CORROSION PREVENTION OF STEEL SAMPLE IN AQUEOUS SOLUTIONS AND ITS MECHANICAL PROPERTIES

YEAP LEONG HOOI

BACHELOR OF ENGINEERING
UNIVERSITI MALAYSIA PAHANG

2010

YEAP LEONG HOOI BACHELOR OF MECHANICAL ENGINEERING 2010 UMP

BORANG PENGESAHAN STATUS TESIS

JUDUL: **CORROSION PREVENTION OF STEEL SAMPLE IN AQUEOUS SOLUTIONS AND ITS MECHANICAL PROPERTIES**

SESI PENGAJIAN: 2010/2011

Saya: YEAP LEONG HOOI (870201-08-5389)
(HURUF BESAR)

mengaku membenarkan tesis (Projek Sarjana Muda/Sarjana/Doktor Falsafah)* ini disimpan di Perpustakaan Universiti Malaysia Pahang dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hakmilik Universiti Malaysia Pahang
2. Perpustakaan Universiti Malaysia Pahang dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (√)

☐ SULIT (Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA RASMI 1972)

☐ TERHAD (Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

☑ TIDAK TERHAD

Disahkan oleh

(TANDATANGAN PENULIS)	(TANDATANGAN PENYELIA)

Alamat Tetap:
64, JALAN TAWAS BARU 15,
TAMAN EHSAN,
30010 IPOH, PERAK

Nama penyelia:
EN. LEE GIOK CHUI

Tarikh: 6 DECEMBER 2010

Tarikh: 6 DECEMBER 2010

CATATAN: * Potong yang tidak berkenaan.
** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh tesis ini perlu dikelaskan sebagai SULIT atau TERHAD.
*** Tesis dimaksudkan sebagai tesis bagi Ijazah Doktor Falsafah dan Sarjana secara penyelidikan, atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau Laporan Projek Sarjana Muda (PSM).

EXAMINERS APPROVAL DOCUMENT

UNIVERSITI MALAYSIA PAHANG
FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "Corrosion Prevention of Steel Sample in Aqueous Solutions and Its Mechanical Properties" is written by Yeap Leong Hooi. I have examined the final copy of this project and in my opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering.

Examiner	Signature

CORROSION PREVENTION OF STEEL SAMPLE IN AQUEOUS SOLUTIONS AND ITS MECHANICAL PROPERTIES

YEAP LEONG HOOI

Report submitted in partial fulfilment of the
requirements for the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

6 DECEMBER 2010

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.

Signature :
Name of Supervisor : LEE GIOK CHUI
Position : LECTURER OF FACULTY OF MECHANICAL ENGINEERING
Date : 6 DECEMBER 2010

STUDENT'S DECLARATION

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.

Signature :
Name : YEAP LEONG HOOI
ID Number : MA 07018
Date : 6 DECEMBER 2010

Dedicated to my parents

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my Final Year Project supervisor, Mr. Lee Giok Chui, SMP, KMN. for his invaluable guidance and adviced during the process of the preparation of this thesis. Mr. Lee not only served as my supervisor but also as a spiritual counselor who always encourage me throughout the process. Besides that, I would like to express my special thanks to the panel member that gave me the valuable comment and suggestion during my Final Year Project 1 presentation.

Apart of this, a sincere thanks goes to Dr Syahrizan Bin Ahmad and all laboratory assistant from Faculty of Mechanical Engineering University Malaysia Pahang for their teaching and helping during the period of my Final Year Project.

Last but not least, I acknowledge my sincere indebtedness and gratitude to my parents, Mr. Yeap Beow Chuan and Mdm. Then Mee Yoon for their love and sacrifice throughout my life. They have always support my dreams and endless caring to me. They did a fine job in raising me up. My sister, Ms. Yeap Li Chian should be also recognized for her support along my Final Year Project.

ABSTRACT

Corrosion has become a main issue for all engineering sector in these few decades. The main purpose of this project is to investigate the corrosion prevention method in order to slow down the process of corrosion and to investigate the effect of the prevention method on the mechanical properties of those sample specimens. Three methods applied on the steel samples which are nickel electroplating, zinc electroplating and powder coating. The corrosion rate was determined by using weight loss method in immersion test according to ASTM G31, whereas the mechanical properties to be investigated were hardness and tensile test. The dimension of tensile test specimens was followed the ASTM E-8M. The results obtained show that the corrosion rate of the coated specimen was lower than that of the specimen without coating. The specimen with nickel electroplating has the lowest corrosion rate among the coated specimens, followed by powder coating and zinc electroplating. The coated specimens also have the higher value in hardness; yield strength and ultimate tensile strength, where the nickel electroplating has the highest value among all others specimens.

ABSTRAK

Pengaratan telah menjadi satu isu yang penting dalam sektor kejuruteraan pada kebelakangan dekad ini. Matlamat utama projek ini adalah untuk menyiasat kaedah-kaedah untuk mengelakkan kejadian pengaratan dan kesan kaedah-kaedah tersebut pada sifat-sifat mekanikal. Kaedah yang digunakan untuk mengelakkan berlakunya pengaratan ialah elektroplating nikel, elektroplating zink dan pelapisan serbuk. Kadar pengaratan ditentukan dengan menggunakan pengurangan berat dalam ujian perendaman mengikut standard ASTM G31, manakala sifat-sifat mekanikal adalah ditentukan dengan menggunakan ujian kekerasan dan ujian penarikan. Dimensi sampel-sampel ujian adalah mengikut standard ASTM E-8M. Keputusan menunjukkan bahawa kadar pengaratan sampel-sampel yang telah dilapiskan adalah lebih rendah daripada sampel yang tiada dilapiskan. Sampel-sampel yang telah dilapiskan juga menunjukkan bahawa sampel-sampel tersebut menpunyai nilai yang lebih tinggi dalam ujian kekerasan dan ujian penarikan.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY

CHAPTER 4 RESULTS AND DISCUSSION

CHAPTER 5 CONCLSION AND RECOMMENFATIONS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AISI	American Iron and Steel Institute
ASTM	American Society for Testing and Materials
ASTM E8-M	Standard Test Methods for Tension Testing of Metallic Materials
ASTM G1	Practice for preparing, cleaning and evaluating corrosion test specimens
ASTM G31	Standard practice for laboratory immersion corrosion testing of metals
TGIC	Triglycidyl isocyanurate
VOC	Volatile Organic Compounds

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The term corrosion has its origin in Latin. The Latin term rodere means ‘gnawing’ and corrodere mean ‘gnawing to pieces’ [5]. It is rather interesting to examine the historical aspect of the developments of corrosion. Metallic corrosion has no doubt been a problem since common metals were first put to use. Most metals occur in nature as compounds, such as oxides, sulfides, silicates, and carbonates. There are very few metals occur in native form. The obvious reason is the thermodynamic stability of the compounds as opposed to the metals. The process of extraction of a metal from the ore is reduction. The equation of the reduction is as below:

$$2Fe_2O_3 + 3C \longrightarrow 4Fe + 3CO_2$$

In the extraction of the iron, the oxide is reduced to metallic iron. On the other hand, the oxidation of iron to produce the brown iron oxide commonly known as rust is the opposite reaction to the production of the metal from the oxide. The extraction of iron from the oxide, must be conducted with utmost careful control of the conditions, such that the backward reaction is prevented. There are many types of corrosion such as below:

- Uniform corrosion
- Galvanic corrosion
- Crevice corrosion

- Pitting corrosion
- Hydrogen damage
- Intergranular corrosion
- Dealloying
- Erosion corrosion

Corrosion has a big impact on the material. It will weaken the bond among the material. At the same time, it also affects the mechanical properties of the material such as the tensile strain, hardness and etc. Apart of this, corrosion also has an impact on the safety factor. The well known bridge collapse at Pt. Pleasant, West Virginia, killed 46 in 1967 and has been attributed to stress corrosion cracking [5].

Besides that, corrosion has another impact which was the economy impact. The US Federal Highway Administration released a study, entitled Corrosion Costs and Preventive Strategies in the United States, in 2002 on the direct costs associated with metallic corrosion in nearly every U.S. industry sector. The study showed that for 1998 the total annual estimated direct cost of corrosion in the U.S. was approximately $276 billion (approximately 3.1% of the US gross domestic product).

Jones writes that electrochemical corrosion causes between $8 billion and $128 billion in economic damage per year in the United States alone, due to degrading structures, machines, and containers. Therefore, the corrosion prevention is important in order to save cost.

For corrosion prevention, there are many preventive methods. For examples:

- Cathodic protection
- Powder coating
- Inhibitors
- Electroplating

Each of the above method can be used to protect the material lifespan and its mechanical properties. All these methods can prevent the corrosion happen for a short period, and at the same time, they do give an extra mechanical properties on the material.

This project investigates the mechanical properties of mild steel after corrosion prevention. The methods used were zinc electroplating, nickel electroplating, quenching of mild steel and powder coating. The mechanical properties such as tensile and bending after a given period were being investigated after a certain period of exposure.

1.2 PROBLEM STATEMENT

Corrosion is a main issue for all engineering sector in these few decades. People are spending a lot of time to study and investigate about the corrosion and its effect. Companies even raised up the fund to investigate the prevention of corrosion as to minimize the cost of replacing the corroded material in their usage. Corrosion will cause the breakdown of the structure of the buildings or machine. This is very dangerous for the people who are using the buildings or the machine. Corrosion will also cause downtime on the machine and this will give a big impact for manufacturing companies in earning.

1.3 OBJECTIVES

The main objective on this project is to investigate the corrosion rate of the material after the prevention method is applied on it. Secondly, is to investigate the mechanical properties of the material after the application of corrosion prevention.

1.4 SCOPES

In this project, there are few sectors being investigated. The literature review is mainly focused on the corrosion types which were general corrosion and pitting corrosion and its prevention methods. Besides that, there were also reviewed on the corrosion rate and techniques on how to apply the prevention method and the experiment to carry out.

The corrosion rate of the specimens was calculated by using weight loss method. The experiment was carried out by using immersion test follow the ASTM standard, which was ASTM G31. There were two mechanical properties been investigated, which were the tensile and the hardness of the specimens. The results of from all the collected data from the experiments mentioned above were being analyzed. Graphs were plotted by using the data obtained and been studied.

After all the experiments, the results were being compared and analyzed. After all testing and analysis was done, it came out with a conclusion about the objective of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

There are some previous studies on the mechanical properties of the mild steel AISI 1010 based on the corrosion is being reviewed in this chapter. Through this paper, the description of the corrosion type and the prevention method of the corrosion was discussed generally at the early part of this chapter. Then, the mechanical properties of the mild steel AISI 1010 and some machine that used are also being discussed in this chapter.

2.2 CORROSION

Corrosion is defined as the destructive result of the chemical reaction between a metal or metallic alloy and its environment. Metal atoms in nature are present in chemical compounds (i.e. minerals). The same amounts of energy needed to extract metals from their minerals are emitted during the chemical reactions that produce corrosion, Corrosion returns the metal to its combined state in chemical compounds that are similar or even identical to the minerals from which the metals were extracted. Thus, corrosion has been called extractive metallurgy in reverse [1].

Many nonmetallic materials, such as ceramics, consists of metals that have their chemical reactivity satisfied by the formation of bonds with other reactive ions, such as oxides and silicates. Thus, such materials are chemically unreactive, and they degrade by physical breakdown at high temperature or by mechanical wear or erosion.

Similarly, the organic polymers(plastics) are relatively unreactive because they have very stable covalent bonding, primarily formed between carbon atoms.

2.3 CORROSION TYPES

Corrosion happens everywhere and everyday around us. There are a lot of different forms of the corrosion and there are eight most common form which are:

(1) uniform, or general attack,
(2) galvanic, or two-metal corrosion,
(3) crevice corrosion,
(4) pitting,
(5) intergranular corrosion,
(6) dealloying,
(7) erosion corrosion, and
(8) stress corrosion cracking.

2.3.1 Uniform or general attack

This is also called general corrosion. The surface effect produced by most direct chemical attacks (e.g., as by an acid) is a uniform etching of the metal. On a polished surface, this type of corrosion is first seen as a general dulling of the surface and, if allowed to continue, the surface becomes rough and possibly frosted in appearance.

While this is the most common form of corrosion, it is generally of little engineering significance, because structures will normally become unsightly and attract maintenance long before they become structurally affected.

Figure 2.1: Picture show how this corrosion can progress if control measures are not taken. [1]

(Source: NASA Corrosion Technology Laboratory)

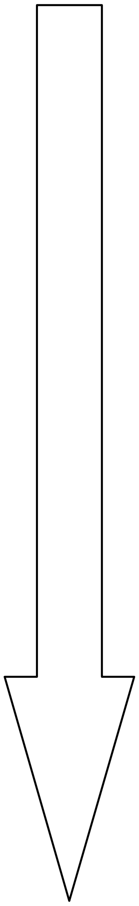
2.3.2 Galvanic, or two-metal corrosion

Galvanic corrosion is an electrochemical action of two dissimilar metals in the presence of an electrolyte and an electron conductive path. It happened when there are two or more dissimilar metals are in contact.

Table 2.1: Galvanic series in seawater [1]

(Source: NASA Corrosion Technology Laboratory)

Galvanic Series In Sea Water	**Noble (least active)**
Platinum	↓
Gold	
Graphite	
Silver	
18-8-3 Stainless steel, type 316 (passive)	
18-8 Stainless steel, type 304 (passive)	
Titanium	
13 percent chromium stainless steel, type 410 (passive)	
7NI-33Cu alloy	
75NI-16Cr-7Fe alloy (passive)	
Nickel (passive)	
Silver solder	
M-Bronze	
G-Bronze	
70-30 cupro-nickel	
Silicon bronze	
Copper	
Red brass	
Aluminum bronze	
Admiralty brass	
Yellow brass	
76NI-16Cr-7Fe alloy (active) Nickel (active)	
Naval brass	

Manganese bronze	
Muntz metal	
Tin	
Lead	
18-8-3 Stainless steel, type 316 (active)	
18-8 Stainless steel, type 304 (active)	
13 percent chromium stainless steel, type 410 (active)	
Cast iron	
Mild steel	
Aluminum 2024	
Cadmium	
Alclad	
Aluminum 6053	
Galvanized steel	
Zinc	
Magnesium alloys	
Magnesium	
	Anodic (most active)

The natural differences in metal potentials produce galvanic differences, such as the galvanic series in sea water (**Table 2.1**). If electrical contact is made between any two of these materials in the presence of an electrolyte, current must flow between them. The farther apart the metals are in the galvanic series, the greater the galvanic corrosion effect or rate will be.

2.3.3 Crevice corrosion

The corrosion produced at the region of contact between metals with metals or metals with nonmetals is defined as crevice or contact corrosion. It may occur at washers, under barnacles, at sand grains, under applied protective films, and at pockets formed by threaded joints.

Screws and fasteners have are common sources of crevice corrosion problems. The stainless steel screws shown below corroded in the moist atmosphere of a pleasure boat hull.

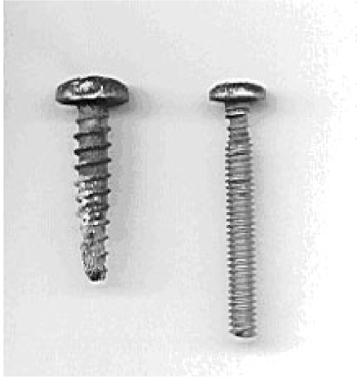


Figure 2.2: Crevice corrosion on the screws. [1]

(Source: NASA Corrosion Technology Laboratory)

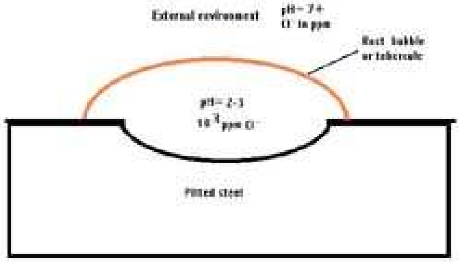
2.3.4 Pitting

Passive metals, such as stainless steel, resist corrosive media and can perform well over long periods of time. However, if corrosion does occur, it forms at random in pits. Pitting is most likely to occur in the presence of chloride ions, combined with such depolarizers as oxygen or oxidizing salts.

Figure 2.3: Showing the pitting corrosion. [1]

(Source: NASA Corrosion Technology Laboratory)

The rust bubbles or tubercules on the cast iron above indicate that pitting is occurring. Researchers have found that the environment inside the rust bubbles is almost always higher in chlorides and lower in pH (more acidic) than the overall external environment. This leads to concentrated attack inside the pits.



Similar changes in environment occur inside crevices, stress corrosion cracks, and corrosion fatigue cracks. All of these forms of corrosion are sometimes included in the term "occluded cell corrosion."

Pitting corrosion can lead to unexpected catastrophic system failure. Sometimes pitting corrosion can be quite small on the surface and very large below the surface. The figure below left shows this effect, which is common on stainless steels and other film-protected metals. The pitting shown below right (white arrow) led to the stress corrosion fracture shown by the black arrows.

2.3.5 Intergranular corrosion

Intergranular corrosion is an attack on the grain boundaries of a metal or alloy. A highly magnified cross section of most commercial alloys will show its granular structure. This structure consists of quantities of individual grains, and each of these tiny grains has a clearly defined boundary that chemically differs from the metal within the grain center. Heat treatment of stainless steels and aluminum alloys accentuates this problem. The figure below shows the typical of intergranular corrosion in austenitic stainless steels.

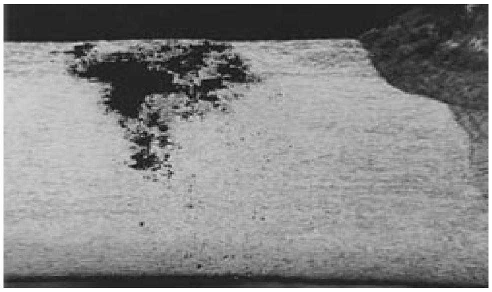


Figure 2.4: Stainless steel which corroded in the heat affected zone a short distance from the weld [1]

(Source: NASA Corrosion Technology Laboratory)

2.3.6 Dealloying

Dealloying is a rare form of corrosion found in copper alloys, gray cast iron, and some other alloys. It happens when the alloy loses the active component of the metal and retains the more corrosion resistant component in a porous "sponge" on the metal surface. Besides, it can also happen by redeposition of the noble component of the alloy on the metal surface.

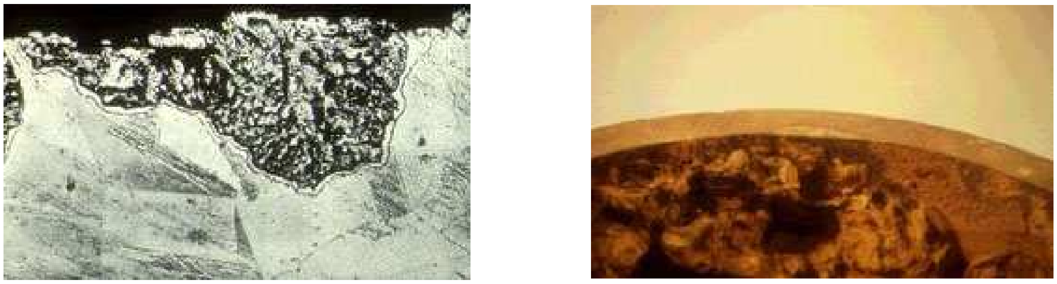


Figure 2.5: The brass on the left dezincified leaving a porous copper plug on the surface. The gray cast iron water pipe shown on the right photo has graphitized and left graphitic surface plugs which can be seen on the cut surface [1]

(Source: NASA Corrosion Technology Laboratory)

2.3.7 Erosion corrosion

The combination of an aggressive chemical environment and high fluid-surface velocities will caused to erosion corrsion. This can be the result of fast fluid flow past a stationary object, such as the case with the oil-field check valve shown on the left below, or it can result from the quick motion of an object in a stationary fluid, such as happens when a ship's propeller churns the ocean.

Figure 2.6: Surfaces which have undergone erosion corrosion are generally fairly clean, unlike the surfaces from many other forms of corrosion. [1]

(Source: NASA Corrosion Technology Laboratory)

This type of corrosion is often the result of the wearing away of a protective scale or coating on the metal surface. The oil field production tubing shown above on the right corroded when the pressure on the well became low enough to cause multiphase fluid flow. The impact of collapsing gas bubbles caused the damage at joints where the tubing was connected and turbulence was greater.

2.3.8 Stress corrosion cracking

Stress corrosion cracking (SCC) is caused by the simultaneous effects of tensile stress and a specific corrosive environment. Stresses may be due to applied loads, residual stresses from the manufacturing process, or a combination of both.

Figure 2.7: Corrosion due to crack that formed by tensile stress[1]

(Source: NASA Corrosion Technology Laboratory)

Cross sections of SCC frequently show branched cracks. This river branching pattern is unique to SCC and is used in failure analysis to identify when this form of corrosion has occurred.

2.4 CORROSION PREVENTION METHODS

There are a number of means of corrosion prevention. The choice of a means of corrosion prevention depends on economics, safety requirements, and a number of technical considerations. The examples are:

- Electroplating,
- Protective Coatings,
- Inhibitors and Other Means of Environmental Alteration,
- Corrosion Allowances,
- Cathodic Protection

2.4.1 Electroplating

Electroplating is a process used to reduce the positively charged ions of a desired material, with the help of an electric current. This process gives a coat on the conductive object with a thin layer of the material, such as a metal.

2.4.1.1 Zinc electroplating

Zinc electroplating is one of the most common forms of electroplating and popular because of its relatively low cost, protective nature and attractive appearance. The coating done through this process gives corrosion protection to ferrous components and it can give colors like gold, black or olive drab finish, by post treatment.

The zinc electroplating process can be used to coat nuts, bolts, washers and automotive parts, such as interior components and gas filters. It also provides an effective undercoat for paints, when high corrosion performance is required. The most widely used zinc plating solutions are acid chloride, alkaline non-cyanide, and cyanide, and the most widely used zinc alloys for electroplating are zinc-nickel, zinc-cobalt, and zinc-iron.

Zinc electroplating changes the chemical, physical, and mechanical properties of the work piece. An example of a chemical change is when nickel plating improves corrosion resistance. An example of a physical change is a change in the outward appearance. An example of a mechanical change is a change in tensile strength or surface hardness. But, for electroplating factories, waste disposal is a major issue to be investigated.

2.4.1.2 Nickel electroplating

Nickel electroplating is a process of nickel deposition on a part, immersed into an electrolyte solution and used as a cathode, when the nickel anode is being dissolved into the electrolyte in form of the nickel ions, traveling through the solution and depositing on the cathode surface.

Nickel electroplating gives corrosion protection and also decorative appearance to the sample of specimens at the same time. Nickel deposited on a part made of a softer metal protects the part from wear.

2.4.2 Protective Coatings

Protective coatings are the most commonly used method of corrosion control. Protective coatings can be metallic, such as the galvanized steel shown below, or they can be applied as a liquid "paint."

Figure 2.8: Corrosion happpened under protective coating. [1]

(Source: NASA Corrosion Technology Laboratory)

Filiform corrosion occurs underneath protective coatings. The air conditioner on the left is starting to show rust stains due to problems with protective coating. The same types of problems are starting to appear on the aluminum airplane wing shown on the right.

2.4.2.1 Powder coating

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 bicycle parts. Newer technologies allow other materials, such as MDF (medium-density fibreboard), to be powder coated using different methods.

Powder coating is well known for its environmental friendly features such as near zero volatile organic compounds (VOC) emission and less hazardous waste production during the mechanical finishing process. No VOC are released due to the fact that solvents are not used throughout the coating process and the coating equipment can be cleaned with compressed air instead of solvent, hence creating less hazardous residues.

Although considered as a safe system, the latest finding of mutagenicity of Triglycidyl isocyanurate (TGIC), a compound widely used in the powder coating industry to produce films with excellent durability, hardness, flexibility and surface properties. Today, the two types of non TGIC Polyester coating that are used most often are the β-hydroxyalkylamides and tetramethoxymethyl glycoluril.

2.4.3 Inhibitors and Other Means of Environmental Alteration

Corrosion inhibitors are chemicals that are added to controlled environments to reduce the corrosivity of these environments. Examples of corrosion inhibitors include the chemicals added to automobile antifreezes to make them less corrosive. Most of the Kennedy Space Center's corrosion inhibitor research involves the effectiveness of inhibitors added to protective coatings.

2.4.4 Corrosion Allowances

Engineering designers must consider how much metal is necessary to withstand the anticipated load for a given application. Since they can make mistakes, the use of the structure can change, or the structure can be misused, they usually are required to over design the structure by a safety factor that can vary from 20% to over 300%. Once the necessary mechanical load safety factor has been considered, it becomes necessary to consider whether or not a corrosion allowance is necessary to keep the structure safe if it does corrode.

Figure 2.9: The picture shows extra steel added to the bottom of an offshore oil production platform. The one inch of extra steel was added as a corrosion allowance. [1]

(Source: NASA Corrosion Technology Laboratory)

2.4.5 Cathodic Protection

Cathodic protection is an electrical means of corrosion control. Cathodic protection can be applied using sacrificial (galvanic) anodes or by means of more complicated impressed current systems.

Figure 2.10: Bottom of the boat with cathodic protection to prevent corrosion happen[1]

(Source: NASA Corrosion Technology Laboratory)

This Louisiana fishing boat has sacrificial zinc anodes welded to the hull to slow down corrosion. No pattern is apparent to how the anodes were attached-the design philosophy seems to be that if one anode is good, more is better.

The Kennedy Space Center's cathodic protection research has concentrated on the use of sacrificial and impressed current systems for minimizing corrosion of embedded steel in concrete structures.

2.5 CORROSION RATE

Calculating the corrosion rates requires several pieces of information and several assumptions. The use of corrosion rate implies that all mass loss has been due to general corrosion and not to localized corrosion such as pitting or intergranular corrosion of sensitized areas on the welded coupons.

The use of corrosion rates also implies that the material has not been internally attacked as by dezincification or intergranular corrosion. Internal attack can be expressed as a corrosion rate if desired. However, the calculations must not be based on weight loss, which is usually small but on microsections which show depth of attack.

Assuming that localized or internal corrosion is not present or is recorded separately in the report, the average corrosion rate can be calculated by the following equation (Equation 2.1): [2]

$$Corrosion\ rate = \frac{K \times W}{A \times T \times D}$$

Where: (Equation 2.1)

K = a constant (refer table 2.2)

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

A= area in cm^2 to the nearest $0.01cm^2$

W= weight loss in g, to nearest 1 mg (corrected for any loss during cleaning)

D= density in g/cm^3

Table 2.2: Constant (*K*) in corrosion rate equation with desired unit.[2]

Corrosion Rate Units Desired	**Constant (*K*) in corrosion rate equation**
miles per year (mpy)	3.45×10^6
inches per year (ipy)	3.45×10^3
inches per month (ipm)	2.87×10^2
milimetres per year (mm/y)	8.76×10^4
micrometres per year (µm/y)	8.76×10^7
picometres per second (pm/s)	2.78×10^4

(Source: Laboratory Corrosion Tests and Standards (14-16 Nov. 1983): a symposium by ASTM Committee G-1 on Corrosion of Metals, Bal Harbour, FL)

2.6 MECHANICAL PROPERTIES

Strength, hardness, toughness, elasticity, plasticity, brittleness, and ductility and malleability are mechanical properties used as a measurement of how metals behave under a load. These properties are described in terms of the types of force or stress that the metal must withstand and how these are resisted.

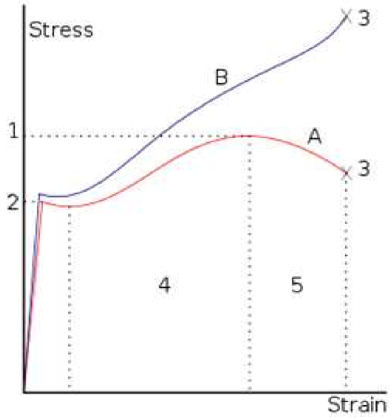
2.6.1 Tensile strength

Tensile strength (σ_{UTS} or S_U) is indicated by the maxima of a stress-strain curve and, in general, indicates when necking will occur. As it is an intensive property, its value does not depend on the size of the test specimen. It is, however, dependent on the preparation of the specimen and the temperature of the test environment and material.

Tensile strength, along with elastic modulus and corrosion resistance, is an important parameter of engineering materials used in structures and mechanical devices. It is specified for materials such as alloys, composite materials, ceramics, plastics and wood.

2.6.1.1 Concept of tensile strength

The definition of the tensile strength are shown in the followng stress-strain graph for low-carbon steel:



1. Ultimate strenght
2. Yield strenght
3. Rupture
4. Strain hardening region
5. Neckling region

A. Apparent stress (F/A_o)

B. Actual stress (F/A)

Figure 2.11: A stress versus strain curve.

Metals including steel have a linear stress-strain relationship up to the yield point, as shown in the figure. In some steels the stress falls after the yield point. This is due to the interaction of carbon atoms and dislocations in the stressed steel. Cold worked and alloy steels do not show this effect. For most metals yield point is not sharply defined. Below the yield strength all deformation is recoverable, and the material will return to its initial shape when the load is removed. This recoverable deformation is known aselastic deformation. For stresses above the yield point the deformation is not recoverable, and the material will not return to its initial shape. This unrecoverable deformation is known as plastic deformation. For many applications plastic deformation is unacceptable, and the yield strength is used as the design limitation

After the yield point, steel and many other ductile metals will undergo a period of strain hardening, in which the stress increases again with increasing strain up to the ultimate strength. If the material is unloaded at this point, the stress-strain curve will be parallel to the original elastic portion of the curve, between the origin and the yield point. If it is then re-loaded it will follow the unloading curve up again to the previous load, which has become the new yield strength, and will then continue following the original plastic curve.

After a metal has been loaded to its yield strength it begins to "neck" as the cross-sectional area of the specimen decreases due to plastic flow. When necking becomes substantial, it may cause a reversal of the engineering stress-strain curve, where decreasing stress correlates to increasing strain because of geometric effects. This is because the engineering stress and engineering strain are calculated assuming the original cross-sectional area before necking. If the graph is plotted in terms of true stress and true strain the curve will always slope upwards and never reverse, as true stress is corrected for the decrease in cross-sectional area. Necking is not observed for materials loaded in compression. The peak stress on the engineering stress-strain curve is known as the ultimate strength. After a period of necking, the material will rupture and the stored elastic energy is released as noise and heat. The stress on the material at the time of rupture is known as the breaking strength.

2.6.2 Hardness

Hardness is defined as a measure of a material's ability to resist plastic deformation or penetration by an indenter having a spherical or conical end. It is used by the design engineer more frequently than any other of the mechanical properties to specify the final condition of a structure part. This is because the hardness tests are inexpensive and not time consuming to conduct.

2.6.2.1 Vickers Hardness Test

Figure 2.12: The Vickers Hardness Test machine

The Vickers hardness test was developed in 1924 by Smith and Sandland at Vickers Ltd as an alternative to the Brinell method to measure the hardness of materials. The Vickers test is often easier to use than other hardness tests since the required calculations are independent of the size of the indenter, and the indenter can be used for all materials irrespective of hardness. The basic principle, as with all common measures of hardness, is to observe the questioned material's ability to resist plastic deformation from a standard source. The Vickers test can be used for all metals and has one of the widest scales among hardness tests. The unit of hardness given by the test is known as the Vickers Pyramid Number (HV) or Diamond Pyramid Hardness (DPH). The hardness number can be converted into units of Pascal. The hardness number is determined by the load over the surface area of the indentation and not the area normal to the force, and is therefore not a pressure

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter explains the experimental process of testing the mechanical properties of the specimen, which was mild steel (AISI 1010) by applying different corrosion prevention methods on it after a certain period. The data obtained was analyzed based on the research objective. There were 3 different methods that applied on the specimen, which were:

1. Zinc electroplating,
2. Nickel electroplating,
3. Powder coating.

Each type of the above corrosion prevention method had its standard process. The specified processes were stated at the sub chapter below. After applied the method, the specimen was left for certain periods, which were 9days. At each single day, the specimen was being weight; the reading of the difference in mass was taken. The corrosion rate was then being calculated based on the weight loss.

Once reached on the period set, the specimen was taken to do the tensile test. All the data during the experiment was taken and a graph was plotted. The result was then analyzed.

3.2 FLOW CHART

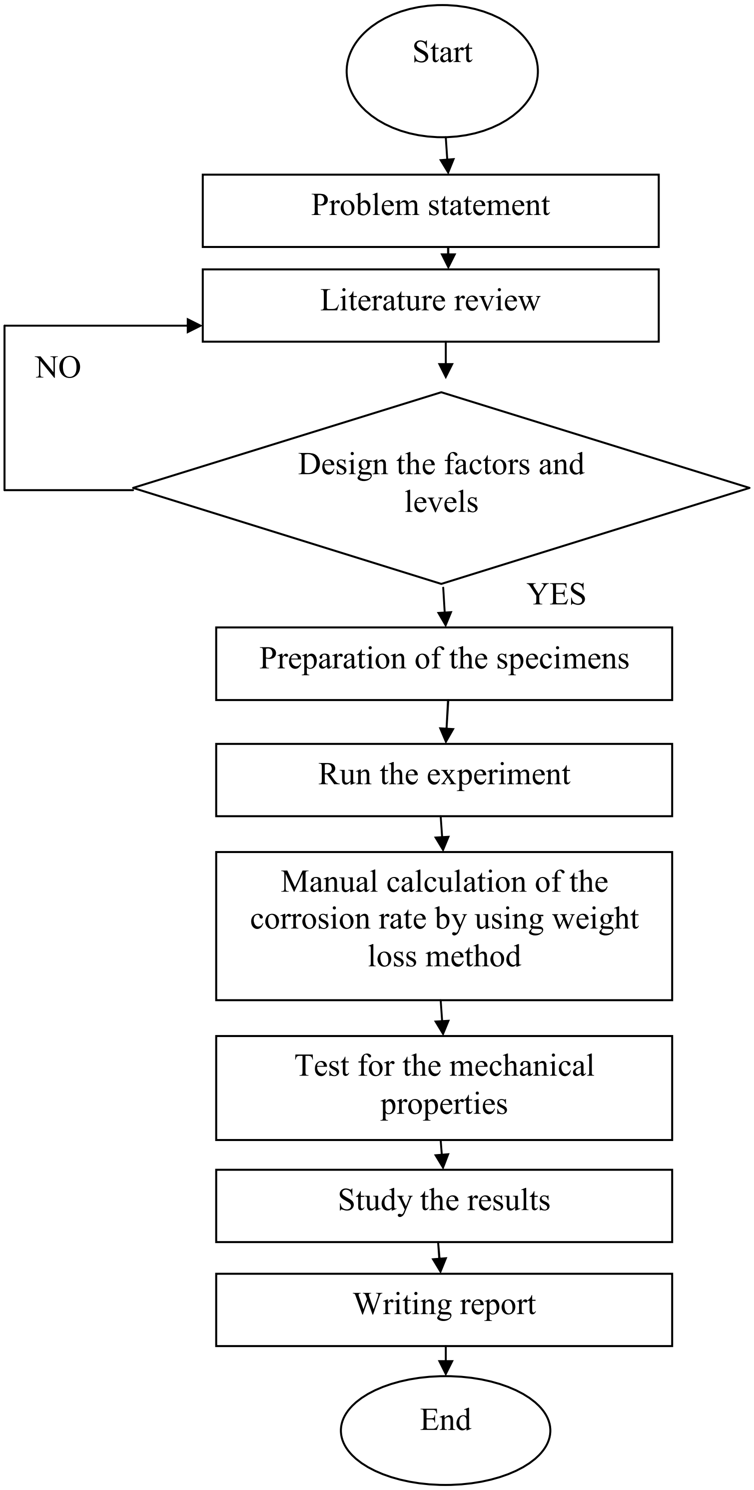


Figure 3.1: Methodology flow chart

3.3 PREPARATION OF THE SPECIMEN

For this project, the material used to run the experiment was the mild steel AISI 1010. Mild steel is the most common form of steel as its price is relatively low while it provides material properties that are acceptable for many applications. Mild steel has low carbon content (up to 0.3%) and is therefore neither extremely brittle nor ductile.

The composition of the material used was tested by using Arc Spark Spectrometer shows in Figure 3.2, and the material compositions obtained was shown in Table 3.1.

Figure 3.2: Arc Spark Spectrometer

Table 3.1: Composition of the elements contains of mild steel AISI 1010

Elements	**Composition (%)**
Fe	99.4
C	0.0710
Si	0.0171
Mn	0.151
P	0.0974
S	0.0204
Cr	0.0489

.

The tensile specimens were stamped out by using stamping machine Chung Tie CTO-05, as shown in Figure 3.3.

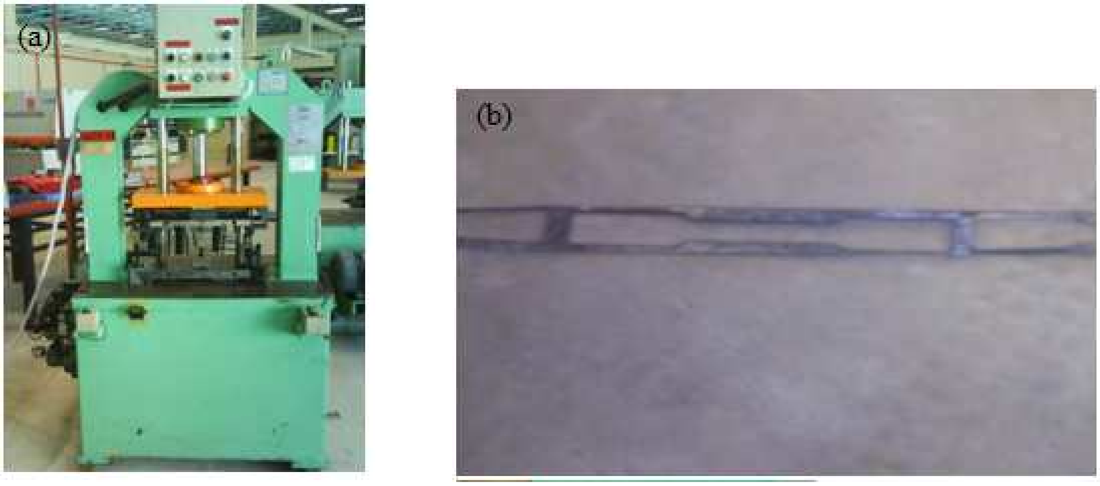


Figure 3.3: Diagram showing (a) stamping machine Chung Tie CTO-05 and (b) residual material.

Before the experiment, the specimen has undergoes the process of the corrosion prevention method. There were 3 methods used, which were:

1. Zinc electroplating
2. Nickel electroplating
3. Powder Coating

3.3.1 Zinc Electroplating

Zinc electroplating process is one of the popular processes used to make a thin layer on the metal surface in order to prevent the corrosion happen. To run this process, the specimen must be cleaned at the first step.

The surface of the specimen was cleaned in alkaline detergent type solutions, and it was then treated with acid in order to remove the dust or the surface scales. This cleaning step is important for a successful zinc electroplating. This is because the molecular layers of oil or rust can prevent adhesion of the coating. The cleaning process was done by using a sandpaper to brush on the specimen surface.

The next step was to deposit the zinc on the specimen by immersing the specimen into a chemical bath which containing dissolved zinc solution, which was acid chloride. Then, a DC current is applied. This step makes the zinc being deposited on the cathode, which is on the specimen.

3.3.2 Nickel Electroplating

Nickel electroplating process is another popular process used to make a thin layer on the metal surface in order to prevent the corrosion happen. The process is almost same as the zinc electroplating process. The specimens' surface was cleaned from mineral oils, rust protection oil, grease, scale and rust by using a sandpaper to brush on the specimen surface.

The next step was to deposit the nickel on the specimen. A small part of pure primary nickel was loaded into titanium baskets were used as anode for this process. Then, a DC current is applied. This step is to make the nickel being deposited on the cathode, which was on the specimen.

3.3.3 Powder Coating

Powder coating is a newer method introduced to prevent the corrosion by forming a layer on the specimen surface. The surface of the specimen was cleaned to remove the oil, grease, scales, rust, dust and etc. by using a sandpaper to brush on the specimen surface.

After that, the powder was being sprayed on the specimen surface by using an electrostatic gun. The gun imparts a positive electric charge on the powder, which is then sprayed towards the grounded object by mechanical or compressed air spraying and then accelerated toward the specimen by the powerful electrostatic charge. When the spraying process was done, the specimen was then put inside a furnace to melt the thermoset powder. The temperature in the furnace was set at 200^{o}C and was heated for 10minutes. This molten powder will then formed a protective layer on the surface of the specimen.

3.4 Hardness Test

After the mild steel AISI 1010 was being coated, the specimens were then cut out (as shown in Figure 3.4) into small pieces by using Iso Met 4000 Linear Precision Saw machine. The small pieces of the specimens were then being to mount using the Simpli Met 1000 Automatic Mounting Press Hot Mounting Machine. After the mounting procedure, the mounted specimens were polished before analyze the thickness of the coating and the Vickers Hardness Test.

Figure 3.4: Cut out area of tensile test specimen into small pieces.

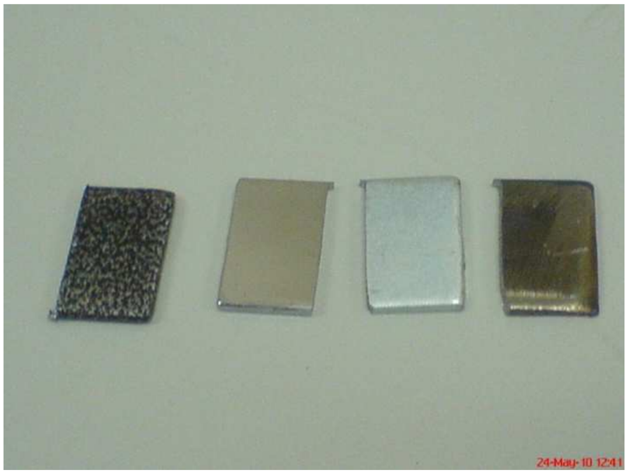
3.4.1 Cutting the specimens into pieces by Iso Met 4000 Linear Precision Saw machine

Figure 3.5: The Iso Met 4000 Linear Precision Saw machine

Figure 3.6: The operating procedure of Iso Met 4000 Linear Precision Saw machine.

The Iso Met 4000 Linear Precision Saw Machine in Figure 3.5 is used to cut the specimens into pieces, there were some procedures to follow with. The blade speed and the feed rate had to be set correctly. For cutting the mild steel AISI 1010, the blade speed was set at 4600 rpm and the feed rate was set at 9.1m/min. After that, closed the cover and switched on the cutting cycle button to let d machine move. Once the blade touches the specimen, the distance was set to 0mm. Then, the distance to be cut out is being calculated and set as that distance.

After that, switched on again the machine by clicking on the cutting cycle button. Figure 3.6 showing the operating procedures of Iso Met 4000 Linear Precision Saw Machine. The cut out small pieces from the tensile specimens was shown in Figure 3.7.



24-May-10 12:41

Figure 3.7: The small pieces of the 4 different specimens cut by using Iso Met 4000 Linear Precision Saw machine (From left to right: Powder coating, Nickel electroplating, Zinc electroplating and without coating)

3.4.2 Mounting Process

3.4.2.1 Hot mounting process

Figure 3.8: The Simpli Met 1000 Automatic Mounting Press Hot Mounting Machine

The small pieces of the specimens were being mounted by using Simpli Met 1000 Automatic Mounting Press Hot Mounting Machine, which showed in Figure 3.8. The parameters of the hot mounting machine were set at 200 degree Celcius of temperature and 300bar of pressure. The bottom ram was then raised up to top of the mold cylinder. By using the Release Agent, 20-8185, to swab both the upper and bottom ram to avoid the specimens from sticking on the ram. Then, placed the specimen in the middle of the bottom ram and the mounting material was added after that. Closed and locked the mold closure and start the cycle. The cycle was completed after about 9 minutes.

3.4.2.2 Cold mounting process

This process was being carried out because one of the coated specimens was not suitable by using hot mounting process. The specimen was the powder coated specimen. This is because the powder coated part was melted up during the heating process under the hot mounting press machine. Therefore, another mounting process, which was the cold mounting process, had to be carried out to replace the hot mounting process. Figure 3.9 shows the cold mounting machine which used to mount the powder coating specimen. Figure 3.10 shows the small pieces of the specimen after hot and cold mounting process.

Figure 3.9: The cold mounting machine.

Figure 3.10: The small pieces of the specimen after hot (left) and cold (right) mounting process.

3.4.3 Microstructure of the specimens

The mounted specimens were then being polished using Metken Forcipol 2V grinding/polishing machine, which is showed in Figure 3.11.

Figure 3.11: The Metken Forcipol 2V grinding/polishing machine.

The mounted specimen was being polished until it is smooth and shinny before taken to study the microstructure and the Vickers Hardness test. Figure 3.12 showed the polishing process of the mounted specimen.

Figure 3.12: The polishing process.

Once the mounted specimens were smooth and shinny, it was taken to study for the thickness of the coated part. The thickness of the coated part was studied by using the Metallurgical Microscopic which shown in Figure 3.13. After that, the specimen was taken for the Vickers Hardness test.

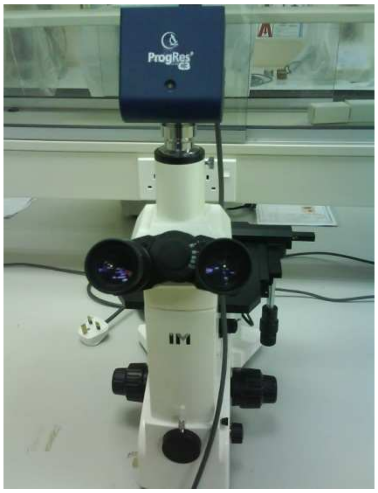


Figure 3.13: The Metallurgical Microscopic.

3.4.4 Vickers Hardness Test

Figure 3.14: The Vickers Hardness Test machine

The mounted specimen was placed on the tester of the Vickers hardness Test machine as shwon in Figure 3.14. The parameter, which was the load was set at 100gf. The load was applied by the diamond intender on the mounted specimen. After the applied load, the length of a diagonal of an indention was then being taken up. The hardness value of the specimen was generated out by the machine and the hardness reading in HV unit was then being taken up and study.

3.5 CORROSION RATE

3.5.1 Immersion Corrosion Test

This immersion corrosion testing method was the conventional method used for determine the weight loss of the metal after a certain period. This Immersion corrosion test was done according to ASTM G31, Standard practice for laboratory immersion corrosion testing of metals. The setting for the designed test was discussed as below.

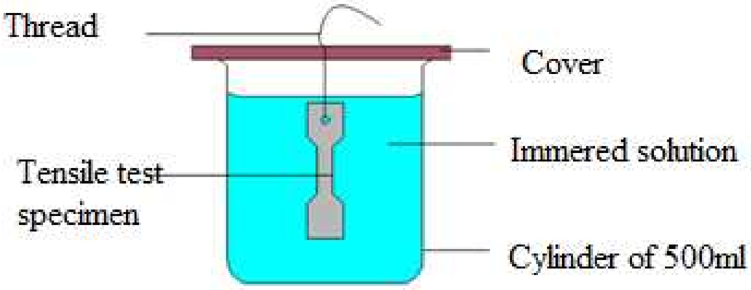


Figure 3.15: Setting for Immersion Test.

All the tests were carried out under room temperature. The test specimen was tied to the cardboard lid to ensure free and full contact with the test solution, as shown in Figure 3.15. The volume of the test solution should be large enough to ensure full coverage of the specimen's entire exposed surface. Duplicate specimens were used for each test category for repeated readings. The designed test period is the maximum period suggested by ASTM G31, which is 168 hours or 7 days. The test solution was changed and replenished daily and the specimen was cleaned before placing into the test solution. Then the data collected were used to calculate the corrosion rate of the metal specimen. There were few steps to take attention for running the immersion corrosion test.

The medium for the immersion test was seawater taken from Teluk Cempedak Kuantan and tap water from UMP mechanical laboratory.

Before starting the immersion test, the salinity of the seawater and tap water was being determined by using portable conductivity meter Hach SenSion 5, as shown in Figure 3.16, and the initial weight of the specimen was being determined by using weighing machine which was shown in Figure 3.17.

Figure 3.16: The portable conductivity meter Hach SenSion 5.

Figure 3.17: The weighing machine.

The salinity of the seawater and tap water were determined by immersing the sensing rod of the portable conductivity meter in the medium. Then medium was stirred with the sensing rod of the portable conductivity meter until the reading get stable. Then the reading of salinity was taken. The process of taking the salinity was shown in Figure 3.18.

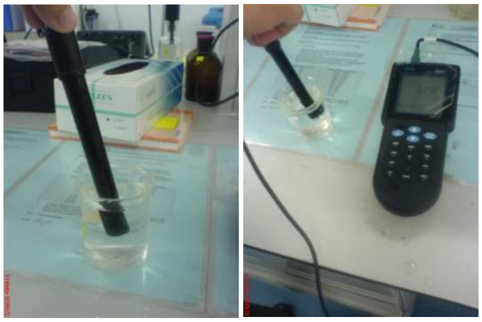


Figure 3.18: The process of taken the reading of salinity.

After salinity was determined, seawater and tap water was poured into different cylinder of 500ml. Then, the specimens were immersed into each different cylinder and tighten up with a rope. The cylinders were then labeled with according to different medium and specimen, as shown in Figure 3.19.

Figure 3.19: The specimen immersed in the cylinder with seawater.

During the immersion test, the specimens were taken out and cleaned up by following ASTM G1, "Practice for preparing, cleaning and evaluating corrosion test specimens". The cleaning process was to remove all the corrosion products from the specimens with a minimum removal of metal. The procedure included the chemical cleaning and mechanical cleaning. Once the specimen was taken out from the medium, it was then immersed in an acid solution for a few second to remove all the dirt. Then, the specimen was brushed to remove the corrosion. After all the cleaning process, the specimens were then taken to weight the mass loss for each single day during the immersion test. The specimen was placed into the cylinder again after the mass loss determination. The mass loss data of each single day was taken for further investigation of the corrosion rate.

3.5.2 Weight Loss Method for Corrosion Evaluation

Each specimen, after cleaned by using stiff bristle brush, was weighed and the weight losses during the test were determined. Correction for the weight loss due to the removal of coating or material surface in the cleaning process was taken into account. To check this, one or more cleaned and weighted specimens were re-cleaned by the same method and re-weighted. Loss due to this second weighing was used as a correction and would then be subtracted from the total weight loss.

Calculating corrosion rate requires several information and assumption. The corrosion rate implies that all mass loss has been due to general corrosion and not to the localized corrosion, such as pitting. The average corrosion rate could be calculated by the following equation which was Equation 2.1.

3.6 TENSILE TEST

The specimens were taken to run the tensile test after the immersion test. The specimens were in conditioned based on ASTM standard. ASTM E-8M is the standard used for tensile test. All the tests were proceed in the standard laboratory atmosphere where the temperature is at 23 ± 2^{o}C and relative humidity of 50 ± 5 %.[3]

The diagram of the tensile specimen was shown in Figure 3.20, whereas the dimension of the specimen was shown in Table 3.2 and the material properties of the specimen was shown in Table 3.3.

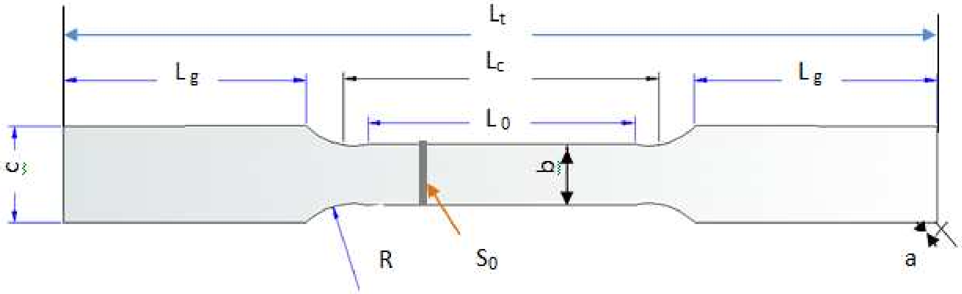


Figure 3.20: Diagram of tensile specimen according to ASTM E-8M.

Table 3.2: Dimension of tensile specimen according to ASTM E-8M

No	Item	Dimensions
1	L_t, Total Length	18.00 cm
2	L_g, Grip Length	5.00cm
3	L_o, Gauge Length	5.5cm
4	L_c, Parallel or reduce Section	6.5 cm
5	R, Radius	1.27 cm
6	a, Thickness	2 mm
7	b, Gauge width	1.25 cm
8	c, Grip width	2.00 cm
9	S_o, Gauge Cross Section Area	25 mm^2
10	A, Total Exposed Surface Area	70.52 cm^2

Table 3.3: Material properties of test specimen at 25°C

Material Grade	AISI 1010 Steel, cold drawn
Mass density (×1000 kg/m^3)	7.87
Modulus of Elasticity (N/mm^2)	205000
Poisson's Ratio	0.29
Thermal Coefficient of Expansion ($°C^{-1}$)	0.0000122

Figure 3.21: INSTRON Testing Apparatus

This tensile test was done by using INSTRON Universal Testing Machine as shown in Figure 3.21, according to ASTM test standard. The specimen was put vertically in the grips of the testing device. The grips were tightened evenly and tightly to prevent the slippage during the experiment. The specimens were tested at rate of 2 mm/min. The speed of the testing was set at the proper rate and the testing machine was started to run. [3] Figure 3.22 shown the setting up procedure of the INSTRON Universal Testing Machine for the tensile test and Figure 3.23 and Figure 3.24 shown the specimens under the tensile test and after tensile test.

Figure 3.22: The setting up procedure of the INSTRON Universal Testing Machine.

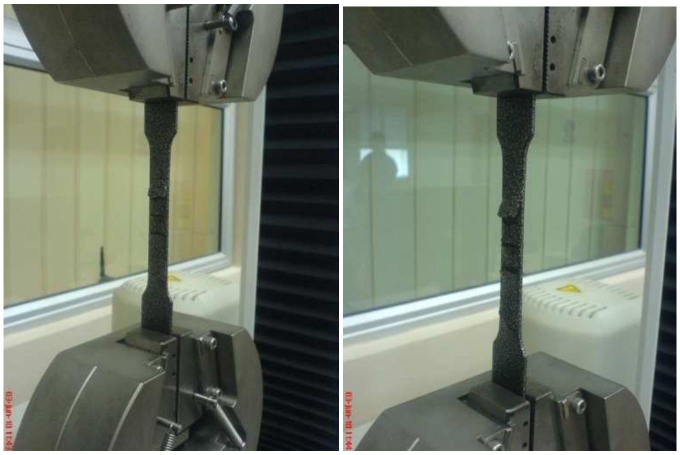


Figure 3.23: The specimens under the tensile test.

Figure 3.24: The different specimens after the tensile test. (From left to right, without coating, powder coating, zinc electroplating and nickel electroplating)

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

This chapter presents the result of a series of immersion tests in which uncoated mild steel AISI 1010 specimens and coated specimens were immersed in different solutions of seawater and natural water. The result of thickness for the coating, hardness of the coating, corrosion rate and the tensile test for all different types of specimens were used for further investigation. The results obtained were then been compared in order to verify the effect of different corrosion prevention method applied.

4.2 THICKNESS OF THE COATING

Table 4.1: The thickness of the different types of coating on the specimens.

Type of Coating	Reading 1 (µm)	Reading 2 (µm)	Reading 3 (µm)	Reading 4 (µm)	Reading 5 (µm)	Average value(µm)
Zinc electroplating	164.7	189.4	203.3	182.8	145.2	177.08
Nickel electroplating	31.65	31.65	29.15	30.36	30.36	30.63
Powder coating	194.9	190.0	194.4	192.6	174.5	189.28

The thickness of the coating was being verified under the metallurgical microscope. There were total of 5 points were taken and the average of the thickness was being calculated.

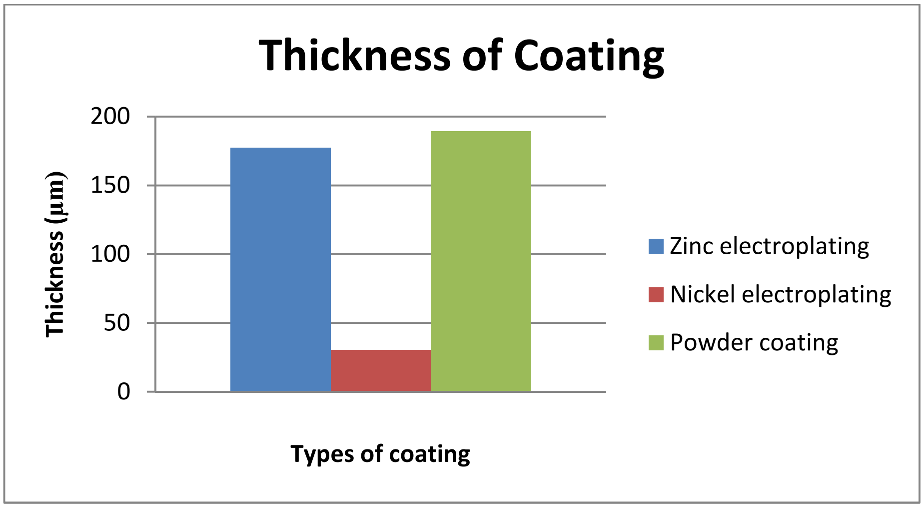


Figure 4.1: Thickness of coating versus types of coating.

Figure 4.1 shows the thickness of the different corrosion prevention methods that applied on the steel sample, AISI 1010. It could be seen that each types of the method used has different thickness. The average value of powder coating method shows the highest value in the thickness, following by zinc electroplating and lastly the nickel electroplating. The average value of powder coating thickness reached 189.28µm, which is the highest. The lowest value is 30.63µm, which was conducted by the nickel electroplating. Zinc electroplating shows the average thickness value of 177.08µm. The captured view of each types of prevention methods were presented in Appendix A.

4.3 HARDNESS TEST

The hardness test was carried out across the small work piece which was being mounted. The tested part was started with the upper coated area to the original steel sample and then to the bottom coated area. Due to the limitation of the instrument, the tested area cannot be captured, but there is a sample shown in Appendix B.

Table 4.2: The hardness value of zinc electroplating versus transverse cross section distance

Zinc Electroplating										
Distance (µm)	60	120	180	200	800	1100	1800	1820	1900	1960
Hardness (HV)	27.2	28.4	29.6	233.6	229.1	230.4	229.8	28.7	27.4	25.2

Table 4.3: The hardness value of nickel electroplating versus transverse cross section distance

Nickel Electroplating										
Distance (µm)	15	20	25	50	800	1200	1950	1975	1980	1985
Hardness (HV)	493.2	483.4	486.9	259.7	248.4	256.7	264.4	486.7	476.9	484.7

Table 4.4: The hardness value of powder coating versus transverse cross section distance

Powder Coating										
Distance (µm)	60	120	180	200	800	1100	1800	1820	1900	1960
Hardness (HV)	9.6	10.4	14	227.4	219.6	216.7	219.1	9.9	8.6	7.4

From the collected data as shown in Table 4.2 to Table 4.4 above, graphs of the hardness versus distance was plotted out for further studies.

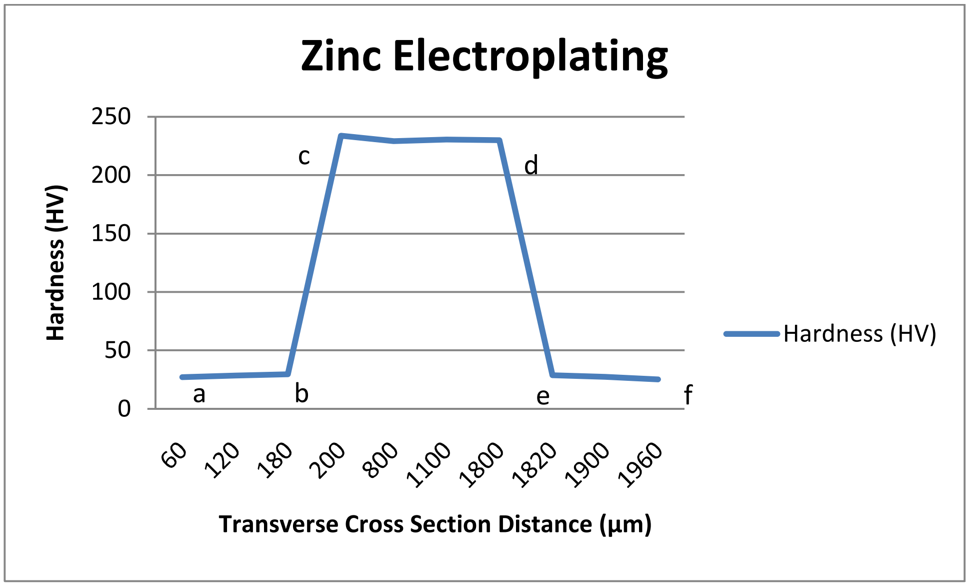


Figure 4.2: Hardness graph (HV) versus Transverse cross section distance (µm) of zinc electroplating.

Figure 4.2 shows the hardness of zinc electroplating specimen versus the distance across the coated part (a-b) to mild steel of AISI 1010 (c-d) and back to the coated part (e-f). Figure 4.2 shows that on the zinc electroplating part has lower hardness value than the mild steel of AISI 1010. The average hardness value of coated part (a-b) was 28.4HV at the initial position. Then, the hardness value jumped up to an average of 230.73HV at mild steel of AISI 1010 (c-d). The hardness value dropped critically to an average of 27.1HV at last (e-f). (The tested part was shown in Appendix B). There was a big difference of the hardness value along the tested part which it originated from lower hardness value to higher hardness value and lastly back to its lower hardness value. This condition was because there were two different materials across the tested part of the mounted specimens. As a conclusion, the zinc electroplating part has lower hardness value at both end of the graph whereas the mild steel of AISI 1010 has higher hardness value at the middle of the plotted graph.

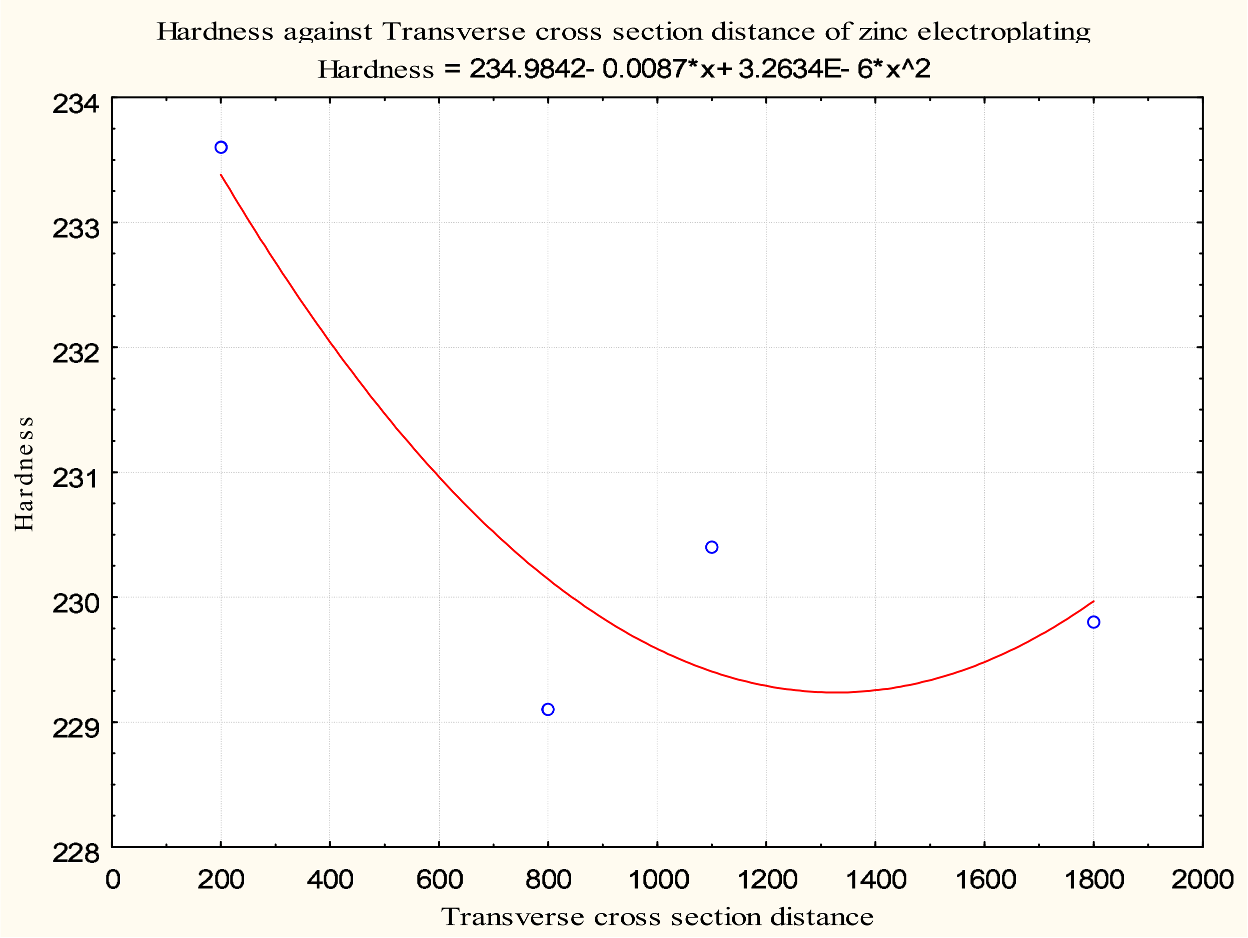


Figure 4.3: Hardness (HV) versus Transverse cross section distance (μm) of the mild steel AISI 1010 on the zinc electroplating specimen.

Figure 4.3 shows a polynomial second order graph of the hardness value (HV) on the mild steel AISI 1010 which was tested along the zinc electroplating specimen. The polynomial graph had a mathematical equation of:

$$234.9842 - 0.0087x + 3.2634 \times 10^{-6} - 6x^2$$

It shows the minimum graph type because there is dropping of the hardness value when it was tested from the area near the coated part to the mild steel of AISI 1010 part.

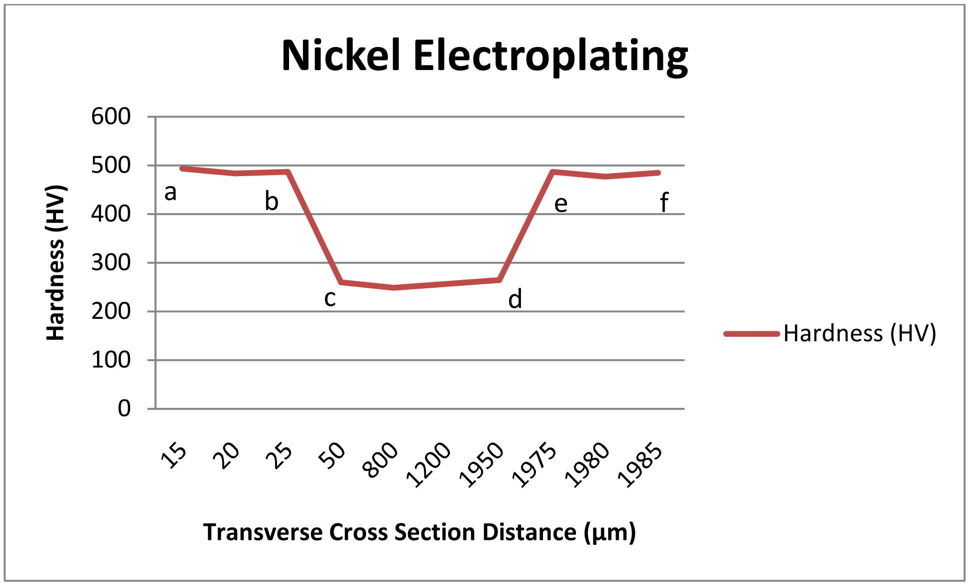


Figure 4.4: Hardness graph (HV) versus Transverse cross section distance (µm) of nickel electroplating.

Figure 4.4 shows the hardness of nickel electroplating specimen versus the distance which across the coated part (a-b) to mild steel of AISI 1010 (c-d) and back to the coated part (e-f). The Figure 4.4 shows that on the nickel electroplating part has higher hardness value than the mild steel of AISI 1010. The average hardness value of nickel electroplating part (a-b) was 487.83HV at the initial position. Then, the hardness value jumped down to an average of 257.30HV at mild steel of AISI 1010 (c-d). The hardness value increased again critically to an average of 482.77HV at last (e-f). (The tested part was shown in Appendix B). There was a big difference of the hardness value along the tested part which it originated from higher hardness value to lower hardness value and lastly back to its higher hardness value. This condition was because there were two different materials across the tested part of the mounted specimens. As a conclusion, the nickel electroplating part has higher hardness value at both end of the graph whereas the original mild steel of AISI 1010 has lower hardness value at the middle of the plotted graph.

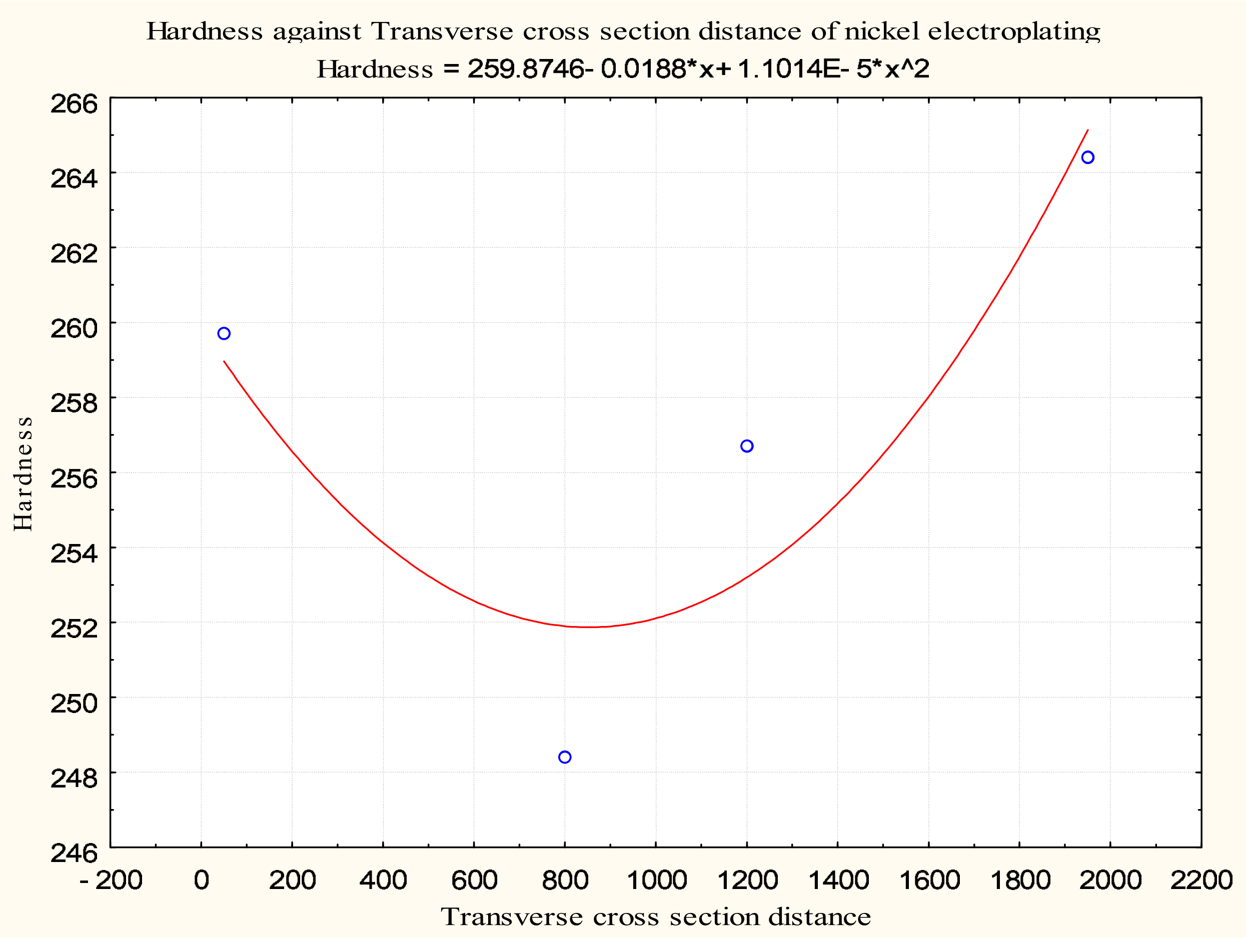


Figure 4.5: Hardness (HV) versus Transverse cross section distance (μm) of the mild steel AISI 1010 of the nickel electroplating specimen.

Figure 4.5 shows a polynomial second order of the hardness value (HV) on the mild steel AISI 1010 which was tested along the zinc electroplating specimen. The polynomial graph had a mathematical equation of:

$$259.8746 - 0.0188x + 1.1014 \times 10^{-5} - 6x^2$$

It shows the minimum graph type because there is dropping of the hardness value when it was tested from the area near the coated part to the mild steel of AISI 1010 part.

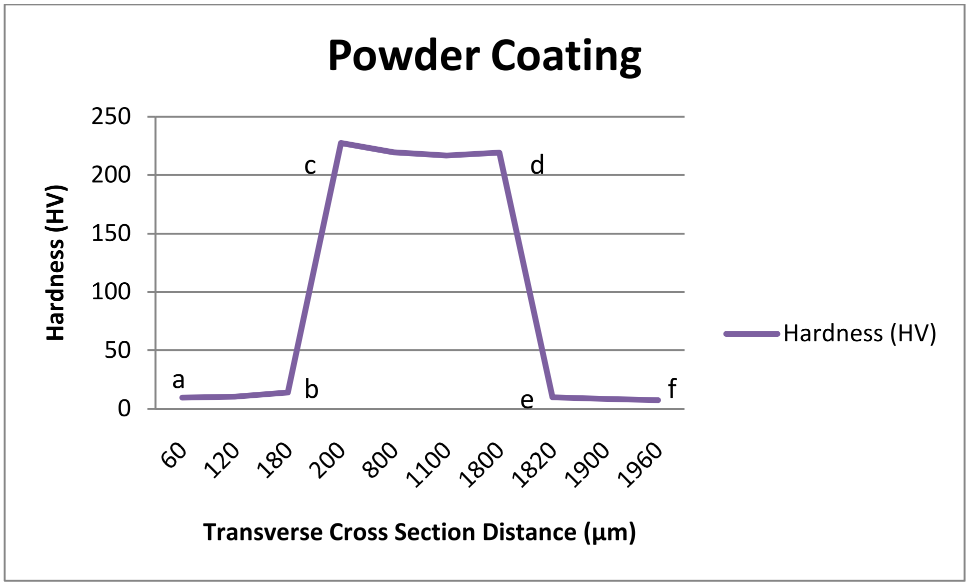


Figure 4.6: Hardness graph (HV) versus Transverse cross section distance (µm) of powder coating.

Figure 4.6 shows the hardness of powder electroplating specimen versus the distance across the coated part (a-b) to mild steel of AISI 1010 (c-d) and back to the coated part (e-f). The Figure 4.6 shows that on the zinc electroplating part has lower hardness value than the mild steel of AISI 1010. The average hardness value of coated part (a-b) was 11.33HV at the initial position. Then, the hardness value jumped up to an average of 220.70HV at mild steel of AISI 1010 (c-d). The hardness value dropped critically to an average of 8.63HV at last (e-f). (The tested part was shown in Appendix B). There was a big difference of the hardness value along the tested part which it originated from lower hardness value to higher hardness value and lastly back to its lower hardness value. This condition was because there were two different materials across the tested part of the mounted specimens. As a conclusion, the powder coated part has lower hardness value at both end of the graph whereas the mild steel of AISI 1010 has higher hardness value at the middle of the plotted graph.

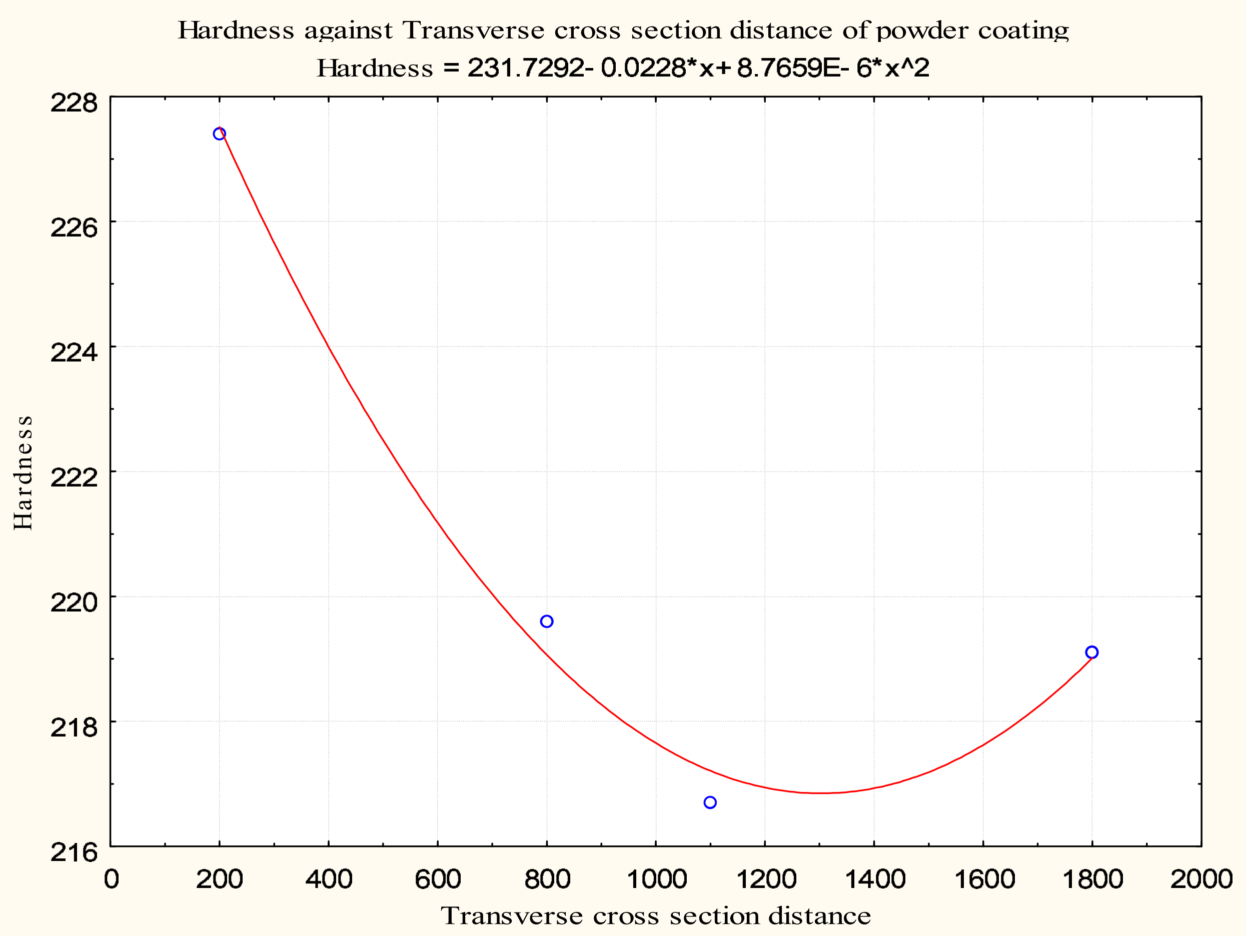


Figure 4.7: Hardness (HV) versus Transverse cross section distance (µm) of the mild steel AISI 1010 of the powder coating specimen.

The Figure 4.7 shows a polynomial second order of the hardness value (HV) on the mild steel AISI 1010 which was tested along the zinc electroplating specimen. The polynomial graph had a mathematical equation of:

$$231.7292 - 0.0228x + 8.7659 \times 10^{-5} - 6x^{2}$$

It shows the minimum graph type because there is dropping of the hardness value when it was tested from the area near the coated part to the mild steel of AISI 1010 part.

From the graphs plotted in Figure 4.2 to 4.7, it is noticed that the coating bring a big effect towards the steel sample, AISI 1010. Although nickel electroplating has the lowest value in thickness, but it gave the highest hardness value among the three prevention methods applied. For powder coating specimen, it is found that its hardness value is the lowest among the three prevention method. Therefore, it is not suitable to be used for the application to support for high impact.

4.4 CORROSION RATE

The corrosion rate was being calculated by using the weight loss data taken. The difference weight of the specimens was recorded everyday during the immersion test. The net weight loss was gained by using the total weight loss of the specimens minus the total weight loss of the reference specimens. The detailed data was shown in Appendix C. The Table 4.5 and Table 4.6 was the average net weight loss in seawater and in natural water.

Table 4.5: The average net weight loss on different prevention methods in seawater.

Day	Seawater			
	Zinc electroplating	Nickel electroplating	Powder Coating	Without coating
	Net weight loss (g)	Net weight loss (g)	Net weight loss (g)	Net weight loss (g)
1	0.0536	0.0416	0.0520	0.0685
2	0.0503	0.0015	0.0327	0.0630
3	0.0221	0.0118	0.0238	0.0253
4	0.0071	0.0010	0.0051	0.0092
5	0.0066	0.0035	0.0054	0.0115
6	0.0079	0.0046	0.0053	0.0108
7	0.0433	0.0213	0.0336	0.0550
8	0.0345	0.0110	0.0212	0.0479
9	0.0047	0.0012	0.0024	0.0062
Average	0.02556	0.01083	0.02017	0.03304

Table 4.6: The average net weight loss on different prevention methods in natural water.

Day	Natural water			
	Zinc electroplating	Nickel electroplating	Powder Coating	Without coating
	Net weight loss (g)	Net weight loss (g)	Net weight loss (g)	Net weight loss (g)
1	0.0740	0.0428	0.0505	0.1166
2	0.0757	0.0114	0.0459	0.0779
3	0.0369	0.0172	0.0290	0.0392
4	0.0082	0.0061	0.0072	0.0106
5	0.0079	0.0049	0.0064	0.0187
6	0.0082	0.0059	0.0075	0.0194
7	0.0520	0.0438	0.0544	0.0624
8	0.0487	0.0124	0.0398	0.0539
9	0.0053	0.0023	0.0036	0.0105
Average	0.03430	0.01631	0.02714	0.04547

The equation to calculate the corrosion rate has shown in chapter 2, which was shown in Equation 2.1. By using the Equation 2.1, the corrosion rate of four different types of corrosion prevention method that use in the immersion test can be clearly seen at the table below:

Table 4.7: The corrosion rate of different types of prevention methods in seawater and natural water.

Types of coating	Corrosion Rate (mm/year)	
	Seawater	Natural water
Zinc electroplating	0.01868	0.02506
Nickel electroplating	0.00791	0.01192
Powder coating	0.01474	0.01983
Without coating	0.02414	0.03323

The data collected shows that the effect of corrosion rate on natural water is more significant than that of seawater. By referring to Table 4.5, the overall corrosion rate of the natural water for zinc electroplating, nickel electroplating, powder coating and specimen without coating is 25.46%, 33.64%, 25.67%, and 27.35% more than those immersed in seawater. This condition contrasts with most of the books where the corrosion rate of seawater should be higher than that in natural water.[6]

The reason for this condition is that when water contains less iron than the maximum that it is capable of carrying in solution, it corrodes iron or steel rapidly. (*Retrieved from Fundamentals of Metallic Corrosion in Fresh Water by J.R. Rossum, Roscoe Moss Company)* [4]

From the corrosion rate, the corrosion rate resistance can be determined too. There is a table stating that at every range of the corrosion rate indicating the corrosion resistance of that specimen.

Table 4.8: Relative corrosion resistance at different range of corrosion rate.[5]

Relative Corrosion Resistance	**mpy**	**mm/yr**	**µm/yr**	**nm/yr**	**pm/yr**
Outstanding	<1	<0.02	<25	<2	<1
Excellent	1-5	0.02-0.1	25-100	2-10	1-5
Good	5-20	0.1-0.5	100-500	10-50	20-50
Fair	20-50	0.5-1	500-1000	50-150	20-50
Poor	50-200	1-5	1000-5000	150-500	50-200
Unacceptable	200+	5+	5000+	500+	200+

(Source: Jones, D. A. (1996). Principles And Prevention Of Corrosion 2nd edition. Department of Chemical and Metallurgical Engineering University of Nevada, Reno)

Since the unit of constant K taken was in mm/yr, therefore, the focus will be only on the mm/yr column. The result show that all the coated specimens also in the range of less than 0.2, which mean that the coated specimens were outstanding for corrosion resistance in both of the seawater and natural water. But for the specimen without coating, it gave the value in the range of 0.02-0.1, which is excellent in corrosion resistance.

The corrosion rate of the coated specimens is lower than that of the uncoated specimen in both immersion tests. The data above show that the nickel electroplating specimen has the lowest value in corrosion rate followed by powder coating and zinc electroplating. This also means that nickel electroplating is the best prevention method for corrosion among the three different methods.

4.5 TENSILE TEST

The tensile test was done until the specimen start to fracture and then the value for yield strength and ultimate tensile strength were taken for analysis.

4.5.1 Before Immersion Test

The first tensile test was carried out on the specimens where it is before the immersion test.

Table 4.9: Data of yield strength and ultimate tensile strength of the specimen before immersion test

Before Immersion Test		
Types of specimen	Yield strength (MPa)	Ultimate tensile strength (MPa)
Without coating	309.9	365.9
Powder coating	317.0	386.2
Zinc electroplating	314.4	379.3
Nickel electroplating	331.5	398.1

The specimen without coating gave the lowest value of the yield strength and ultimate tensile strength, which were 309.9MPa and 365.9MPa. The nickel electroplating specimen has the highest value of ultimate tensile strength and yield strength, which were 398.1MPa and 331.5MPa.

4.5.2 After Immersion Test

The tensile test was then carried out after the immersion test. The first tensile test was carried out after day 2 immersion, followed by day 6 and day 9. The data of yield strength and ultimate tensile strength were recorded and analyzed.

4.5.2.1 Yield Strength

Table 4.10: Yield strength of specimens without coating in seawater and natural water

Yield strength (without coating)				
Day	0	2	6	9
Seawater	309.9	300.4	289.7	287.3
Natural water	309.9	297.5	288.3	279.7

Table 4.11: Yield strength of specimens with powder coating in seawater and natural water

Yield strength (Powder coating)				
Day	0	2	6	9
Seawater	317.0	310.6	306.9	303.2
Natural water	317.0	308.4	302.8	300.6

Table 4.12: Yield strength of specimens with zinc electroplating in seawater and natural water

Yield strength (Zinc electroplating))				
Day	0	2	6	9
Seawater	314.4	303.2	398.8	288.8
Natural water	314.4	298.8	296.3	284.3

Table 4.13: Yield strength of specimens with nickel electroplating in seawater and natural water

Yield strength (Nickel electroplating)				
Day	0	2	6	9
Seawater	331.5	320.6	314.1	303.5
Natural water	331.5	320.0	311.0	301.4

The yield strength of the different types of specimens was recorded as in Table 4.10 to Table 4.13. The data is then used to plot 4 different graphs for further analysis.

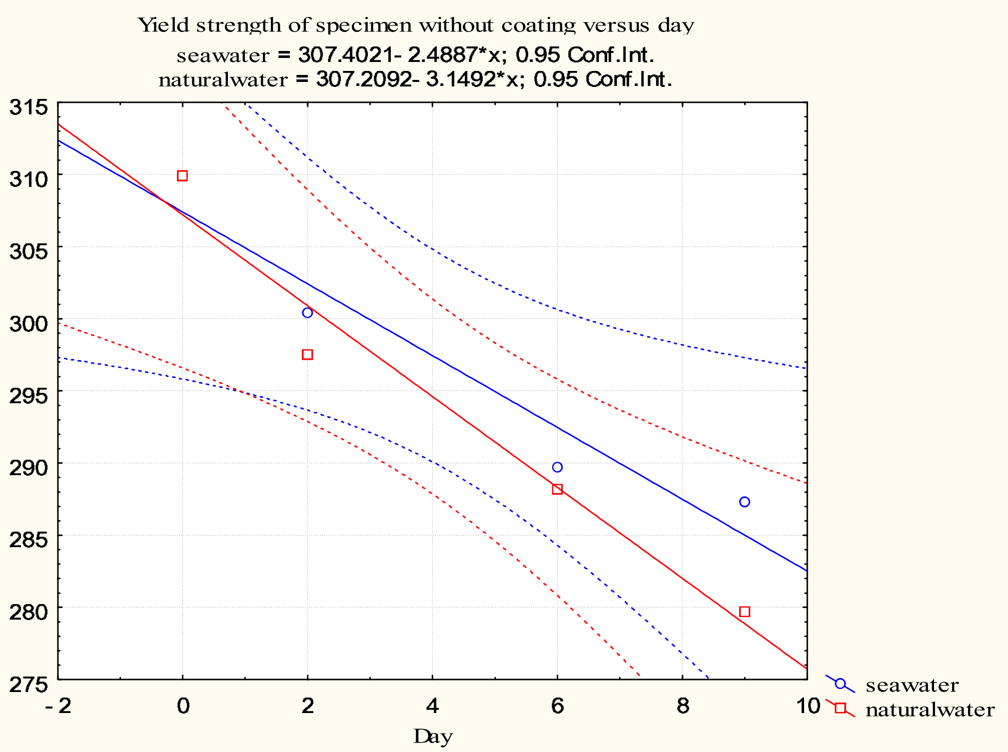


Figure 4.8: Yield strength of specimen without coating versus day

Figure 4.8 shows the yield strength of specimen without coating versus days. The blue line indicated the specimen immersed in seawater whereas the red line indicated the natural water.

Both of the linear line have own mathematical formula, which were 307.4021 – 2.4887X and 301.2092 – 3.1492X for seawater and natural water. The dotted lines show the confidence interval of 95%.

The yield strength was decreasing from day 0 to day 9. The initial yield strength recorded was 309.9MPa. By using the mathematical equation, it was found that at day 8, the yield strength of seawater and natural water were recorded as 287.4925MPa and 282.0156MPa respectively. The results show that there was greater dropped in natural water than seawater.

There is an intersection point in this graph too. The intersection point shows that the yield strength value is the same for both specimens that immersed in the seawater and natural water on day 0.

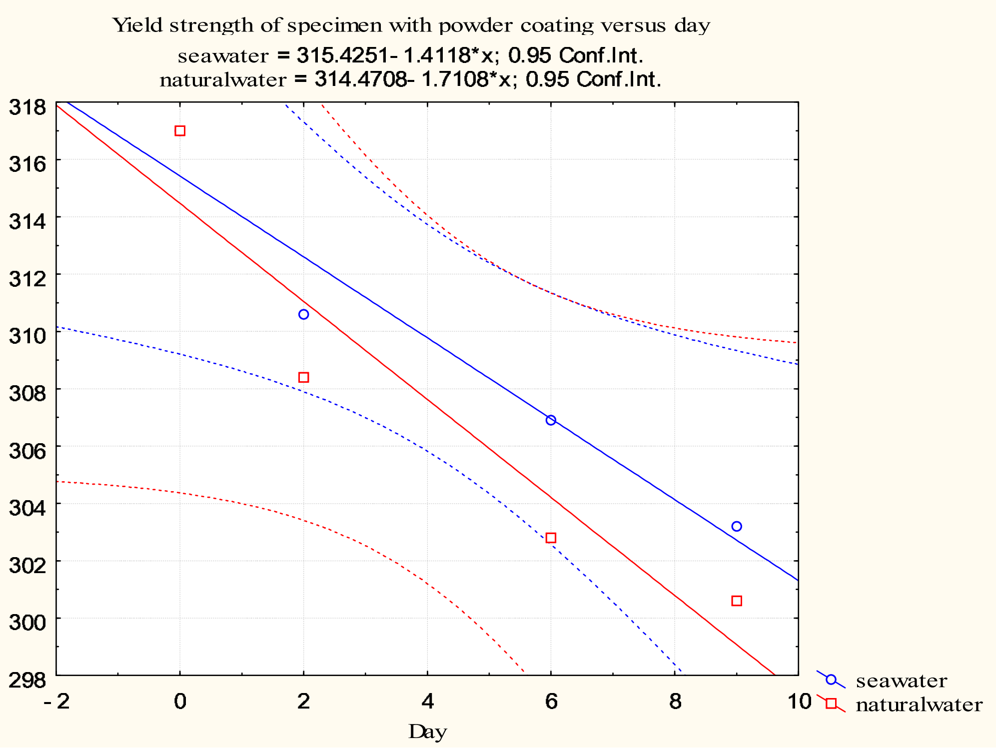


Figure 4.9: Yield strength of specimen with powder coating versus day

Figure 4.9 shows the yield strength of specimen with powder coating versus days. The blue line indicated the specimen immersed in seawater whereas the red line indicated the natural water.

Both of the linear line have own mathematical formula, which were 315.4251 – 1.4118*X* and 314.4708 – 1.7108*X* for seawater and natural water. The dotted lines show the confidence interval of 95%.

The yield strength was decreasing from day 0 to day 9. The initial yield strength recorded was 317.0MPa. By using the mathematical equation, it was found that at day 8, the yield strength of seawater and natural water were recorded as 304.1307MPa and 300.7214MPa respectively. The results show that there was greater dropped in natural water than seawater

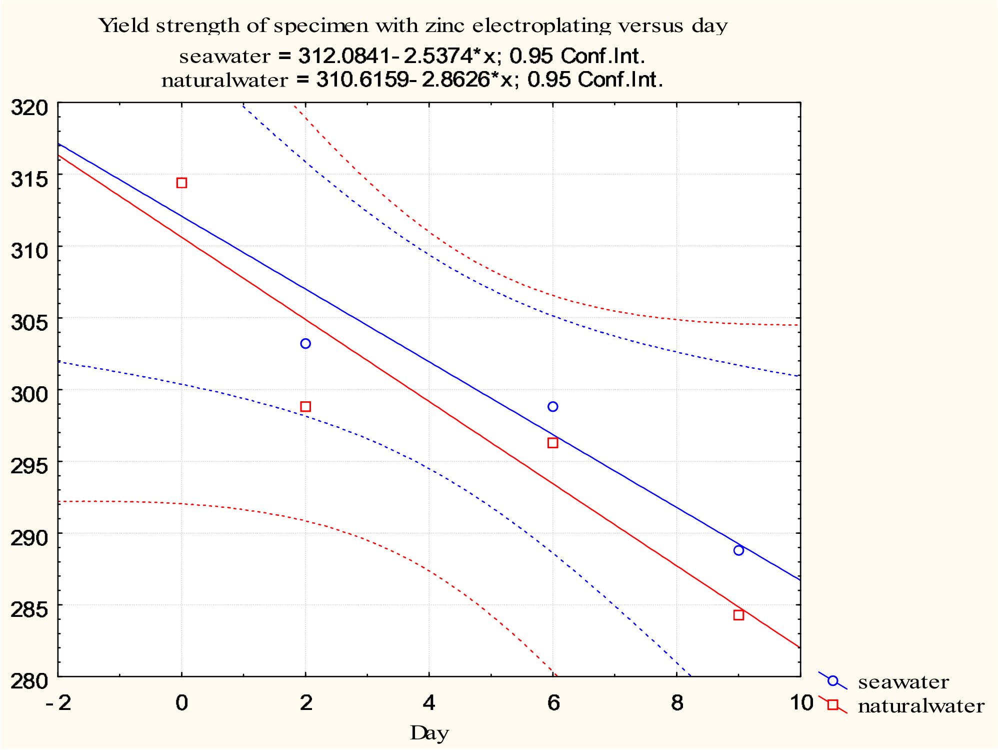


Figure 4.10: Yield strength of specimen with zinc electroplating versus day

Figure 4.10 shows the yield strength of specimen with zinc electroplating versus days. The blue line indicated the specimen immersed in seawater whereas the red line indicated the natural water. Both of the linear line have own mathematical formula, which were 312.0841 – 2.5374*X* and 310.6159 – 2.8626*X* for seawater and natural water. The dotted lines show the confidence interval of 95%.

The yield strength was decreasing from day 0 to day 9. The initial yield strength recorded was 314.4MPa. By using the mathematical equation, it was found that at day 8, the yield strength of seawater and natural water were recorded as 291.7849MPa and 287.7151MPa respectively. The results show that there was greater dropped in natural water than seawater.

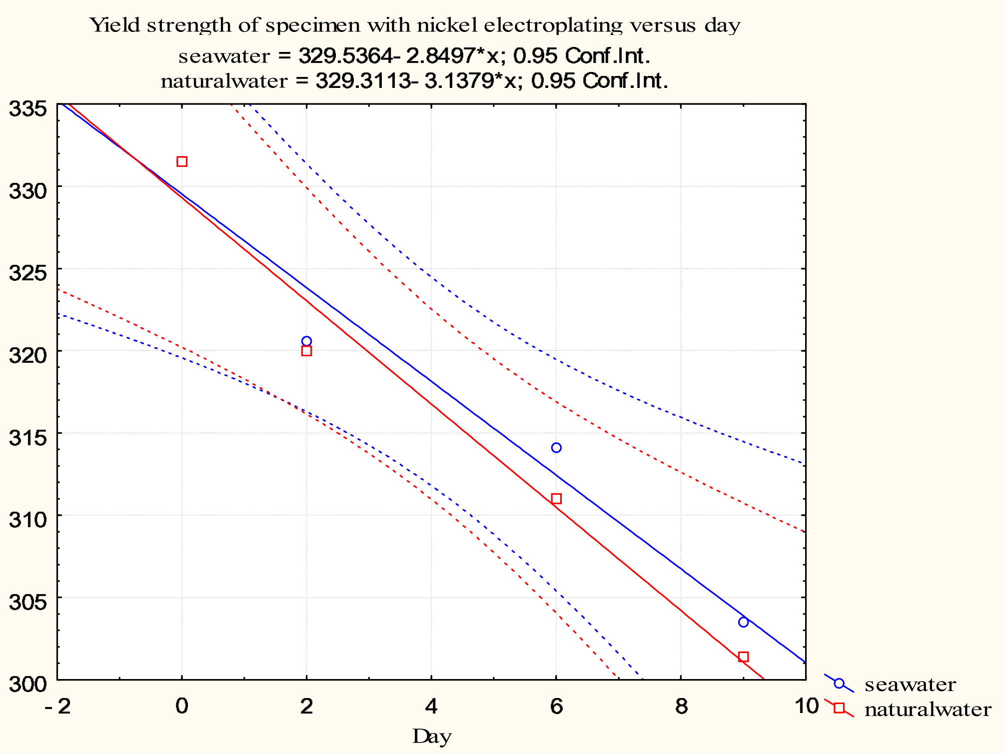


Figure 4.11: Yield strength of specimen with nickel electroplating versus day

Figure 4.11 shows the yield strength of specimen with nickel electroplating versus days. The blue line indicated the specimen immersed in seawater whereas the red line indicated the natural water. Both of the linear line have own mathematical formula, which were $329.5364 - 2.8497X$ and $329.3113 - 3.1379X$ for seawater and natural water. The dotted lines show the confidence interval of 95%.

The yield strength was decreasing from day 0 to day 9. The initial yield strength recorded was 331.5MPa. By using the mathematical equation, it was found that at day 8, the yield strength of seawater and natural water were recorded as 306.7388MPa and

304.2081MPa respectively. The results show that there was greater dropped in natural water than seawater.

There is an intersection point in this graph too. The intersection point shows that the yield strength value is the same for both specimens that immersed in the seawater and natural water on day 0.

From Figure 4.8 to Figure 4.11, it can be clearly seen that the yield strength of the specimen was decreasing from day 0 to day 9 during the immersion test. The graphs also show that the yield strength of natural water was lower than that in seawater. This incident was depended on the corrosion that happened in two different types of solutions.

By using the mathematical equation obtained in each specimen, there was another table that can be generated, as shown in Table 4.14. Table 4.14 shown the yield strength at day 8 which calculated by using the mathematical equation obtained. The result shows that the specimen with nickel electroplating has the highest value in yield strength, followed by powder coating, zinc electroplating and specimen without coating.

Table 4.14: Yield strength obtained by mathematical equation at day 8

Yield strength (MPa) at day 8		
	Seawater	Natural water
Nickel electroplating	306.7388	304.2081
Powder coating	304.1307	300.7214
Zinc electroplating	291.7849	287.7175
Without coating	287.4925	282.0156

4.5.2.2 Ultimate Tensile Strength

Table 4.15: Ultimate tensile strength of specimens without coating in seawater and natural water.

Ultimate tensile strength (without coating)				
Day	0	2	6	9
Seawater	367.3	365.9	359.1	350.0
Natural water	367.3	364.2	358.1	348.9

Table 4.16: Ultimate tensile strength of specimens with powder coating in seawater and natural water.

Ultimate tensile strength (Powder coating)				
Day	0	2	6	9
Seawater	386.2	378.8	375.1	370.3
Natural water	386.2	375.2	370.6	368.1

Table 4.17: Ultimate tensile strength of specimens with zinc electroplating in seawater and natural water.

Ultimate tensile strength (Zinc electroplating))				
Day	0	2	6	9
Seawater	379.3	375.9	371.1	369.1
Natural water	379.3	374.8	370.0	367.3

Table 4.18: Ultimate tensile strength of specimens with nickel electroplating in seawater and natural water.

Ultimate tensile strength (Nickel electroplating)				
Day	0	2	6	9
Seawater	398.1	394.9	389.1	378.1
Natural water	398.1	393.4	384.0	372.4

The yield strength of the different types of specimens was recorded as in Table 4.12 to Table 4.15. The data is then used to plot 4 different graphs for further analysis.

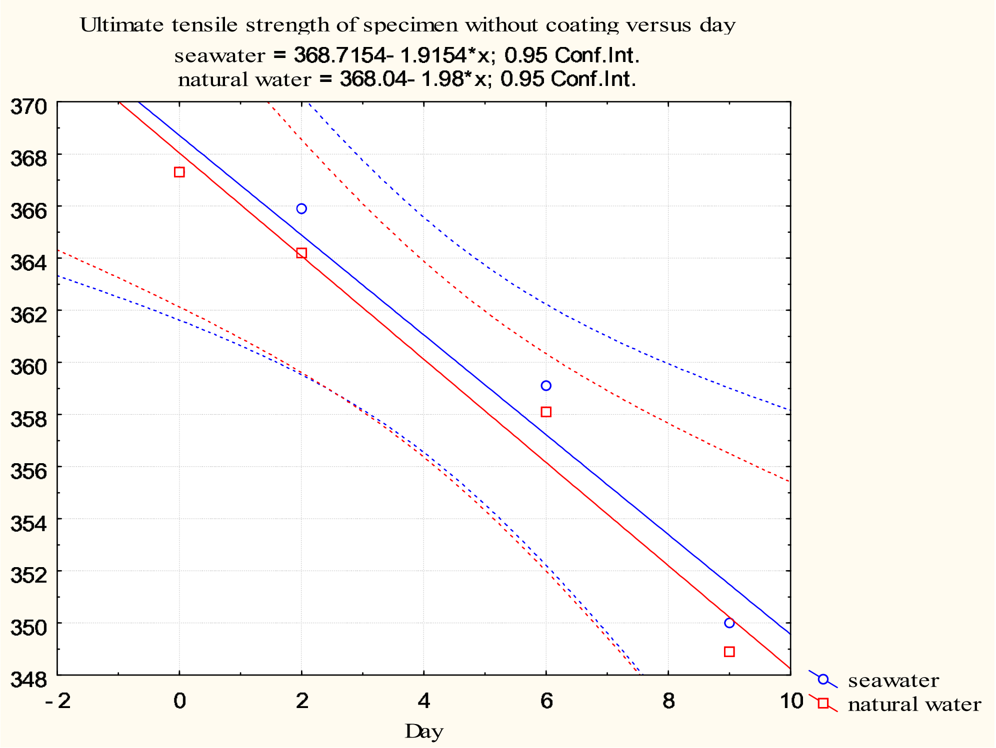


Figure 4.12: Ultimate tensile strength of specimen without coating versus day

Figure 4.12 shows the ultimate tensile strength of specimen without coating versus days. The blue line indicated the specimen immersed in seawater whereas the red line indicated the natural water. Both of the linear line have own mathematical formula, which were $368.7154 - 1.9154X$ and $368.04 - 1.98X$ for seawater and natural water. The dotted lines show the confidence interval of 95%.

The ultimate tensile strength was decreasing from day 0 to day 9. The initial ultimate tensile strength recorded was 367.3MPa. By using the mathematical equation, it was found that at day 8, the ultimate tensile strength of seawater and natural water were recorded as 353.3922MPa and 352.2MPa respectively. The results show that there was greater dropped in natural water than seawater.

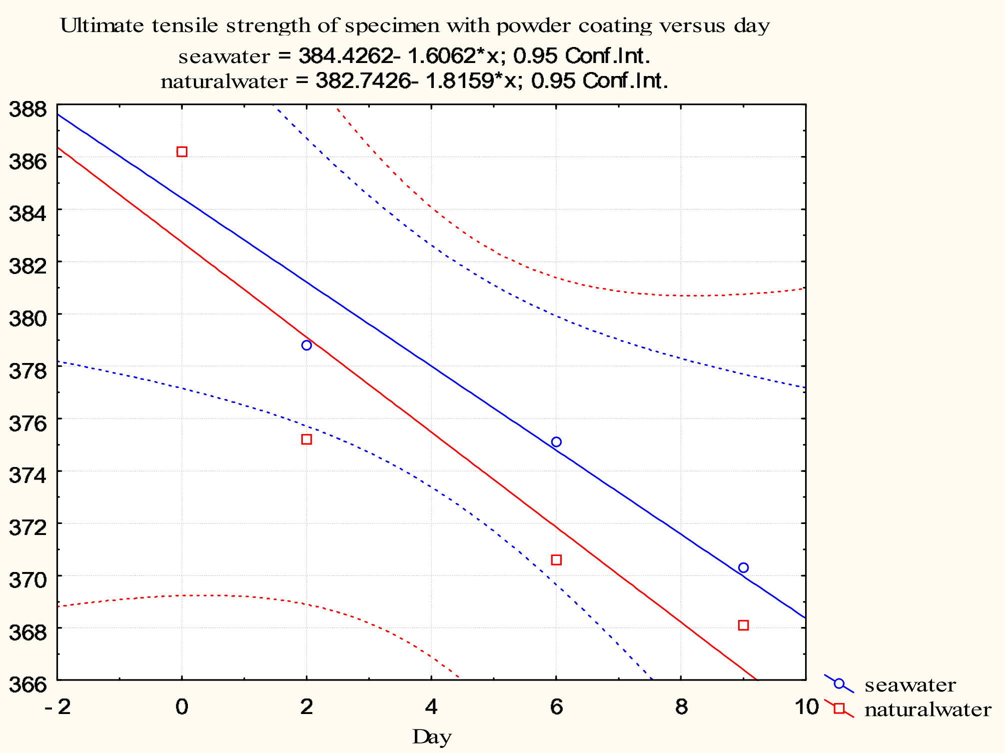


Figure 4.13 Ultimate tensile strength of specimen with powder coating versus day

Figure 4.13 shows the ultimate tensile strength of specimen with powder coating versus days. The blue line indicated the specimen immersed in seawater whereas the red line indicated the natural water. Both of the linear line have own mathematical formula, which were 384.4262 – 1.6062X and 382.7462 – 1.8159X for seawater and natural water. The dotted lines show the confidence interval of 95%.

The ultimate tensile strength was decreasing from day 0 to day 9. The initial ultimate tensile strength recorded was 379.3MPa. . By using the mathematical equation, it was found that at day 8, the ultimate tensile strength of seawater and natural water were recorded as 371.5766MPa and 368.2190MPa respectively. The results show that there was greater dropped in natural water than seawater.

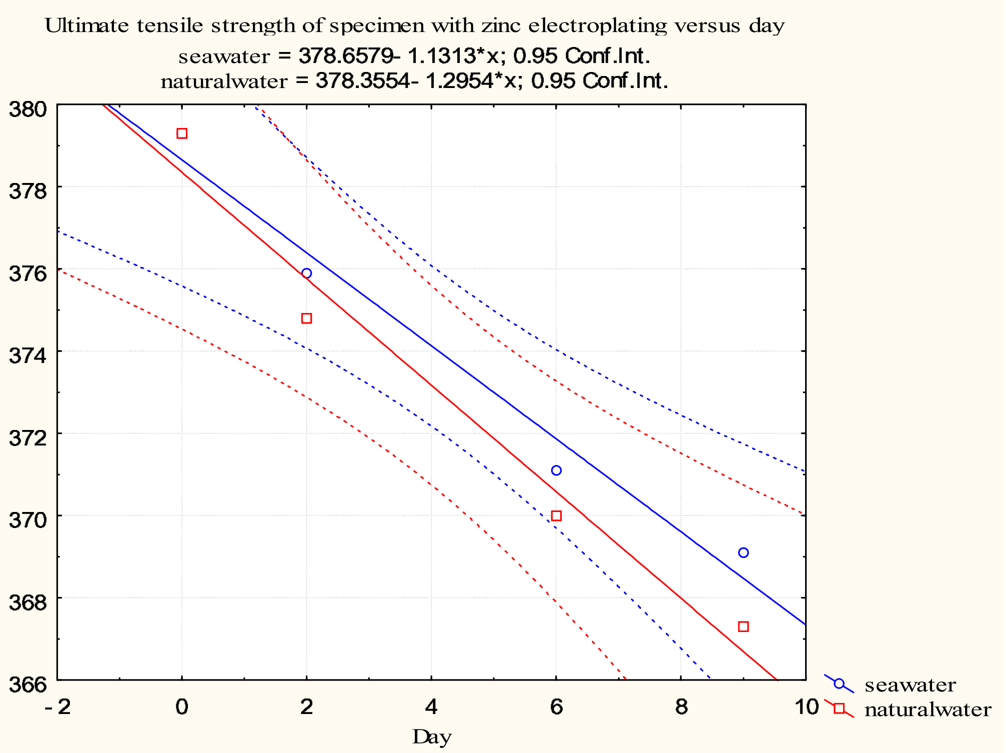


Figure 4.14: Ultimate tensile strength of specimen with zinc electroplating versus day

Figure 4.14 shows the ultimate tensile strength of specimen with zinc electroplating versus days. The blue line indicated the specimen immersed in seawater whereas the red line indicated the natural water. Both of the linear line have own mathematical formula, which were 378.6579 – 1.1313X and 378.3554 – 1.2954X for seawater and natural water. The dotted lines show the confidence interval of 95%.

The ultimate tensile strength was decreasing from day 0 to day 9. The initial ultimate tensile strength recorded was 386.2MPa. . By using the mathematical equation, it was found that at day 8, the ultimate tensile strength of seawater and natural water were recorded as 369.6075MPa and 367.9922MPa respectively. The results show that there was greater dropped in natural water than seawater.

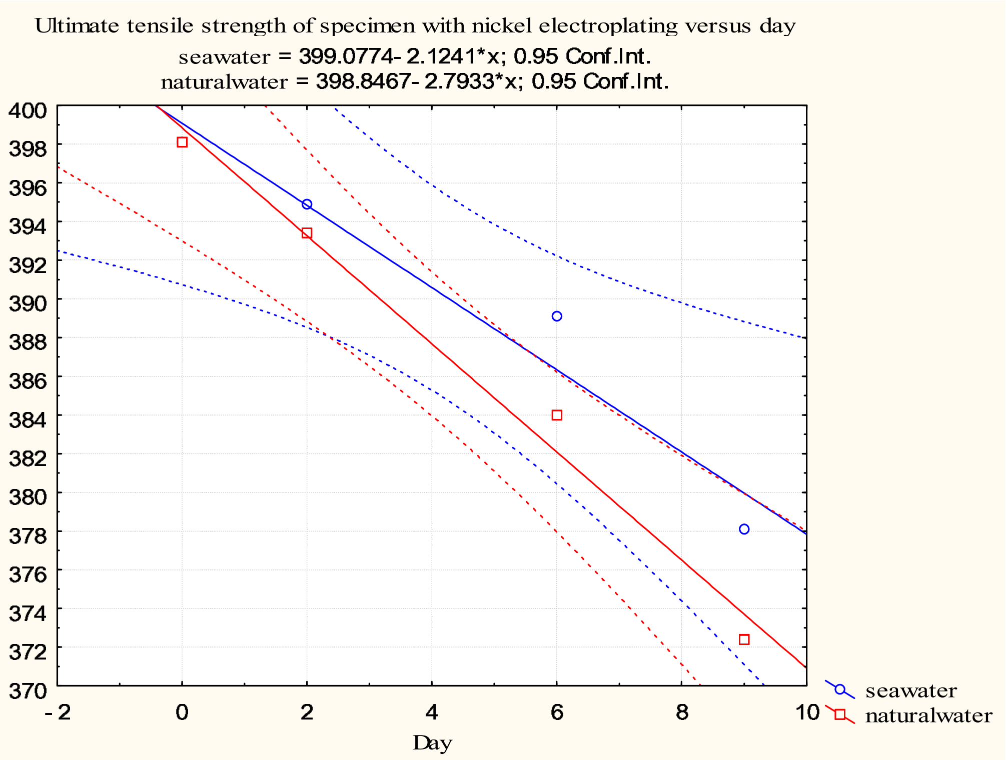


Figure 4.15: Ultimate tensile strength of specimen with nickel electroplating versus day

Figure 4.15 shows the ultimate tensile strength of specimen with nickel electroplating versus days. The blue line indicated the specimen immersed in seawater whereas the red line indicated the natural water. Both of the linear line have own mathematical formula, which were 399.0774 – 2.1241X and 398.8467 – 2.7933X for seawater and natural water. The dotted lines show the confidence interval of 95%.

The ultimate tensile strength was decreasing from day 0 to day 9. The initial ultimate tensile strength recorded was 398.1MPa. . By using the mathematical equation, it was found that at day 8, the ultimate tensile strength of seawater and natural water were recorded as 382.0846MPa and 376.5003MPa respectively. The results show that there was greater dropped in natural water than seawater.

There is an intersection point in this graph. The intersection point shows that the ultimate tensile strength value is the same for both specimens that immersed in the seawater and natural water on day 0.

From Figure 4.13 to Figure 4.16, it can be clearly seen that the ultimate tensile strength of the specimen was also decreasing from day 0 to day 9 during the immersion test as in yield strength graphs plotted. The plotted graphs also show that the ultimate tensile strength of natural water was lower than that in seawater. This condition happened is because the corrosion that happened on the sample specimens has weakened the mechanical properties of the immersed specimens.

By using the mathematical equation obtained in each specimen, there was another table that can be generated, as shown in Table 4.19. Table 4.19 shown the ultimate tensile strength at day 8 which calculated by using the mathematical equation obtained. The result shows that the specimen with nickel electroplating has the highest value in ultimate tensile strength, followed by powder coating, zinc electroplating and specimen without coating.

Table 4.19: Ultimate tensile strength obtained by mathematical equation at day 8

Ultiamte tensile strength (MPa) at day 8		
	Seawater	Natural water
Nickel electroplating	382.0846	376.5003
Powder coating	371.5766	368.2190
Zinc electroplating	369.6075	367.9922
Without coating	353.3922	352.2000

4.6 DISCUSSION

The thickness and hardness result obtained, it shown that the nickel electroplating has the lowest value in thickness, but it gives the highest value in hardness. Besides that, the result in immersion test shown that the nickel electroplating specimen was the best corrosion prevention method among the others coated specimens where it has the lowest value of the corrosion rate, which is 0.00791 mm/year in seawater and 0.1192 mm/year in natural water.

Powder coating specimen has the lowest value in hardness test, but it has lower corrosion rate than zinc electroplating specimen, which mean that powder coating is better corrosion prevention method than zinc electroplating due to its lower corrosion rate.

Tensile test carried out the value of yield strength and ultimate tensile strength. The yield strength and the ultimate tensile strength were greatly influenced by the preparation, and also the happened of corrosion. The coating process on the specimens gives a great impact on the corrosion prevention.

From all the graphs plotted, it can be clearly seen that the yield strength and ultimate tensile strength were gradually decreased from day 2 until day 9. This incident happened is because of the corrosion that occurred on the specimens during the immersion test.

The plotted graphs also gave us another data, where the coated specimen has different yield strength and ultimate strength for different types of the coating. The specimen with nickel electroplating has the highest value in yield strength and ultimate tensile strength, follow by the powder coating, zinc electroplating and specimen without coating.

The graphs also show that the specimens immersed in natural water has a lower value compare to the specimens that immersed in seawater for yield strength and ultimate tensile strength. This is because the corrosion happened faster in natural water than in seawater. Therefore, the yield strength and ultimate tensile strength for specimen immersed in natural water is lower.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

From the result shown in Chapter 4, it can be concluded that the coating specimens can delayed corrosion. The prevention methods that applied on the specimens show that it slows down corrosion where the corrosion rate is lower than the specimen without coating. Among the coated specimens, it is found that the nickel electroplating is the best prevention method, followed by powder coating and zinc electroplating.

Besides the corrosion rate, the coated specimens also give impact on the mechanical properties on the tested specimens. Coating increased hardness where nickel electroplating has the highest value in Vickers Hardness test, followed by the zinc electroplating, powder coating and lastly is the specimen without coating. The yield strength and ultimate tensile strength also being influenced by the prevention method applied. The coated specimens give higher value of the yield strength and ultimate tensile strength for the tensile test than the uncoated specimens.

5.2 RECOMMENDATIONS

There are many recommendations which can be done in order to improve the results. The recommendations which can be taken into consideration are listed below:

i. The specimens must be cleaned properly before taken to electroplating and coating process.

ii. The immersion test should run for a longer time in order to investigate the corrosion rate between seawater and natural water.

iii. The hardness test should run on more different specimens to gain the accurate average data on the hardness value.

iv. The tensile test should be run for more times in order to get the average data on the yield strength and ultimate tensile strength.

REFERENCES

A.Abdul Jamal, H.P. Nagaswarupa, P.V. Krupakara (2009). Evaluation of Corrosion Rate of Al 6061/ Zircon Metal Matrix Composite in Sea water. International Journal of Oceans and Oceanography

Alok Nayar(2005). Testing of Metals. Tata Mc-GrawHill.[3]

A.Ragab, H.Alawi & K.Sorein (1993). Effect of Atmospheric and Marine Corrosive Environments on Tensile, Impact and Hardness Properties of Some Steels. Cairo University, Egypt.

Arthur J. McEvily (2002). Metal Failures, Mechanisms, Analysis, Prevention. Wiley-Interscience Publication, John Willey & Sons, INC.

ASM Handbook(1985), Vol.9, ASM International, Materials Park, Ohio, USA.

Budman, E. and Sizelove, R. R. (2007) Zinc Alloy Plating.

Calle.L.M., NASACorrosion Technology Laboratory[1]
Retrieved from http://corrosion.ksc.nasa.gov/

D.A. Bayliss and D.H. Deacon(2002). Steelwork Corrosion Control(2nd edition). Spon Press, Tylor & Francis Group.

E.Bardal (2003).Corrosion and Protection. Springer-Verlag London.

F.C.Campbell(2008). Elements of Metallurgy and Engineering Alloys. ASM International, Materials Park, Ohio, USA.

Gavrila, A. M., Millet, A J.P., Mazille, A. H., Marchandise, B. D., Cuntz, B. J.M. Corrosion Behaviour of Zinc–Nickel Coatings, Electrodeposited On Steel. Aerospatiale, Louis Ble´Riot Corporate Research Center, France

Jones, D. A. (1996). Principles And Prevention Of Corrosion 2nd edition. Department of Chemical and Metallurgical Engineering University of Nevada, Reno[5]

Joseph Datsko(1997). Materials Selection For Design and Manufacturing Theory and Practice. Marcel Dekker, Inc. New York

J.R Rossum. Fundamentals of Metallic Corrosion in Fresh Water, Roscoe Moss Company[4]

Laboratory Corrosion Tests and Standards (14-16 Nov. 1983): a symposium by ASTM Committee G-1 on Corrosion of Metals, Bal Harbour, FL. [2]

Marder, A. R. (2000). The metallurgy of zinc-coated steel. Department of Materials Science and Engineering, Lehigh University, USA.

M.Gavrilla, J.P. Millet, H. Mazille (26 April 1999). Corrosion Behaviour of Zinc-Nickel Coatings, Electrodeposited on Steel. Laboratoire de Physicochimie Industrielle.

Philip A. Schweitzer(2006). Corrosion Engineering Handbook(2nd edition), Fundamentals of Metallic Corosion Atmospheric and Media Corrosion of Metals. CRC Press, Taylor & Francis Group.

Roberge, P. R. (2007) Corrosion Inspection and monitoring. Royal Military Collegye of Canada Ontario, Canada.

Sastri, V.S., Ghali E. and Elboujdaini M. (2007). Corrosion Prevention and Protection Practical Solution.

Smith, W.F., & Hashemi, J. (2006). Foundations of Materials Science and Engineering (4th ed.). Singapore. McGraw-Hill.

S.Montserrat, Y.Calventus, J.M. Hutchinson (2005). Physical Aging of Thermosetting Powder Coatings. University Politecnica de Catalunya,Terrassa, Spain.

Waterhouse, R. R., Rrook, F'. A., And Lee, G. M. C. (1962) The Effect of Electrodeposited Metals On The Fatigue Behaviour of Mild Steel Under Conditions Of Fretting Corrosion. Department Of Metallurgy. University Cf Nottingham, Gveat Britain.

Xi-Cheng Wei, Ren-yu Fu, Lin Li (2006). Influence of Zinc Electro-plated Coating on Dynamic Tensile Properties od TRIP-Aided Steels. Shanghai University, China.

Zaki Ahmad(2004). Principles of Corrosion Engineering and Corrosion Control. Butterworth-Heinemann, imprint of Elsevier.[6]

APPENDIX A
THICKNESS OF THE COATING

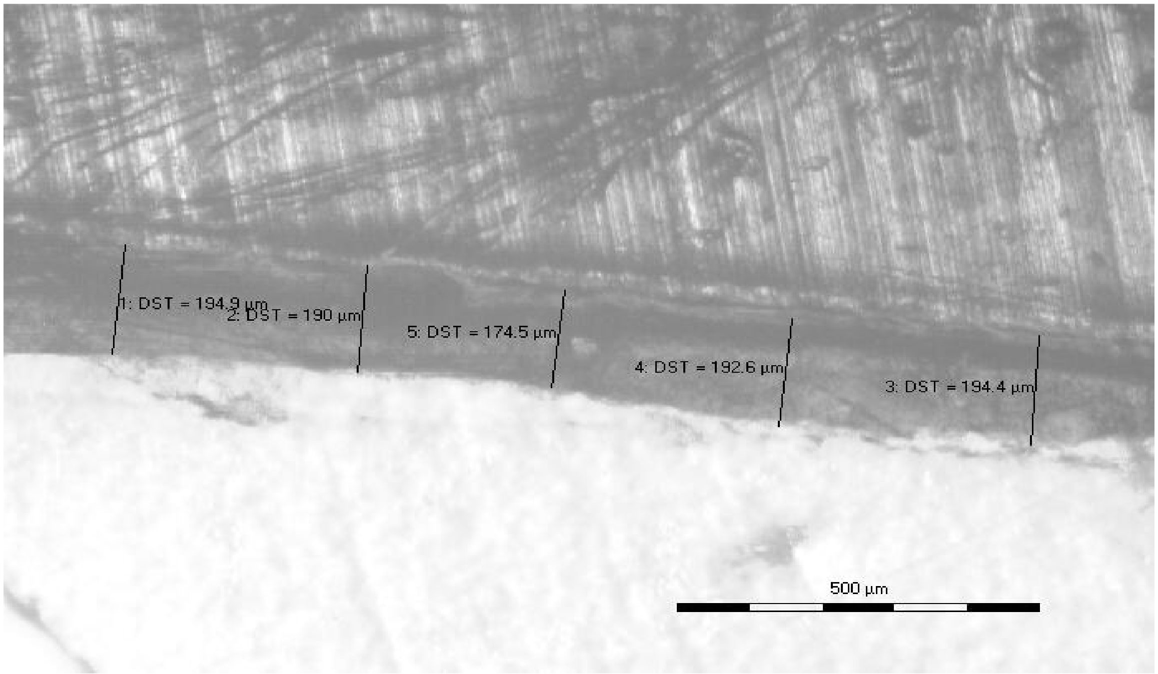


Figure A1: The thickness of the powder coating specimen.

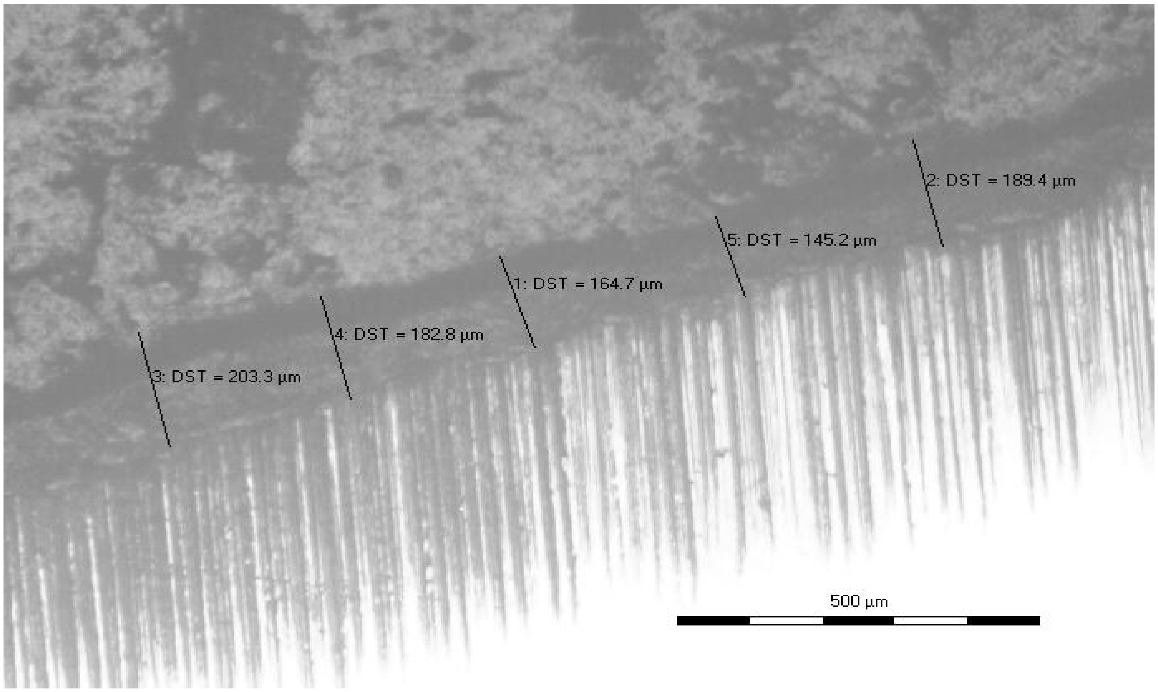


Figure A2: The thickness of the zinc electroplating specimen

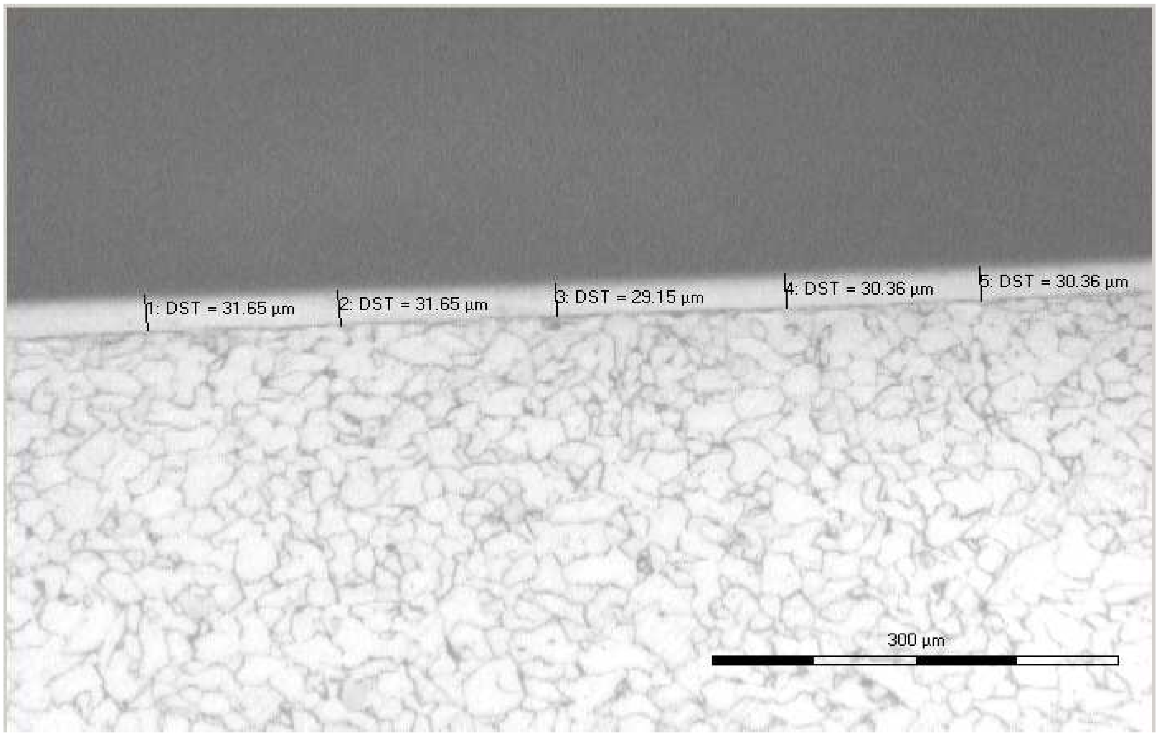


Figure A3: The thickness of the nickel electroplating specimen

APPENDIX B
TESTED AREA OF HARDNESS

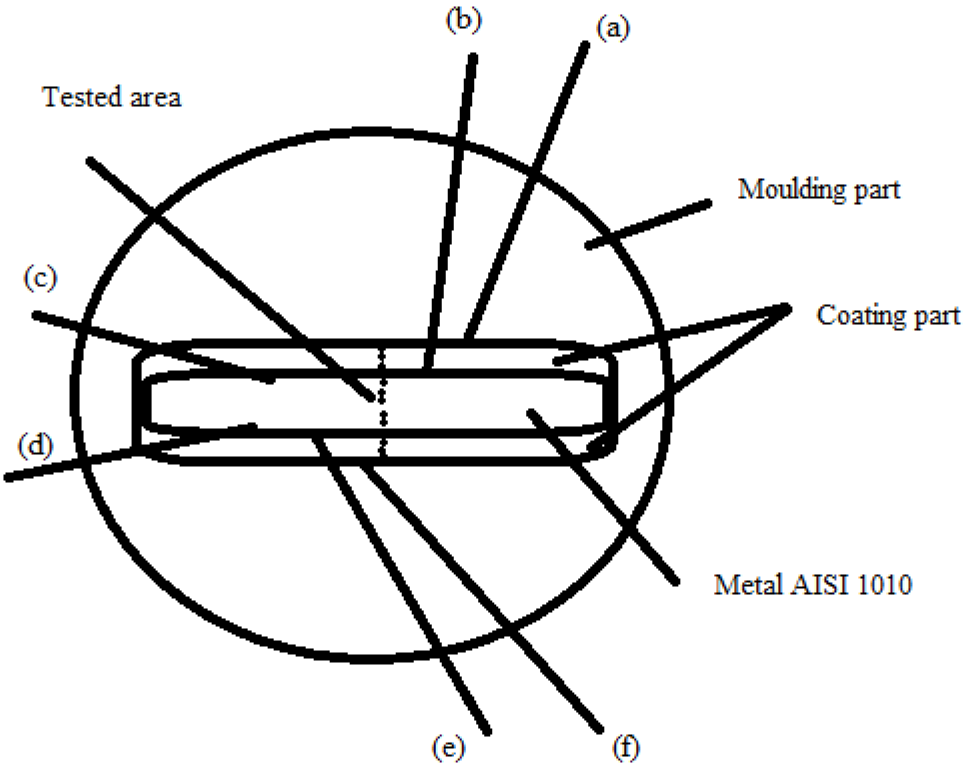


Figure B1: The tested area of Vickers Hardness Test from top view

APPENDIX C
NET WEIGHT LOSS DATA

Day 1 Weight Loss

Reference weight loss

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)
Zinc electroplating	46.4279	46.4190	0.0089
Nickel electroplating	47.3791	47.3736	0.0055
Powder Coating	46.8704	46.8631	0.0073
Without coating	44.5417	44.5290	0.0127

Weight loss (Seawater)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.3650	46.3325	0.0325	0.0536
Nickel electroplating	48.2719	48.2248	0.0471	0.0416
Powder Coating	47.8001	47.7408	0.0593	0.0520
Without coating	44.9712	44.8900	0.0812	0.0685

* Net weight loss = Total loss – Reference total loss

Weight loss (Natural water)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.3308	46.2479	0.0829	0.0740
Nickel electroplating	47.3627	47.3144	0.0483	0.0428
Powder Coating	47.5778	47.5200	0.0578	0.0505
Without coating	45.1585	45.0293	0.1292	0.1166

* Net weight loss = Total loss – Reference total loss

Day 2 Weight Loss

Reference weight loss

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)
Zinc electroplating	46.4190	46.3865	0.0325
Nickel electroplating	47.3736	47.3506	0.0230
Powder Coating	46.8631	46.8479	0.0152
Without coating	44.5290	44.4369	0.0921

Weight loss (Seawater)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.3325	46.2497	0.0828	0.0503
Nickel electroplating	48.2248	48.2003	0.0245	0.0015
Powder Coating	47.7408	47.6929	0.0479	0.0327
Without coating	44.8900	44.7349	0.1551	0.0630

* Net weight loss = Total loss – Reference total loss

Weight loss (Natural water)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.2479	46.1397	0.1082	0.0757
Nickel electroplating	47.3144	47.2800	0.0344	0.0114
Powder Coating	47.5200	47.4589	0.0611	0.0459
Without coating	45.0293	44.8593	0.1700	0.0779

* Net weight loss = Total loss – Reference total loss

Day 3 Weight Loss

Reference weight loss

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)
Zinc electroplating	46.3865	46.3587	0.0278
Nickel electroplating	47.3506	47.3394	0.0112
Powder Coating	46.8479	46.8311	0.0168
Without coating	44.4369	44.3644	0.0725

Weight loss (Seawater)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.2497	46.1998	0.0499	0.0221
Nickel electroplating	48.2003	48.1773	0.0230	0.0118
Powder Coating	47.6929	47.6523	0.0406	0.0238
Without coating	44.7349	44.6371	0.0978	0.0253

* Net weight loss = Total loss – Reference total loss

Weight loss (Natural water)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.1397	46.0750	0.0647	0.0369
Nickel electroplating	47.2800	47.2516	0.0284	0.0172
Powder Coating	47.4589	47.4131	0.0458	0.0290
Without coating	44.8593	45.7476	0.1117	0.0392

* Net weight loss = Total loss – Reference total loss

Day 4 Weight Loss

Reference weight loss

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)
Zinc electroplating	46.3587	46.3467	0.0120
Nickel electroplating	47.3394	47.3321	0.0073
Powder Coating	46.8311	46.8256	0.0055
Without coating	44.3644	44.3497	0.0147

Weight loss (Seawater)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.1998	46.1807	0.0191	0.0071
Nickel electroplating	48.1773	48.1600	0.0173	0.0010
Powder Coating	47.6523	47.6417	0.0106	0.0051
Without coating	44.6371	44.6132	0.0239	0.0092

* Net weight loss = Total loss – Reference total loss

Weight loss (Natural water)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.0750	46.0548	0.0202	0.0082
Nickel electroplating	47.2516	47.2382	0.0134	0.0061
Powder Coating	47.4131	47.4004	0.0127	0.0072
Without coating	45.7476	45.7223	0.0253	0.0106

* Net weight loss = Total loss – Reference total loss

Day 5 Weight Loss

Reference weight loss

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)
Zinc electroplating	46.3467	46.3345	0.0122
Nickel electroplating	47.3321	47.3242	0.0079
Powder Coating	46.8256	46.8155	0.0101
Without coating	44.3497	44.3282	0.0215

Weight loss (Seawater)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.1807	46.1619	0.0188	0.0066
Nickel electroplating	48.1600	48.1486	0.0114	0.0035
Powder Coating	47.6417	47.6262	0.0155	0.0054
Without coating	44.6132	44.6099	0.0033	0.0115

* Net weight loss = Total loss – Reference total loss

Weight loss (Natural water)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.0548	46.0347	0.0201	0.0079
Nickel electroplating	47.2382	47.2254	0.0128	0.0049
Powder Coating	47.4004	47.3854	0.0165	0.0064
Without coating	45.7223	45.6821	0.0402	0.0187

* Net weight loss = Total loss – Reference total loss

Day 6 Weight Loss
Reference weight loss

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)
Zinc electroplating	46.3345	46.3285	0.0060
Nickel electroplating	47.3242	47.2912	0.0033
Powder Coating	46.8155	46.8097	0.0058
Without coating	44.3282	44.3173	0.0109

Weight loss (Seawater)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.1619	46.1480	0.0139	0.0079
Nickel electroplating	48.1486	48.1407	0.0079	0.0046
Powder Coating	47.6262	47.6151	0.0111	0.0053
Without coating	44.6099	44.5882	0.0217	0.0108

* Net weight loss = Total loss – Reference total loss

Weight loss (Natural water)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.0347	46.0205	0.0142	0.0082
Nickel electroplating	47.2254	47.2162	0.0092	0.0059
Powder Coating	47.3854	47.3721	0.0133	0.0075
Without coating	45.6821	45.6518	0.0303	0.0194

* Net weight loss = Total loss – Reference total loss

Day 7 Weight Loss

Reference weight loss

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)
Zinc electroplating	46.3285	46.3188	0.0097
Nickel electroplating	47.2912	47.2853	0.0059
Powder Coating	46.8097	46.8004	0.0093
Without coating	44.3173	44.3041	0.0132

Weight loss (Seawater)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.1480	46.0950	0.0530	0.0433
Nickel electroplating	48.1407	48.1135	0.0272	0.0213
Powder Coating	47.6151	47.5722	0.0429	0.0336
Without coating	44.5882	44.5200	0.0682	0.0550

* Net weight loss = Total loss – Reference total loss

Weight loss (Natural water)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.0205	45.9588	0.0617	0.0520
Nickel electroplating	47.2162	47.1665	0.0497	0.0438
Powder Coating	47.3721	47.3084	0.0637	0.0544
Without coating	45.6518	45.5662	0.0756	0.0624

* Net weight loss = Total loss – Reference total loss

Day 8 Weight Loss

Reference weight loss

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)
Zinc electroplating	46.3188	46.2802	0.0386
Nickel electroplating	47.2853	47.2710	0.0143
Powder Coating	46.8004	46.7807	0.0197
Without coating	44.3041	44.2564	0.0477

Weight loss (Seawater)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.0950	46.0219	0.0731	0.0345
Nickel electroplating	48.1135	48.0882	0.0253	0.0110
Powder Coating	47.5722	47.5313	0.0409	0.0212
Without coating	44.5200	44.4244	0.0956	0.0479

* Net weight loss = Total loss – Reference total loss

Weight loss (Natural water)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	45.9588	45.8715	0.0873	0.0487
Nickel electroplating	47.1665	47.1398	0.0267	0.0124
Powder Coating	47.3084	47.2489	0.0595	0.0398
Without coating	45.5662	45.4646	0.1016	0.0539

* Net weight loss = Total loss – Reference total loss

Day 9 Weight Loss

Reference weight loss

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)
Zinc electroplating	46.2802	46.2460	0.0342
Nickel electroplating	47.2710	47.2639	0.0071
Powder Coating	46.7807	46.7604	0.0203
Without coating	44.2564	44.2197	0.0367

Weight loss (Seawater)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	46.0219	45.9830	0.0389	0.0047
Nickel electroplating	48.0882	48.0799	0.0083	0.0012
Powder Coating	47.5313	47.5086	0.0227	0.0024
Without coating	44.4244	44.3815	0.0429	0.0062

* Net weight loss = Total loss – Reference total loss

Weight loss (Natural water)

Type of coating	Initial Weight (g)	Final weight (g)	Total loss (g)	Net weight loss (g)
Zinc electroplating	45.8715	45.8320	0.0395	0.0053
Nickel electroplating	47.1398	47.1304	0.0094	0.0023
Powder Coating	47.2489	47.2250	0.0239	0.0036
Without coating	45.4646	45.4174	0.0472	0.0105

* Net weight loss = Total loss – Reference total loss

APPENDIX D
STRESS-STRAIN GRAPH

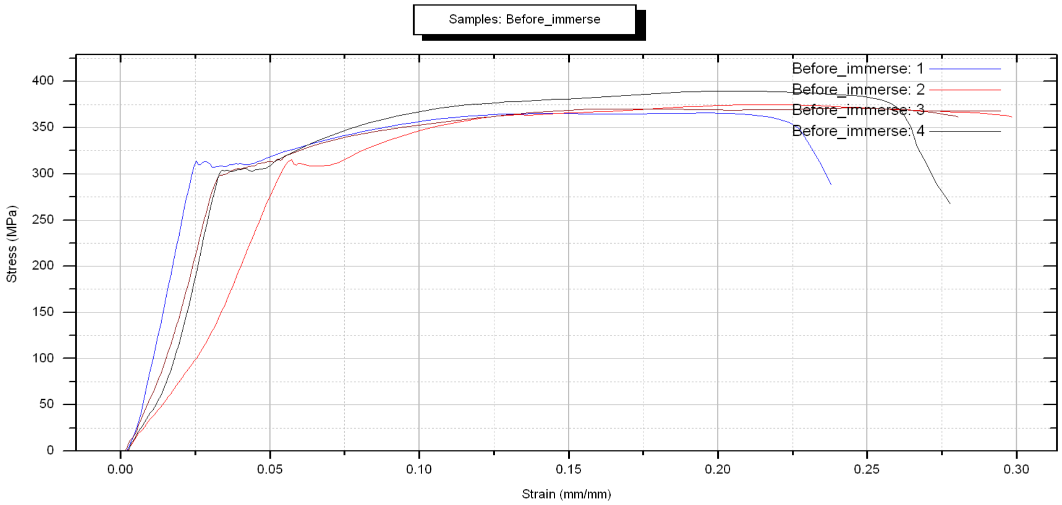


Figure D1: Stress-strain curve of tensile test for specimens before immersion test, where specimen 1, 2, 3 and 4 were specimen without coating, with powder coating, zinc electroplating and nickel electroplating

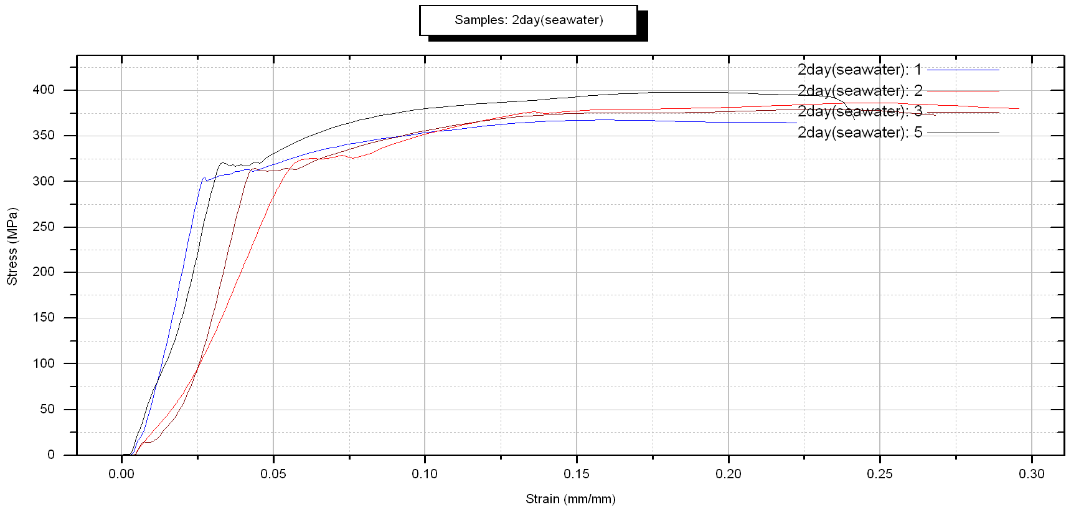


Figure D2: Stress-strain curve of tensile test for specimens immersed in seawater 2 days, where specimen 1, 2, 3 and 5 were specimen without coating, with powder coating, zinc electroplating and nickel electroplating

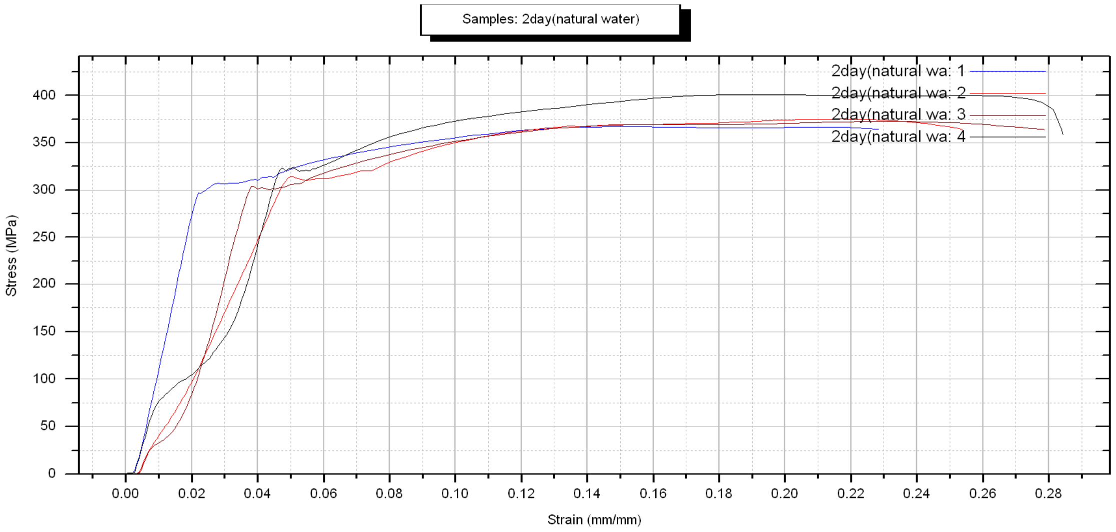


Figure D3: Stress-strain curve of tensile test for specimens immersed in natural water 2 days, where specimen 1, 2, 3 and 4 were specimen without coating, with powder coating, zinc electroplating and nickel electroplating

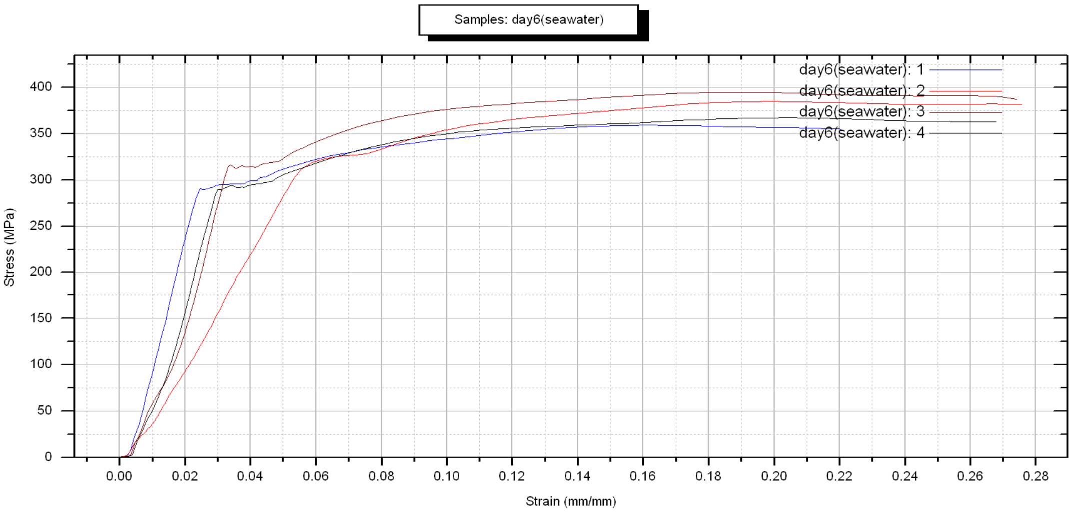


Figure D4: Stress-strain curve of tensile test for specimens immersed in seawater 6 days, where specimen 1, 2, 3 and 4 were specimen without coating, with powder coating, zinc electroplating and nickel electroplating

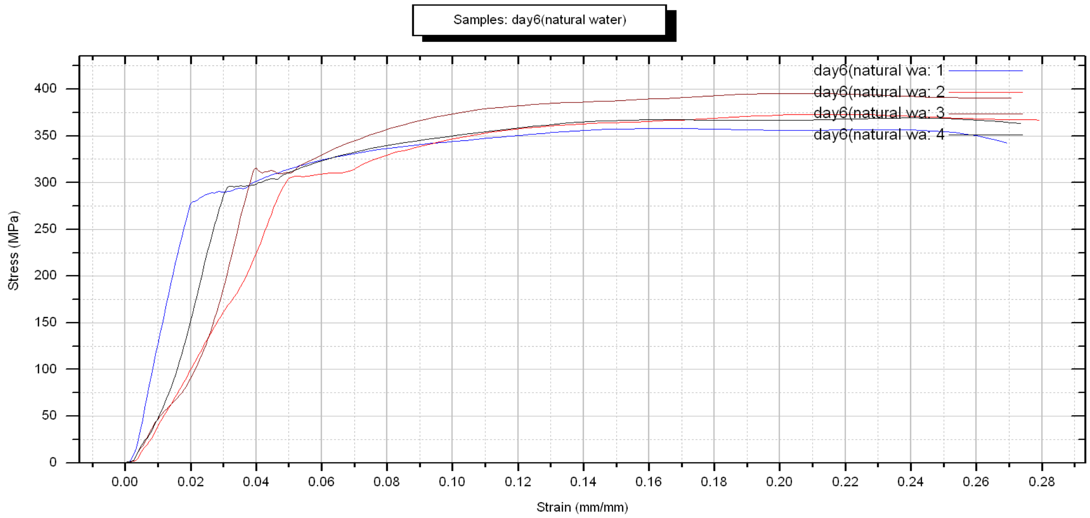


Figure D5: Stress-strain curve of tensile test for specimens immersed in natural water 6 days, where specimen 1, 2, 3 and 4 were specimen without coating, with powder coating, zinc electroplating and nickel electroplating

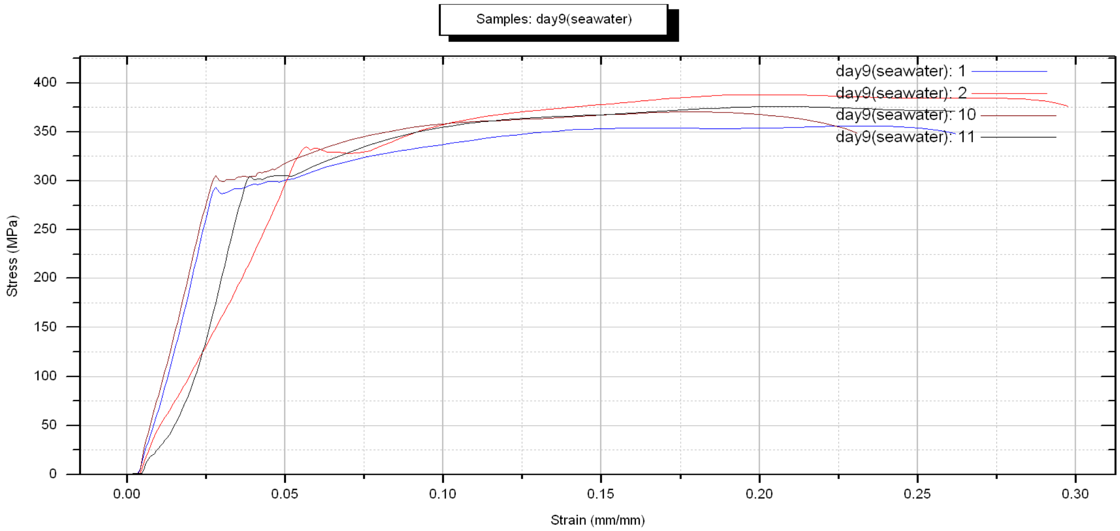


Figure D6: Stress-strain curve of tensile test for specimens immersed in seawater 9 days, where specimen 1, 10, 11 and 2 were specimen without coating, with powder coating, zinc electroplating and nickel electroplating

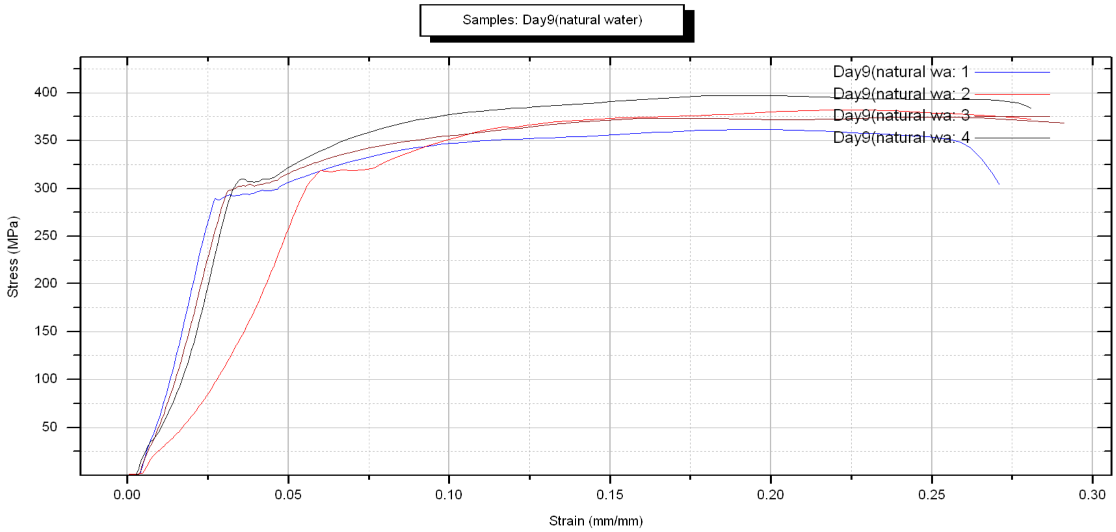


Figure D7: Stress-strain curve of tensile test for specimens immersed in natural water 9 days, where specimen 1, 2, 3 and 4 were specimen without coating, with powder coating, zinc electroplating and nickel electroplating