The Comparison between SMAW and FSW Performances on Microstructure, Hardness and Corrosion Susceptibility of Carbon Steel

by

Abdul Haris Bin Abdullah

16103

Dissertation submitted in partial fulfilment of

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Universiti Teknologi PETRONAS,

Bandar Seri Iskandar,

31750 Tronoh,

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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(Dr. Saeid Kakooei)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2016

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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ABDUL HARIS BIN ABDULLAH

ABSTRACT

Corrosion tends to occur at various rates in the base metal, heat affected zones (HAZ) and the weld or fusion metal. The corrosion rate of API X52 carbon steel by Shielded Metal Arc Welding (SMAW) and Friction Stir Welding (FSW) were investigated using Linear Polarization Resistance (LPR) test. The microstructure of the base metal, HAZ and weld metal for SMAW and FSW were studied using optical microscope. The hardness values for both SMAW and FSW on carbon steel were determined using Rockwell Hardness Test. The optical microscope test results indicated that for both SMAW and FSW, the grain size decreases starting from the base metal to the HAZ, followed by the weld metal. The hardness test results showed that the weld metal yields highest hardness values, while the base metal yields lowest hardness values. In conclusion, SMAW exhibited higher hardness values compared to FSW. The LPR test results showed that for both SMAW and FSW, the weld metal has the highest corrosion susceptibility as compared to the HAZ and base metal. In addition, FSW weldment was more susceptible to corrosion than SMAW.

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ABBREVIATIONS AND NOMENCLATURES

SMAW	: Shielded Meta Arc Welding
FSW	: Friction Stir Welding
HAZ	: Heat Affected Zone
CO_2	: Carbon Dioxide
NaCl	: Sodium Chloride

CHAPTER 1

INTRODUCTION

1.1 Background

In a containment design such as steel pipelines used in oil and gas industries, corrosion is an important consideration. Corrosion is known to be the major factor of failure in a marine offshore environment [4]. In oil and gas industries, pipeline failures are frequently caused by serious localized corrosion. The degradation of the pipelines can lead to toxic spillage or leaking of products, which will result in environmental disasters [5-7].

Since welded pipelines are widely used, severe corrosion has been detected mainly at and near the weld joints. In addition, corrosion tends to happen at various rates in the base metal, heat affected zones (HAZ) and the weld or fusion metal [4, 8, 9]. The process of permanently joining dissimilar or similar metals with or without the presence of heat and pressure is known as welding. There are many types of welding methods that are available nowadays. However, in this project, the welding methods that were chosen are the Shielded Metal Arc Welding (SMAW) and Friction Stir Welding (FSW).

Commonly, a weldment will consists of a transition from the base or parent metal to the heat affected zone (HAZ) and the weld metal. The different regions inside a weldment may have varying effects on the microstructure, mechanical properties and corrosion rates. According to a few researches, grain size has a major influence on mechanical properties of most metals. In material strengthening, grain refinement is an important factor [1-3].

The microstructure and surface composition of the different regions in a weldment can be affected by the cycle of heating and cooling of the welding process [1, 10]. In relation with weldments, it can experience various form of corrosion such as galvanic corrosion, stress corrosion cracking and carbon dioxide (CO_2) corrosion. Every position of a weldment exhibits slightly different corrosion susceptibility and microstructural features [10].

1.2 Problem Statement

In a containment design such as steel pipelines used in oil and gas industries, corrosion is an important consideration. Even though there are reliance on corrosion protection coatings and cathodic protection, corrosion is still known to be the major factor of failure in a marine offshore environment. This is probably due to the insufficient anti-corrosion measures [4].

In oil and gas industries, pipeline failures are frequently caused by serious localized corrosion. The failures are not usually caused by the consequences of uniform corrosion but from localized corrosion such as galvanic corrosion, pitting and preferential corrosion of the welds. The degradation of the pipelines can lead to toxic spillage or leaking of products, which will result in environmental disasters [5-7].

Since welded pipelines are widely used, severe corrosion has been detected mainly at and near the weld joints. In addition, corrosion tends to happen at various rates in the base metal, heat affected zones (HAZ) and the weld or fusion metal [1-3]. Due to this, there is still no clear research about the influence of welding on corrosion of X52 carbon steel by SMAW and FSW in CO_2 environment. This study is intended to compare the performance between SMAW and FSW for carbon steel in order to fill the gap in this field.

1.3 Objectives:

1. To compare between SMAW and FSW performances on the microstructure, hardness and corrosion susceptibility of X52 carbon steel.

1.4 Scope of Study

1. The electrochemical test will be conducted in CO_2 environment, at room temperature (27 ^{o}C), pH of 5.5 and 3 % NaCl solution
2. The material used is X52 low carbon steel with SMAW and FSW welding technique

CHAPTER 2

LITERATURE REVIEW

2.1 Welding

The process of permanently joining dissimilar or similar metals with or without the presence of heat and pressure is known as welding. Welding process is not similar to other manufacturing process in producing a single component as it is designed to join different metals to yield the desired configuration. In joining of metals, welding is an efficient and cost saving method. A high number of industry have benefited from the process of welding as it is known to increase productivity, service life and efficiency of plant and equipment [2, 11-14].

Nowadays, a lot of applications used in industries such as infrastructures, automotive, electrical and even medical equipment cannot be created without the process of welding. A wide variety of products and materials have used the application of welding, involving advanced technologies such as plasma arcs and lasers. In addition, welding holds a very promising future as methods are being designed to join dissimilar and non-metallic materials, while producing products of complex shapes and designs [2, 12, 15].

There are many types of welding methods that are available nowadays. However, in this project, the welding methods that were chosen are the Shielded Metal Arc Welding (SMAW) and Friction Stir Welding (FSW).

2.2 Shielded Metal Arc Welding (SMAW)

Shielded Metal Arc Welding (SMAW) is one of the most well-known fusion welding processes as it is known for its cost effectiveness and flexibility. SMAW have been used in many applications especially for construction of buildings, vehicles and power plants. In oil and gas industries, SMAW is commonly used to join pipelines and offshore structures. Due to the flexibility and versatility of SMAW method, it is very suitable to be used even in awkward circumstances [35, 36].

SMAW as can be seen in Figure 1 is generally called stick welding is a manual welding process that involves the use of flux-covered consumables electrodes. The SMAW process starts with the combustion and decomposition of the flux which will produce a protective gas for the electrode tip, weld puddle and welding area. The protective gas will prevent the reaction between air and the molten metal. This will reduce the formation of oxides and nitrides. Further protection is also provided by the formation of slag during welding [16]. The SMAW process can be seen in Figure 1. Figure 2 shows the basic setting of an SMAW process.

In SMAW, many kinds of electrodes are used and the electrodes are categorised by the depth of penetration, allowable welding position and tensile strength of the weld metal. Furthermore, in SMAW process, both direct current (DC) and alternating current (AC) can be used [16]. Figure 2shows the basic setting of a SMAW process.

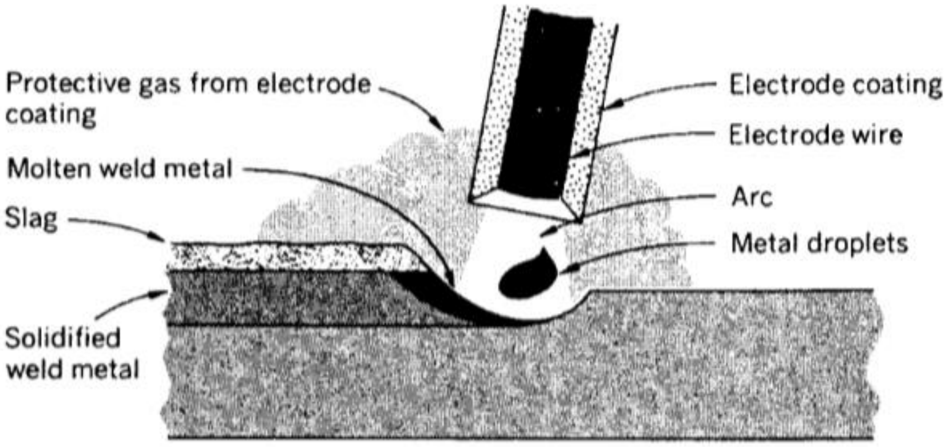


Figure 1: SMAW Process [16].

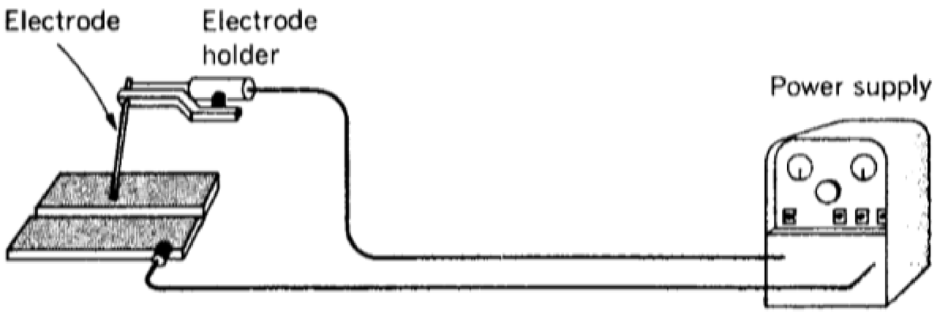


Figure 2: Basic Setting of SMAW Process [16].

2.3 Friction Stir Welding (FSW)

Friction Stir Welding (FSW) is a rather new joining process that is known to produce no fumes and environmentally friendly. Unlike SMAW, FSW uses no filler metal. In addition, FSW can be used to join various metal alloys such as copper, aluminium, steels, titanium and zinc [1, 13, 17-21].

In FSW, it is also known as a solid-state joining process, where melting of metals does not occur during FSW process. FSW uses a shouldered cylindrical tool with a profiled probe that is rotated and plunged into the welding joint of the metal work pieces. The work pieces are clamped on the FSW working area in order to prevent the joint faces of the work pieces from being moved out of position [1, 13, 17-21]. Figure 3 shows the FSW process.

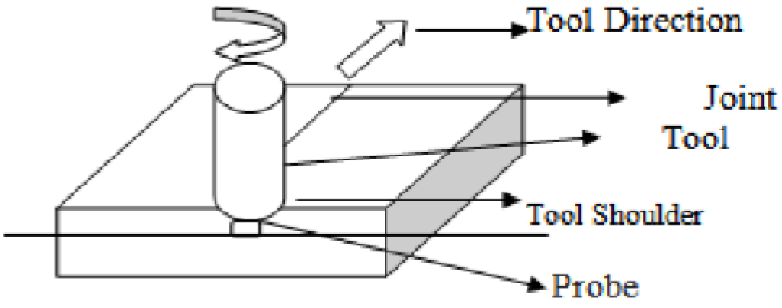


Figure 3: FSW Process [22].

In addition, the rotation of the tool will produce frictional heat between the work piece and the tool. The frictional heat will soften the metal at the joint while the rotational force and mechanical pressure by the tool will fuses and intermixes the soften metal. The two work pieces will be left in a solid-phase bond. In FSW, a high quality weld is produced as melting does not occur and the fusion of the metal occurs below the melting temperature of the work piece. Due to this, the negative effect of the high exposure to heat, solidification defects and distortion can be reduced [1, 13, 17-21]. Figure 4 shows the different stages of FSW process.

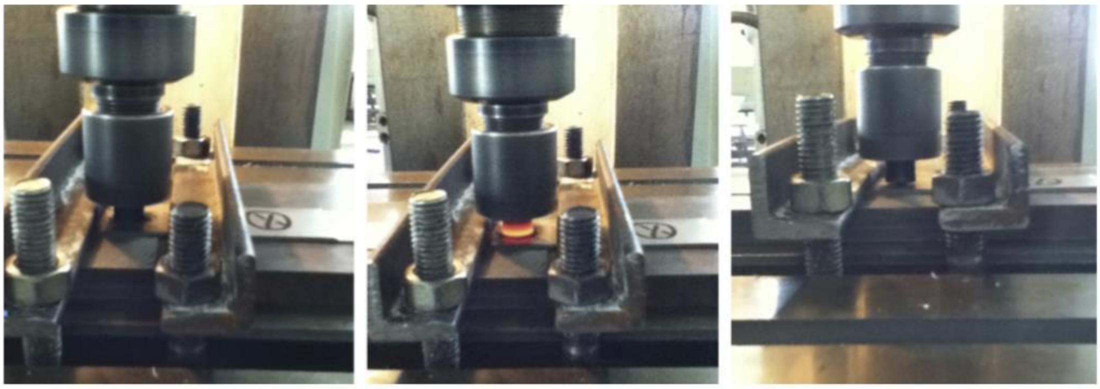


Figure 4:Different Stages of FSW Process [22].

. Nowadays, FSW is known to receive world-wide attention as it can produce high quality weld materials in manufacturing industries such as aeroplanes, trains and ships. Moreover, FSW is also used in many other research and production applications such as coolers, railways, heat exchanger and coolers [1, 13, 17-21].

. FSW has a lot of advantages such as the work piece has good mechanical properties and good weld appearance, thus reducing the need for costly machining after welding. In addition, FSW process will create a safer working environment for personnel due to the absence of toxic fumes. Unlike other conventional welding process, FSW uses no filler metals and has a lower environmental impact [20, 21].

Even though FSW has its advantages, it also has a few disadvantages such as the need to have a heavy duty clamping to hold the work piece together. In addition, unlike conventional welding such as SMAW, FSW is known to be less flexible. Other than that, FSW is to be more time consuming compared to some welding method [21].

2.4 Basic Regions of a Welding Work Piece

Commonly, a weldment will consists of a transition from the base or parent metal to the heat affected zone (HAZ) and the weld metal. Figure 5 shows the basic regions of a SMAW weldment, while Figure 6 shows the basic regions of a FSW weldment.

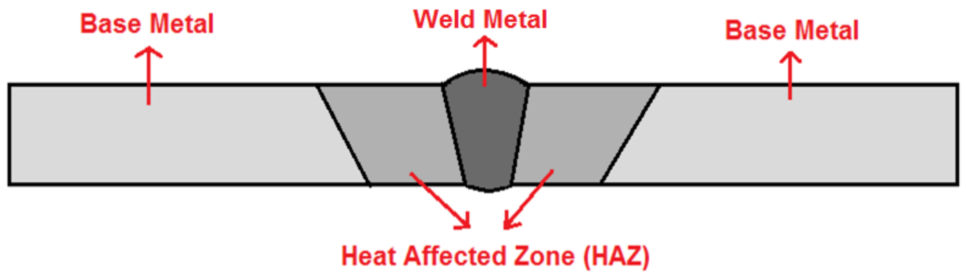


Figure 5: Basic Regions of a SMAW Weldment [10].

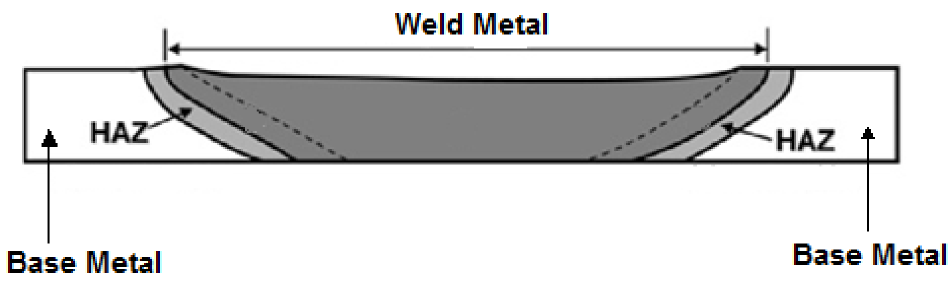


Figure 6: Basic Regions of a FSW Weldment [6].

As can be seen in Figure 6, the base metal or also known as the parent metal is the part of the work piece that is not affected by any metallurgical change due to the welding process. Even though there is no metallurgical change in the base metal, the base metal and the whole work piece would still likely experienced a state of high residual stress [10].

Other than the base metal, the heat affected zone (HAZ) also exists in a welding workpiece. The portion of the weld joint which have been exposed to high temperatures that are high enough to cause metallurgical change but not too high that can cause melting of the metals is known as the HAZ. The HAZ experiences complex thermal experiences in terms of peak temperatures and cooling rate during the welding process. Therefore, every position exhibits slightly different corrosion susceptibility and microstructural features [10].

Besides that, as can be seen in Figure 5 and Figure 6 , the weld metal is the result of the joining of the metals. The weld metal or also known as the fusion zone usually has a composition that is different from the base metal. The composition of the weld metal would usually be different than the base metal if the welding process involves the usage of filler metals in the joining of the work piece. The compositional difference in the weld metal can lead to the increase in corrosion rate [10].

2.5 Effect of Welding on Microstructure

During welding, the work pieces is heated up to the fusion of the joints and then followed by cooling to room temperature. Due to the different exposure of heat, the area of the work piece that is further away from the weld joint will experience the least amount of heat. However, higher temperatures are exposed to the work piece as the weld area or joint area is approached, resulting in a complex microstructure. In addition, the process of heating and cooling could also result in the presence of residual stress in the weldment. Due to welding, the chemical, physical and metallurgical properties are likely to change [1, 14].

The microstructure and surface composition of the welds, heat affected zone (HAZ) and base metal are affected by the cycle of heating and cooling during the welding process [10, 11]. Some researchers have claimed that in a weldment, the weld metal contains very fine grains due to the dynamic recrystallization that happened during the welding process. The grains at the weld metal are the smallest compared to other areas of the work piece. Moreover, the microstructure at the base metal is expected to be largest in the work piece [11, 23]. Figure 7, Figure 8 and Figure 9 displays the microstructure at the base metal, HAZ and weld metal.

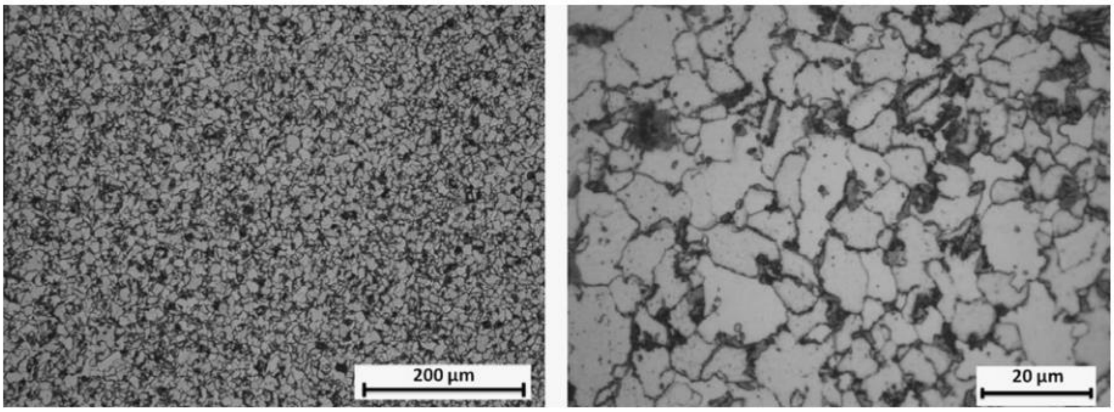


Figure 7: Microstructure at the Base Metal [4].

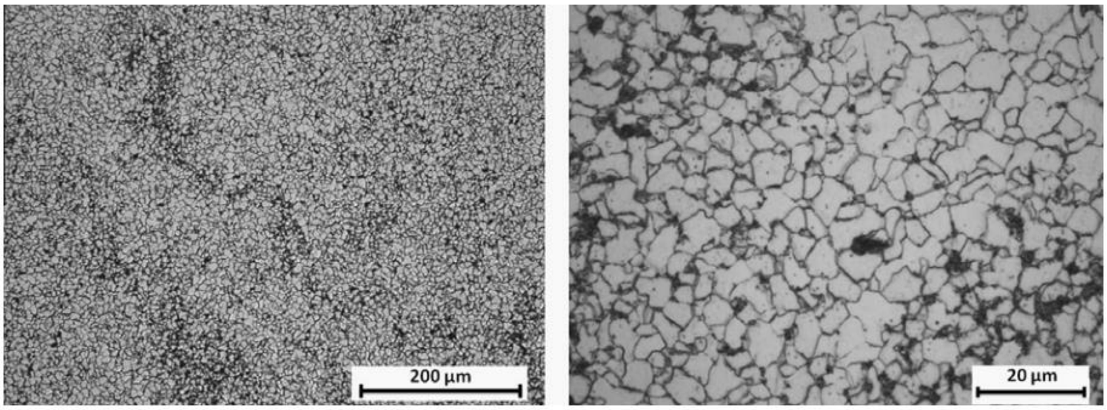


Figure 8: Microstructure at the HAZ [4].

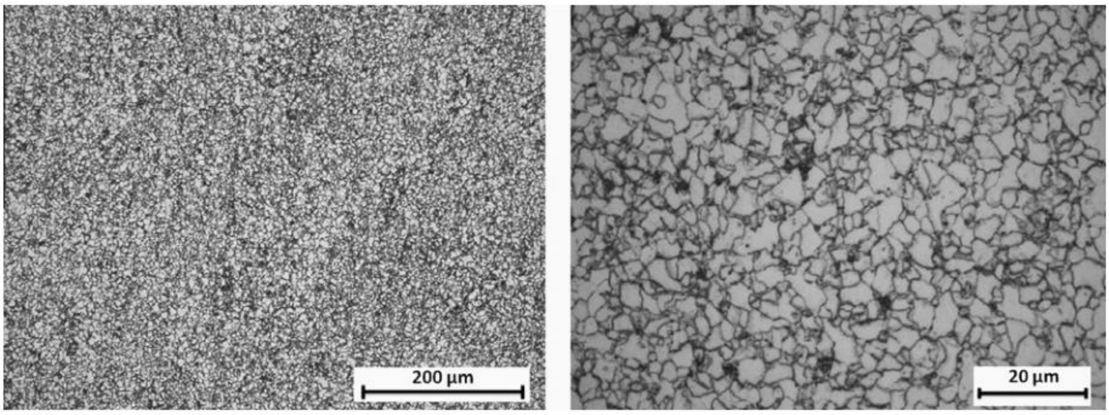


Figure 9: Microstructure at the Weld Metal [4].

2.6 Effect of Welding on Mechanical Properties

According to a few researches, grain size has a major influence on mechanical properties of most metals. Typically, irrespective of the welding condition, the base metal is expected to have a lower hardness compared to the weld metal [2, 11]. One of the researches that studied about FSW on AISI1018 have claimed that the hardness of the stir zone or weld metal were higher than the hardness of the base metal [24]. The presence of very fine grains in the stir zone could lead to the increase in hardness [2, 11].

During welding process, the formation of finer grains due to optimum level of heat generation would result in the increase of the mechanical properties of the joints in terms of hardness. In material strengthening, grain refinement is an important factor. This is the main reason for the increase hardness of the weld metal as compared to the base metal. In addition, it is also claimed that the improvement in hardness are also due to the formation of small particles of intermetallic compounds [13].

However, even though welding of metals could lead to structural changes during solidification, welding could also lead to the formation of defects in various welding conditions. It is stated that the hardness of the weldment could be caused by carburization during the welding process. Even though the weld metal has an increase in hardness values, it is claimed that the weld metal will be prone to brittleness as compared to the base metal [15].

2.7 Effect of Welding on Corrosion

In relation with weldments, it can experience various form of corrosion and this is mostly due to the variations in microstructure and composition of the work piece. The common types of corrosion that must be considered when designing a welded structure such as steel pipelines are galvanic corrosion, stress corrosion cracking, preferential corrosion, microbiological influenced corrosion and inter-granular corrosion [10].

In welding, filler metals are usually used although some alloys can be welded autogenously. The different composition from the base metal due to the use of filler metals may produce and electrochemical potential difference. This could lead to reactivity of some regions of the weldment to be more active towards galvanic corrosion [10].

In addition, under specific environmental conditions, weldments can be susceptible to stress corrosion cracking (SCC). SCC involves the combination of tensile stress, corrosive media and susceptible microstructure. The weld metals are frequently loaded in tension due to residual stress during welding. The various microstructural features of the weld metal thus becomes an excellent candidate for SCC [10].

In carbon and low steel alloy used for pipelines and process piping systems in CO2- containing products, preferential welding corrosion (PWC) is usually observed. The increase in hardness and the grain refinement by the welding process could lead to the increase in preferenetial weld corrosion [25].

There are many possible reasons for the corrosion of weldments such as the weldment design, welding practices, welding sequences and fabrication methods. In addition, contamination by moisture, formation of oxides film and formation of weld slag could also play roles in the corrosion of weldments. Furthermore, incomplete fusion or weld penetration , improper filler metal and cracks due to the welding process may also lead to corrosion [10].

Other than that, the microstructure is one of the factors that can affect corrosion behaviour. In most welding methods, the HAZ and the base metal should possess the same composition. However, the difference in microstructure can lead to the acceleration of corrosion. It has been claimed that the preferential weld corrosion of carbon steels can be affected by the increase in grain size and hardness [26]. The microstructure and surface composition of the welds and base metal can be affected by the cycle of heating and cooling of the welding process [10, 11].

2.8 Carbon Dioxide (CO_2) Corrosion

In carbon steel pipelines, carbon dioxide (CO_2) corrosion is one of the common type of corrosion that is likely to occur. There are many researches that have studied on CO_2 corrosion mechanisms. Since 1940, CO_2 corrosion has been one of the most serious problems in the oil and gas industries due to a high corrosion rate and localized corrosion. CO_2 corrosion can cause delays in gathering, production and processing facilities [27].

CO_2 corrosion begins with the formation of carbonic acid through hydration of water when CO_2 gas dissolves in water [28]. This can be seen in the following equations:

$$\mathrm{CO_2} + \mathrm{H_2O} \rightarrow \mathrm{H_2CO_3} \qquad (1)$$

On the cathodic site, there are two possible reactions as can be seen in Eguation (2) and Equation (3) . Equation (2) shows the hydrogen evolution reaction. In equation (3), the carbonic acid (H_2CO_3) will then dissociates and forms bicarbonate ion. The bicarbonate ion will then dissociate further to yield the carbonate ion [28]. These can be seen in the following equations:

$$2H^+ + 2e^- \rightarrow H_2 \qquad (2)$$

$$2H_2CO_3 \rightarrow H_2{}^+ + 2HCO_3 \qquad (3)$$

Other than that, on the anodic site, the dissolution of iron occurs to provide electrons for the cathodic site process [28]. The dissolution of iron can be seen in Equation (4).

$$Fe \rightarrow Fe^{2+} + 2e^- \qquad (4)$$

The anodic process in Eq. 4 could produce $FeCO_3$ or Fe_3O_4 film which can either be protective or non-protective. The formation of the films depends on certain conditions [28].

CHAPTER 3

METHODOLOGY

3.1 Base Metal: API X52 Carbon Steel

In this project, the base metal or also known as the parent metal that was chosen is API X52 carbon steel. This steel was chosen in order to simulate a carbon steel pipeline in an oil and gas industry. The chemical composition of the API X52 carbon steel samples can be seen in Table 1.

Table 1: Chemical composition of API X52 steel samples [29].

Element	C	Si	Mn	P	S	Al	Cu	Nb	Ni
Composition (wt%)	0.09	0.186	0.867	0.006	0.003	0.016	0.01	0.023	0.016

3.2 Welding Parameters

There are many types of welding methods that are available nowadays. However, in this project, the welding methods that were chosen are the Shielded Metal Arc Welding (SMAW) and Friction Stir Welding (FSW). Both welding of SMAW and FSW were conducted by trained technicians of Universiti Teknologi PETRONAS (UTP). Each welding technique has been set with suitable welding parameters based on studies on some research papers regarding SMAW and FSW.

3.2.1 Shielded Metal Arc Welding (SMAW) Parameters

Table 2 shows the SMAW parameters that has been chosen, while Table 3 displays the chemical composition of deposited.

Table 2: SMAW Parameters.

Parameters	Details
Location	Block 21, UTP
Filler Metal / Electrode	E6013
Base Metal	X52 Carbon Steel
Current	110-120A
Voltage	22-24V
Welding Speed	120-150 mm/min
Type of Joint	Butt Joint

Table 3: Chemical Composition of Deposited Metal (AWS A5.1 Class E6013).

Element	C	Cr	Mn	Mo	Ni	P	Si	S	V
Composition (%)	0.08	0.04	0.39	0.01	0.04	0.012	0.25	0.016	0.01

3.2.2 Friction Stir Welding (FSW) Parameters

Table 4 displays the parameters that have been chosen for the FSW process. The FSW machine can be seen in Figure 11. Figure 12 and Figure 13 shows the close-up view of the FSW process.

Table 4: FSW parameters.

Parameters	Details
Location	Block 16, UTP
Filler metals / Electrode	None
Shoulder Diameter	20 mm
Probe Material	Q235 (carbon steel)
Probe Diameter	5mm
Probe Length	5mm (tapered)
Rotational Speed	80 mm/min
Plunge Rate	5 mm/min
Shielding Gas	Argon
Gas Flow	5 bar

Figure 10: FSW machine located at Block 16, UTP.

Figure 11: Close-up view of the FSW process.

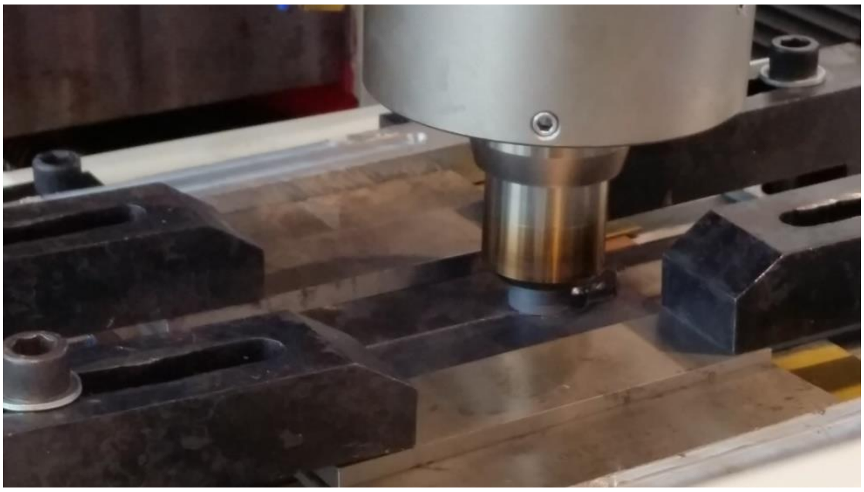


Figure 12: Close-up view of the FSW process.

3.3 Sample Preparation

3.3.1 Cutting of Samples Before Welding

1. The original base metal plate that were received were 15cm x 15cm (width x height). The carbon steel plate as in Figure 13 were cut into two pieces with dimensions of 7.5 cm x 15cm (width x height).

Figure 13: API X52 Carbon steel plates.

2. The two pieces of 7.5 cm x 15 cm plates were then joint back together again by the chosen welding method of SMAW.
3. These processes were repeated for the other chosen welding method which was FSW.

3.3.2 Cutting of Samples after Welding

1. After welding, the work piece were cut into strips with use of linear hack-saw machine as can be seen in Figure 1. The linear-hack saw machine can be located at Block 21, UTP. Figure 15 shows the basic view of the line cut of the work piece.

Figure 14: Linear Hack-Saw Machine.

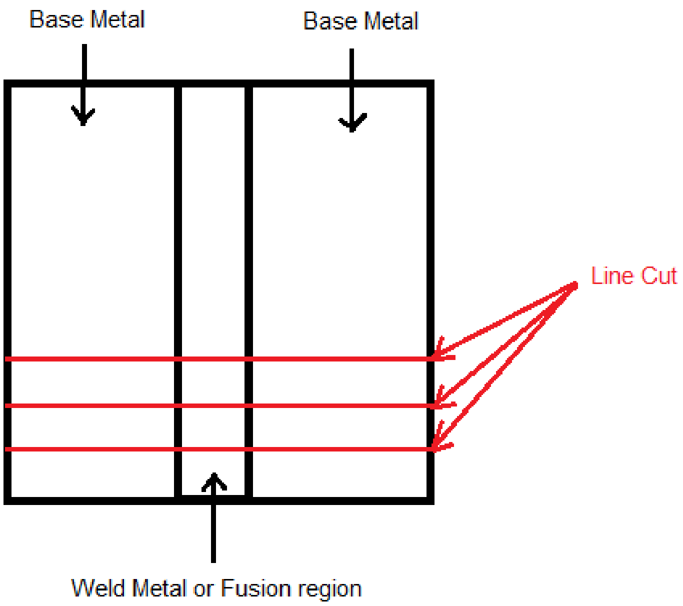


Figure 15: Basic view of the line cut of the work piece.

2. The strips of the work piece were then cut into smaller samples depending on the position of the base metal, heat affected zone (HAZ) and weld metal. This process was conducted using abrasive cutter and hand saw. Each welding method requires 6 samples. Figure 16 shows the abrasive cutter machine located at Block 17, UTP.

Figure 16: Abrasive Cutter.

3.3.3 Mounting of Samples

1. After the samples have been received, mounting of the samples were conducted. Mounting of the samples were required before conducting any tests. The mounting method that has been chosen was cold mounting.
2. First, the epoxy resin was mixed slowly with the hardener. The ratio of epoxy resin to hardener was 5:1.
3. The plastic moulds that were used for the mounting of the samples are then applied with releasing agent.
4. The samples were then placed in the plastic mould.
5. After the epoxy mixture has been properly mixed, the epoxy were poured inside each plastic mould containing the samples. This can be seen in Figure 17.

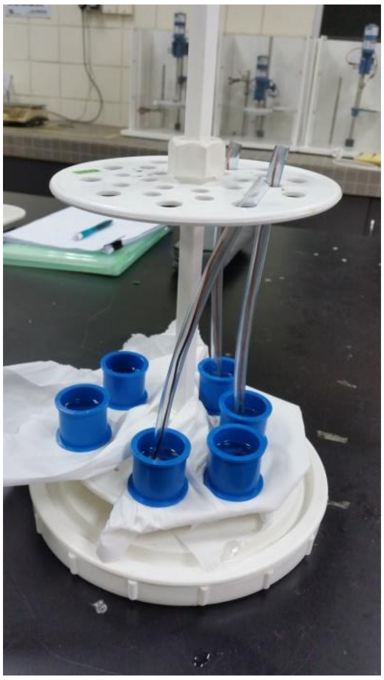


Figure 17: Basic set-up of cold mounting.

6. For both SMAW and FSW, the total number of samples to be mounted was 12. The samples after cold mounting can be seen in Figure 18 and Figure 19.

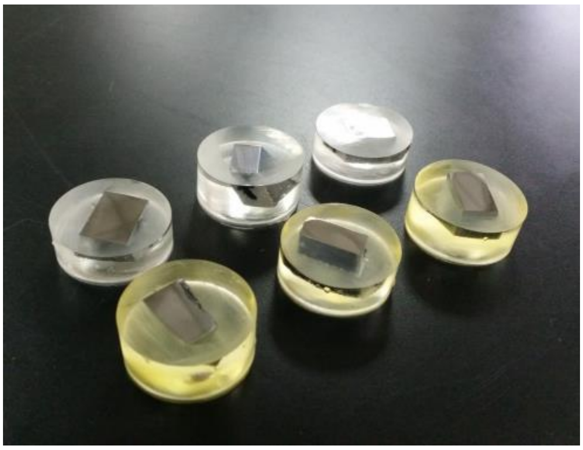


Figure 18: Cold mounted samples.

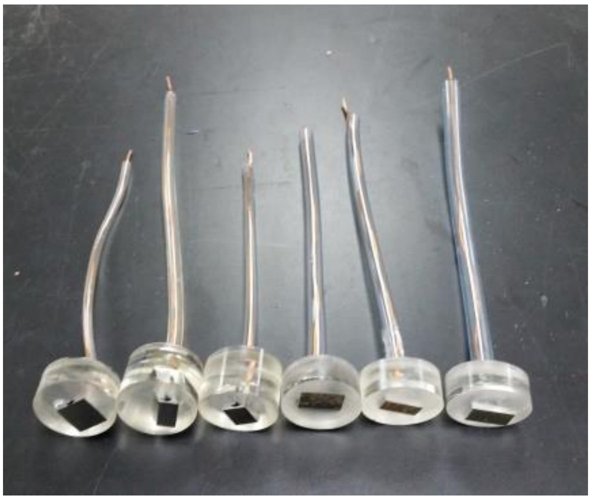


Figure 19: Cold mounted samples.

3.3.4 Grinding of Samples

1. After mounting of the samples, the mounted samples were grinded in order to expose the surface of the samples.
2. The grinding of the samples were conducted using grinding machine as can be seen in Figure 20.
3. The grinding process requires grit paper with grit size of 60, 120, 240, 320, 600, 800 and 1200.

Figure 20: Grinding Machine.

3.4 Rockwell Hardness Test

1. Rockwell hardness test have been selected to determine the hardness of a material to deformation. The standard for the Rockwell Hardness Test is ASTM E18.
2. The number of measurements taken was five times for each specimen and its average value will be taken. The results were discussed and evaluated.
3. The Rockwell Hardness Test will be conducted at Block 17, UTP. Figure 21 shows the Rockwell Hardness Test machine.

Figure 21: Rockwell Hardness Test.

3.5 Microstructure Examination: Optical Microscope

1. Analyses of the microstructures of welded samples were done using an optical microscopy as can be seen in Figure 22. The structural changes in parent zone, weld metal zone and HAZ region were analysed.

Figure 22: Optical Microscope.

2. Firstly, the mounted samples were polished to obtain a mirror-like surface finish.
3. Then, the polished samples were washed and sprayed with ethanol. The samples were then dried using a heater.
4. After that, the samples were etched with Nital solution for 15 seconds. After etching, the samples were washed and sprayed with ethanol. The samples were then dried using a heater.
5. Finally, the samples were observed under the optical microscope.

3.6 Corrosion Test: Linear Polarization Resistance (LPR) Test

The corrosion test that has been selected to study the corrosion rate of the samples was Linear Polarization Resistance (LPR) test. This test is based on the ASTM G 59. Figure 23 shows the schematic diagram of an LPR test. Table 5 shows the parameters for the LPR test.

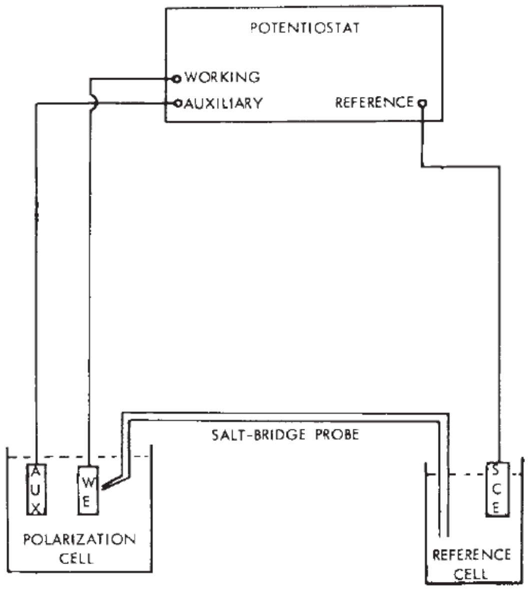


Figure 23: Schematic diagram of LPR (ASTM G59).

Table 5: LPR tests parameters.

Parameter	Details
Standard	ASTM G 59
Reference Electrode	Silver/Silver Chloride Electrode (Ag/AgCl)
Auxiliary Electrode	Stainless Steel Electrode
Working Electrode	Samples
Chemical Solution	3.0 % NaCl Solution
pH value	5.5
Temperature	Room Temperature
Pressure	1 bar
Presence of CO2	Yes
Volume of Solution	2 litres
Duration of Tests	24 hours

1. The 3.0 % NaCl solution was first prepared by using 2 litres of distilled water and NaCl powder. The solution was stirred using a magnetic stirrer as can be seen in Figure 24.

Figure 24: Stirring of NaCl solution.

2. After the solution has been prepared, the solution was purged with CO_2 gas for 30 minutes.
3. After purging with CO_2 gas, the pH of the solution was measured. Addition of NaOH was required to adjust the pH value.
4. Next, the electrodes were set up as can be seen in Figure 25.

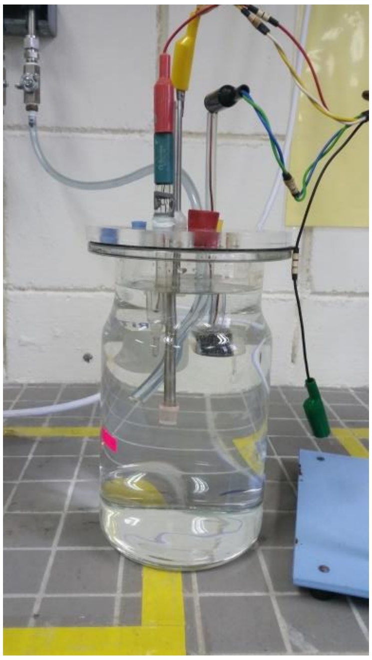


Figure 25: Set-Up of Glass Cell.

5. The electrodes were then connected to the potensiostat as can be seen in Figure 26. All the necessary settings were set before running the tests.

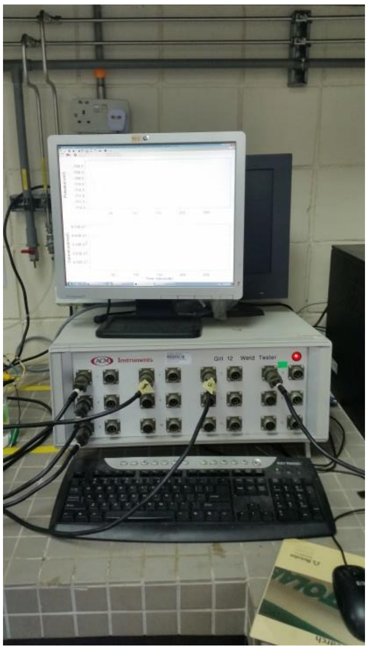
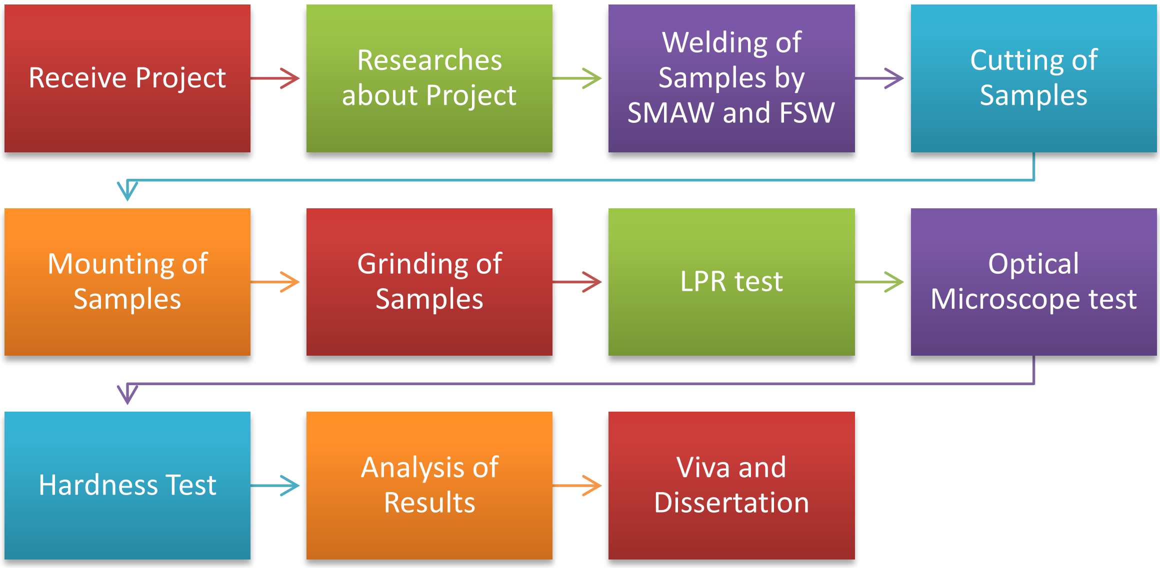


Figure 26: Potensiostat.

6. Finally, each test was conducted for 24 hours. The results obtained were recorded.

3.7 Project Key Milestone

The chart below shows the key milestones of this project.



3.8 Project Timeline (Gantt Chart)

The Gantt Chart below shows the timeline of this project. This project had been received in week 9 due to some complications with the previous project. This project was conducted and completed in only one month.

FYP 2														
Details/Work	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14
Receive project														
Reseaches about project														
Pre-Sedex presentation														
Welding of samples by SMAW														
Cutting of SMAW samples														
Mounting and grinding of SMAW samples														
LPR test for SMAW samples														
Welding of samples by FSW														
Cutting of FSW samples														
Mounting and Grinding of FSW samples														
LPR test for FSW samples														
Optical Microscope tests														
Rockwell hardness test														
Analysis of results														
Viva and Dissertation														

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Microstructure Examination: Optical Microscope

As can be seen in Figure 27-28, the grain structure of the base metal region by both SMAW and FSW can be seen to be very similar. For both SMAW and FSW, the base metal or also known as the parent metal does not experience heat that is high enough cause metallurgical change during the welding process [10]. The microstructure at the base metal is expected to be largest in the work piece [11, 23].

Figure 27: SMAW Base Metal Microstructure at 50x Magnification.

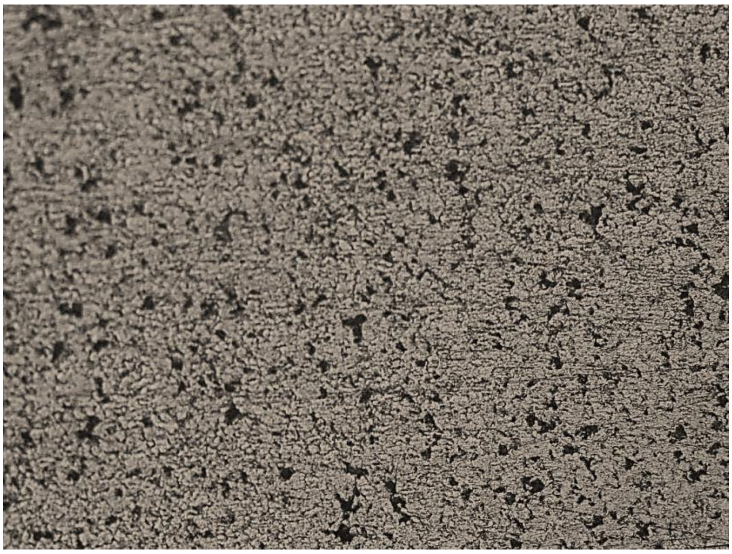


Figure 28: FSW Base Metal Microstructure at 50x Magnification.

Other than that, based on Figure 29-30, it can be seen that the grain structure at the HAZ region for both SMAW and FSW are finer compared to the base metal region. This is probably due to the exposure of the HAZ portion to temperatures high enough to cause metallurgical change but not too high that can cause melting of the metals [10]. Since SMAW method requires higher temperature than FSW, it may have resulted in the finer grain size formation compared to FSW. This grains size is expected to be smaller in the HAZ than in the weld metal [11, 23].

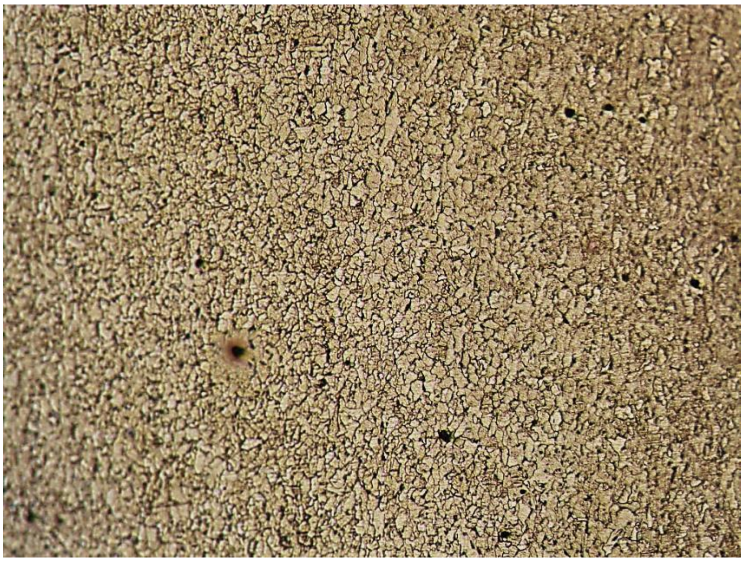


Figure 29: SMAW HAZ Microstructure at 50x Magnification.

Figure 30: FSW HAZ Microstructure at 50x Magnification.

Furthermore, Figure 31-32 display the microstructure of the weld metal region by both SMAW and FSW method. It can be seen that the SMAW method yields a smaller grain size compared to FSW. The irregularity in the SMAW weld metal microstructure might be caused by the deposition of the filler metal during welding. In FSW, the fusion of the joints form uniformly distributed grain sizes due to the automated welding process. Nevertheless, the grains at the weld metal are the smallest compared to other areas of the work piece [11, 23].

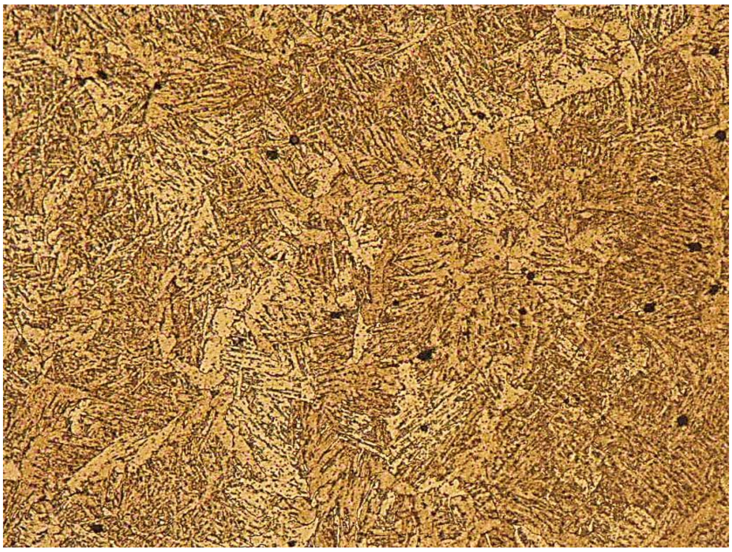


Figure 31: SMAW Weld Metal Microstructure at 50x Magnification.

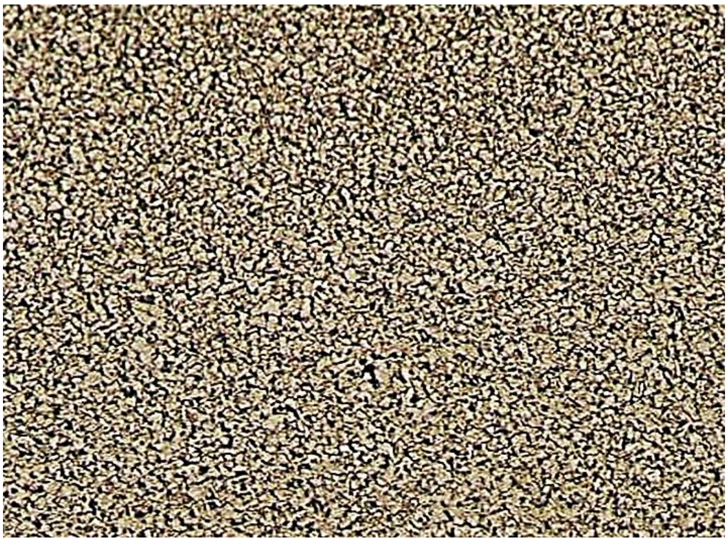


Figure 32: FSW Weld Metal Microstructure at 50x Magnification.

4.2 Rockwell Hardness Test

As can be seen in Table 6, the average hardness values for both SMAW and FSW at the base metal region do not vary significantly. This is due to same composition of the X52 carbon steel base metal used in both welding methods. As can be seen in previous Figure 27-28, the microstructure of the base metal region for both welding methods can be seen to be similar. This could lead to the similarity in hardness values in the base metal region for both SMAW and FSW. Irrespective of the welding condition, the base metal is expected to have a lower hardness compared to the weld metal [2, 11].

Table 6: Hardness values for base metal region.

Base Metal		
Point Number	SMAW	FSW
1	57.7	53.8
2	55.6	55.2
3	50.3	47.3
4	45.3	48.3
5	44.8	48.8
Average value (HRB):	50.74	50.68

Other than that, based on Table 7, the average hardness values for both SMAW and FSW at the HAZ region indicates that SMAW has higher hardness values compared to FSW. These results could be due to the difference in microstructure at the HAZ region. As can be seen in Figure 29-30, the grain structure of the HAZ by FSW is larger than compared to SMAW method. In material strengthening, grain refinement is an important factor [13]. This is the main reason for the increase hardness of the HAZ as compared to the base metal.

Table 7: Hardness Values for HAZ region.

HAZ		
Point Number	SMAW	FSW
1	51.3	36.5
2	50.4	45.4
3	66.4	54.2
4	68.4	62.9
5	67.9	63.9
Average value (HRB):	60.88	52.58

In addition, Table 8 shows the average hardness values for both SMAW and FSW at the weld metal region. The result also shows similar trend of result as at the HAZ region. The FSW yields a lower hardness value than the SMAW method. The weld metal region by SMAW has experienced very high temperature to melt the electrode during welding. Unlike SMAW, FSW does not require high temperature as the fusion of the metal occurs below the melting point of the metal. In addition of the fine grain size, the exposure to high temperature could increase the hardness of the weld metal. During welding process, the formation of finer grains due to optimum level of heat generation would result in the increase of the mechanical properties of the joints in terms of hardness [13].

Table 8: Hardness Values for weld metal region.

Weld Metal		
Point Number	SMAW	FSW
1	63.6	60.1
2	68.3	48.7
3	68.5	59.5
4	72.9	62
5	69.9	58
Average value (HRB):	68.64	57.66

4.3 Corrosion Test: Linear Polarization Resistance (LPR) Test

For both SMAW and FSW method, it can be seen Figure 33-34 and Table 9 that the corrosion rate varies at different regions. These results shows similar trend in a few research papers. In [1-3], the researchers also claimed that corrosion tends to happen at various rates in the base metal, heat affected zones (HAZ) and the weld or fusion metal. As the grain structure gets more refined from the base metal to the HAZ, followed by the weld metal region, this can have an effect on corrosion susceptibility.

Since the base metal has the largest grain structure, this would be one of the factors for the lowest corrosion rate as compared to the other regions. As also mention by a few researches, the microstructure at the base metal is expected to be largest in the work piece [11, 23]. Due to this, since the microstructure at the base metal for both SMAW and FSW is similar, the corrosion rate showed results that were alike.

Other than that, it is known that microstructure can affect corrosion behaviour. In most welding methods, the HAZ and the base metal should possess the same composition. However, the difference in microstructure can lead to the acceleration of corrosion [10, 11]. This would indicate on why the results obtained in Table 9 shows that the corrosion rate at the HAZ is higher than the base metal.

Other than that, since the grain structure gets more refined towards the weld metal, it can be seen from Table 9 that the weld metal region for both SMAW and FSW exhibits the highest corrosion rate compared to the HAZ and base metal. The grains at the weld metal are the smallest compared to other areas of the work piece. Since the grain sizes are the finest at the weld metal region, the corrosion rate would be the highest.

In comparison of SMAW and FSW, SMAW exhibits lower corrosion rate as compared to FSW. This is most likely due to the presence of high temperature during the welding process. SMAW requires very high temperature in melting of metals during welding, while the temperature in FSW does not need to reach the melting point of the metals. Since the work piece of SMAW experienced a higher heat input, this would have probably caused the difference in corrosion rate between SMAW and FSW. Based on the results, it can be concluded that FSW has higher corrosion susceptibility than SMAW.

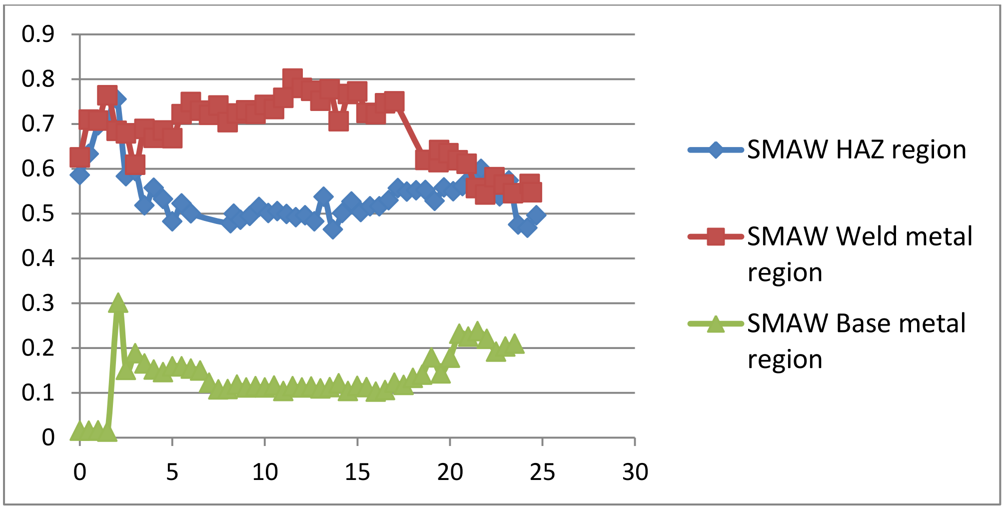


Figure 33: Graph of Corrosion Rate (mm/yr) versus Duration (hr) for SMAW method.

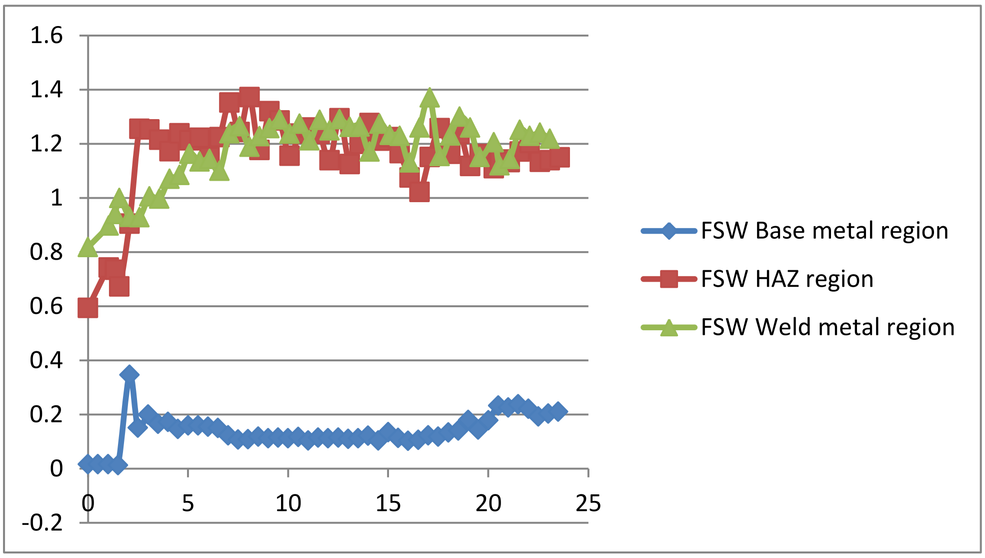


Figure 34: Graph of Corrosion Rate (mm/yr) versus Duration (hr) for FSW method.

Table 9: Average Corrosion Rate for SMAW and FSW in different regions

	Average Corrosion Rate (mm/yr)		
Region:	Base Metal	HAZ	Weld metal
SMAW	0.13654	0.53948	0.681
FSW	0.13851	1.1502	1.1601

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the objective of this project has been achieved. Based on the results obtained, it can be concluded that the microstructure of the work piece varies with different weldment regions. For both SMAW and FSW, the base metal yields the largest grain structure followed by the HAZ and weld metal. Furthermore, the hardness test results show that the hardness values are the highest in the weld metal region and lowest in the base metal. This is true for both SMAW and FSW. However, in comparison of the two welding methods, SMAW method exhibits higher hardness than FSW.Other than that, as can be seen in the corrosion rate test results, it can be seen that the weld metal region has the highest corrosion susceptibility compared to the HAZ and base metal. Grain refinement plays an important role in the rate of corrosion [10, 11]. Since the base metal has the largest grain size, the corrosion rate at the base metal is the lowest. These are applicable for both SMAW and FSW methods. Since the work piece of SMAW experienced a higher heat input, this would have probably caused the difference in corrosion rate between SMAW and FSW. However, based on the results, it can be concluded that FSW has higher corrosion susceptibility than SMAW.

5.2 Recommendations

For future studies, method of welding such as Gas Tungsten Arc Welding (GTAW) can be conducted for further comparison. Other tests that could be conducted for future studies on this matter are tensile strength test. The effect of welding on tensile strength of the weldment could be studied. Furthermore, in order to achieve a more accurate hardness value, Vickers hardness could be done. Besides that, in order to study the surface morphology of the different regions of a weldment, it is recommended to conduct the Scanning Electron Microscope (SEM) test. In addition, the LPR test could also be conducted in various parameters. Different parameter such as temperature, pH and concentration of solution would give out various results.

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