# CERTIFICATION OF APPROVAL

## Effect of Deformation to the Performance of Aluminium Sacrificial Anode

by

Norafif Afnan Mohd Nordin

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(Dr Bambang Ariwahjoedi)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2008

# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NORAFIF AFNAN MOHD NORDIN

# ABSTRACT

This report basically will discuss research that being done and basic understanding of chosen topic which is **"Effect of Deformation to the Performance of Aluminium Sacrificial Anode"**. The objective of the project is to study and analyze the performance of aluminium anode in laboratory scale after undergo different kind of deformations. The basic part for this project is to make literature review about corrosion process and Sacrificial Anode Cathodic Protection (SACP) as deep as possible to get as much information that could be. Moreover, research will be done on performance view of SACP; from here the advantages and disadvantages of SACP system in oil and gas industry will be known. This report covered about what is corrosion, factor affecting performance of anode and material used in SACP. This report also discusses about methodology and progress work for this project. The hypothesis in this research is; more deform the Al (anode) surface, the performance will be increase. To prove this hypothesis, the samples have being prepared and the corrosion rate of the steel will be compared. At the end of the study, the objective has been achieved. From the experiment of qualitative and quantitatively, the Al anode with more deformation is the best for anode as the corrosion rate of itself increase. Using the SCE (Reference Cell), the anode sample IV which is the highest performance due to deformation anode protects the mild steel at potential on the order of -792.936 mV.

# ACKNOWLEDGEMENT

First and foremost, the first and highest gratitude goes to God because of His mercy and kindness that the author has successfully completed this project within the time provided. Throughout the 2 semesters, it has greatly benefited the author in various aspects especially in engineering knowledge; corrosion engineering and sacrificial anode cathodic protection. These experiences gained are believed to be very useful to the author in his future career and endeavors. Hopefully all the information gained from this project may benefit others especially UTP students and staff for reference. The successful completion of this project has been made possible through the help and support of many individuals and organizations.

The author would like to express his special gratitude to his FYP supervisor, Assoc. Prof. Dr. Bambang Ariwahjoedi for giving the author an opportunity to learn a lot of knowledgeable experiences throughout this project. The author again would like to extend his thanks and deep appreciation to his supervisor, whose guidance and advice had helped him a great deal in completing this project.

The author gratefully acknowledges the assistance and guidance from the PhD and Master student, Mr. Yuli Panca Asmara and Mr. Martin for their helpful advices during the project execution, especially in matters regarding the practical usage of equipment in the laboratory such as ACM machine and sample preparation.

The author also thanks to the family and friends of him, who believed in and constantly supported the work throughout the 2 semesters.

Overall, thanks a lot for those who involved in this project.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# ABBREVIATIONS AND NOMENCLATURES

| | |
|---|---|
| CP | Cathodic Protection |
| SACP | Sacrificial Anode Cathodic Protection |
| ICCP | Impressed Current Cathodic Protection |
| Zn | Zinc |
| Al | Aluminium |
| Mg | Magnesium |
| Cu | Copper |
| Pb | Plumbum |
| Sn | Stanum |
| In | Indium |
| Hg | Amalgam |
| Pt | Platinum |
| Al-Zn-In | Aluminium-Zinc-Indium |
| KCl | Potassium Chloride |
| LPR | Linear Polarization Resistance |
| Cu/CuSO4 | Copper/Copper Sulphate as used for the Copper/Copper Sulphate type of reference electrode. |
| SCE | Saturated Calomel Electrode |

# CHAPTER 1
# INTRODUCTION

## 1.1 Background Studies

### 1.1.1 What are Cathodic Protection (CP) and Sacrificial Anode (SA)?

CP is a process of reducing or preventing corrosion of metal structures in contact with an electrolyte by the flow of direct current from the electrolyte into the structure surface. Through this method, the metal structures will become a cathode of an electrochemical cell. The potential of the metal shifts in the negative direction by the use of an external power source (referred to as Impressed Current CP) or by utilizing SA. Cathodic protection was first developed by Sir Humphrey Davy in 1824 as a means of controlling corrosion on British naval ships. Virtually all modern pipelines are coated with an organic protective coating that is supplemented by cathodic protection systems sized to prevent corrosion at holidays (defects) 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.

Both Impressed Current (ICCP) and SACP are the type of CP that practically used in Oil and Gas field but through this report, the author only focus on SACP as the core subject of study.

SACP is a sufficient mass of less noble metal attached to the surface of the structure to be protected in the same electrolyte. Galvanic action from the anode provides the CP current. The anodes will experience simultaneous consumption by electrochemical dissolution and protect the structure related. Practically, SACP will be used in industrial application for a short period of lifetime such as ten (10) to twenty (20) years compare to ICCP which take period up to fifty (50) years.

### 1.1.2 Application of SACP

Below is the application of SACP according to Einar Beddal:-

a) The majority of offshore installations, particularly in aggressive environments such as in the North Sea are protected with SACP. On submerged parts of platforms, this is in most cases the only protection system.

b) A few oil companies have used a companies have used a combination of a paint coating system and SACP while a combination of thermally sprayed Al and SACP have been used in special cases.

c) Combinations of coatings and CP and/or a combination of SACP and ICCP may be of particular interest for the reduction of weight and drag forces from the anodes on structures in deep water.

d) Floating platforms are generally protected by CP (SACP or ICCP) combined with a high-quality paint system.

e) Pipelines with an organic coating and an external concrete coating are also protected by SACP.

f) For bare steel on offshore structures in seawater, the SACP is commonly made of special Al alloys because these give the highest current output for a certain anode weight as well as the lowest cost.

g) When SACP (usually Zn or Al anodes) are used on ship hulls they are combined with a paint system. The anodes are mounted close to each other on the area around the propeller, partly because the propeller “steals” some of the current and partly because of turbulence leading to higher demand of cathodic current density. Zn and Al anodes are also used in ballast tanks on tankers and bulk carriers.

h) For some other applications, such as on steel structures in soil and in hot water tanks for fresh water, magnesium anode is used to a higher extent. In these cases Mg anodes have a great benefit in higher driving voltage than the Al and Zn anodes. In high-resistivity environments, a combination of CP and coating is particularly beneficial with the aim to reduce the total current and thereby the potential drop near the anodes and thus to obtain a better distribution of the current to the spots where it is needed.

## 1.2 Problem Statement

In industrial application, SACP is widely used to protect the structure. The anode is manufactured in various kinds of shape, size and application in corrosion prevention field. There are many types of anode such as Mg, Zn and Al. These types of anode have being alloyed with other impurities such as Cu, Sn, In, Pb, Hg and others.

By the way, these impurities have affected the environment. As example the Cu released to the seawater from the consumption of the alloy Al anode. When copper ends up in soil it strongly attaches to organic matter and minerals. As a result it does not travel very far after release and it hardly ever enters groundwater. In surface water copper can travel great distances, either suspended on sludge particles or as free ions.

Copper does not break down in the environment and because of that it can accumulate in plants and animals when it is found in soils. On copper-rich soils only a limited number of plants have a chance of survival. This wills kill the plankton and other seawater plant and disturbs the food chain of underwater lives. The bigger effect is from the mercury Hg. Hg is not naturally found in foodstuffs, but it may turn up in food as it can be spread within food chains by smaller organisms that are consumed by humans, for instance through fish. Mercury concentrations in fish usually greatly exceed the concentrations in the water they live in. Cattle breeding products can also contain eminent quantities of mercury.

Moreover, the alloying anode is expensive as the fabrication cost of it is very high. Industrial application need to reduce the cost on purchasing the anode as to increase profit and in the same time protect the oil and gas industry.

In order to do so, the author has the target to create a new invention to overcome this problem by using cold working onto the pure anode. Through this study, the author has made a hypothesis of more deformation of the anode will yield to increase its performance.

In principle of CP or particularly SACP, the anode needs to corrode relative to the steel structure (steel) so that the structure will be protected. This will be the guide for the author to do the study. The most corroded Al anode is the most reliable for corrosion prevention.

## 1.3 Objective and Scope of Study

At the end of this study, objectives that need to achieve are stated as below:

- To test the pure Al in pre-experiment so that the author knows the Al can be used in this study as a SACP.
- To prepare the anode into various profile.
- To know the best percentage of NaCl in a solution that can be used in the experiment.
- To design the arrangement of LPR experiment due to additional electrode (anode) in LPR experiment.
- To study the corrosion data (specifically the corrosion potential; $E_{corr}$ and Icorr) of different anode profile.

The scope of study of this project covers a wide range of engineering scope as follow:

- Corrosion Engineering
- CP and SACP
- Experimental study – ACM machine for LPR experiment
- Engineering documentation

# CHAPTER 2
# LITERATURE REVIEW

## 2.1 Principle of Corrosion

Corrosion is the destruction or deterioration of essential properties in a material due to reactions with its environment (electrolyte). The examples of electrolytes are soil, fresh water and seawater. The corrosion process occurred in anodic area where in anodic area the positively charged metal ions leave the metal surface. At cathodic area, electrons leave the metal surface which means there is reduction reaction in the electrolyte. The basic electrochemical reactions are stated below:

Anodic area : $Fe \rightarrow Fe^{++} + 2e^-$ …………………………………………….. 1

Cathodic area : $2H^+ + 2e^- \rightarrow H_2$ @ $\frac{1}{2} O_2 + H_2 + 2e^- \rightarrow 2OH^-$ ………..…. 2

The unit for corrosion rate is mils per year which calculated from the weight loss of the metal specimen given below:-

mpy = (534W ) / (DAT) …………………..……………………………………. 3

where W = weight loss, mg

D = density of specimen, g/cm3

A = area of specimen, sq.in.

T = exposure time, hr

## 2.2 Protection by Sacrificial Anode

### 2.2.1 Electrochemical Series

When two dissimilar metals are placed in an electrolyte and joined by a conductor, an electric current tends to flow from one metal to the other depending on their relative position in the electrochemical series (see Table 2-1). Any such current flow will increase the corrosion of the less noble (anodic) metal and reduce that of the more noble (cathodic) one. This is the basis of cathodic protection sacrificial anode.

Steel structures are protected by connecting them to anodes (magnesium, aluminium alloy or zinc). These metals are less noble than steel and are available at an economic price.

In the same way, iron or steel sacrificial plate and plugs can be used to prevent corrosion and de-zincification of brass, or reduce crevice attack on austenitic stainless steels and titanium. These metals are more noble than steel.

Table 2-1: Electrochemical Series of Metals

| | **Material** | **Approximate potential in seawater (mV vs. Ag/AgCl reference)** |
|---|---|---|
| LESS NOBLE | Magnesium | -1650 |
| ↓ | Aluminium | -1100 |
| | Zinc | -1050 |
| | Steel | -630 |
| | Cast Iron | -630 |
| | Stainless steel (active) | -600 to -550 |
| | Copper/Brass | -380 |
| | Cupro-Nickel | -300 |
| MORE NOBLE | Stainless steel (passive) | -200 to -70 |

### 2.2.2 Anode Characteristics

Each anode material has its typical electrochemical potential. This potential determines the driving voltage of the anode, i.e., the voltage difference between the anode and the (protected) steel (see Table 2-1). The driving voltage is the difference in potential between anode and protected steel. The more negative the open anode potential, the greater the driving voltage and the more powerful the anode system. This is particularly important when sacrificial anodes are used in high resistivity soils.

### 2.2.3 Current Output of Anodes

The current output of an anode depends on the driving voltage and on the circuit resistance. Assuming that the resistance of metallic connections is low, this resistance is mainly determined by the soil or water resistivity and the shape of the anode.

Current output determines the rate of consumption, i.e. the service life of an anode. This can be expressed as anode consumption rate (kilograms of anode material consumed per Ampere.year, kg/A.y) or as the anode Capacity (the number of Ampere-hours (Ah) that can be supplied by one kg of anode material, Ah/kg), see Table 2-2

Table 2-2: Properties of Sacrificial Anodes

| ANODE ALLOY | THEORETICAL CAPACITY (Ah/kg) | PRACTICAL CAPACITY, (Ah/kg) | PRACTICAL CONSUMPTION (kg/A.y) |
|---|---|---|---|
| Zinc (Mil-Spec) | 820 | 780 | 11 |
| Aluminium-Indium | 3000 | 2500 | 3.3 |
| Magnesium (commercial) | 2200 | 450-900 | 10-19 |
| High output Mg | 2200 | 1100 | 8 |

## 2.3 Al SACP

### 2.3.1 Anode Material

Al alloys have found wide application for CP of offshore structures. The advantage of Al as anode material is its high current capacity and therefore its relatively low installation weight. Al may show a tendency to passivate with a resulting under protection of the system. Therefore the anode composition is not always a guarantee for success and additional test is recommended to show the tendency to passivation.

However, with the proper alloy chemistry and after successful passivation testing, Al-Zn-In alloy is used in all applications including pipelines and deep water systems.
The composition of anodes is often proprietary although typical (effective) compositions are shown in Table 2-3(See Appendix). The high performance indium activated alloy has a more stringent specification in chemistry and is the recommended alloy for pipelines in cold water and deep water applications. (The high performance specification is proposed as the recommended standard in ISO documents.)

The indium-activated type is preferred. For health and environmental reasons, it is Group policy to prohibit the use of cadmium- and a mercury-activated anode. Some anode compositions are claimed to be suitable in mud as well as in seawater. Special alloys for high temperature are offered. In practice, at elevated temperatures, the efficiency of Al anodes decreases strongly and the consumption pattern shows a localized attack like intergranular corrosion.

Al anodes are not recommended for other services than in seawater. In fresh water and in soil their performance is ineffective. In this research, the metal that will be used as anode is the Al and the protected metal is carbon steel (mild steel).

Manufacturers fabricate the anode in various kind of geometry wise that give different kind of performance of anodes. Among the examples that practically used in industrial application are:

a) Al alloy rod anode for SACP
b) Al pencil anode for heat exchanger and condenser
c) Al disc anodes for marine applications
d) Sacrificial CP Al plate anode
e) Al ribbon / bracelet anode for submerged pipeline
f) Al prepackaged SACP

## 2.4 Principle of Cold Working

Principle methods for cold forming are cold extrusion, cold drawing, cold forging, cold rolling, and bending, etc. Popular forms are such as wire drawing and deep drawing.

Bending is a process widely employed in, such as sheet forming. Other cold forming processes are such as spinning (to form, e.g. aluminum pot), stretch forming

Cold working is employed to obtain the following effects: improved mechanical properties, better machine ability, special size accuracy, bright surface, and the production of thinner gages than hot-work can accomplish economically.

Cold working by cold rolling consists of passing unheated, previously hot-rolled bars, sheets or strip (cleaned of scale) through a set of rolls, often many times, utilize the final size is obtained. Cold Forging is similar to hot forging but requires the use of special lubrication techniques and tooling design. It is now being used for the forming of small parts. Through cold forging, superior mechanical properties and tight dimensional tolerances can be reached with minimal machining and consumption of energy.

In the cold drawing process a bar, rod, wire or tube, after being cleaned, is pulled through a die having an opening smaller than the entering piece to reduce the latter to the required size.

The cold extrusion of steel is carried out in a manner similar to the hot-extrusion process, with two main exceptions: (1) The metal is at room temperature, and (2) the surface of the piece is treated by some chemical process such as bonderizing to assist in reducing friction between the metal and the container wall and die, in conjunction with special lubricants.

## 2.5 Tafel Extrapolation & LPR

The Tafel Extrapolation method for determining corrosion rate for used by Wagner and traud to verify the mixed-potential theory. In Figure 2-1**,** the line marked is the applied polarization curve becomes linear semi logarithmic plot. This region is referred to as the Tafel region. The total anodic and cathodic polarization curves corresponding to hydrogen evolution and metal dissolution are superimposed as dotted lines. To determine the corrosion rate from such polarization measurements, the Tafel region is extrapolated to the corrosion potential. At the corrosion potential, the rate of hydrogen evolutions is equal to the rate of metal dissolution, and this point corresponds to the corrosion rate of the system expressed in terms of current density.

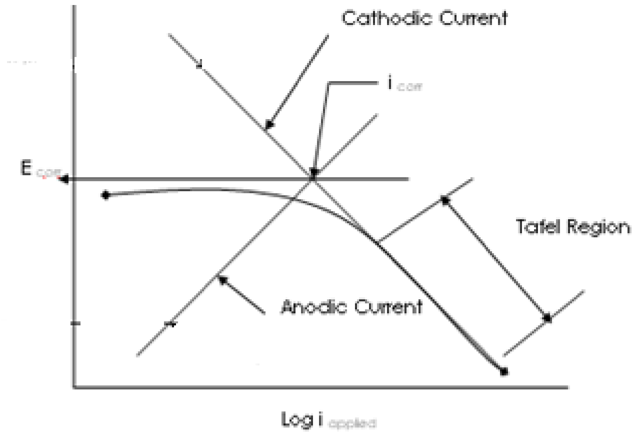


Figure 2-1: Tafel Extrapolation

To ensure reasonable accuracy, the Tafel region must extend over a current range of at least one order of magnitude. In many systems this cannot be achieved because of interference from concentration polarization and other extraneous effects. Further, the method can be applied only to systems containing one reduction process since the Tafel region is usually distorted if more than one reduction process occurs. In summary, the Tafel method is very useful and can be used in certain circumstances to measure corrosion rates rapidly.

Linear polarization analysis is the method to overcome the disadvantage of Tafel extrapolation. Within 10 mV nobler or more active than the corrosion potential, it is observed that the applied current density is a linear function of the electrode potential. In Figure 2-2(See Appendix)**,** the corrosion potential is used as an over voltage reference point and a plot of over voltage versus applied anodic and cathodic current is shown on a linear scale. The slope of this linear polarization curve is related to the kinetic parameters of the system as follows:

$$\{\Delta E / \Delta\ i_{app}\} = \{\beta_a\beta_c\ / 2.3\ (i_{corr})(\ \beta_a + \beta_c)\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 4$$

where $\beta_a$ and $\beta_c$ are the Tafel slopes of the anodic and cathodic reactions respectively. The term $\Delta\ E\ /\ \Delta\ i_{app}$ is given in ohms (volts/amperes or milivolts / milliamperes). Corrosion rate may be calculated if beta values for the reactions are known.

The advantages of electrochemical corrosion-rate measurements for linear-polarization techniques:-

1. The permit rapid corrosion rate measurements and can be used to monitor corrosion rate measurements and can be used to monitor corrosion rate in various process streams.

2. These techniques may be used for accurately measuring very low corrosion rates (less than 0.1 mpy), which are both difficult and tedious to perform with conventional weight loss or chemical analytical techniques. The measurement of low corrosion rates is especially important in nuclear, pharmaceutical and food processing industries, where trace impurities and contamination are problems.

3. Electrochemical corrosion rate measurements may be used to measure the corrosion rate of structures that cannot be visually inspected or subjected to weight loss tests. Underground pipes and tanks and large chemical plant components are examples.

# CHAPTER 3

# METHODOLOGY

## 3.1 Pre-Experiment

### 3.1.1 Anode Deformation Test

A solution containing Potassium Chloride (KCl), Phenolphthalein and de-ionized water is used to determine if the deformation of the anode will effect the corrosion reaction (oxidation) of the anode or not. Three types of anode were tested. The rods undergo the Rolling machine (Cold Working) to get the different deformations. More concentrated the pink color showed the oxidation reaction is more aggressive compared to another. This is qualitative experiment to prove whether there is different in corrosion reaction or not.

## 3.2 Sample Preparation

### 3.2.1 Mild Steel

The mild steel was cut into four (4) pieces with dimension of 8.0cm x 6.0cm x 0.5cm (L x W x H) each. The surface grinded to make sure the entire corrosion product (Ferum Oxide) is not there on the mild steel. The weight of each piece is 228 g.

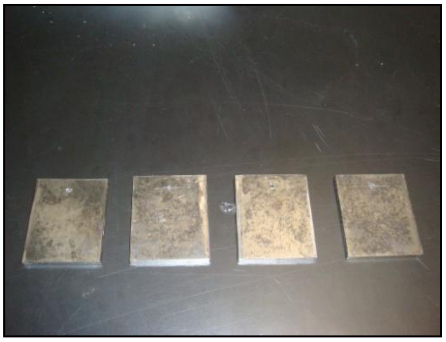


Figure 3-1: Four Pieces Mild Steel

### 3.2.2 Al Anode

The Al rod which diameter 3 mm cut into six (6) which have similar length of 85 mm. Anode B and C undergo the Rolling machine (cold working) to get the different deformation of anode except for anode A. See Table 3-1 for the detail dimension of all six (6) rods both:

Table 3-1: Al anode sample

| **Anode** | **No. of Anode** | **Dimension** | **Function** |
|---|---|---|---|
| A | 2 | Lo = 85 mm<br>D = 3mm | One for determined anode characteristic and one for LPR experiment |
| B | 2 | L1 = 120 mm<br>w = 5 mm<br>t = 1 mm | One for determined anode characteristic and one for LPR experiment |
| C | 2 | L2 = 230 mm<br>w = 6 mm<br>t = 0.5 mm | One for determined anode characteristic and one for LPR experiment |

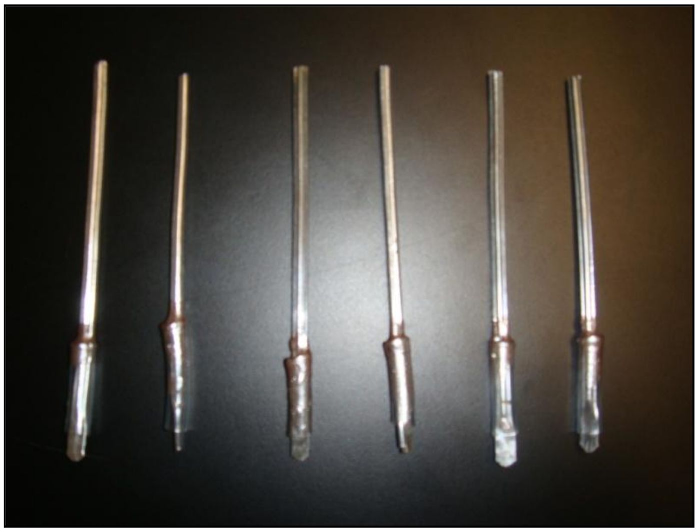


Figure 3-2: Couple of Anode Sample A, B and C that will be undergo cold working

## 3.3 LPR Experiment

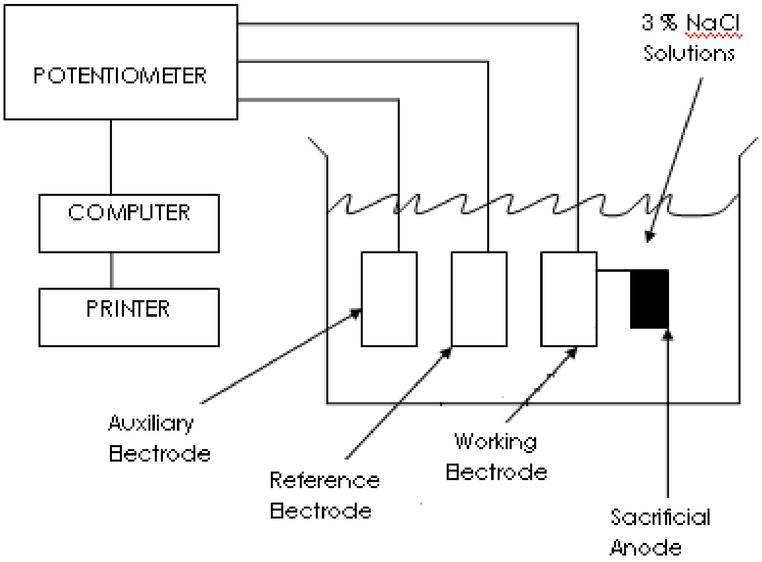


Figure 3-3: The arrangement of sample in LPR experiment

Above is the arrangement of the sample in LPR experiment. The potentiometer called the ACM Machine which connects to the computer to gather the data. The electrode that being used in this experiment are:

1. Reference Electrode : SCE
2. Working Electrode : Mild Steel
3. Auxiliary Electrode : Pt

The anodes have been connected to the mils steel and being named as sample I, II, III and IV. See Table 3-2 for detail:

Table 3-2 Samples due to its function

| Sample | Arrangement of Mild Steel | Function |
|---|---|---|
| I | Not connected with any anode | As a control |
| II | Connected with one anode A | To determine the level of protection by anode A |
| III | Connected with one anode B | To determine the level of protection by anode B |
| IV | Connected with one anode C | To determine the level of protection by anode C |

Below are the steps on how the experiment has been done by the author:

**Determine the anode characteristic alone:**

1. Three anodes (A, B and C), AU and RE have been immersed into a 3 % NaCl.
2. Anode A was connected to the LPR system.
3. The experiment was run by click the RUN NOW button.
4. Graph of potential vs. current plotted by the software.
5. The file saved into the database.
6. Steps 1 to 5 repeated with anode B and C.

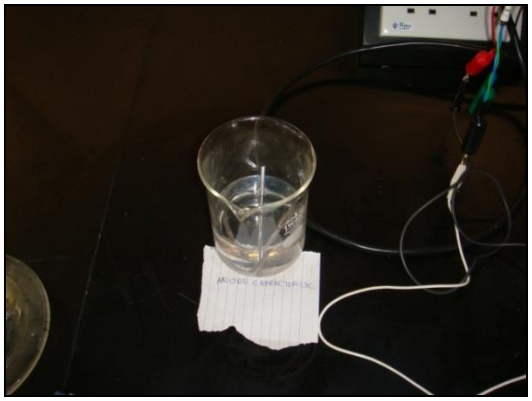


Figure 3-4: Anode Characteristic Sample

**Determine the level of protection provide by the anode:**

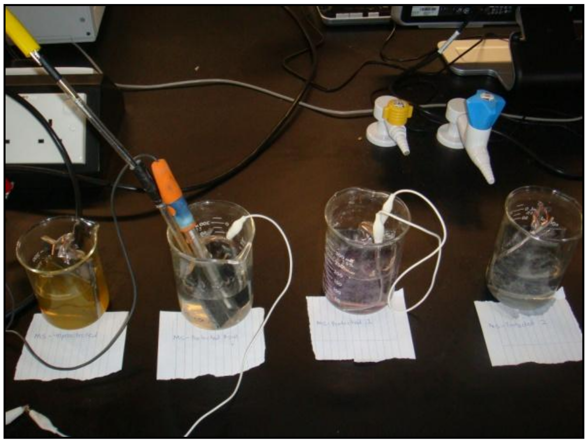


Figure 3-5: Sample I, II, III and IV from left to right

1. The AU and RE immersed in a beaker in 3 % NaCl together with sample I.
2. Sample I was connected to the LPR system
3. The experiment was run by click the RUN NOW button.
4. Graph of potential vs. current plotted by the software.
5. The file saved into the database.
6. Steps 1 to 5 repeated with sample II, III and IV.

# CHAPTER 4

# RESULT & DISCUSSION

## 4.1 Results

### 4.1.1 Pre- Experiment

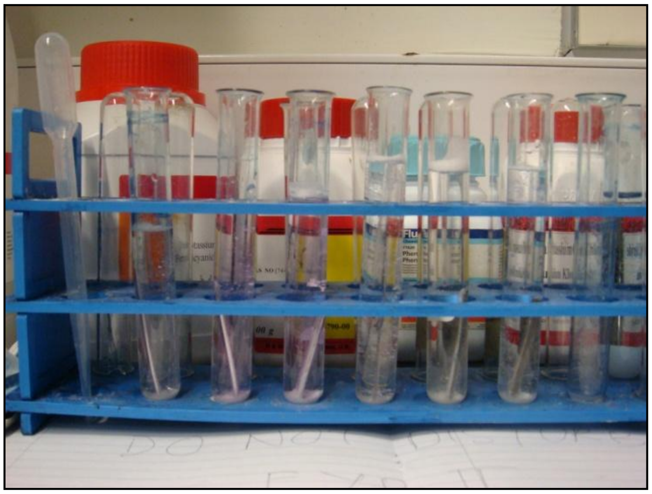


Figure 4-1: Sample 1, 2 and 3 of Pre-experiment

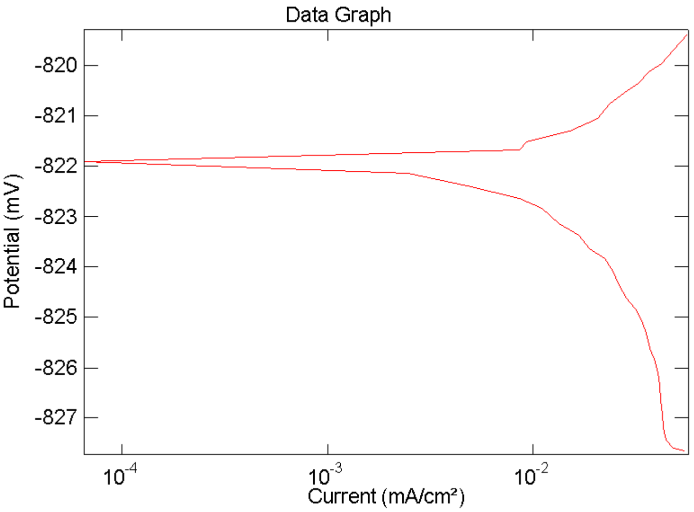
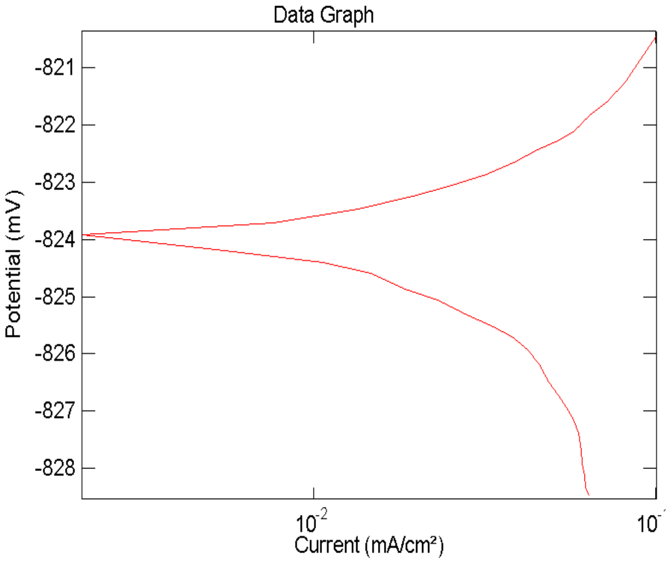
This method (Qualitative) is applied only to show that with different deformation of Al (anode), there will be different level of protection. This is the beginning of the experiment.

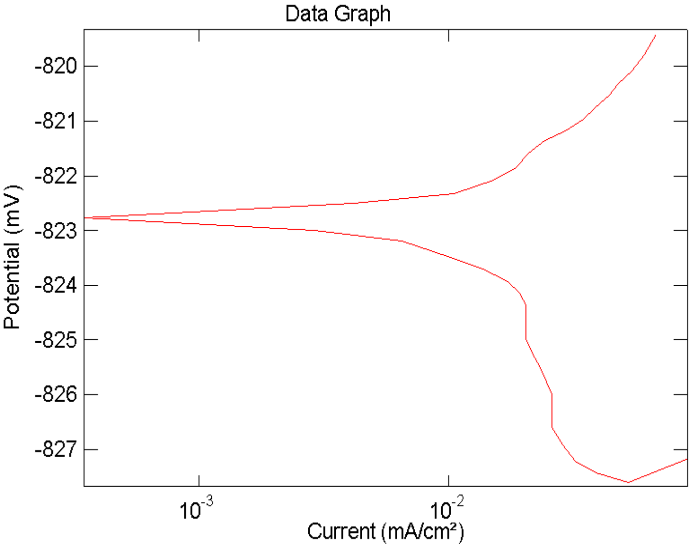
Table 4-1: Qualitative Result of Deformation Test (Pre-Experiment)

| Sample | Thickness of Al (mm) | Pink Color Concentration |
|---|---|---|
| 1 | 3 | Low |
| 2 | 2 | Moderate |
| 3 | 1.5 | High |

### 4.1.2 Anode Charateristic

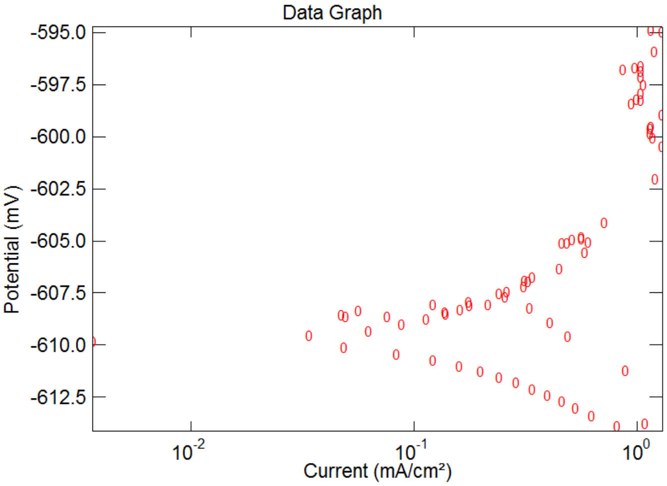
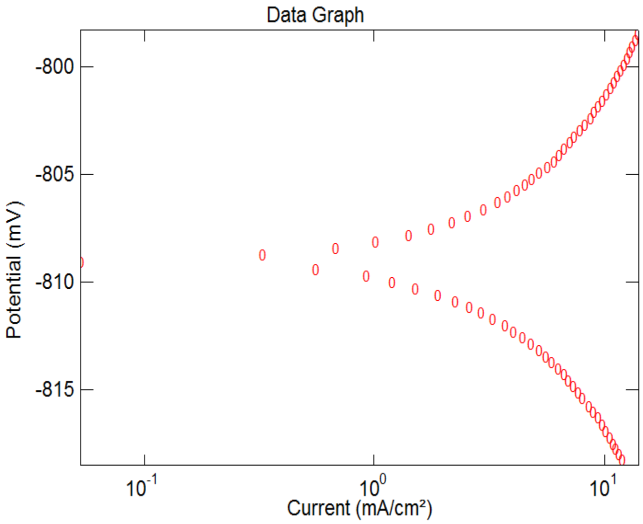
**Table 4-2: Ecorr for Al Anode only**

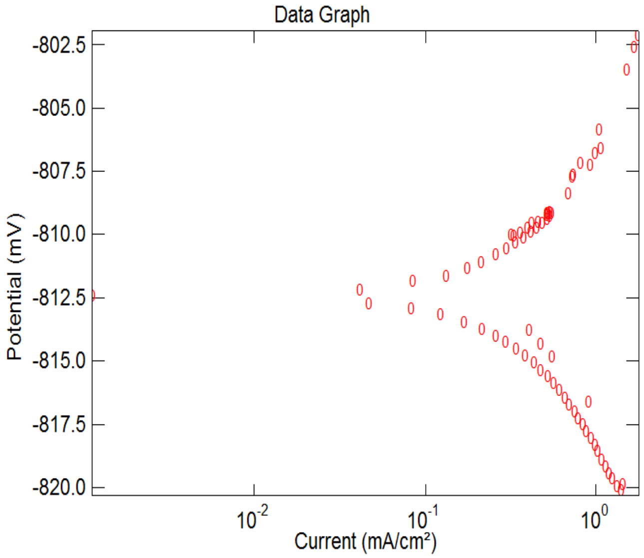
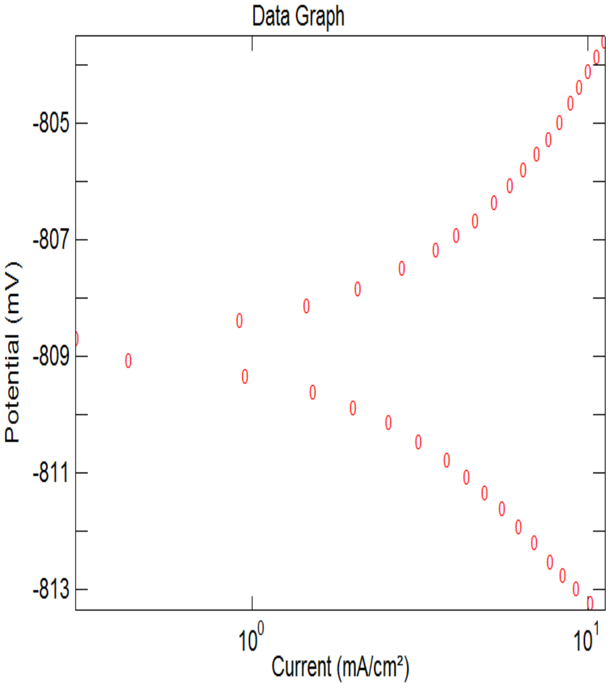
| Anode | Details | Graph |
|---|---|---|
| A | #Ecorr = -823.62mV<br>#Icorr = 0.313043 mA / cm$^2$ |  |
| B | #Ecorr = -824.64mV<br>#Icorr = 0.5893098 mA / cm$^2$ |  |

| | | |
|---|---|---|
| C | #Ecorr = -823.68 mA / cm$^2$<br>#Icorr = 0.3259712 mA / cm$^2$ |  |

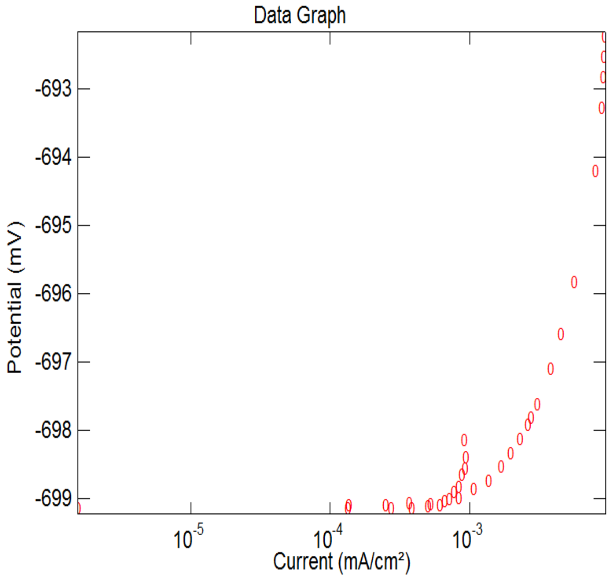
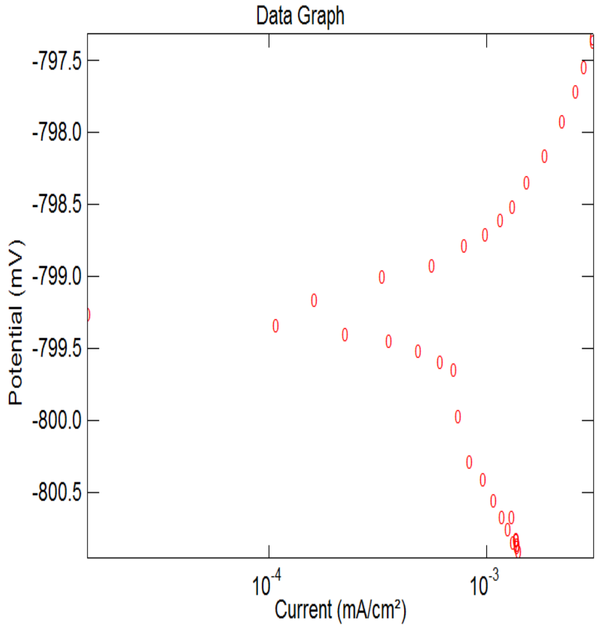
### 4.1.3 LPR Experiment

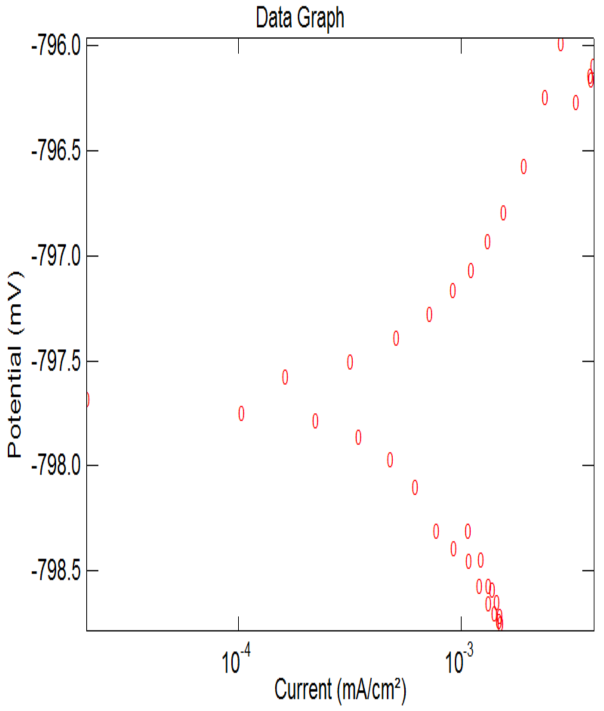
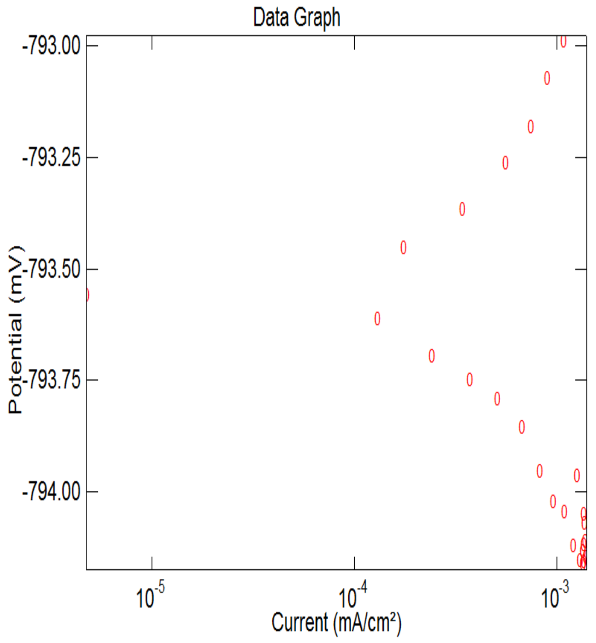
**Table 4-3: Ecorr of samples on 30 April 2008 at time 1400 hours**

| Sample | Details | Graph |
|---|---|---|
| Sample I | #Ecorr = -605.44mV<br>#Icorr = 2.9571 mA / $cm^2$ |  |
| Sample II | #Ecorr = -808.64mV<br>#Icorr = 33.766 mA / $cm^2$ |  |

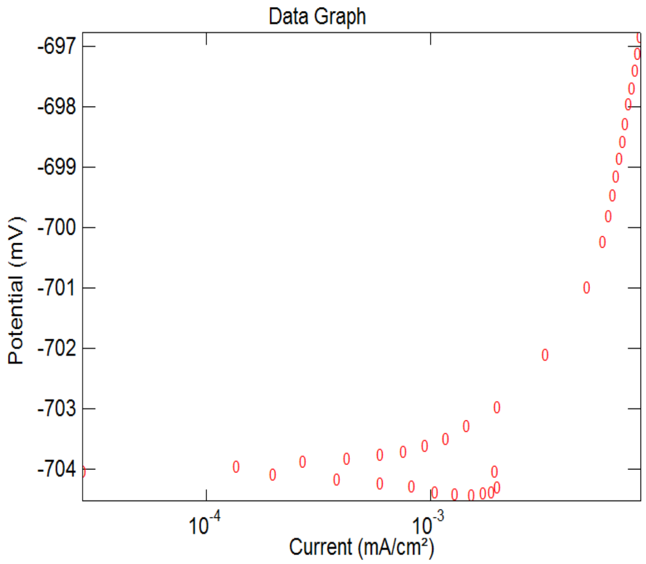
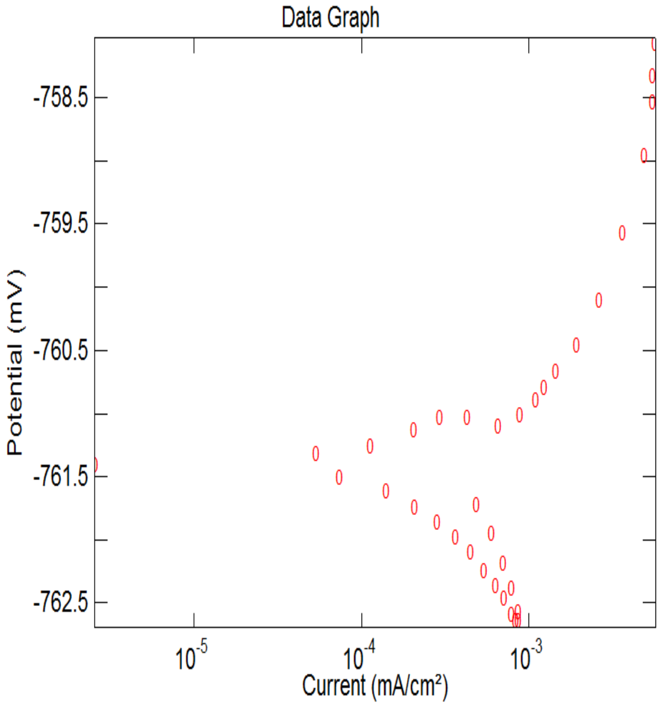
| | | |
|---|---|---|
| Sample III | #Ecorr = -809.07 mA / cm$^2$<br>#Icorr = 5.4765 mA / cm$^2$ |  |
| Sample IV | #Ecorr = -808.75mV<br>#Icorr = 54.331 mA / cm$^2$ |  |

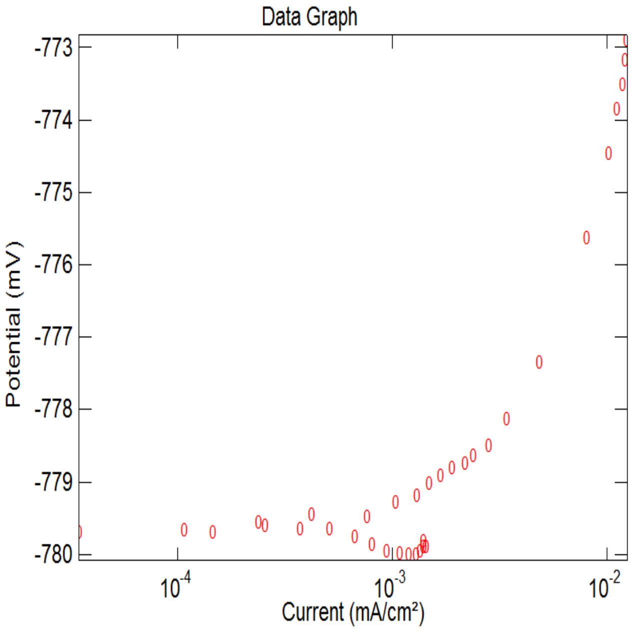
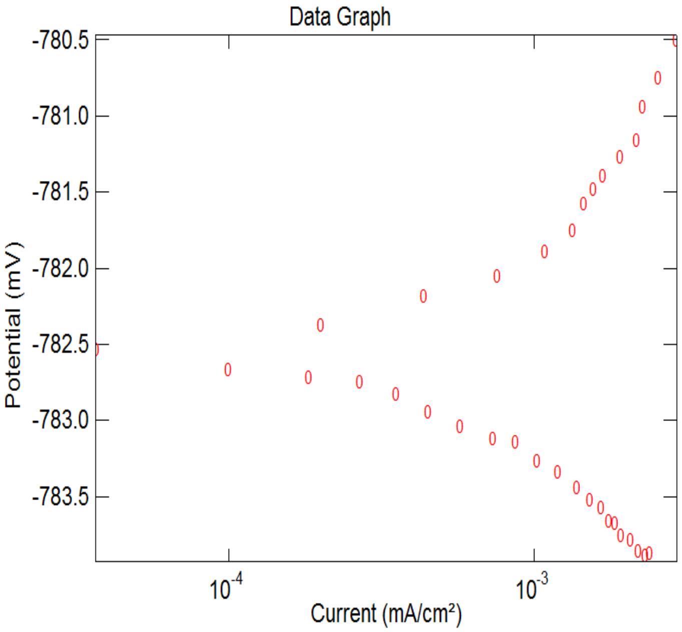
## Table 4-4: Ecorr of samples on 30 April 2008at time 1800 hours

| Sample | Details | Graph |
|---|---|---|
| Sample I | #Ecorr = -697.2 mV<br>#Icorr = 0.0466161 mA / cm$^2$ |  |
| Sample II | #Ecorr = -799.1 mV<br>#Icorr = 0.0324839 mA / cm$^2$ |  |

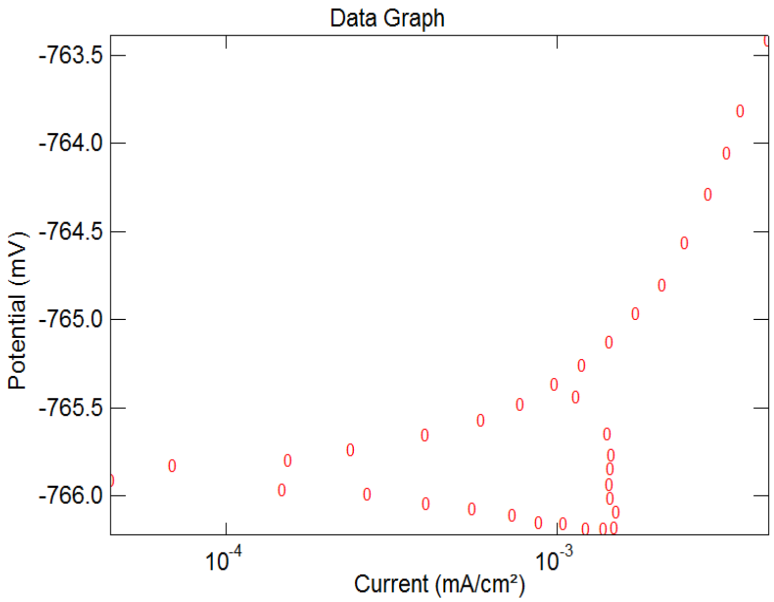
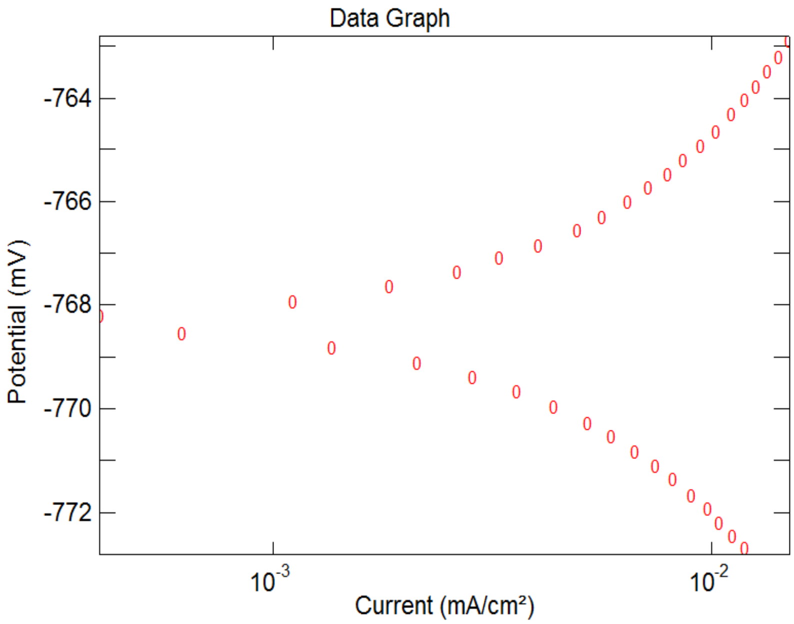
| | | |
|---|---|---|
| Sample III | #Ecorr = -797.44 mV<br>#Icorr = 0.0431987 mA / cm$^2$ |  |
| Sample IV | #Ecorr = -793.3 mV<br>#Icorr = 0.0591281 mA / cm$^2$ |  |

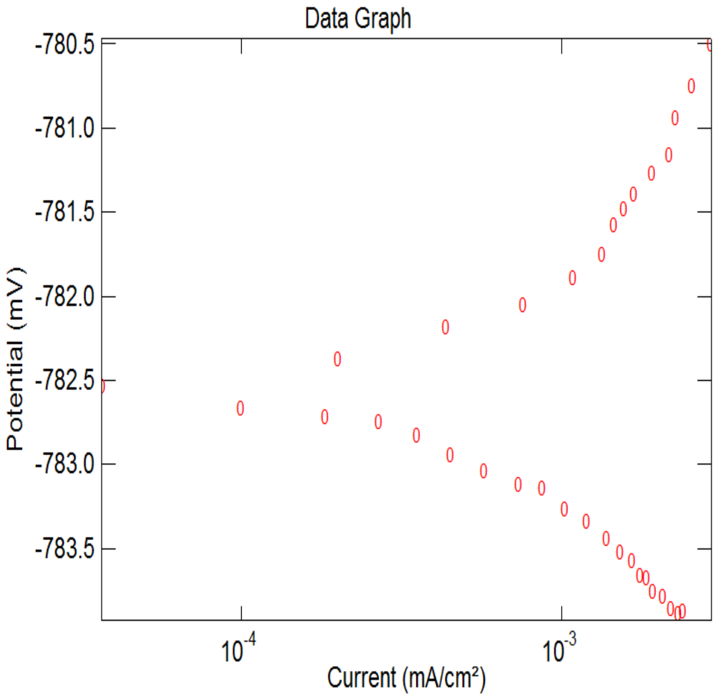
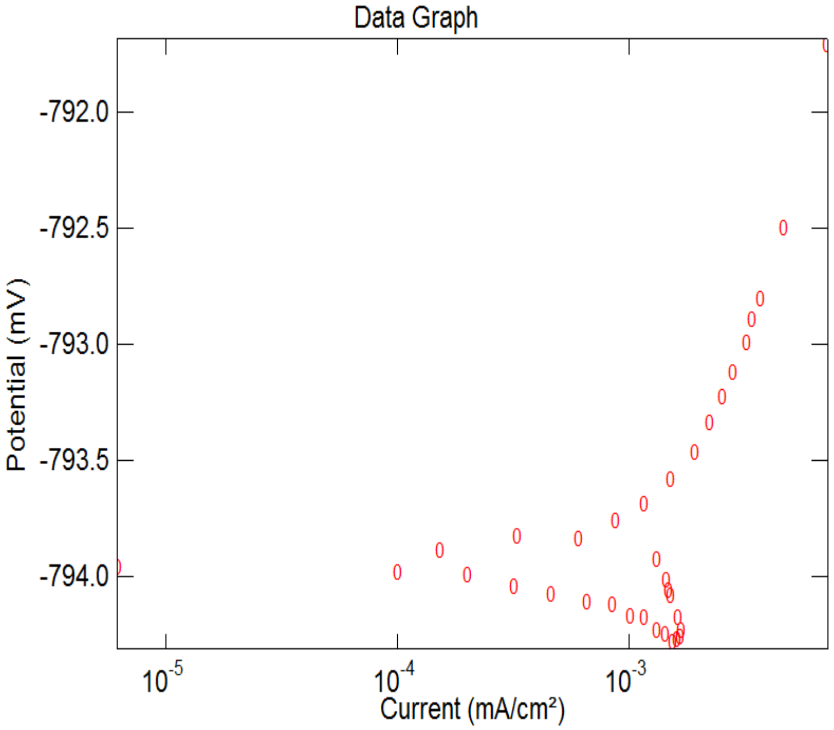
## Table 4-5: Ecorr of samples on 1 May 2008 at time 1300 hours

| **Sample** | **Details** | **Graph** |
|---|---|---|
| Sample I | #Ecorr = -702.04 mV<br>#Icorr = 0.0373186 mA / cm$^2$ |  |
| Sample II | #Ecorr = -760.73 mV<br>#Icorr = 0.0410359 mA / cm$^2$ |  |

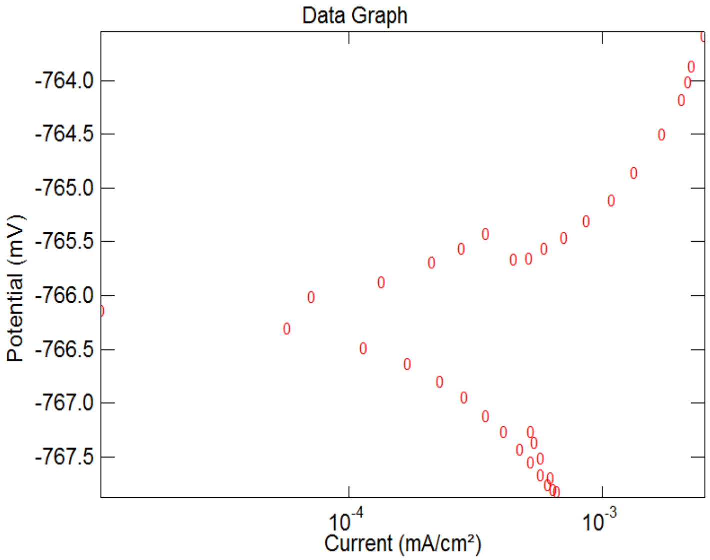
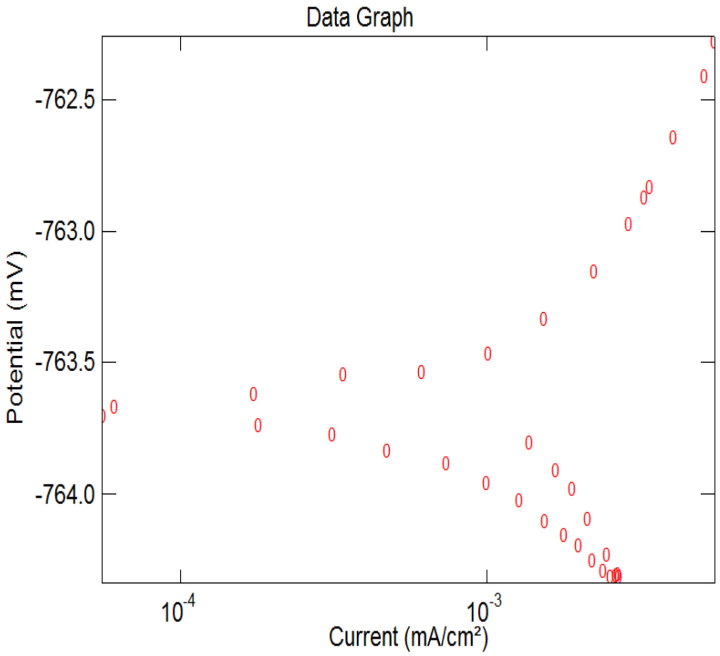
| | | |
|---|---|---|
| Sample III | #Ecorr = -777.98 mV<br>#Icorr = 0.0539053 mA / cm$^2$ |  |
| Sample IV | #Ecorr = -782.13 mV<br>#Icorr = 0.0403399 mA / cm$^2$ |  |

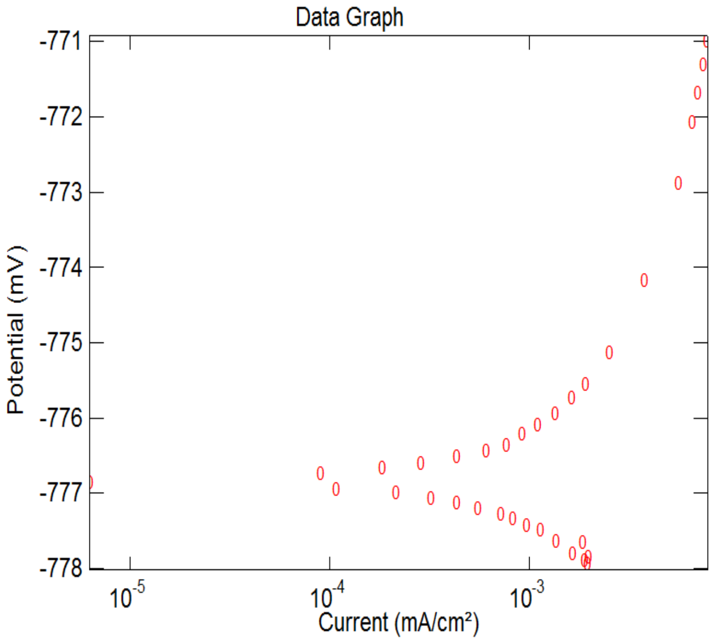
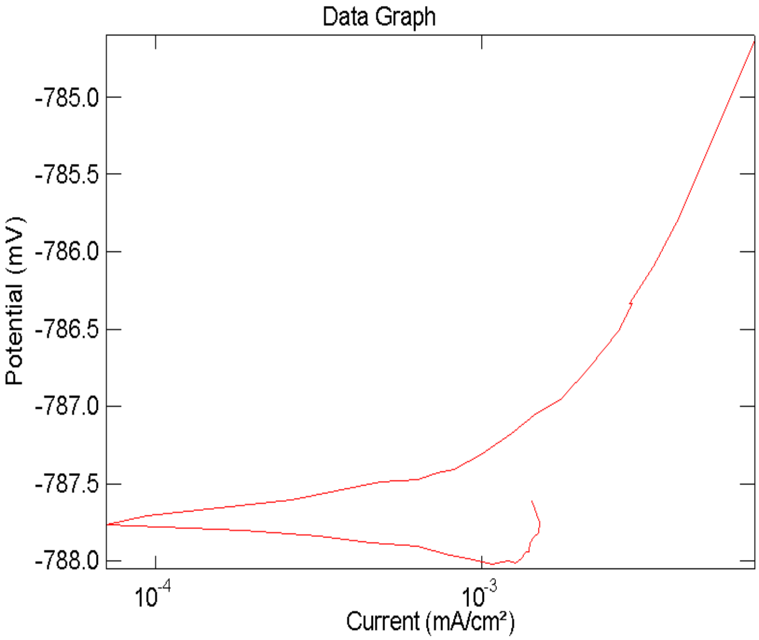
## Table 4-6: Ecorr of samples 1 May 2008 at time 1500 hours

| Sample | Details | Graph |
|---|---|---|
| Sample I | #Ecorr = -765.4<br>#Icorr = 0.0681885 |  |
| Sample II | #Ecorr = -768.18<br>#Icorr = 0.0713494 |  |

<table>
<tr>
<td>Sample<br>III</td>
<td>#Ecorr = 782.13<br>#Icorr = 0.0403399</td>
<td>
</td>
</tr>
<tr>
<td>Sample<br>IV</td>
<td>#Ecorr = -793.36<br>#Icorr = 0.1040539</td>
<td>
</td>
</tr>
</table>

## Table 4-7: Ecorr of samples on 1 May 2008 at time 1800 hours

| Sample | Details | Graph |
|---|---|---|
| Sample I | #Ecorr = -765.89 mV<br>#Icorr = 0.0185247 mA / cm$^2$ |  |
| Sample II | #Ecorr = -763.3 mV<br>#Icorr = 0.1073493 mA / cm$^2$ |  |

| | | |
|---|---|---|
| Sample III | #Ecorr = -775.96 mV<br>#Icorr = 0.0380108 mA / cm$^2$ |  |
| Sample IV | #Ecorr = -787.14 mV<br>#Icorr = 0.0708561 mA / cm$^2$ |  |

### 4.1.4 Table and Graph of summary for LPR experiment

Table 4-8: Readings of $\mathbf{E_{corr}}$ for every sample

| **Time** | **Potential for Each Sample** | | | |
|---|---|---|---|---|
| | **I** | **II** | **III** | **IV** |
| **30 Apr(2)** | -605.04 | -808.64 | -809.07 | -808.75 |
| **30 Apr (6)** | -697.2 | -799.1 | -797.44 | -793.3 |
| **1 May (12)** | -702.04 | -760.73 | -777.98 | -782.13 |
| **1 May (3)** | -765.4 | -768.18 | -782.13 | -793.36 |
| **1 May (6)** | -765.89 | -763.3 | -775.96 | -787.14 |
| **TOTAL** | -3535.57 | -3899.95 | -3942.58 | -3964.68 |
| **AVERAGE** | -707.114 | -779.99 | -788.516 | -792.936 |

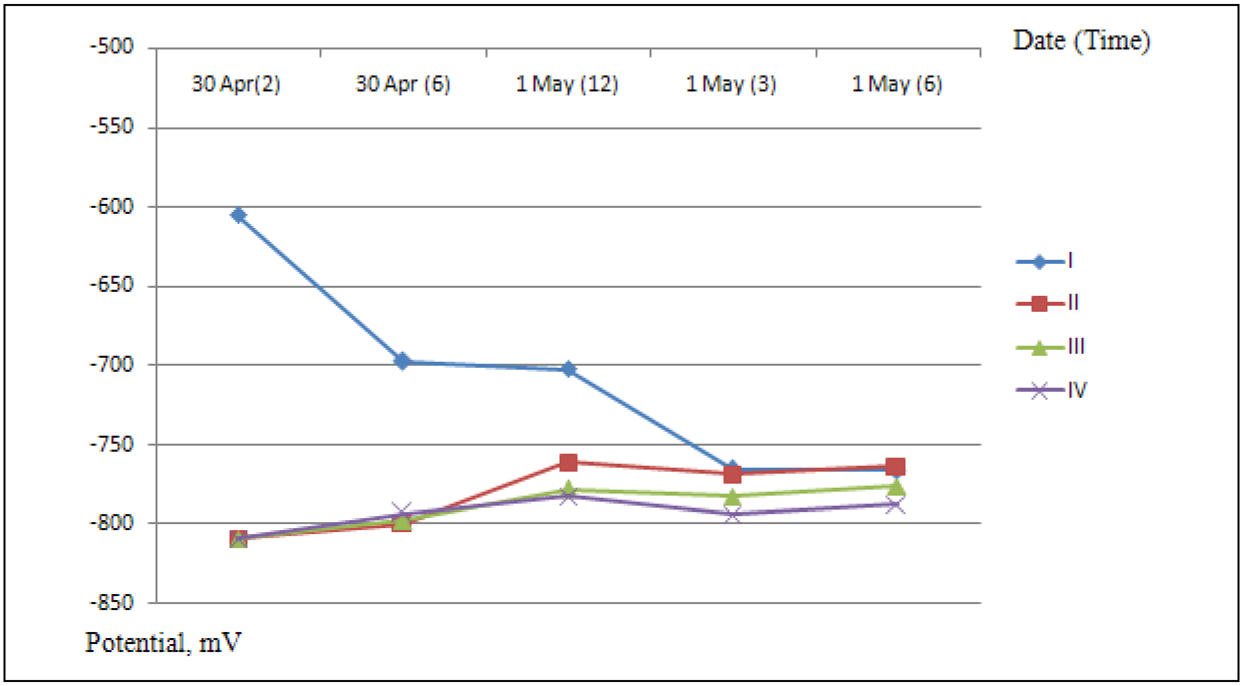


Figure 4-2: Summary of Ecorr for sample I, II, III and IV.

## 4.2 Discussion

### 4.2.1 Pre-Experiment

The result shows that the different profile of anode deformation will experience different kind of oxidation reaction. Sample 3 is the best one as an anode as the pink color concentration is high relative to the others. The quantitative results should be getting as a proof that the deformation of anode will affect the performance of anode.

### 4.2.2 LPR Experiment

The $E_{corr}$ (Corrosion Potential) value for all samples in different time has been gathered and analyze. $E_{corr}$ is the potential where the oxidation process occurs. In SACP principle due to electrochemical graph (See Figure 4-2) the higher negativity in $E_{corr}$ a metal has, more easily for the metal to oxidize then lead to increase in performance of the anode. So this is good for anode usage.

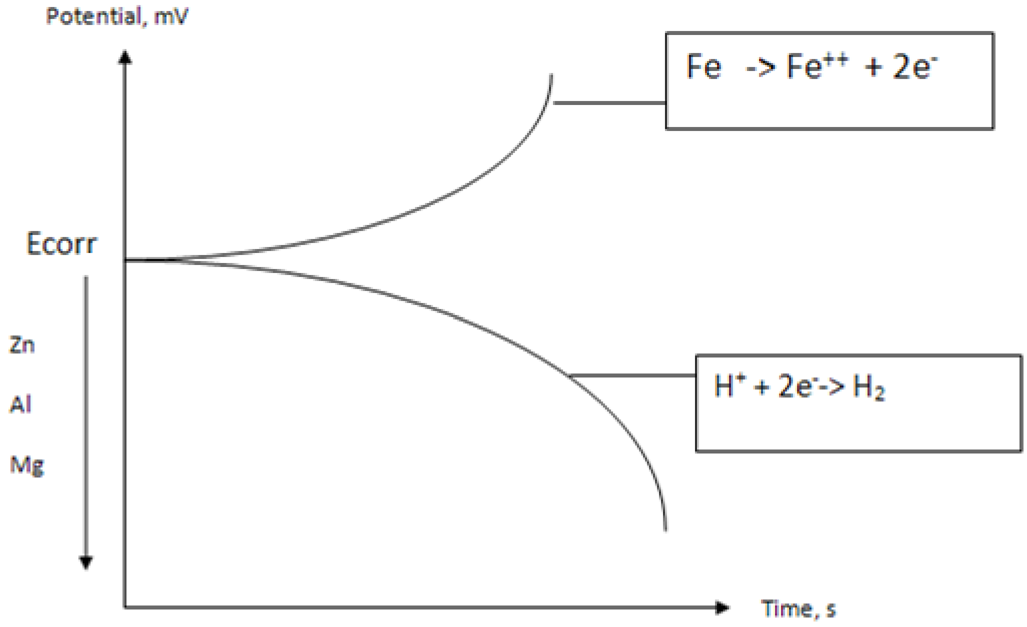


Figure 4-3: General polarization curve of metal in electrochemical series

From the Graph 4-1 above, the sample IV is higher negativity in $E_{corr}$ compare to other samples with the value of:

$$E_{corr} \text{ (sample IV)} = -792.936 \text{ mV}$$

The value of Ecorr can be get from the ACM Instrument Version 5 software. (See Appendix Figure 4-3)

The anodes undergo the cold working method which is through rolling machine. By this method, there are two factors that lead to increase the anode's performance:

1. Microstructure formation
   a. The grain boundaries become more
   b. The orientation and dislocation of the Al atoms

2. Internal stress increased

Due to the new formation of the Al microstructure, the total energy for the anode to corrode becomes lesser. This is aligns to the principle of SACP to make the anode prone to corrode. It is normal for Al anode to disturb in the readings as Al can easily oxidize to form the $Al_2O_3$. But still from the average of the result, sample IV give high performance due to its ability to corrode more than other sample as the microstructure has been reborn.

From ACM Instrument Version 5 software, the measurement of current density also measured which is stated as Icorr by the software data bank. These Icorr actually determine the corrosion rate of each sample itself. The method is like below:

Current flow can be related to mass via Faraday's Law.

$$Q = n F M \quad \text{……} \quad 5$$

where

| | |
|---|---|
| $Q$ | is the charge in coulombs resulting from the reaction of species S |
| $n$ | is the number of electrons transferred per molecule or atom of S |
| $F$ | is Faraday's constant = 96,486.7 coulombs/mole |
| $M$ | is the number of moles of species S reacting |

A more useful form of Equation (5) requires the concept of equivalent weight. The equivalent weight (EW) is the mass of species S that will react with one Faraday of charge. For an atomic species, EW = AW/n (where AW is the atomic weight of the species).

Recalling that M = W/AW and substituting into Equation (5) we get:

$$W = EW\ Q\ / F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 6$$

where W is the mass of species S that has reacted.

For a complex alloy that undergoes uniform dissolution, the equivalent weight is a weighted average of the equivalent weights of the alloy components. Mole fraction, not mass fraction, is used as the weighting factor. If the dissolution is not uniform, you may have to measure the corrosion products to calculate EW.

Conversion from a weight loss to a corrosion rate (CR) is straightforward. We need to know the density, d, and the sample area, A. Charge is given by Q = I T, where T is the time in seconds and I is a current. We can substitute in the value of Faraday's constant. Modifying Equation 1-5:

$$CR = Icorr\ K\ EW\ /\ d\ A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 7$$

| | |
|---|---|
| CR | The corrosion rate. Its units are given by the choice of K (see Table 4-9) |
| Icorr | The corrosion current in amps |
| K | A constant that defines the units for the corrosion rate |
| EW | The equivalent weight in grams/equivalent |
| d | Density in grams/$cm^3$ |
| A | Sample area in $cm^2$ |

Table 4-9: Constants that defines the units of corrosion rate

| **Corrosion Rate Units** | **K** | **Units** |
|---|---|---|
| mm/year (mmpy) | 3272 | mm/(amp-cm-year) |
| millinches/year (mpy) | $1.288 \times 10^5$ | milliinches(amp-cm-year) |

# CHAPTER 5

# CONCLUSSION & RECOMMENDATION

## 5.1 Problem faced & Recommendation

During experiment, sample III showed that there is an oxidation process of mild steel as the NaCl become pink color at mild steel area. This is due to $OH^-$ ion has been released by water ($H_20$). This affects the result of sample III and proportionally the result of the experiment.

As the recommendation, the anode needs to clean from its oxide. If the oxide still covers the Al surface, the anode can be labeled as unreliable for protecting the mild steel as the principle of SACP is the anode need to be corrode in order to protect the structure protected.

Figure 5-1: Sample III contains pink color appearance as the $OH^-$ ion released by $H_20$ during the oxidation process.

The samples need to be submerged into the 3% NaCl solution by the same height. This is to present the same area of exposure to the electrolyte so will yield to more accurate data.

## 5.2 Conclusion

The objective of this study has been achieved. The performance of the anode can be increase by cold working. In this study, the cold working that being used is rolling. A novelty has been made as using the pure Al, the author has proved that the performance of the anode can be increased by increase the deformation of the anode. Two factors that yield to this conclusion is the new formation of Al microstructure and increase in internal stress of the Al anode. So the oxidation process experience by the anode will be easier due to reduce of potential energy to become corrode.

The author has revealed a new invention of Al SACP which is environment friendly and cheaper in fabrication. The anode does not contain any impurities that can give a big bad impact to the environment such as Hg and Cu. It is safe for the person in charge in application of anode installation. During the service life of the anode, it protects the structure as well as the environment it's took place.

As a pure Al anode, it is easier to fabricate compare to traditional anode which is need to allying which need lots of work in foundry. Without all this complex system in alloying, the cost of fabrication will be reduced. This will save lots of money and energy thus can be place in the market in cheaper price.

Further study can be made to study more on how to increase the performance of the anode if the time consumption is longer. Besides the cold working, the heat treatment also can be made to increase the performance of the anode. If this study can be continued, the author would like to prolong the study on this matter to enhance the anode.

# REFERENCES

A.W. Pearbody, *Pearbody's Control of Pipeline Corrosion,* Second Edition 2001

G. Dieter: Mechanical Metallurgy, 2nd Ed.

Kurt Lange: Hand Book of Metal Forming. SME, 1985.

Making, Shaping and Treating of Steel. 1985 ed.

Mars G. Fontana, *"Modern Theory-Applications, Corrosion Principle, Corrosion Prevention."* Corrosion Engineering, 1910.

M.A. Talavera[1], S. Valdez[2], J.A. Juarez-Islas[2], B. Mena[2] and J. Genesca[1]. 2002, "*EIS Testing of New Aluminium Sacrificial Anodes,"* Journal of Applied Electrochemistry 32: 897–903, 2002.

PETRONAS Technical Standard, PTS 30.10.73.10 NOVEMBER 2003. *Protection of Marine Structure.* Manual Cathodic Protection, PETRONAS, Malaysia.

W.F. Smith & J. Hashemi, "*Microscopic Galvanic Cell Corrosion of Single Electrode."* Foundation of Material Science and Engineering.

http://en.wikipedia.org/wiki/corrosion15 August 2007

http://www.gamry.com27 September 2007

http://www.functional-materials.at/products_10 February 2008