas

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Alhamdulillah, all praises be to Allah S.W.T., The Most Gracious, The Most Merciful, for His blessing and guidance. Thanks to Him for lightening my journey of this final year and giving me the opportunity to complete this Universiti Teknologi Petronas (UTP) Final Year Project Report. I would like to extend my expression of grateful to everybody who involves directly and indirectly in this project.

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Besides, I would like to express my warmest gratitude and appreciation to lab technicians for giving me great assistance in doing technical part of the project, especially En. Shaiful Hisham bin Shamsudin, En. Paris Mohd Said, En. Mohd Anuar bin Abdul Muin, and En. Mahfuzrazi bin Misbahulmunir.

I also would like to dedicate this acknowledgment to the members that are doing friction stir welding projects which are alike for sharing valuable information. They are Ahmad Khalil bin Ahmad Radzi, Nurfarahin binti Shamsuddin, and Mohd Nur Farhan bin Mohd Yasin.

In addition, my deepest appreciation goes to Mechanical Engineering Department personnel; FYP Coordinator, Mr. Faizairi bin Mohd Nor; my internal examiners, AP Dr. Mustafar bin Sudin and Dr. Saravanan Karuppanan for their contribution that made this Final Year Project a wonderful experience also a memorable one. Acknowledgment also goes to UTP management who had dedicatedly provided me with additional support, lab equipments and materials.

Finally, an honorable mention goes to my family and friends for their understandings and supports toward me in completing this project. Without them, I might face many difficulties all this while.

Jazakumullahukhairan kathiran.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

Friction welding process was introduced in industries in 1960s and only few machines were in operation in Soviet Union, Czecholovakia and China. Today the process is fully exploited by industries all over the world due to its special advantages; efficient energy utilization, consistent weld quality, high production rates, welding of many types of similar and dissimilar metal combinations as well as plastics.[2] Friction welding has been used by the automotive industry for decades in the manufacture of a range of components. The process is attractive for several reasons:

- The friction heating is generated locally, so there is no widespread softening of the assembly
- The weld is formed across the entire cross-sectional area of the interface in a single shot process
- The technique is capable of joining dissimilar materials
- The process is completed in a few seconds with very high reproducibility - an essential requirement for a mass production industry.

Now, a new variant from the same stable of friction processes, known as 'Friction Stir Welding' (FSW), is finding increasing use in the fabrication of automotive components, even though its processing speed is not yet as rapid. One day in 1991, in a flash of inspiration, Wayne Thomas from The Welding Institute (TWI) in UK, realized that with the use of a rotational probe of a harder material than the workpieces, the workpiece material could be plasticized and an effective transportation mechanism could be provided for the plasticized material to join workpieces together. This eventual moment of realization after a long period of gestation, market the discovery of FSW as we know it nowadays.[1]

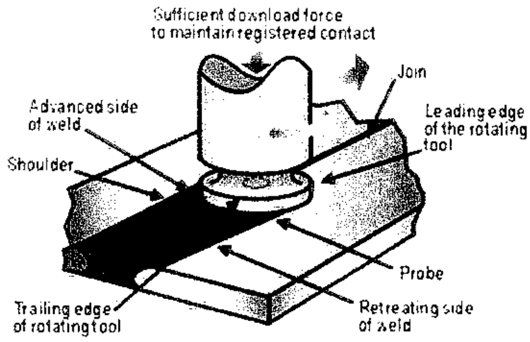


Figure 1.1: Schematic of friction stir welding process[3]

FSW produces welds by using rotating, non-consumable welding tool to locally soften a workpiece, through heat produced by friction and plastic work, thereby allowing the tool to "stir" the joint surfaces.[1] The dependence on friction and plastic work for the heat source precludes significant melting in the workpiece, avoiding many of the difficulties arising from a change in state, such as changes in gas solubility and volumetric changes, which often plague fusion welding processes. Further, the reduced welding temperature makes possible dramatically lower distortion and residual stresses, enabling improved fatigue performance, new construction techniques, and making possible the welding of very thin and thick material.

The process advantages result from the fact that the FSW process (as all friction welding of metals) takes place in the solid phase below the melting point of the materials to be joined. The benefits therefore include the ability to join materials which are difficult to fusion weld, for example 2000 and 7000 aluminium alloys. Friction stir welding can use purpose-designed equipment or modified existing machine tool technology. The process is also suitable for automation and adaptable for robot use. Other advantages are as follows:[4]

- Low distortion, even in long welds
- Excellent mechanical properties as proven by fatigue, tensile and bend tests
- No arc
- No fume
- No porosity

- No spatter
- Low shrinkage
- Can operate in all positions
- Energy efficient
- Non-consumable tool
- One tool can typically be used for up to 1000m of weld length in 6000 series aluminum alloys
- No filler wire
- No gas shielding for welding aluminum
- No welder certification required
- Some tolerance to imperfect weld preparations - thin oxide layers can be accepted
- No grinding, brushing or pickling required in mass production
- Can weld aluminum and copper of >50mm thickness in one pass

The limitations of the FSW process are being reduced by intensive research and development. However, the main limitations of the FSW process are at present:[4]

- Workpieces must be rigidly clamped
- Backing bar required (except where self-reacting tool or directly opposed tools are used)
- Keyhole at the end of each weld
- Cannot make joints which required metal deposition (e.g. fillet welds)

1.2 Problem Statement

An experimental study about FSW need to be performed to explore alternative material instead of widely used aluminum alloy. Even though this technology is widely used, FSW for copper is still limited. Besides, there is growing interest in the use of FSW to join copper to aluminum. Thus, further development is needed in this area.

1.3 Objective

The objective of this project is to perform friction stir welding (FSW) of dissimilar metals (aluminum alloy to copper) and to study the microstructure of different welded region. By examining the microstructure, we could develop better understanding about the material behavior when undergoes FSW process.

1.4 Scope of Study

This project covers about FSW process principles and its microstructural development of 6061 aluminum alloy welded to copper. The section on microstructural aspects of FSW presents a general description of the different weld zones and their main characteristics. The microstructural of 6061 aluminum alloy welded to copper is described in detail in the paper.

CHAPTER 2
LITERATURE REVIEW

2.1 Aluminum Alloys

At the time of writing more than 99% of all friction stir welds are made in aluminum alloys. This figure is unlikely to reduce by very much in the near future, as new aluminum applications seem to appear as fast as new applications in other alloys. The mainstream activity for friction stir welding of aluminum is in long straight welds, and in this area the economics are so favourable that the process is hard to beat. Even so, the adoption of the process has long way to go, and is little used, for example in products such as aluminum truck chassis, truck bodies (skip type and tankers), unpressurised or low pressure tanks for storage, processing, etc. There is also a growing market for the process in thicker section materials, in particular for military applications where joining high strength armour has presented a number of challenges to which friction stir welding has responded well. In addition, lightweight transportable bridges and other transportable structures are areas where the process could make a significant impact, and progress is now being made in this areas.[1]

Friction stir welding has been used to weld all wrought aluminium alloys, across the 2xxx, 5xxx, 6xxx and 7xxx series of alloys, some of which are bordering on being classed as virtually unweldable by fusion welding techniques. The process can also weld dissimilar aluminium alloys, whereas fusion welding may result in the alloying elements from the different alloys interacting to form deleterious intermetallics through precipitation during solidification from the molten weld pool.[3]

Friction stir welding can also make hybrid components by joining dissimilar materials such as aluminium and magnesium alloys. The thicknesses of 6082-T6 that have so far been weld have ranged from 1.2mm to 50mm in a single pass, to more than 75mm when welding from both sides. Welds have also been made in pressure die cast aluminium material without any problems from pockets of entrapped high pressure gas, which would violently disrupt a molten weld pool encountering them.[3]

2.2 Copper

Copper and its alloys are widely used in industrial applications due to their excellent electrical and thermal conductivities, good strength, and corrosion and fatigue resistances.[5]

Due to its high thermal conductivity, copper is a difficult material to weld. Nonetheless the technology to allow friction stir welding has been well demonstrated, even in single pass welds of 50mm thick. The process is used for the fabrication of heat exchangers, and other components, and this market will presumably grow. There is growing interest in the use of friction stir welding to join copper to aluminum, mostly for electrical conductors, and the feasibility of doing this has been demonstrated, even though the technology may not be sufficiently refined for commercial usage. This is, however, an important area, and further development is inevitable.[2]

2.3 Parameter effects

There are a lot of welding parameters to consider when using FSW as a machining process. It is important to examine these factors to determine if FSW is right for your application. [6]

2.3.1 Tool Speeds

As noted above, FSW can be a slower process than other forms of welding, such as arc or laser welding. This is because the cylindrical tool must turn to generate heat on the joint, and then traverse the length of the joint transmitting that heat. The tool is tipped with a probe, called a pin or nib, which typically rotates within the range of 200 to 2000 rotations per minute (rpm). The traverse rate of the tool along the joint line is between 10 to 500 millimeters per minute (mm/min). However, these figures are averages, and rates outside of those ranges are still used. The speed is largely determined by the application and the metal being joined, but they are not mutually exclusive—a slowly rotating tool cannot move incredibly fast across the joint line, for instance. [6]

2.3.2 Tool Tilt

The tilt of the cylindrical tool can have major effects on the welding process. A general range for tool tilt is between 2 and 4 degrees, in such a way that the tool leans into the joint. While very minor, the tilt can affect how easily the tool can move across the joint line because less pressure is put in the direction of the joint line. [6]

2.3.3 Plunge Depth

The plunge depth is the depth to which the shoulder of the tool sinks into the material. While the pin extends farther (the "head," in relation to the tool shoulder), in this distance friction creates the heat necessary to plasticize the metal. Plunge depth is determined by rotating times. Certain automated systems build up concentrated friction for a given period of time, then insert the tool down to its predetermined plunge depth. Others are automated to follow the plunge depth calculated beforehand based on how long the tool would need to work for that particular depth. [6]

2.4 Microstructural features of friction stir welding (FSW)

On occasion it is necessary or desirable to examine the structural elements and defects that influence the properties of materials. Some structural elements are of *macroscopic* dimension; that is, they are large enough to be observed with the unaided eye. Relatively large grains having different textures are clearly visible on the surface of the sectioned lead ingot. However, in most materials the constituent grains are of *microscopic* dimensions, having diameter that may be on the order of microns, and their details must be investigated using some type of microscope. Grain size and shape are only two features of what is termed the microstructure.[7]

Optical, electron, and scanning probe microscopes are commonly used in microscopy. These instruments aid in investigations of the microstructural features of all material types. Microscopic examination is an extremely useful tool in the study and characterization of materials.

The first attempt at classifying microstructures was made by P L Threadgill. This work was based solely on information available from aluminum alloys. However, it has become evident from work on other materials that the behaviour of aluminum alloys is not typical of most metallic materials, and therefore the scheme cannot be broadened to encompass all materials. A more comprehensive scheme has been developed by TWI, and has been discussed with a number of appropriate people in industry and academia. This has also been accepted by the Friction Stir Welding Licensees Association.[8] The system divides the weld zone into distinct regions as follows:

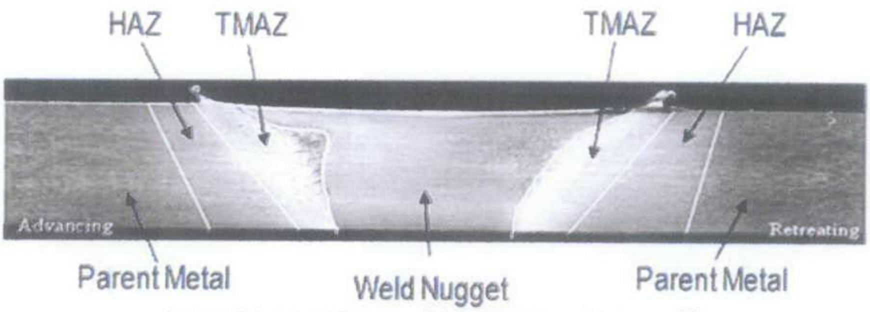


Figure 2.1: Classification of friction stir welded zones[9]

- *Unaffected material* or *parent metal* is the material remote from the weld, which has not been deformed, and which although it may have experienced a thermal cycle from the weld is not affected by the heat in terms of microstructure or mechanical properties.[8]

- *The heat-affected zone (HAZ)* is common to all welding processes. As indicated by the name, this region is subjected to a thermal cycle but is not deformed during welding. The temperatures are lower than those in the TMAZ but may still have a significant effect if the microstructure is thermally unstable. In fact, in age-hardened aluminum alloys this region commonly exhibits the poorest mechanical properties.[8]

- *The thermo-mechanically affected zone (TMAZ)* occurs on either side of the stir zone. In this region the strain and temperature are lower and the effect of welding on the microstructure is correspondingly smaller. Unlike the stir zone the microstructure is recognizably that of the parent material, albeit significantly deformed and rotated.[8]

- *The stir zone (*also nugget, dynamically recrystallised zone) is a region of heavily deformed material that roughly corresponds to the location of the pin during welding. The grains within the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material. A unique feature of the stir zone is the common occurrence of several concentric rings which has been referred to as an 'onion-ring' structure. The precise origin of these rings has not been firmly established, although variations in particle number density, grain size and texture have all been suggested. [8]

CHAPTER 3
METHODOLOGY

Research methodology of the project work is described in *Figure 3.1*. Related applications from the start towards the end of the project are described in this section.

3.1 Project Identification

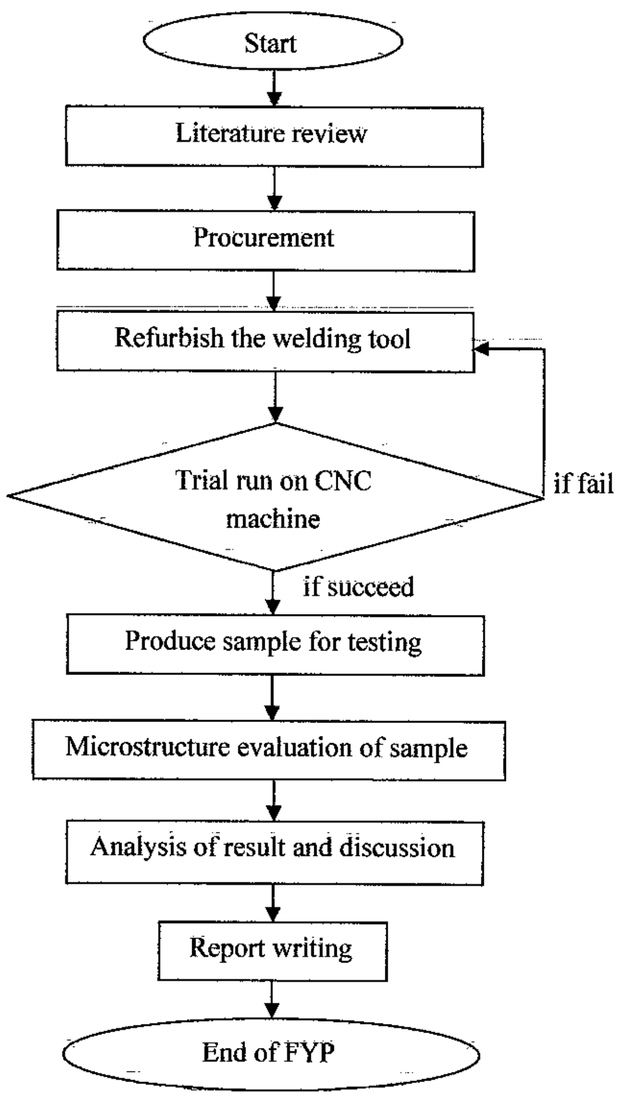


Figure 3.1: Flow Chart of the project

First and foremost, the important thing to do before starting any project is by having literature review. The project is started by collecting materials such as books, journals and technical papers specifically on friction stir welding. This has helped me to understand better on FSW and identify its problem. Besides, the objectives and scope of the study has been setup earlier clearly.

Secondly, the procurement has been settled as early as possible to make sure the project run smoothly. It involves contact supplier, product review, negotiation, purchase, and claim. When one or more suitable suppliers have been identified, requests for quotation or direct contact may be made with the suppliers.

Thirdly, the welding tool has been refurbished by having heat treatment for surface hardening. It is desirable that the tool material is sufficiently strong, tough and hard wearing, at the welding temperature.

Then trial run has been done on CNC machine. If the test was fail, it might happen due to incomplete heat treatment. Thus, the refurbishment process should be done again. If the test succeeded, the sample of FSW could be produced.

Two samples of FSW between 6061 aluminum alloy and copper have been produced. Welding parameter of each sample has been varied in order to compare its microstructure.

Next, the microstructures of each sample have been evaluated with regard of the different weld zone which are unaffected material (parent metal), heat-affected zone, thermo-mechanically affected zone, and stir zone. For microstructural test, optical microscope (OM) and field emission scanning electron microscope (FESEM) have been used.

The results obtained from the microstructural test have been studied and further discussed. Last but not least is the report writing.

3.2 Welding Tool used for Friction Stir Welding (FSW)

Tool steel materials are generally acceptable for FSW of aluminum alloys. However, much like the situation today with welding tool geometry, even for welding aluminum alloys there is no accepted standard tool material. For applications where aluminum alloys from 6 mm to 12 mm thickness are welded, H13 tool steel is generally adequate. For such applications, it is also often possible to use one-piece welding tool design. However, if high productivity is needed or it is necessary to weld thicker aluminum materials, a more elaborate tool design and material and material selection may be required. In such cases, the pin might be made from a material that has higher strength at the temperature of welding, such as MP159, while the shoulder might still be made from H13. For application that require other materials, such as titanium, steel, and copper, welding tools might be made from tungsten-based materials, from polycrystalline cubic boron nitride, or from any number of other materials that offer high performance at high temperatures.[1]

Tool steel is the most common tool material used in friction stirring. This is because a majority of the published FSW literature is on aluminum alloys, which are easily friction stirred with tool steels. The advantages of using tool steel as friction stir tooling material include easy availability and machinability, low cost, and established material characteristics. After considering several aspects, I have decided to use AISI H13 tool steel to weld aluminum alloy to copper for this project. AISI H13 is chromium-molybdenum hot-worked air-hardening steel and is known for good elevated-temperature strength, thermal fatigue resistance, and wear resistance. In addition to friction stir welding aluminum alloys , H13 tools have been used to friction stir weld both oxygen-free copper (Cu-OF) and phosphorus-deoxidized copper with high residual phosphorus (CU-DHP). However, the limited travel speed in CU-DHP would limit the production used of H13.[13]

Table 3.1: Chemical composition of H13 tool steel

AISI No	C %	Mn %	W %	Si %	Cr %	Mo %	V %	Co %
H13	0.35	0.40	-	1.0	5.0	1.5	1.0	-

3.3 Refurbishment of H13 Tool Steel

As H13 tool steel is already available at the lab, new tool has not been designed. The available tool has been reused to perform FSW. For this project, H13 tool steel with flat surface is used as shown in *Figure 3.2*. However, it needs to be refurbished before used by having heat treatment in order to achieve an optimum hardness. The parameter for the heat treatment process is shown in *Figure 3.3*. Firstly, the tool is refurbished by having turning process to remove thin layer of the tool shoulder and tool pin surfaces by using conventional lathe machine in Block 21. Then, the tool steel had gone through heat treatment process for hardening as shown in *Figure 3.4*.

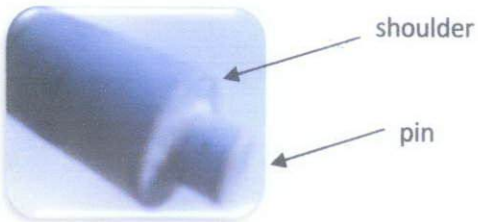


Figure 3.2: H13 tool steel with flat pin

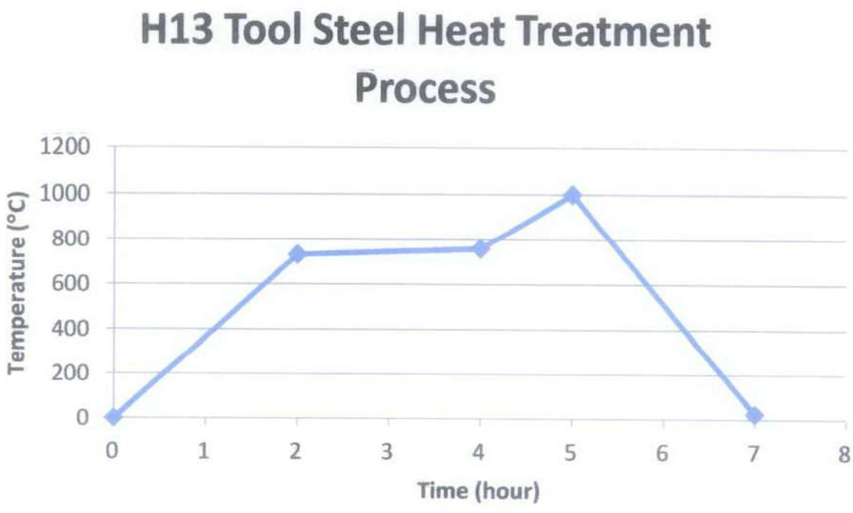


Figure 3.3: Temperature versus time of H13 Tool Steel Heat Treatment Process

Figure 3.4: H13 tool steel after heat treated

The heat treatment process was done by using CARBOLITE Heat Treatment Furnace located at Level 1, Mechanical Building Block 17. The procedures for the H13 Tool Steel heat treatment process are listed in *Figure 3.5*:

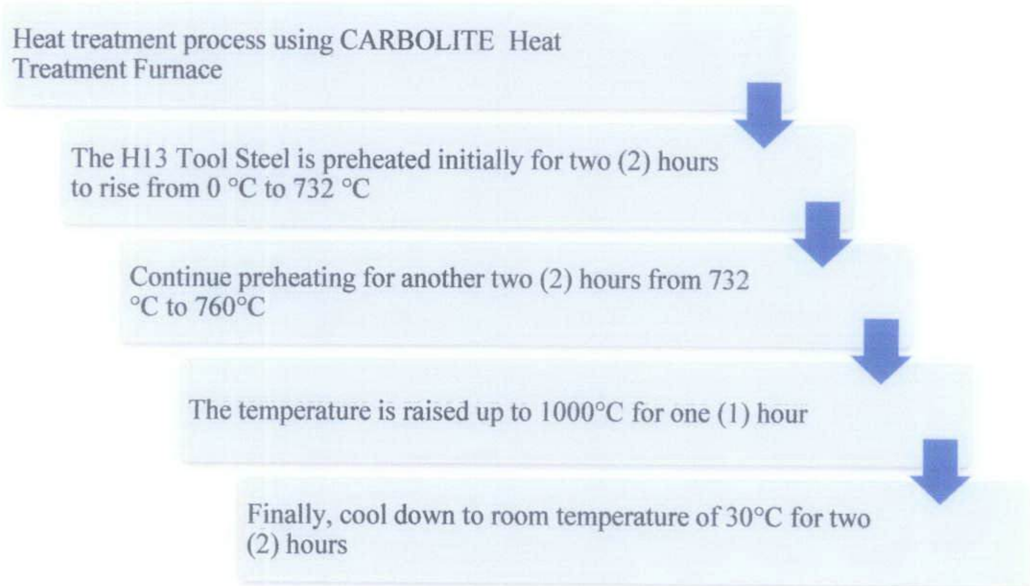


Figure 3.5: H13 Tool Steel Heat Treatment Process

H13 tool steel dimension is listed in *Table 3.2:*

Table 3.2: H13 tool steel dimension

Pin diameter	8.8 mm
Pin length	8.0 mm
Shoulder diameter	18.9 mm

3.4 Chemical Composition Characterization of Workpieces

3.4.1 Aluminum Alloy

The intended aluminum alloy for this project is the aluminum alloy 6061. For this project, aluminum alloy is obtained from lab at Block 21. The material has been analyzed by using Energy Dispersed X-ray (EDX) machine to obtain the chemical composition for material characterization purposes.

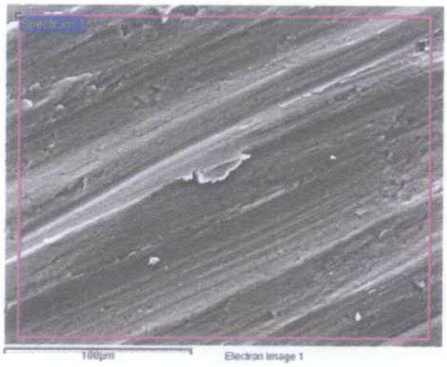


Figure 3.6: Electron image of 6061 aluminum alloy

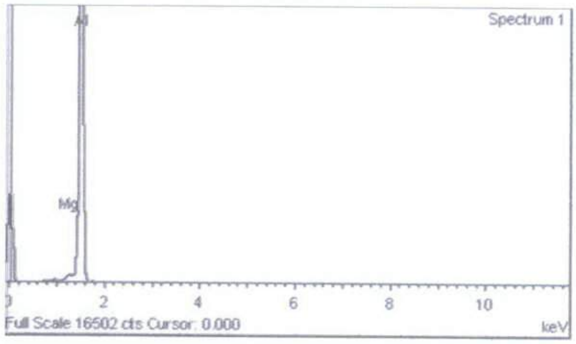


Figure 3.7: EDX spectrum of 6061 aluminum alloy

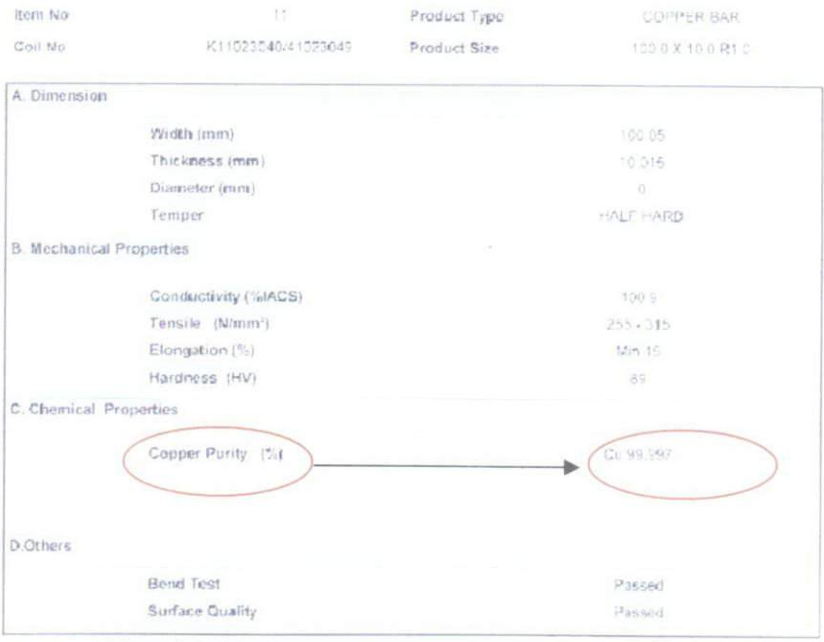
From the FESEM – EDX Testing, it is found out that the aluminum alloy is classified as **Aluminum Alloy 6061 Series.** *Table 3.3* shows the results composition of the aluminum alloy plate by using EDX:

Table 3.3: Composition of 6061 Aluminum Alloy

Element	Weight%	Atomic%
Mg K	0.86	0.95
Al K	98.48	98.41
Si K	0.66	0.64

3.4.2 Copper

Figure 3.8 is the Quality Assurance Inspection Certificate of Copper which is used for this project which includes its chemical properties:



Item No	11	Product Type	COPPER BAR
Coil No	K11023040/41023049	Product Size	100.0 X 10.0 R1.0

A. Dimension		
	Width (mm)	100.05
	Thickness (mm)	10.015
	Diameter (mm)	0
	Temper	HALF HARD
B. Mechanical Properties		
	Conductivity (%IACS)	100.9
	Tensile (N/mm²)	255 - 315
	Elongation (%)	Min 15
	Hardness (HV)	89
C. Chemical Properties		
	Copper Purity (%)	Cu 99.997
D.Others		
	Bend Test	Passed
	Surface Quality	Passed

Figure 3.8: Quality Assurance Inspection Certificate of Copper

The copper material has also been analyzed by using Energy Dispersed X-ray (EDX) machine to obtain the chemical composition for material characterization purposes. The result of EDX is as illustrated in *Figure 3.9* and *Figure 3.10*:

Figure 3.9: Electron image of copper

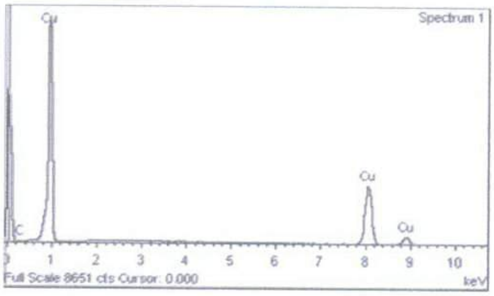


Figure 3.10: EDX spectrum of copper

From the FESEM – EDX Testing the compositions of the copper plate have been known by using EDX as shown in *Table 3.4*:

Table 3.4: Composition of copper

Element	Weight%	Atomic%
C K	7.89	31.20
Cu K	91.11	68.80

3.6 Welding and Experimental Procedures

Two experimental runs of FSW have been made, altering each run with different rotational speed or spindle speed, N (rev/min) and also the move feed rate, S (mm/min). An additional parameter is added which is the plunge depth or the penetration of the pin of welding tool, D (mm). By varying these parameters, a better comparison between different samples will be produced.

This project uses Bridgeport Milling Machine to perform the welding process as shown in *Figure 3.11.*

Figure 3.11: Bridgeport milling machine at Block N

The welding process is facilitated with a jig which acts as the platform to support the workpieces during FSW as shown in *Figure 3.12*.

Figure 3.12: Aluminum alloy is butted closely to copper and tightened with bolts and nuts

The workpieces need to be set up first before undergoing FSW process. Descriptions for workpieces set up are as follows:

1. Four holes are drilled across the jig by using pedestral drill in *Figure 3.13*. (Two holes are drilled on each of the workpieces). These holes are drilled in order to hold the workpieces in a firm position and ensure the forces created by the welding tool does not spread and cause the final product to be oriented out of the position.

Figure 3.13: Pedestral drill in Block 21 is used to drill the workpiece

2. The aluminum alloy and copper plate is butted together and attached to the jig with bolts and nuts. Both workpieces are oriented closely to one another and aligned properly. If there was any gap between the joint, a rubber hammer will be used to align them closely.
3. Then they are ready to be clamped in the Bridgeport Milling Machine for FSW process as shown in *Figure 3.15*.

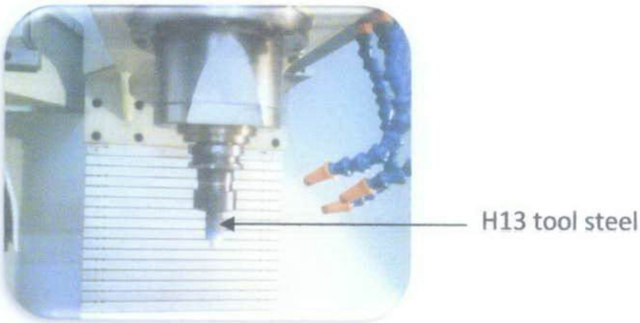


Figure 3.14: H13 tool steel is ready for FSW

Figure 3.15: The wokpieces are clamped onto the vise jaw of Bridgeport Milling Machine

3.7 Metal Specimen Preparation for Microstructure Test

In order to construct the microstructure examination, a sample preparation is needed by applying Metallographic Techniques. It consists of several processes to obtain microsections with smooth and mirror-like surfaces. *Figure 3.16* lists down the flow of sample preparation.

Figure 3.16: Flow of sample preparation

a) Sectioning

Sectioning is the removal of a conveniently sized and representative specimen from a larger piece. An abrasive cutter in Block 21 and a ferrous abrasive cutter in Block 17 as shown in *Figure 3.17* are used for sectioning part. The intended areas to be examined are the cross section of the welded region.

Figure 3.17: Band saw machine at Block 21 and abrasive cutter (ferrous) at Block 17 used to cut the intended regions

b) Mounting

The next step after the sectioning will be the mounting process. Reason for the sample to be mounting is often for desirable or necessary for subsequent handling and metallographic polishing. The examined sample is mounted in Black Epoxy Thermosetting Powder. The Auto Mounting Press machine as shown in *Figure 3.18* was used for this stage to produce Metallographic specimen as shown in *Figure 3.19.*

Figure 3.18: Auto Mounting Press Machine at Block 17

Figure 3.19: Metallographic specimen of FSW

A few parameters involved with this process:

- Heating Time = 3 min
- Cooling Time = 5 min
- Pressure Applied = 4000 psi

Figure 3.20 below shows the steps of mounting: steereng

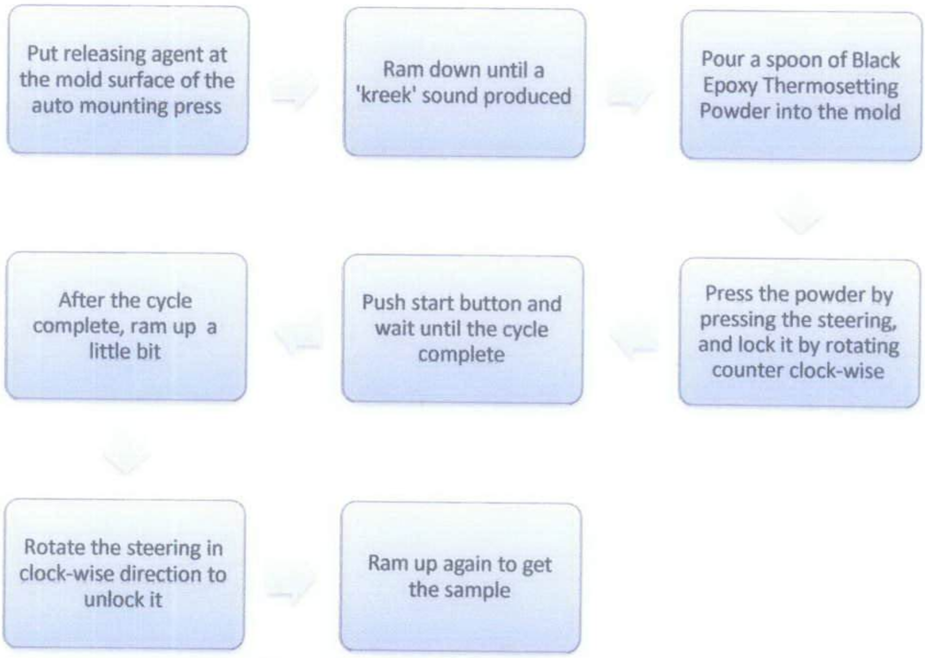


Figure 3.20: Steps of mounting

c) Grinding

After mounting, the specimen is wet ground by using grinder as illustrated in *Figure 3.21* to reveal the surface of the metal.

Figure 3.21: Grinder/ polisher at Block 17

The specimen is successively ground with finer and finer abrasive media. Silicon carbide abrasive paper was the first method of grinding and is still used today including for this metallographic technique. The main aims of grinding are:

- To remove material deformed during cutting (rough, plane grinding)
- To remove the superficial layer of specimen that covers the material destined for examination (rough, plane grinding)

- To prepare a flat surface while introducing only some residual or superficial deformation that can be eliminated during polishing (fine grinding).

The silicon carbide (SiC) abrasive papers are being used with vary grids. *Table 3.5* below shows the flow of grinding process for every sample.

Table 3.5: The flow of grinding process for every sample

Step	Abrasive	Gradation	Lubricant	Rotational Speed (rev/min)
1	SiC	120	H_2O	Vary
2	SiC	180	H_2O	Vary
3	SiC	240	H_2O	Vary
4	SiC	280	H_2O	Vary
5	SiC	320	H_2O	Vary
6	SiC	400	H_2O	Vary
7	SiC	600	H_2O	Vary
8	SiC	1200	H_2O	Vary
9	SiC	2400	H_2O	Vary

d) Polishing

After grinding the specimen, polishing is performed by using polisher as shown in *Figure 3.21*. The specimen is polished with a slurry of napless cloth to produce a scratch-free mirror finish, free from smear, drag, or pull-outs and with minimal deformation remaining from the preparation process. A Grade 3 Diamond Compounds (paste) with mesh 8000 is used for polishing.

e) Etching

Etching is used to reveal the microstructure of the metal through selective chemical attack. Etching process is done in fume chamber as in *Figure 3.22*. In alloys with more than one phase etching creates contrast between different regions through differences in topography or the reflectivity of the different phases. The rate of etching is affected by crystallographic orientation, so contrast is formed between grains, for example in pure metals. The reagent will also preferentially etch high energy sites such as grain boundaries. This results in a surface relief that enables different crystal orientations, grain boundaries, phases and precipitates to be easily distinguished.

Figure 3.22: Etching process need to be done in fume chamber by wearing protective gloves for safety precaution

The specimen is etched using a reagent. The etching reagents used for the microscopic examination are listed in *Table 3.6*:

Table 3.6: Etching reagent for 6061 Aluminum Alloy and Copper

Material	Etchant	Etching mode	Comment
6061 Aluminum alloy	***Keller's*** 190 ml distilled H_2O 3 ml HCl 5 ml HNO_3 2 ml HF	1-3 minutes	Reveals grain size, rolling direction, welding zone
Copper	***Aqueous Ferric Chloride*** 10 g FeCl 20 ml HCl 80 ml H_2O	Seconds to minutes	Produce grain contrast

Below are the lab procedures for etching specimens:

1. The specimen is placed on the table under the Fume Hood with the polished surface up.
2. The Fume Hood is turned on.
3. Without touching the specimen surface, the surface is cleaned with alcohol and let it dry using the drier machine.

   NOTE: Do not let anything but the alcohol touch the specimen surface!

4. Using the Eye-Dropper, a few drops of Etchant is applied to the specimen surface covering the entire metallic surface of the specimen.
5. After about 20 to 30 seconds, the Etchant is rinsed into the sink with water and the specimen is then rinsed quickly with alcohol without touching the surface.
6. The drier machine as shown in *Figure 3.23* is used to dry the sample.
7. Next is the microscopic examination. If further etching is required, steps 1 through 6 should be repeated by varying the time in step 5 depending on the results.
8. If the specimen has many scratches and marks or the microstructure cannot be seen after several etches, fine grinding and other necessary steps should be repeated.

Figure 3.23: Drier Machine at Block 17

3.7 Microscopic examination

Two types of microscopes have been used for microscopic examination which are optical microscope (OM) and field emission scanning electron microscope (FESEM) as shown in *Figure 3.24* and *Figure 3.5.*

3.7.1 Optical Microscope (OM)

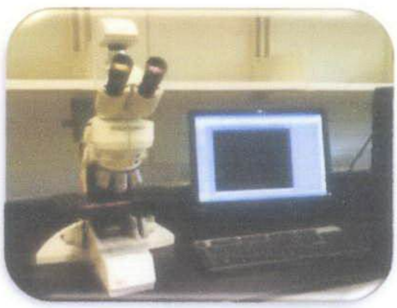


Figure 3.24: Optical microscope used for microstructure examination at Block 17

The optical microscope, often referred to as the "light microscope", is a type of microscope which uses visible light and a system of lenses to magnify images of small samples. Optical microscopes are the oldest design of microscope and were designed around 1600. Basic optical microscopes can be very simple, although there are many complex designs which aim to improve resolution and sample contrast. Historically optical microscopes were easy to develop and are popular because they use visible light so the sample can be directly observed by eye.[10]

For each specimen, the microstructure is examined by having several magnifications, e.g. 10x, 50x. The images from the optical microscope are then be captured by normal light-sensitive camera to generate a micrograph. Then, the images will be saved and ready to be analyzed and discussed further.

Ideally the surface to be examined optically should be perfectly flat and level. If not, then as the viewing area is moved across the surface it will pass in and out of focus. In addition, it will make it difficult to have the whole of the field of view in focus - while the centre is focused, the sides will be out of focus.

3.7.2 Field Emission Scanning Electron Microscope (FESEM)

A more recent and extremely useful investigative tool is the scanning electron microscope (SEM). The surface of a specimen to be examined is scanned with an electron beam, and the reflected (or back-scattered) beam of electrons is collected, then displayed at the same scanning rate on a cathode ray tube (similar to a CRT television screen). The image on the screen, which may be photographed, represents the surface features of the specimen. The surface may or may not be polished and etched, but it must be electrically conductive; a very thin metallic surface coating must be applied to nonconductive material. Magnifications ranging from 10 to excess of 50 000 times are possible, as are also very great depths of field. Accessory equipment permits qualitative and semiquantitative analysis of the elemental composition of very localized surface areas.[7]

Figure 3.25:Zeiss SUPRA 55VP FESEM in CAL Lab, Block P

Under vacuum, electrons generated by a Field Emission Source are accelerated in a field gradient. The beam passes through Electromagnetic Lenses, focussing onto the specimen. As result of this bombardment different types of electrons are emitted from the specimen. A detector catches the secondary electrons and an image of the sample surface is constructed by comparing the intensity of these secondary electrons to the scanning primary electron beam. Finally the image is displayed on a monitor.[11] The FESEM principle is as drawn in *Figure 3.26.*

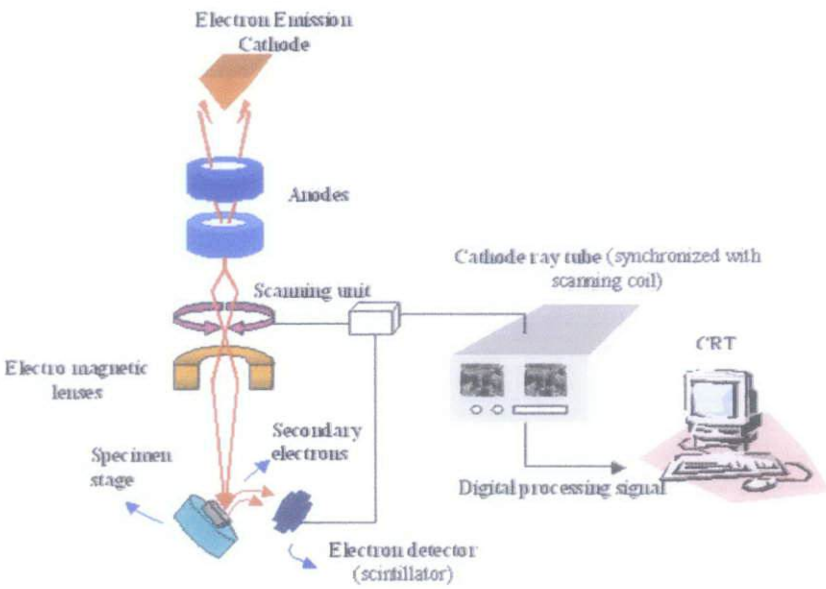


Figure 3.26: FESEM principle[11]

CHAPTER 4
RESULT & DISCUSSION

In this section, all results and discussion are documented with regard to the objectives of this project. For this project, two samples of Friction Stir Welding of aluminum alloy to copper have been produced. Experiment 1 and experiment 2 are explained further below:

4.1 Experiment 1

The first run of FSW on aluminum alloy to copper was done on 10th November 2010 by using Portbridge Milling Machine at Block N. *Table 4.1* shows the parameters that have been used for the trial run:

Table 4.1 Parameter for FSW of aluminum alloy to copper

Parameter	Value
Spindle Speed, N (rpm)	1200
Plunge Feed Rate (mm)	10
Move Feed Rate, S (mm/min)	10
Penetration/ Depth of Plunge (mm)	8.0
Dwell time (sec)	15
Length of Weld Line (mm)	85

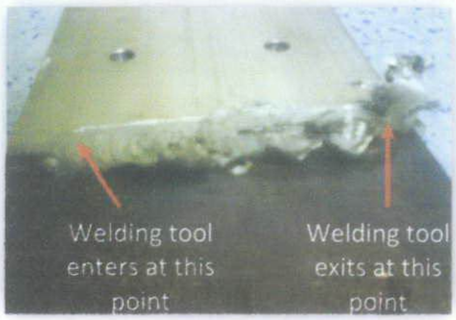


Figure 4.1: Welding line produced using the above parameter for experiment 1

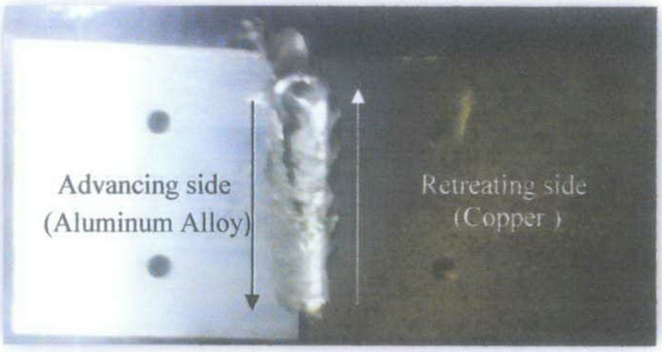
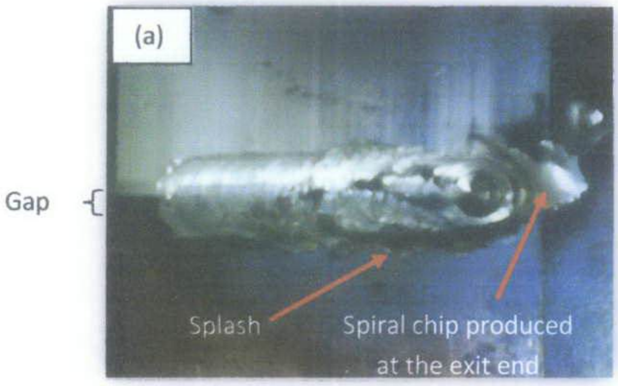


Figure 4.2: Retreating and advancing side of work piece for experiment 1



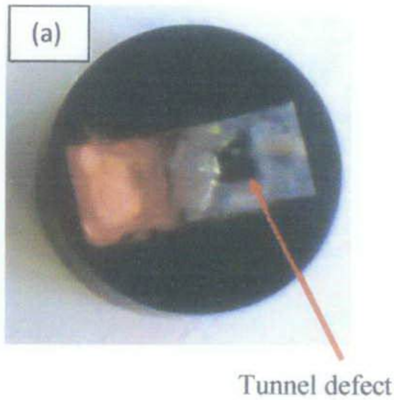


Figure 4.3: Defects of FSW process for experiment 1 (a) splash and spiral chip (b) tunnel defect

From *Figure 4.3 (a)*, it can be observed that splash has uniformed on the retreating side towards the exit side. Also there has been a spiral chip produced at the end of the work piece, indicating the continuity of the aluminum from the welding process while generated in hot working operation. Besides, it seems to have lack of surface fill (open voids) and tunnel defect as presented in *Figure 4.3 (b)*. Based on the flaw types, it might occur due to FSW under too cold a processing condition.

There is also a gap exist at the joint of the two metals during FSW. Before running the experiment, the joint has been made sure that there is no gap. It may happen due to different hardness and melting temperature of aluminum alloy and copper. Copper has higher melting temperature than aluminum alloy. The melting temperature of copper is 1083°C while the melting temperature of aluminum is 617°C.[12] Thus, it needs more heat to melt the copper. The machine seems vibrating during the welding process and this may lead the metals to move and induce the existence of the gap. This case is also called as poor bonding. Poor bonding of the joint can often be attributed to inadequate pressure placed onto the workpiece material either due to tool pin design, e.g. the use of non-profiled cylindrical pins when possessing materials with a high resistance to deformation, or due to a lack of axial force placed onto the surface of the workpieces by tool shoulder position or inadequate axial load.[1]

On the other hand, the stir zone is not so smooth. It might be due lack of penetration. So the plunge depth will be increased for the next experiments to 8.1 mm. The short dwell time also might be the causes of poor FSW result. Thus, the dwell time will be increased for the second experiment to provide more heat to the workpieces.

Even though the FSW of this first trial result is not so good, but it can be improved by changing the parameters, which are the spindle speed, move feed rate, and plunge depth. Spindle speed will be varied in the range of 1000 rpm to 2500 rpm while move feed rate will be varied in the range of 8 mm/min to 70 mm/min.

4.1.1 Weld Microstructure of Dissimilar 6061 Aluminum Alloy/ Copper Welds

The microstructure of the parent materials 6061 aluminum alloy and copper are shown in Figure 4.4. The grains of the 6061 aluminum alloy are elongated along the rolled direction as shown in *Figure 4.4 (a)*. The copper substrates exhibit an irregular grain as shown in *Figure 4.4 (b)*.

A through-thickness longitudinal section of dissimilar 6061 aluminum alloy/copper weld at spindle speed of 1200 rpm and move feed rate 10 mm/min is shown in *Figure 4.5*.

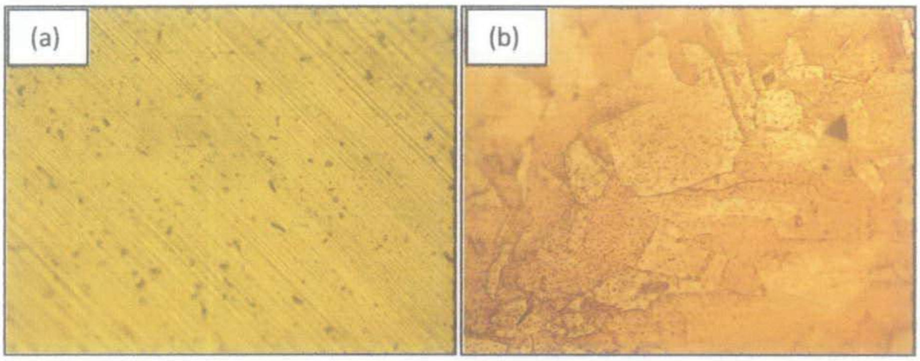


Figure 4.4: The parent materials microstructures at 50x magnification of (a) 6061 aluminum alloy (b) copper

From *Figure 4.5*, we can make a few comparisons between the parent metals and the welded metals.

From *Figure 4.5(d)*, it was recognized that grains in the copper close to the Al/Cu interface was finer than those of the copper parent metal in *Figure 4.4(b)*. This difference in the grain size can be attributed to the effect of rotating pin on the deformation and recrystallization of grains in the stir zone of copper metal. Transport of material from the retreating side to advancing side at the top surface of the weld is a well-known phenomenon in FSW, which results in vertical flow of material about the longitudinal axis of the weld.

The structure of the Al/Cu interface was complex. A layer structure which consists of mechanical mixed Cu and Al rich layers formed in the area close to the interface as shown in *Figure 4.5(e)*. The layer structure was accompanied by the grey structure as indicated in *Figure 4.5(a)*.

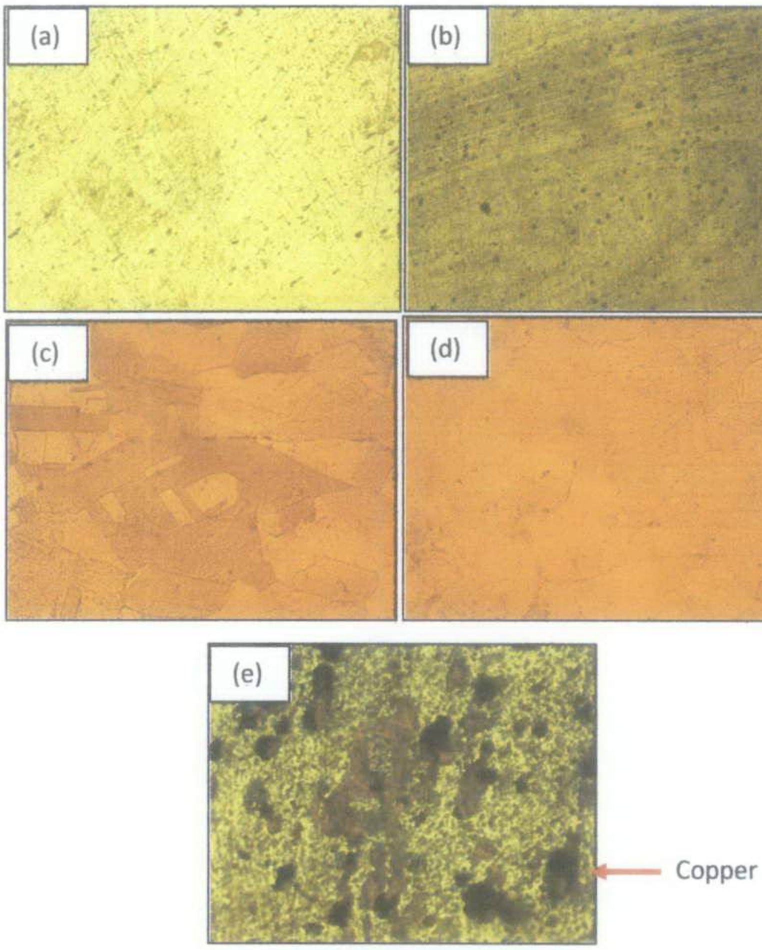


Figure 4.5: Microstructural features of cross-sections of a dissimilar 6061 aluminum alloy/ copper weld under the condition of 1200 rpm for rotational speed and 10 mm/min for welding speed at 50x magnification: (a) HAZ of 6061 aluminum alloy (advancing side); (b) TMAZ of 6061 aluminum alloy; (c)HAZ of copper (retreating side); (d)TMAZ of copper; (e) friction stir processed zone or nugget

SEM micrographs of the welding regions are shown in *Figure 4.6* below. It shows the microstructure of the weld. The difference in grain shape and dimensions between the weld nugget in *Figure 4.6(d)* and the parent material *Figure 4.6(e)* is quite evident: the grain size is smaller in the weld nugget compared to the parent metal.

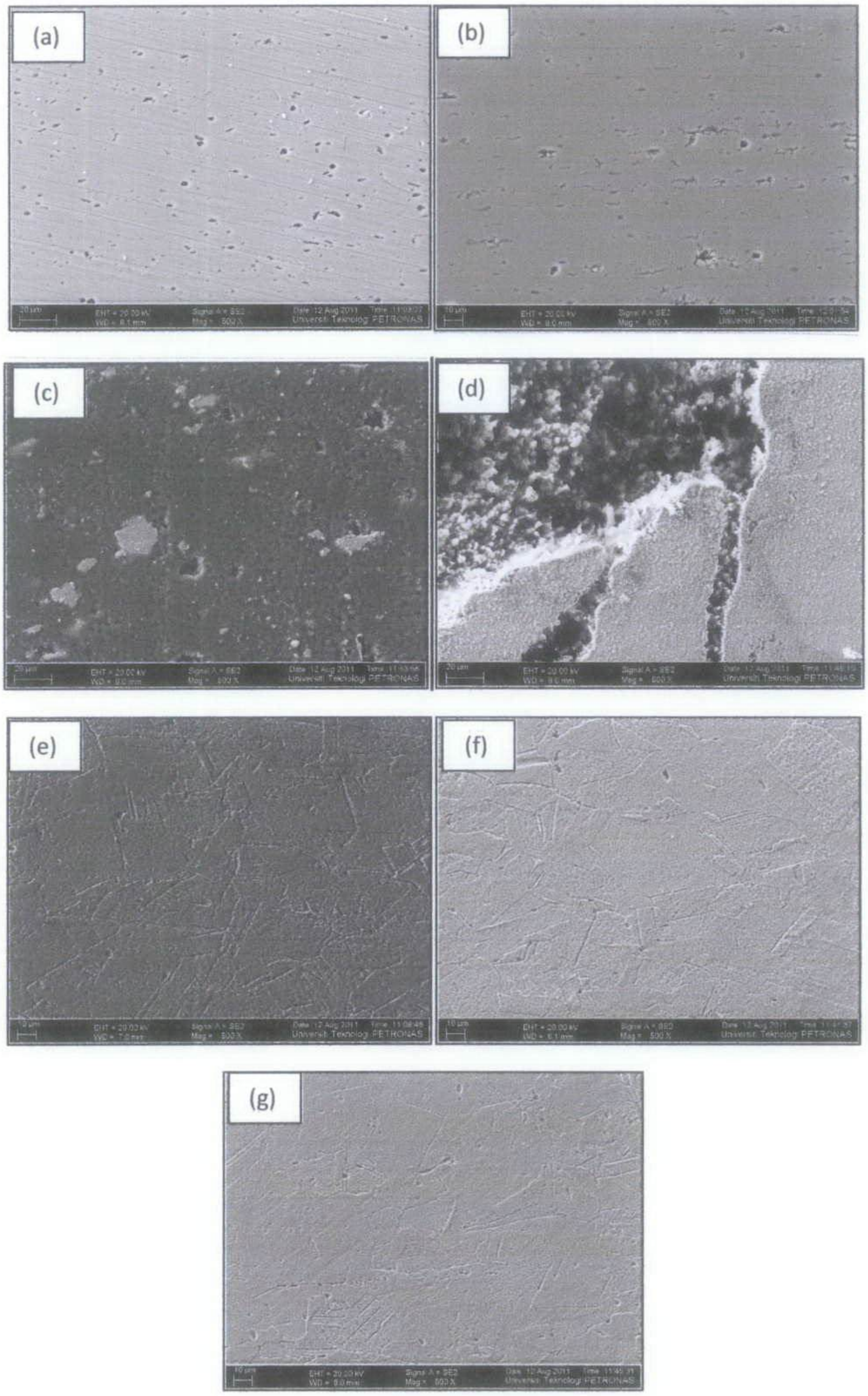


Figure 4.6: SEM micrograph of cross-sections of a dissimilar 6061 aluminum alloy/ copper weld under the condition of 1200 rpm for rotational speed and 10 mm/min for welding speed at 500x magnification: (a) 6061 aluminum alloy (parent metal); (b) HAZ of 6061 aluminum alloy (advancing side); (c) TMAZ of 6061 aluminum alloy; (d) friction stir processed zone or nugget; (e) Copper (parent metal); (f)HAZ of copper (retreating side); (g)TMAZ of copper

4.2 Experiment 2

The second run of FSW on 6061 aluminum alloy to copper was done on 12th July 2011 by using Portbridge Milling Machine at Block N.

Table 4.2 lists down the parameters that have been used:

Table 4.2: Parameter for FSW of aluminum alloy to copper

Parameter	Value
Spindle Speed, N (rpm)	1100
Plunge Feed Rate (mm)	10
Move Feed Rate, S (mm/min)	8
Penetration/ Depth of Plunge (mm)	8.1
Dwell time (sec)	22
Length of Weld Line (mm)	85

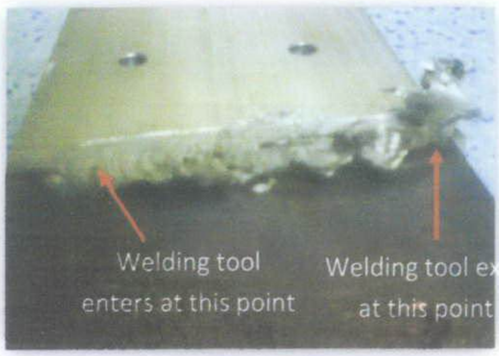
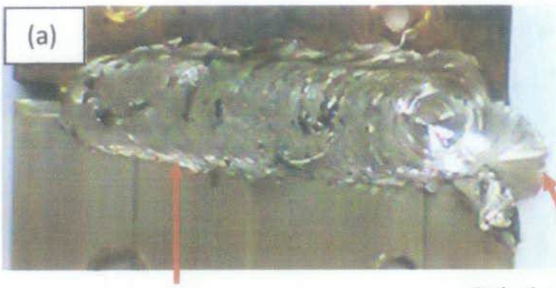


Figure 4.7: Welding line produced using the above parameter for experiment 2

Figure 4.8: Advancing and retreating side of work piece for experiment 2



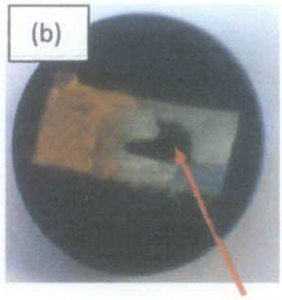


Figure 4.9: Defects of FSW process for experiment 2 (a) splash and spiral chip (b) tunnel defect

This experiment has some differences compared to the previous one. The spindle speed has been slowed down from 1200 rpm to 1100 rpm. Otherwise, the move feed rate is decreased from 10 mm/min to 8 mm /min. The penetration depth also has been increased from 8.0 mm to 8.1 mm. Besides, the dwell time is prolonged from 16 seconds to 22 seconds. This experiment shows better results compared to the first experiment.

From *Figure 4.6(a)*, it can be observed that splash has uniformed on the retreating side towards the exit side. However, the splash produced for this experiment is lesser than the previous experiment. Also there has been a spiral chip produced at the end of the work piece, indicating the continuity of the aluminum from the welding process while generated in hot working operation. Besides, it seems to have lack of surface fill (open voids) and tunnel defect as presented in the *Figure 4.9(b)*. However, the defect is not so severe compared to the first experiment.

There is also a gap exist at the joint of the two metals during FSW. Before running the experiment, the joint has been made sure that there is no gap. It may happen due to different hardness and melting temperature of aluminum alloy and copper. Copper has higher melting temperature than aluminum alloy. The melting temperature of copper is 1083°C while the melting temperature of 6061 aluminum alloy is 617°C.[12] Thus, it needs more heat to melt the copper. Small vibration may also occur during the welding process and this may lead the metals to move and induce the existence of the gap. This case is also called as poor bonding. Poor bonding of the joint can often be attributed to inadequate pressure placed onto the workpiece material either due to tool pin design, which is cylindrical tool pin. Tapered tool pin is better for FSW.

On the other hand, the stir zone is not so smooth, but it is better for the second experiment since the penetration depth is increased to 8.1 mm. both materials can stir together better. The rough welding surface may happen due to the small capacity of the Portbridge Milling Machine. If a special FSW welding machine is used, I believe that it can results in a very good welding.

4.2.1 Weld Microstructure of Dissimilar 6061 Aluminum Alloy/ Copper Welds

Similar to experiment 1, it was recognized that grains in the copper close to the Al/Cu interface as shown in *Figure 4.10(d)* was finer than those of the copper parent metal as shown in *Figure 4.4(b)*. This difference in the grain size can be attributed to the effect of rotating pin on the deformation and recrystallization of grains in the stir zone of copper metal. Transport of material from the retreating side to advancing side at the top surface of the weld is a well-known phenomenon in FSW, which results in vertical flow of material about the longitudinal axis of the weld.

The structure of the Al/Cu interface was complex. A layer structure which consists of mechanical mixed Cu and Al rich layers formed in the area close to the interface as shown in *Figure 4.10(e)*. The layer structure was accompanied by the grey structure as indicated in *Figure 4.10(a)*.

Figure 4.10(e) has shown that there was more copper mixture in the friction stir processed zone/nugget compared to *Figure 4.5(e)*.

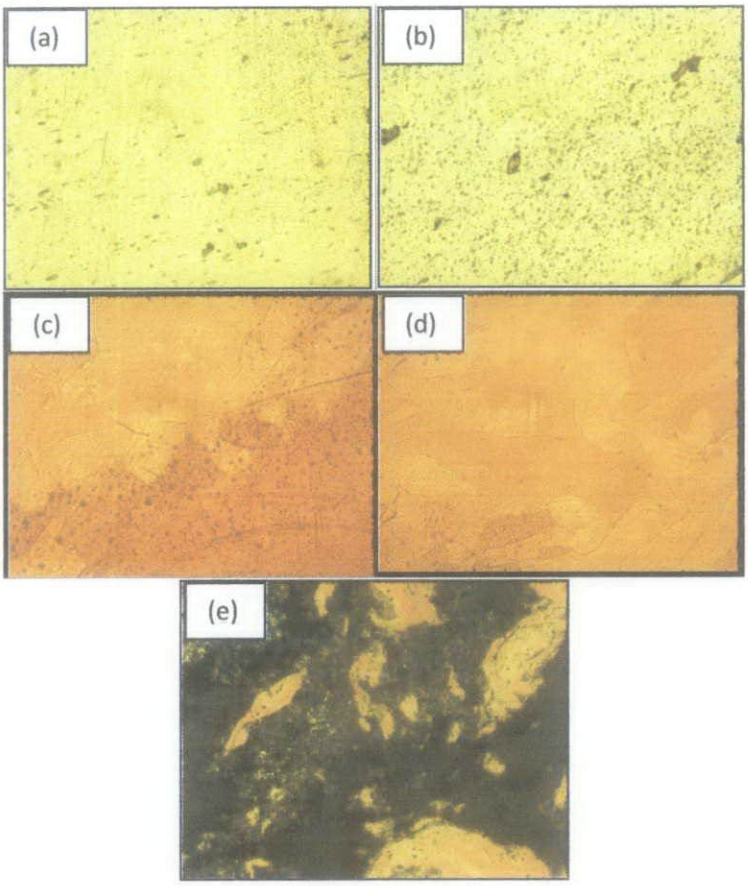


Figure 4.10: Microstructural features of cross-sections of a dissimilar 6061 aluminum alloy/ copper weld under the condition of 1100 rpm for rotational speed and 8 mm/min for welding speed at 50x magnification: (a) HAZ of 6061 aluminum alloy (advancing side); (b) TMAZ of 6061 aluminum alloy; (c) HAZ of copper (retreating side); (d)TMAZ of copper; (e) friction stir processed zone or nugget

SEM micrographs of the welding regions are shown in Figure above. It shows the microstructure of the weld. The difference in grain shape and dimensions between the weld nugget in *Figure 4.11(d)* and the parent material *4.11(e)* is quite evident: the grain size is smaller in the weld nugget compared to the parent metal.

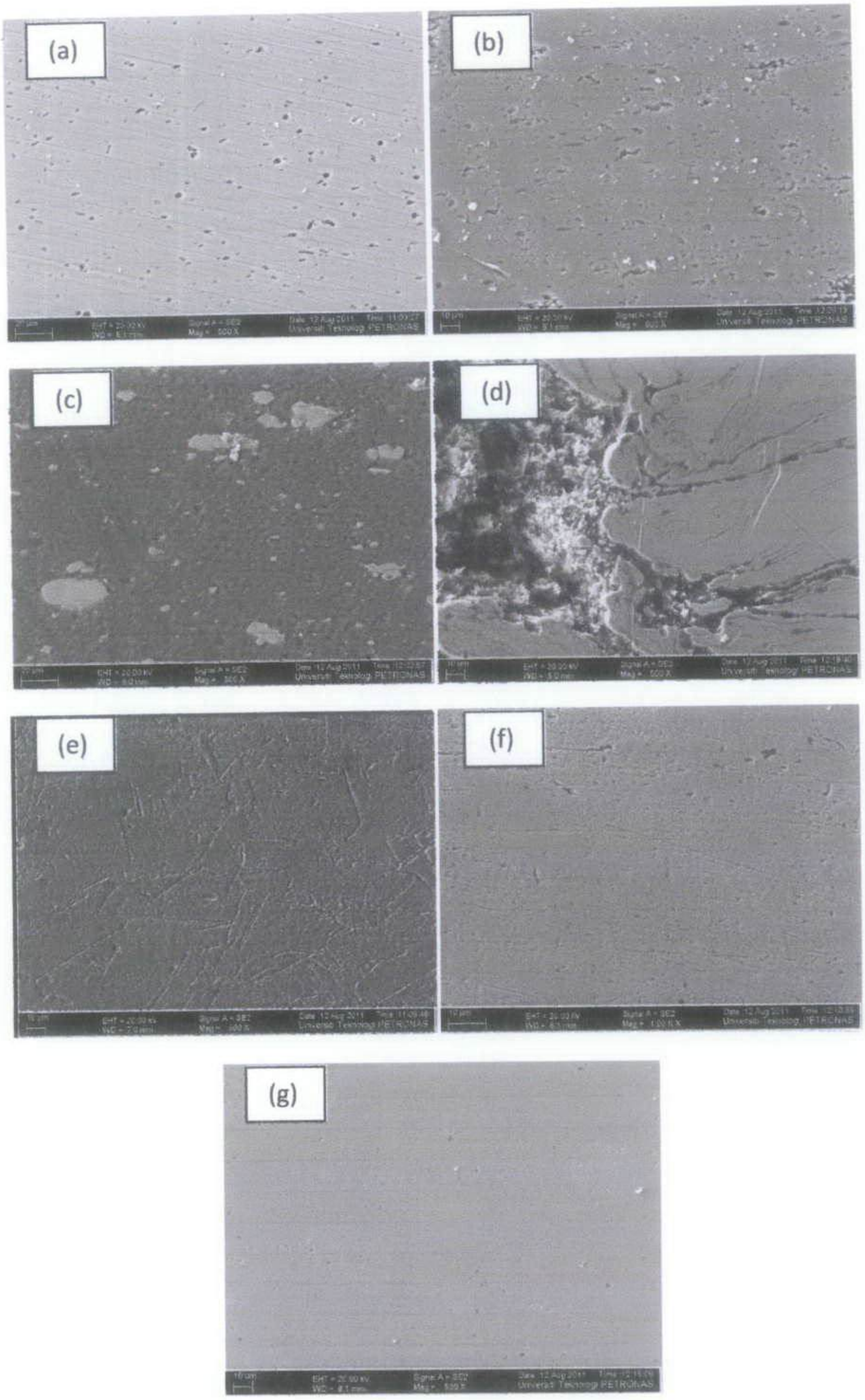


Figure 4.11: SEM micrograph of cross-sections of a dissimilar 6061 aluminum alloy/ copper weld under the condition of 1100 rpm for rotational speed and 8 mm/min for welding speed at 500x magnification: (a) 6061 aluminum alloy (parent metal); (b) HAZ of 6061 aluminum alloy (advancing side); (c) TMAZ of 6061 aluminum alloy; (d) friction stir processed zone or nugget; (e) Copper (parent metal); (f)HAZ of copper (retreating side); (g)TMAZ of copper

4.3 Discussion

Figure 4.12 and *Figure 4.13* show EDX spectrum of dissimilar 6061 aluminum alloy/ copper welds at the nugget area. Based on *Table 4.3*, for Sample 1, the average chemical composition measured from Energy Dispersive X-ray (EDX) analysis is (at wt%) 48.29 Cu, 38.88 Al, 6.25 C, and 3.99 O. Otherwise, for Sample 2, the average chemical composition measured from Energy Dispersive X-ray (EDX) analysis is (at wt%) 59.10 Cu, 28.90 Al, 8.14 C, and 3.77 O. By comparing the chemical composition between these two samples, it can be seen that there is more mixture of copper in the nugget area of Sample 2 which is 48.29%. It means that, the copper has been stirred better in Sample 2. On the other hand, it can be seen that there is more mixture of aluminum alloy in the nugget area of Sample 1 which is 38.88%. %. It means that, the aluminum has been stirred better in Sample 1.

Table 4.3: Table of chemical composition of different welding region

Welded region	Element	Weight (%)		Atomic (%)	
		Exp. 1	Exp. 2	Exp. 1	Exp. 2
HAZ (Aluminum alloy)	C	9.36	0.00	18.52	0.00
	O	2.70	3.07	4.01	5.09
	Mg	0.50	0.79	0.51	0.86
	Al	86.71	94.29	76.36	92.57
	Si	0.70	1.31	0.60	1.24
	Cu	0.00	0.59	0.00	0.24
TMAZ (Aluminum alloy)	C	9.46	7.49	19.33	15.79
	O	3.99	4.15	6.12	6.57
	Al	77.95	77.69	70.92	72.91
	Si	0.62	0.95	0.54	0.86
	Cu	7.99	9.71	3.09	3.81
Weld stir zone/ nugget	C	6.25	8.14	16.6	23.24
	O	6.58	3.77	13.14	8.09
	Al	38.88	28.90	46.00	36.73
	Cu	48.29	59.10	24.26	31.94
TMAZ (Copper)	O	1.64	6.72	6.22	27.60
	Cu	98.36	93.28	93.78	72.40
HAZ (Copper)	C	6.88	6.87	27.01	27.11
	O	1.76	1.57	5.18	4.64
	Cu	91.36	91.56	67.81	68.26

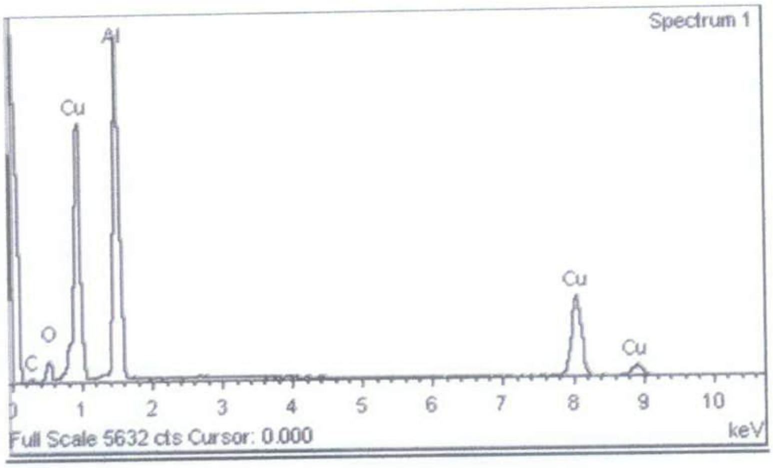


Figure 4.12: EDX spectrum of weld stir zone/ nugget of Experiment 1

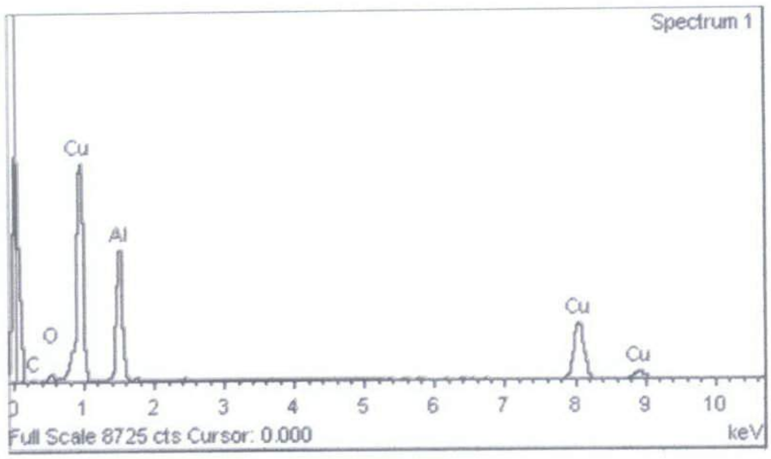


Figure 4.13: EDX spectrum of weld stir zone/ nugget of Experiment 2

The 6061 aluminum alloy/ copper welds exhibits a considerable discontinuity and crack propagation, and they are not good welds. Some welds fail due to the thermal cracking and lack of bonding. Sample 2 exhibits better results of FSW compared to Sample 1 as it produces lesser defects.

The FSW of 6061 aluminum alloy to copper is not only notably influenced by the welding parameters, but a more contiguous weld occurred during Experiment 2 at 1100 rpm for the rotational speed 8 mm/min for the welding speed. Complex microstructural issues are found in 6061 aluminum alloy/ copper system where intermetallic compounds can form as a consequence of temperature variations (well below the melting point of the parent metals) and a wide range of compositional fluctuations. Some of these features are discussed in below in detail for the information of intermetallic compound.

In a dissimilar 6061 aluminum alloy/ copper weld, a mixed layer of aluminum and copper that includes brittle intermetallic compounds are formed from the EDX results and microstructural observation. It is considered that the softening of the stirred 6061 aluminum alloy facilitates the formation of the mixed layer and intermetallic compounds. A consensus has not been reached upon the mechanism of the phase transformation when small amounts of copper is stirred into the 6061 aluminum alloy at elevated temperature during FSW. One great source of difficulty is the low solubility of copper in aluminum and the existence of different intermetallic phases under the welding conditions. Almost all the copper stirred in to the 6061 aluminum alloy is found to form the intermetallic compounds under these experimental conditions. However, the situation is different when aluminum is stirred into the copper.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A new welding technique, FSW, was successfully applied to the joining Al 6061 alloy and pure copper. The microstructure of friction stir welded 6061 aluminum alloy to pure copper have been studied in the present work. Following conclusion and recommendations are drawn:

1) The present study has demonstrated and proven that 6061 aluminum alloy can be joined to dissimilar copper metal using friction stir welding (FSW). Different parameters have been applied to both experiments including its spindle speed (N) in rev/min, feed rate (S) in mm/min, plunge depth in mm, and dwell time in second. The welding parameters have very great influence towards the result.

2) The microstructure if the welding zone in friction stir welded 6061 aluminum alloy to copper was divided into seven zones: parent copper; HAZ in the copper at retreating side of weld; TMAZ in the copper at retreating side of weld; weld nugget; TMAZ in the 6061 aluminum alloy at advancing side of weld; HAZ in the 6061 aluminum alloy at advancing side of weld; parent 6061 aluminum alloy.

3) 6061 aluminum alloy slightly diffuses in copper at the interface between base copper and Al 6061 alloy of weld nugget, but copper very little diffuse in 6061 aluminum alloy. The diffuse transition between copper particles and Al 6061 alloy in the weld nugget is not pronounced. Based on the cross-sectional

of both samples, aluminum alloy melts more than copper due to difference in melting temperatures.

4) Direct FSW of 6061 aluminum alloy to pure copper has proved difficult due to the brittle nature of the intermetallic compounds formed in the weld nugget.

All in all, this project is not only a comprehensive research study about friction stir welding of 6061 aluminum alloy to copper, but it also involves technical skills in welding. The project is very much related to the study on material microstructural features. From the studies, we could compare and study the different region of welded materials.

5.2 Recommendations

Tunnel defect only occurs at the advancing side (aluminum side). However, this tunnel defects could be reduced by changing to new FSW tool with different geometry (i.e. tapered cylindrical pin tool). A few studies have shown that tapered cylindrical pin is produces better joint quality compared to straight cylindrical pin tool.

Since CNC Bridgeport Milling Machine is not design specifically to perform FSW, the results obtained are not so good. In conclusion, a higher capacity machine especially for FSW is extremely recommended to replace CNC Bridgeport Milling Machine for better result.

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APPENDIX I: *Gantt chart and key milestone of FYP1*

Gantt Chart and Key Milestone of FYP 1

SEM	No.	Activities	Duration (days)	Date		Semester 1														
						Week														
				Start	Finish	1	2	3	4	5	6	7	8	9	10	11	12	13	14	SW
1	1	Literature review	20	2-Aug-10	21-Aug-10		■	■	■											
	2	Submit preliminary report	1	20-Aug-10	20-Aug-10				▲											
	3	Procument	11	23-Aug-10	2-Sep-10					■	■									
	4	Sumbit progress report	5	20-Sep-10	24-Sep-10								▲							
	5	Attend seminar	5	20-Sep-10	24-Sep-10								▲							
	6	Refurbish the tool	5	27-Sep-10	1-Oct-10									■						
		a) Turning process	1	27-Sep-10	27-Sep-10									■						
		b) Heat treatment process	1	28-Sep-10	28-Sep-10									■						
	7	Trial run on CNC machine	16	4-Oct-10	19-Oct-10										■	■				
	8	Submit interim report	1	1-Nov-10	1-Nov-10														▲	
	9	Oral presentation	5	8-Nov-10	12-Nov-10															▲

▲ Suggested milestone

SW Study Week

APPENDIX II: *Gantt chart and key milestone of FYP2*

Table 3.2: Gantt Chart and Key Milestone of FYP 2

SEM	No.	Activities	Duration (days)	Date		Semester 3														
						Week														
				Start	Finish	1	2	3	4	5	6	7	8	9	10	11	12	13	14	SW
3	10	Literature review	5	23-May-11	27-May-11	■														
		2nd run of FSW	1	30-May-11	30-May-11		■													
		Produce sample	52	1-Jun-11	22-Jul-11		■	■	■	■	■	■	■	■						
		a) Sectioning	2	1-Jun-11	2-Jun-11		■													
		b) Mounting	3	7-Jun-11	9-Jun-11			■												
		c) Grinding	15	16-Jun-11	28-Jun-11				■	■	■									
		d) Polishing	1	6-Jul-11	6-Jul-11							■								
		e) Etching	2	11-Jul-11	12-Jul-11								■							
	11	Evaluate microstructure	9	12-Jul-11	20-Jul-11								■	■						
	12	Sumbit progress report	1	15-Jul-11	15-Jul-11								▲							
	13	SEM	8	22-Jul-11	29-Jul-11									■	■					
	14	Analyze results	8	23-Jul-11	30-Jul-11									■	■					
	15	Report writing	27	14-Jul-11	9-Aug-11								■	■	■	■	■			
	16	Pre- EDX	1	1-Aug-11												▲				
	17	Submit dissertation (draft/softbound)	1	11-Aug-11	11-Aug-11													▲		
	18	Submit technical paper	1	18-Aug-11	18-Aug-11													▲		
	19	Oral presentation	1	STUDY WEEK															▲	
	20	Submit hardbound dissertation	1	7 DAYS AFTER ORAL PRESENTATION																▲

▲ Suggested milestone

SW Study Week