INVESTIGATION OF CORROSION EFFECTS ON ALUMINUM-STAINLESS STEEL WELD JOINT

NURUL ASMIDA BINTI KAMARUDDIN

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UNIVERSITI MALAYSIA PAHANG

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ABSTRACT

In this study, effect of changing welding parameters on microstructure, mechanical properties and corrosion rate was investigated. Aluminum alloy AA6061 joined stainless steel AISI304 with same thickness of 2 mm welded using automatic MIG welding with filler metal ER5356 where arc current and arc voltage were chosen as variable parameters. Microstructure of welded area was studied using metallurgy microscope, mechanical properties observed by Vickers hardness and corrosion rate determined in artificial corrosion test with seawater aqueous solution. Results indicated that weld metal consist Al-Si in dendritic structure and formation brittle intermetallic compound at interface aluminum alloy-stainless steel. Weld metal performed with finer microstructure and heat affected zone (HAZ) in coarse grain structure. Black surface and pitting formed after corrosion. Minimum hardness was found at fusion zone of weld metal and after corrosion hardness slightly decreased due to the pitting corrosion. Corrosion rate was determined by potentialdynamic polarization curves. Sample which has lower corrosion rate means better corrosion resistance. The optimum parameters were 93A current and 13.5V voltage.

ABSTRAK

Dalam kajian ini, kesan perubahan kimpalan parameter pada mikrostruktur, sifat mekanik, dan kadar kakisan telah disiasat. Aloi aluminium AA6061 digabungkan dengan keluli tahan karat AISI304 dengan ketebalan yang sama iaitu 2mm yang mana dikimpal menggunakan automatik kimpalan gas lengai dengan logam pengisi ER5356 dimana arus arka dan voltan arka telah dipilih sebagai pemboleh ubah bebas. Mikrostruktur kawasan kimpalan telah dikaji menggunalan mikroskop metalurgi,manakala sifat mekanik yang diperhatikan oleh kekerasan Vickers dan kadar kakisan yang ditentukan dalam ujian tiruan kakisan dengan larutan air laut. Hasil kajian menunjukkan bahawa logam kimpalan terdiri daripada aluminium-silikon dalam struktur dentritik dan kompoun pembentukan intermatalik rapuh di permukaan aloi aluminium dan keluli tahan karat. Mikrostruktur yang diperhatikan di dalam logam kimpal adalah lebih halus dan haba zon terkena adalah dalam struktur bijian kasar. Permukaan hitam dan bopeng terbentuk selepas kakisan. Kekerasan minima didapati di zon pelakuran logam kimpal dan selepas kakisan berlaku, kekerasan sedikit menurun disebabkan oleh kakisan bopeng. Kadar kakisan telah ditentukan oleh keluk polaraisasi potensi dinamik. Sampel yang mempunyai kadar kakisan yang lebih rendah bermaksud rintangan kakisan yang lebih baik. Parameter yang optimum adalah menggunakan 93A arus dan 13.5V voltan.

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LIST OF SYMBOLS

U	Welding voltage
I	Welding current
V	Welding speed
J	Heat input
HV	Vickers Hardness
F	Applied load
d	Diameter

LIST OF ABBREVIATIONS

AA	Aluminium alloy
Al	Aluminium
C	Carbon
Cr	Chromium
Cu	Copper
e	Electron
Fe	Ferum
H	Hydrogen
H_2O	Water
HAZ	Heat affected zone
IMC	Intermetallic compound
Mg	Magnesium
MIG	Metal inert gas
Mn	Manganese
N	Nitrogen
NaCl	Sodium Chloride
Ni	Nickel
O	Oxygen
P	Phosphorus
S	Sulphur
Si	Silicon
TWB	Tailor welded blank
Zn	Zinc

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Welding is a fabrication or scriptural process of joining materials, usually metals by using coalescence. This is often done by melting the work pieces and adding a filler metal to form a pool of molten material (the weld pool) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. Corrosion is degradation of materials properties due to interactions with their environment where corrosion is failure of welds occur when the cycle of heating and cooling that occur during the welding process affects the microstructure and surface composition of welds and adjacent base metal. All structural metals and metal joints corrode to some extent in natural environments like the atmosphere, soil, and also waters.

Most corrosion processes involve at least two electrochemical reactions (one anodic and one cathodic). A short circuit is the electrical connection made by a conductor between the two physical sites, which are often separated by very small distances. Electrochemical corrosion in aqueous solutions is caused by a flow of electricity from one metal to another, where this condition allows the flow of electricity. This project is to investigate the corrosion effect on welding joint of dissimilar materials, namely aluminum-stainless steel joints.

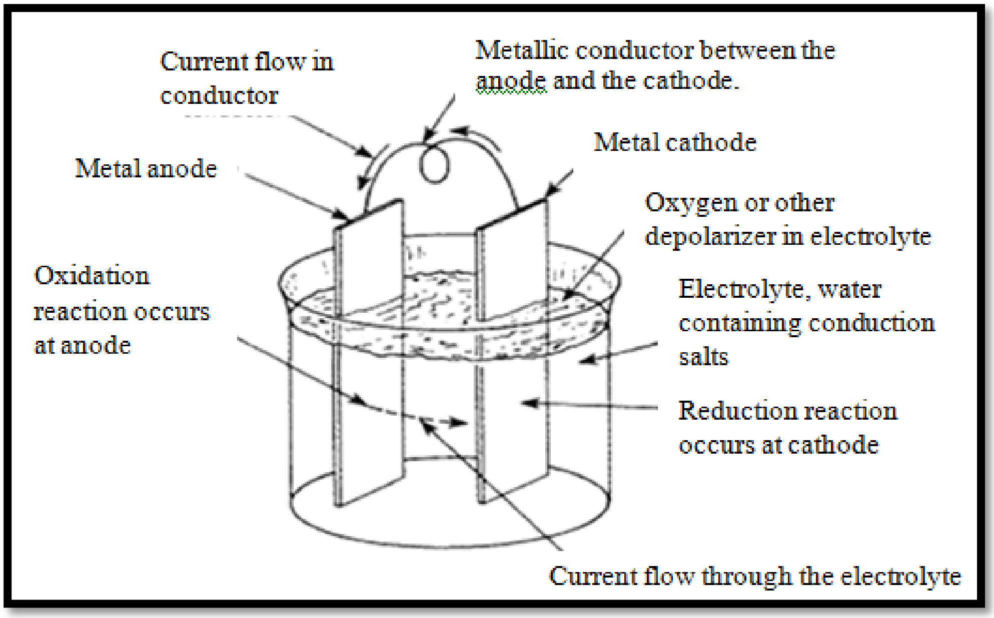

Figure 1.1: Simple electrochemical cell

Source: Surface Engineering for Corrosion and Resistance book (2001)

The cell shown in Figure 1.1 illustrates the electrochemical corrosion process in the simplest form. In this figure, the experiment uses water that contains salt as electrolyte. The electrolyte is necessary for corrosion to occur. The anode would be corroding. This is also an oxidation reaction. The formation of hydrated red iron rust by electrochemical reactions may be expressed as follows:

Anode:

$4Fe \rightarrow 4Fe^{2+} + 8e^{-}$

$$4Fe + 3O_2 + H_2O \rightarrow 2Fe_2O_3 \cdot H_2O \quad (1.1)$$

Cathode:

$4Fe + 2O_2 + 4H_2O \rightarrow 4Fe(OH)_2$

$$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3 \cdot H_2O + 2H_2O \quad (1.2)$$

During metallic corrosion, the rate of oxidation equals the rate of reduction. Thus, a nondestructive chemical reaction, reduction, would proceed simultaneously at the cathode. The hydrogen gas is produced on the cathode. If oxygen and water are both present, corrosions will normally occur on iron and steel.

In this project, the welding joint is exposed under seawater for purpose of corrosion phenomenon in the joint. The result of the research should indicate the corrosion effect on the weld joint of aluminum and stainless steel sheets by using sea water. The weld quality, defects as well as microstructure of the joint will be examined and analyzed.

1.2 PROBLEM STATEMENT

In recent years, study of corrosion on weld joints has become significant. The main reasons for concern and study about corrosion are safety, economy, and conservation. For example in the real life, corrosion causes a lot of predicaments such as decreasing the strength of the material, compromising the hardness of the material and automatically affecting the performance of the structure. The concern of corrosion study on the weld joint is important to overcome this problem. Thus, in this project, to investigate the corrosion effects on weld joint of dissimilar materials, an important thing to know is the optimum value of parameters selected such as welding parameters and filler metal. It is hoped that the optimum selection of parameter values will results in better welding joint and better corrosion resistance. The filler material can be important due to its ability to increase or decrease the corrosion resistance of the joint material.

The aimed of this project is to investigate the data on the formation of stress corrosion cracking on the aluminum alloy-stainless steel dissimilar weld joint, as well as change in the specimen’s weld joint microstructure properties, which may effect on mechanical properties of material.

1.3 PROJECT OBJECTIVES

The main objectives of doing this project are:

i. To investigate dissimilar welding of aluminum-stainless steel sheets.
ii. To investigate the weld quality and defects before and after corrosion.
iii. To investigate corrosion rate by varying welding parameters.
iv. The effect on corrosion rate with changing the parameters of welding using MIG welding.

1.4 SCOPE OF THE PROJECT

The scopes of this project are:

i. Fabrication of aluminum alloy-stainless steel weldment using MIG welding.
ii. Investigate the microstructure and mechanical properties before and after corrosion.
iii. Investigate what are the optimum welding parameters that give lower corrosion rate on weld joint.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter will discuss about the related issues in this project. It explains about joining two dissimilar materials which are aluminum and stainless steel by using Metal Inert Gas (MIG) and also some explanations about important areas on the weld joint.

2.2 WELDING AND WELDED AREA

Welding is a material joining process for a permanent combination of two or more parts that involves melting and subsequent solidification of the material thus forms a strong joint between them. Weldability means the welding process is intended to produce as homogenous properties as possible in the weld, and the materials affected by the weld must have at least the same strength, corrosion resistance, oxidation resistance as the base material. The properties of the weld metal are determined largely by the choice of filler material, the type of base material, the welding method and the welding methodology (Weman, 2003).

Some other terms we should be familiar with are used to describe areas or zones of welds. The fusion zone, as shown in Figure 2.1 is the region of the base metal that is actually melted. The depth of fusion is the distance that fusion extends into the base metal or previous welding pass. The fusion zone is the result of melting which fuses the base metal and filler metal to produce a zone with a composition that is most often different from that of the base metal. The fusion zone also has a thin region adjacent to the fusion line, known as the unmixed (chilled) region, where the base metal is melted and then quickly solidified to produce a composition similar to the base metal. Another zone of interest to the welder is the heat affected zone (HAZ), as shown in Figure 2.1. This zone includes that portion of the base metal that has not been melted. However the structural or mechanical properties of the metal have been altered by the welding heat. Its microstructure is different from the base material prior to welding because it has been subjected to elevated temperature during welding. The properties of the HAZ are determined primarily by the composition of the base material and the amount of thermal energy delivered during welding (Baeslack et al., 1979). HAZ experienced peak temperatures high enough to produce solid-state microstructure changes but too low to cause any melting. Every position in the HAZ relative to the fusion line experiences a unique thermal experience during welding, in terms of both maximum temperature and cooling rate. Thus, each position has its own microstructure features and corrosion susceptibility. The partially melted region is usually one or two grains into the HAZ relative to the fusion line. It is characterized by grain boundary liquation, which may result in liquation cracking (Savage, 1969).

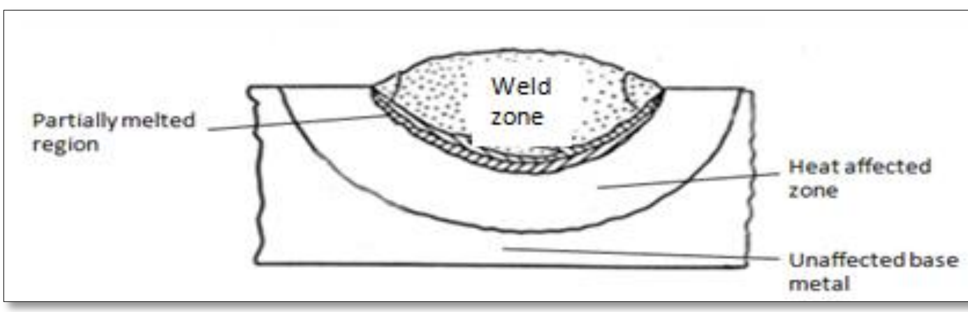

Figure 2.1: Nomenclature of zones and boundaries in heat affected zone

Source: Manufacturing Welding Fusion Weld (2011)

A weldment consists of a transition from wrought base metal through a heat affected zone and into solidified weld metal and includes five microstructure distinct regions normally identified as the fusion zone, the partially melted region, the heat-affected zone, and the base metal (Savage, 1969).

2.3 TYPE OF WELDING

Welding process is divided into two groups according to the state of the base material such as liquid-state welding (fusion welding) and solid-state welding. In industrial applications, fusion welding is far more important (Marinov, 2011).

Fusion welding means the base material is heat to melt and the several types of fusion welding are:

i. Oxy-fuel Gas Welding – an oxyfuel gas produces a flame to melt the base material.
ii. Arc Welding – heating and melting of the material is accomplished by an electric arc.
iii. Electric Resistance Welding – the source of heat is the electrical resistance on the interface between two parts held together under pressure
iv. Laser Beam Welding – utilize a high power laser beam as the source of heat to produce a fusion weld.
v. Electron Beam Welding – heat generated by high velocity narrow beam electron. The kinetic energy of electron is converted into heat as they strike the work piece.
vi. Thermite Welding - produces coalescence of metals by heating them with superheated liquid metal from a chemical reaction between a metal oxide and aluminum with or without the application of pressure (Marinov, 2011).

2.4 GAS METAL ARC WELDING (GMAW)

Metal Inert Gas (MIG) or also known as Gas Metal Arc Welding (GMAW) is type of arc welding process in which consists of heating, melting and solidification of parent metals and a filler material in localized fusion zone by a transient heat source to form a joint between the parent metals. Initially GMAW was called as MIG Welding because only inert gasses were used to protect the molten puddle. In addition of using inert shielding gases, deoxidizers usually are present in the electrode metal itself in order to prevent oxidation of the molten-weld puddle, so multiple-weld layers can be deposited at the joint (Cunat, 2007). In MIG welding, the common variations of shielding gases, power supplies and electrodes have significant effects resulting in several different and important process variations. All commercially important metals such as carbon steel, stainless steel, aluminum and copper can be welded with this process in all positions by choosing the appropriate shielding gas, electrode and welding condition (Palani and Murugan, 2006).

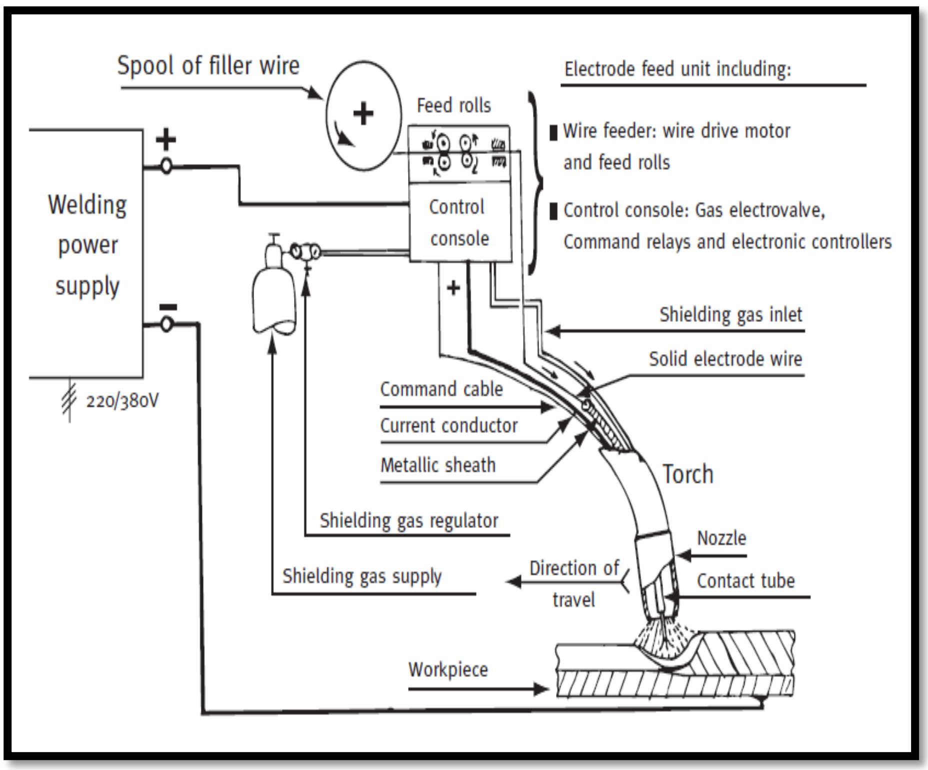

Figure 2.2: MIG operation

Source: The Welding of Stainless Steel 2nd Edition (2007)

The welding heat in MIG is produced by an arc struck between a continuously fed metal wire electrode and workpiece, shown in Figure 2.2. The other advantages of choosing this welding process are MIG works faster because of continuously fed electrode, it can produce joints with deep penetration, can be used on a various of materials and thicknesses, large metal deposition rates are achieved by MIG welding process, and also the operation is easily to handle and it used very commonly for welding ferrous metal in thin sections. Besides, there is no flux involved, hence MIG welding produces smooth, neat, clean and spatter free welded surfaces which require no further cleaning. This helps to reduce total cost welding, and it also could reduce distortion because its higher arc travels. This type of welding is the most widely used for the arc welding processes, suitable for everything from small fabrication or repairs, through to large structures, shipbuilding and robotic welding (Cunat, 2007).

2.5 TAILOR WELDED BLANKS (TWB)

Tailor welded blank (TWB) is one of the common welding method that is very familiar nowadays. It is because this method is a joining process of two or more materials of similar or different strengths, different thicknesses, or different surface coating to form a single part before forming operation. TWB are commonly used in automotive manufacturing such as door inner panel, center pillar, bumper, side frame rails, deck lids, and many more (Irving, 1991). In the heavy industry, TWB technological concept enables the production of stronger and light panels and the reduction of material waste which are important in environmental concerns. Moreover, this technology can induce significant differences in mechanical properties between the weld and base metals (Rodrigues et al., 2007). A TWB contains a heat-affected zone (HAZ) which has quite different mechanical properties from base materials (Jambor and Beyer, 1997). The advantage of using TWB is because of it makes material more stronger or thicker at critical part of sheet metal blank in order to increase local stiffness. This application also works to reduce the weight of automotive panels, and also to improve tolerances. There are 30% to 50% of sheet metal purchased by some stamping process which end up as scrap, and this scrap can be used for new blanks using tailor welded blank technology. Besides that, TWB also provide greater flexibility for component designers (Ghoo et al., 2001).

TWB technology is almost over 25 years in automotive applications. Some difficulty when applying TWB is continued constraining its general use in industries. Those difficulties are, the decreased formability of the welded panel when compared with non-welded one, the difficulty of welding some materials without defects or strength reduction on the weld line especially for aluminum alloys and high strength steel (Kampus and Balic, 2003).

2.6 MATERIALS

In this century, the usage of stainless steel materials increased continuously in many industrial applications and also in medical applications. This usage is applied for vessels, kitchen, building, and transportation, because of their high corrosion resistivity, beautiful appearance and it is really reasonable weldibility (Reiter et al., 2006). Austenitic stainless steels are one of the best choices of materials, as they combine very good corrosion behavior with excellent mechanical properties such as strength and toughness (Castro et al., 2003). In many cases, these stainless steels must be welded, for example, the welding of stainless-steel pipe, the welding of automotive exhaust gas systems, and welding repair of chemical industrial equipment (Lothongkum et al., 1999).

Aluminum alloy is the leader in the metallurgy of non-ferrous metals. The production of aluminum has increasing steadily since 1950. The development of applications for aluminum and its alloys, as well as the sustained rise in consumption can be attributed to several of its properties which are decisive criteria in users' choice of metals, especially in the fields of transport, building, electrical engineering and packaging. Aluminum alloy is able to retain good ductility at subzero temperature, has high resistance to corrosion, and is not toxic (Mandal, 2002). Pure aluminum melts at $660°C$. The advantages of using aluminum are about its properties which are lightness, thermal conductivity, electrical conductivity, suitability for surface treatments, corrosion resistance, diversity of aluminum alloys, diversity of semi-products, functional advantages of extruded and cast semi-products, ease with which aluminum can be formed, ease of recycling (Vargel et al., 2004).

When two or more dissimilar material are joined together, it give great advantage such as providing a whole structure with unique mechanical property. Aluminum alloy can reduce the weight of structural parts for its light weight and stainless steel has a high strength and excellent corrosion resistance. The combination of aluminum alloy and stainless steel are suggested in many aerospace applications, automotive, and also steamship which can improve the fuel efficiency, increase the fly range, and control air pollution by reducing the weight (Qju et al., 2009). Besides that, it is also gives great challenges to join these two materials because of the differences in their melting point, due to the nearly zero solid solubility of iron in aluminum and the formation of brittle Al-Fe intermetallic compound at elevated temperature (Uzun et al., 2006). Joining these dissimilar materials give differences in thermo-physical properties such as expansion coefficient, conductivity, and specific heat which can lead to residual stresses after welding that can make joining suffer from heavy cracking with brittle failure (Dong et al., 2010).

In this project, the grade of material that has been chosen is AA6061 aluminum alloy and stainless steel AISI304. The AA6061 aluminum alloy has gathered wide acceptance in the fabrication of light weight structures requiring a high strength-to-weight ratio and good corrosion resistance. Heat treatable wrought Al-Mg-Si alloys conforming to AA6061 are of moderate strength and possess excellent welding characteristics over the high strength aluminum alloys. Hence, alloys of this class are extensively employed in marine frames, pipelines, storage tanks and aircraft applications because of it is an age hardenable alloy possessing enhanced strength due to the precipitation of Mg_2Si phase upon solutionizing and artificial aging (Alexandre et al., 2007). On the other hand, the AISI304 alloy properties are resist to corrosion, product contamination prevention, resist to oxidation, ease to fabrication, excellent formability, beauty of appearance, ease of cleaning, high strength with low weight, good strength and toughness at cryogenic temperatures, and ready availability of wide range of product forms. This alloy is widely used in equipment and utensils for processing and handling food, beverages and dairy products. Heat exchangers, piping, tanks and other process equipment in contact with fresh water also utilize this alloy (Liu et al., 2006).

To make sure joining of these two materials not fail, it has to possess sufficient tensile strength and ductility. However, joining AA6061 with AISI304 by conventional fusion welding like MIG welding is a bit difficult because of the formation intermetallic compound (IMC) which could lead to decrease mechanical properties in weld joint. Because of the high difference in melting point, the material flow and formation of its microstructure will make this weldability of dissimilar welding become poor (Bang et al., 2011).

2.7 FILLER METAL

Filler metal is one of the parameter that we have to concern. This is because filler metal can gives impact on the weld joint. The Al-Mg (ER5356) filler metal is used in this experiment since it can provides an optimum combination of mechanical properties, corrosion resistance, ductility, crack resistance, and easy to welding. This filler metal can increase the strength of weld and reduce the crack sensitivity. Because of this filler is consisting major alloying element of magnesium which is ranging from 4.5%-5.5%, it will improves the tensile strength. To achieve the strong joint, base metals should react with this Al-Mg filler metal in range of 571°C-635°C, which is closed to melting point of standard aluminum alloy (Mutombo and Toit, 2011).

2.8 CORROSION

Corrosion is defined as deterioration of a material by a chemical or electrochemical attack. Metallic corrosion under aqueous conditions can take place by many mechanisms with a varied impact on the integrity of the material. Different metals corrode for different reasons, each with its own mechanisms (London and Bardal, 2003).

Understanding the corrosion degradation mode like general, localized, environmentally assisted cracking, intergranular is a key to controlling and preventing corrosion. Careful material selection, good design, and quality fabrication can help prevent the most serious corrosion problems and extend the lifetime of a component in a corrosive environment (Winston and Herbert, 2008).

General corrosion is a uniform loss of material from the surface of a metal and is the most commonly encountered type of corrosion. The metal gradually becomes thinner and eventually loses structural integrity. The following methods should be considered to minimize general corrosion (Roberge, 2008):

i. Choose the best construction materials, and then assign a corrosion allowance to the equipment that is being used. A corrosion allowance is extra thickness added to the wall to compensate for the metal expected to be lost over the equipment's life.
ii. In many corrosive environments, the weld metal may be preferentially attacked because the cast structure of the weld can be quite different from the parent wrought structure. To avoid preferential corrosion of the weld metal, use filler metals with higher alloying content (Roberge, 2008).

Seawater is classified as aqueous corrosion. Seawater is used by many industries such as shipping, offshore oil and gas production, power plants and coastal industrial plants. The main use of seawater is for cooling purpose and also firefighting in oilfield. Seawater is normally more corrosive than fresh water and thus it has more significant impact on the mechanical properties of metals because of the higher conductivity and the penetrating power of the chloride ion through surface film on the metal. Seawater is normally more corrosive than fresh water because of the higher conductivity and penetrating power of the chlorine ion through surface films on a metal. The rate of the corrosion is controlled by the chlorine content, oxygen availability and the temperature (Ahmad, 2006).