Characterization of Double-sided Friction Stir Welding (FSW)

by

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Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS

in partial fulfillment of the requirement for the

BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

____
(Dr Azmi Bin Abdul Wahab)

UNIVERSITI TEKNOLOGI PETRONAS,

TRONOH, PERAK

September 2013

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.

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FAHMI BIN CHE A. HALIM

ABSTRACT

The objective of this project is to characterize the microstructure of double-sided friction stir welding (FSW) using optical microscopy (OM) and comparing it to the microstructure of single-sided friction stir welding (FSW) and non-welded metal. Single-sided friction stir welding tend to produce defect such as tunnel defect or worm hole [1]. The defect can be possibly reduced by performing double-sided FSW but the reasons behind it are not well reported. Thus the author intends to produce a detail report on the microstructure behavior of double-sided FSW. This project also will act as an extensive microstructure study on the double-sided FSW because the number of research regarding the topic is still low and it also can act as a reference in the future. Microstructure studies are done with the limitation of optical microscopy only at the welded area of the weld plate. Specifically the microstructure studies are aimed at the characterization of four different regions which is weld nugget, heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and base metal. This can be achieved by preparing a separate samples for double-sided single-sided friction stir welding (FSW) and non-welded. The samples underwent welding process and after the process, the specimens are brought into metallography phase for microstructure review. Based on the result observed, double-sided friction stir welding (FSW) produced microstructure variations throughout the different regions. For the double-sided (FSW) a finer grain size is observed compared to the single-sided FSW. In addition the wormhole sizes are reduced by 20% by performing double-sided FSW. Furthermore, the micro hardness test also reveals that double-sided FSW resulted in higher strength. Last but not least, the double-sided FSW also have a smaller grain size compared to the single-sided FSW.

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Last but not least, I hope that this report would be helpful to those who want to find more information on FSW in the future.

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LIST OF ABBREVIATIONS

FSW	Friction Stir Welding
Al	Aluminum
HAZ	Heat Affected Zone
TMAZ	Thermo-mechanically Affected Zone
OM	Optical Microscopy
SEM	Scanning Electron Microscope
FESEM	Field Emission Scanning Electron Microscopy
EDS	Energy dispersive X-ray Spectroscopy
HF	Hydrogen fluoride
HCl	Hydrochloric acid
HNO_3	Nitric acid
H_2O	Water

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Friction stir welding is a new distinct welding technique compared to other welding techniques such as submerged friction arc welding [2]. FSW allows the use of virtually any joint configuration as we know them from traditional fusion welding. With the application of FSW in certain industries, it is capable of replacing the usage of fastened joint and significantly removes unnecessary weight and cost to the design. Many industries have benefited by the introduction of the FSW, mainly transportation sectors such as railway, automotive, shipbuilding and aerospace [3]. These industries benefit the most because they use aluminum or aluminum alloy as their materials and FSW is the best option to weld these materials.

To date, the predominant focus of FSW has been for welding aluminum alloys, although the process has been well developed for other alloys. In addition considerable work has focused on using FSW to join dissimilar aluminum alloys [2,4]. Since FSW is a solid state process, it can be used to join all common aluminum alloys, including the 2xxx, 7xxx and 8xxx series which are normally challenging or impractical to weld by fusion processes [5, 6]. For this project aluminum alloy 6061 is chosen as the sample for testing.

A successful combination of two actions which is frictional heating and mechanical deformation produce the welds on the targeted work piece [7]. Usually there are four different types of region that will be observed and analyzed when aluminum alloy is welded using FSW. They are base metal, heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and weld nugget. The rotation of non-consumable tool plays an important role in affecting the formation of the above regions [8-10].

1.2 PROBLEM STATEMENT

In this project aluminum alloy 6061 is joined together by butt joint using double-sided friction stir welding (FSW). Single-sided friction stir welding tend to produce defect such as tunnel defect or worm hole [1]. With the proposition of double-sided FSW, it can possibly reduce this defect.

This project will act as an extensive microstructure study on the double-sided FSW. This is because most of the previous study done before focus on single-sided FSW only. Double-sided FSW produce a different microstructure behavior compared to single-sided FSW. As an improvement to the previous studies, characterization on double-sided FSW is done and it will be compared to the single side FSW and non-welded aluminum alloy 6061.

1.3 OBJECTIVES

The objective of this project is to characterize the microstructure of double-sided friction stir welding (FSW) using Optical Microscopy (OM) and compared it to single-sided friction stir welding (FSW) and non-welded metal.

1.4 SCOPE OF STUDY

The project will be focused on microstructure of aluminum alloy 6061 when it is welded together by using double-sided friction stir welding (FSW). Microstructure studies are done with the use of optical microscopy only (OM) at the welded area of the weld plate. Specifically the microstructure studies are aimed at the characterization of four different regions which is weld nugget, heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and base metal.

CHAPTER 2

LITERATURE REVIEW

2.1 FRICTION STIR WELDING (FSW)

Friction Stir Welding (FSW) was developed by The Welding institute (TWI) in 1991, is a solid state welding process that are can be another options other than fusion [11]. Friction stir welding (FSW) is a technique that utilizes a non-consumable rotating welding tool to generate frictional heat and plastic deformation at the welding location, thereby affecting the formation of a joint while the material is in the solid state [12-`14]. The principal advantages of FSW, being a solid-state process, are low distortion, absence of melt-related defects and high joint strength [11]. FSW are used to weld many similar or dissimilar alloys, and it also are able to weld the alloys that are considered non-weldable [4]. In this project, for the double-sided FSW configuration, the work piece will be rotated 180 degree and then a second weld pass is performed.

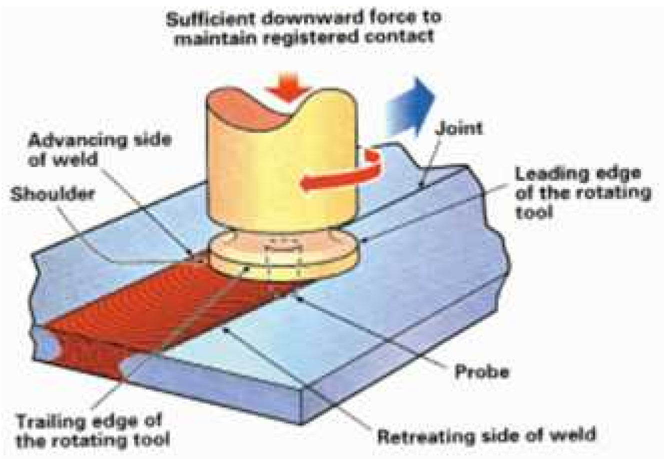

Figure 2.1: Schematic illustration of the FSW process [11].

The entire process appears relatively simple in that a rotating tool is plunged between the surfaces of two abutting plates and is then traversed along the length of the plates. The advancing and retreating sides of the weld are defined by the direction of tool rotation with respect to the tool translation. On the advancing side, the tool rotation and translation are in the same relative direction while tool rotation and weld direction oppose each other at the retreating side. The tool consists of a shoulder that rotates against the plate surface and a pin that rotates beneath the plate surfaces [2, 1].

During FSW process, frictional forces between the tool and plates create intense local heating. Instead of melting, a highly plasticized region of material around the rotating tool is created [1]. Material flow during FSW is very complex, but can be explained as a simple extrusion process. Tool rotation causes material transfer around the tool, stirring the two plates together. As the tool is translated, it essentially extrudes the stirred material through a "die" created by the tool and the unsoftened plate material [2, 12,13].

2.1.1 Wormhole Defect in Single-Sided Friction Stir Welding (FSW)

Tunnel or wormhole defect usually occurs at the advancing side and it usually consist of a tunnel of improperly consolidated and forged material running in the longitudinal direction [15]. The defect is created by extreme travel speed (rpm) for given rotational speed (rpm). It is also caused by cold weld. Severe wormhole creates a reduction in mechanical properties [15].

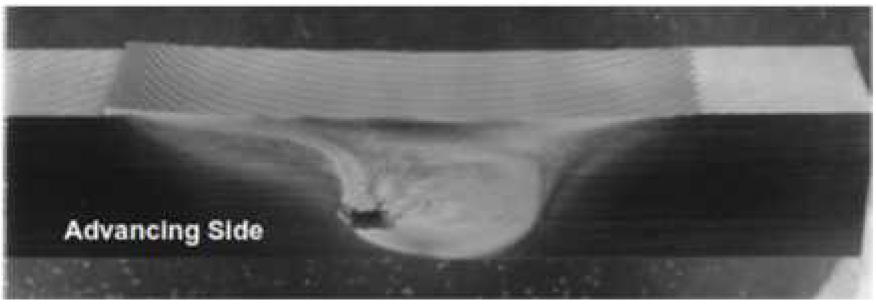

Figure 2.2: Wormhole defect [15].

Figure 2.3: Wormhole defect [15].

2.1.2 Double-Sided Friction Stir Welding (FSW)

S. Klingesmith et. al. [16] in his study had investigated the double-sided FSW, in the study two plates of superaustenitic stainless steel joined via a double-sided FSW in a butt joint configuration. The plate thickness was 6.35 mm and the welds were produced with a proprietary tungsten based tool using a travel speed of approximately 0.847 mm/s, a tool rotational speed of 150 rpm, and a z-axis load of approximately 80 kN. Cross sections of the transverse view of the welds were sectioned and prepared for microstructural analysis. Samples were mounted in a thermosetting epoxy and prepared according to standard metallographic preparation methods. Samples were then electrolytically etched in a 10% oxalic acid solution and analyzed using light optical microscopy (LOM) and scanning electron microscopy (SEM) [16].

This study was taken as a reference because it is a double-sided friction stir welding (FSW) process. Although in this project, superaustenitic stainless steel and different welding tool is used, it is still a good reference for the current work. In this study, the microscopy work were done using Scanning and Transmission Electron Microscopy (SEM/TEM), as well as Energy Dispersive Spectroscopy (EDS) [16] compared to the author’s project which only limited to Optical Microscope (OM) only.

Based on the Klingesmith's study, below are a few important conclusion that are related to the author's project:

- The intense distortion and temperatures experienced by the nugget produce a very fine microstructure of equated grains [16].

- The HAZ and the TMAZ are transition zones between the base metal and the nugget. The HAZ microstructure is characterized by large grains alike to the base metal with recrystallization at grain boundaries. There are no actual signs of deformation in this region. The TMAZ is simply a microstructural transition from the HAZ to the nugget [16]. Approaching the weld centerline, the bigger grain deformation and recrystallization at grain boundaries are the effects of the increasing strains and higher temperatures produced during FSW.

- Throughout the different regions created during FSW, micro hardness traces reflect the microstructural changes in the regions. Generally, the base metal is softer than any weld-affected region. Hardness increases toward the centerline, through the HAZ and TMAZ, as a result of increasing microstructural refinement. The fine-grained structure of the nugget yields maximum hardness [16].

The information extracted from the study is very helpful because, in this project the author are expecting a quite similar results.

2.1.3 Comparison Study between Double and Single-Sided FSW

The double-sided friction stir welding (FSW) are expected to produce less wormhole defects or none at all. From microstructure study that are done by optical microscope (OM), a different result will be observed at the selected region: weld nugget, heat affected zone (HAZ), thermo mechanically affected zone (TMAZ) and base metal. It is expected that double side FSW will produce a better weld than single-sided FSW.

Mcpherson et. al. [17] have made a comparison study of double-sided and single-sided FSW. The only difference is that in the study, Aluminum alloys is not used as their sample instead they used micro-alloyed steel.

Based on the study done, it is concluded that:

- Double-sided FSW welded joint yield a higher strength and hardness compare to the of the single-sided FSW welded joint [17].

- An improvement in toughness which is are related to microstructural differences are observed after performing the second pass in the double-sided FSW process [17].

2.2 METALLOGRAPHY

Metallography is the branch of science dealing with the study of the constitution and structure of metals and alloys, its control through processing, and its influence on properties and behavior [1]. Its original implementation was limited by the resolution of the reflected light microscope used to study specimens. This limitation has been overcome by the development of transmission and scanning electron microscopes (TEM and SEM) [18]. The analysis of x-rays generated by the interaction of electron beams with atoms at or near the surface, with wavelength- or energy-dispersive spectrometers (WDS, EDS) with the SEM has added quantitative determination of local compositions of intermediate phases, to the deductions based upon observations. Metallography is also an introduction of metrological and stereological methods, and the development of computer-aided image analyzers, permits measurement of microstructural features [19].

2.3 OPTICAL MICROSCOPY

Optical Microscopy is an efficient and inexpensive means for characterizing the morphological features of material over a wide range of magnifications (0.5X-1500X) [20]. The optical investigation provides valuable microstructure information and in addition, can be used for selecting specific features regarding more detailed analysis. In many investigations, the optical evaluation is sufficient to resolve the specific problem under investigation, thus eliminating more costly methods of analysis. Bright Field, Dark Field, Polarized and Phase Contrast methods are used to depict specific features or optical properties of the material. [21]

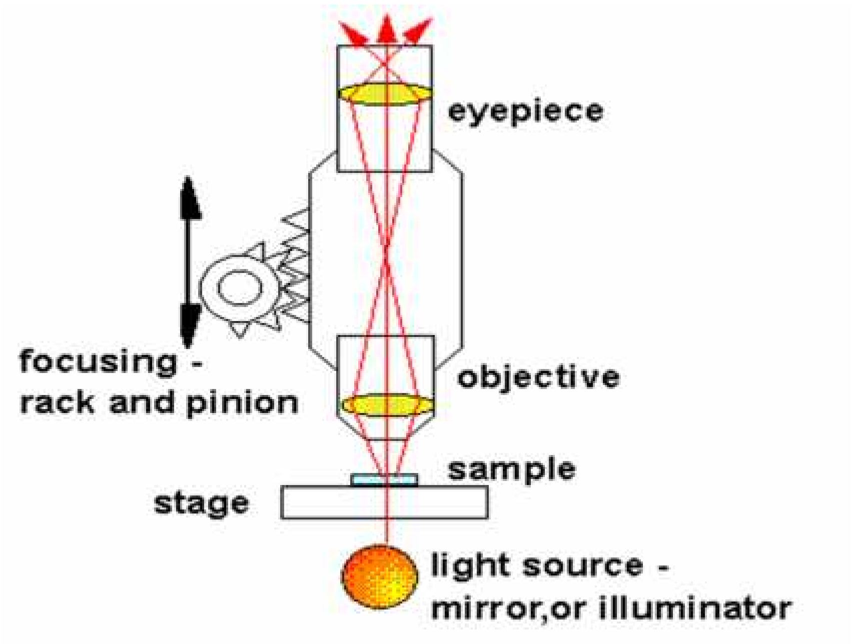

Figure 2.4: The illustration of Optical Microscope [21].

The objective lens forms a real intermediate image which is then greatly magnified by the eyepiece. The objective lens and eyepiece are maintained at a fixed distance and focusing is achieved by moving the whole assembly up and down in relation to the sample [20]. High magnification requires very bright illumination of the sample and a condenser lens is usually placed between the light source and the sample stage to focus light onto the sample.

CHAPTER 3

METHODOLOGY

3.1 PROJECT FLOW

Basically the project flow is summarized in the chart below. In the first semester of FYP, the author were doing more literature research on the topic and at the end of the first semester the author start to proceed with the experimental works. The project flow is as below:

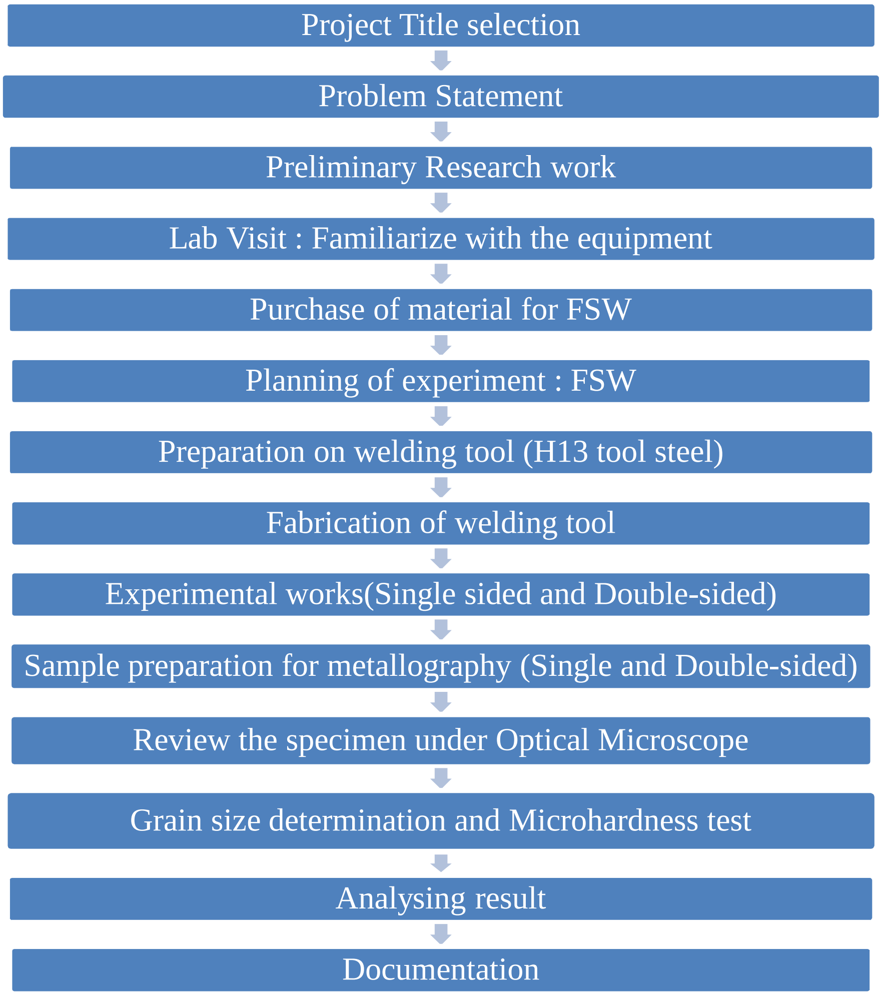

Figure 3.1: The project flow.

3.2 SAMPLE PREPARATION PROCEDURE FOR METALLOGRAPHY

Metallographic sample preparation is the crucial part of the process before doing other tasks on the samples. In order to get such a true surface, sample preparation must be done with accuracy and clear understanding of what must be accomplish in each stage. A proper preparation of the samples is the key to obtain an accurate interpretation of a microstructure as it will be representative of the material being examined. The preparation methods are as follows: [22].

3.2.1 Sectioning

Sectioning is the first step of sample preparation whereby the representative sample is removed from the parent pieces. In this case abrasive cutting offers the best solution to minimize the heat and deformation.

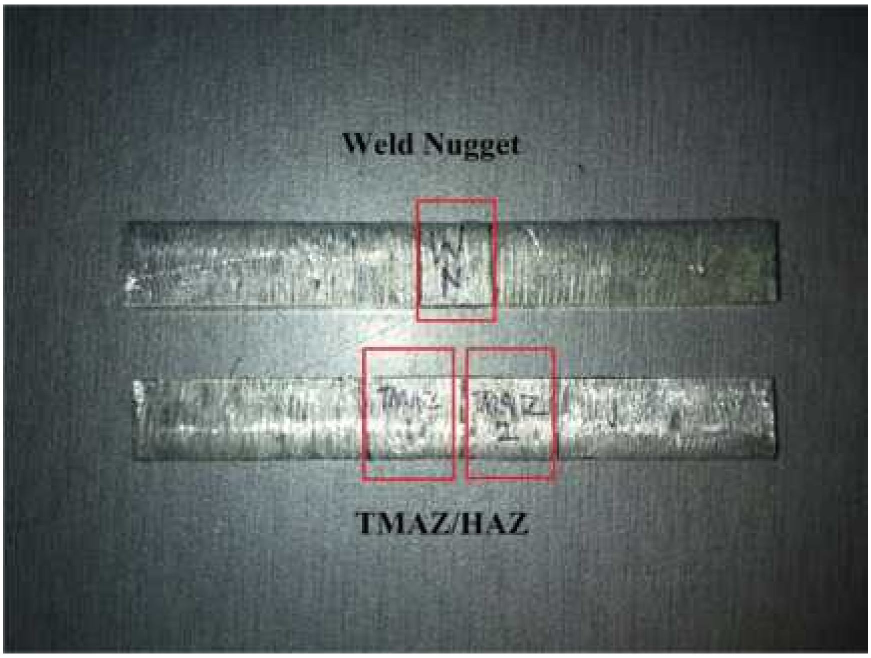

Figure 3.2: Sectioned area of interest.

3.2.2 Mounting

Mounting is a process of embedding the sample in plastic medium for ease in manipulation and to prevent fragility, edge preservation or edge retention. Hot compression mounting process had been used. It can preserve edge and minimize the shrinkage. Mounting medium that was used in this project is diallyl phthalate mineral blue in powder form. Thermosetting material had been used to mount the sample with the molding temperature and molding pressure of 300-360°F and 3800-4400 psi respectively.

The mounting medium is being put inside the automatic mounting machine as in the Figure 3.3 below. A heat time of 3 minutes, cool time of 5 minutes and pressure of 4000psi were used for both samples. The medium was being pre-heated first before starting the heating process. It will heat the mounting medium for 3 minutes, followed by cooling process. Releasing agent is one of the important elements that need to be applied to the upper part of mold before start mounting as it is used for mold release.

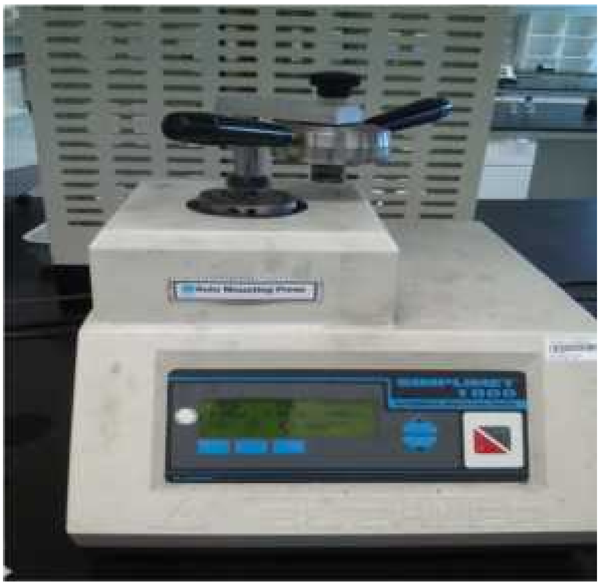

Figure 3.3: Automatic mounting machine.

3.2.3 Grinding

There are two types of grinding process, which are coarse grinding and fine grinding. Coarse grinding is a process to produce an initial flat surface. Fine grinding is a process to remove the zone of deformation caused by sectioning and coarse grinding and limit the depths of deformation during this stage by proper abrasive size sequencing. Figure 3.4 shows the Grinding/Polishing machine used in this project.

Figure 3.4: Grinding/Polishing machine.

Mechanical grinding was performed in successive steps using SiC abrasive papers of different grit sizes, usually 180, 220, 320, 600, 800, 1000, 1200, 2400 grit. The starting grit depends on the type of cut surface to be removed. A wet grinding (water) to flush away these particles and a small pressure on the specimen were recommended since the abrasive particles embedded easily into soft aluminum alloys. The sample was placed on the surface of the grinding paper, and the grinding process continued until the surface of the samples is shining. During the grinding process, the handling the samples is important, if not, the surface will not be flat, and this will affect the image in the optical microscope.

3.2.4 Polishing

After both grinding processes, polishing needed to be done. The recommended polishing procedure depended upon the hardness and ductility of the specimen. Polishing is used to remove the deformation zone produced by fine grinding. It is also used to produce a shining surface or scratch-free surface to ease the characterization process.

The polishing process is accomplished primarily with diamond abrasives ranging from 9 micron down to 0.25-micron diamond. Polycrystalline diamond because of its multiple and small cutting edges, produces high cut rates with minimal surface damage, therefore it is the recommended diamond abrasive for metallographic rough polishing on low napped polishing cloths.

The sample was polished using the semi-automated polishing machine as in the Figure 3.5. The polishing process was done for a longer time to get the best result.

Figure 3.5: Automated Polishing machine

3.2.5 Etching

Etching is defined as favored attack of a metal surface with an acid or basic chemical solution to reveal structural details. It is to obtain sufficient contrast between phases. It is clear for example that the grain structure cannot be easily revealed in every alloy. The etching reagent for the aluminum alloy sample is Keller's reagent.

Keller's reagent consists of 2ml HF (48%), 3ml HCl, 5ml HNO_3, and 190ml H_2O. Chemical etching selectively attacks specific microstructural features. It generally consists of a mixture of acids or bases with oxidizing or reducing agents. The proper protective garb such as glasses, gloves, and apron should be used when pouring, mixing, or etching. For weighing, mixing, containing, and storage of solutions, proper devices had been used. The measurement of each the chemical need to be precisely done, because it will affect the reading of the microstructure on the surface.

The sample was immersed in the composition for 10 to 20 seconds, and then rinsed in a stream of water. For some unexplained reason, in this project the author finds that the etching process could take up to 6 minutes for the microstructure to develop. The quality of the polishing influences the development of the true microstructure. A faulty preparation can lead to misinterpretation of the structure.

3.3 GANTT CHART

Below are the Gantt charts of this project for semester I and II. The important weeks that needed to be alerted are marked with yellow dot. On these particular weeks, there were due date for submission extended proposal, proposal defense, Interim report of draft, dissertation (softbound), technical paper and dissertation (hardbound). In week 11 of FYP II, there was pre-SEDEX. The last milestones would be VIVA with the examiners.

Table 1: Final year project I Gantt chart

No 1	Details	Week														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	FYP briefing															
2	Choosing FYP title															
3	Preliminary Research work															
4	Fabrication of Welding Tool															
5	Purchase of Material															
6	Familiarize with Lab equipment															
7	Submission of Extended Proposal															
8	Proposal defence															
9	Planning of Experiment															
10	Experimental Works (FSW)															
11	Sample Preparation for metallography (Sectioning)															
12	Sample Preparation for metallography (Grinding)															
13	Submission of Interim Report															

Suggested Milestones Progress

Table 2: Final year project II Gantt chart

No 1	Details	Week														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Polishing															
2	Optical Microscopy (OM)															
3	Grain size determination and Micro hardness test															
4	Analyse result															
5	Submission of Progress Report															
6	Poster preparation															
7	Pre-SEDEX															
8	Submission of Draft Report															
9	Dissertation (softbound)															
10	Submission of Technical Paper															
11	Oral Presentation															
12	Project Dissertation preparation															
13	Submission of Project Dissertation (hardbound)															

Suggested Milestones Progress

3.4 EQUIPMENT

There are a few number of equipment used in order to complete the sample preparation and microstructure study. These equipment are vital in the progression of the project. They are listed in the following sections.

3.4.1 Optical Microscope (OM)

The samples were viewed via optical microscope. There are several important features of the optical microscope as in the Figure 3.6 below are lenses, eyepieces (oculars), light source and camera. These parts are essential in acquiring the accurate images of the samples. It consists of two lens systems (combination of lenses) to magnify the image. Each lens has a different magnifying power. Light source or a beam is being used for focusing on the images.

Figure 3.6: Optical Microscope

The magnification employed in this analysis ranges from 50 times to 1500 times. The samples were etched before viewing the microstructure of the aluminum. The focusing of the lens was adjusted according to the image created in the computer. The picture is taken spot by spot, in order to make sure that the surface is fully viewed.

3.4.2. Automatic Mounting Machine

Automatic metallography specimen mounting press is a kind of full automatic mounting press, equipped with in-out water cooling system. It is suitable for the heat mounting (thermo hardening & thermoplastic) for all kinds of materials. After the parameters such as heating temperature, heat preserving time and applied force etc. are set up, put the specimen and mounting material into the machine, close the cover and press the start button, then the machine will finish the job automatically. It is not necessary for the operator to be on duty.

3.4.3 Grinding Machine

This is a wet style pre-grinding machine. It fits the specimens of various metal and alloys by using various granularity of metallic sand paper. It can replace manual operation and avoid the specimens from being over-heated during grinding and polishing stage.

3.4.4 Automatic Polishing machine

Metallography specimen polishing machine is suitable for the polishing of the specimen which has been previously grinded. The specimen surface is very smooth after processing and can be used to observe and measure the metallography structure of specimen under microscope.

CHAPTER 4

RESULT AND DISCUSSION

4.1 FRICTION STIR WELDING MICROGRAPH

The cross-section was hot-mounted, polished, and etched with the Keller's reagent for optical microscopy (OM) at room temperature. The sectioned FSW samples are labeled and then micrographs of the interested region are taken using OM.

The examination of many FSW of aluminum alloys has revealed that there are four major microstructural zones [9], as indicated in Figure 4.1. The formation of the regions is affected by the material flow behavior under the action of rotating non-consumable tool [10]. The microstructure of the weld is complex and highly dependent on the position within the welded zone [9].

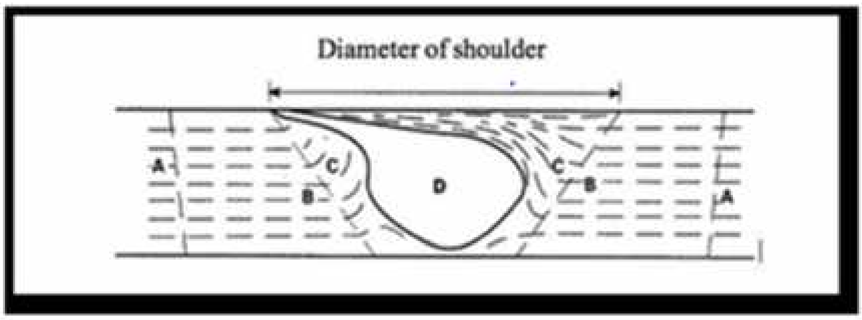

Figure 4.1: The cross section of FSW weld (**A**) - Base Metal (BM), (**B**) – Heat Affected Zone (HAZ), (**C**) - Thermo-Mechanically Affected Zone (TMAZ) and (**D**) - Weld Nugget

Figure 4.1 above shows the cross section of single-sided FSW weld. For the double-sided FSW, the cross section is slightly different. But the region of Weld Zone, TMAZ, HAZ and base metal for the cross section is not much of a different.

4.1.1 Double-Sided FSW Micrograph

There are total of 6 samples have been sectioned and mounted to investigate the microstructural behavior of the double side FSW. Micrographs of the region of interest for study which is weld nugget, TMAZ and HAZ are taken using OM. Figure 4.2 below are the micrograph taken by OM at 100X magnification. Two of the best micrographs are taken for each region.

Weld Nugget

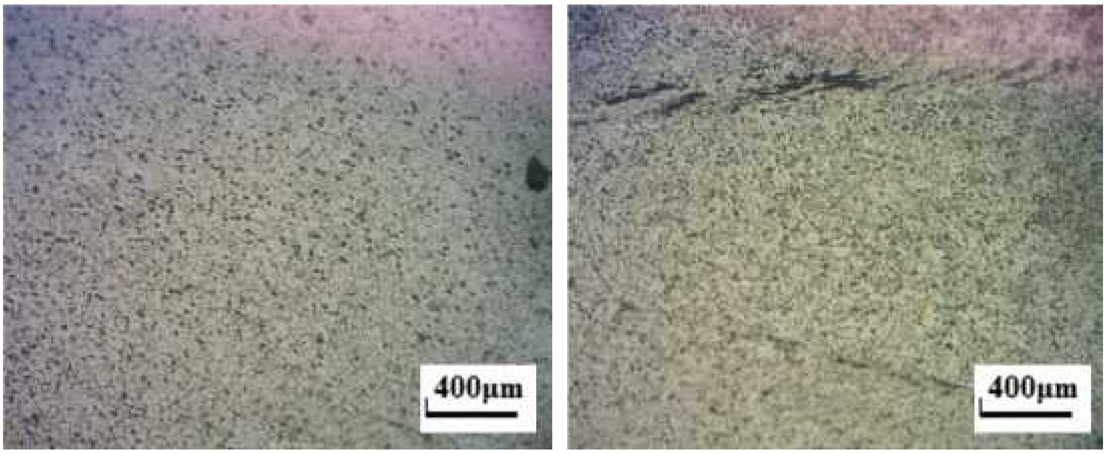

Figure 4.2: OM of Weld Nugget (Double-sided FSW)

TMAZ

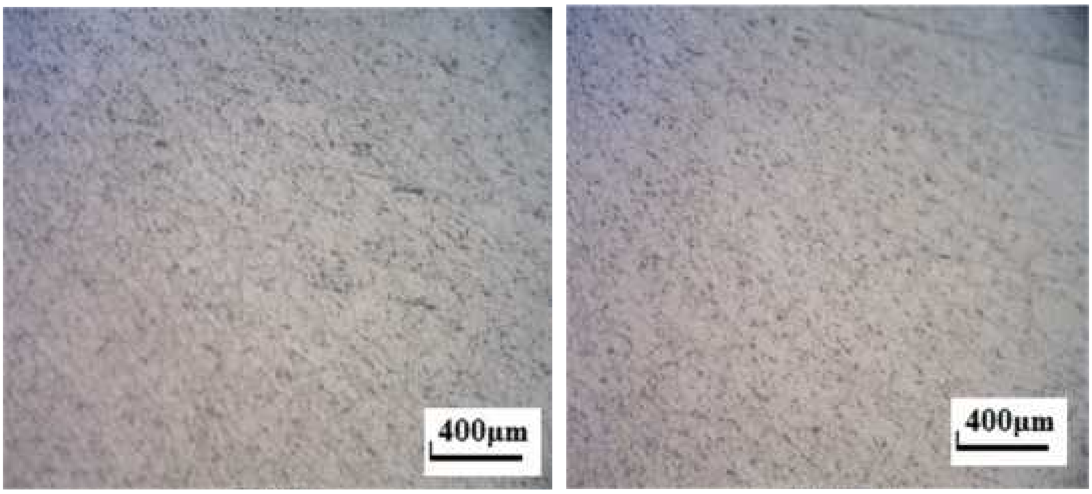

Figure 4.3: OM of TMAZ (Double-sided FSW)

HAZ

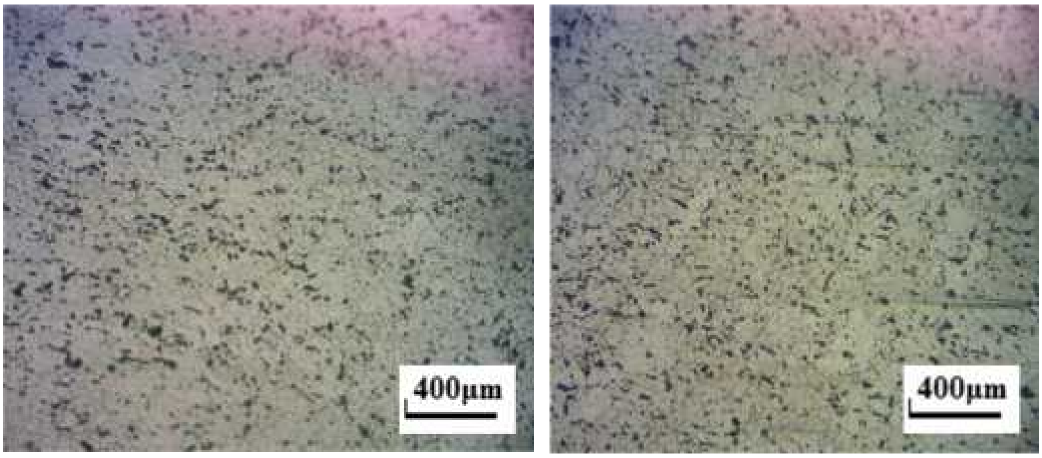

Figure 4.4: OM of HAZ (Double-sided FSW)

4.1.2 Single-Sided FSW Micrograph

For the single-sided FSW, there are also 6 samples that have been prepared for micrograph. For the each of the interested region: Weld Nugget, TMAZ, HAZ the best 2 micrograph are chosen.

Weld Nugget

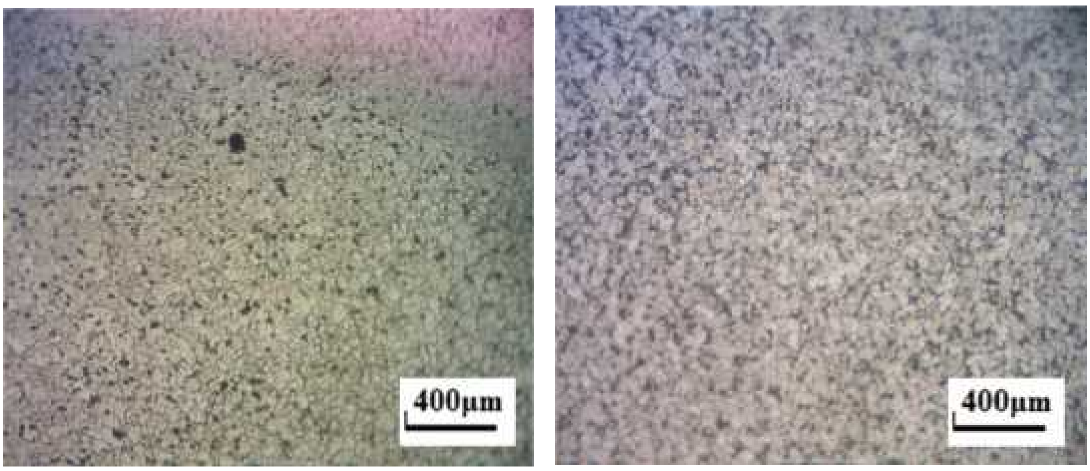

Figure 4.5: OM of Weld Nugget (Single-sided FSW)

TMAZ

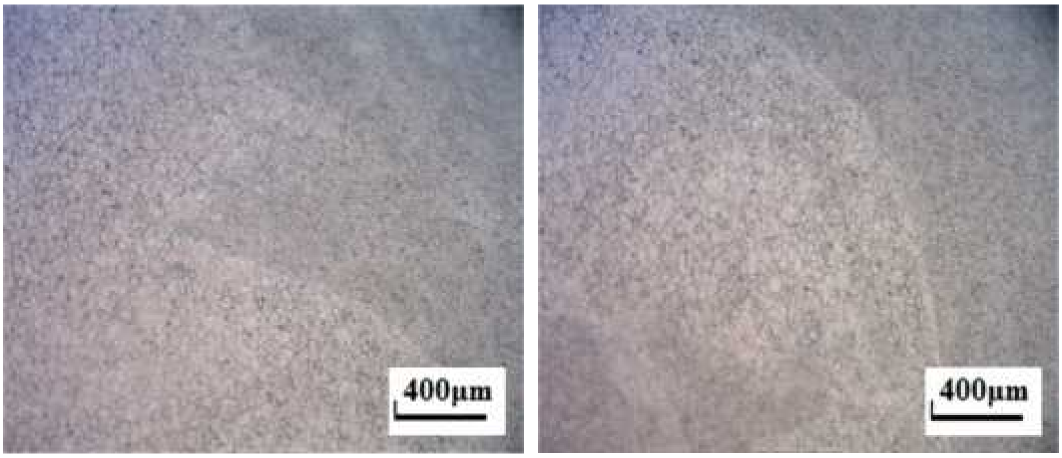

Figure 4.6: OM of TMAZ (Single-sided FSW)

HAZ

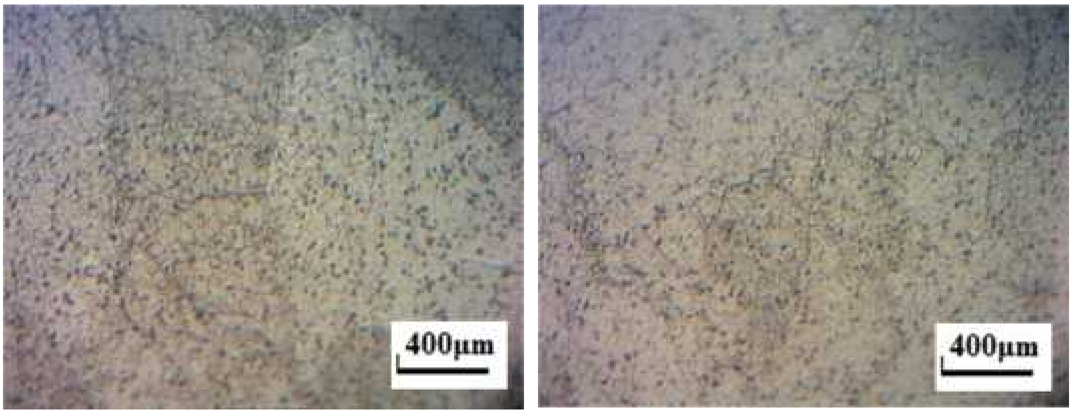

Figure 4.7: OM of HAZ (Single-sided FSW)

Based on the micrograph for both double-sided and single FSW, the microstructure behavior in the weld nugget region, TMAZ, HAZ are explained below:

In this weld nugget region, it is observed that the region have a really fine grain structure. The nugget is the region of the TMAZ undergoing dynamic recrystallization with grain size refined and homogenized. The TMAZ/nugget interface enhances the significant difference between the structure of initial grain and the equiaxial grains resultant of the dynamical recrystallization process with fine dispersion of the precipitates in the solid solution.

The HAZ is only affected by the heat energy and presents typically some slight coalescence of grain relatively to the original grain size but is subjected to internal point and linear defects rearrangements. Thus, for the heat treatable wrought aluminum alloys the HAZ may presents some reduction in the distribution of precipitates at grain boundaries

4.2 WORMHOLE SIZE COMPARISON

Both double-sided and single-sided FSW produced wormholes. But the size of the wormhole differs for both. In the single-sided FSW the wormhole size is on average 2.5 mm while in the double-sided FSW the size is around 2 mm. Thus double-sided FSW produce welds with approximately 20% smaller wormholes

.

Figure 4.8 : Comparison of wormhole size

4.3 MICROHARDNESS OF DOUBLE-SIDED AND SINGLE-SIDED FSW

A series of micro hardness tests were done on the samples. Three reading were taken at the specific regions; HAZ, TMAZ and Weld Nugget. Results are shown in Tables 3 and 4.

Table 3: Micro hardness of Double-sided FSW

	HAZ	TMAZ	Weld Nugget
1	53.8	59.7	65.0
2	54.0	59.3	67.1
3	51.5	59.8	62.0
Average	**53.1**	**59.6**	**64.7**

Table 4: Micro hardness of Single-sided FSW

	HAZ	TMAZ	Weld Nugget
1	54.2	55.4	61.2
2	51.0	58.1	60.2
3	53.5	59.6	59.5
Average	**52.9**	**57.7**	**60.3**

4.4 GRAIN SIZE DETERMINATION

Below are results obtained for the grain size of both double-sided and single-sided FSW. The method for the grain size determination is extracted from section 9 of ASTM E112. The full procedure is listed in the appendix.

Table 5: Grain size of Double-sided FSW.

Regions	Value of *n*
Base metal	7.11
HAZ	7.27
TMAZ	7.62
Weld Nugget	7.73

Table 6: Grain size of Single-sided FSW.

Regions	Value of *n*
Base metal	7.11
HAZ	7.21
TMAZ	7.55
Weld Nugget	7.69

The regions with bigger ASTM grain size number, *n* have:

- More grains per area
- Smaller grains

4.5 COMPARISON BETWEEN DOUBLE-SIDED AND SINGLE-SIDED FSW

Both of the double-sided and single-sided FSW compared in term of the microstructure behavior at the specific region: Weld Nugget, TMAZ and HAZ. For double-sided FSW, a finer grain is observed compared to the single-sided FSW. A finer grain size produces higher yield strength for a material. This was verified by the result of the micro hardness tests that have been done on the samples. Towards the weld center (weld nugget) the hardness value is increased. Double-sided FSW produce a slightly harder weld compared to the single-sided FSW.

Besides that, grain size is determination is also done on both the double and single-sided FSW. Based on the result obtained, double-sided FSW yield a higher value of *n*. Higher value of *n* means that the samples have more grains per area and the grains are smaller compared to those of lower value of *n*.

Apart from that, it is observed that the size of the wormhole formed in the double side FSW are comparatively smaller than of the single-sided FSW. Based on Figure 4.8, the size of the wormhole is 20% smaller in the double side FSW compared to the single-sided FSW.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

As a conclusion double-sided FSW produce a variation across the weld. All the microstructure behavior of the double-sided FSW are characterized and successfully compared to the single-sided FSW. Optical microscopy had been done on the sample. From the OM result, we can distinguish the microstructure into four different regions; base metal, TMAZ, HAZ and Weld Nugget. In terms of wormhole, double-sided FSW process was able to reduce the size of the wormhole. The wormholes formed in the double-sided FSW are comparatively smaller than of the single-sided FSW. From the grain structure of the regions, it is also concluded that double-sided FSW produce a better weld than single-sided FSW. In addition, micro hardness and grain size result also support the statement that double-sided FSW produce a better weld than single-sided FSW.

5.2 RECOMMENDATIONS

For further expansion and continuation of this project, the author suggested that the project can be improved by adding more microscopy device for a better and accurate microstructure review. For example in this project we can use other microscopy techniques (SEM, FESEM, EDS).

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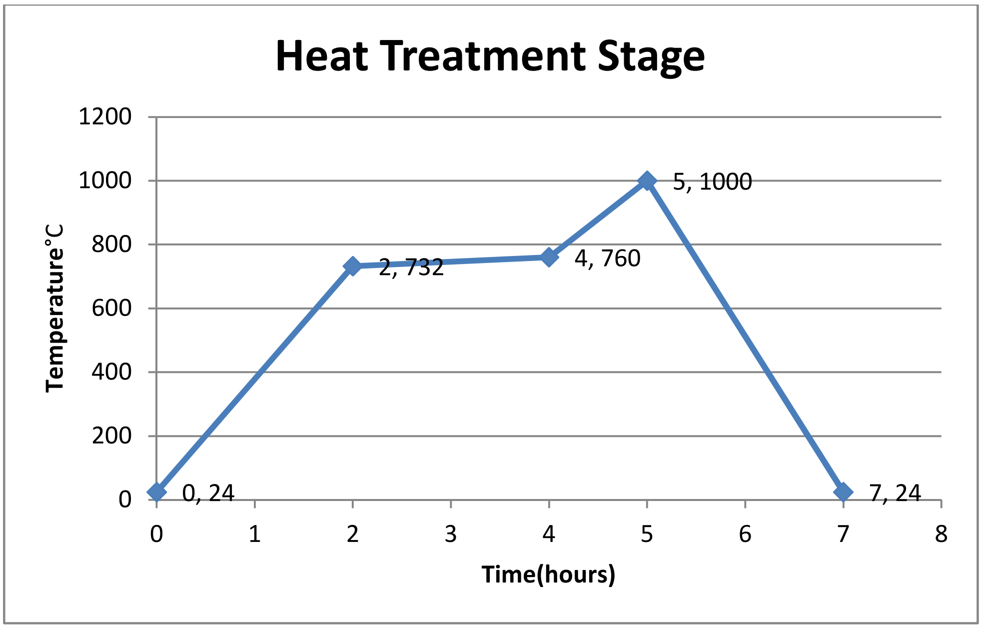
APPENDIX I

Parameter for FSW

Spindle Speed (rpm)	Plunge Speed	Move Feed Rate mm/s	Dwell (Sec)	Angle
1200	10	30	20	2.2

	Shoulder Diameter	Tip Length	Type
12mm	25mm	7mm	Taper
15.8mm	25mm	8mm	Taper

Heat Treatment stage for H13 tool steel for Friction Stir Welding (FSW)



Time	Temperature
0	24
2	732
4	760
5	1000
7	24

Stage 1: Preheated initially for 2 hours to increase temperature from 24°C to 732°C

Stage 2: Constantly preheated slowly from 732°C – 760 °C for another 2 hours

Stage 3: Temperature raise slowly to 1000 °C for 1 hour

Stage 4: After the temperature reach 1000 °C, Air quench was conducted to room temperature (24°C) for 2 hours

APPENDIX II

Procedure for grain size determination

PROCEDURE FOR GRAIN SIZE DETEMINATION

A specimen must be properly prepared to reveal the grain structures, which is photographed at a magnification of 100X. The method used for estimating the grain size number is grain counting method, whereby the number of grains per unit area is counted directly. The average number of grains per square inch at a magnification of 100X is related to grain size number according to the equation below:

$$N' = 0.155 \times 10(0.301)\ (n\text{-}1)$$

N' represents the average number of grains per square centimeter at magnification of 100X and n the grain size number. Based on the equation above, these two parameters are related to each other.

a. Inscribe a circle (or other shape) of known area, A, on an image of magnification, M ;
b. Count the number of grains (completely within the area A);
c. Count the number of grains (partially within the area A);
d. Divide the result in (c) by 2;
e. Add the result in (d) and (b);
f. Divide the result in (e) by area A;
g. Convert the result in (f) to grains/in^2 @ 100X ;
h. Use the definition of ASTM grain size number to determine n.