Effect of Chloride on Offshore Structure Welding Procedure

by

Zakaria Bin Mohamed

A dissertation in partial fulfilment of

the requirement for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

JANUARY 2009

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CERTIFICATION OF APPROVAL

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Approved by,

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(Assoc. Prof. Dr. Razali Bin Hamzah)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2009

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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ZAKARIA BIN MOHAMED

ABSTRACT

The objective of this research was to determine the effect of chloride to the welded ASTM A516 Grade 70 materials. The used of proper welding procedure may eliminate the probability of crack occurrences, but there were still cracking happen in some offshore welding. That was because the failures may occur hours or days after the welding work completed. The scope of the study was on ASTM A516 Grade 70 steels welded using WPS FSP-HLE-17-49 procedure and exposed under salt environment according to ASTM G41-90 at 35°C for period of 1 to 5 days. Non Destructive Examination such dye penetrant and magnetic particle testing were used to investigate the initial conditions of specimen and the conditions after exposing the materials under the simulated offshore environment. Metallographic examinations of the specimen were crucial in this study. The study had shown that the welded structure using the WPS produced complete welds with no visible surface crack. The hardness of the weld and the HAZ was 213(HV10) and 224 (HV10) respectively. There were found to be well below critical hardness value i.e. 300 (HV10) for weld metal and 248 (HV10) for HAZ, as according to PTS 20.112. There were no surface cracks found throughout the duration of the study. The study concludes that if the welding was done in strict compliance with the code and standard, high weld integrity would be produced.

ACNOWLEDGEMENT

I would like to take this opportunity to acknowledge and thank everyone that has given me all the supports and guidance throughout the whole period of completing the final year project.

I must also acknowledge the endless help and support received from my supervisor, AP Dr. Razali Hamzah throughout the whole period of completing the final year project. His supervision and opinion are very much appreciated. Apart from that, many thanks to the PCSB personnel, Ir. A. Rahim Bahruddin for helping me and arranging the meeting with Dulang Gas Capacity Enhancement and Mercury Project Site Team. Also, high appreciation to person in charge at Kenchana KL Fabrication Yard, En M Izuddin B Zulkifli Dulang (Dulang CGCE – Construction Engineer), Amal Nafissa bt M Tabi (Dulang CGCE – QA/QC Engineer), Mr. Yuuarajah QA/QC personnel, and all site team members.

I would also like to thank all the material lab technician and manufacturing lab technician that guide me along the completion of the project experiment. Their continuous support and help throughout the whole period of experiments are very much appreciated.

Finally, many thanks to my colleagues for their help and ideas throughout the completion of this project. It seems that the word “thanks” would not be enough for their contributions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CGCE	Compressed Gas Capacity Enhancement
FSP	Fabricator Standard Procedure
MMHE	Malaysian Marine and Heavy Engineering
NDT	Non-Destructive Testing
PQR	Procedure Qualification Record
PTS	PETRONAS Technical Standard
PWHT	Post-Weld Heat Treatment
WPQT	Welding Procedure Qualification Test
WPS	Welding Procedure Specification

CHAPTER 1
INTRODUCTION

1.1 Background of study

Major offshore structures are welded steel and concrete material. These materials must perform in harsh environment, subjected to many corrosive and erosive actions of sea as well as under dynamic cyclic and impact conditions over wide range of temperatures [1]. Because of these kinds of conditions, fatigue is potentially one of the main problems causing degradation in the long-term integrity of the structure [2].

Crack initiation and crack growth has been found as fatigue failure in welded joints. This failure commonly occurs at welded steel joints since these joints are kind of connection used widely in the construction of fixed offshore structure. The failures commonly occur at the welded joint due to stress concentration, member loads, environment, quality of the weld, and residual stress.

The long-term integrity of these welded joints must be maintained to ensure safety and reliable operation of the structure. Maintenances of integrity of the structure can be achieved by fatigue-analysis and regular in-service inspection [2]. When a defect is located in a weld, the weld should be repaired. Generally, the weld metal is removed by grinding and inspected to verify the effective removal of the defect in order to re-weld under a qualified welding procedure [3].

Due to large, complex and costly structure, any failure will be catastrophic both financially and in terms of human lives. Thus, special criteria and requirements are imposed on the repaired process used. These criteria (procedure) should be prepared detailing steels grade, joints, welding parameter, joint design, and heat treatment process [1][2]. Welding in the offshore environment will lead to failure without proper procedure. The present of hydrogen mainly from the nature of the process i.e. weld properties, temperature condition and moisture from the environment itself leads to weld failure immediately or after certain period after the welding process

[4]. Hence, this study is aimed at achieving the best and most cost effective preventive procedure in welding repair at offshore environment. The main defect considered is the present of chloride or environmentally assisted failure.

1.2 Problem statement

Weld repairs to aged and degenerated materials are proned to early failure unless strict preparation and controlled welding procedure are followed [5]. The failure may occur hours or days after the works been accepted (delayed cracks). This type of failure is among the primary concern with welding in-service pipelines and platform structures [6]. The crack failures occur mainly because of presence of chloride (environmentally assisted) during welding process. Although welding engineering is designed to minimize the probability of occurrence of cracking, or with appropriate design code, there are still cracks happening in offshore structure welding.

1.3 Objective of the study

The objectives of the study were;

a. To determine the effect of chloride on the welded ASTM A516 Grade 70.
b. To prove that the welding procedure specification (WPS FSP-HLE-17-49) could be used to successfully weld ASTM A516 Grade 70 materials in offshore environment.
c. To identify the effect of material's hardness on the susceptibility to failure in welded ASTM A516 Grade 70 materials.

1.4 Project scope of work

Carbon and Carbon-manganese steels are generally used as construction materials for offshore structure, pressure vessel, supports, and pipings [7]. Material used in this project is ASTM A516 Grade 70 steel. This material was welded by qualified welder from Kenchana HL (Fabricator) using WPS FSP-HLE-17-49. Laboratory tests were run to configure failure occurrence after welding process in aqueous solution as simulation to offshore environment condition. ASTM G41-90: Standard practice for determining cracking of metals exposed under stress to a hot salt environment will be used as a guide but some alterations were made to the experimental procedure. NDT used to examine the crack occurrence is dye penetrant and magnetic particle test. Metallographic specimen preparation is important to investigate the microstructure of the weld region and important to measure the Vickers microhardness of the respective weld region. Results will be analyzed and recommendation to the procedure to minimize welding failure will be implemented.

1.5 Relevancy of the project

There are extensive developments of offshore structure in Malaysia. The structures are exposed to ocean environment and long exposure will degrade the materials. The degraded section will need repair works in order to maintain the overall structural integrity of the platform. There has been development of welding procedure that will minimize cost of repair works on site. The study in welding defect prevention will be useful in order to avoid double repair that will be a costly process.

1.6 Feasibility of the project

The project scope is to study the welding repair procedure used in Malaysia conditions, the material used for test specimen, and the type of failure occurrence within timeframe available will make this project feasible.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Literature review

2.1.1 Welding failure

There are two primary concerns with welding onto in-service pipelines. First concern is to avoid burning through and the second concern is for hydrogen cracking [6]. The latter will be studied further in this project. Environmental Assisted Cracking implies whatever cracking occurs is assisted and accelerated by the environments [8]. Hydrogen cracking is considered as environmental assisted cracking. Regardless of the name assigned – ammonia cracking, corrosion assisted cracking, hydrogen embrittlement, hydrogen assisted cracking, hydrogen assisted stress corrosion cracking, stress-oriented hydrogen induced cracking (SOHIC), sulphide stress cracking (SSC) – the consequences of these environmental assisted cracking are potentially catastrophic, frequently resulting in "sudden unscheduled disassembly" of the affected structure, machinery, or vessel [9].

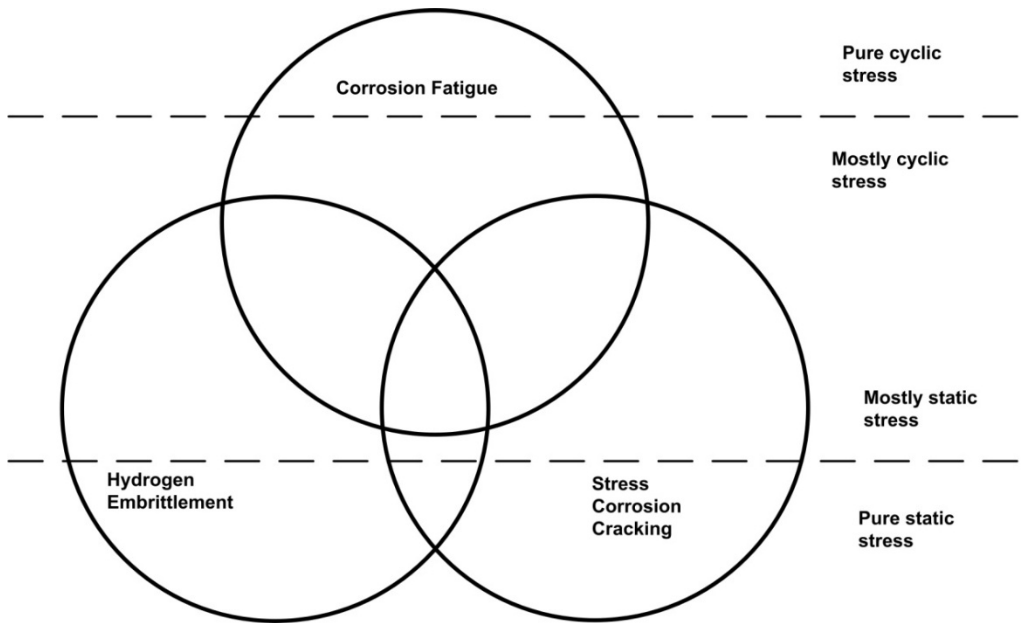


Figure 2.1: Venn diagram illustrating the interrelationship between stress corrosion cracking, corrosion fatigue, and hydrogen embrittlement [3]

The Venn diagram in figure 2.1 is an illustration of the interaction between hydrogen embrittlement, stress corrosion cracking, and the corrosion fatigue. Kou [11] in his book list the typical welding problems and practical solution in carbon and alloy steels. The typical problems includes, porosity, hydrogen cracking, lamellar tearing, reheat cracking, solidification cracking. And the solutions of each failure were discussed further in the book.

2.1.2 Welding procedures

Welding procedure is important in order to have a good welding quality. T. Lant et al. conclude that a strict preparation and controlled welding procedure must be followed to prevent early failure in welding. A consideration in welding procedure includes material condition, weld material, weld pre-heat, post-weld heat treatment, and weld technique used. To be successful and to offer an economic return in terms of operational life, careful planning and control are required [5]. Stevenson [10] concludes that the primary factors that led to the weld cracking were procedural in nature.

2.1.3 Factors of welding failure

There are many factors contributed to welding repair has been studied. Individual welding parameter, such as electrode selection, joint design, and pre / post-heating, played a role in the failure, and a number of human factors relating to the actual fabrication practices also contributed to the failure process [10]. High levels of longitudinal stress (such as upper passes in multipass thick sections), transverse metal cracking can occur [12]. Moreover, Dong [13] state that weld repair typically increase the magnitude of transverse residual stresses along the repair compared with the initial weld and the shorter the repair length the greater the increase in the transverse stress, hence the more tend to failure occurrences.

Turnbull [8] in his studies listed several reasons why cracking may still be of concern even though engineering design were optimised to minimise the probability of occurrence of cracking. Some of the reasons are;

a. The operating conditions may have been altered to improve process,

b. Welding may not be ideal and may introduce defects and change the material characteristics,

c. Transient variation in stress, temperature or environment chemistry may occur,

d. Change of the metal surface,

e. Localised corrosion processes may be initiated and become precursor for cracking,

f. The ideal engineering choice of material for the specific process conditions may not be economically viable, and

g. Laboratory testing and modelling assumptions may not be realistic.

2.1.4 Prevention methods

Preventive action should start earlier before the construction or works starts. As quote by Stevenson et al from "In Defense of the Metallurgist", involvement of metallurgist and welding engineer early in the project would have ensured that proper framework is established to prevent a textbook-type failure. The framework would consist of preparing a suitable procedure and the specific procedures are followed by third-party monitoring [10]. In this case, breakdown communication process between personnel and those performing fabrication works can result in unnecessary failures.

2.2 Theory

2.2.1 Welding codes and standards

Welding codes and standards are guidelines covering minimum mandatory requirements essentials to guarantee public safety and reliability of the structure [16]. This guideline is important in order to control characteristic of welded structure that may affect service requirements [17].

2.2.1.1 PTS 30.10.60.18 Welding of metals

This standard specifies the requirement and gives recommendations for welding steels and non-ferrous metals. General information on qualifications, welding processes and welding methods are discussed and outlined. The important points in this PTS are sections that specify heat treatment procedures, and the guidelines for welding of specific materials [15].

Heat Treatment procedure

Heat treatment procedure must be reviewed and approved by the Principles (party that initiates project and pays for design and construction). The procedure may be carried out either full-body or locally depending on type of heat treatment, materials, configuration, availability and cost of energy, and design code requirement. There are two heat treatment procedure described, preheating and post weld heat treatment. For pipings welds made in the field, methods of preheating include;

Pipe diameter ≤ 250mm, heating by appropriate torches is applied

Pipe diameter > 250mm, electrical heating or heating by means of infra-red or ringburners is required.

Post weld heat treatment in this standard outlines that PWHT may be required for $C_{eq} \geq 0.45$ or $C > 0.23$ depending on application and hardness requirements.

Guidelines for the welding of specific materials

This section outlines guidelines for welding specific materials in constructions. Some important material includes;

i. Carbon and Carbon-Manganese Steels,
ii. 5% and 9% Nickel Steels,
iii. 0.3% and 0.5% Molybdenum Steels,
iv. Stainless Steels, and
v. Low-Alloy Chromium-Molybdenum Steels,

It outlines welding consumables, weld preparation, preheating, welding procedure specification, and post-weld heat treatment for each steels listed.

2.2.1.2 PTS 20.104 Construction of Structural Steelwork

The scope of this standards covers material specifications, shop and field welding fabrication and inspection requirements of all structural steel for; platform support jacket, deck, structural steel, jetties, and steel skirt foundation. Some crucial part for this study is in fabrication section. This section is heat treatment requirement and repair & remedial procedure [20].

Heat treatment

In this part, general preheating and temperature requirements for preheating and interpass temperature are outlines. Additionally, there are also general requirements for stress relieving, PWHT, temperature, and method in stress relieving procedure.

Repair and remedial procedure

This procedure must be done in accordance to approved welding procedure. If there are cracks that need to be repaired, the cause of the crack must be known before repair works are allowed.

2.2.1.3 API Standard 1104: Welding of pipelines and related facilities

The scope of this API standard covers the gas and arc welding of butt, fillet, and socket welds in carbon and low-alloy steel piping. The materials are used in the compression, pumping and transmission of petroleum product, crude petroleum, carbon dioxide and fuel gases. Repair and removal of defect is main consideration for this project together with in-service welding section [6].

Repair and removal of defects

Authorizations for repair are cracked weld and defect other than cracks. Cracked weld must be removed from the parent metal and other defect may be repaired prior to owner authorization. Qualified welding procedure required and should at least include;

a. Methods of detecting the defect
b. Methods of removing the defect
c. To confirm complete removal of defect, the groove need to be examined
d. Requirements for preheat and interpass heat treatment
e. Welding processes
f. Requirement for interpass NDT.

In-service welding

This part covers recommended welding practices in repair and installing appurtenances on pipelines and piping systems that are in service. In-service defined as those materials that contain crude petroleum, petroleum product, or fuel gas. The primary concerns with this welding process are burning through and occurrence of hydrogen cracking. The majority of this part outlines to preventing hydrogen cracking in in-service welds.

For repair and removal of defect, the requirements previously explain in 3.1.3.1 should be applied in in-service welds.

2.2.1.4 AWS D1.1 Structural Welding Code – Steel

This code contains the requirements for fabricating and erecting welded steel structures. Significant parts of this code for this project are repairs section, guideline on alternative methods for determining preheat, and strengthening and repairing of existing structures [21].

Repairs

Removals of defect for repair are by means of machining, grinding, chipping, or gouging. This should be done without effecting weld metal or nearby weld metal. After removal, the surface should be cleaned thoroughly before applying welding process.

Guideline on Alternative Methods for Determining Preheat

This section provides optional methods in avoiding cold cracking. Methods that used for estimating welding conditions to avoid cold cracking are;

a. HAZ hardness control

   This method is only for fillet welds. It is based on assumption that cracking will not occur if the hardness of HAZ is kept below some critical value. This is achieved by controlling cooling rate of the welding process depending on hardenability of steel.

b. Hydrogen control

   This method based on assumption that cracking will not occur if the average quantity of hydrogen remaining in weld metal after it cools down to 50ºC does not exceed critical value. Preheat necessary to allow enough time for hydrogen to diffuse out from the weld part.

2.2.2 Welding procedure/process used in recent offshore weld repair

Procedure is a set of instruction which is accepted in performing a particular action intended to achieve a specific results. AWS defined welding procedure as “the detailed methods and practices including all joint welding procedures involved in the production of weldments”. Welding procedures should be prepared, detailing steel grades, joint/groove design, thickness range, welding process, welding consumables, welding parameters, principal welding position, preheating/working temperature, and post-weld heat treatment [22]. These procedures were based on standard and codes discussed earlier in 3.1. The welding procedures for the weld repair can often be very similar to the original welding with respect of preheat, type of consumable, and welding conditions [22].

Procedure will be applied by contractor in performing actual works on site. In order to make sure the integrity of work done, a welding procedure must be tested and approved. This qualification of welding procedure includes welding procedure specification (WPS), welding procedure qualification test (WPQT) and procedure qualification records (PQR). Qualification of the welders and welding operators are important consideration in a welding qualification. One example of welding procedure studied are Weld metal & Base metal Repair procedure from MMHE.

2.2.3 Qualification of welding procedure

2.2.3.1 Welding Procedure Specification (WPS)

WPS should contain important parameter in welding operation such material specification, welding process, joint and groove design and etcetera [5] [20] [23]. Welding Procedure Qualification Test (WPQT) is the procedure to perform in order to qualify WPS.

2.2.3.2 Welding Procedure Qualification Test (WPQT)

WPS will be simulating during WPQT. All the details in preliminary WPS will be weld and test before WPS is approved. All the details in WPS will be recorded in PQR.

2.2.3.3 Procedure Qualification Records (PQR)

Specific fact and test data will be recorded in this document.

2.2.4 Qualification of the welder and welding operator

Welder must pass qualification test in specific welding process and position. Only qualified welder will perform welding works for qualification of procedure. There are record for welder qualification and it has period of effectiveness.

2.2.5 MMHE welding repair procedure

MMHE, one of the biggest fabricators of oil and gas offshore platforms in Malaysia, has developed and in possession of quite a comprehensive spectrum of established welding repair procedure.

This is one of example procedures used in weld repair used in Malaysian environment. This procedure details the repair management process and repair techniques that can be used for various types of defects found in structural fabrication [24]. Main part of this procedure is the management of repairs and repair procedure as detailed below;

2.2.5.1 Management of repairs

From the procedure item 7.0 (management of repairs) any detected defect by Visual Examination (VE) or NDE shall be identified and marked. The repair weld process shall be made from the greatest amount of accessibility. Repair made over metal shall be the same as original welding process used. Examination method that originally documented must be used for the repair.

2.2.5.2 Repair technique

The repair outlined in the procedure is for various types of defects. The defects that ate listed below are common defects found in the fabrication of the structure.

a. Weld metal defect
b. Base metal defect
c. Weld build-up
d. Weld bevel edge defect
e. Cracks
f. Damage plate, and
g. All other defect.

Each item describes how to repair the defect using either by grinding, air-arc carbon gouging, or by welding.

2.2.5.3 Inspection

In order to make sure that the weld meets requirements, all the repairs must be 100% visually examined. NDE will be based on original welding procedure that it is not discussed in this report.

2.2.6 Welding failure

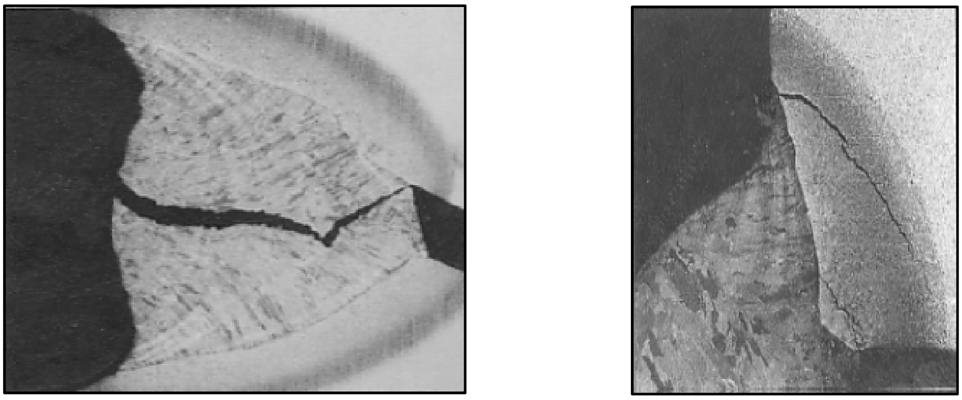
Welding work performed on site in offshore environment has quite a high percentage of failures rates. These failures may be because of the environment, welding process itself or welder incompetency. For the purpose of this project, the most common type of welding defects due to hydrogen was studied. This hydrogen crack occurs at heat affected zone or weld metal. This section will list the types of weld defects, factors that lead to the defect and common prevention method to avoid the occurrence of the failure.

2.2.6.1 Types of welding failure

API [6] states that primary concerns for welding in in-service condition are hydrogen cracking besides the "burning through". Most studies were concerned about hydrogen cracking in welding and ways to prevent it [5][18][25]. Timmins [25] divided hydrogen attack in two types which are; 1) Low Temperature Hydrogen Attack (LTHA), this kind of types is failure occur at temperature below 200ºC, 2) attack is High-Temperature Hydrogen Attack (HTHA). This attack is a form of internal decarburization associated with steels that are exposed to hydrogen at high temperatures and pressure. The attack occurs above approximately higher than LTHA. Other types of hydrogen failure are;

a. Corrosion and Corrosion-Assisted Cracking
    i. Weight Loss Corrosion
    ii. Environmental Cracking
    iii. Cracking in an H_2S Environment
b. Preferential Weld Corrosion
c. Hydrogen Cracking Associated With Welding Process Piping
    i. HAZ Cracking
    ii. Fisheyes

For the purpose of this project, a welding defect will be studied. Besides, other cracking failure, hydrogen-induced cold cracking will be further elaborated. This failure termed as *cold cracking* or *delayed cracking*. Cracking may occur several hours, days, weeks after the weld cooled. It occurs either in weld metal as in figure 2.2 (a) or HAZ as in figure 2.2(b) of low-alloy and other hardenable steels.



(a) (b)

Figure 2.2: Example of Cracking at (a) Weld Metal, and (b) HAZ

For cold crack to occur in steels, there are three principle factors: susceptible microstructure, atomic hydrogen, and a high stress resulting from restraint. Controlling one or more of these factors may reduce the occurrence of cold cracking.

Controlling the principle factors of cold crack can be done by slow cooling rate, and heat treatment process to avoid susceptible microstructure. Low hydrogen electrode can be used and clean the weld surface to have hydrogen free welding. Cracking in the base metal is often attributed to high carbon, alloy, or sulphur content. In order to avoid cold cracking of the base metal, it requires the use of low hydrogen electrodes, high preheat, high interpass temperature. [21].

2.2.6.2 Factors leading to welding (hydrogen) cracking

In order to prevent the occurence of welding crack, factors for a crack happen should be understood. There are several factors causing a failure depending on the type of failure. As discussed previously, cracking is the most common failure occuring whether in weldments or HAZ. Generally, for a cracking in welding, the root causes of the failure are discussed below;

Hydrogen

Hydrogen sources will be from welding process itself or from moisture on the parent material, damp welding fluxes and water vapour in the surrounding air. Welding process such TIG has lowest hydrogen content for 100 grams of weld metal deposited as shown in Table 2.1 [28].

Table 2.1: Hydrogen content for specific welding process

Welding Process	Hydrogen Content
TIG (Tungsten Inert Gas) or GTAW	< 3ml
MIG (Metal Inert Gas)	< 5ml
SMAW (Shielded Metal Arc Welding)	< 5ml
Electro Slag Welding (ESW)	< 5ml
SAW (Submerge Arc Welding)	< 10ml
FCAW (Flux Core Arc Welding)	< 15ml

Hydrogen can also originate from hydrocarbon, grease, rust, or other organic contaminants on the pipe or the welding wire [25].

Susceptible Microstructure

Hard microstructures in HAZ are susceptible to hydrogen cracking. This kind of microstructures is promoted by steels with high carbon equivalent value and by rapid welding cooling rates. Carbon equivalent is expressed in Equation 1 below as:

$$CE=C+\frac{Mn}{6}+\frac{Cu+Ni}{15}+\frac{Cr+Mo+V}{5} \quad (1)$$

Besides, martensite, especially hard and brittle high-carbon martensite is susceptible to hydrogen cracking. This crack occurs at relatively low temperature because of nature of the martensite formation temperature [11].

Stress acting on the weld

Stress acting on the weld can be either because of applied stress or residual stress. Applied stress because of force acting on the welded parts while residual stresses arise from the restraint of the welded connection and strains because of the contraction of weld metal during cooling process.

Human error

Human factors also played important role in order to ensure that welding repair is successful. PTS [26] mention that "The CONTRACTOR shall ensure that the qualified welders and welding operators are employed during fabrication only on welding the type, process and position of weld for which their qualification test so qualifies them." This states that human error can be eliminated by using qualified welder to remove factors that lead to crack occurrences.

2.2.7 Prevention method

Several methods are used to minimize the cracking failure in a repair welding. Generally, these methods were also used in preventing welding defect. The most important method was discussed below;

Careful selection of welding parameter

Welding parameter includes welding process, position and direction, filler metal and welding currents, and etcetera are important to ensure a good welding works. DNV [16] states that the working temperature shall be maintained until the repair has been completed. Consumables used must be within specification to prevent occurrence of failure. Consumables that have been contaminated by moisture, rust, oil, grease, dirt or other deleterious matter, shall be discarded unless properly reconditioned. PTS [26] mention that electrodes, wires and fluxes shall be supplied in fully sealed packages and stored in a dry storage room where a minimum temperature of 20°C is maintained. These precautions represent a safety measure to make sure that no defect will occur after the welding process is done.

Heat treatment

a. Preheat

   This process involves rising the temperature of parent material locally on both sides to be joined to a specific value above ambient temperature [18]. The reason for preheat are;

   i. To slow the rate of cooling, especially in HAZ, to reduce hardness since reducing hardness reduce the risk of cracking.
   ii. Control the diffusion rate of hydrogen in a welded joint.
   iii. To reduce thermal stresses.
   iv. Compensation for heat losses.

b. Postheat

   Postheat is the extension of preheat on completion of welding to maintain or increase the temperature.

c. Post-Weld Heat Treatment

   This is a process for stress relief in welding. Post weld heat treatment can assist in transporting of hydrogen from the weldments and reduce susceptibility to hydrogen cracking [27]. PTS requires a minimum duration of 48 hours shall elapse between the completion of welding and the commencement of PWHT [15].

Proper material selection and preparation

a. Surface preparation

   A proper cleaning process in the event of repair process is crucial. The removing of previous weld metal should be done using process approved in procedures.

b. Welding consumables

   Proper selection of welding consumables can reduce the hydrogen uptake in weld metal during welding process.

To conclude, practical solutions to a welding crack are to control the hydrogen effect and microstructural control. Hydrogen effect control includes using low-hydrogen electrode, moisture removal before welding process, uses of low-hydrogen process (GMAW/GTAW) and heat treatment process. Whereas, carbon equivalent can effect on hardness of HAZ, high CE will have higher HAZ hardness. Thus, the risk of hydrogen cracking will be higher.

2.2.8 Non-destructive testing (NDT) inspection methods

The NDT is inspection method that allows material tested (examined) without changing or destroying their usefulness. The purpose of the tests is to locate the discontinuities in weldments. NDT is performed on weldments to verify that weld quality meets specification and to determine whether weld quality has degraded during service. In this scope of project, NDT is used to trace the crack occurring in welded material [29].

NDE methods commonly used for inspection of weldments are;

a. Detailed Visual Testing (VT),
b. Radiographic Testing (RT),
c. Ultrasonic Testing (UT),

d. Magnetic Particle Testing (MT),
e. Liquid Penetrant Testing (PT),
f. Electromagnetic Testing (ET), And
g. Acoustic Emission Testing.

Table 2.2 below shows the type of discontinuities and non-destructive exams that fit to be used [30]. It is preferable to used radiographic testing in welding discontinuities. For the SCC, the first and second preference is to use fluorescent and visible penetrant method.

For the purpose of this study, three NDT methods will be used. The methods include visual testing, liquid penetrant, and magnetic particle testing. The details about the methods are discussed below.

2.2.8.1 Detailed visual examination

Visual testing (VT) is non-destructive examination method that often used for weldment inspection.

Theory and principles

There are two factors that affect visual examination which are object and human factor. Light, cleanliness, and surface condition are the object factors, whereas environment, perception, and visual angle & distance are human factors that affect result of VT. Best result from a visual inspection is obtained when the object is brought close to eye within distance 250-600 mm with an angle of <30˚ from the plane of test surface.

Application

This test method is used to inspect discontinuities on the surface only.

Equipment

Visual aid and gauges are sometimes used to assist the detection of discontinuities in weld. Magnifying glass is also used to aid the detection of the defect.

Table 2.2: Discontinuity Guide

Non-Destructive Test Methods	Visual Inspection	Fluorescent Penetrant	Visible Penetrant	Wet D.C	Dry D.C	Dry A.C	Eddy Current	Thermal Infrared	Radiography	Straight Beam Ultrasonic	Angle Beam Ultrasonic
				Magnetic Particle							
Type of Discontinuities	Surface and near surface								Subsurface		
Welding/joining											
1. Subsurface Cracks	U	U	U	U	U	U	P	U	A(1)	A(1)	A(1)
2. Surface Cracks	P	P	P	U	P	P	P	U	A(2)	U	A(1)
3. Underbead Cracks	U	U	U	U	U	U	P	U	A(1)	A(1)	A(1)
Service											
Stress Corrosion Cracking	P	A(1)	A(2)	P	U	U	A(3)	U	P	U	P

Key:

U: Unsatisfactory
P: Possible
A (1): First Order Preference
A (2): Second Order Preference
A (3): Third Order Preference

Advantages

It is simple, quick, and easy to apply. It is also economical and requires relatively little training and equipment for most application.

Disadvantages

The major disadvantage of VT inspection is the need for an inspector who has the experience and knowledge in many different areas. It is also limited to external or surface condition. It is also limited to the visual ability of the examiner.

2.2.8.2 Liquid penetrant testing

Liquid penetrant testing (PT) is one of the most widely used non-destructive testing method for detection of surface discontinuities in nonporous solid materials.

Theory and principle

Fundamental to PT is the ability of the penetrant liquid to wet the specimen surface completely, and then to penetrate the depths of the surface crack. Surface tension, contact angle and surface wetting, capillarity, and dwell time is important consideration in PT [7].

Equipment and material

PT requires little equipment. The equipment is;

a. Penetrant
    i. Water-washable
    ii. Postemulsifiable
    iii. Solvent removal
b. Emulsifier
c. Solvent remover
d. Developers

Procedures

The steps for any penetrant test are as follows:

a. Preparing specimen surface (pre-clean)
b. Verifying the temperature of the specimen and the penetrant materials

c. Applying penetrant to specimen surface
d. Dwell time
e. Removing excess penetrant from surface
f. Applying developer
g. Locating and interpreting indications
h. Post-clean

Minimum dwell time depends on type of material, form of material and temperature involved in the test. Usually, the test temperature used is 10 to 52 degree Celsius. Table 2.3 below shows the dwell time for specific material and the type of discontinuity that appears. For casting and weld of steel the minimum dwell time is 5minutes for penetrant and 7 minutes for developer.

Table 2.3: Minimum Dwell Time as per ASME SEC V: Non-destructive Method of Examination

			Dwell Times (minutes)	
Material	**Form**	**Type Of Discontinuity**	**Penetrant**	**Developer**
Aluminum, magnesium, steel, brass and bronze, titanium and high-temperature alloys	Castings and welds	Cold shuts, porosity, lack of fusion, cracks (all forms)	5	7
	Wrought materials - extrusions, forgings, plate	Laps, cracks (all forms)	10	7
Carbide-tipped tools		Lack of fusion, porosity, cracks	5	7

Interpretation and indication

Surface cracks are most common defects revealed by penetrant examination. An indication of a crack will be very sharp [29]. Most crack exhibit and irregular shape, and the indication produced by the penetrant takes the same shape but it is larger.

Advantages and disadvantages

Table 2.4 summarized the advantages and limitation of liquid penetrant examination.

Table 2.4: Advantages and Disadvantages of Dye Penetrant Test

Advantages	Disadvantages
a) Inexpensive b) Easy to apply c) Use on most material d) Rapid and portable e) Wide range of sizes and shapes of test object f) Does not require power source g) 100% surface inspection	a) Surface defect only b) Poor on hot, dirty, rough surface c) Messy d) Environmental concern e) Temperature range limitation f) Final inspection is visual

2.2.8.3 Magnetic particle testing

Magnetic particle inspection is used to detect surface or near-surface discontinuities in ferromagnetic materials.

Theory and principle

The magnetic particle method is based on the principle that magnetic field lines when present in a ferromagnetic material will be distorted by a change in material continuity, such as a sharp dimensional change or a discontinuity.

Equipment

Different magnetic testing (MT) equipment is available. They are classified as stationary, mobile, or portable unit. In this project, portable unit of MT is used. AC yoke were used in detecting the slightly subsurface flaws in welded specimen. This yoke have articulating legs to facilitate various inspection area profiles.

Procedures

The MT procedures were;

1. Cleaning the surface
2. Apply contrast aid paint
3. Apply yoke

4. Energize yoke
5. Apply magnetic particle
6. Inspect

Interpretation and indication

Evaluation of test result is greatly dependent on the observer or inspector. In this MT, once a crack is detected, the indications should be classified as either false, nonrelevant, or relevant before final evaluation.

Advantages and disadvantages

The magnetic particle testing is a sensitive means of detecting small and shallow surface or near surface discontinuities in ferromagnetic materials. It is considerably less expensive than radiographic or ultrasonic inspection and is generally faster and economical than penetrant testing.

The limitation of this method is, it is only for ferromagnetic material. Large current sometimes are needed for very large part. Discontinuities must be open to the surface or slightly sub surface to create flux leakage of sufficient strength to accumulate magnetic particles.

CHAPTER 3
METHODOLOGY

3.1 Procedure identification

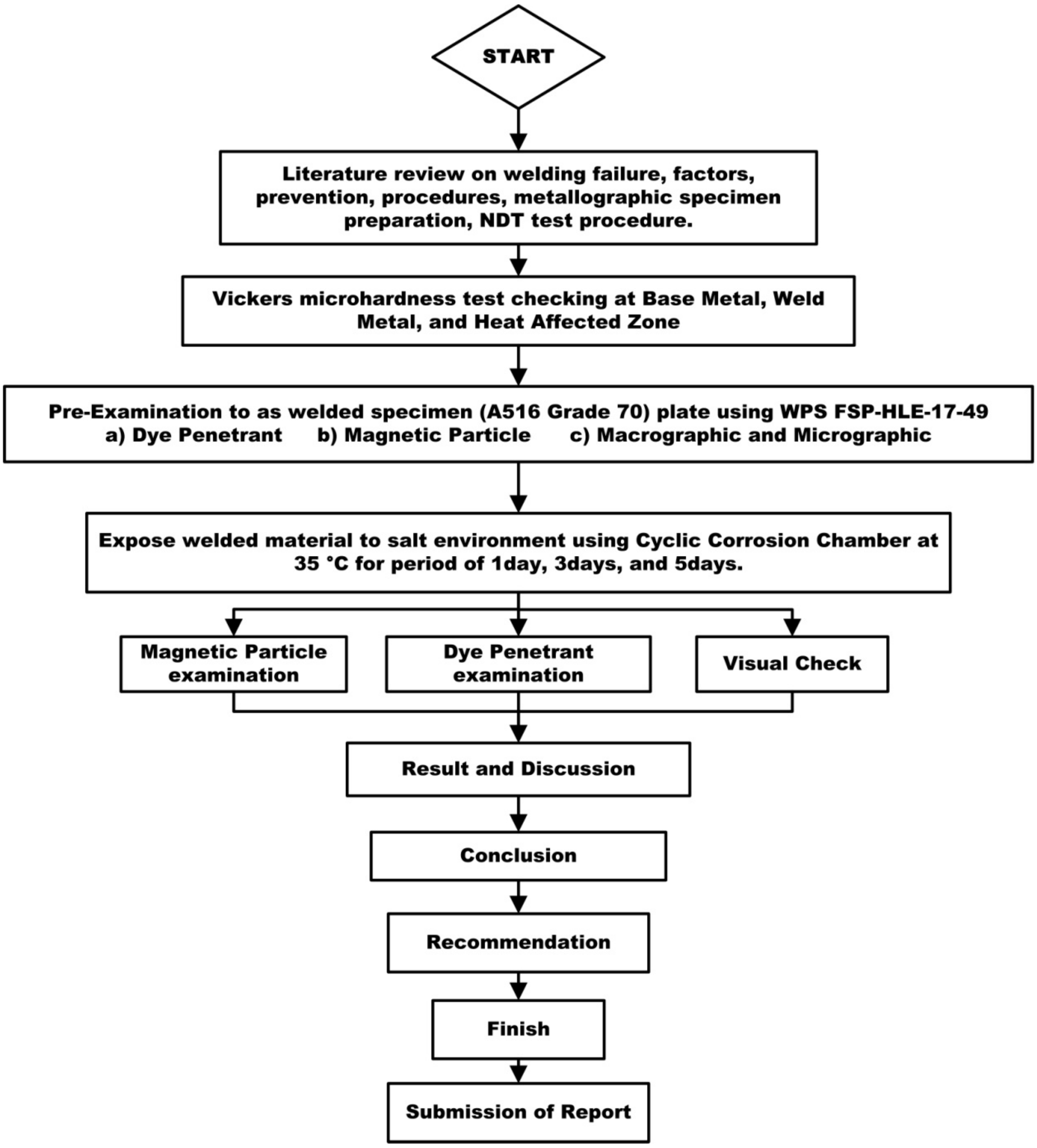


Figure 3.1: Summary of activities of the study

Figure 3.1 shows methodology used for completing the research. Sufficient studies were done about welding codes, repair procedure, type of failure, and factors of failure, prevention methods, and metallographic preparation of a specimen. With help from Dulang Gas Capacity Enhancement and Mercury Project team, the 'as welded' specimen welded under WPS (FSP-HLE-17-49) is then used in testing. Prior to testing in simulated offshore environment, pre-test NDE were made to have a baseline conditions. Metallographic specimen preparations were prepared. The specimen were then exposed to salt environment using cyclic corrosion chamber at temperature 35°C for a period of 1-day, 3-days and 5-days. Three non-destructive tests will be run after the exposure; visual test, magnetic particle test, and penetrant test. Detailed experiment procedure and processes discussed below.

3.2 Experimental Methods

3.2.1 Purpose

The purpose of this experiment is to observe and inspect crack failure in weldments before and after exposing to salt environment.

3.2.2 Reference document

a. ASTM standards:

   i. E 165 – 95 Standard Test Method for Liquid Penetrant Examination

   ii. E 709 – 01 Standard Guide for Magnetic Particle Examination

   iii. G 41 – 90 Standard Practice for Determining Cracking Susceptibility of Metal Exposed Under Stress to a Hot Salt Environment

   iv. G 52 – 00 Standard Practice for Exposing and Evaluating Metals and Alloys in Surface Seawater

   v. G 58 – 85 Standard Practice for Preparation of Stress-Corrosion Test Specimen for Weldments

   vi. G 161 – 00 Standard Guide for Corrosion-Related Failure Analysis

b. Det Norske Veritas Offshore Standard [14]

3.2.3 Weldments and test specimen preparation

3.2.3.1 Weldment dimensions

The size and shape of the weldments from which specimens will be tested and removed will be governed by the intent of the test procedure.

3.2.3.2 Welding procedure specification (WPS)

Minimum specification contains the following information [20] as per FSP-HLE-17-49;

a. Material: ASTM A516 Grade 70
b. Dimension: 6 inch wide × 1 inch long × 1 inch thick
c. Welding process: Manual SMAW
d. Joint or groove: Single V
e. Welding position: 2G
f. Welding consumables: low hydrogen KOBE LB52-U (root) and KOBE LB52-18 (cap); 2.6-4.0 mm diameter
g. Welding sequence: 17 passes
h. Electrical parameters; voltage range: 20-26, current range: 70-170 , polarity: DC
i. Travel speed: 40-150 mm/min
j. Preheat and interpass temperatures: 300°C max.
k. Post weld heat treatment parameters: n.a

3.2.3.3 Removal of test specimens from the weldments

The end of the weldments must be discarded. Each test specimen is 1x6 inch.

3.2.3.4 Specimen preparation

The weldments will be left in the "as-welded" condition because the effect of the surface conditions will be evaluated. Prior to exposure, the specimen must be thoroughly cleaned.

3.2.4 Pre-test

3.2.4.1 Macrographic examination

1 sample, 25mm wide and 25mm long, were cut from welded plate for macrographic examination. After grinding and polishing, sample was etched with Nital etchant for 45 seconds to check the uniformity of the weld groove and HAZ.

3.2.4.2 Metallography

A metallographic analysis performed to characterize the microstructure resulting from the welding process done on the welded plate. A Nital solution was used to etch the sample. An optical microscope model Nikon Eclipse ME600 was used for the observations.

3.2.4.3 Vickers hardness test

This test was based on ASTM E384-99: Standard Test Method for Microindentation Hardness Materials. The macrographic samples were used to measure the hardness. Microhardness tester LM 247AT machine were used to measure Vickers Microhardness with the load of 10gf. The area that measured was base metal, HAZ, and weld metal. Fifteen reading taken from each part of the material and the average is the hardness of the part.

3.2.4.4 Non-destructive examination

a. Visual inspection

   Inspect the weldment using naked eyes and magnifying glass. The type, geometry, size, location, and orientation of the discontinuities identified and locate.

b. Liquid penetration examination

   This test will use fluorescent liquid penetrant exam using the water-washable process as in E1209-99. The summary of test methods is; A liquid penetrant is applied evenly over the surface being tested and allowed to enter open discontinuities. After suitable dwell time, excess surface penetrant is removed with water and the surface is dried prior to the application of a dry or non-aqueous developer. The test surface is then examined visually under a darkened area to determine the presence or absence of indication.

c. Magnetic particle test

   Standard: ASTM E1444-01 Standard Practice for Magnetic Particle Examination.

   The Magnetic Particle Inspection method of Non-Destructive testing is a method for locating surface and sub-surface discontinuities in ferromagnetic material. The surface to be examined cleaned, dried, and free of any contaminant. A non-destructive coating applied to the surface. Magnetized the surface using a yoke and applying wet magnetic particles to study the crack.

3.2.5 Exposure

The materials exposed in salt environment using ASTM G41-90. Figure 3.2 below shows the cyclic corrosion test chamber used in the exposure experiment. The temperature of the test environment is set at 35°C. The machine setting is according to ASTM standard installed. The test period is 1-day, 3-days, and 5-days respectively. One of the specimens taken out each of the test period is finished.

Figure 3.2: Cyclic Corrosion Cabinet Model SF/450/CCT

3.2.6 Inspection after Exposure

Specimen will be inspected for the following condition:

a. Microstructure of welded specimen before exposing to salt water
b. Presence or absence of cracks over the time interval and its location
c. Microstructure of the cracked area if any
d. Hardness of the material using Vickers Microhardness test machine.

3.2.7 Reports

Result will be detailed on the WPS used. Time taken for crack occurrences if any will be recorded. All the discontinuities found in weldment after non-destructive examination will be also recorded.

3.3 Preparation of Metallographic Specimens

One of the important procedures in inspecting the welding part is preparing Metallography specimens. The objective of this examination is to reveal the constituents and structure of metals and their alloys. Standard used in performing the specimens were ASTM E3-01: Standard Guide for Preparation of Metallographic Specimens. The steps for proper metallographic specimen preparation include: Selection, size, sectioning and cutting, cleanliness, mounting, and grinding & polishing of metallographic specimens. Etching process, microscopic analysis and hardness testing were done after polishing of the specimen.

a. Selection of metallographic specimens

In examining the microstructure of base metal (BM), heat affected zone (HAZ), and weld metal (WM), half section that represent all the part were cut. Figure 3.3 below shows the sections that were cut for examining the microstructure.

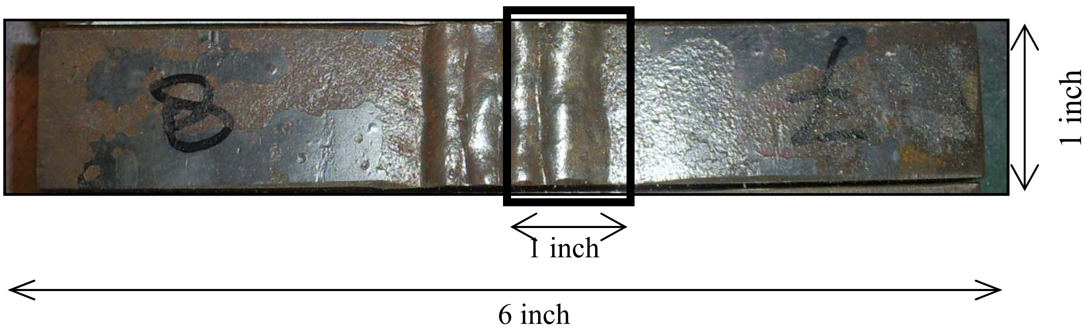


Figure 3.3: Size (1 inch^2) of section cut from original specimen

b. Size of metallographic specimens

For convenience, specimens to be polished are generally not more than about 12 to 25mm (0.5 to 1.0 inch) square. The size of the specimens is 1.0 inch square.

c. Cutting of metallographic specimens

Care must be exercised to minimize altering the structure of the metal studied. Using bend saw with continuous flow of coolant, the metallographic specimen were cut off from body of weld metal. Figure 3.3 below shows the bend saw used in cutting process.

Figure 3.4: Bend Saw Machine

d. Cleanliness

All grease, oils, coolants and residue from cut-off blades on the specimen were removed. Layer of rust also removed using solvent available.

e. Mounting

Mounting of the specimen usually performed on small, fragile, or oddly shaped specimen. Welded specimen used to be inspected in this project is big enough to hold during grinding and polishing, so mounting process is not necessary.

f. Grinding and polishing

Grinding is process for removal of surface metal by abrasive material. There are two type of grinding stage used. First is rough grinding by using 240 grit (P220) and coarser paper on continuous flow of tap water on rotating grinder. Figure 3.5

below shows the grinding machine used. This planar grinding used to flatten an irregular cut surface, remove sectioning damage, and remove substantial amount of specimen material to reach desired plane for polishing, and level the mount surface. Fine grinding used 360 grit (P600) paper and finer in the same condition as first stage. After all grinding is done; the specimen is cleaned thoroughly before polishing process.

Figure 3.5: Grinding machine

Polishing steps used to remove the damage produced during cutting and planar grinding. Polishing accomplished with diamond abrasive ranging from 6 micron down to 1 micron diamond. Figure 3.6 below shows polishing machine used. Polishing will result in mirror like surface before etching process.

Figure 3.6: Auto Grinder Polisher

g. Etching

The purpose of etching is to optically enhance microstructural features such as grain size and phase features. Nital 2 etchant which consist of 100ml Ethanol together with 2ml nitric acid were etched to polished surface for 45 seconds. After 45 seconds, the specimen placed under water stream to stop etching action. The specimen then cleaned with alcohol and dried using dryer. Microscopic examination is then used to see the microstructural features.

3.4 Tools and equipment required

The main equipment and tool required for this research project are as follows;

a. Material: as welded ASTM A516 Grade 70
b. Welding equipment and consumables (which is stated in WPS)
c. Metallographic preparation equipment
d. Vickers micro hardness test machine
e. Cyclic corrosion chamber
f. NDT test equipment

3.5 Project planning

Gantt chart was prepared for the planning of the project from the proposal phase until completion of the project phases. The chart used to illustrate the progress and planning of the entire final year project.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Material Description

ASTM A516 Grade 70 is a carbon steel plate made to a fine grain practice. It is intended for use in moderate and lower temperature pressure vessel applications.

4.1.1 Chemical Composition

Table 4.1 below shows chemical composition of metal studied.

Table 4.1: ASTM A516 Gr. 70 chemical composition

Composition	Over ½ inch through 2 inch (%)
Carbon	0.28
Manganese	0.85/1.20
Phosphorus	0.035
Sulphur	0.035
Silicon	0.15/0.40

4.1.2 Mechanical Characteristic

Tensile Strength: 70,000 - 90,000 psi

Min. Yield Strength: 38,000 psi

Elongation in 2 inch: 21% minimum.

Elongation in 8 inch: 17% minimum.

4.2 Macrography

Prior to making the exposure test, a macrographic examination of section taken from the welded joint was performed. Half of the weld section were cut using bend saw to check the uniformity of the weld and HAZs. Macrographic examination was also performed to study the hardness of weld metal, HAZ, and base metal. Figure 4.1 shows the different region of welded joint of the weld metal.

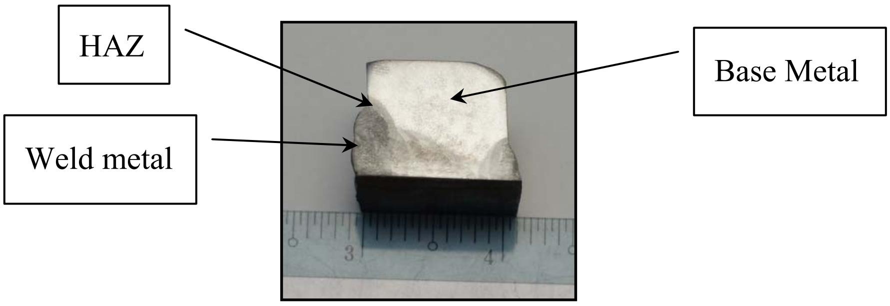
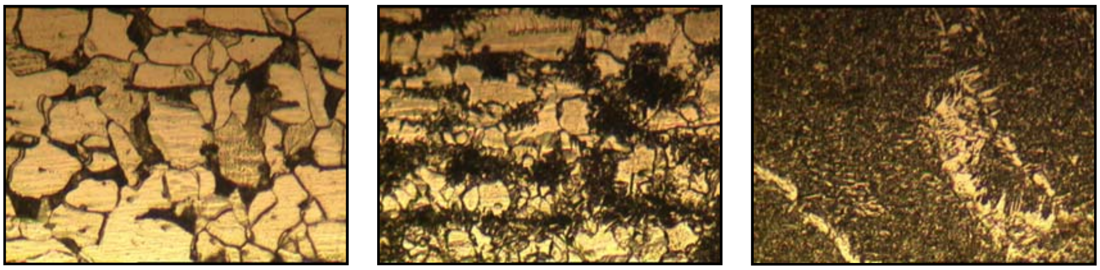


Figure 4.1: Macrography of the welded section.

4.3 Metallography

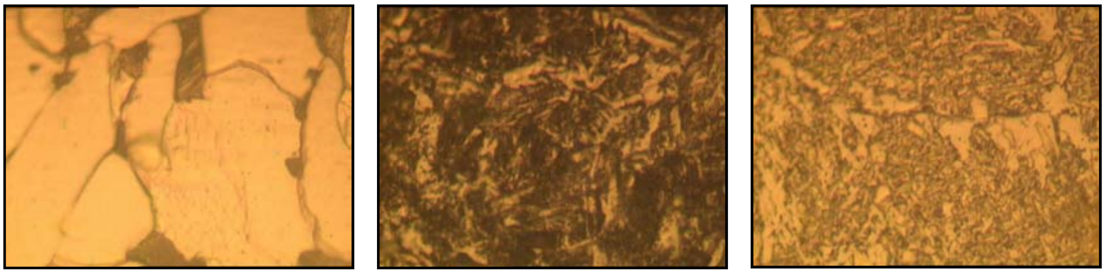
The primary objective of metallographic examination is to reveal the constituents and structure of metal and their alloys. From the metallographic specimen studied, the weld metal, HAZ, and base metal microstructure were discussed below.



(a) **(b)** **(c)**

Figure 4.2: Microstructure of weld region under 20X magnification of (a) Base Metal, (b) HAZ, and (c) Weld Metal

The grain structure of weld metal is finer than the HAZ and base metal. This is due to mechanism of partial grain refining in welding process. Figure 4.2 shows the respective area under fifty times magnification. Figure 4.3 below shows the different of grain structure of parent metal and HAZ. HAZ in the figure have smaller grain structure compared to the parent metal.



(a) (b) (c)

Figure 4.3: Microstructure of weld region under 50X magnification of (a) Base Metal, (b) HAZ, and (c) Weld Metal

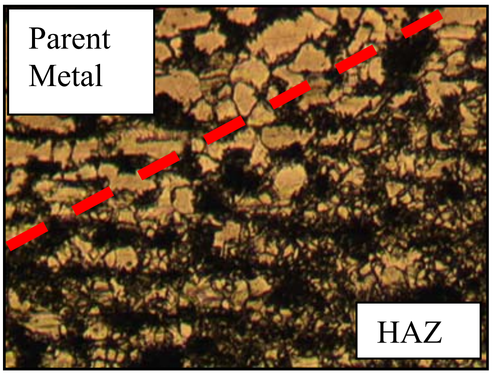


Figure 4.4: Microstructure of HAZ and PM with 10X magnification.

4.4 Vickers Hardness measurement

Hardness measurements were made on the BM, HAZ, and WM. The measurement was made scattered in the respective are. Fifteen reading were taken using Microhardness Testing Machine (LM247 AT). The value of the Vickers Hardness is the average of the reading taken was shown in table 4.2 below.

Table 4.2: Hardness value of the welded part using 10gf load

Base Metal	HAZ	Weld Metal
179	224	213
Load: 10gf Dwell time: 15 sec Indentor: diamond pyramid with face angle of 136°±0.5°		

Since there is no work done to the specimen, the hardness of the specimen will be almost the same after the exposure. The HAZ has higher hardness value compared to WM and BM. The HAZ in carbon steel can be related to the Fe-C phase diagram, as shown in figure 4.5, if the kinetic effect of rapid heating during welding on phase transformation is neglected. The HAZ can be considered to correspond to the area in the workpiece that is heated to between the lower critical temperature A1 (the eutectoid temperature) and the peritectic temperature. Similarly, the PMZ can be considered to correspond to the areas between the peritectic temperature and the liquidus temperature, and the fusion zone to the areas above the liquidus temperature [11].

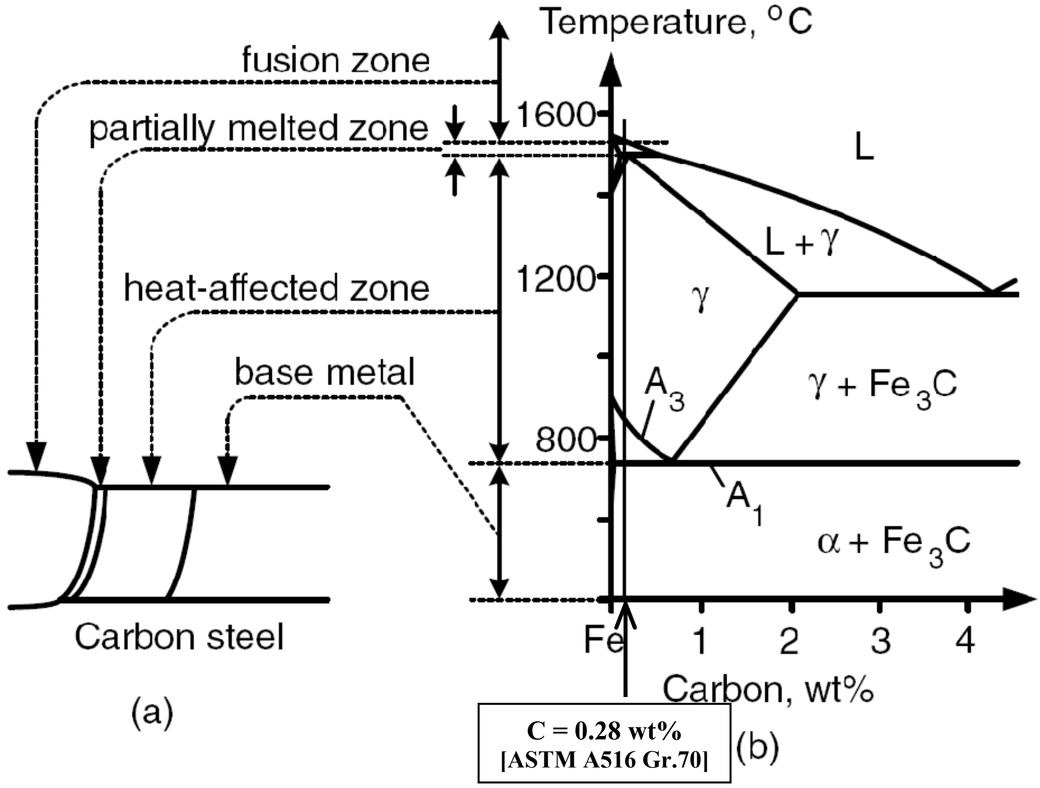


Figure 4.5: Carbon steel weld: (a) HAZ; (b) phase diagram [11]

The HAZ microstructure can be divided into essentially three regions: partially grain-refining, grain-refining, and grain-coarsening regions. The grain refining of the coarse-grain fusion zone by multiple-pass welding has been reported to improve the weld metal toughness.

Figure 4.6 and Figure 4.7 below shows the mechanism of partially grain refining in a carbon steel as found by Kou [11]. PTS 20.112 state that for weld in carbon steel components or pipe designated for sour service, the hardness shall not exceed 248 HV10. Individual hardness values in the weld, or in the HAZ of normalized carbon steel, must be below than 300 (HV10) [26].

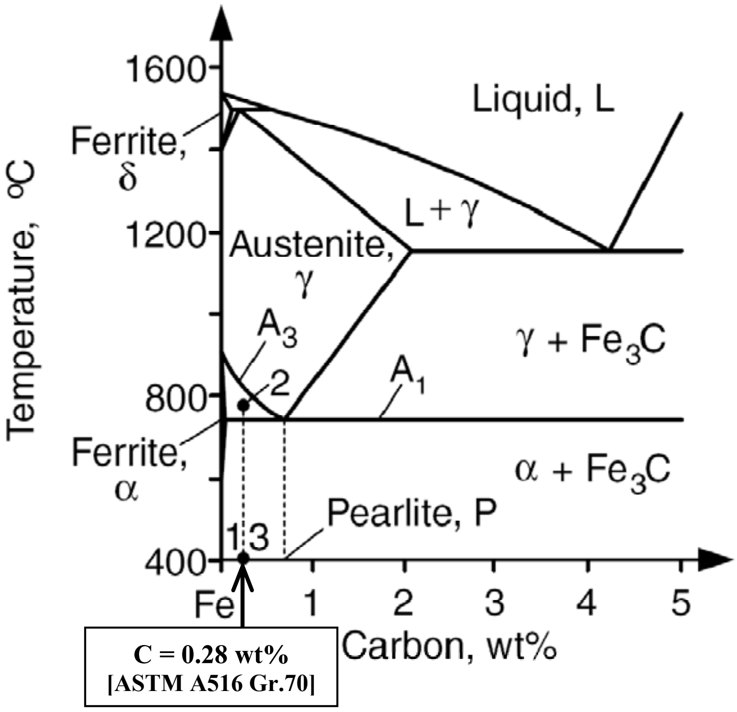


Figure 4.6: Mechanism of partial grain refining in carbon steel [11]

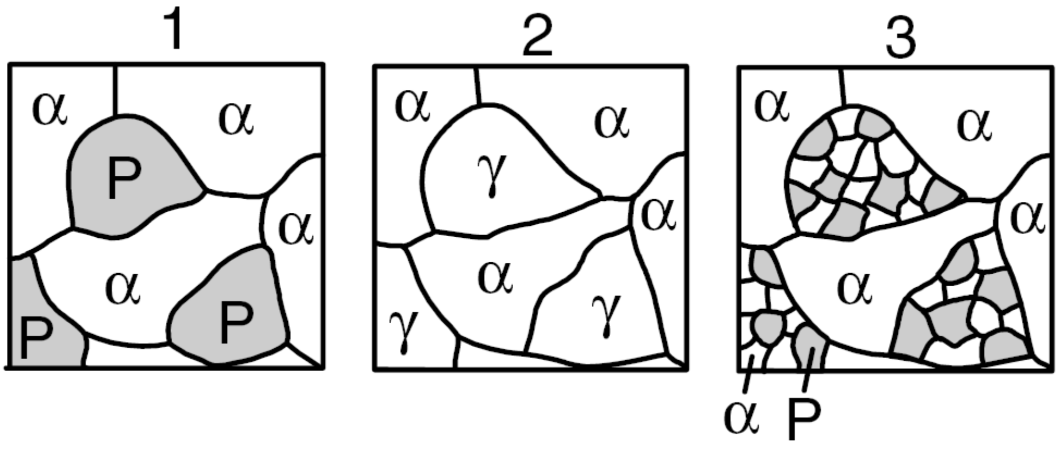


Figure 4.7: Pearlite (P) colonies transform to austenite (γ) and expand slightly into the prior ferrite (α) colonies upon heating to above A_1 and then decompose into extremely fine grains of pearlite and ferrite during cooling [11].

Figure 4.8 below shows the microstructure of ferrite (α) and Pearlite (P) of low carbon steel ASTM A516 Grade 70 after the welding process.

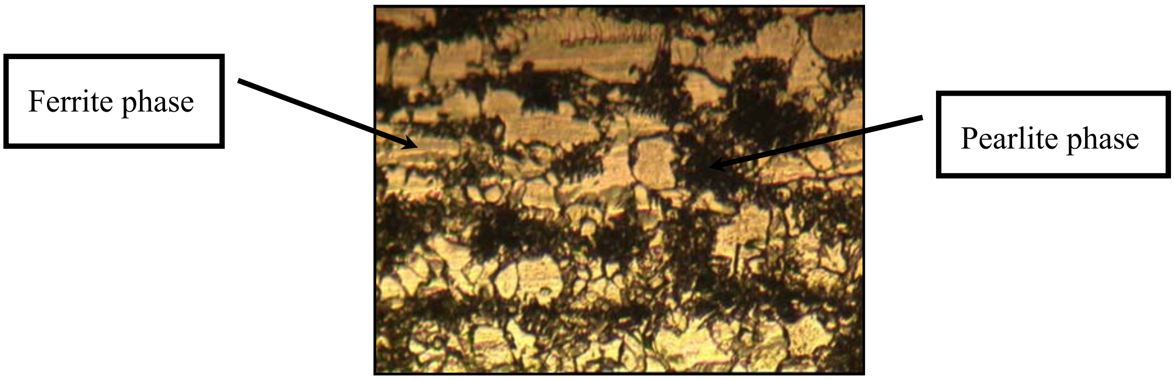


Figure 4.8: Microstructure of Pearlite and Ferrite after grain refining process

4.5 Exposure to salt environment

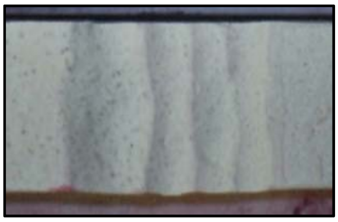
Specimen No.	Initial condition		Observation
	Dye penetrant examination	Magnetic particle examination	
1.			No crack initiation detected
2.			No crack initiation detected
3.			No crack initiation detected

Figure 4.9: Initial condition inspected with dye penetrant examination

Three as welded specimens placed in cyclic corrosion salt chamber were taken out after different periods of exposures. After 24-hours of exposure, one of the specimens was studied. Non-destructive examinations were performed to examine and study the surface crack occurrences. The test includes magnetic particle test and liquid penetrant test. Figure 4.9 show the initial condition of the welded specimen before it is exposed to the test chamber. From the observation, there are no cracks appearing before the weld material is exposed to test conditions.

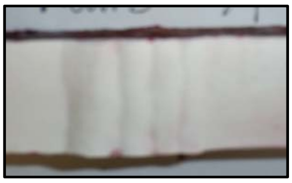
No.	Exposure period	NDT Inspection result		Observation
		Dye-Penetrant test	Magnetic particle test	
1.	1-Day			Crack does not initiate. The surface has a tiny layer of rust.
2.	3-Days			No crack indication. More layer of rust happen at the surface of specimen.
3.	5-Days			No crack happen and the metal start to corrode more

Figure 4.10: Observation after 1-day, 3-days, and 5-days exposure period

Figure 4.10 shows the welded specimens after exposing them to salt environment. Each of the specimens was having rust after it was exposed to the salt environment. But, the upper surface of the specimen does not have any rust. After 5-days of exposing the welded material in cyclic corrosion chamber in salt environment, there is no crack appearing on each of the specimen. Using all the NDT method available, there are no surface cracks and slight subsurface crack were visible. There may be internal crack occurring, but within the limit of the equipment available, the internal crack cannot be detected.

It is understood from Turnbull [8] that maybe the laboratory testing and modelling assumption may not be realistic in this testing to promote a crack occurrence. A longer period of exposure together with more extreme condition should be tested to evaluate the behaviour of welded specimen.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The influence of simulated offshore environment on welded of an ASTM A516 Grade 70 Pressure Vessel Steel using WPS FSP-HLE-17-49 subjected to different duration of exposure were studied. The results obtained from the non-destructive tests, macrographic and micrographic evaluations and hardness measurement led to the following conclusion;

a. The effect of chloride due to offshore environment on the welded specimen had shown that, after 1-day, 3-days, and 5-days of exposure, there were no surface crack found. The NDT techniques confirmed that the surface crack did not appear. However, there were layer of rusts appear after the exposure.
b. The parameter such as welding process, preheating and interpass temperature, and electrical parameter (voltage and current) used in the WPS FSP-HLE 17-49 has prevented the occurrence of welding discontinuities on the welded low-carbon steel ASTM A516 Grade 70. The welds were completely fused without any initial crack.
c. The hardness of the welded materials had shown that the weld and HAZ average hardness of 213 (HV10) and 224 (HV10) respectively. This was well below Vickers hardness 300 (HV10) for weld and 248 (HV10) for HAZ in order to prevent any crack as per PTS 20.112. The microstructures of the HAZ were found to be Austenitic and Pearlitic without the present of Martensitic structure. Prevention of the occurrence of Martensitic structure was successfully done by heating process before and after each weld pass.

The main positive conclusion would be if the welding is done in strict compliance with the code and standard, high weld integrity will be produced.

5.2 Recommendation

However, due to the limited test conditions during the study, the following recommendation may be considered for further studies;

a. To determine the mechanical properties such as tensile strength, impact resistance, and fracture toughness of the welded materials due to chloride attack.
b. To determine the components of materials using XR-D machine.
c. To study the internal discontinuities, the used of Radiography Examination machine and Ultrasonic Testing machine should be utilized.
d. Besides mechanical testing and Non-Destructive Examination, exposing the weld to the on-site environment is one of the requirements to qualifying a WPS.

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