CORROSION PROTECTION OF STEEL STRUCTURE FOR INDUSTRIAL APPLICATION

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We certify that the project entitled “*Corrosion Protection of Steel Structure for Industrial Application* “ is written by *Asmerol Bin Alias*. We have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. We herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

....
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CORROSION PROTECTION OF STEEL STRUCTURE FOR INDUSTRIAL APPLICATION

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A report submitted in partial fulfillment of
The requirements for the award of the degree of
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With Automotive Engineering

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Automotive Engineering.

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I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurently submitted for award of other degree.

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To my Beloved Family:

EN. ALIAS BIN SIMAT
PUAN ROSNANI BINTI MOHD YUSOF PAN
ASMIRON BIN ALIAS
ASROHAIN BINTI ALIAS

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ABSTRACT

The present paper discusses the study of effect of corrosion protection on steel structure, effect of PH medium on steel structure and effect of deformation on corrosion rate in order to find the best solution for the corrosion problem. The objective of this is to experiment and analyze the corrosion behaviour of steel structure, to investigate the effect of corrosion protection for industrial application and to analyze the effectiveness of corrosion protections in various medium. The thesis use mild steel as the specimen and 3 medium as for the type of environment which is acid, air and alkali. The thesis presents the effectiveness of protection between cathodic protections, coating and controlled specimen as default data. The sample preparation based on ASTM guide which involving specimen cutting, specimen deformation and specimen cleaning. Specimen deformation is the step where the specimen is bended 90° at the centre of specimen. The experiment is steps where the protection applied to specimen and expose to mediums for 28 days. The analysis step start from surface analysis using SEM to specimen cleaning using reagent and weight losses measurement at the end. From the result, it is observed that cathodic protection has the lowest corrosion rate compare to coating although there’s no big differences between them and acid medium has the recorded the highest corrosion rate while alkali medium recorded the lowest corrosion rate. The obtained result indicate that acidic medium tend to increase the corrosion rate while alkaline medium tend to decrease the corrosion rate. Although cathodic protection has the best result but the coating protection chosen the best protection due the limitation that cathodic protection can be applied. Nevertheless there are some recommendation to improve the quality of protection and its environment thus corrosion reaction can be avoided.

ABSTRAK

Tesis ini membentangkan penyelidikan mengenai kesan pelindugan karat diatas permukaan keluli (aloi keras dari besi dan karbon), kesan PH persekitaran keatas permukaan keluli dan kesan pembentukan terhadap kadar pengaratan keluli atas tujuan untuk mencari penyelesaian mengenai masalah karat. Objektif tesis ini adalah mengkaji dan menganalisa sifat karat terhadap keluli, menyiasat kesan pelindugan karat dalam aplikasi industri dan menganalisa keberkesanan pelindungan karat didalam pelbagai persekitaran. Dalam tesis ini, keluli lembut digunakan sebagai spesimen dan 3 jenis persekitaran digunakan iaitu asid, udara dan alkali. Tesis ini membentangkan keberkesanan pelindungan karat antara pelindugan katod, lapisan pelindung dan spesimen kawalan sebagai data rujukan. Penyediaan spesimen mengikut piawai ASTM termasuk pemotongan spesimen, pembentukan spesimen dan pembersihan spesimen. Pembentukan spesimen ialah langkah dimana spesimen dibengkokan 90° di tengah-tengah spesimen. Eksperimen bermula dari langkah mengenakan pelindungan keatas spesimen sehingga spesimen berkarat selama 28 hari. Bahagian analisa bermula dari melakukan analisa permukaan keluli menggunakan SEM ke pembersihan spesimen menggunakan asid hidroklorik dan akhir sekali timbang perubahan berat. Berdasarkan keputusan spesimen, pelindungan katod mencatatkan kadar pengaratan yang terendah berbanding spesimen yang dikenakan cat walaupun perbezaan tidak begitu ketara dan persekitaran asid mencatatkan kadar pengaratan yang paling tinggi manakala persekitaran alkali sebaliknya.Keputusan tersebut menunjukkan bahawa persekitaran asid mempercepatkan kadar pengaratan manakala alkali sebaliknya. Walaupun pelindungan katod mempunyai keputusan yang terbaik namun pelindungan lapisan(cat) dipilih sebagai pelindugan terbaik kerana terdapat pembatasan dimana pelindungan katod boleh diaplikasikan.Walaubagaimanapun,terdapat beberapa cadangan untuk memperbaiki kualiti pelindungan dan persekitaran supaya reaksi karat dapat dielakkan

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 EXPERIMENT SETUP

CHAPTER 4 RESULT AND DISCUSSION

CHAPTER 5 CONCLUSION

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

M	Magnesium
H	Hydrogen
O	Oxygen
e	Electron
Fe	Ferum
m	meter
cm	centrimeter
°c	Degree Celcius
ml	mililiter
As	Surface Area
J	Current density

K	Constant
W	Mass losses/weight
A	Area
T	Time of exposure
D	Density
g	Gram

LIST OF ABBREVIATIONS

ASTM	American National Standard
SEM	Scanning Electronic Microscopic
mpy	Mils per year

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Corrosion is one of the major loss to industry area-costly billion per year in one state. The accepted concept of corrosion is that it is a result of an electrochemical reaction taking place on the surface of the metal where the metal is converted into metal oxides or other corrosion products. With some metals, they produce a tight skin on the metal surface, which hinders further corrosion, and if this surface layer is broken it is self-healing. These metals are said to be passivated and include lead, nickel, cadmium, chromium and aluminium. Zinc corrosion products form a fairly tight layer on zinc and further corrosion is slow. A tight layer of iron and chromium oxides forms on the surface of stainless steel and is the reason for the resistance of this metal. Iron and steel, however, form rust as a corrosion product, which is porous, is not firmly adherent and does not prevent continued corrosion[1].

There 4 basic methods for corrosion control and corrosion protection[11]:

1.Material resistant
2.Protective coating
3.Cathodic protection
4. Corrosion Inhibitors

In this study, there only 3 methods will be taken which is coating, cathodic protection and corrosion inhibitors. In this study also, there are specimens will be taken as default specimen which known as controlled specimen. This will become as a reference to the protected specimen.

1.2 PROBLEM STATEMENT

Milions of dollars are lost each year because of corrosion including cost of prevention, maintaining and loss. Much of this loss is due to the corrosion of iron and steel, although many other metals may corrode as well. The condition of the environment in the factory also main causes of corrosion happened where humidity, temperature, and PH of air become the major part. Many of factory owner didn’t realize the disaster of corrosion and how to prevent it correctly causing many accident and bad quality result in product.

1.3 PROJECT OBJECTIVE

- Study the corrosion behavior of steel structure
- Investigate the corrosion protection of steel structure for industrial application
- Study and analyze the corrosion protection and its effectiveness.
- To provide a better view on effect of corrosion to industry

1.4 PROJECT SCOPES

- Sample preparation based on standard
- Exposures period
- The Effectiveness of the protection
- Corrosion analysis
    - Surface observation
    - Corrosion rate
    - Composition analysis

1.5 PARAMETER OF PROJECT

- Coating
- Inhibitors
- Cathodic protection
- Condition of environment in factory

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The meaning of the word corrosion is "the deterioration of the substance (usually a metal) or its properties because of a reaction with its environment"[10]. Normally it specifically applies to metals, although plastics and other non-metals such as concrete, bricks and timber also deteriorate in natural environments. Corrosion causes enormous losses, which rise yearly with the increased usage of metals in industrial development.

Corrosion also means the breaking down of essential properties in a material due to chemical reactions with its surroundings. In the most common use of the word, this means a loss of electrons of metals reacting with water and oxygen. Weakening of iron due to oxidation of the iron atoms is a well-known example of electrochemical corrosion. This is commonly known as rusting. This type of damage typically produces oxide(s) and/or salt(s) of the original metal. Corrosion can also refer to the degradation of ceramic materials as well as the discoloration and weakening of polymers by the sun's ultraviolet light.

Most structural alloys corrode merely from exposure to moisture in the air, but the process can be strongly affected by exposure to certain substances. Corrosion can be concentrated locally to form a pit or crack, or it can extend across a wide area to produce general deterioration. While some efforts to reduce corrosion merely redirect the damage into less visible, less predictable forms, controlled corrosion treatments such as passivation and chromate-conversion will increase a material's corrosion resistance.

2.2 CORROSION COST

The total national yearly cost of metallic corrosion in the United States was estimated at $275 billion, or 3.1% of the U.S. gross domestic product (GDP) of $8790 billion, in 1998 .This total includes replacement costs and lost production costs as well as the decrease in lifetime and the expected replacement value of a given component subject to damage by corrosion. The cost of corrosion also includes the means by which the effects of corrosion are mitigated, such as the use of cathodic protection, inhibitors, alternative materials of construction, overdesign, and protective coatings[3].

- **Direct Costs**
- $276 billion USD annually
- 3.1% of US GDP (1998)

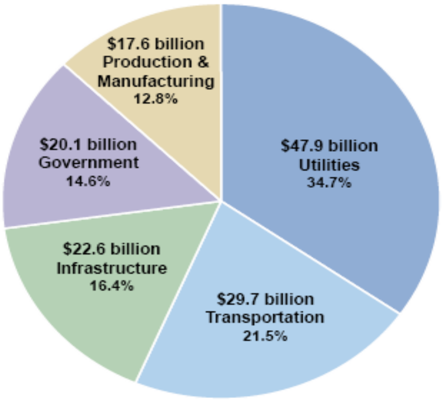


Figure 2.1: Direct cost/losses in US

Source: Barbara A. Shaw and Robert G Kelly, What is corrosion.

Indirect Costs

Catastrophe

-Public safety, property damage, environmental contamination

Natural Resources

- Waste production, increased energy

consumption

Public Outcry

-Traffic, inconvenience

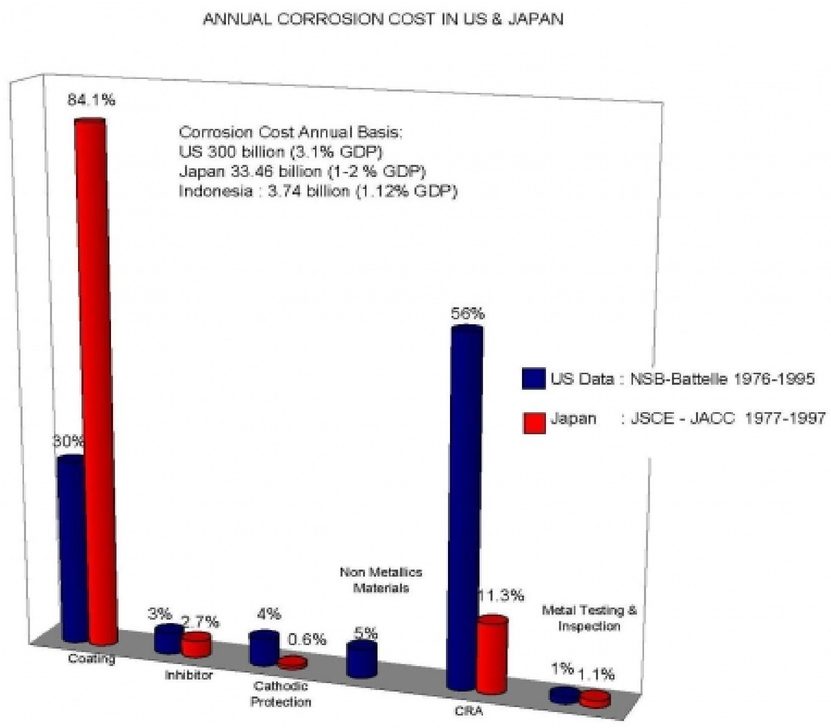


Figure 2.2: Corrosion cost distribution in US & Japan.

Source: Aswin Tino (Mottmac UAE), Dr.Ir.Slameto Wiryolukito (Material Engineering ITB), Muhammad Abduh (Reksolindo), “Corrosion: Technical and Economic Driver for Indonesia Oil and Gas Industry” Petroenergy Magazine Edition Jan -Feb 2008

2.3 CAUSES OF CORROSION

Corrosion is defined as the deterioration of a material, usually a metal, because of a reaction with its environment and which requires the presence of an anode, a cathode, an electrolyte, and an electrical circuit. To understand the application of protective coatings or cathodic protection in corrosion control, the basic concepts of corrosion of metals in the presence of moisture needs to be reviewed [11].

i. Corrosion occurs by an electrochemical process. The phenomenon is similar to that which takes place when acarbon-zinc “dry” cell generates a direct current. Basically, an anode (negative electrode), a cathode (positive electrode),man electrolyte (environment), and a circuit connecting the anode and the cathode are required for corrosion to occur (see Figure 2.3). Dissolution of metal occurs at the anode where the corrosion current enters the electrolyte and flows to the cathode. The general reaction (reactions, if an alloy is involved) that occurs at the anode is the dissolution of metal as ions:

$M \rightarrow Mn\ e\ n$

where

M = metal involved

n = valence of the corroding metal species

e = electrons

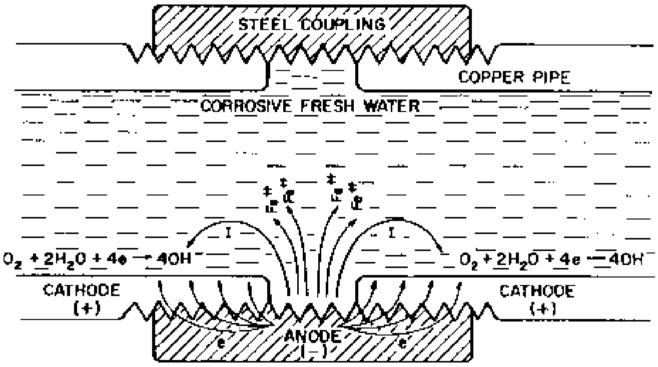


Figure 2.3: The basic corrosion cell consists of an anode, a cathode, an electrolyte, and a metallic path for electron flow. Note that the corrosion current enters the electrolyte at the anode and flows to the cathode.

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

Examination of this basic reaction reveals that a loss of electrons, or oxidation, occurs at the anode. Electrons lost at the anode flow through the metallic circuit to the cathode and permit a cathodic reaction (or reactions) to occur [11]. In alkaline and neutral aerated solutions, the predominant cathodic reaction is

$O2\ 2H2O\ 4e \rightarrow 4(OH)$

The cathodic reaction that usually occurs in deaerated acids is

$2H\ 2e \rightarrow H2$

In aerated acids, the cathodic reaction could be

$$\mathrm{O2\ 4H\ 4e} \rightarrow \mathrm{2H2O}$$

All of these reactions involve a gain of electrons and a reduction process.

ii. The number of electrons lost at the anode must equal the number of electrons gained at the cathode. For example, if iron (Fe) was exposed to an aerated, corrosive water, the anodic reaction would be

$$\mathrm{Fe} \rightarrow \mathrm{Fe\ 2e}$$

At the cathode, reduction of oxygen would occur

$$\mathrm{O2\ 2H2O\ 4e} \rightarrow \mathrm{4(OH\ )}$$

Because there can be no net gain or loss of electrons, two atoms of iron must dissolve to provide the four electrons required at the cathode. Thus, the anodic and cathodic reactions would be

$$\mathrm{2\ Fe} \rightarrow \mathrm{2Fe\ 4e\ (anodic)}$$

$$\mathrm{O2\ 2H2O\ 4e} \rightarrow \mathrm{4(OH\ )\ (cathodic)}$$

These can be summed to give the overall oxidationreduction reaction

$$\mathrm{2Fe\ O2\ 2H2O} \rightarrow \mathrm{2Fe\ 4(OH\ )}$$

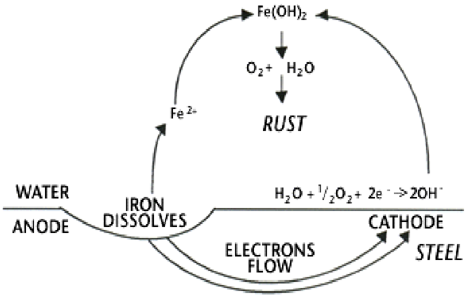


Figure 2.4: Illustration of electron transfer between anode and cathode in order to protect cathode thus anode corrode for cathode.

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

c. After dissolution, ferrous ions (Fe++) generally oxidize to ferric ions (Fe+++); these will combine with hydroxide ions (OH^{-}) formed at the cathode to give a corrosion product called rust (FeOOH or Fe2O3 x H2O). Similarly, zinc corroding in an aerated, corrosive water (i.e., Zn →□Zn++ + 2e-) will form the corrosion product Zn(OH)2. The important issue to remember is that anodic dissolution of metal occurs electrochemically; the insoluble corrosion products are formed by a secondary chemical reaction.

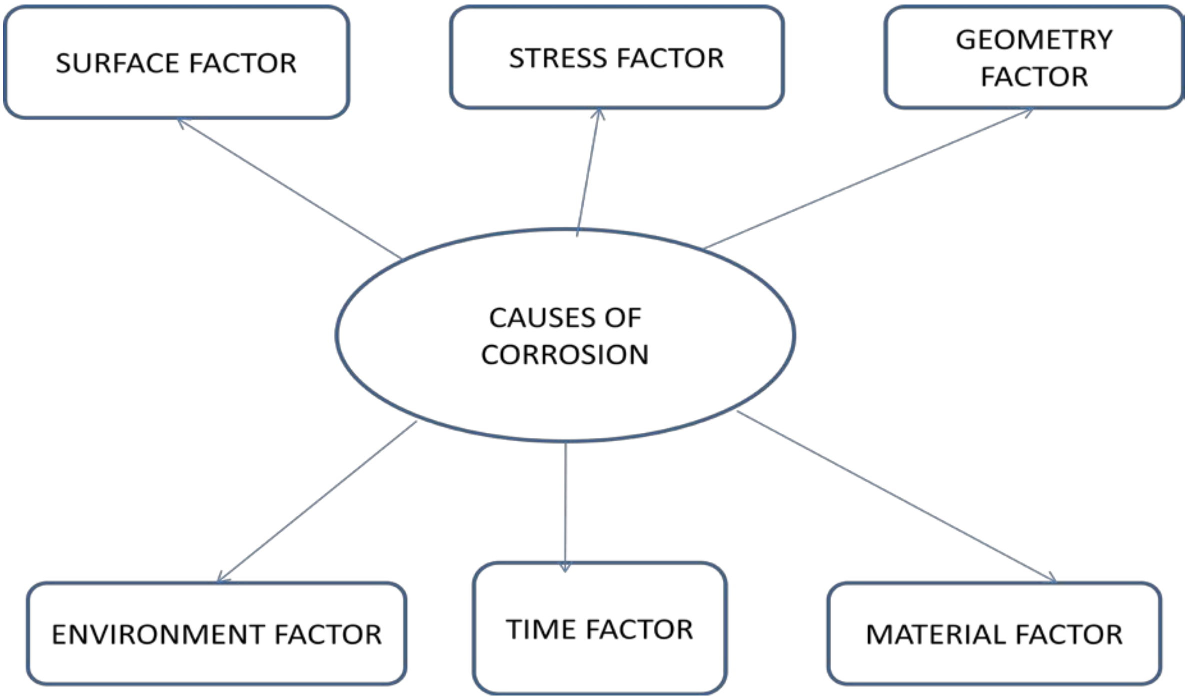


Figure 2.5: Causes of corrosion in term of the environment and properties in generally

2.1 TYPE OF CORROSION

In Industry application, there are five types of steel corrosion[12]:

1. Uniform corrosion
2. Crevice corrosion
3. Pitting corrosion
4. Galvanic corrosion

2.1.1 Uniform Corrosion

The most familiar type of corrosion is termed uniform corrosion. It tends to proceed evenly over the entire exposed surface of any uncoated part and eventually causes a general thinning of the metal. While best known, it is the least damaging.

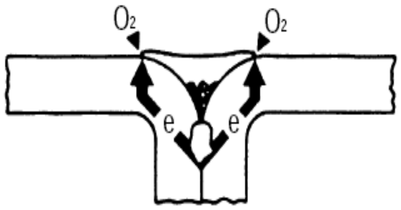
However, uniform corrosion is relatively easily measured and predicted, making disastrous failures relatively rare. In many cases, it is objectionable only from an appearance standpoint. As corrosion occurs uniformly over the entire surface of the metal component, it can be practically controlled by cathodic protection, use of coatings or paints, or simply by specifying a corrosion allowance. In other cases uniform corrosion adds color and appeal to to a surface. Two classics in this respect are the patina created by naturally tarnishing copper roofs and the rust hues produced on weathering steels [12].

The breakdown of protective coating systems on structures often leads to this form of corrosion. Dulling of a bright or polished surface, etching by acid cleaners, or oxidation (discoloration) of steel are examples of surface corrosion. Corrosion resistant alloys and stainless steels can become tarnished or oxidized in corrosive environments. Surface corrosion can indicate a breakdown in the protective coating system, however, and should be examined closely for more advanced attack. If surface corrosion is permitted to continue, the surface may become rough and surface corrosion can lead to more serious types of corrosion.

2.1.2 Crevice corrosion

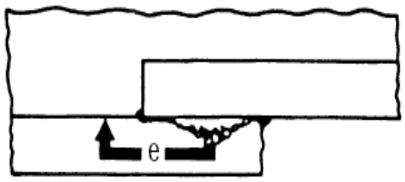
Crevice corrosion is often associated with small volumes of stagnant solution or electrolyte trapped in crevices of joints, or in surface deposits and poultices. Pitting corrosion is a localized attack, usually caused by chlorides. Pits form resulting in a roughened surface. Crevice corrosion and pitting corrosion result in an accelerated attack on the metal. In some instances, the attack is severe enough to lead to premature, and often catastrophic, functional failures [12].

Crevice corrosion is a damaging type of corrosion because it is sharply focused on localized areas,usually invisible in its early stages. The attack is swift, often resulting in unexpected or premature failure. Crevice corrosion is often associated with small volumes of stagnant solution or electrolyte trapped in holes, on gasket surfaces, at joints, under fasteners, and in surface deposits or poultices



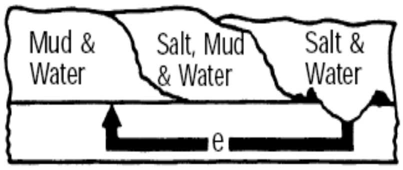
Crevice corrosion is caused by a gradient between the oxygen at the surface of the electrolyte and oxygen-starved electrolyte at the bottom of the crevice. Typical of the weldments, sheet-metal joints, and rough surfaces where water may be trapped, the oxygen gradient also causes a rough microfinished surface to corrode faster than a smooth surface.

Figure 2.6: Crevice corrosion at weld joint



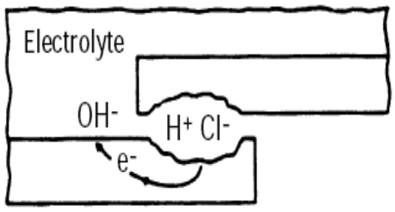
Crevice corrosion also can occur between tightly sealed joints where the concealed metal surface is oxygen starved and electrolyte may seep between irregularities in the mating surfaces. This condition also occurs where moisture-bearing materials (such as felt) are in contact with the steel.

Figure 2.7: Crevice corrosion at lap joint



Electrolyte composition gradients are probably the most common cause of corrosion. Clumps of mud frequently collect under car fenders. The varying concentrations of salt and water encourage corrosion.

Figure 2.8: Crevice corrosion under poultice



Crevice corrosion showing acid formation and increased chloride ion concentration within the crevice.

Figure 2.9: Crevice corrosion at lap joint

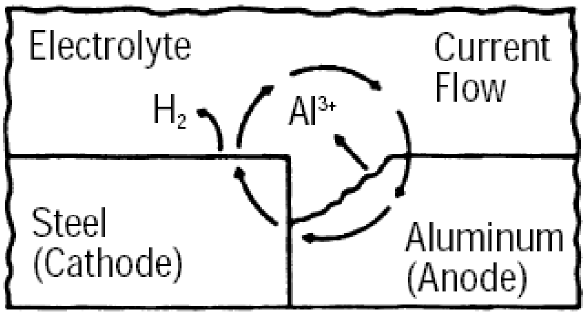
Figure 2.6,2.7,2.8,2.9: This figures showing 4 different types of crevice joint based on the location of corrosion happened.

Source: A guide to corrosion protection, Light Truck Frame Project Team Auto/Steel Partnership 2000 Town Center, Suite 320 Southfield, Michigan 48075-1123 1999

2.1.3 Galvanic corrosion

Galvanic corrosion occurs when dissimilar metals are in contact with one another in the presence of an electrolyte. It can be detrimental or beneficial.For example, an aluminum component in contact with a steel component may corrode in order to protect the steel. This situation is injurious to the aluminum component. On the other hand, steel is often given a metallic zinc coating. The zinc sacrifices itself, thereby prolonging the life of the component made from the zinc coated steel. Corrosion that initiates on a visible surface of a vehicle, usually at nicks or scratches in a post-coating, is called cosmetic corrosion. Of primary concern is poor appearance due to red rust, stain and paint blisters [12].

Galvanic corrosion, also referred to as two-metal or bimetallic corrosion, occurs when dissimilar metals are in contact in the presence of an electrolyte. The more active, or anodic, metal corrodes rapidly while the more noble, or cathodic, metal is not damaged. On the galvanic scale, aluminum and zinc are more active than steel and, in the presence of a chloride-containing electrolyte, will corrode preferentially when in contact with steel.



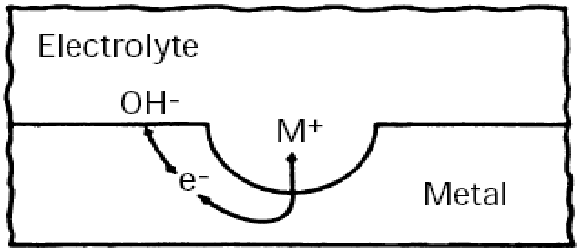
Galvanic corrosion occurs when two metals of dissimilar activity are placed in contact with one another in the presence of an electrolyte. The more active metal will anodically corrode in preference to the less active metal which, as the cathode, is protected.

Figure 2.10: Galvanic or bimetallic corrosion

Source: A guide to corrosion protection, Light Truck Frame Project Team Auto/Steel Partnership 2000 Town Center, Suite 320 Southfield, Michigan 48075-1123 1999

2.1.4 Pitting Corrosion

Pitting corrosion is a localized attack, usually caused by chlorides. The mechanism governing pit growth is similar to that of crevice corrosion. In fact, pits are “mini” crevices which usually have diameters equal to their depth. They can occur so closely spaced that they give the appearance of a roughened surface. Pitting corrosion is a self-initiating form of crevice corrosion, in that the corrosion process creates the pit or crevice, which propagates at an accelerated rate and eventually perforates the metal. Initiation of pits usually results from non homogeneity in the metal, breaks in protective films, surface deposits, defects or Imperfections [12].



Similar to crevice corrosion, pitting corrosion occurs at localized areas where oxygen has been depleted, pH has become lowered and chloride has become enriched.

Figure 2.11: Pitting corrosion

Source: A guide to corrosion protection, Light Truck Frame Project Team Auto/Steel Partnership 2000 Town Center, Suite 320 Southfield, Michigan 48075-1123 1999

2.2 CORROSION CONTROL AND PROTECTION

2.2.1 Coating

Coating is a covering that is applied to an object. The aim of applying coatings is to improve surface properties of a bulk material usually referred to as a substrate. One can improve amongst others appearance, adhesion, wetability, corrosion resistance, wear resistance, scratch resistance, etc.. They may be applied as liquids, gases or solids. Coatings can be measured and tested for proper opacity and film thickness by using a Drawdown card[11].

Powder coating is a type of coating that is applied as a free-flowing, dry powder. The main difference between a conventional liquid paint and a powder coating is that the powder coating does not require a solvent to keep the binder and filler parts in a liquid suspension form. The coating is typically applied electrostatically and is then cured under heat to allow it to flow and form a "skin." The powder may be a thermoplastic or a thermoset polymer. It is usually used to create a hard finish that is tougher than conventional paint. Powder coating is mainly used for coating of metals, such as "whiteware", aluminium extrusions, and automobile and motorcycle parts. Newer technologies allow other materials, such as MDF (medium-density fibreboard), to be powder coated using different methods [11].

2.2.1.1 Advantage and disadvantages of the powder coating

There are several advantages of powder coating over conventional liquid coatings:

1. Powder coatings emit zero or near zero volatile organic compounds (VOC).
2. Powder coatings can produce much thicker coatings than conventional liquid coatings without running or sagging.
3. Powder coating overspray can be recycled and thus it is possible to achieve nearly 100% use of the coating.
4. Powder coating production lines produce less hazardous waste than conventional liquid coatings.
5. Capital equipment and operating costs for a powder line are generally less than for conventional liquid lines.
6. Powder coated items generally have fewer appearance differences between horizontally coated surfaces and vertically coated surfaces than liquid coated items.
7. A wide range of specialty effects is easily accomplished which would be impossible to achieve with other coating processes.

While powder coatings have many advantages over other coating processes, there are limitations to the technology. While it is relatively easy to apply thick coatings which have smooth, texture-free surfaces, it is not as easy to apply smooth thin films.

As the film thickness is reduced, the film becomes more and more orange peeled in texture due to the particle size and TG (glass transition temperature) of the powder.

For optimum material handling and ease of application, most powder coatings have a particle size in the range of 30 to 50 μm and a TG > 40°C. For such powder coatings, film build-ups of greater than 50 μm may be required to obtain an acceptably smooth film. The surface texture which is considered desirable or acceptable depends on the end product. Many manufacturers actually prefer to have a certain degree of orange peel since it helps to hide metal defects that have occurred during manufacture, and the resulting coating is less prone to show fingerprints.

There are very specialized operations where powder coatings of less than 30 micrometres or with a TG < 40°C are used in order to produce smooth thin films. One variation of the dry powder coating process, the Powder Slurry process, combines the advantages of powder coatings and liquid coatings by dispersing very fine powders of 1–5 micrometre particle size into water, which then allows very smooth, low film thickness coatings to be produced.

Powder coatings have a major advantage in that the overspray can be recycled. However, if multiple colors are being sprayed in a single spray booth, this may limit the ability to recycle the overspray.

Figure 2.12: Coating on pole.

2.2.2 Cathodic Protection

Cathodic protection is an electrochemical means of corrosion control in which the oxidation reaction in a galvanic cell is concentrated at the anode, which suppresses corrosion of the cathode in the same cell [11].

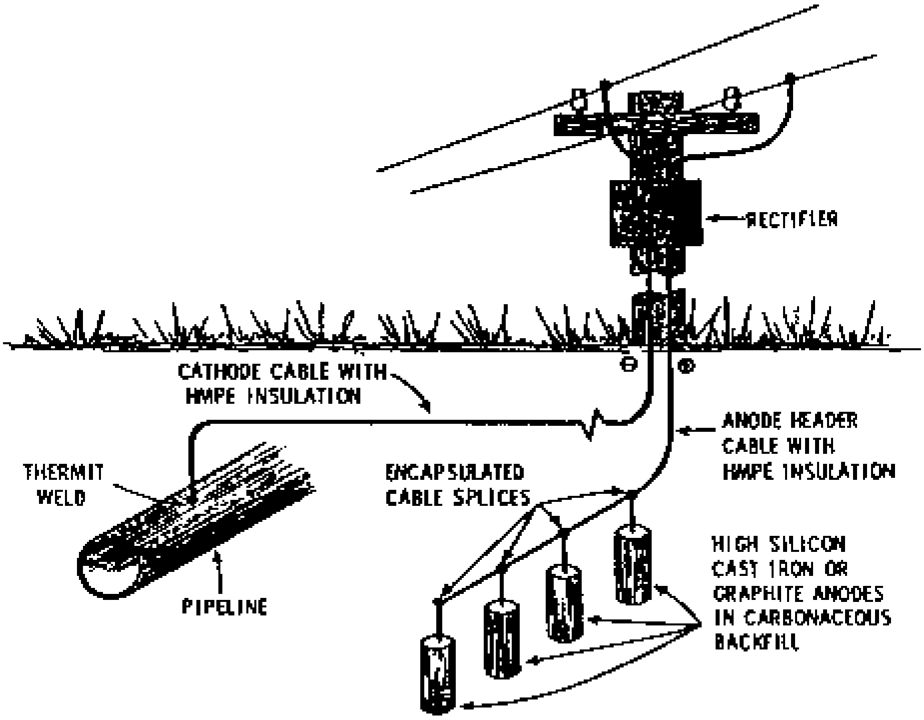


Figure 2.13: Illustration on application of cathodic protection on pipeline.

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

Cathodic protection differs from anodic protection. In cathodic protection, the object to be protected is the cathode; however, in anodic protection, the object to be protected is the anode. Anodic protection can be used on a limited number of alloys in certain restricted environments, but cathodic protection can, in principle, be applied to any metal. In practice, cathodic protection is primarily used to protect carbon steel structures.

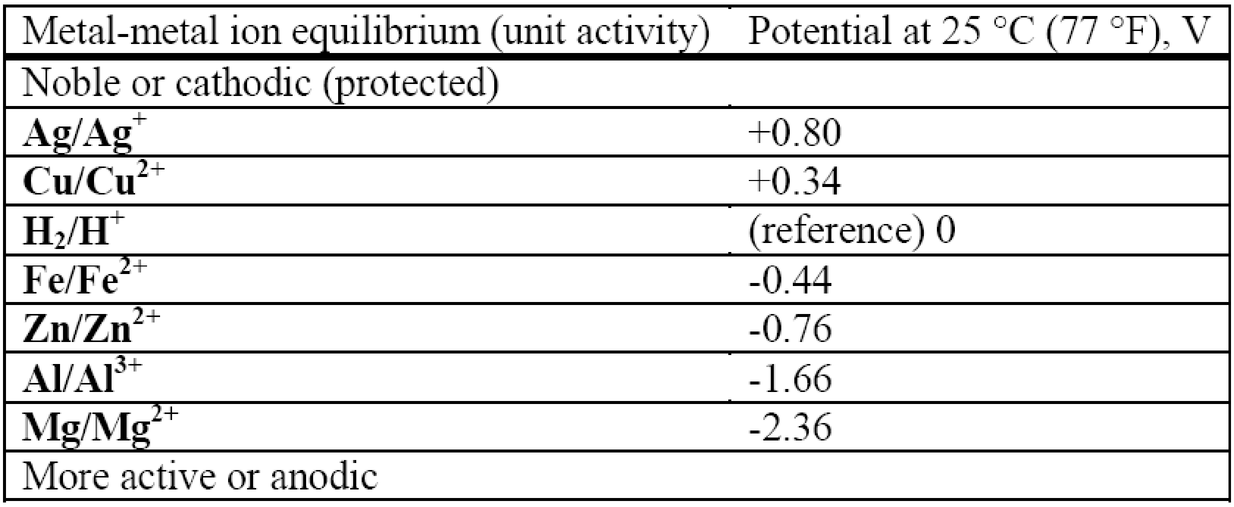
Cathodic protection allows carbon steel, which has little natural corrosion resistance, to be used in such corrosive environments as seawater, acid soils, salt-laden concrete, and many other corrosive environments. Properly designed and maintained cathodic protection systems can prevent corrosion indefinitely in these environments.

Cathodic protection was first suggested by Sir Humphrey Davy in the 1820s as a means of controlling corrosion on British naval ships. It became common in the 1930s on the Gulf Coast of the United States, where it was used to control the corrosion of pipelines carrying high- pressure natural gas and petroleum products. Much of the terminology of cathodic protection still relates to corrosion control of onshore buried steel pipelines.

Virtually all modern pipelines are coated with an organic protective coating that is supplemented by cathodic protection systems sized to prevent corrosion at gaps or holidays in the protective coating. This combination of protective coating and cathodic protection is used on virtually all immersed or buried carbon steel structures, with the exception of offshore petroleum- production platforms and reinforced-concrete structures. Offshore platforms are usually uncoated, but cathodically protected. Cathodic protection causes changes in the chemistry of seawater near the protected structure, and this causes the precipitation of a natural coating on the structure that reduces the need for cathodic protection current. Concrete structures normally rely on the protection of the concrete cover to prevent the corrosion of embedded steel. When corrosion of embedded steel occurs because of a loss of this protection due to ingress of moisture, cathodic protection is sometimes used to extend the life of the already deteriorated structure.

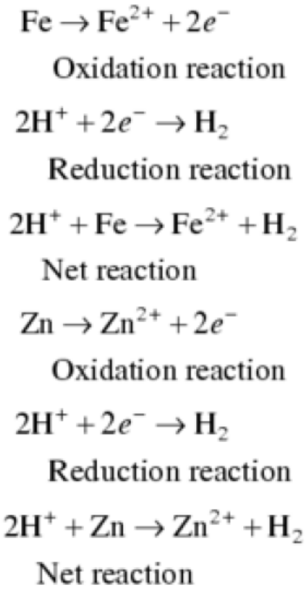
2.2.2.1 Fundamentals of Cathodic Protection

Table 2.1: Theoretical electrochemical potentials obtained by pure metals in 1 N solution of their own ions.



Metal-metal ion equilibrium (unit activity)	Potential at 25 °C (77 °F), V
Noble or cathodic (protected)	
Ag/Ag^+	+0.80
Cu/Cu^{2+}	+0.34
H_2/H^+	(reference) 0
Fe/Fe^{2+}	-0.44
Zn/Zn^{2+}	-0.76
Al/Al^{3+}	-1.66
Mg/Mg^{2+}	-2.36
More active or anodic	

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection



$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2e^-$$

Oxidation reaction

$$2\mathrm{H}^+ + 2e^- \rightarrow \mathrm{H}_2$$

Reduction reaction

$$2\mathrm{H}^+ + \mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + \mathrm{H}_2$$

Net reaction

$$\mathrm{Zn} \rightarrow \mathrm{Zn}^{2+} + 2e^-$$

Oxidation reaction

$$2\mathrm{H}^+ + 2e^- \rightarrow \mathrm{H}_2$$

Reduction reaction

$$2\mathrm{H}^+ + \mathrm{Zn} \rightarrow \mathrm{Zn}^{2+} + \mathrm{H}_2$$

Net reaction

Figure 2.14: The chemical raction between two metals—iron and zinc—separately immersed in a weak mineral acid.

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

Both metals corrode, and both oxidation reactions are balanced by an equal reduction reaction, which in both cases involves the liberation of hydrogen gas from the acid environments. The two corrosion reactions are independent of each other and are determined by the corrosivity of hydrochloric acid on the two metals in question.

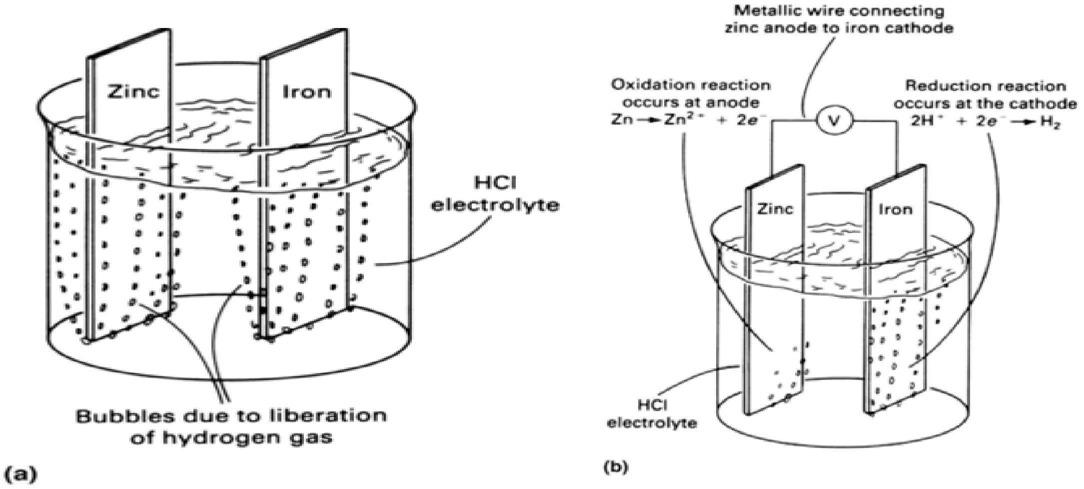


Figure 2.15: Iron and zinc in hydrochloric acid. (a) Corrosion of zinc and iron in hydrochloric acid. (b) Cathodic protection of iron by zinc in hydrochloric acid

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

If the two metals were immersed in the same acid and electrically connected
(Fig. 2.15b), the reactions would become:

$$Zn \rightarrow Zn^{2+} + 2e^-$$

Oxidation

$$2H^+ + 2e^- \rightarrow H_2$$

Reduction

Almost all of the oxidation reaction (corrosion of zinc) has been concentrated at the zinc electrode (anode) in Fig. 2.15(b), and almost all of the reduction reaction (hydrogen liberation) has been concentrated at the iron electrode (cathode). The oxidation of the zinc anode in Fig. 2.15(b) is much faster than that in Fig. 2.15(a). At the same time, most of the corrosion of iron in Fig. 2.15(a) has stopped in Fig. 2.15(b). The zinc anode (Fig. 2.15(b) has been used to cathodically Open cross-sectional areaprotect the iron cathode. Of course, some corrosion of the iron may still occur; whether or not this happens depends on the relative sizes of the zinc and iron electrodes. Some reduction of hydrogen may still occur on the zinc anode. The anode is the electrode at which a net oxidation reaction occurs, whereas cathodes are electrodes at which net reduction reactions occur. With proper design, the oxidation rate on the cathode will be suppressed to the point at which it becomes negligible and effective cathodic protection has been achieved.

All cathodic protection systems require an anode, a cathode, an electric circuit between them, and an electrolyte. Cathodic protection will not work on structures exposed to air environments. Air is a poor electrolyte, and it prevents current from flowing from the anode to the cathode.

The reduction reactions that accompany cathodic protection are normally the reduction of dissolved oxygen from the water surrounding the cathode. All reduction reactions result in an increase of the alkalinity (pH) in the electrolyte near the cathode surface. This increase in alkalinity causes the precipitation of mineral deposits on the cathodically protected structure.

2.2.2.2 Types of Cathodic Protection

There are two types of cathodic protection: sacrificial-anode (passive) systems and impressed-current (active) systems. Sacrificial-anode systems are simpler. They require only a material anodic to the protected steel in the environment of interest [11].
Figure 2.16 shows an impressed-current system used to protect a pipeline. The buried anodes and the pipeline are both connected to an electrical rectifier, which supplies direct current (dc) to both. Unlike sacrificial anodes, impressed-current anodes need not be naturally anodic to steel, and in fact they seldom are. Most impressed current anodes are made from nonconsumable electrode materials that are naturally cathodic to steel. If these electrodes were wired directly to a structure, they would act as cathodes and would cause accelerated corrosion of the structure they are intended to protect. The dc source reverses the natural polarity and allows the materials to act as anodes. Instead of corrosion of the anodes, some other oxidation reaction—that is, oxygen or chlorine evolution—occurs at the anodes, and the anodes are not consumed.

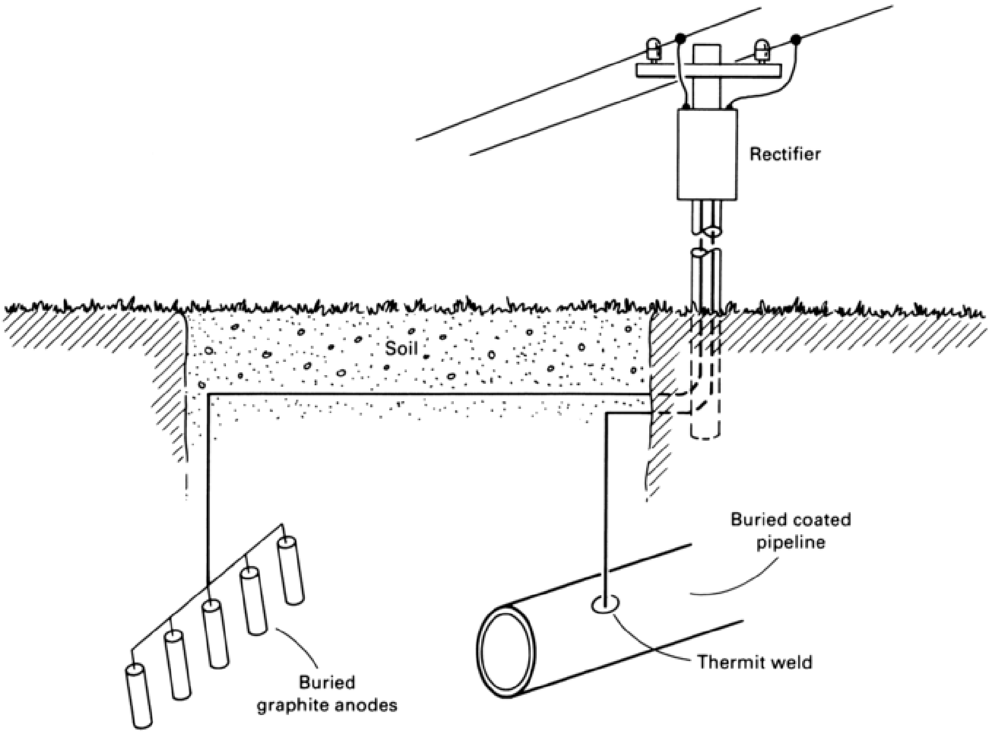


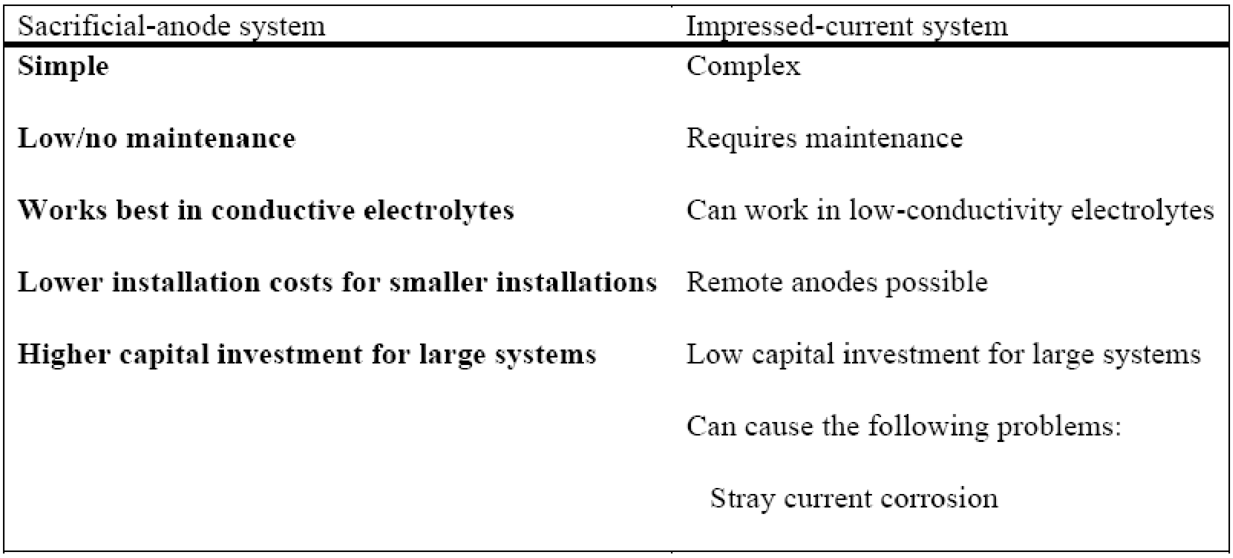
Figure 2.16: Impressed-current cathodic protection of a buried pipeline using graphite anodes

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

In recent years, small steel tanks intended for burial have usually been sold with prepackaged sacrificial anodes. These systems do not require a cathodic protection system, but it is important to install them correctly. Some of these anodes, either zinc or magnesium, may be inappropriate for the local soil-resistivity conditions. In sacrificial-anode systems, the maximum voltage between anode and cathode is approximately 1 V, depending on the anode material and the specific environment. Impressed-current systems can use larger voltages; this allows anodes to be located more remotely, producing more efficient current-distribution patterns on the protected cathode. These larger voltages are also useful in low-conductivity environments, such as freshwater and concrete, in which sacrificial anodes would have insufficient power. Larger voltages can have disadvantages. It is possible to overprotect high-strength steels and cause hydrogen embrittlement. Coating debonding is also possible. Debonding occurs when moisture penetrates a coating and hydrogen is generated at the metal surface beneath the coating. The gas can accumulate until pressure causes blisters or cracks in the protective coating. Once this coating damage occurs, the demands for protective current increase and may exceed the capabilities of the system. Aluminum is especially vulnerable to overprotection. All cathodic reactions cause the immediate environment to become somewhat more basic (less acidic). Unlike steel, aluminum is an amphoteric metal with increased corrosion susceptibility in acids and bases. If the environment around an aluminum structure becomes too basic, it will corrode at an accelerated rate. Thus, the cathodic protection of aluminum can cause cathodic corrosion if too much current is supplied to the cathode.

Table 2 lists some of the important differences between impressed-current and sacrificial-anode cathodic protection systems. Selection of a cathodic protection system usually depends on trade- offs among the advantages of each type of system. For example, most offshore petroleum- production platforms use sacrificial anodes because of their simplicity and reliability, even though the capital costs would be lower with impressedcurrent systems [11].

Table 2: Differences between impressed-current and sacrificial-anode cathodic protection systems



Sacrificial-anode system	Impressed-current system
Simple	Complex
Low/no maintenance	Requires maintenance
Works best in conductive electrolytes	Can work in low-conductivity electrolytes
Lower installation costs for smaller installations	Remote anodes possible
Higher capital investment for large systems	Low capital investment for large systems
	Can cause the following problems:
	Stray current corrosion

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

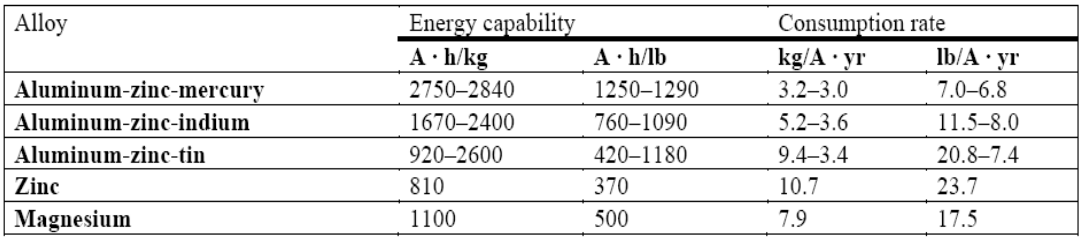
2.2.2.3 Anode Materials

Different requirements for sacrificial anodes and impressed-current anodes lead to the use of different materials for these applications. Sacrificial anodes are anodic to steel in the environment of interest and must corrode reliably, avoiding passivation. Impressed-current anodes can be cathodic to steel, but they must have low consumption rates when connected to a cathodic protection power source.

2.2.2.4 Sacrificial Anodes

Commercial sacrificial anodes include magnesium, zinc, and aluminum alloys. The energy characteristics of these alloys are given in Table 3.

Table 3: Energy characteristic of sacrificial anode alloy



Alloy	Energy capability		Consumption rate	
	A · h/kg	**A · h/lb**	**kg/A · yr**	**lb/A · yr**
Aluminum-zinc-mercury	2750–2840	1250–1290	3.2–3.0	7.0–6.8
Aluminum-zinc-indium	1670–2400	760–1090	5.2–3.6	11.5–8.0
Aluminum-zinc-tin	920–2600	420–1180	9.4–3.4	20.8–7.4
Zinc	810	370	10.7	23.7
Magnesium	1100	500	7.9	17.5

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

Magnesium anodes are the only sacrificial anodes that are routinely specified for use in buried-soil applications. Most magnesium anodes in the United States are supplied with a prepackaged bentonite clay backfill in a permeable cloth sack . This backfill ensures that the anode will have a conductive environment and will corrode reliably. The additional materials are less expensive than the soil-resistivity surveys that would be needed to determine whether the backfill is necessary.

Some magnesium anodes have been used offshore in recent years to polarize the structures to a protected potential faster than zinc or aluminum alloy anodes. Magnesium tends to corrode quite readily in salt water, and most designers avoid the use of magnesium for permanent long- term marine cathodic protection applications.

Figure 2.17 shows a commonly used magnesium anode that controls corrosion on a glass-lined domestic water heater.

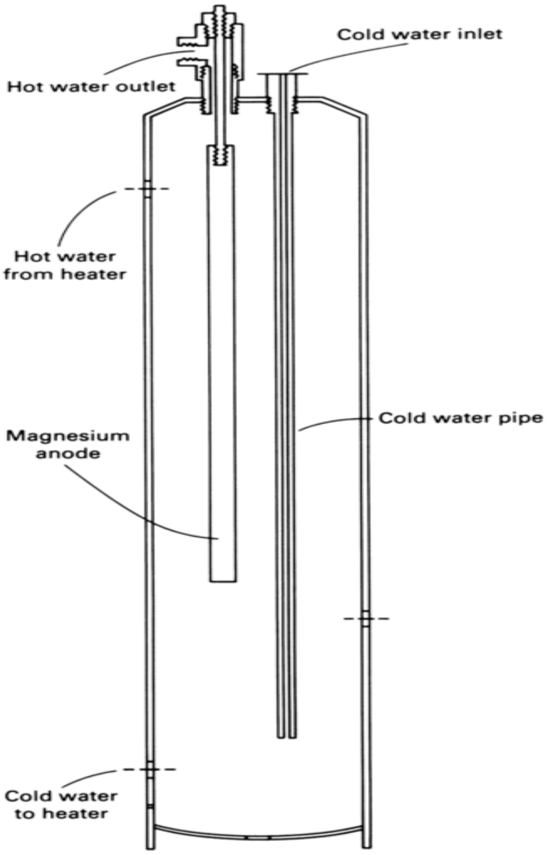


Figure 2.17: Magnesium anode used to cathodically protect glass-lined steel water heater

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

Zinc is used for cathodic protection in freshwater and salt water. Zinc is especially well suited for cathodic protection on ships that move between salt water and harbors in brackish rivers or estuaries. Figure 2.17 shows zinc anodes on the underside of a small fishing boat. Aluminum anodes would passivate in the harbors and might not work when they return to sea. Zinc anodes are also used to protect ballast tanks, heat exchangers, and many mechanical components on ships, coastal power plants, and similar structures. The weight of zinc is an advantage for marine pipelines. Bracelet anodes (Fig. 2.18) are attached at pipe joints to provide ballast and to prevent corrosion in the water-mud environment, in which aluminum might passivate.

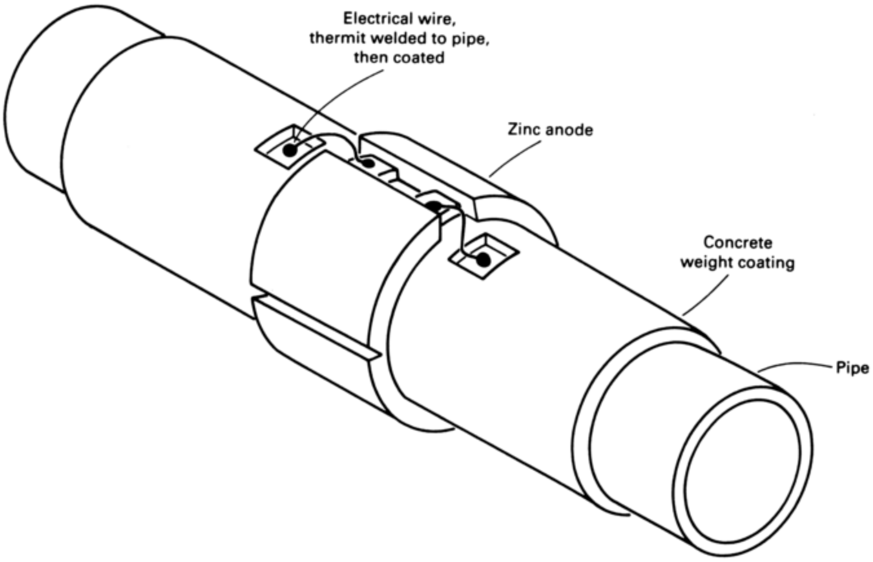


Figure 2.18: Zinc bracelet anode at a joint in an offshore pipeline

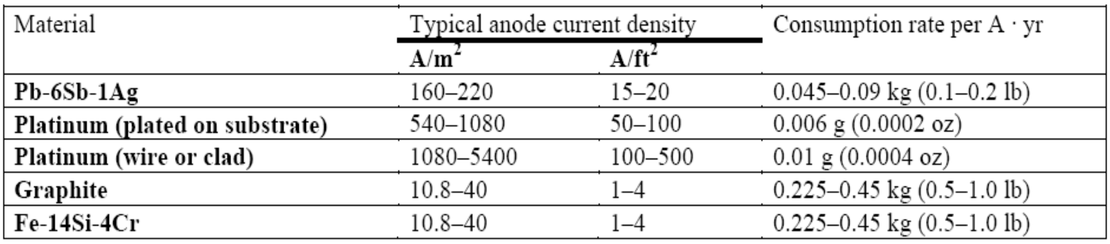
Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

Aluminum is used on offshore structures where its light weight provides significant advantages. Welded-on aluminum anodes for an offshore platform are shown in Fig. 4 and 14. Aluminum does not passivate in salt water if certain alloying elements, such as tin, antimony, and mercury, are present. Toxicity questions prevent the use of aluminum alloys with mercury additions in U.S. waters.

Impressed-Current Anodes

Impressed-current anodes must be corrosion resistant and otherwise durable in the environment in which they are used. Consumption rates for lead alloy, platinum, graphite, and high-silicon cast iron impressed-current anode materials are given in Table 4[11].

Table 4: Consumption rates of impressed-current anode materials



Material	Typical anode current density		Consumption rate per A · yr
	A/m^2	**A/ft^2**	
Pb-6Sb-1Ag	160–220	15–20	0.045–0.09 kg (0.1–0.2 lb)
Platinum (plated on substrate)	540–1080	50–100	0.006 g (0.0002 oz)
Platinum (wire or clad)	1080–5400	100–500	0.01 g (0.0004 oz)
Graphite	10.8–40	1–4	0.225–0.45 kg (0.5–1.0 lb)
Fe-14Si-4Cr	10.8–40	1–4	0.225–0.45 kg (0.5–1.0 lb)

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

Inhibitors

Atmospheric corrosion of metals and alloys is responsible for a large percentage of the total corrosion cost. Indirect consequences of corrosion, such as depletion of the natural resources and structural damage leading to failure of industrial and military systems, are also critical. The use of inhibitors is one of the corrosion- control technologies directed toward combating corrosion. For inhibitors there is a lot type of material that we can use and two of them is metol (N-methyl-p-amino phenol sulphate) and zinc oxide

Mechanism of corrosion inhibition

The organic compounds containing S, N and O are known to be effective inhibitors. Its effectiveness depends on the electron density at the functional groups. The electron density can be varied with the help of suitable constituents and thus the inhibition action of an inhibitor[11] . The corrosion inhibition property of the metol can be attributed to the presence of heteroatom and p electrons on benzene ring. These factors play the vital role in the adsorption of the inhibitor and the formation of co-ordinate bond with metal. The adsorption of inhibitor on the steel surface can occur either directly by the interactions between the p electrons of the inhibitor and the vacant d-orbitals of metal surface atoms. Also there may be an interaction of inhibitor with adsorbed sulphate ions leads to the adsorption of inhibitor. The adsorption of inhibitor on steel may also be due to the interaction of sulphur and oxygen with the surface atoms of metal. The interaction causes the adsorption of metol on corroding sites of metals and prevents the anodic reaction. As inhibitor concentration increases, it covers more and more surface area and results in the reduction of corrosion rate.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter is explaining the entire step that I will do during corrosion testing. Every test has their own step or procedures where it different from others. I'm using 100 x 150 mm sheet mild steel as my specimen. Generally, my methodology is divided to 2 big categories which is deformed and undeformed. Each process will be discussed thoroughly at this chapter. This test will include 3 type of protection which is coating and cathodic protection but each big categories will be include a default specimens which is will not been put to any kind of protection as comparison to the protected specimen. The specimen will be steel sheet for all 14 type of experiment. The composition, weight, surface structure analysis will be done on specimen before and after the experiment. The steps in this research was referred from the American National Standard (ASTM) depends on the suitability, which referred to the tool and material available in the Faculty Mechanical Laboratory.

3.2 METHODOLOGY CHART

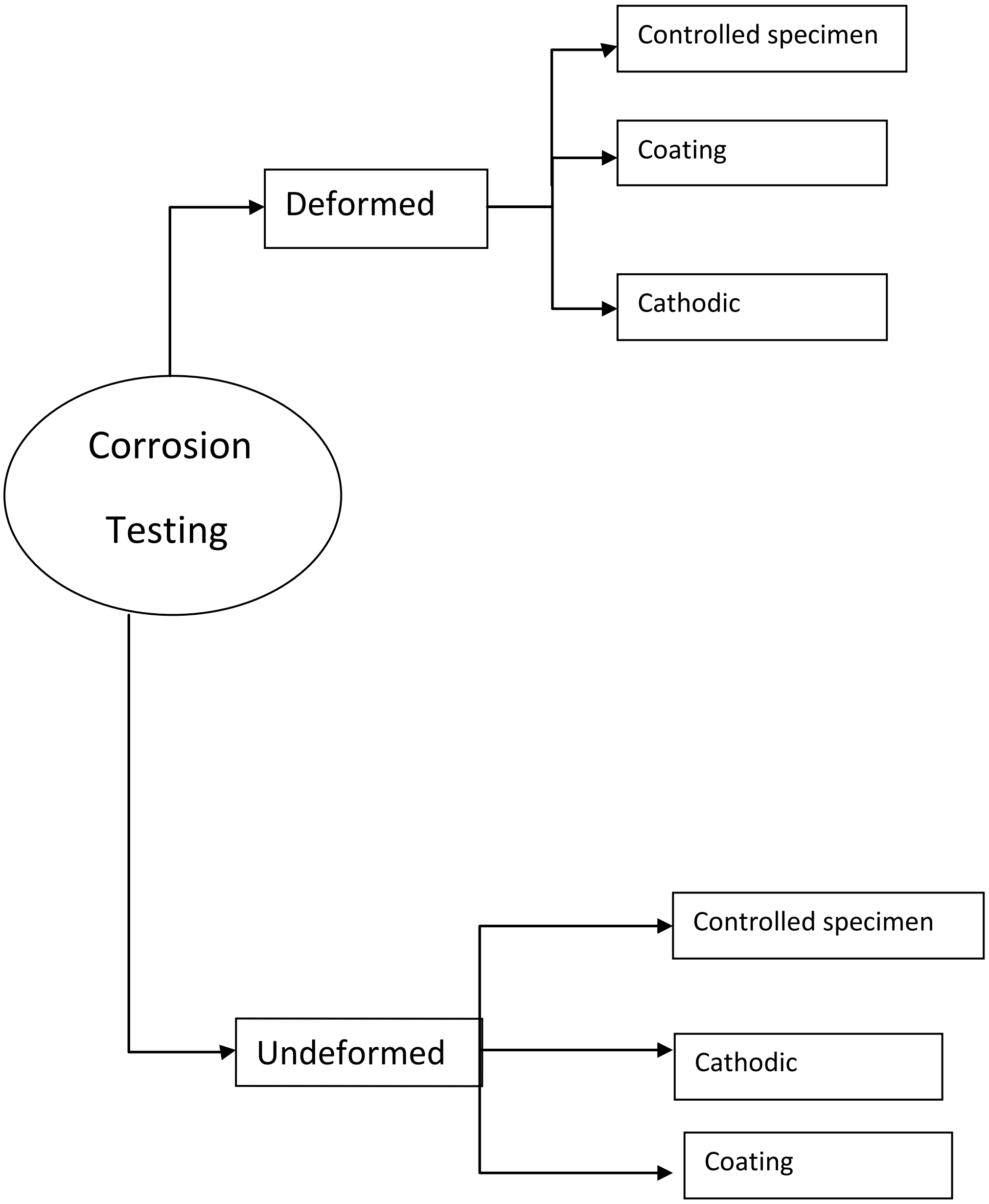


Figure 3.1: Methodology chart 1

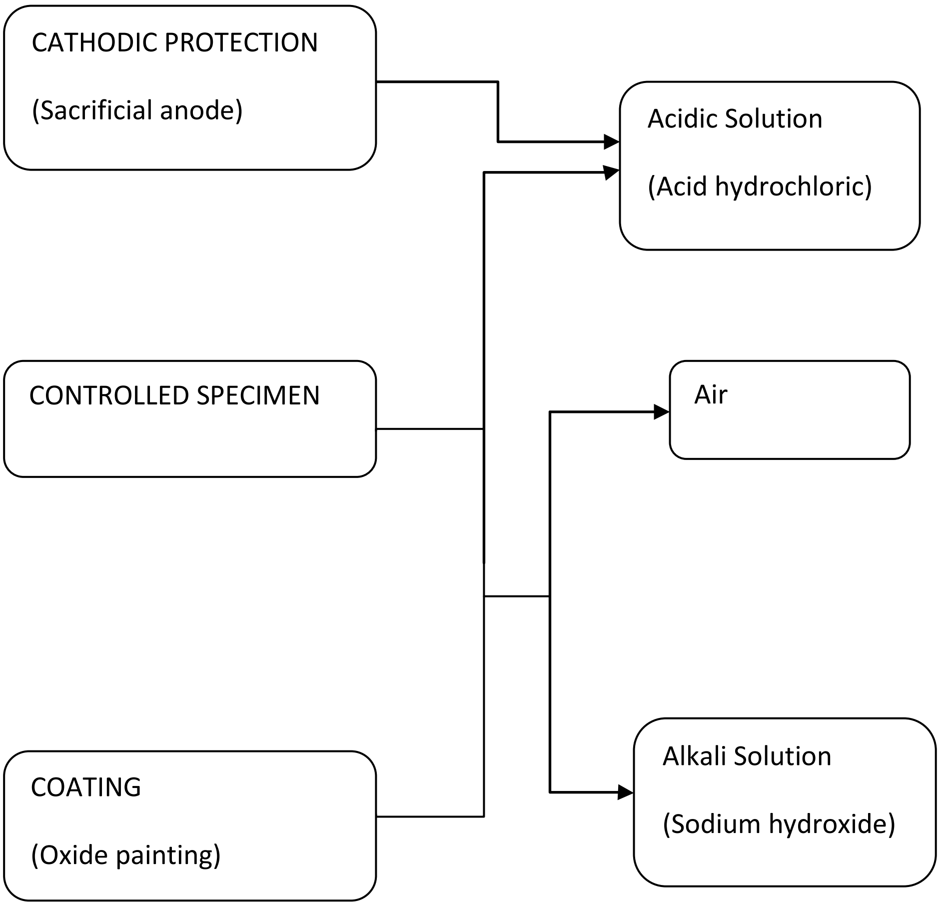


Figure 3.2: Methodology chart 2

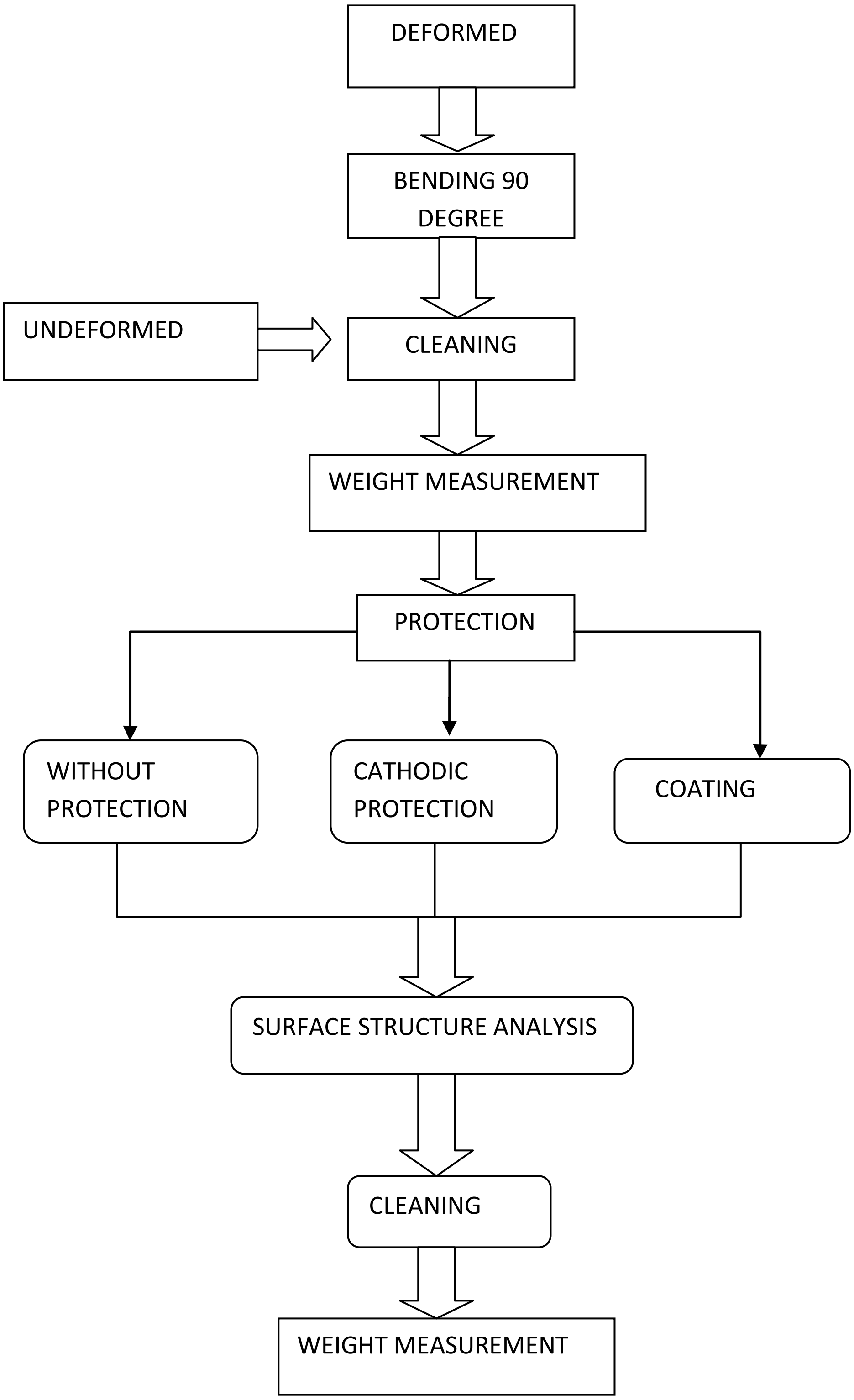


Figure 3.3: Methodology chart 3

3.3 SPECIMEN PREPARATION

For the underformed category, all specimen is test without changing the shape of specimen. The specimen will be 100x150 mm dimension where it will be in form of sheet steel. Sheet specimen is chosen because it’s easy to get and easy to do any changes on it such bending or cutting. For underformed category, there will be 7 specimen which will be divide to 3 group which is controlled specimen, cathodic protection and coating. Each group will be test in acidic and alkali solution. So the will be 7 specimen in each group. For deformed category, all test will be done with deformed specimen. The specimen will be 100x150 mm and will be bend to 90 degree from normal axis. This changes is to study the effect of the shape or condition of steel specimen on corrosion rate, either is faster or slower or neither. The total specimen used is same with undeformed category which is 7 specimens. The total will be 14 specimen or experiment.

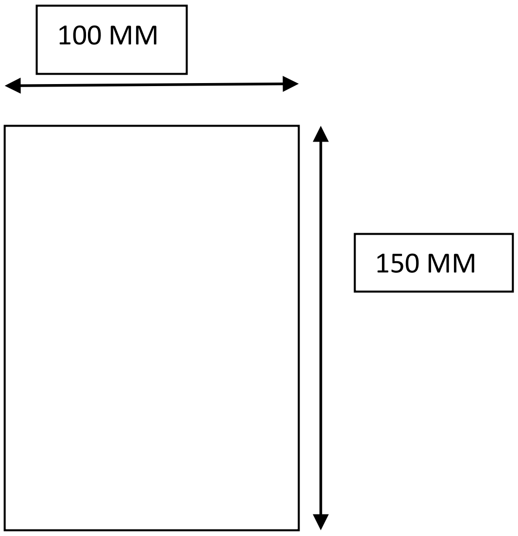


Figure 3.4: Dimension of Specimen

The surface of each specimen is cleaned from any dirt, oil, or anything that can affect the result with sand paper or solvent cleaner. Each pieces of sheet steel are weighing and the weight and dimension of each specimen are measured. The compositions of specimen are determined using the Scanning Electronic Microscopy (SEM) before specimen been put to any protection.

3.4 CLEANING

3.4.1 Methods for Cleaning before experiment

As for the cleaning process, we can divide it to 2 parts which is before and after test. This procedure is very is important as its influence and the accuracy of result at the end of the experiment. The purpose of this part is to remove any dirt or anything that may affect the surface of the specimen that may affect the outcome. As the cleaning material, we use either sand paper to smoother the surface or any solvent that cleans the surface such as thinner or both. This important as the unneeded element disturbing the result which can cause this project failed [13].

3.4.2 Methods for Cleaning After Testing

Corrosion product removal procedures can be divided into three general categories: mechanical, chemical, and electrolytic. An ideal procedure should remove only corrosion products and not result in removal of any base metal. As the material for cleaning, I’m using 1000 mL acid hydrochloric to remove any corrosion from the specimen’s surface. The corrosion needed to be removed from the specimen surface in order to get mass loss due to corrosion. To determine the mass loss of the base metal when removing corrosion products, replicate uncorroded control specimens should be cleaned by the same procedure being used on the test specimen. By weighing the control specimen before and after cleaning, the extent of metal loss resulting from cleaning can be utilized to correct the corrosion mass losses. The cleaning procedure should be repeated on specimens several times. The mass loss should be determined after each cleaning by weighing the specimen [13].

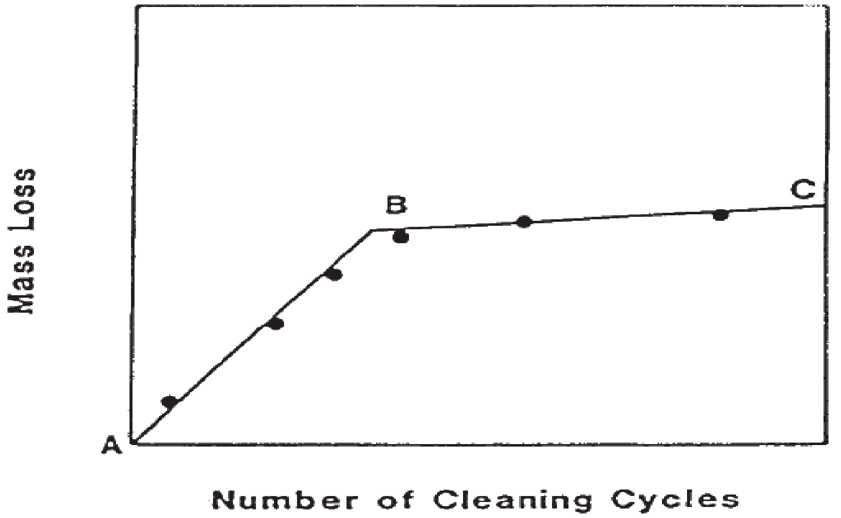


Figure 3.5: Mass Loss of Corroded Specimens Resulting from Repetitive Cleaning Cycles

Source: ASTM G1-03, Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens

The mass loss should be graphed as a function of the number of equal cleaning cycles as shown in Fig. 1. Two lines will be obtained: AB and BC. The latter will correspond to corrosion of the metal after removal of corrosion products. The mass loss due to corrosion will correspond approximately to point B.To minimize uncertainty associated with corrosion of the metal by the cleaning method, a method should be chosen to provide the lowest slope (near to horizontal) of line BC [13].

3.5 WEIGHING

The specimen are weighted after sample preparation procedure was finish, the clean and dry specimens are weighed to take the initial weight of the specimens. After the specimen is exposure at atmosphere with protection, the specimen is weighed to take the 2nd weight of the specimens by using digital micro weighing scale. Once again, the weight data is taken again after the specimen had been put into acidic/alkali solution. The weight different between before and after exposure are representing the weight of corrosion product. From the weight data we can know the weight loss that cause by corrosion.

3.6 SURFACE STRUCTURE ANALYSIS

Microstructure and surface morphology can be determined by optical and electron microscopy. Optical microscopy is typically used for 10 to 1000 times magnification. Numerous sample preparation and microscopic techniques have been developed for examination of flat polished surfaces to determine grain structure and, possibly, identify phases. Electron microscopy, especially scanning electron microscopy (SEM), has essentially an infinite depth of field and can magnify in excess of 100,000 times. Scanning electron microscopy is ideally suited for examination of surface features. Many SEMs are equipped with auxiliary features that allow for phase differentiation (secondary electron detection), atomic number differentiation (backscattered electron detection), quantitative and qualitative chemical analysis using energy dispersive spectroscopy (EDS), wavelength dispersive spectroscopy (WDS), and even rudimentary xray diffraction analysis (backscattered Kikuchi line analysis). Table below show some of the analytical technique and its application.

Surface visualization will be carried out after the test. Observations on the surface structure of the samples for determine the types of corrosion will be observed by using Scanning Electron Microscope (SEM).

3.7 PROTECTION

3.7.1 Controlled specimen

This kind of group is tested without putting any kind of protection. Thus this stand as the default specimen and its experiment become default and reference to other kind of protection. Its corrosion rate should be much less than specimen in acidic medium and weight loss due to corrosion should be greater compare to other. There are 4 specimens in this group. 2 specimens will be put in acidic solution and 2 specimens will be put in alkali solution. This will be representing as the environment condition of the factory.

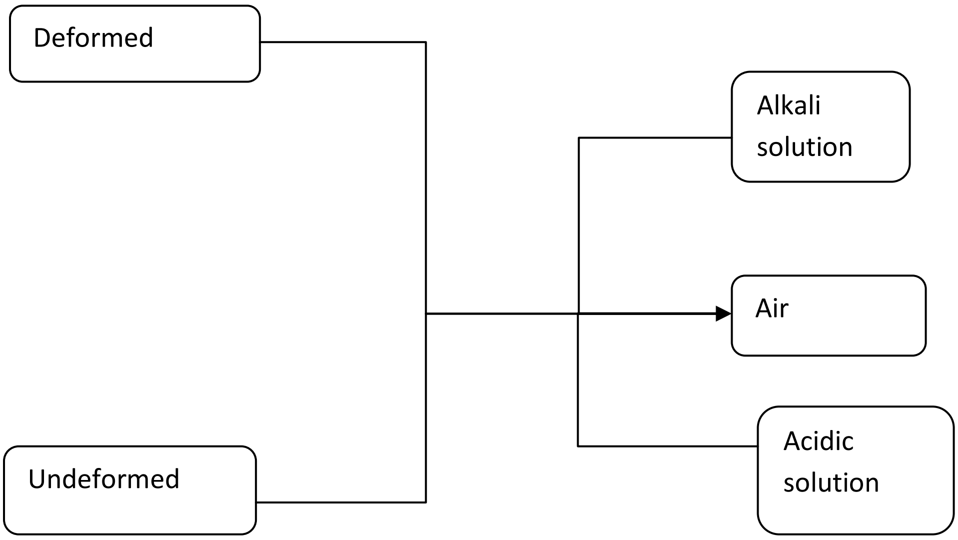


Figure 3.6: Methodology chart for controlled specimens.

3.7.2 Cathodic protection

As for the 2nd method of protection, I'm using cathodic protection. Cathodic protection is where I'm taking cathode as the specimen I want to protect while anode as the sacrificial anode where it's taking corrosion from cathode and corrode itself. As for the cathode I'm using steel while the anode, I'm using zinc anode. Both specimens will put into acidic and alkali solution as in figure but using material as I stated above. This experiment will be exposed in 30 days duration. Any modification due to exposure time will be done if the result is far from the expected result.

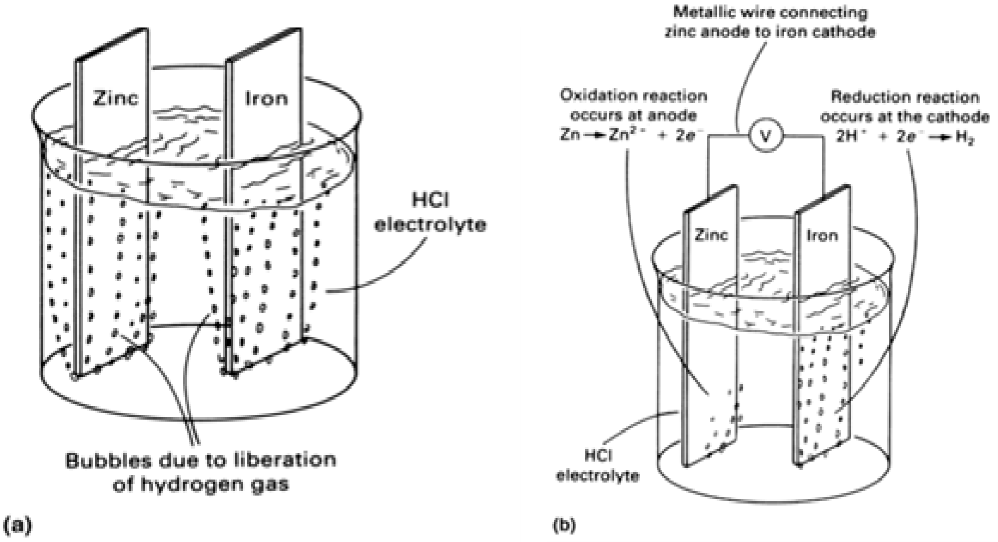


Figure 3.7 (a),(b): Illustration on reaction anode and cathode

Source: ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection

Cathode calculation [15]

1)Calculate the area sheet steel to be protected(External surface)

As = 100mmx150mmx2=0.03 m^2

2) Calculate current demand or current required, I(A)

I = J x A=1.2mA

Where, J = current density

A = Area to be protected (m^2)

J=current density = 40 mA/m^2

3) Find current capacity for anode

- For Aluminum anodes

Theoretical current capacity= 810 Ah /kg

Efficiency = 90%

The useful output of zinc = (810 Ah/kg) x (90%)

= 729 Ah/kg

4) Calculate consumption rate for each anode

$$\text{The consumption rate(h/kg)} = \frac{\text{Current capacity of anode}}{\text{current demand}} = \frac{729 \text{ Ah/kg}}{1.2 \text{ mA}}$$

5) Find the weight of magnesium per year (kg/yr):

$$\text{Weight(kg/yr)} = \frac{8760 \text{ (h/yr)}}{\text{consumption rate(h/kg)}}$$

6) For a system life of 0.0817 years (30 days) the anode required is

Weight of anode = weight (kg / yr) x (0.0817 yr)

= Weight (kg)

3.7.3 Coating

Coating is most common protection applied in metal. It’s cheap and easy to be used yet still depending on the situation and metal. Not all type of condition can use coating as protection. There are many type of coating such as powder coating, electrocoat(E-coat), hot melt wax coating and painting. As for this experiment, I’m using paint as my coating material. A layer of paint will applied on the surface of the specimen and will be exposed in 30 days duration.

3.8 ALKALI AND ACID SOLUTION

This is the next step after the coating applied where specimen is immersed into acid and alkali solution. Alkali and acidic solution represent the condition or the composition of air in the factory where it could be more to alkali condition or more to acidic solution because as we know there’s a lot operation going in there that may cause PH of the air decrease or increase. At result we can know if acidic or alkali condition increases the rate of corrosion or decreases it or neither. We also can whether specimen in acidic more corrode or in alkali more corrode where we can come out with one more condition that may effect the corrosion rate. Strong alkali and acid is needed during the experiment such as acid hydrochloric and sodium hydroxide.

3.9 DEFORMATION

In industry, the applications of mild steel come in different shape. Thus in this thesis, the effect of deformation is taken as one of the factor that may effect the corrosion rate. When there’s a deformation happen, the position of microstructure is changed where it may become packed thus stressed surface exist. As stated in chapter 2, stress is one of the factors that cause the corrosion to happen so the deformed specimen is predicted to have higher corrosion rate compare to specimens in original state.

3.10: CORROSION RATE

Corrosion rate can be determine by measuring the weight of the specimen before experiment start and after experiment end. All weighing must be done after cleaning process to remove any corrosion or dirt to avoid error in result. Corrosion rate can be calculated as some variable is constant as stated in ASTM G31-72 and ASTM G1-03, Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens [13].

Calculation based on this formula:

Mass losses= Weight before start experiment -Weight after cleaning

Corrosion Rate= KxW / (AxTxD)

K= A constant (based on ASTM G31-72, Take 3.45x10^6 (mils per year-mpy))

W=weight/mass losses

A=Area of specimen in cm^2 to the nearest $0.01cm^2$

T=Time of exposure in hours to the nearest 0.01h

D=Density of mild steel in g/cm^3 (taken from appendix XI of ASTM practice G1=7.85 g/cm^3)

Many different units are used to express corrosion rates. For *T*, *A*, *W*, and *D*, the corrosion rate can be calculated in a variety of units with the following appropriate value of *K*:

Corrosion Rate Units Desired	Constant (K) in Corrosion Rate Equation
mils per year (mpy)	3.45 3 106
inches per year (ipy)	3.45 3 103
inches per month (ipm)	2.87 3 102
millimetres per year (mm/y)	8.76 3 104
micrometres per year (um/y)	8.76 3 107
picometres per second (pm/s)	2.78 3 106
grams per square meter per hour (g/m2·h)	1.00 3 104 3 D
milligrams per square decimeter per day (mdd)	2.40 3 106 3 D
micrograms per square meter per second (µg/m2·s)	2.78 3 106 3 D

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

In this chapter, the result from the experiment that been done according to methodology will be interpret in term of numerical and graphical data. The results will be compare in term of method, physical, SEM analysis, corrosion rate, weight lose and type of corrosion happened. There should be different 12 result gather from 12 specimens and data will be present in graph diagram and tables.

All result is required according ASTM procedure to ensure no error or mistake happen during and after the experiment. Beside ASTM guide, the guidance from expertise and experience personal also needed especially during the experiment and obtaining results. Nevertheless this is just a experiment which can happen to have an error and mistake, thus any recommendation and improvement for the perfection can be done next.

4.2 EXPERIMENT RESULT

Basically, the result can be divide into 3 main categories which is:

- Graphical/Picture
- Graph diagram
- Tables

Graphical result is the pictures taken before and after the experiment using camera (whole specimens) and SEM (corrosion surface). Graph diagram will use to compare result among the specimens result and table is used to show data of corrosion rate and weight lose. All the detail about regent and material will be use is stated below:

- Type of material: Mild steel
- Anode: zinc anode
- Cleaning tool: Thinner(removing dirt or oil), Sand paper(remove corroded part) Acid hydrochloric (remove corrosion)
- Acid medium: Acid hydrochloric (HCℓ 2mol)
- Alkali medium: Sodium hydroxide (NaOH).
- Coating: Oxide painting

4.2.1 Graphical Result-SEM result

4.2.1.1 Acid medium

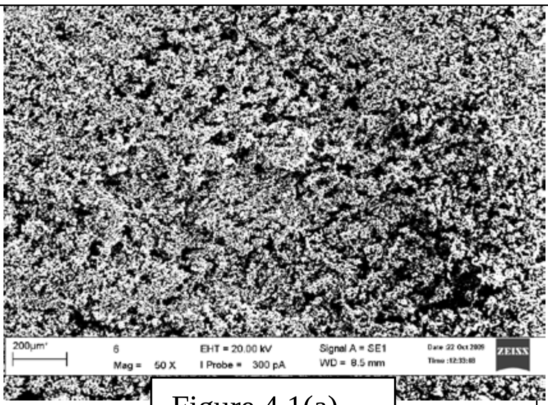
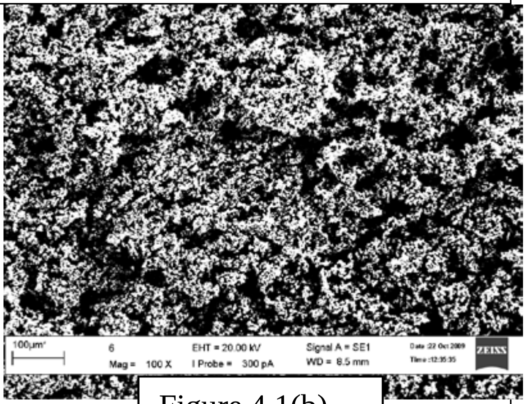
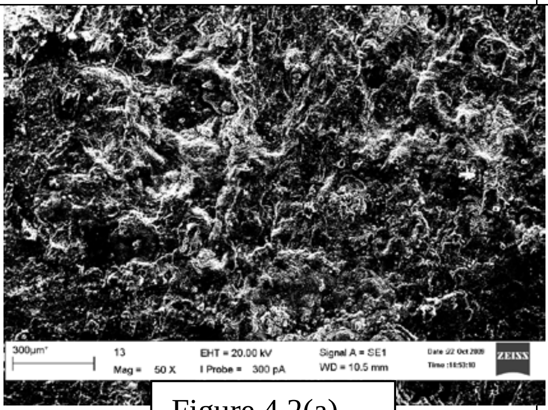
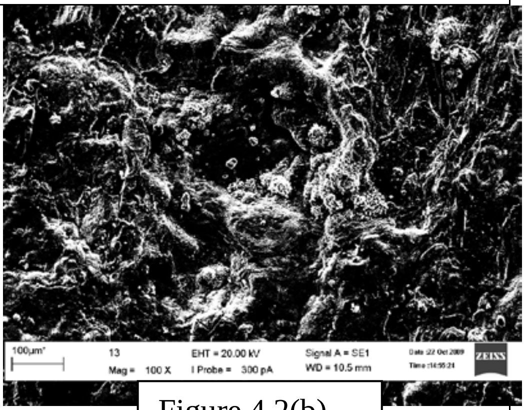
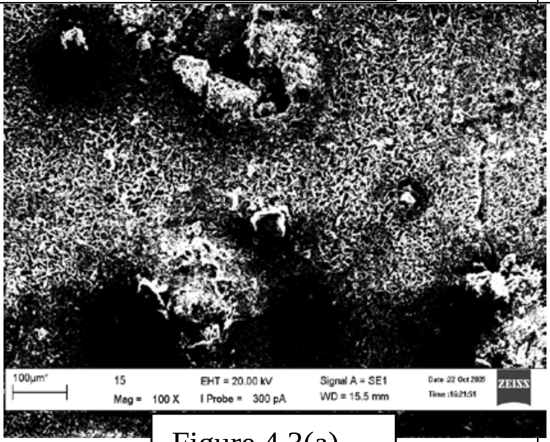
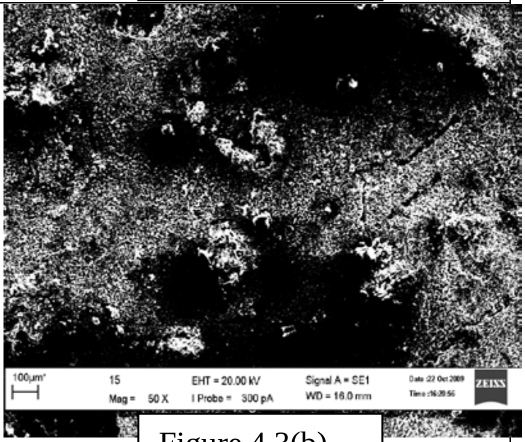
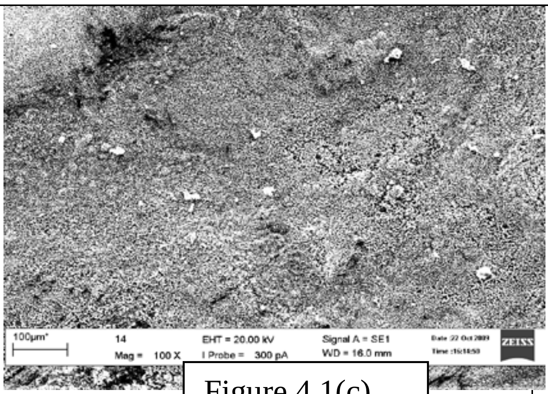
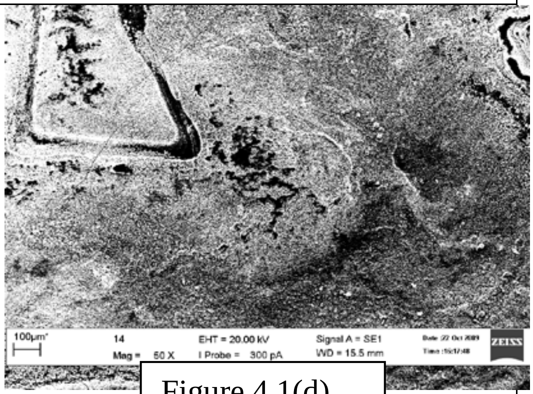
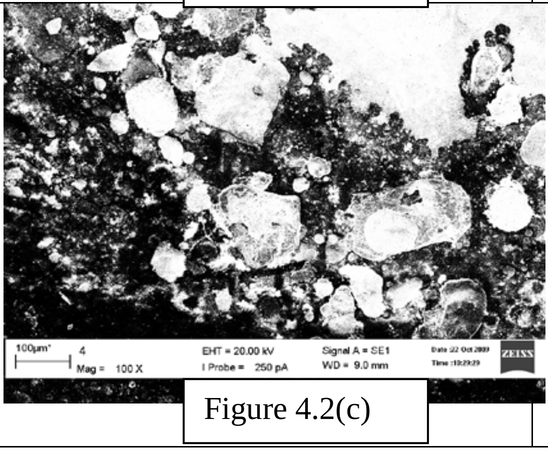
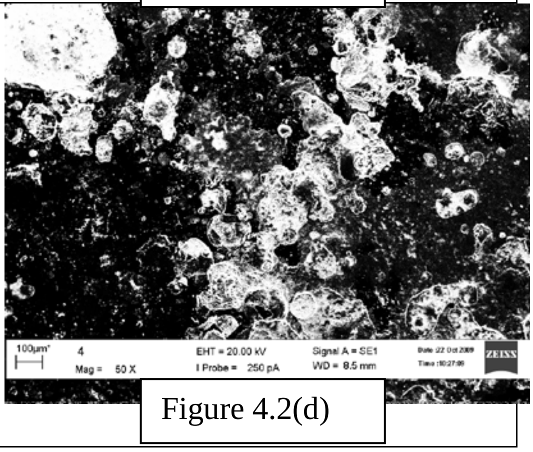
	DEFORMED	
WITHOUT PROTECTION	 Figure 4.1(a)	 Figure 4.1(b)
PAINT	 Figure 4.2(a)	 Figure 4.2(b)
CATHODIC PROTECTION	 Figure 4.3(a)	 Figure 4.3(b)

Figure 4.1-4.3: SEM analysis on deformed specimen in acid medium

Figure above showing a diagram of steel structure in acid medium in deformed condition. Figure 4.1(a) is using 50X magnification while figure 4.1(b) using 100X magnification. These samples obtain the highest corrosion rate due the medium and protection factor. No erosion happens on sample because sample is on steady immersion (no movement). As we can see, this sample is highly corroded causing a lot defect on it. Figure 4.2(a) and 4.2 (b) is showing sample on coating protection. The magnification used is 50x and 100X. In physical picture, most of the paint is removed due to acid and the mild steel is corroded in almost half of total area. In SEM diagram, we can see dark region and white region. Dark region is the corroded area while white region is the area which still on coating protection. For 4.3(a) and 4.3(b) diagram showing samples on cathodic protection using zinc anode. This sample obtain the less corrosion rate and weight loss rate. There a lot of pitting corrosion happened but the defect area is uniformly distributed. The galvanic corrosion happened to the zinc anode as the zinc anode that protecting the steel.

	UNDEFORMED	
WITHOUT PROTECTION	 Figure 4.1(c)	 Figure 4.1(d)
PAINT	 Figure 4.2(c)	 Figure 4.2(d)

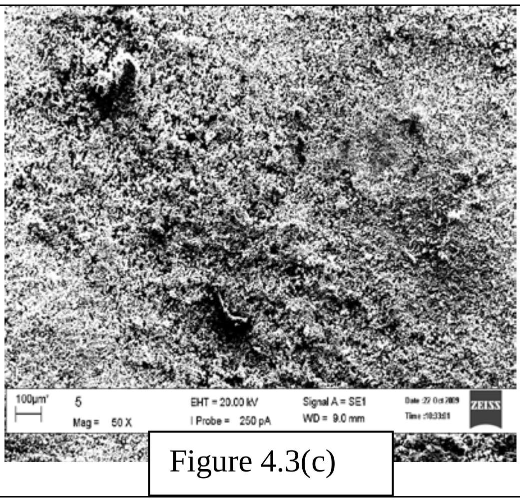
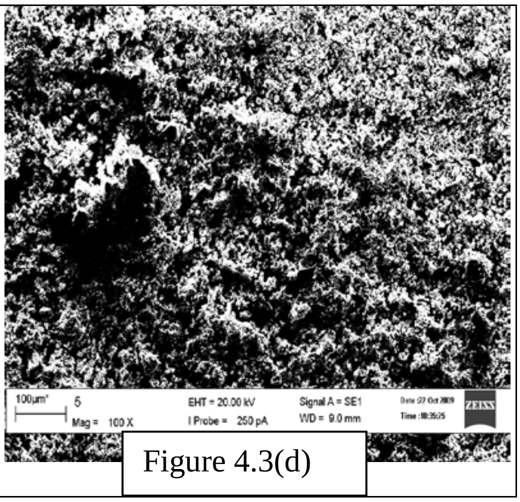
CATHODIC PROTECTION	 Figure 4.3(c)	 Figure 4.3(d)

Figure 4.1-4.3: SEM analysis on undeformed specimen in acid medium

Figure above showing sample in acidic medium but on its original condition (undeformed). This sample having high corrosion rate but still less compare to deformed sample in acid. For figure 4.1(c) and 4.1(d), we can see that the entire surface of sample is heavily corroded causing a lot of defect and roughness on surface. The surface of sample become much darker and defects due to the corrosion and acid effect. The corrosion happen almost similarly distributed along the area and not focusing on several places as expected. For figure 4.2(c) and 4.2(d), the sample is under paint coating protection thus it less corrode compare sample 4.1(c) and 4.1(d) but it still heavily corroded where almost half of the total area is corrode and other area is still under coating protection. For figure 4.3(c) and 4.3(d), the corrosion happened uniformly throughout the entire surface of the sample. Physically, the surface of the sample turn to red due to corrosion but no severe defect happened. From analysis, it shows that cathodic protection giving the lowest corrosion rate among other protection.

4.2.1.2 Air Medium

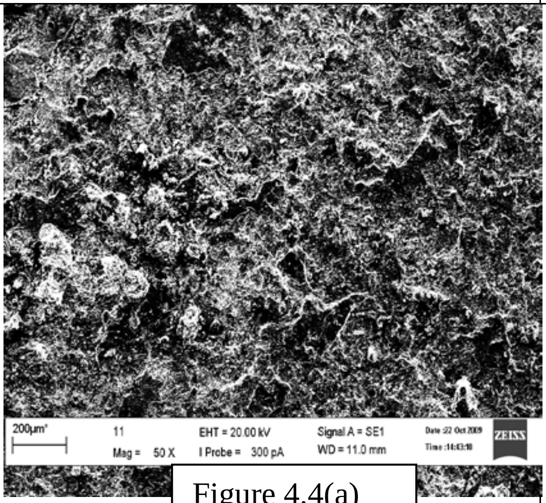
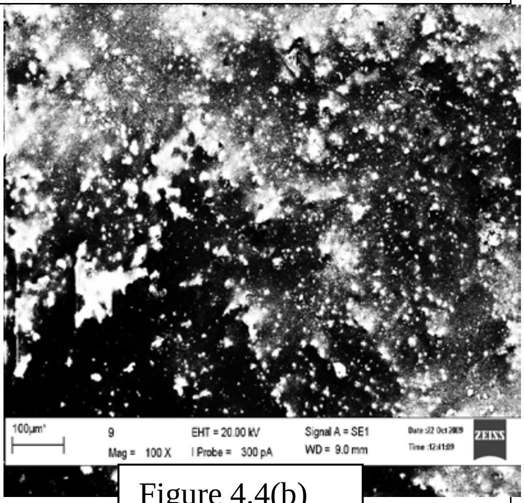
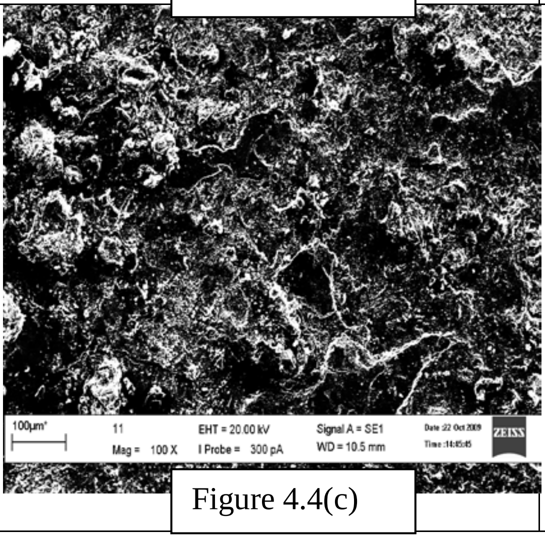
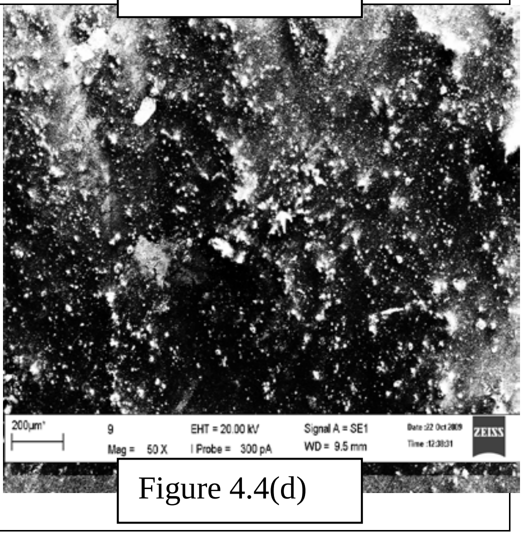
	WITHOUT PROTECTION	PAINT
DEFORMED	 Figure 4.4(a)	 Figure 4.4(b)
	 Figure 4.4(c)	 Figure 4.4(d)

Figure 4.4: SEM analysis on deformed specimen in air medium

Figure above showing SEM diagram of sample in air medium of 2 different protections. Figure 4.4(a) and 4.4(b) is SEM diagram of sample without protection in deformed condition. The uniform type of corrosion happened on the surface of the sample. The corrosion didn't happen big area but small area because the experiment done indoor to avoid any element such as rain water and moisture that can effect of catalyze the process of corrosion. No big damage on the surface of sample but some bubble were form due the moisture in air enter the surface of sample. For figure 4.4(c) and 4.4(d), the sample is under coating protection where the corrosion hardly can be seen because the experiment done in short period where it take a long time to corrosion happen on sample and remove the coating protection.

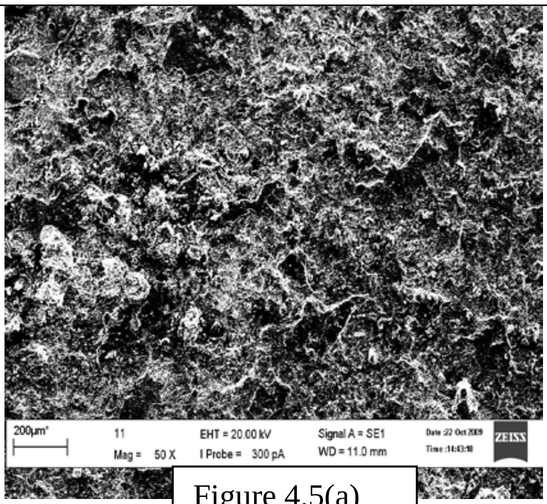
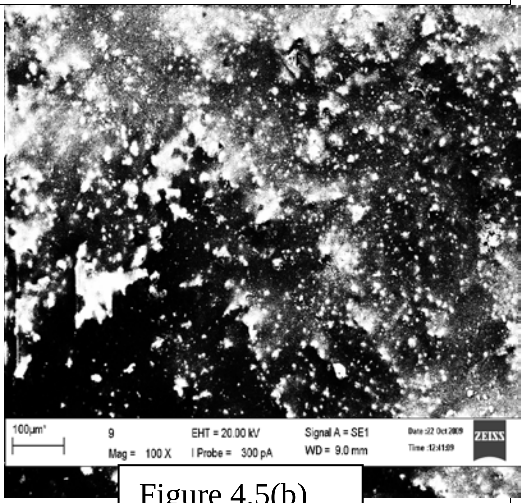
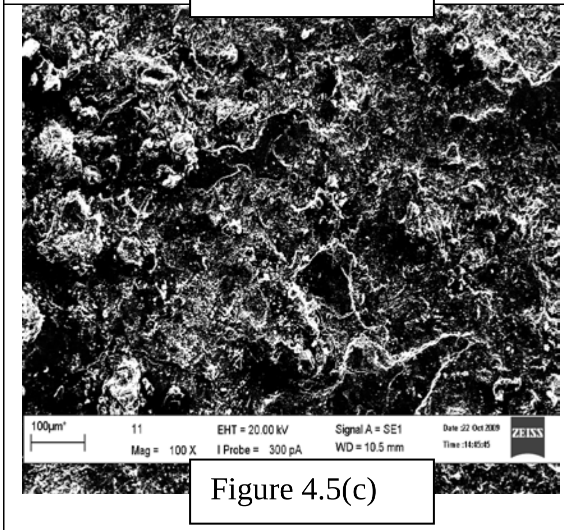
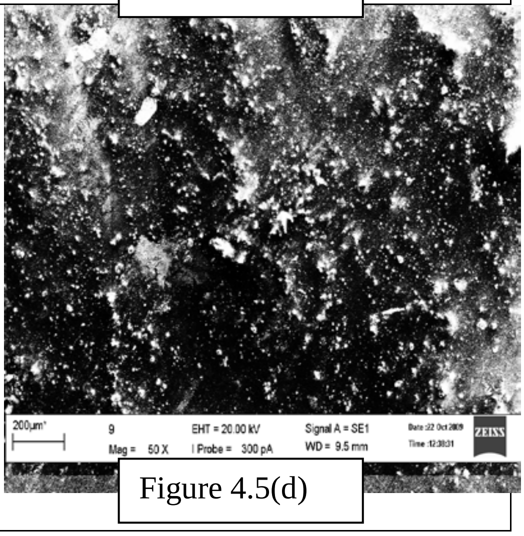
	WITHOUT PROTECTION	PAINT
UNDEFORMED	 Figure 4.5(a)	 Figure 4.5(b)
	 Figure 4.5(c)	 Figure 4.5(d)

Figure 4.5: SEM analysis on undeformed specimen in air medium

Figure above showing the surface of undeformed specimens in air medium. Same as previous table picture, figure 4.5(a) and 4.5 (b) having a uniform corrosion at small area of the surface. We can see that the corrosion is distributed at the entire area but in small portion. For figure 4.5(c) and 4.5(d), this specimen is under coating protection thus the corrosion is hardly can be seen but there are corrosion happen on the surface causing a few area become thinner.

4.2.1.3 Alkali medium

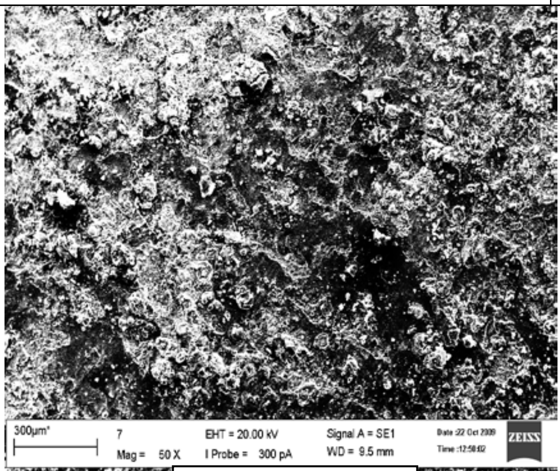
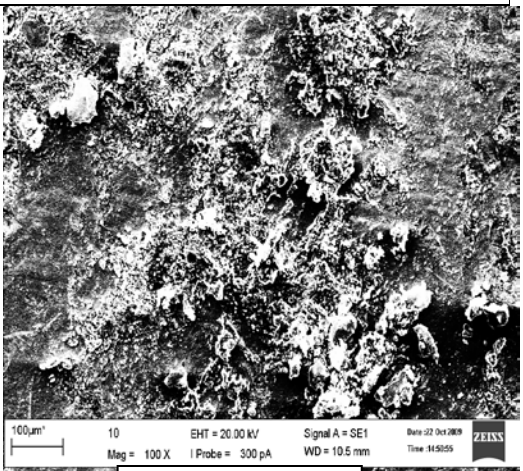
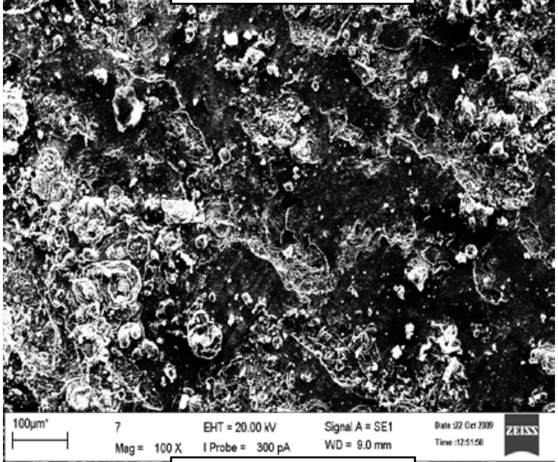
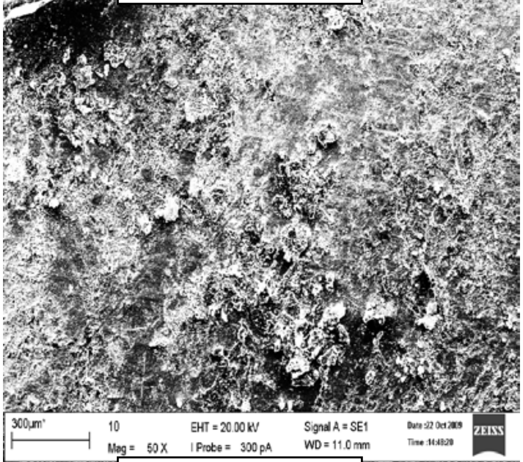
	WITHOUT PROTECTION	PAINT
DEFORMED	 Figure 4.6(a)	 Figure 4.6(b)
	 Figure 4.6(c)	 Figure 4.6(d)

Figure 4.6: SEM analysis on deformed specimen in alkali medium

Figure above showing SEM diagram of sample in alkali medium of 2 different protections. Figure 4.6(a) and 4.6(b) is SEM diagram of sample without protection in deformed condition. The uniform type of corrosion happened on the surface of the sample. The corrosion didn’t happen big area but small area because the experiment done indoor to avoid any element such as rain water and moisture that can effect of catalyze the process of corrosion. Compare to sample 4.4(a) and 4.4(b), this sample is less corrode due the alkali properties which is drying the environment which is less moisture in surrounding area. For figure 4.6(c) and 4.6(d), the sample is under coating protection where the corrosion hardly can be seen because the experiment done in short period where it take a long time to corrosion happen on sample and remove the coating protection. It have less corrosion compare to sample in air.

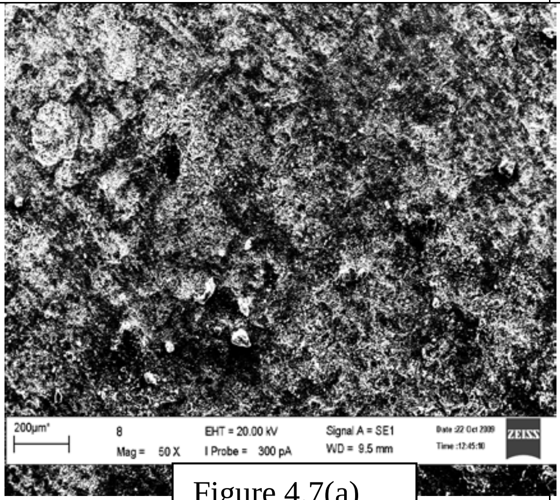
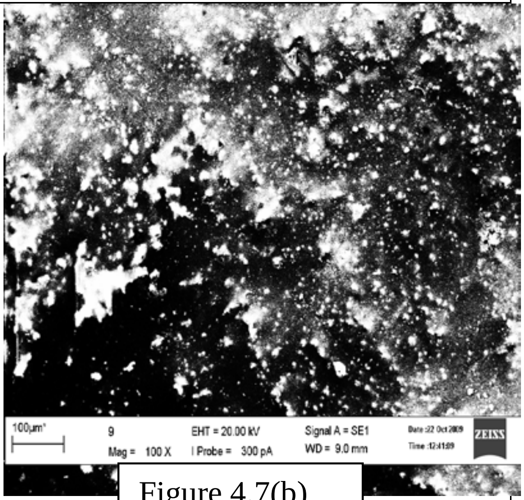
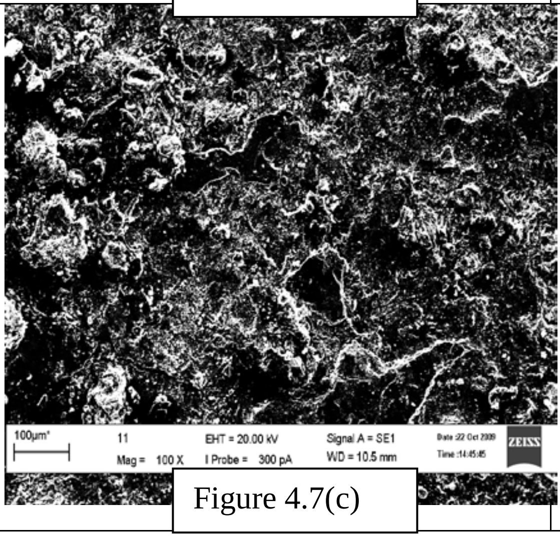
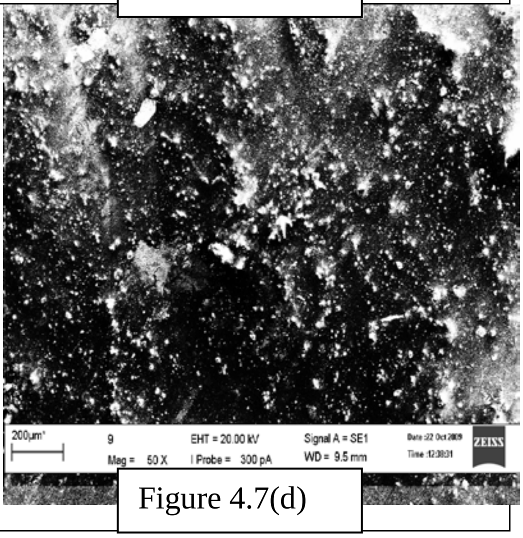
	WITHOUT PROTECTION	PAINT
UNDEFORMED	 Figure 4.7(a)	 Figure 4.7(b)
	 Figure 4.7(c)	 Figure 4.7(d)

Figure 4.7: SEM analysis on undeformed specimen in alkali medium

For figure 4.7(c) and 4.7(d), we can see some corrosion happen on the surface but in really small area and hardly to detect to difference between specimens before experiment and after. Uniform corrosion happened on this specimen where some area become thinner and turn to red. For figure 4.7(c) and 4.7(d), we can see most regions are colored bright due to peel of paint. The darker region showing that these area is slightly thinner compare to the bright region. Corrosion hardly can be seen in these specimens.

4.2.2 Table Data

Table 4.1: Table of Corrosion Rate

Item	Weight Before(g)	Weight After(g)	Weight lose(g)	Corrosion Rate(mpy)
Without Protection				
Acid-deformed	163.74	162.39	1.35	5.886
Acid-undeformed	164.57	163.15	1.42	6.191
Air-deformed	164.68	164.36	0.32	1.395
Air-undeformed	162.12	161.75	0.37	1.439
Alkali-deformed	162.84	162.61	0.23	1.003
Alkali-undeformed	165.54	165.32	0.22	0.959
Cathodic Protection				
Acid-deformed	163.18	162.05	1.13	4.927
Acid-undeformed	164.83	163.66	1.17	5.101
Coating-Paint				
Acid-deformed	163.73	162.82	0.91	3.967
Acid-undeformed	164.25	163.36	0.89	3.880
Alkali-deformed	162.88	162.79	0.09	0.392
Alkali-undeformed	161.04	161.04	0.08	0.349
Air-deformed	162.04	162.04	0.17	0.741
Air-undeformed	162.92	161.92	0.12	0.523
Anode				
Zinc 1	171.69	171.06	0.63	
Zinc 2	170.88	170.16	0.72	

4.2.3 Graph Data

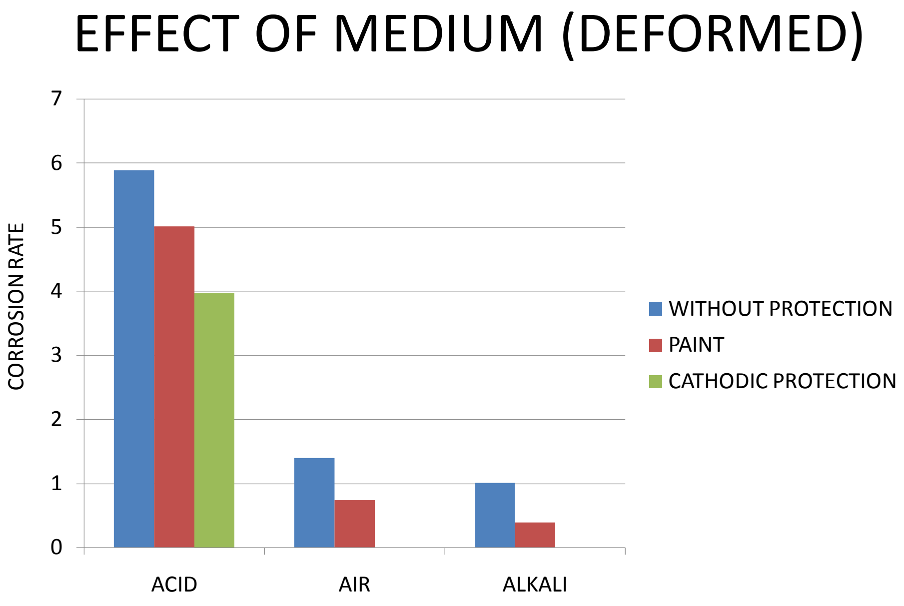


Figure 4.8: Effect of medium on deformed samples.

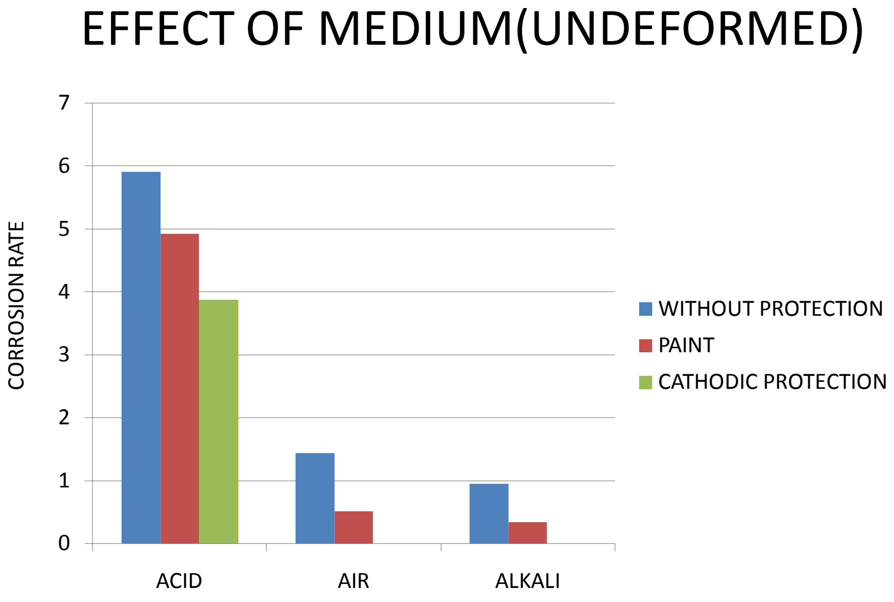


Figure 4.9: Effect of medium on undeformed samples

From the Figure 4.8 and 4.9, we were focusing on the effect of medium on the samples from 3 different type protections which stated at legend site (the right part of the diagram). In acid we considered 3 different groups and 2 different groups for both air and alkali. From the graph, we can see that in acid medium, the samples achieved the highest corrosion rate compare to other medium while the alkali achieved the lowest corrosion rate among other medium. This is because the effects of acid itself which act as catalyze to increase the corrosion rate due to its corrosive property. In alkali, an increase in alkalinity of the environment raises the PH of steel surface. The corrosion rate correspondingly decreased because the mild steel becomes increasingly passive in the presence of alkalies and dissolved oxygen. Although increase in oxygen concentration at first accelerates corrosion of steel, it is found that, beyond a critical concentration, the corrosion drops again to a low value.

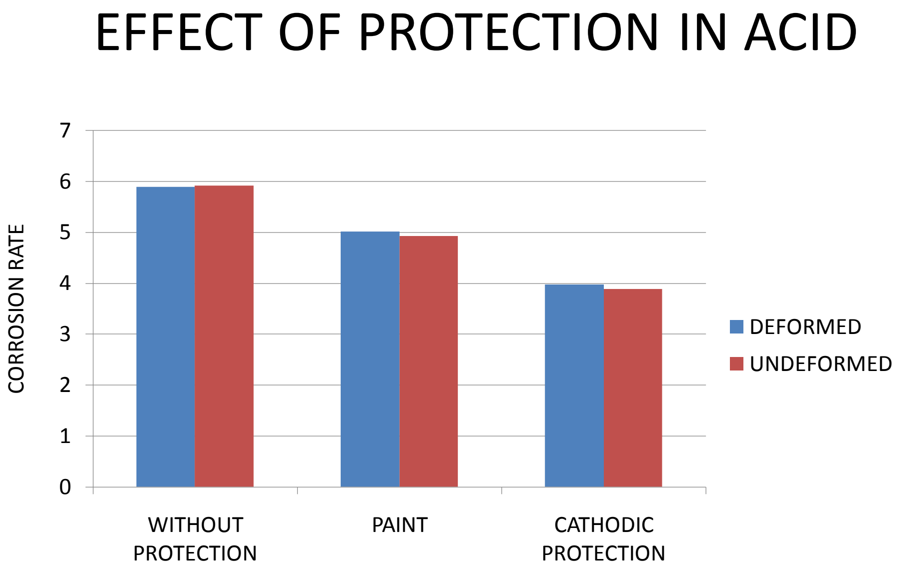


Figure 4.10: Effect of protection in acid

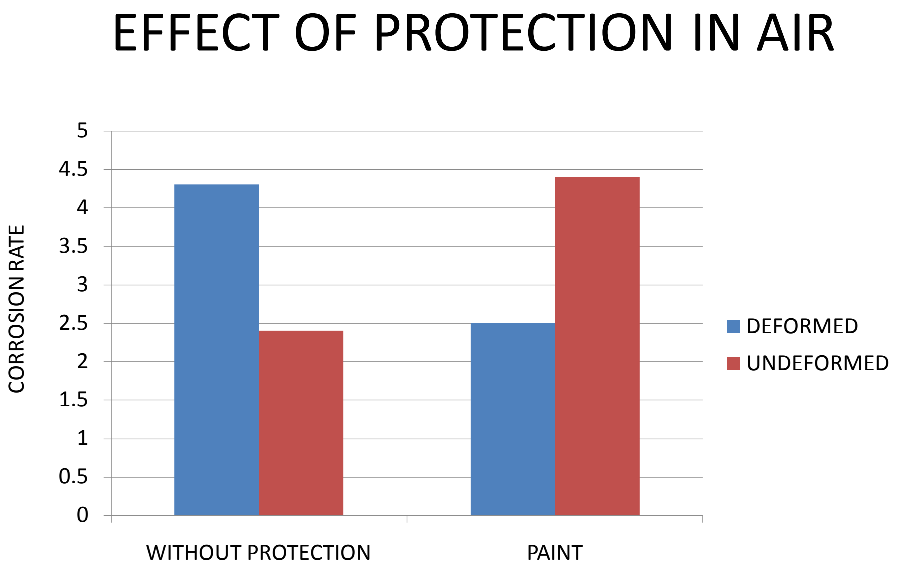


Figure 4.11: Effect of protection in air

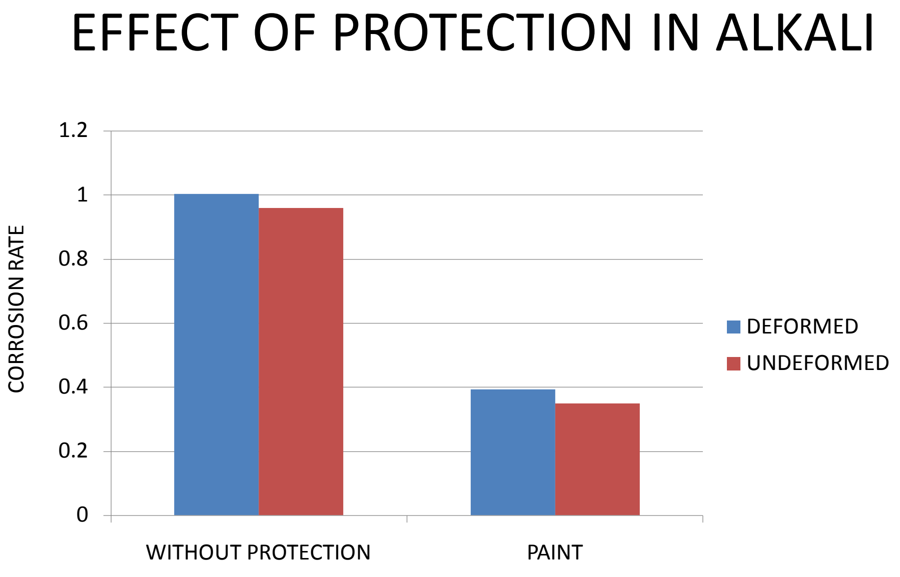


Figure 4.12: Effect of protection in alkali

Previous figures (Figure 4.10, 4.11, 4.12) are focusing on the effect of protection in 3 different medium which are acid, air, and alkali. From this graph, I’m comparing the effectiveness of protection applied in 3 different medium. Based on graph 4.3, we can see that cathodic protection has the lowest corrosion rate compare to others showing that cathodic protection is the most effective protection in acid medium. Meanwhile at graph 4.4 and graph 4.5, coating protection showing conspicuous changes compare to the unprotected samples showing that coating protection is effective against corrosion. Although the environment play big role in corrosion resistance, but with the combination of protection and environment control, thus we can create much less corrosion phenomenon.

Based on graph 4.3, 4.4 and 4.5, we can find the effect of deformation on samples. From the graphs, we can see that there a slight changes between these 2 group where deformed specimens tend to have higher corrosion rate compare to the undeformed specimens. This is because the changes in microstructure of the mild steel that causing much rapid corrosion rate thus deformed specimen have higher corrosion rate.

4.3 DISCUSSION

4.3.1 Comparison to other study/journal/book

This comparison of graph of corrosion rate versus ph between 2 sources which is from my experiment and “Corrosion and corrosion control 4th edition by R. winston revie and Herbert H. Uhlig”. We can see a similarity of pattern between these 2 graphs. The more decrease ph value is, the higher corrosion rate will be.

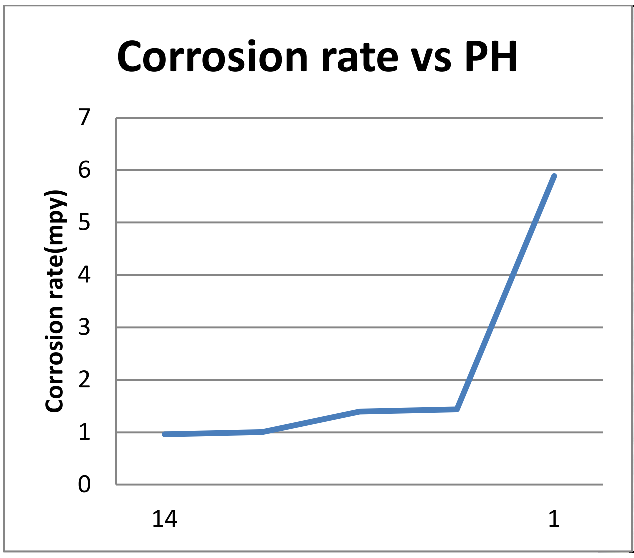


Figure 4.13: Graph corrosion rate vs Ph

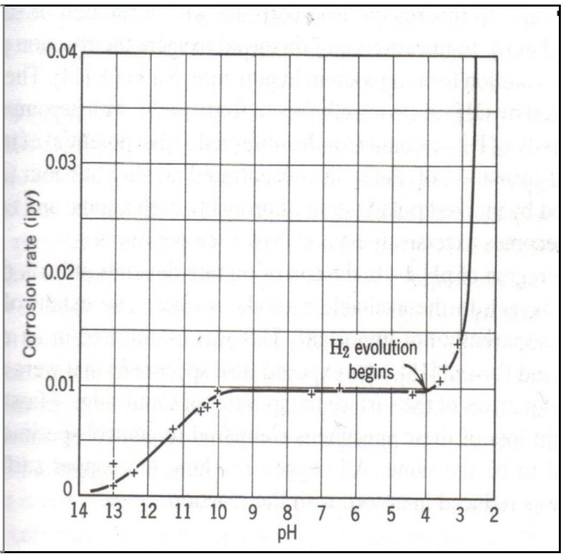


Figure 4.14: Graph corrosion vs PH

Source: R. Winston Revie, Herbert H. Uhlig,2008, Corrosion and corrosion control-An introduction to corrosion science and Engineering.

The pictures below is the comparison between my SEM analysis with SEM analysis taken from the “Characterization of corrosion product on steel surfaces” by Y maseda and S. Suzuki. We can see a similarity of the characterization on the surface of the specimen between this 2 picture.

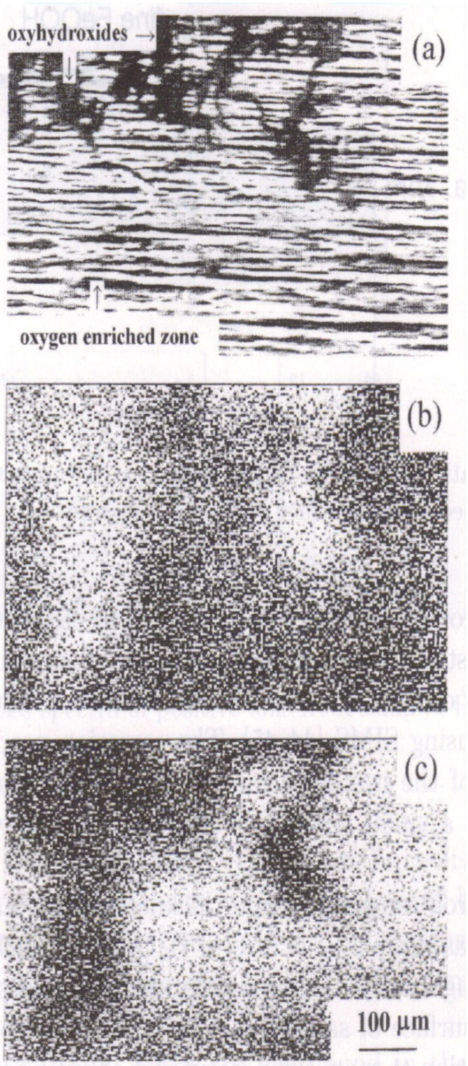


Figure 4.15: SEM analysis done by Ymaseda & S. Suzuki, Characterization of corrosion product on steel surfaces

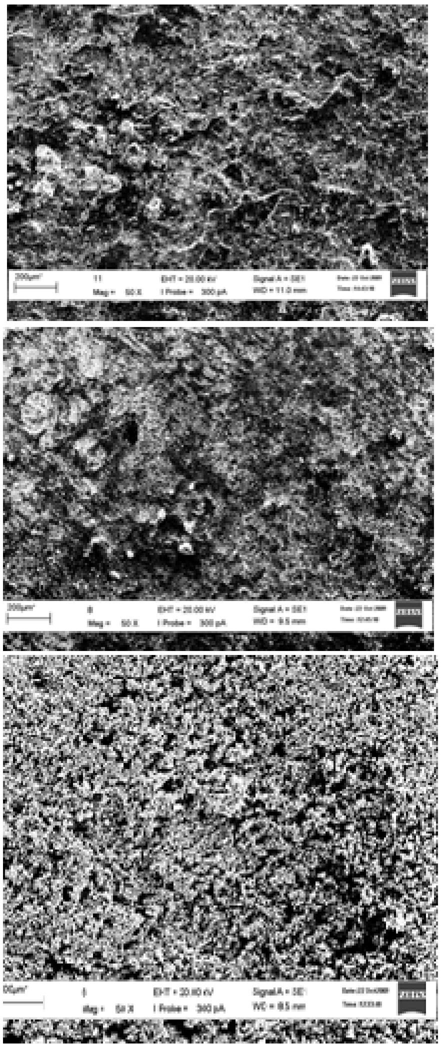


Figure 4.16: SEM analysis from result

The pictures above is the comparison between my SEM analysis with SEM analysis taken from the “Characterization of corrosion product on steel surfaces” by Y maseda and S. Suzuki. We can see a similarity of the characterization on the surface of the specimen between this 2 picture.

4.3.2 Some result differ from theory or expectation

This is because the reaction in the environment is too complex where we are unable to control certain elements or reaction during the process. Other elements that may rapid or decreasing the corrosion rate exist beyond the expectation. Thus the result have slightly different to theory or expectation.

4.3.3 Coating and cathodic protection

Although the cathodic protection has the best result but coating is chosen for better and suitable protection because there are limitation of where the practise of cathodic protection can be done but coating protection is applicable is most area in industry due to its methodology and properties. Cathodic protection protect the steel better than coating but in big area of metal such water tank, cathodic protection can’t protect the entire area where the area located far from anode is tend to corrode faster due to the electron is unable to transfer to anode causing corrosion reaction happened.

CHAPTER 5

CONCLUSION

Based on the result acquire, most of the objective of this final year project is accomplished.There are a lot of data acquire from SEM analysis to the corrosion rate for each specimen.The effect of medium and the effect of protection can be seen from the graph show in chapter 4. From here, there are some conclusion can be stated which is:

5.1 PH of environment

The effect of PH in the environment main big role in both increasing and decreasing the effect of corrosion and corrosion rate. Acidic environment (PH 1-4) tends to increase the corrosion rate of mild steel due to its corrosive property and the presence of rich hydrogen situation where it rapidly increase the corrosion rate. Alkaline environment (PH 10-14) tend to decreasing the corrosion rate because its property where alkaline environment tend to have much less H2O element and the corrosion rate correspondingly decreased because the mild steel becomes increasingly passive in the presence of alkalis and dissolved oxygen.

5.2 Effectiveness of protection

Based on the result, cathodic protection has the best result among others showing its strength in protecting the mild steel but in industry, the practice of cathodic protection can’t be done in all area. It’s suitable for underground piping and water tanks but less effective on machine and tools. Thus in term of the effectiveness of the protection, coating protection has a major advantage. Coating protection is involving a lot of type of coating as stated in literature review means that it can be applied and practice on most area in industry. Although it cathodic has a better result but the difference is isn’t too big and with the additional help with a suitable environment thus much less corrosion will happened.

5.3 Changes in microstructure

Although the difference between original condition and deformed specimen is too small but we can’t deny its effect on corrosion rate. The changes in microstructure tend to increase the corrosion rate but in minor effect only. Thus we can see the reality, bended or deformed products corrode faster compare to its original state. This happened due to the stress on microstructure of mild steel where the stress in one of the corrosion factor.

RECOMMENDATION

There are some recommendations in order to improve the quality of product and environment as well as decreasing the effect of corrosion.

5.4 Combining coating and cathodic protection

In industry, there a lot of equipment used daily and some of them cost millions thus the risk of corrosion need to be taken seriously. The combination of these 2 protection may help improve the quality and life span of the equipment/material such in water tanks. In water tanks, cathodic protection can’t cover the top and bottom part of the tank effectively thus this is where coating protection is needed where it can apply and improve the protection on that area. It has the same concept on the underground piping where the same method can be applied.

5.5 Combining coating with inhibitors

Most of the industry did use coating as their main protection but they ignoring other factor that cause the corrosion which the environment. In this case, it’s recommended that to use of coating and inhibitors protection together. Inhibitors protection is a type of protection where it didn’t applied on the mild steel but in the environment instead. The inhibitors change the condition of the environment to decreasing the effect of corrosion such as removing/reducing the corrosion element in the environment. With the combination of inhibitors and coating thus we can achieve zero corrosion situations.

5.6 Application of sacrificial anode in automotive industry

The use of sacrificial anode didn’t limited on liquid medium only. We can see that each year there’s a lot of modification or refinement such as painting on car due the corrosion effect. We can’t simply cover the corroded area with new coating thus the color of the car will be unbalanced thus we have to paint the entire car body all over again and this cost a lot of money. The sacrificial anode is widely use in shipping industry where the metal which tend to corrode faster such as zinc is attached to the main metal such as mild steel thus the corrosion element can be transfer to zinc causing the zinc corrode instead of the mild steel. This concept can be applied in automotive industry where the same method can be use. The anode is attached to the main body or important area so that the anode will corrode instead of the body and anode can simply removed and replaced once it’s already entirely corrode. Thus we can get much longer of car lifespan.

REFERENCES

1. William D callister and jr. david G Rethwish ,2007,Fundamental of material science and engineering
2. , Ronald Gibala (University of Michigan), Matthew Tirrell (University of Minnesota) Charles Wert (Emeritus-University of Illiois) 2008,Corrosion engineering, Third Edition, McGraw-hill series in Material science and Engineering
3. Aswin Tino (Mottmac UAE), Dr.Ir.Slameto Wiryolukito (Material Engineering ITB), Muhammad Abduh (Reksolindo), “Corrosion: Technical and Economic Driver for Indonesia Oil and Gas Industry” Petroenergy Magazine Edition Jan -Feb 2008
4. National Association of Corrosion Engineers , *corrosion Basics*,Houston,1984
5. Handbook of Corrosion, Engineering, Pierre R. Roberge
6. Principle and Prevention of Corrosion, Second Edition , Denny A. Jones
7. Steelwork Corrosion Control, second edition .D.A Bayliss and D.H Deacon “Corrosion in Underground Restrained Piping Systems,” EBAA
8. R. Winston Revie, Herbert H. Uhlig, 2008, Corrosion and Corrosion Control-An introduction to corrosion science and engineering.
9. Y.Waseda, S.Suzuki,2005,Characterization of corrosion product on steel surfaces.
10. Barbara A. Shaw and Robert G Kelly,2006,What is corrosion?
11. ASM Metals Handbook Volume 13A-Corrosion Fundamentals, Testing and Protection
12. A guide to corrosion protection, Light Truck Frame Project Team Auto/Steel Partnership 2000 Town Center, Suite 320 Southfield, Michigan 48075-1123 1999
13. ASTM G1-03, Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens
14. ASTM E3-01, Standard Practice for Recording Data from Atmospheric Corrosion Tests of Metallic-Coated Steel Specimens1
15. http://www.canadametal.com/products/anode__calculation.htm

APPENDIX F

PROJECT SCHEDULE FOR FINAL YEAR PROJECT 1

PROJECT ACTIVITIES		**WEEKS**													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Discuss title and objective	■													
2	Discuss scope and problem statement	■	■												
3	Chapter 1		■	■											
4	Discuss the format of the project			■	■										
5	Literature – journals and ref. books	■	■	■	■	■	■	■	■	■	■	■	■	■	■
6	Chapter 2- Literature review				■	■	■	■	■	■					
7	Chapter 3-Methodology									■	■	■	■	■	
8	Prepare for Presentation													■	
9	Presentation														■
10															
11															
12															

APPENDIX G

PROJECT ACTIVITIES		WEEKS													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Literature review	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2	Discuss the problem solving with supervisor	■	■	■											
3	Specimen preparation				■										
4	Experiment					■	■	■	■						
5	SEM analysis									■					
6	Chapter 4-Result and discussion									■	■	■			
7	Chapter 5												■		
8	Prepare Final report												■	■	
9	Presentation														■
10															
11															

PROJECT SCHEDULE FOR FINAL YEAR PROJECT 2