COMPARISON OF EROSION CORROSION OF TITANIUM AND STAINLESS STEEL IN SEAWATER

MOHAMAD IZWAN BIN ABDUL GHANI

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

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

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FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled “Comparison of Erosion Corrosion of Titanium and Stainless Steel” is written by Mohamad Izwan Bin Abdul Ghani. I have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering.

Mdm.Juliawati Binti Alias Signature
Examiner

SUPERVISOR'S DECLARATION

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

Signature : ....
Name of Supervisor: Mdm.Nor Imrah Binti Yusoff
Position : Lecturer
Faculty of Manufacturing Engineering
Universiti Malaysia Pahang
Date :

STUDENT'S DECLARATION

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

Signature : ....
Name : Mohamad Izwan Bin Abdul Ghani
ID Number: MA08049
Date :

Special thanks to my parents on their support and cares,

En. Hj.Abdul Ghani Bin Lassim
Pn. Hjh.Kelsom Binti Abdul Jalil

Also for my siblings.

Special dedications for my supervisor,

Pn. Nor Imrah Binti Yusoff

On her guiding towards my project

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Thank you all.

ABSTRACT

The application of Stainless steel and Titanium alloy had been rising in marine application that promoted this study to investigate erosion corrosion behaviour for Stainless steel grade 301 and Titanium. Erosion corrosion test were conducted for both material at constant rate velocity, 900 rpm and at ambient temperature in the range 27°C-30°C. The erosion corrosion were carried out by immersing specimens in an aqueous 3.5%NaCl and presence of 10 wt % sand particles. The erosion corrosion tests were done by using electrochemical test which involve oxidation and reduction process. Graphite is use as counter electrode while specimens as working electrode and saturated calomel electrode (SCE) as reference electrode. Potentiodynamic polarization has been carried out by using potentiostat model WPG100i with potential scan rate use is 20 mVs^{-1} and potential range of -0.8V until 0.2V. Analysis of image and surface roughness, were taken before and after erosion corrosion test. Titanium alloy show small pitting form and low value of surface roughness compare to Stainless steel. The full observation on the result from the test shows that corrosion rate of Stainless steel is higher than the corrosion rate for Titanium alloy.

ABSTRAK

Aplikasi keluli tahan karat dan Titanium aloi dalam industri marin semakin mendapat perhatian dan meningkat.Tesis ini mengkaji hakisan karatan akibat pergerakan bendalir yang mempercepatkan pengaratan dari permukaan logam.Ujian untuk proses pengaratan yang melibatkan pergerakan dijalankan dengan menggunakan halaju yang tetap iaitu 900 rpm dengan suhu sekeliling pada suhu bilik iaitu 27^{o}C-30^{o}C.Ujian dijalankan dengan merendam spesimen di dalam larutan akueus 3.5%NaCl dengan kehadiran 10% pasir pantai daripada larutan akueus.Analisis dilakukan dengan menggunakan ujian elektrokimia yang melibatkan proses pengoksidaan dan penurunan.Grafit digunakan sebagai 'counter electrode' ,specimen pula sebagai elektrod yang mengalami proses penurunan manakala 'saturated calomel electrode'(SCE) sebagai elektrod rujukan. Pembelauan dengan menggunakan alat WPG100 potentiostat menggunakan kadar imbasan $20mVs^{-1}$ dan skala voltan ialah -0.8V hingga 0.2V.Analisis kesan daripada pengaratan dan impak yang terhasil daripada pelanggaran pasir ke atas specimen mendapati kadar pengaratan Titanium aloi lebih kurang berbanding dengan keluli tahan karat yang menunjukkan kadar pengaratan lebih tinggi.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY

CHAPTER 4 RESULT AND DISCUSSION

CHAPTER 5 CONCLUSION AND RECOMMENDATION

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

mdd	Mg/ dm2/day
ipy	Inch penetration/ year
mpy	Mils penetration/year
W	Weight loss (mg)
D	Density of metal (g/cm3)
A	Area of specimen (in.^{2})
CO_2	Carbon dioxide
H_2S	Hydrogen sulphide
ϕ	Diameter
N	Newton

LIST OF ABBREVIATIONS

Ti	Titanium
SS	Stainless steel
Cr	Chromium
Zn	Zinc
SCC	Stress Corrosion Cracking
NaCl	Natrium Chloride
CF	Corrosion fatigue
Ni	Nickel
Cu	Copper
Mo	Molybdenum
Ta	Tantalum
Zr	Zirconium
EEC	Erosion-enhanced corrosion
CAE	Corrosion-affected erosion
Wt	Weight
CP	Cathodic protection
SCE	Saturated calomel electrode
HRC	Hardness Rockwell C

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Most commonly used metals are unstable in the atmosphere. These unstable metals are produced by reducing ores artificially, and therefore they tend to return to their original state or to similar metallic compounds when exposed to the atmosphere. Exceptions to this are gold and platinum, which are already in their metal state. Corrosion by its simplest definition is the process of a metal returning to the material's thermodynamic state. For most materials, this means the formation of the oxides or sulphides from which they originally started when they were taken from the earth before being refined into useful engineering materials.

These changes are electrochemical reactions that follow the laws of thermodynamics. Understanding the interactions of materials with their environment now takes on the added dimension of chemistry and electricity. These concepts help explain why corrosion processes are time and temperature dependent. They also establish that the corrosion reactions, or rates, are affected by ion and corrodent concentrations, and explain why some reactions are reversible or controllable while others are not. Corrosion in aqueous solutions is the most common of all corrosion processes.

Water, seawater, and various process streams in industry provide an aqueous medium. Moisture in the atmosphere and water in the soil account for the aqueous corrosion in these media. In all these cases, water is seldom present in pure form. Rather, various salts and gases remain dissolved in it, and their dissociation renders the water somewhat conducting. For all practical purposes, it acts as an electrolyte. The chemical nature of this electrolyte may be acidic, alkaline, or neutral.

Erosion-corrosion is one of tribocorrosion process which includes abrasion-corrosion and cavitation-corrosion for examples. These are not specific form of corrosion but are degradation processes which involve the action of a mechanical process in conjunction with electrochemical corrosion process. The importance of erosion-corrosion in term of cost incurred by industry due to premature material failures. Erosion-corrosion was ranked as the fifth most important degradation mechanism in offshore and chemical sectors.

Erosion-corrosion is associated with a flow-induced mechanical removal of the protective surface film that results in a subsequent corrosion rate increase via either electrochemical or chemical processes. It is often accepted that a critical fluid velocity must be exceeded for a given material. The mechanical damage by the impacting fluid imposes disruptive shear stresses or pressure variations on the material surface and/or the protective surface film. Erosion-corrosion may be enhanced by particles (solids or gas bubbles) and impacted by multi-phase flows. The morphology of surfaces affected by erosion-corrosion may be in the form of shallow pits or horseshoes or other local phenomena related to the flow direction.

1.2 PROBLEM STATEMENT

Study of erosion-corrosion due to failure in marine application such as shaft, propeller and piping because of impingement of sand particles on metals.

1.3 OBJECTIVES OF PROJECT

i. To study the effect of different material to erosion-corrosion behaviour
ii. To study the erosion corrosion impact to material in aqueous slurries

1.4 SCOPES OF PROJECT

i. Comparison of Titanium and Stainless steel
ii. Constant velocity
iii. Investigation of surface roughness change
iv. Surface image analysis using image analyzer

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Corrosion stands for deterioration or damage to material or metal surfaces in an aggressive environment. Corrosion is a chemical or electrochemical oxidation process, in which electron transfer to the environment and lead valence changes from zero to positive values. The environment can be liquid, gas or hybrid-liquefied soil. This environment is called an electrolyte because they have their conductivity for electron transfer.

Corrosion also defines as term of attack on a metallic material by reaction with its environment. The concept of corrosion not only limited to the metallic materials, but also attack on non-metallic materials. But, in this study, we will focus on metallic material corrosion. Corrosion of metallic materials can be divided into three main groups (Metals Handbook, 1987):

1. Wet corrosion, where the corrosive environment is water with dissolved species. The liquid is an electrolyte and the process is typically electrochemical.
2. Corrosion in other fluids such as fused salts and molten metals.
3. Dry corrosion, where the corrosive environment is a dry gas. Dry corrosion is also frequently called chemical corrosion and the best-known example is high temperature corrosion.

2.1.1 Wet corrosion

Wet corrosion is corrosion that cause by exposure of material to aqueous solution. The mechanism of wet corrosion is show in Figure 2.1.

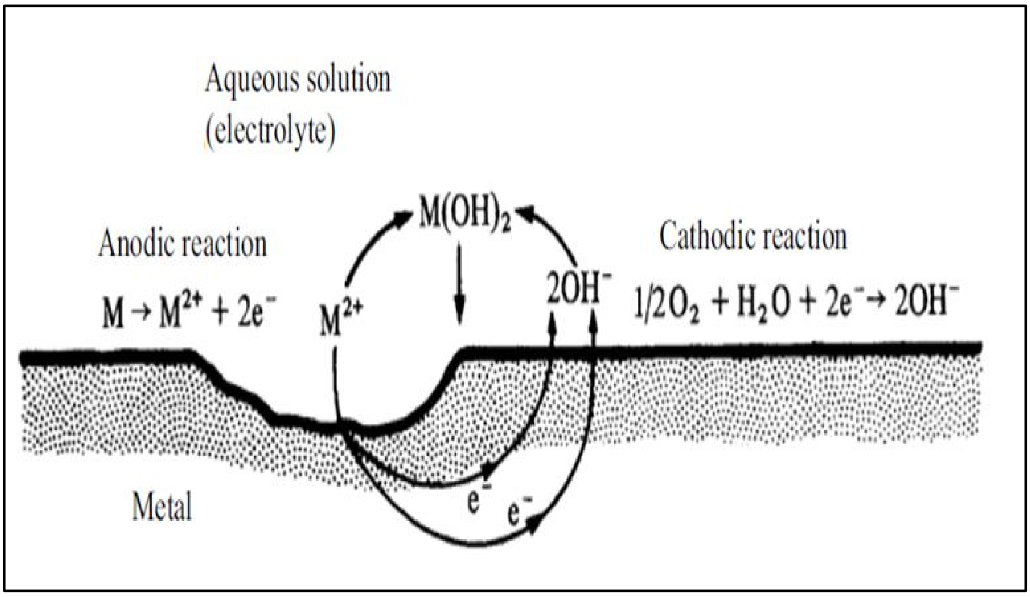


Figure 2.1: Wet corrosion of a divalent metal M in an electrolyte containing oxygen

Source: Einar Bardal (2003)

The dissolution process in Figure 2.1 is known as wet corrosion and electrochemical mechanisms normally. In electrochemistry aspects, corrosion process consists of anodic and cathode reactions. In the anodic reaction (oxidation), the metal dissolved and transferred to the solution as M^{2+} ions. The reaction of oxygen reduction in cathode is example. It is seen that the process of making electrical circuits without the collection of any charges. Electrons that produced from anodic reaction are carried out through the metal to the cathode where they are involved in the cathode reaction. The conditions necessary for the process of corrosion is that the environment is fluid running (electrolytes) that is in contact with metal. Electrical circuit is closed by the flow of ions through the electrolyte (Einar Bardal, 2003).

2.2 TYPE OF CORROSION

Although there is only one basic mechanism of corrosion, electrochemical cell, there are certain types of rust or corrosion that can occur. Each attack has a certain order form anodes and cathode and the erosion that occurs with a specific location and pattern. The types of the most important corrosion (Einar Bardal, 2003):

1. Uniform (general) corrosion
2. Galvanic (two–metal) corrosion
3. Thermogalvanic corrosion
4. Crevice corrosion (including deposit corrosion)
5. Pitting corrosion
6. Intergranular corrosion (including exfoliation)
7. Erosion and abrasion corrosion
8. Cavitation corrosion
9. Fretting corrosion
10. Stress corrosion cracking
11. Corrosion fatigue

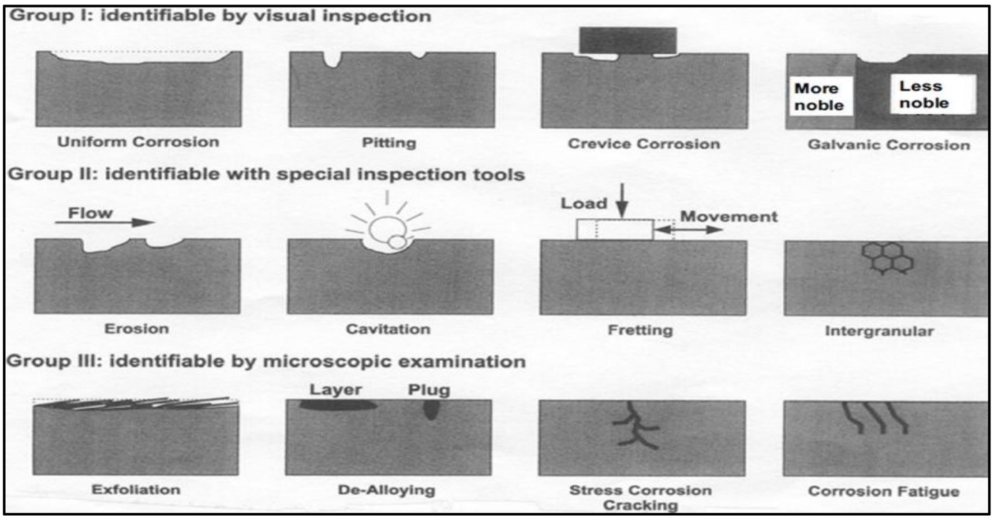
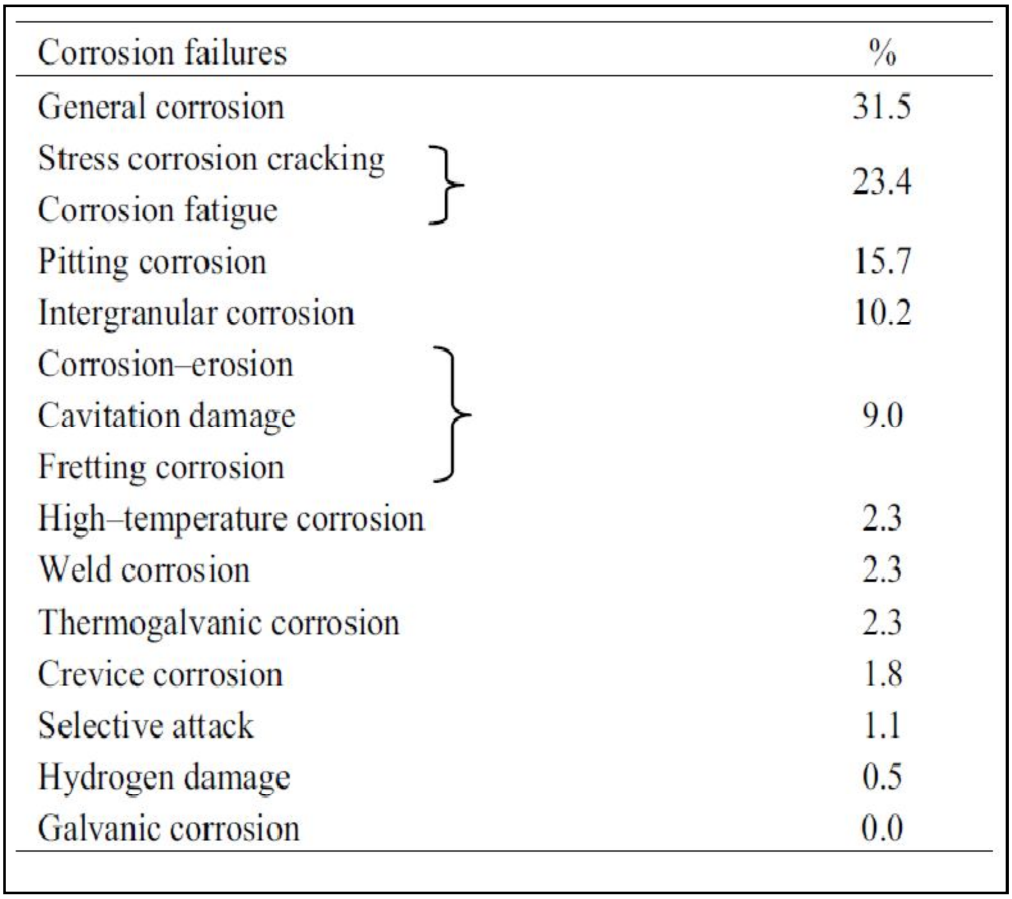


Figure 2.2: Main forms of corrosion grouped by their ease of recognition

Source: Roberge PR (1977)

Figure 2.3 shows that data collect for corrosion occur done by Japan oil refineries and petrochemical industries. More than 80% of material failure due to corrosion (wet and dry). The high proportion of stress corrosion cracking/corrosion fatigue is particularly noticed.



Corrosion failures	%
General corrosion	31.5
Stress corrosion cracking	23.4
Corrosion fatigue	
Pitting corrosion	15.7
Intergranular corrosion	10.2
Corrosion–erosion	9.0
Cavitation damage	
Fretting corrosion	
High–temperature corrosion	2.3
Weld corrosion	2.3
Thermogalvanic corrosion	2.3
Crevice corrosion	1.8
Selective attack	1.1
Hydrogen damage	0.5
Galvanic corrosion	0.0

Figure 2.3: Material failures over a two-year period (56.9 % corrosion and 43.1% mechanical)

Source: Pludek VR. (1977)

2.2.1 Uniform (general) corrosion

Type of corrosion which attack on material surface distributed uniformly over the surface. This process will lead to relatively uniform thickness reduction of surface that open to reaction (Nestor Perez, 2004).

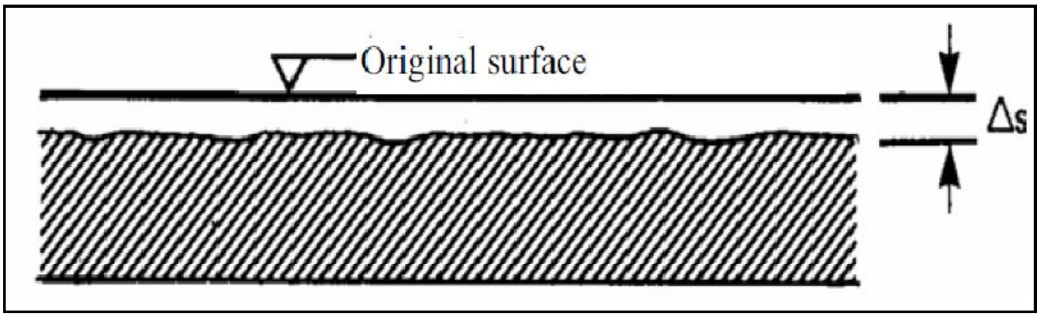


Figure 2.4: Uniform (general) corrosion

Source: Einar Bardal (2003)

Uniform corrosion is assumed to be the most common form of corrosion and particularly responsible for most of the material loss. Traditionally, however, it is not recognized as a dangerous form of corrosion, because:

1. Prediction of thickness reduction rate can be done by means of simple tests.
2. Corrosion allowance can be added, taking into account strength requirements and lifetime.

2.2.2 Galvanic corrosion

Galvanic corrosion of either chemical or electrochemical corrosion .This is due to the potential difference between two different metals connected through the circuit for current flow occurs from the more active metal (more negative potential) to the more noble metal (the more positive potential). There also must have an electrolytic connection between the metals so that close circuit is established (Nestor Perez, 2004).

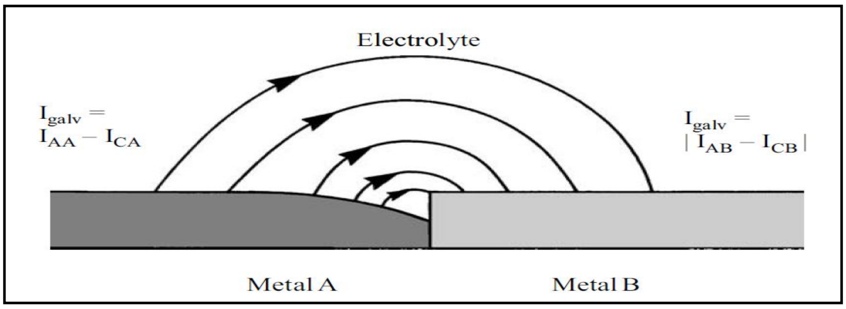


Figure 2.5: Galvanic corrosion

Source: Einar Bardal (2003)

Figure 2.5 show the mechanism of galvanic corrosion. The closer the standard potentials of two metals the weaker the galvanic effect and vice versa.

2.2.3 Thermogalvanic corrosion

When the material in a corrosive environment subject to temperature gradients, galvanic element may arise, causing what we call thermo-galvanic corrosion. Typically, the hot surface is form the anode and a cold is cathode (Figure 2.6).This is because the anodic properties of the material depend on temperature. In addition, the characteristics of the environment along the surface of the metal will also vary due to different temperatures and different temperature gradients normal to metal surfaces. This often affects the cathode reaction, which also must be taken about the corrosion of analysis (Einar Bardal, 2003).

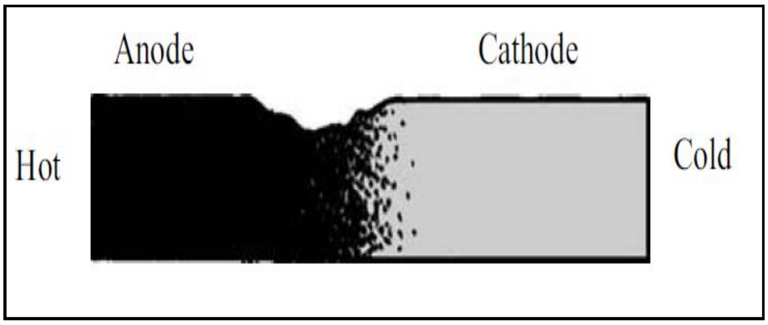


Figure 2.6: Thermogalvanic corrosion

Source: Einar Bardal (2003)

2.2.4 Crevice corrosion

This is a localized corrosion which concentrated at gap that big enough for the liquid to penetrate cracks and narrow enough for the liquid to be stagnant. For example, given the conditions under which corrosion occurs at flange gaskets, nail and screw head and the edge of the paint coating and many other examples can be studied for this type of corrosion.

Typical crevice corrosion occur between the passive material before hand, or materials that can be easily passivated such as stainless steel, aluminium, unalloyed or low alloy steels in a more or less alkaline, the material is exposed to an aggressive species such as chloride can lead to local breakdown of surface oxide layer. Materials such as stainless steel can be a lot of conventional attack by corrosion deposits in stagnant waters or slow flowing. The critical velocity of about 2 m / s has been assumed, but corrosion cracks can also occur at high velocity. The most common form of corrosion observed in environments containing chloride, but can also occur in other salt solutions (Ijsseling, 1979–1998).

The mechanism of crevice corrosion is electrochemical in nature and illustrated in Figure 2.7. It requires a prolong time to start the metal oxidation process, but it may be accelerated afterwards.

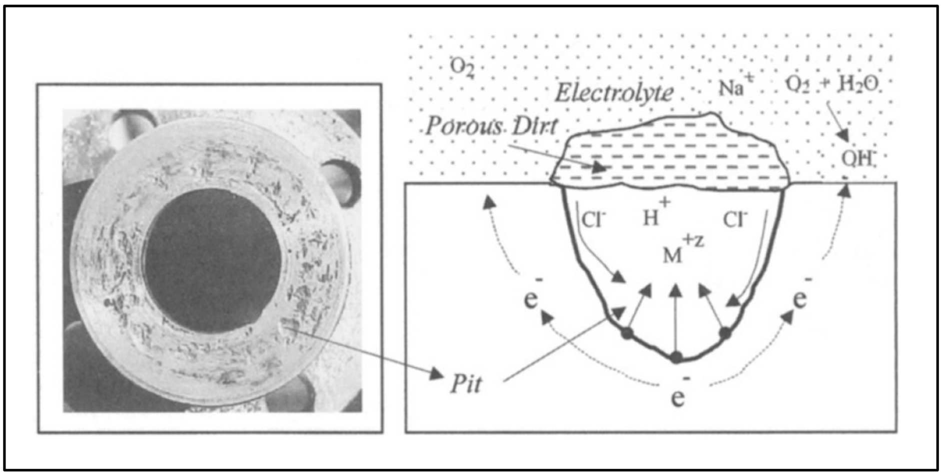


Figure 2.7: Crevice corrosion. a) Stainless steel flange b) mechanisms

Source: M.G. Fontana (1986)

2.2.5 Pitting corrosion

Pitting corrosion occurs on more or less passivated metal and alloys in environment containing chloride, bromide, iodide or pechlorate ion when electrode potential exceed a critical value, the pitting potential, which depend on various condition.

This form of corrosion is characterized by narrow pits with a radius of the same order of magnitude as, or less than, the depth. The pits may be of different shape, but a common feature is the sharp boundary as shown in Figure 2.8. Pitting is a dangerous form of corrosion since the material in many cases may be penetrated without a clear warning (because the pits often are narrow and covered) and the pit growth is difficult to predict. This is connected to the fact that the extent and the intensity of pitting corrosion are difficult to measure because the number and size of pits (diameter and depth) vary from region to region and within each region (Einar Bardal, 2003).

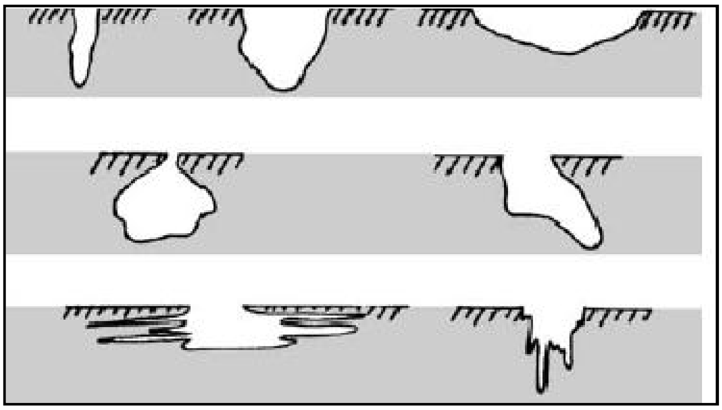


Figure 2.8: Different shapes of corrosion pits

Source: Annual Book of ASTM Standards Part 10, Philadelphia

2.2.6 Intergranular corrosion

Intergranular corrosion is localized attack on or at grain boundaries with the corrosion in other parts of the surface material. The attack propagates into the material. This is a dangerous form of corrosion because cohesive forces between grains cannot withstand the tensile stress and fracture can occur without warning.

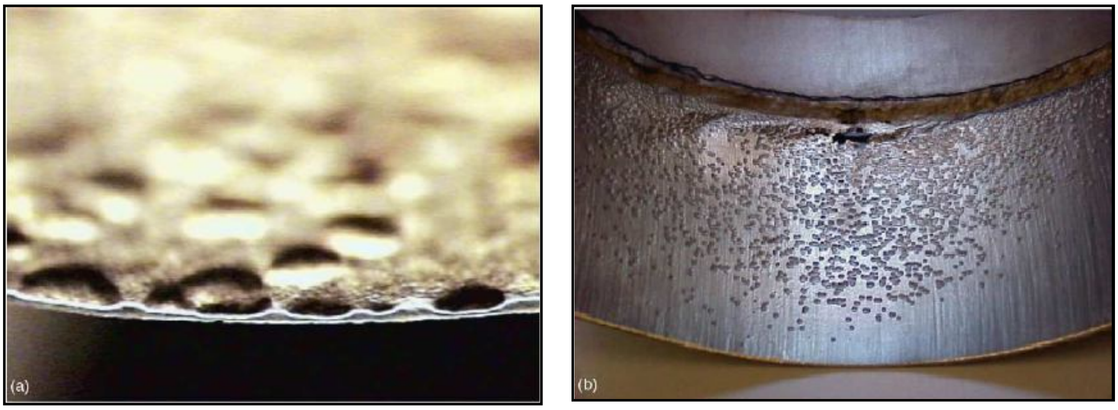
Grains may fall out, leaving pits or grooves, but this may not be particularly important. The general cause of intergranular corrosion is the presence of galvanic elements due to differences in concentration of impurities or alloying elements between the material in or at the grain boundaries and the interior of the grains (Einar Bardal, 2003):

a) Impurities segregated to the grain boundaries (for example, causing the AlFe secondary phase aluminium).
b) Larger amount of a dissolved alloying element at the grain boundaries (for example Zn in brass).
c) Smaller amount of a dissolved alloying element at the grain boundaries (for example Cr in stainless steel).

2.2.7 Erosion and abrasion corrosion

Erosion corrosion is acceleration in the rate of corrosion attack in metal due to the relative motion of a corrosive fluid and a metal surface (Einar Bradal, 2003). In piping, the increased of turbulence cause by pitting on the internal surfaces of a tube can result in rapidly increasing erosion rates and eventually a leak. Erosion-corrosion also can cause from faulty workmanship. For example, burrs left at cut tube ends can upset smooth water flow, because localized turbulence and high flow velocities, resulting in erosion-corrosion. A combination of erosion and corrosion can lead to extremely high pitting rates.

Erosion-corrosion is most prevalent in soft alloys such as copper, aluminium and lead alloys. Alloys which form a surface film in a corrosive environment commonly show a limiting velocity above which corrosion rapidly accelerates. With the exception of cavitation, flow induced corrosion problem are generally termed erosion-corrosion, encompassing flow enhanced dissolution and impingement attack. The fluid can be aqueous or gaseous, single or multiphase (Einar Bardal, 2003).



a) b)

Figure 2.9: Macrographs of in-service failure of AISI 304L pipe (a) Inner wall thinning (b) Wall thinning and leaking close to the weld bead

Source: Einar Bardal (2003)

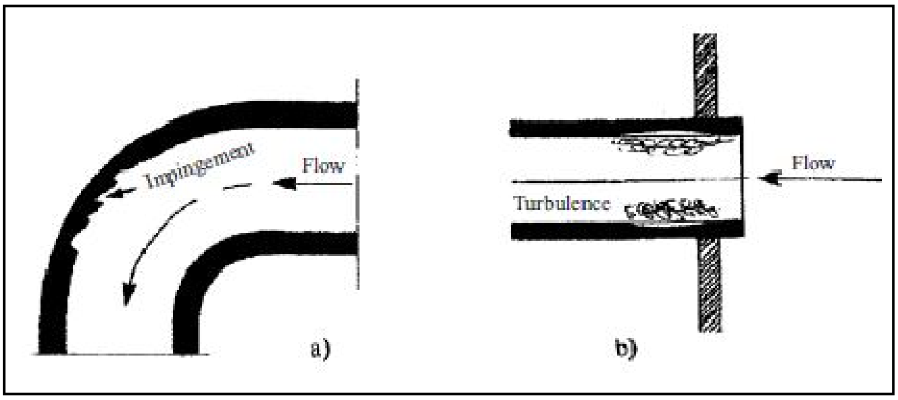


Figure 2.10: Impingement in piping during flow a) Impingement and b) turbulence corrosion

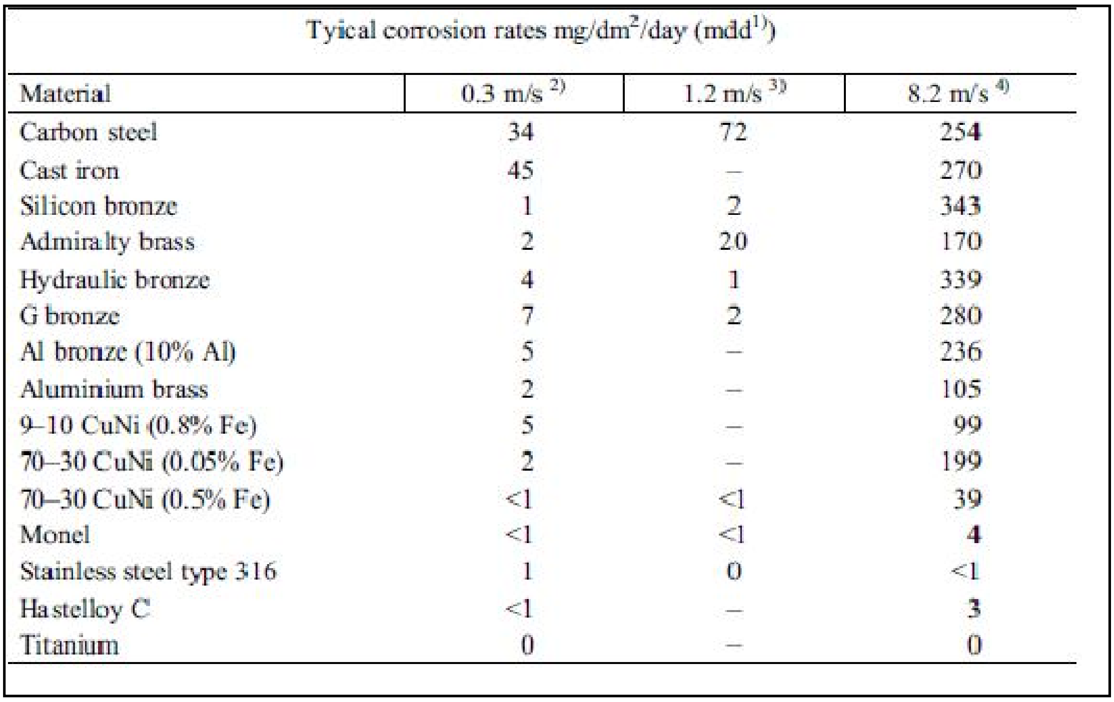
Source: Einar Bradal (2003)

Erosion corrosion and abrasion can be divided into three types, a), b) and c), as described below. The first two types of corrosion-erosion, while type c) is regarded as abrasion erosion. All three types may overlap each other and partially coincides in the same system (Einar Bardal, 2003).

a) Impingement corrosion, often occurring in systems with two-phase or multiphase flow, particularly where the flow is forced to change direction. Numerous impacts from liquid drops in a gas stream, or particles or gas bubbles in a liquid flow lead to pits with a direction pattern as shown in Figure 2.10 a).
b) Turbulence corrosion, which occurs in areas with particularly strong turbulence such as the inlet end of heat exchanger tubes Figure 2.10 b).
c) Increased corrosion due to removal of corrosion products by wear due to particles moving along and in contact with the corroding surface, or by wear between components in moving contacts with each other.

Reasonably, the corrosion form is typical at relatively high velocities between the material surface and the fluid, and it is particularly intensive in cases of two-phase or multiphase flow for example liquid–gas and liquid–solid particle flow. Components often liable to erosion corrosion are propellers, pumps, turbine parts, valves, heat exchanger tubes, nozzles, bends, and equipment exposed to liquid sputter or jets.

Most sensitive materials are those normally protected by corrosion products with inferior strength and adhesion to the substrate such as lead, copper and its alloys, steel, and under some conditions aluminium/aluminium alloys. Stainless steel, titanium and nickel alloys are much more resistant because of a passive surface film with high strength and adhesion (Einar Bardal, 2003).



Tyical corrosion rates mg/dm^2/day (mdd$^{1)}$)

Material	0.3 m/s $^{2)}$	1.2 m/s $^{3)}$	8.2 m/s $^{4)}$
Carbon steel	34	72	254
Cast iron	45	–	270
Silicon bronze	1	2	343
Admiralty brass	2	20	170
Hydraulic bronze	4	1	339
G bronze	7	2	280
Al bronze (10% Al)	5	–	236
Aluminium brass	2	–	105
9–10 CuNi (0.8% Fe)	5	–	99
70–30 CuNi (0.05% Fe)	2	–	199
70–30 CuNi (0.5% Fe)	<1	<1	39
Monel	<1	<1	4
Stainless steel type 316	1	0	<1
Hastelloy C	<1	–	3
Titanium	0	–	0

Figure 2.11: Corrosion rates of materials in seawater at different flow velocities (data from International Nickel Co)

Source: Fontana and Greene (1986)

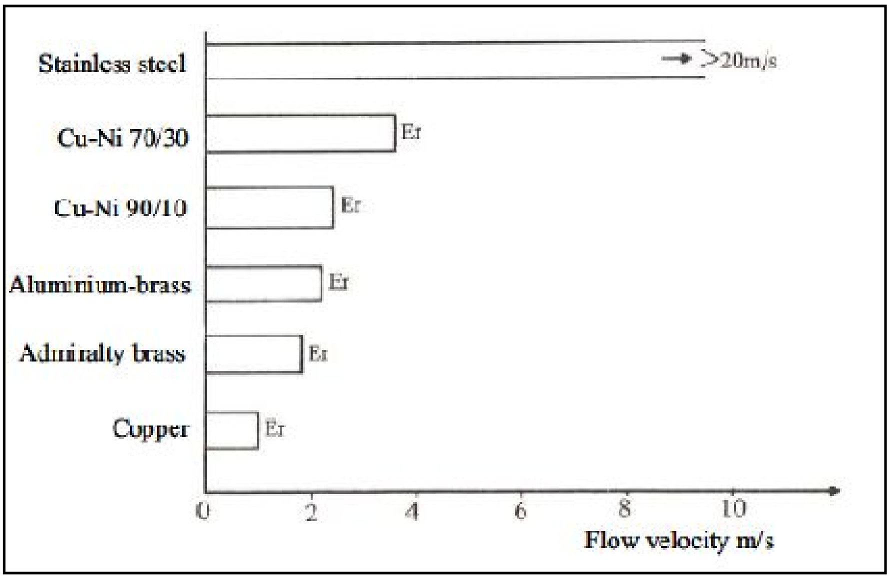
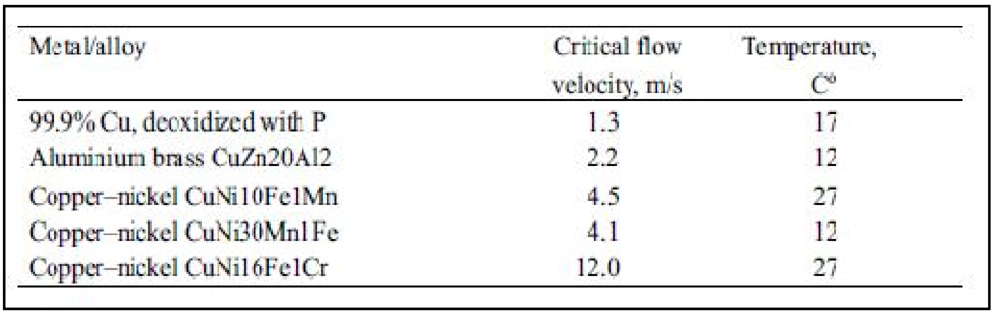


Figure 2.12 Critical velocities for erosion corrosion of different materials in seawater

Source: Gemmel G and Nording S. Monit (1980)



Metal/alloy	Critical flow velocity, m/s	Temperature, C°
99.9% Cu, deoxidized with P	1.3	17
Aluminium brass CuZn20Al2	2.2	12
Copper–nickel CuNi10Fe1Mn	4.5	27
Copper–nickel CuNi30Mn1Fe	4.1	12
Copper–nickel CuNi16Fe1Cr	12.0	27

Figure 2.13: Critical velocities for copper and copper alloys in seawater

Adapted from: Efird

Figure 2.11 does not give any clear information about the critical velocity, but it shows that the threshold exists for copper alloys in the range of velocities represented in the table (1.2- 8.2 m / s). More specifically, the two Figure 2.12 and Figure 2.13 show an example of the critical velocity for erosion corrosion. They depend on the composition of the environment, temperature, geometry, history of exposure, the exact composition and treatment materials.

In connection with Figure 2.12 it can be mentioned that the stainless steel shows very good resistance to corrosion in the erosion of pure liquid flows at high velocity, while a number of ferritic and austenitic ferritic steels are attacked less than the austenite if the liquid is carrying particles the solid. The data in Figure 2.13 is derived from work by Efird, states that for each alloy in certain environments, there is a critical shear stress between the liquid and the surface material. When this excess shear stress, the surface films produced and the rate of corrosion increases significantly (Einar Bradal, 2003).

2.2.8 Cavitation corrosion

This form of erosion is closely related erosion corrosion, but the appearance of attack as shown in Figure 2.14 and Figure 2.15 differs from the erosion corrosion attack. While those with a pattern that reflects the direction of flow, cavitations attacks in the growing hole perpendicular to the surface. The holes are often localized close to each other or planted together in smaller or larger, making the surface rough, spongy surface.

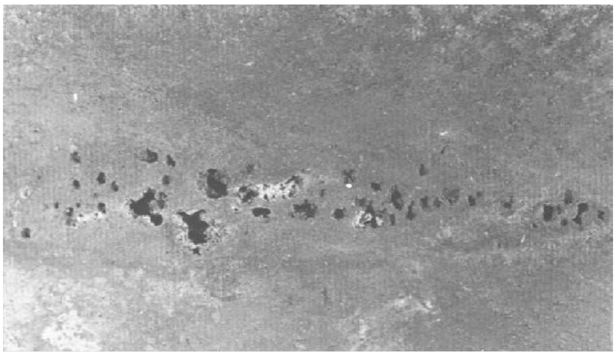


Figure 2.14: External cavitation corrosion on a cast iron cylinder lining in a diesel engine

Source: Abusland, Sintef Corrosion Centre

Cavitation corrosion occurs at high flow velocities and fluid dynamic conditions causing large pressure variations, as often is the case for water turbines, propellers, pump rotors and the external surface of wet cylinder linings in diesel engines. Vapour bubbles formed in low-pressure zones, or at moments of low pressure at the actual positions, collapse very rapidly when they suddenly enter a high-pressure zone or high-pressure moment. When this happens close to the metal surface, the bubble collapse causes a concentrated and intense impact against the metal, with the induction of high local stress and possibly local plastic deformation of the material. Parts of any protecting film are removed. Repeated impacts may lead to microscopic fatigue and crack formation, and subsequent removal of particles from the material itself. During this process, the material is strongly activated at the attacked points, and high local corrosion rates are possible (Einar Bardal, 2003).

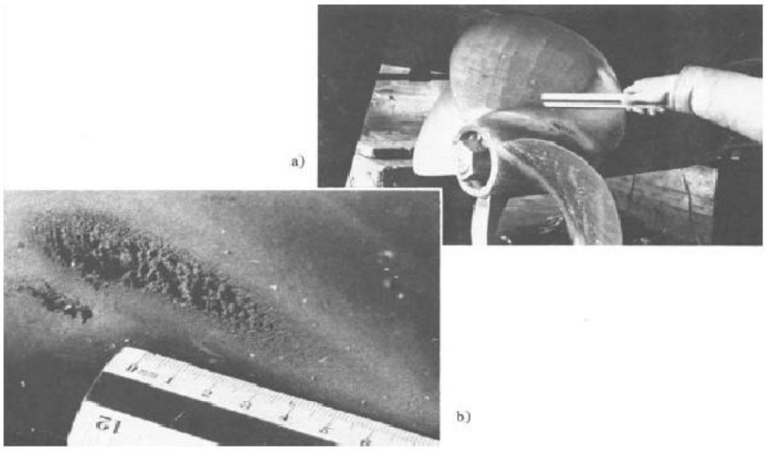


Figure 2.15: a) Cavitations corrosion on the propeller of a high-speed passenger ship b) Close up of the damages

Source: T.E. Hammervold and O Saetre

2.2.9 Fretting corrosion

Fretting wear occurs at the interface between two closely fitting components when they are subjected to repetitive motion is relatively small. The relative motion may vary from less than one nanometre to several micrometers in amplitude.

Vulnerable objects are shrink fits, press fits, bolted joints, and other assemblies where the interface is under load.

Figure 2.16 show critical position at the end of the collar. Sometimes, the attack was serious, because it can lead to macroscopic motion between the parts, or fatigue cracks can develop in the shaft.

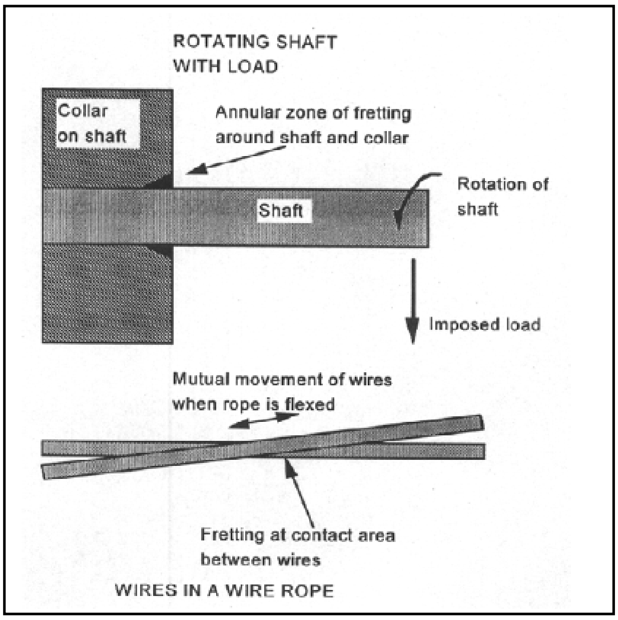


Figure 2.16: Location of fretting wear in some common engineering components

Source: Batchelor (1999)

2.2.10 Stress Corrosion Cracking (SCC)

Stress corrosion cracking can be defined as crack formation due to simultaneous effects of static tensile stresses and corrosion. The tensile stresses may originate from external load, centrifugal forces or temperature changes, or they may be internal stresses induced by cold working, welding or heat treatment. The cracks are mainly formed in planes normal to the tensile stresses, and propagate intergranularly or transgranularly, more or less branched. If they are not detected in time, they will cause fast, unstable fracture (Einar Bardal, 2003).

Macroscopically, the crack surfaces may look brittle and discoloured, dull or darkened by oxide layers. The initiation site may be discovered as a pit (formed by pitting or deposit corrosion) or as a defect caused by forming or machining. On parts in service it may, however, be difficult to discover cracks, because they are narrow and filled or covered by corrosion products (Einar Bradal, 2003).

Figure 2.17 shows stress corrosion cracks in a pipe of stainless steel AISI 304 that has carried glucose containing about 16% water, 0.02–0.03% NaCl, with a pH of 5.2. The cracks have developed from small corrosion pits in the weld (associated with small weld defects) on pipe sections heated by a heating cable.

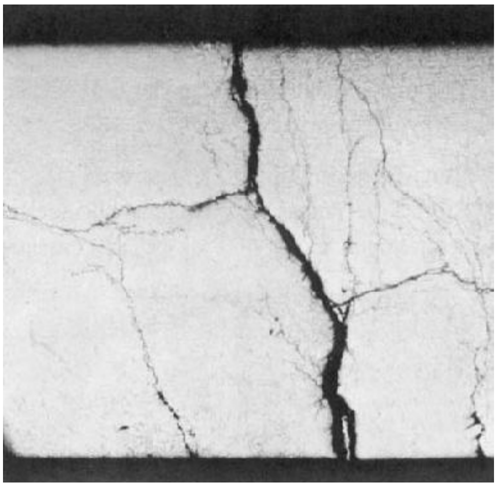


Figure 2.17: Stress corrosion cracks in tubes of AISI 304 steel

Source: J.M. Drugli, SINTEF Corrosion Centre

2.2.11 Corrosion fatigue

Corrosion fatigue (CF) is the formation of cracks caused by the different stress combined with corrosion. In addition, it can be defined as the fatigue induced and accelerated by corrosion. The problem is caused by tensile stress, just as it is for SCC. The difference between the two forms of rural decline is that the CF to develop under different stresses and SCC under static stress.

Typical fatigue fractures that have occurred in non-corrosive environments show a large smooth crack surface area where the crack has grown by fatigue and an (often smaller) area with a rough and crystalline surface formed by fast fracture when the maximum stress reached the ultimate strength. Characteristic beach marks on the smooth part show the form and position of the crack front at different stages. Fatigue fractures of cathodically protected steel in seawater are also characterized by such beach marks. An example is shown in Figure 2.18 (Einar Bardal, 2003).

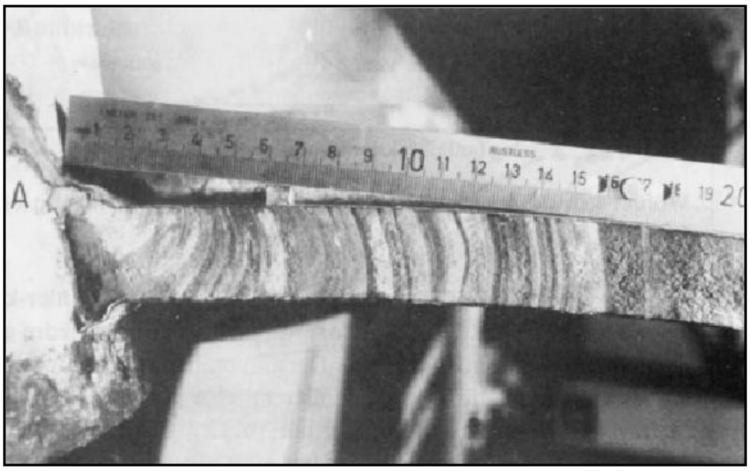


Figure 2.18: Crack surface after fatigue of steel in seawater under cathodic protection

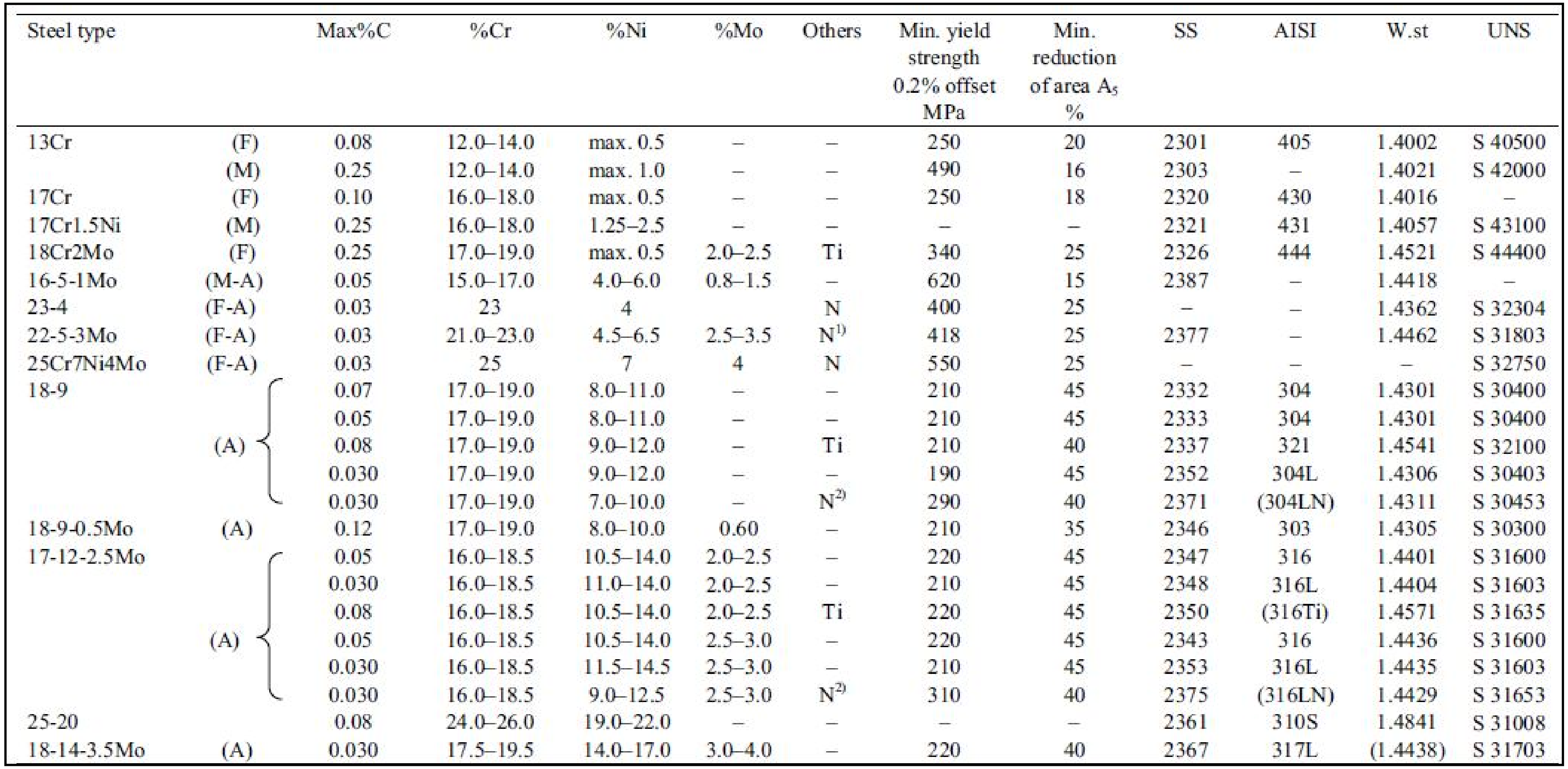
Source: Photo: B. Lian, Statoil

2.3 MATERIAL PROPERTIES

2.3.1 Stainless Steels

A survey of different stainless steels is given in Figure 2.19, comprising composition and structure, yield strength, reduction of area, and numbers of various standards. The corrosion resistance of stainless steel is due to passivation by a surface film of chromium oxide.

In natural seawater, the risk of corrosion is high for most stainless steels. This is due to the effects of the bacterial slime layer that is usually formed in this environment. On stainless steels, slime layer is usually formed, and below 30–40°C this slime layer may have a dramatic effect (Einar Bardal, 2003).



Steel type		Max%C	%Cr	%Ni	%Mo	Others	Min. yield strength 0.2% offset MPa	Min. reduction of area A_5 %	SS	AISI	W.st	UNS
13Cr	(F)	0.08	12.0–14.0	max. 0.5	–	–	250	20	2301	405	1.4002	S 40500
	(M)	0.25	12.0–14.0	max. 1.0	–	–	490	16	2303	–	1.4021	S 42000
17Cr	(F)	0.10	16.0–18.0	max. 0.5	–	–	250	18	2320	430	1.4016	–
17Cr1.5Ni	(M)	0.25	16.0–18.0	1.25–2.5	–	–	–	–	2321	431	1.4057	S 43100
18Cr2Mo	(F)	0.25	17.0–19.0	max. 0.5	2.0–2.5	Ti	340	25	2326	444	1.4521	S 44400
16-5-1Mo	(M-A)	0.05	15.0–17.0	4.0–6.0	0.8–1.5	–	620	15	2387	–	1.4418	–
23-4	(F-A)	0.03	23	4		N	400	25	–	–	1.4362	S 32304
22-5-3Mo	(F-A)	0.03	21.0–23.0	4.5–6.5	2.5–3.5	$N^{1)}$	418	25	2377	–	1.4462	S 31803
25Cr7Ni4Mo	(F-A)	0.03	25	7	4	N	550	25	–	–	–	S 32750
18-9	(A)	0.07	17.0–19.0	8.0–11.0	–	–	210	45	2332	304	1.4301	S 30400
		0.05	17.0–19.0	8.0–11.0	–	–	210	45	2333	304	1.4301	S 30400
		0.08	17.0–19.0	9.0–12.0	–	Ti	210	40	2337	321	1.4541	S 32100
		0.030	17.0–19.0	9.0–12.0	–	–	190	45	2352	304L	1.4306	S 30403
		0.030	17.0–19.0	7.0–10.0	–	$N^{2)}$	290	40	2371	(304LN)	1.4311	S 30453
18-9-0.5Mo	(A)	0.12	17.0–19.0	8.0–10.0	0.60	–	210	35	2346	303	1.4305	S 30300
17-12-2.5Mo	(A)	0.05	16.0–18.5	10.5–14.0	2.0–2.5	–	220	45	2347	316	1.4401	S 31600
		0.030	16.0–18.5	11.0–14.0	2.0–2.5	–	210	45	2348	316L	1.4404	S 31603
		0.08	16.0–18.5	10.5–14.0	2.0–2.5	Ti	220	45	2350	(316Ti)	1.4571	S 31635
		0.05	16.0–18.5	10.5–14.0	2.5–3.0	–	220	45	2343	316	1.4436	S 31600
		0.030	16.0–18.5	11.5–14.5	2.5–3.0	–	210	45	2353	316L	1.4435	S 31603
		0.030	16.0–18.5	9.0–12.5	2.5–3.0	$N^{2)}$	310	40	2375	(316LN)	1.4429	S 31653
25-20		0.08	24.0–26.0	19.0–22.0	–	–	–	–	2361	310S	1.4841	S 31008
18-14-3.5Mo	(A)	0.030	17.5–19.5	14.0–17.0	3.0–4.0	–	220	40	2367	317L	(1.4438)	S 31703

Figure 2.19: Composition, mechanical properties and standard numbers of stainless steels

Source: Jernkontoret, 1979; Sandvik Steel & Avesta Sheffield (1994)

2.3.2 Titanium

Titanium is an interesting material but high cost material, so that not been particularly widespread in use, but the number and extent of applications are increasing. For demanding conditions, selection of titanium may be an economic solution because it has a series of good properties. Its primary field of application has been in the aerospace industry. For examples are compressor wheel discs, blades in gas turbines and more applications. It has traditionally been used also in the chemical industry. Its use in oil industry has increased due to the properties.

The corrosion properties of titanium versus the actual environments are superior to the properties of competing materials. The experience with titanium in heat exchangers is excellent, both in nuclear power plants, offshore installations and process industry. The material resists seawater up to $130^{o}C$.

For oil production systems it is of interest that CO_2 is not aggressive versus titanium and that neither hydrocarbons nor sulphides or chlorides usually cause corrosion on this material. Some attacks have been detected on titanium exposed to solutions with high H_2S concentration, but on most oil fields this has not been a problem. The material is resistant to hypochlorites and wet chlorines, as well as nitric acids including hot acids. In the process industry, titanium has performed well in pumps, valves, gas purification plants and pipelines (Fontana MG Greene, 1978, 1986).

Titanium alloys constitute the group of metallic materials showing the highest strength/weight ratio. A grade widely used under corrosive conditions is commercially pure titanium, which has yield strength in the range 300–400 MPa, but far stronger alloys exist. The fatigue properties are also beneficial. For example the fatigue strength of material without surface notches in air at 107 cycles may be about 60% of the ultimate tensile strength, a percentage that is high compared with steel (Fontana MG Greene 1978, 1986).

Here, it must also be taken into account that the wall thickness of titanium can be less, partly because of higher strength and partly due to superior corrosion properties compared with Cu alloys. It should also be noted that, at low and moderate flow velocities, the biological growth tendency is larger on titanium than on copper materials, which may, however, be counteracted by chlorination of the water or allowing higher velocities.

Titanium alloys are sensitive to absorption of hydrogen, which makes the materials brittle. Contact with any corroding material that can be the site for hydrogen evolution must therefore be avoided. Ti should not be used in pure hydrochloric, sulphuric and hydrofluoric acids or dry chlorine.

Titanium forms a stable, protective, strongly adherent oxide film. This film forms instantly when a fresh surface is exposed to air or moisture. Addition of alloying elements to titanium affects the corrosion resistance because these elements affect the composition of the oxide film. The oxide film of titanium is very thin and is attacked by only a few substances, the most notable of which is hydrofluoric acid. Because of its strong affinity to oxygen, titanium is capable of healing ruptures in this film almost instantly in any environment when a trace of moisture is present (Philip A. Schweitzer, 2010).

2.4 CORROSION RATES MEASUREMENT

Measurement of corrosion rates may be necessary for the evaluation and selection of materials for a particular environment, given certain applications, or for metal or old or new alloys to determine the environment in which it is appropriate. Typically, a corrosive environment to make a less aggressive treatment and some measure of the rate of corrosion in an environment that is not treated will reflect the effectiveness of the treatment. In addition, a measurement of corrosion rates is also important in the study of corrosion mechanisms.

2.4.1 Corrosion Rate Expressions

Corrosion involves dissolution of metal, as a result of which the metallic part loses its mass (or weight) and becomes thinner. Corrosion rate expressions are therefore based on either weight loss or penetration into the metal. The most widely used weight expression, based on weight loss, is mg/ dm2/day (mdd) and the rate expression on penetration is inch penetration/ year (ipy) and mils penetration/year (mpy). One mil is one thousandth of an inch.

The last expression is very convenient because it does not involve a decimal point or zeroes. Thus, 0.002 ipy is simply expressed as 2 mpy. The expression is readily calculated from the weight loss of the metal specimen during the corrosion test by the empirical formula:

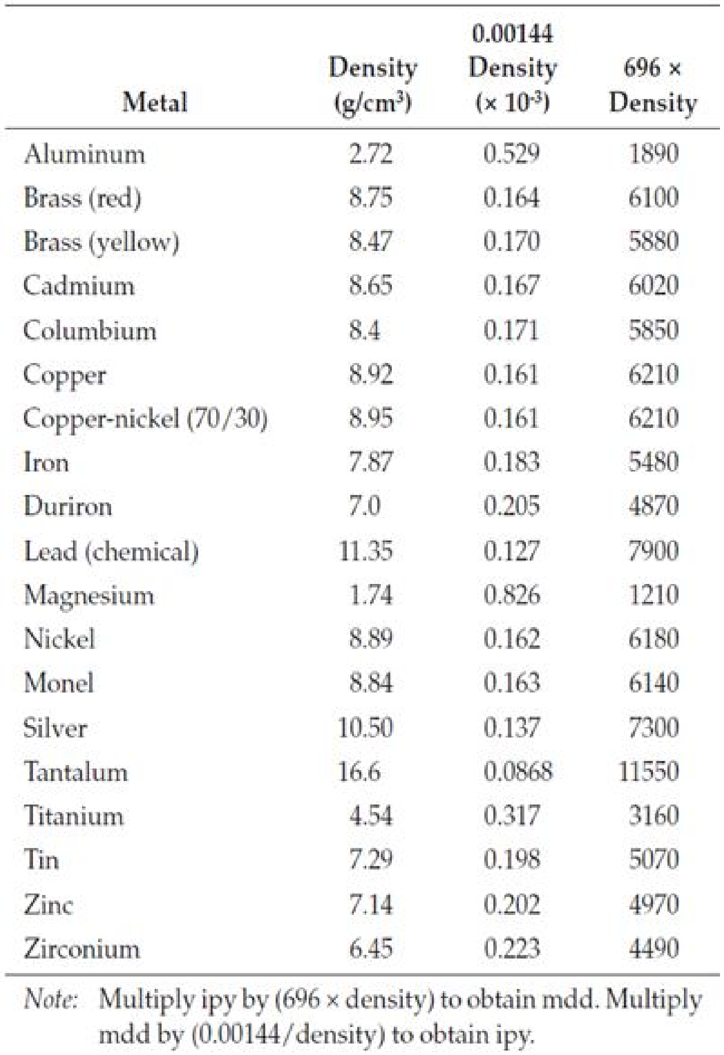
$$\text{mpy} = \frac{534W}{DAt} \qquad \textbf{(2.1)}$$

where W is weight loss (mg), D is density of metal (g/cm3), A is area of specimen (in.^{2}), t is exposure time (h), and mdd and mpy are convertible through the following multiplying factors:

$$\text{mpy} = \frac{1.44\ \text{mdd}}{\text{density}} \qquad \textbf{(2.2)}$$

$$\text{mdd} = \text{mpy}\ (0.696)\ (\text{density}) \qquad \textbf{(2.3)}$$

Conversion factors for the above equations are given in Figure 2.20.



Metal	Density (g/cm³)	0.00144 Density (× 10⁻³)	696 × Density
Aluminum	2.72	0.529	1890
Brass (red)	8.75	0.164	6100
Brass (yellow)	8.47	0.170	5880
Cadmium	8.65	0.167	6020
Columbium	8.4	0.171	5850
Copper	8.92	0.161	6210
Copper-nickel (70/30)	8.95	0.161	6210
Iron	7.87	0.183	5480
Duriron	7.0	0.205	4870
Lead (chemical)	11.35	0.127	7900
Magnesium	1.74	0.826	1210
Nickel	8.89	0.162	6180
Monel	8.84	0.163	6140
Silver	10.50	0.137	7300
Tantalum	16.6	0.0868	11550
Titanium	4.54	0.317	3160
Tin	7.29	0.198	5070
Zinc	7.14	0.202	4970
Zirconium	6.45	0.223	4490

Note: Multiply ipy by (696 × density) to obtain mdd. Multiply mdd by (0.00144/density) to obtain ipy.

Figure 2.20: Conversion Factors from Inches per Year (ipy) to Milligrams per Square Decimeter per Day (mdd)

Source: Philip A. Schweitzer (2010)

2.5 FACTORS AFFECTING CORROSION

Temperature can have an enormous influence on the erosion process. This is not unexpected because it is an electrochemical reaction and the reaction rate increased with increasing temperature. There is an additional influence on corrosive erosion other than itself. Relative velocity between the components and the media can have a direct effect on the rate of erosion. In some circumstances, increase the velocity of more surface corrosive metals will increase the rate of corrosion.

When concentration polarization occurs, the increased velocity of the media will disperse the concentrating species. However, with passive materials, increasing the velocity can actually result in lower corrosion rates. This occurs because the increased velocity shifts the cathodic polarization curve such that it no longer intersects the anodic polarization curve in the active corrosion region, as shown in Figure 2.20 (Philip A. Schweitzer, 2010).

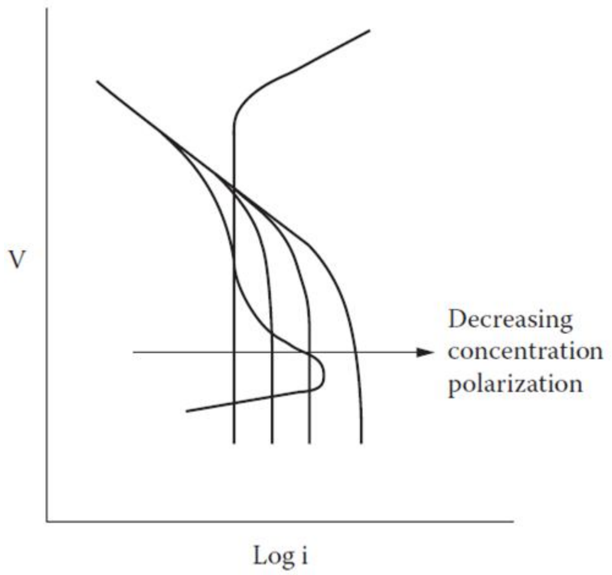


Figure 2.21: Increased corrodent velocity can shift the cathodic polarization curve such that passive behaviour can be induced

Source: Philip A. Schweitzer (2010)

Component surface finish also has an impact on the mode and extent of erosion that can occur. Rough surfaces or tight cracks can facilitate the formation of concentration cells. Clean the surface can also be an issue, with a deposit or film which acts as the starting page. Biological growth may act as a deposit or to change the underlying surface chemistry to promote erosion (Philip A. Schweitzer, 2010).

Other variations within the metal surface on a microscopic level influence the corrosion process. Microstructural differences such as secondary phases or grain orientation will affect the way corrosion manifests itself. For corrosive environments where grain boundaries are attacked, the grain size of the material plays a significant role in how rapidly the material’s properties deteriorate. Stresses, either residual or applied, impact the mode of corrosion and lower the energy needed for corrosion to begin. Stress is a requirement for stress corrosion cracking or corrosion fatigue, but can also influence the rate of general corrosion (Philip A. Schweitzer, 2010).

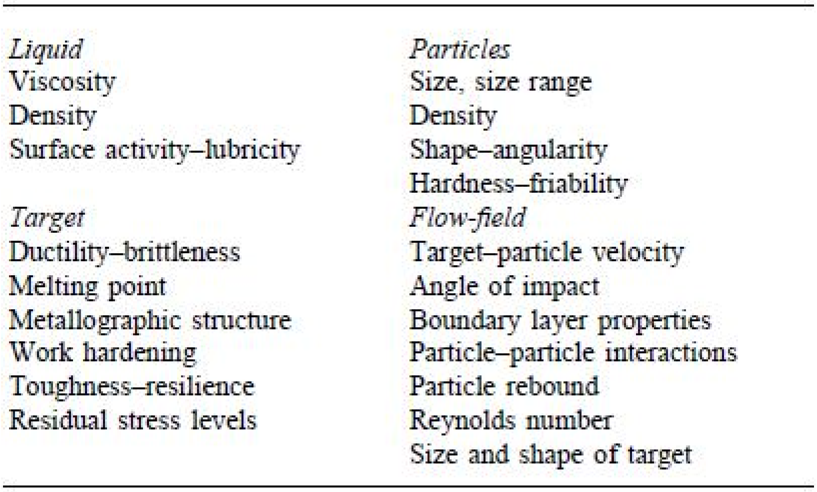
2.6 PREVIOUS STUDY

For this study, many aspect need to be consider as well related research done. This is as reference and guide to get information as much as can. This can help much in theory and designing experimental. From the related research also we can analyze the result that they have get after experimental have done.

2.6.1 Examining corrosion effects and corrosion/erosion on metallic materials in aqueous slurries (A.Neville, M.Reyes, H.Xu)

Erosion-corrosion fall into broad categories tribocorrosion processes including erosion abrasion and cavitation erosion for example. This is not specific forms, but the degradation of corrosion, which involves mechanical processes such as the effect of solid particles with an electrochemical corrosion process.

Slurry erosion (without taking into account factors such erosion) is a complex process of degradation in which the rate depends on a number of liquids, particles, fields, and targets flow (material effect) parameters. This is summarized in Figure 2.22.



Liquid	*Particles*
Viscosity	Size, size range
Density	Density
Surface activity–lubricity	Shape–angularity
	Hardness–friability
Target	*Flow-field*
Ductility–brittleness	Target–particle velocity
Melting point	Angle of impact
Metallographic structure	Boundary layer properties
Work hardening	Particle–particle interactions
Toughness–resilience	Particle rebound
Residual stress levels	Reynolds number
	Size and shape of target

Figure 2.22: Factors affecting slurry erosion rates

Source: Clark HMcI (1992)

Incorporating the effect of corrosion in slurry erosion corrosion further complicates degradation processes and it has been extensively demonstrated that erosion processes affect corrosion kinetics and corrosion can affect the rate and mechanisms of erosion (Weber J.Flow, 1992). In several works investigating tribocorrosion processes, interactions between mechanical and electrochemical processes have been identified and quantified.

When materials are exposed to an impinging flow of liquid containing solid particles, the electrochemical response can become complex, involving contributions from impacts and their effects on removal or destruction of protective films (Neville A, Reyes M, Hodgkiess T, Gledhill A,2000).

2.6.2 Erosion–corrosion of stainless steels, titanium, tantalum and zirconium (Maria-Dolores Bermudez, Francisco J. Carrion, Gines Martinez-Nicolas, Rosa Lopez)

Stainless steels are the most commonly used materials in industrial environments, but titanium and titanium alloys are seeing increasing application in industrial sectors outside the military and commercial aerospace sectors (A. Neville and McDougall, 2001).The study of erosion and wear of materials in corrosive environments has been the object of great attention in recent years (G.T. Burstein and K. Sasaki, 2000). This is due to the so-called synergism between the different processes.

Erosion–corrosion can be defined as the simultaneous interactions between erosion and corrosion, including cavitation and liquid erosion (ASM Handbook, 1992). As a result of this synergism, the metal loss rate can increase significantly beyond that due to either erosion or corrosion alone.

The erosion–corrosion regimes have been separated into two broad categories (ASM Handbook, 1992): erosion-enhanced corrosion (EEC) in which the damaged region is confined within the oxide scale, and corrosion-affected erosion (CAE), in which the damage zone includes both the scale and the metal.

CHAPTER 3

METHODOLOGY

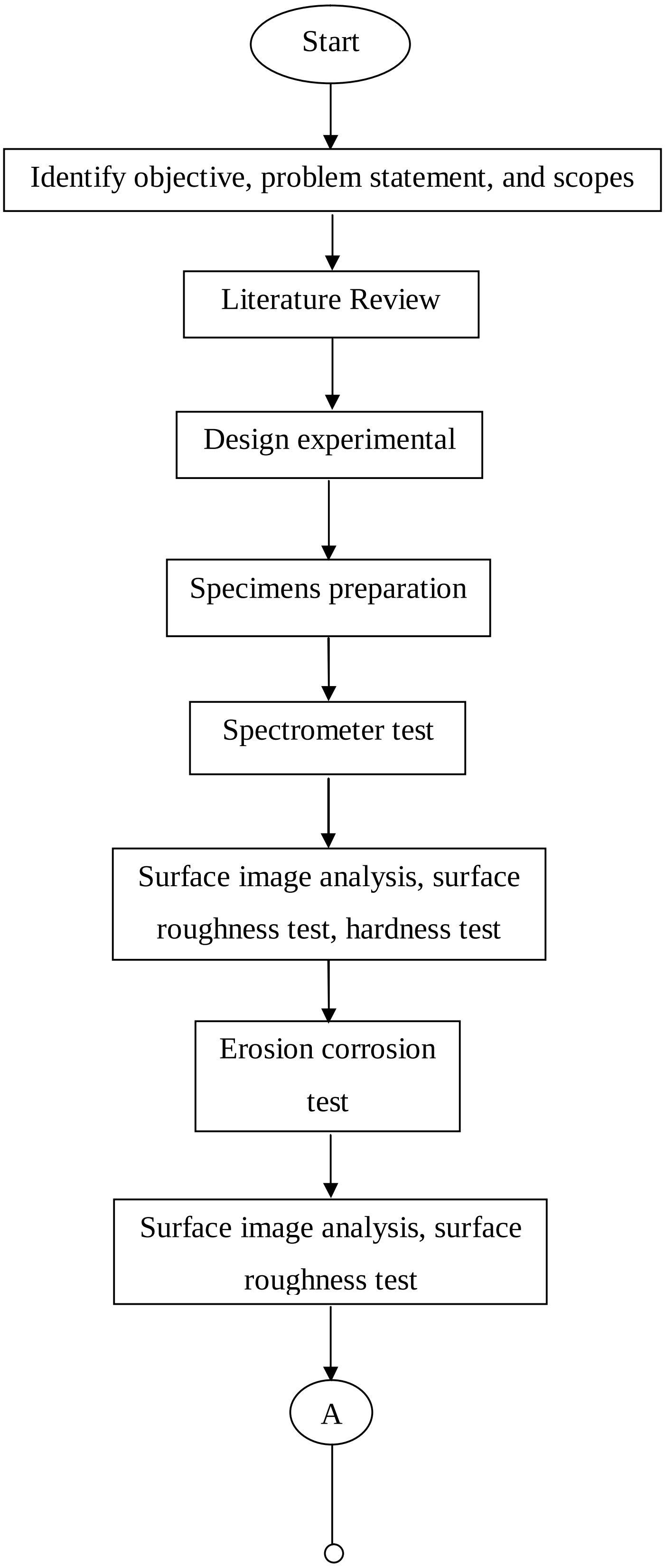
3.1 INTRODUCTION

In this chapter will focus on flowchart of experimental and methods use in this project in detail. This is to show proper guide on how to run experimental test with clearly and easy to understand.

In this project, there were aim for erosion corrosion test and inspection of erosion corrosion parameter before and after the process. Erosion corrosion test were carried out by using sea water as corrosion medium in presence of 10% slurry sand particles. Uniform velocity was set in this experiment which is 900 rpm and at condition of room temperature, 27^oC-30^oC. The impact of collision between sand and specimens is randomly. The erosion corrosion was conduct only in few minutes with proper setting in potentiodynamic input. Both of the experiment specimens were analyst by surface image analysis, surface roughness test and also the hardness test.

3.2 FLOW CHART

Figure 3.1 shows that the flow chart of running erosion-corrosion tests in detail. This flow chart help researcher a lot to understand process and to planning method systematically.


Start
Identify objective, problem statement, and scopes
Literature Review
Design experimental
Specimens preparation
Spectrometer test
Surface image analysis, surface roughness test, hardness test
Erosion corrosion test
Surface image analysis, surface roughness test
A

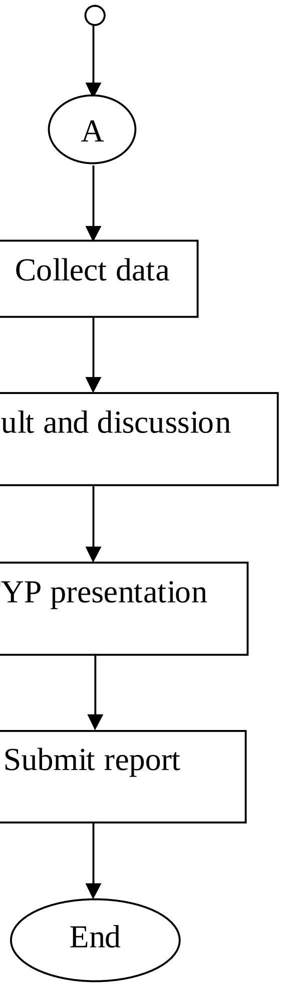
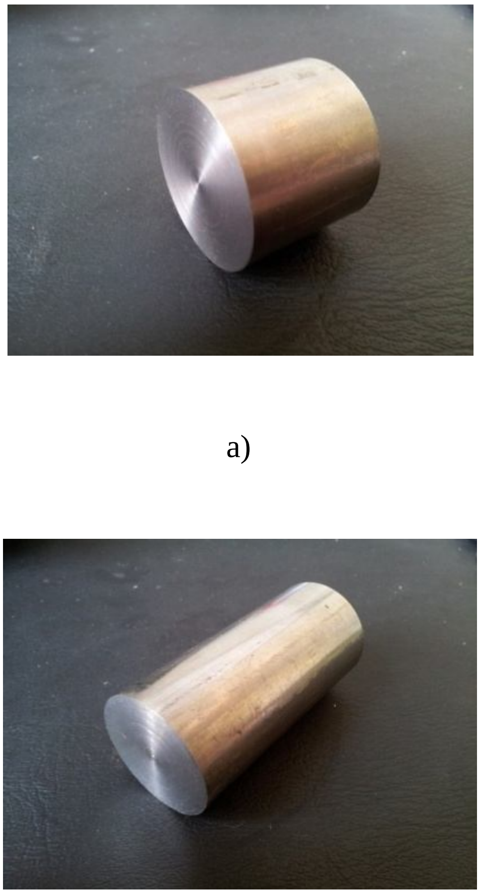


Figure 3.1: Project flow chart

3.3 RAW MATERIAL

My study is on testing erosion corrosion of two different materials in seawater. The materials involve is stainless steel (SS) and Titanium (Ti). Both of these materials have good corrosion resistance. Firstly, raw material for Stainless steel and Titanium need to cut in piece by using band saw machine into bar with a 15 mm length and 30 mm in diameter. This is because specimens only need in small dimension and also to easy the next process in preparing specimen that will be discuss on specimens preparation.



a)

b)

Figure 3.2: Raw materials a) Stainless steel b) Titanium

3.4 MACHINING PROCESS

The available dimension after cutting for Titanium and Stainless steel is 15 mm length, and 30 mm in diameter,ϕ .In the erosion-corrosion test, the desired dimension that will be use for specimens is 15 mm in diameter,ϕ and 15 mm for thickness. This can be performing by using lathe machine as shown in Figure 3.3 to reduce dimension for Stainless steel and Titanium round bar. The materials also will be parting to separate them into small specimen as in Figure 3.4.

Figure 3.3: Lathe machine

Figure 3.4: Sample of specimens

3.5 COMPOSITION ANALYSIS

Spark emission spectrometer test is used to analysis the composition of the metal before erosion corrosion test as shown in Figure 3.5. Before the spectrometer tests were run, the surface of the specimen must make sure to be flat and smooth. Machining of material need to be done smoothly to makes sure surface of specimen that will be test is smooth and flat. If not, the result of composition cannot be obtain and machining process need to repeat again to get flat surface.

Figure 3.5: Spark emission spectrometer

In order to conduct the metal analysis process, the spark chamber need to clean every before testing analysis is started. This can help to prevent the spark chamber from promoted to the next analysis. Besides that, the specimen need to ensure that the specimens is place fully close the spark chamber and a holder place on the specimen to avoid hold tied of the specimen to the spark chamber. Every specimen must conduct for metal analysis more than 1 time and take the average to get more accuracy result.

Table 3.1: Composition analysis of Stainless steel

Fe	C	Si	Mn	P	S	Cr	MO
71.1	0.0301	0.362	1.77	0.041	<0.0050	17.5	0.296

Ni	Al	Co	Cu	Nb	Ti	V	W
8.07	0.0038	0.133	0.513	<0.0020	0.0047	0.0691	<0.0200

Table 3.1 show the composition of Stainless steel that gets from spectrometer test. The composition can show the grade of steel by comparing the composition to standard composition of Stainless steel. From the composition, the stainless steel is grade of 301.

3.6 COLD MOUNTING PROCESS

The objective of cold mounting is to avoid unused surface of specimens exposed to the slurry because it will affect the result obtain. We can see in Figure 3.6 a) that shown the cold mounting machine. The mounting process also is to make tight connection of the specimen to an electrical wire as shown in figure 3.6 b). This wire need to contact for electrical circuit. Cold mounting is the general term used to describe multi-component systems such as epoxies, acrylics, and polyesters. This is mixed together and cast at (or near) room temperature.

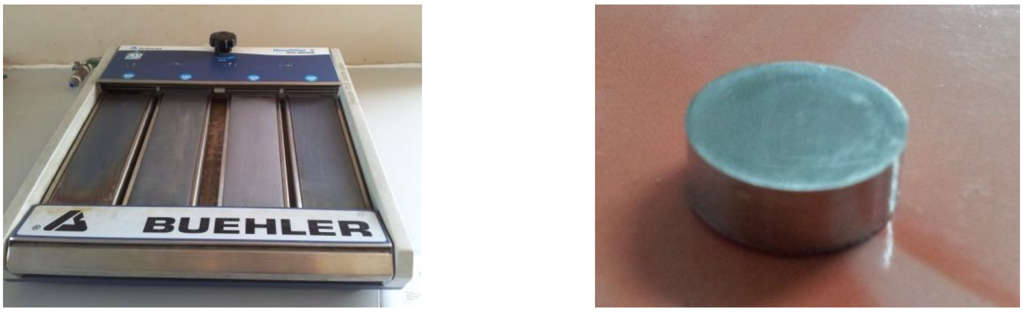
In making mounting compound, we use resin and mounting powder. The ratio of mixing use is following the standard in making cold mounting which is 2 mounting powder to 1 resin scale. This compound is measured by using mounting container with same size. This process must do quickly to avoid that bubble produce during pour of mounting compound to container that have specimen with wire connected and put into cold mounting machine in 15 minutes. Before that, we must ensure that wire is connected to specimens by using Voltmeter and the position of specimens during we pour into mounting container is stabilize.

a) b)

Figure 3.6: Cold mounting process a) cold mounting machine b) sample of polishing specimen

3.7 SPECIMENS PREPARATION

After machining, flat and unscratched surface finish need to obtain by using the vertical grinding machine which has been divided into four grades which are 240 grit, 320 grit, 400 grit and 600 grit as shown in Figure 3.7 b). The task must be perform follow the direction that have set for each grit with water flow to get smooth grinding.



a) b)

Figure 3.7: Grinding specimens a) Vertical grinding machine b) sample of polish

Next method after grinding is we need to polish the specimens. Objective of this method is to get smooth surface before test and to easy measurement of surface roughness test. We also want to make easy comparison before and after erosion corrosion test were run. We need to ensure that, surfaces of specimens have no holes or scratch because after test some scratch and pitting may form and we want to differentiate the condition at initial and after test.

In polishing, the apparatus use is rotating polishing machine which will use polishing material of 6µm, 1µm and 0.05µm.Figure 3.8 show the process during polishing.

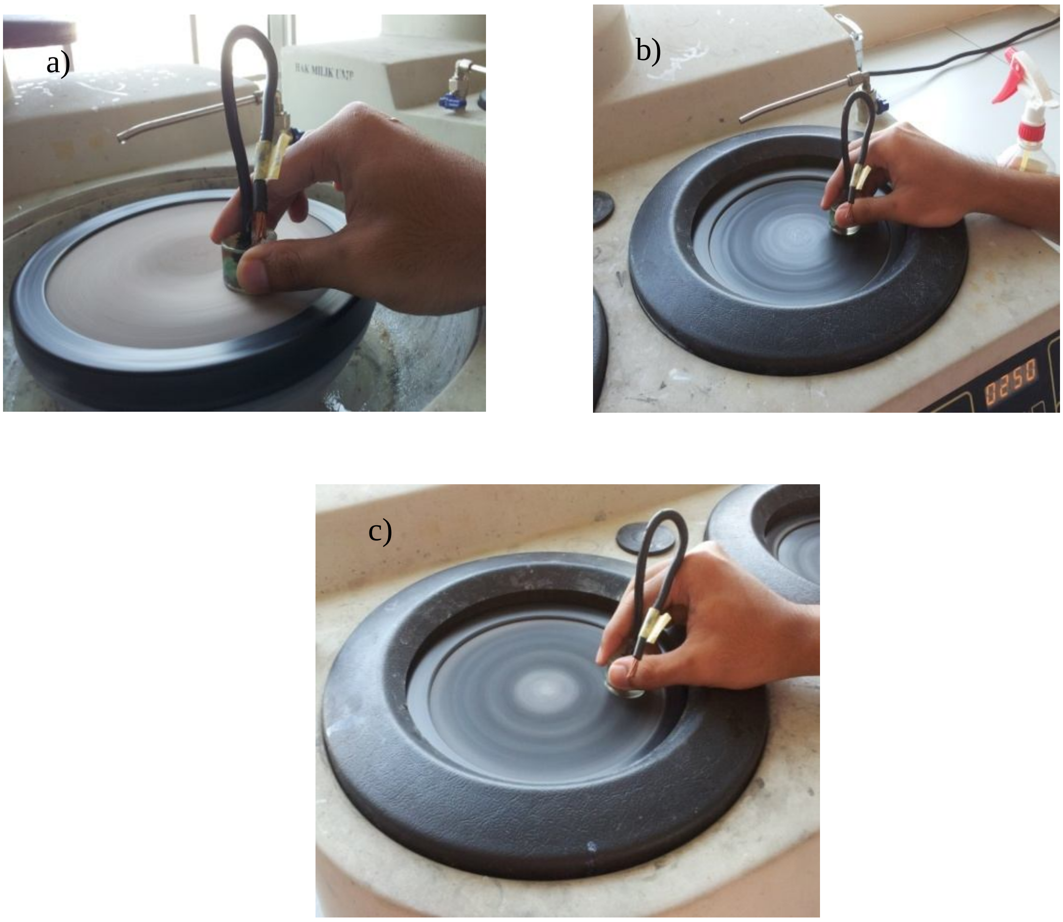


Figure 3.8: a),b) and c) Polishing process by using polishing particles 6μm,1μm and 0.05μm

3.8 INSPECTION OF EROSION CORROSION PARAMETERS

Inspection of erosion corrosion parameters is to observe and determine the material behaviour to erosion corrosion and mechanical properties corresponding to each specimen. There are two time inspections to perform before and after conduct the experiment. Inspection involve are surface image inspection, Rockwell hardness test, and surface roughness test.

3.8.1 Surface image analysis

Surface image of specimens is viewed with an inverted microscope as shown in Figure 3.9. Before start analyzing, specimen is placed under inverted microscope and need to be in dry condition. Then, the surface image of specimen can be captured and stored by using inverted microscope lens that have magnification 100X, 200X and 300X . Magnificent power can be manipulated to get clear microstructure image but in this study, magnification use is 200X.

Figure 3.9: Inverted microscope

3.8.2 Surface roughness test

Surface roughness test is to find out the value of Ra for specimens that represent the smoothness of surface. This test is performed before and after each trial or test. Surface roughness, often shortened to roughness, is a measure of surface texture. It is quantified by the vertical deviation of the actual surface of an ideal form. Perthometer is use in measure surface roughness as shown in Figure 3.10 a) and Figure 3.10 b).

a) b)

Figure 3.10: Surface roughness test a) specimen holder b) surface roughness controller

If this deviation is large, rough surface, if they the deviation is small smooth surface. Roughness plays an important role in determining how the real object will interact with the environment. Rough surfaces usually wear more quickly and have a higher coefficient of friction than smooth surfaces. Roughness is often a good predictor of performance of mechanical components, because of irregularities in the surface can form cracks or corrosion nucleation sites.

3.8.3 Rockwell Hardness test

Lastly, the hardness of the specimen was test using the Rockwell hardness test. The Rockwell hardness test shown in Figure 3.11 a) is the most common method for determines the hardness of ferrous and many nonferrous metals. In this test, a standard minor load is applied to set a hardness steel ball or a diamond cone in the surface of the metal, followed by the application of a standard major load. Apply load for Titanium and Stainless steel is 150N and hardness scale use is C because both specimen is in range of hard material.

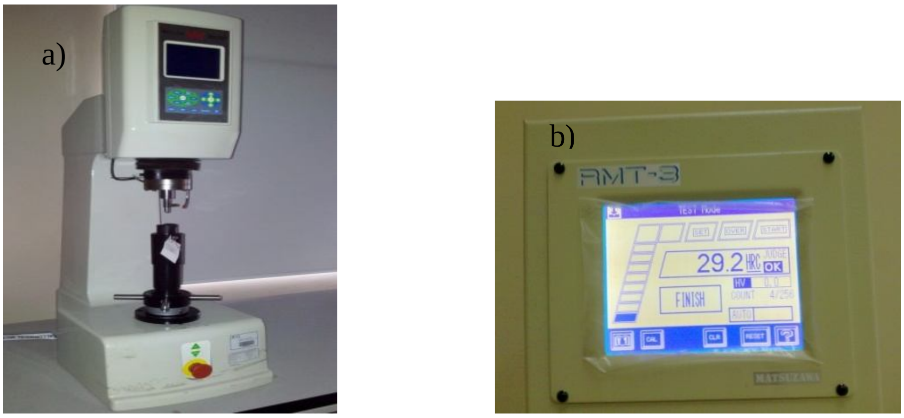


Figure 3.11: Hardness test a) Rockwell hardness tests machine b) Hardness reading

The indenter is force into the test material under a preliminary minor load and after equilibrium is achieves an indicating device, which follows the movement of the indenter, is set to the datum position. An additional major load is then applied with resulting increase in penetration. The conditions are then allowed to stabiles and then the additional major load is removed, leaving the minor load in places. In this test, a hard steel ball or diamond cone indenter is pressed into the surface of the material being test. The result of the test is read directly from machine as shown in Figure 3.11 b).

3.9 EXPERIMENTAL DESIGN

By using magnetic stirrer, the apparatus can be use to modelling erosion corrosion model. Sample of design of erosion-corrosion jig is refer to Figure 3.12 (Experimental by S.S. Rajahram, T.J. Harvey, R.J.K.Wood National Centre for Advanced Tribology at Southampton, School of Engineering Sciences, University of Southampton Highfield, Southampton SO17 1BJ, UK).

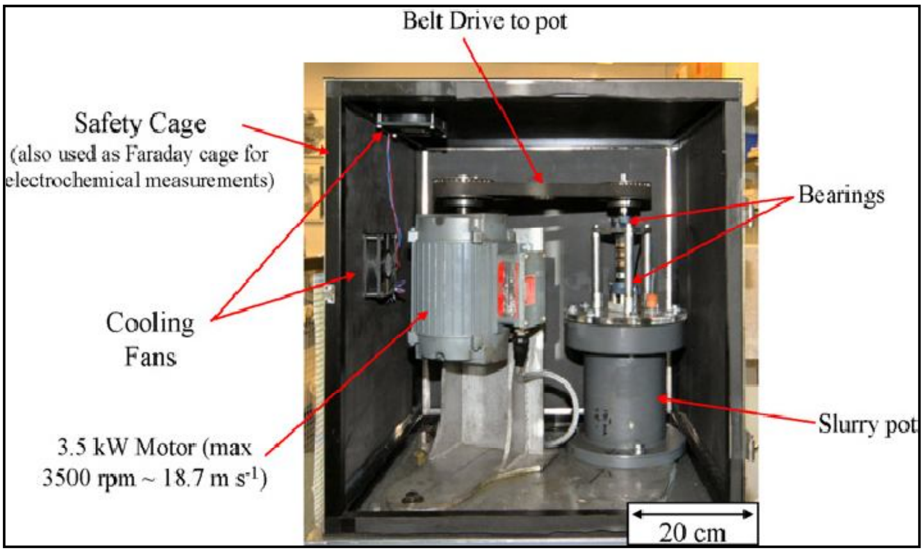


Figure 3.12: Erosion-corrosion jigs model

Source: R.J.K.Wood National Centre for Advanced Tribology

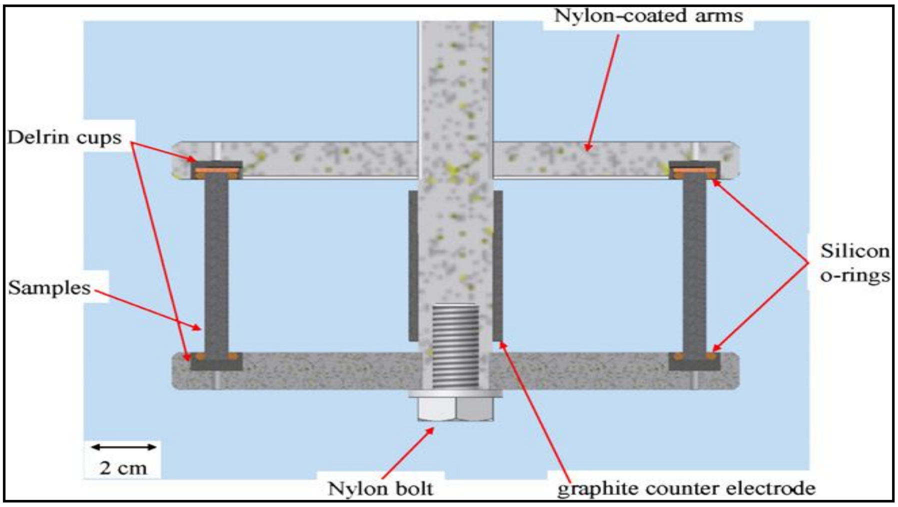


Figure 3.13: Placement of samples on two nylon-coated arms, secured with o-rings

Source: R.J.K.Wood National Centre for Advanced Tribology

3.9.1 Erosion tool setup

In Figure 3.13, design use is such complicated because it uses complex mechanism to modelling erosion-corrosion test. In this case study, the jig is constructing in simple way but still use same principle to generate motion jig.

Erosion-corrosion is corrosion process that involves motion. So, experimental jig need to design so that we can make the specimen in motion and collide with sand particles. Magnetic stirrer is use to generate motion to slurry and make the sand impact on specimens in various way at constant velocity. Magnetic stirrer will be connected to electrode as shown in Figure 3.14

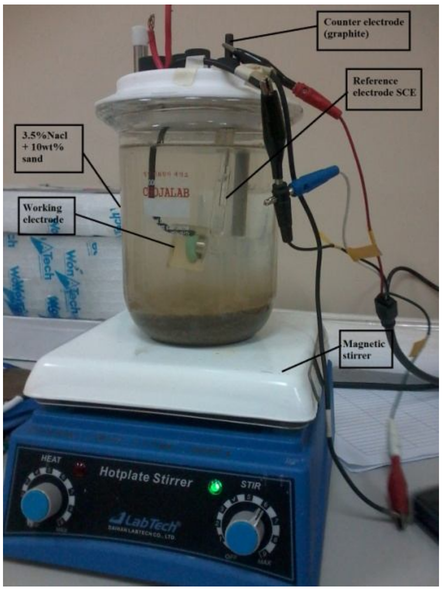


Figure 3.14: Connection of Magnetic stirrer to electrode

Slurry use in this test is 1 litre 3.5%NaCl with 10wt% sand added. In preparing 3.5%NaCl, 3.5 gram NaCl or salt is measure and mixed into 900 ml of distilled water that have been prepared. After that distilled water is added until slurry achieves 1 litre volume and then 10wt% sand is added. For the container, the design for cover is to put electrode through the cover. For specimen, it will be working electrode, graphite as counter electrode and SCE (saturated calomel electrode) as reference electrode.

3.9.2 Potentiodynamic test setup

The specimens were prepared with electrochemical apparatus as shown in Figure 3.15 by encapsulating them in non-conducting epoxy resin with rear-side of the specimen was mounting to an electrical wire. The potentiodynamic polarization test utilized a simple standard three electrode cell, where the potential shift or the working electrode (specimen) from E_{corr} to more positive potentials was measured using a saturated calomel reference electrode (SCE) together with the current flow in the circuit.

Figure 3.15: Potentiostat connection with computer

The function of the potentiodynamic tests (anodic polarisation) is to facilitate a measurement of the electrochemical corrosion rate (or other indicators of corrosion activity) of the material in static and liquid–solid impingement conditions. To do this, the electrochemical cell was connected to a computer controlled potentiostatic and used to control the potential of the working electrode (specimen under examination) with respect to the saturated calomel electrode (SCE).

The current flowing in the external circuit between the counter electrode (platinum) and the working electrode was then used to assess the kinetics of the reactions occurring under specific conditions. Potentiostatic tests at a controlled potential of -0.8 V on the saturated calomel (SCE) scale, were conducted for the primary purpose of applying cathodic protection (CP) to samples whilst under impinging conditions and therefore suppressing the corrosion influence on material loss (A. Neville , M. Reyes, H. Xu, 2002).

3.9.3 Parameters use for Potentiostat measurement

Before starting erosion-corrosion test, some data need to be entering before graph is get. The data involve is area, density, equivalent weight. For Titanium equivalent weight is 5.5 while density is 4.51 g/cm^3.For Stainless steel, equivalent weight is 27.92 and density is 7.87 g/cm^3.

For initial E and final E for both specimens is -0.8V and 0V.This setting need to be same for both specimens because this effect corrosion rate.

3.9.4 Polarisation curve

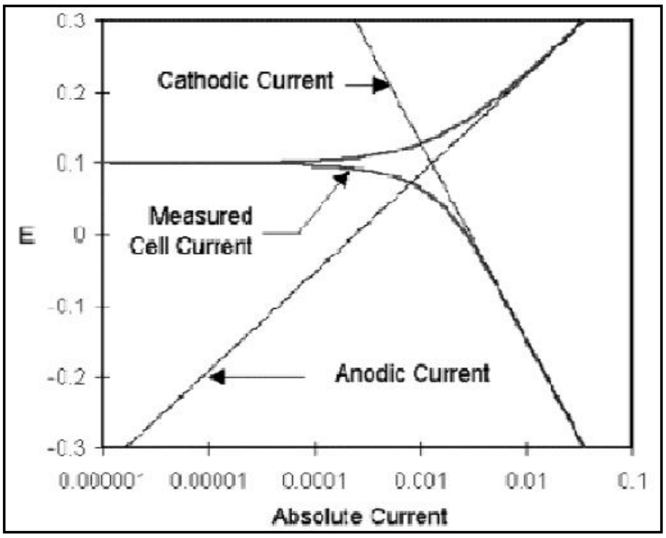


Figure 3.16: Corrosion Process Showing Anodic and Cathodic Current Components.

Source: Novak P (1993)

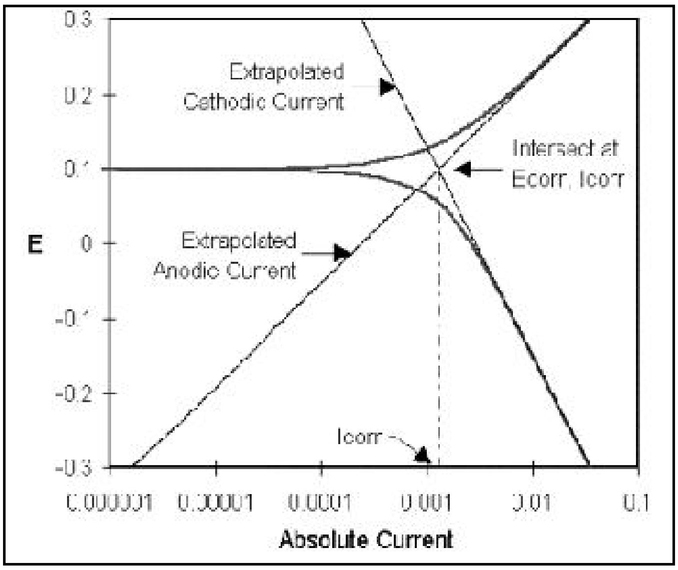


Figure 3.17: Classic Tafel Analysis

Source: Novak P (1993)

The vertical axis is potential and the horizontal axis is the logarithm of absolute current. The theoretical current for the anodic and cathodic reactions are shown as straight lines. The curved line is the total current which is the sum of the anodic and cathodic currents. The sharp point in the curve is actually the point where the current changes signs as the reaction changes from anodic to cathodic, or vice versa. The sharp point is due to the use of a logarithmic axis. The use of a log axis is necessary because of the wide range of current values that must be displayed during a corrosion experiment. Because of the phenomenon of passivity, it is not uncommon for the current to change by six orders of magnitude during a corrosion experiment.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

This chapter will discuss in detail about the data collected from corrosion test and the analysis that can be express from the data. The erosion corrosion test were conduct for Titanium alloy and Stainless steel 301 in 3.5% NaCl solution with 10wt% of beach sand added at velocity 900 rpm. The data obtained from experiment was recorded and was analyzed in detail.

4.2 HARDNESS TEST

Hardness test is done on Titanium alloy and Stainless steel 301 by using Rockwell hardness test at apply load F = 150N. Table 4.1 show the HRC number for Titanium alloy and Stainless steel.

Table 4.1: Rockwell hardness test for Titanium and Stainless steel

Stainless steel(HRC)	Titanium(HRC)
26.8	30.7

Hardness is a representative of materials mechanical properties. Normally, harder materials have higher yield stresses. In erosion–corrosion applications, harder materials, which are ductile, are preferred since they provide a combination of strength and formability, which enhances their properties for the service. According to platelet mechanism (A.V. Levy, Solid Particle Erosion and Erosion–Corrosion of Materials, ASM International, Materials Park, Ohio, 1995), accumulation of strain in the roots of platelets formed due to multiple particle impacts results in their final detachment from the surface, therefore it is important that the material handles more deformation so that the detachment of the platelets requires more impacts.

From Table 4.1, the hardness of Titanium alloy is 30.7 and for Stainless steel is 26.8. From Mohr hardness scale, stainless steel in range 5.5 to 6.3, while Titanium in range 6.5.The lower hardness of Stainless steel compared to Titanium alloy, makes this metal particularly susceptible to failure by impinging particles. Additions of tungsten, such as in Ta–2.5W, increase hardness with respect to stainless steel.

The velocity exponents usually involve in erosion of metal vary between 2m/s and 3m/s. Above a critical velocity, the erosion is increase significantly and velocity exponent will increase close to 3 m/s. If hardness of the target is high, the velocity exponent will decrease during collision on high hardness target. When velocity impact is decrease so corrosion rate of material also decrease (M.M. Stack, J. Chacon-Nava, F.H. Stott, 1994).

4.3 IMAGE ANALYSIS

The impact of 10wt% sand particles added in 3.5%NaCl solutions and oxidation reaction will cause pitting to the surface of specimens. Pitting form on specimens is different because of different materials properties that influence corrosion rates.

4.3.1 Surface Image of Titanium and Stainless Steel before Erosion Corrosion Test

Figures 4.1 and 4.2 show the surface structure for Titanium and Stainless steel before erosion corrosion test were run at different point.

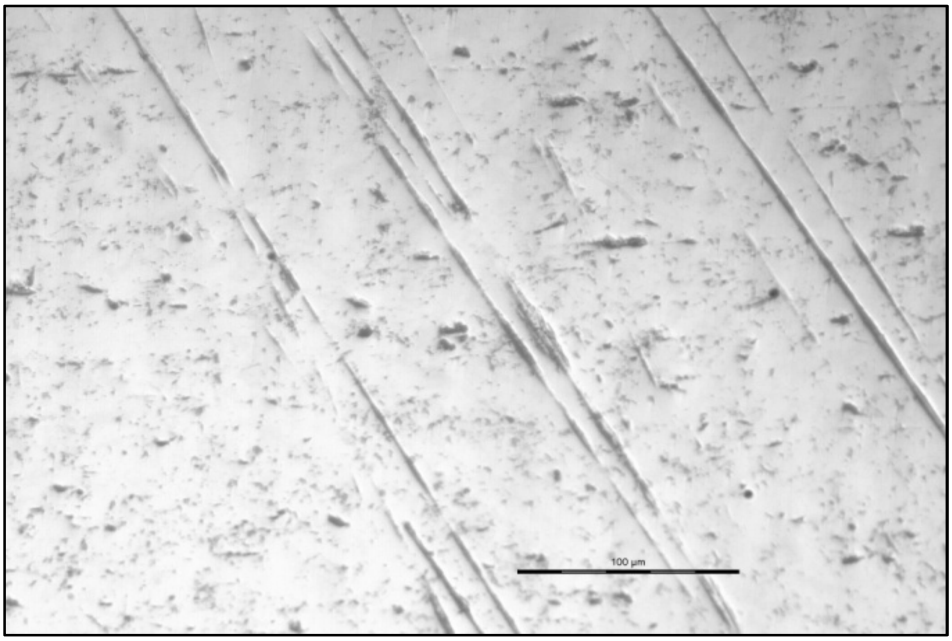


Figure 4.1: a) Surface structure of Titanium specimen at Point1

(Magnification 200X)

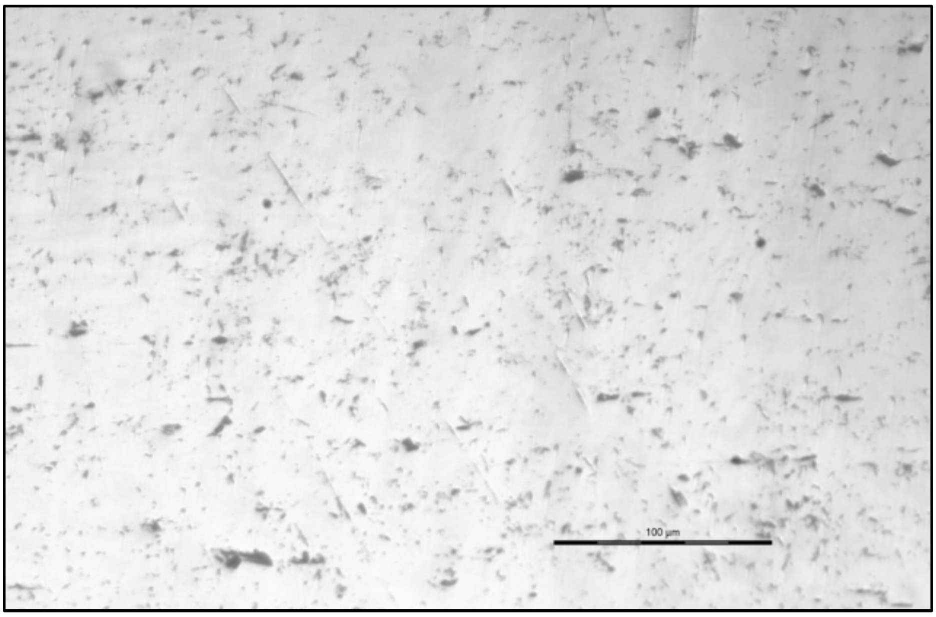


Figure 4.1: b) Surface structure of Titanium specimen at Point 2

(Magnification 200X)

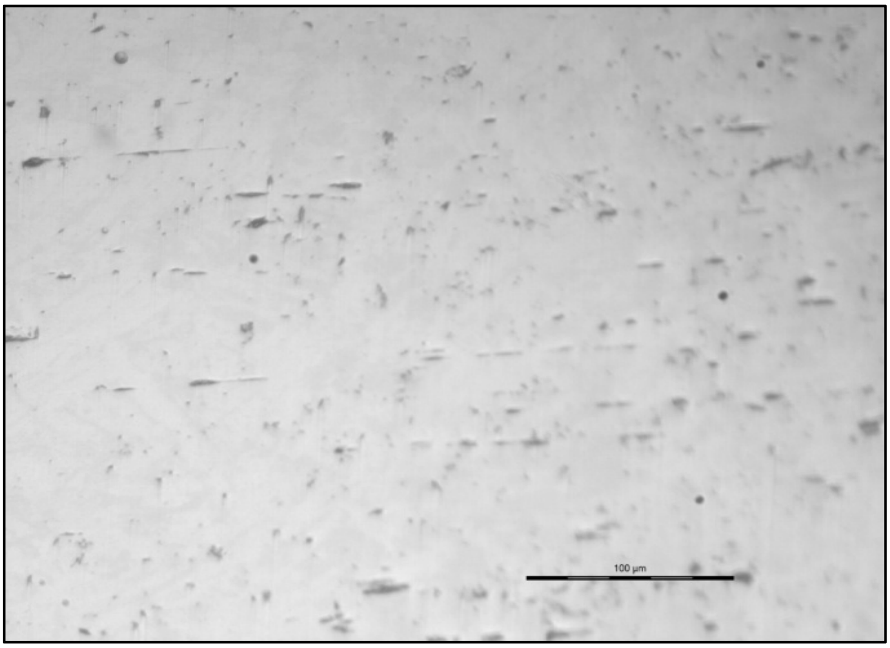


Figure 4.1: c) Surface structure of Titanium specimen at Point3

(Magnification 200X)

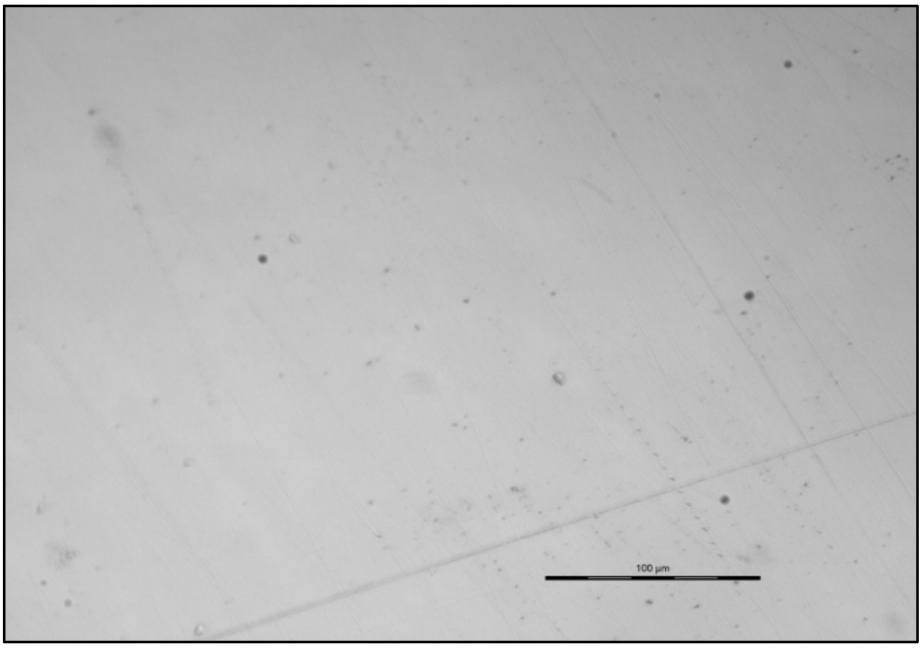


Figure 4.2: a) Surface structure of Stainless steel at Point 1

(Magnification 200X)

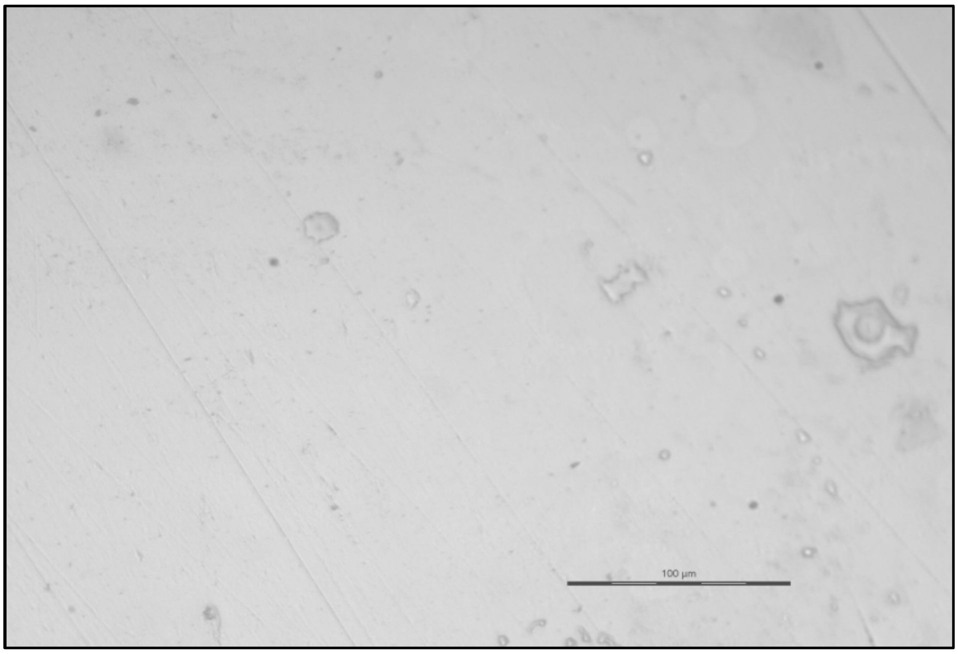


Figure 4.2: b) Surface structure of Stainless steel at Point 2

(Magnification 200X)

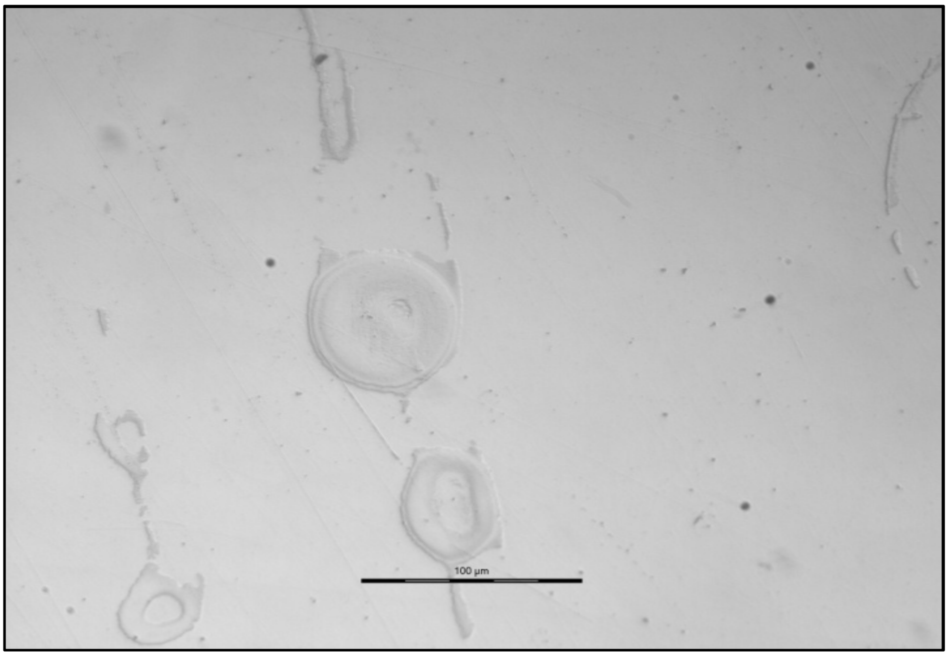


Figure 4.2: c) Surface structure of Stainless steel at Point 3

(Magnification 200X)

4.3.2 Surface Image of Titanium and Stainless Steel after Erosion Corrosion Test

Figures 4.3 and 4.4 show the surface structure for Titanium and Stainless steel after erosion corrosion test were run. Abrasion marks and erosion impacts are visible on Titanium and Stainless steel specimens in the macrograph shown.

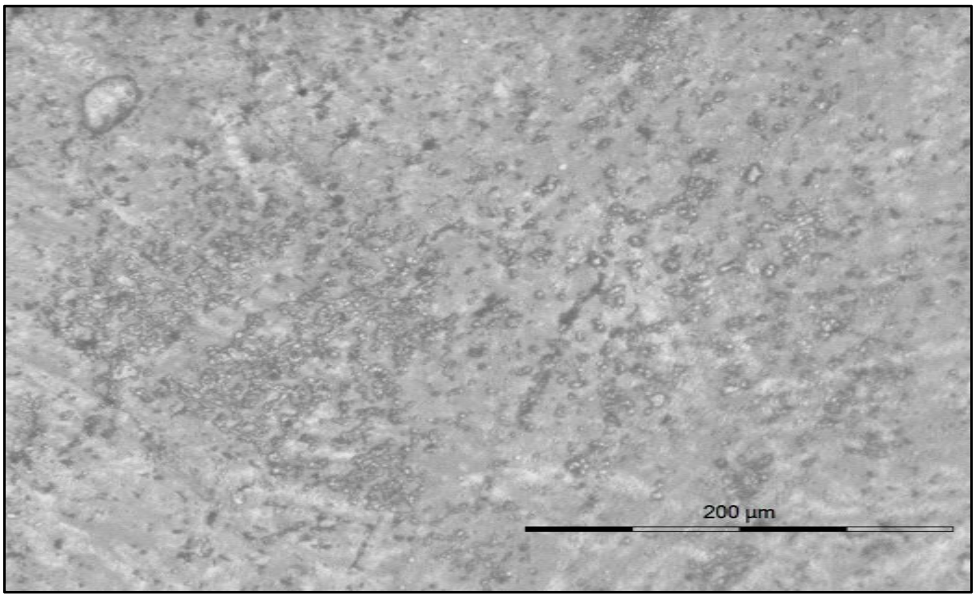


Figure 4.3: a) Surface structure of Titanium at Point 1

(Magnification 200X)

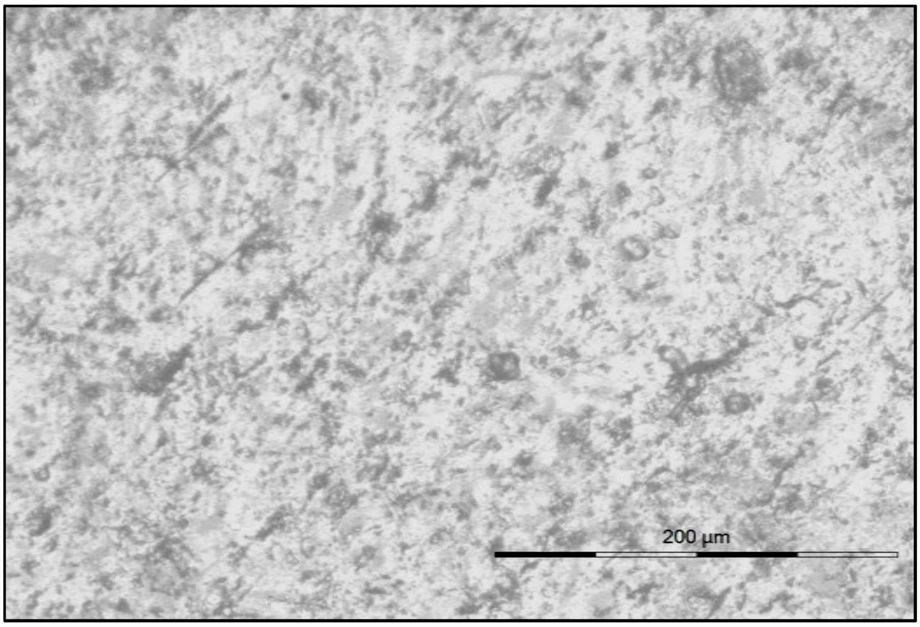


Figure 4.3: b) Surface structure of Titanium at Point 2

(Magnification 200X)

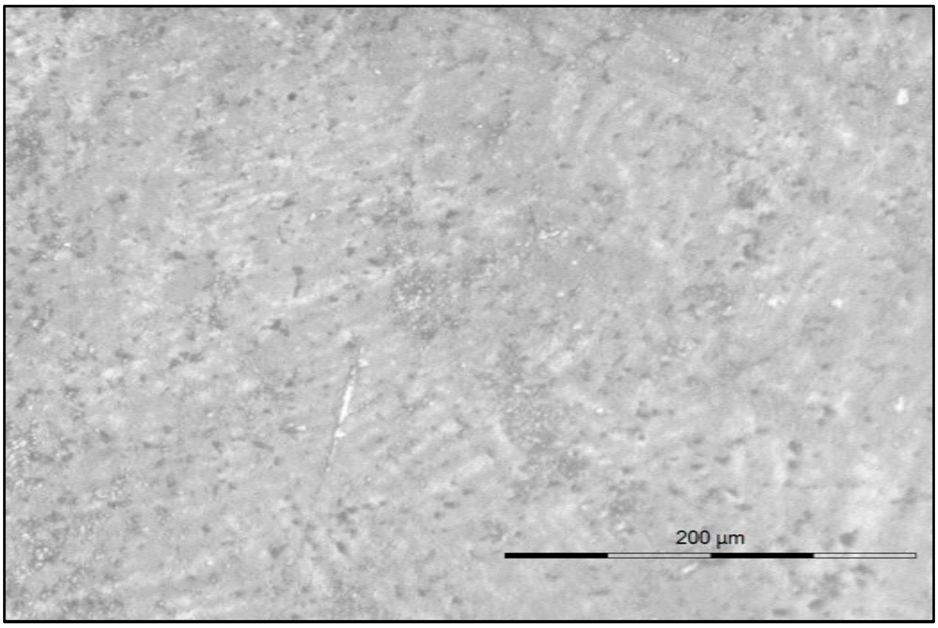


Figure 4.3: c) Surface structure of Titanium at Point 3

(Magnification 20X)

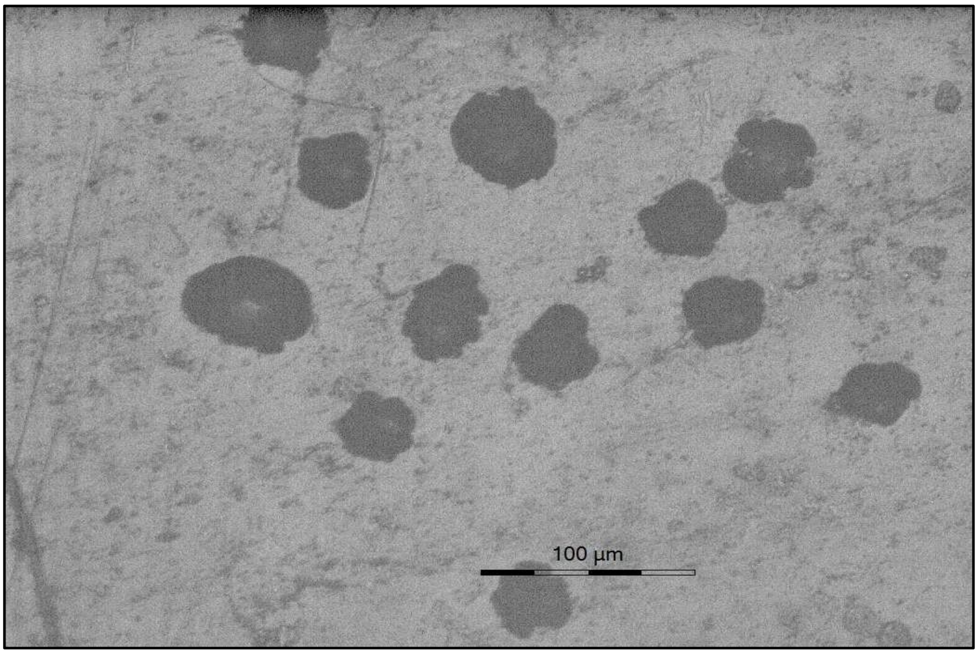


Figure 4.4: a) Surface structure of Stainless steel at Point 1

(Magnification 200X)

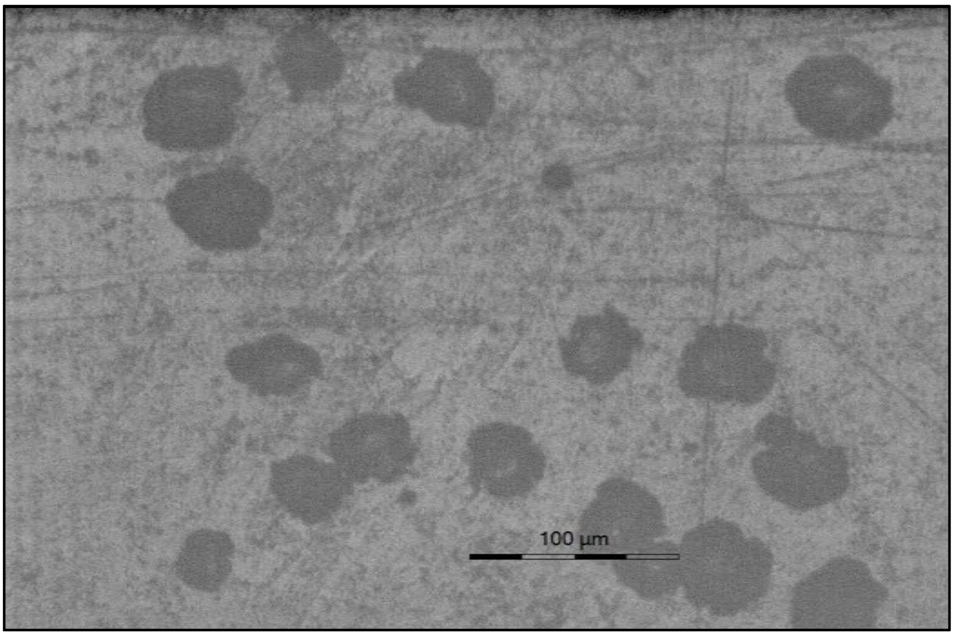


Figure 4.4: b) Surface structure of Stainless steel at Point 2

(Magnification 200X)

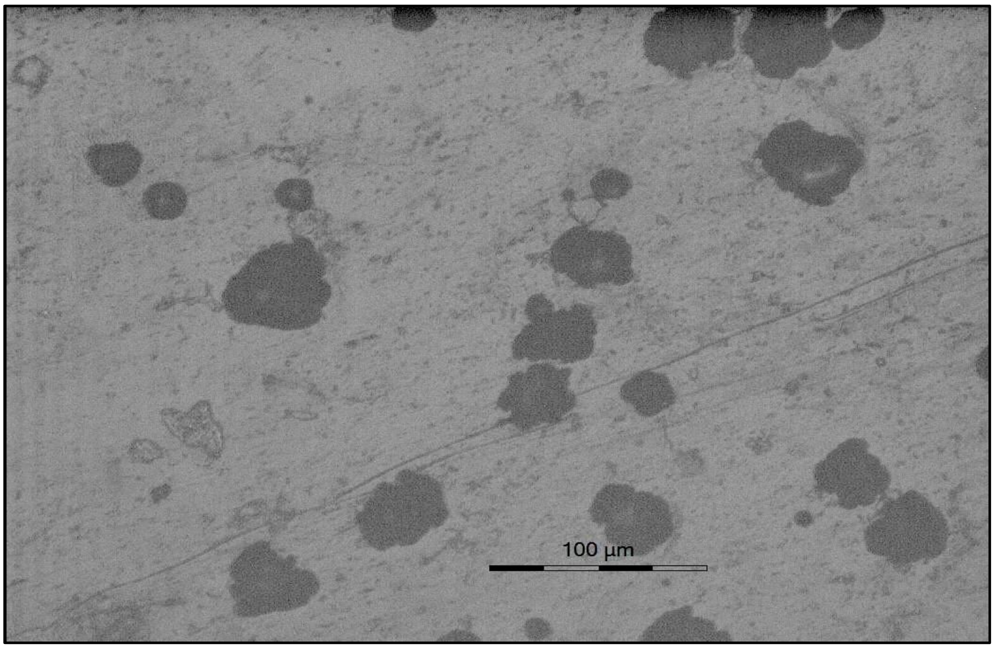


Figure 4.4: c) Surface structure of Stainless steel at Point 3

(Magnification 200X)

Figure 4.1 a, b and c show the surface image of Titanium before erosion-corrosion test while Figure 4.3 a, b and c show surface image for Titanium after erosion-corrosion test were run. Then, for Figure 4.2 a, b and c is surface image of stainless steel before erosion-corrosion test and Figure 4.4 a, b and c are surface image of Stainless steel after erosion-corrosion test.

After tests were run, pitting was form on surface of Titanium and Stainless steel. If we compare the pitting form on Titanium surface and Stainless steel surface, pitting that form on Stainless steel surface is more large in diameter and also can be observe clearly compare to pitting form on Titanium. This can relate due to different hardness of Titanium and Stainless steel which Titanium is harder than Stainless steel.

It has been previously shown that the erosion and erosion–corrosion rate of a specific material depend on the relative hardness of that material and the abrasive. Furthermore, although different factors affect the erosion–corrosion of materials with different hardness, harder materials are shown to be usually more resistant to erosion and erosion–corrosion.

Pitting corrosion occurs on more or less passivated metal and alloys in environment containing chloride, bromide, iodide or pechlorate ion when electrode potential exceed a critical value. This form of corrosion is characterized by narrow pits with a radius of the same order of magnitude as, or less than, the depth. In this case study, slurry which contain chloride is medium of corrosion for Titanium and Stainless steel (Einar Bardal, 2003).

In this study, sand was added to the liquid stream. Mechanical effects were insufficient to destroy the passivity of the stainless steels and Titanium but the hard silica sand particles were capable of immediately removing areas of the passive film by repeatedly collision to surface, revealing unprotected metal on which degradation by corrosion could easily proceed. From the moment the sand in the system reached the surface, the effect was to dramatically increase the anodic current and general corrosion prevailed over the entire surface (A. Neville, T. Hodgkiess, J.T. Dallas, 1995).

There is an interaction between solid particles, corrosive fluid and a target material When materials are exposed to an impinging flow of liquid containing solid particles the electrochemical response can become complex, involving contributions from impacts and their effects on removal or destruction of protective films (A. Neville , M. Reyes, H. Xu,2002).

For a passive metal like SS316L, the increase in velocity accelerates the mechanical removal rate of the passive film thus accelerating the overall erosion–corrosion process. At the same time the increase in flow velocity can also accelerate the repassivation rate by increasing the supply of dissolved oxygen and chromium ions necessary to repair the chromium oxide film that has been destroyed by solid particle impingement (P. Roberge, B.C. Syrett, Erosion–Corrosion, NACE International, 2004).

4.4 SURFACE ROUGHNESS MEASUREMENT

Table 4.2 shows the result of surface roughness for Titanium and Stainless steel before and after erosion corrosion test.

Table 4.2: Ra value for Titanium and Stainless steel before and after erosion corrosion test

	Roughness before the test(R_a, µm)	Roughness after the test(R_a, µm)	surface roughness increment
Titanium	0.056	0.121	0.065
Stainless steel (301)	0.025	0.472	0.447

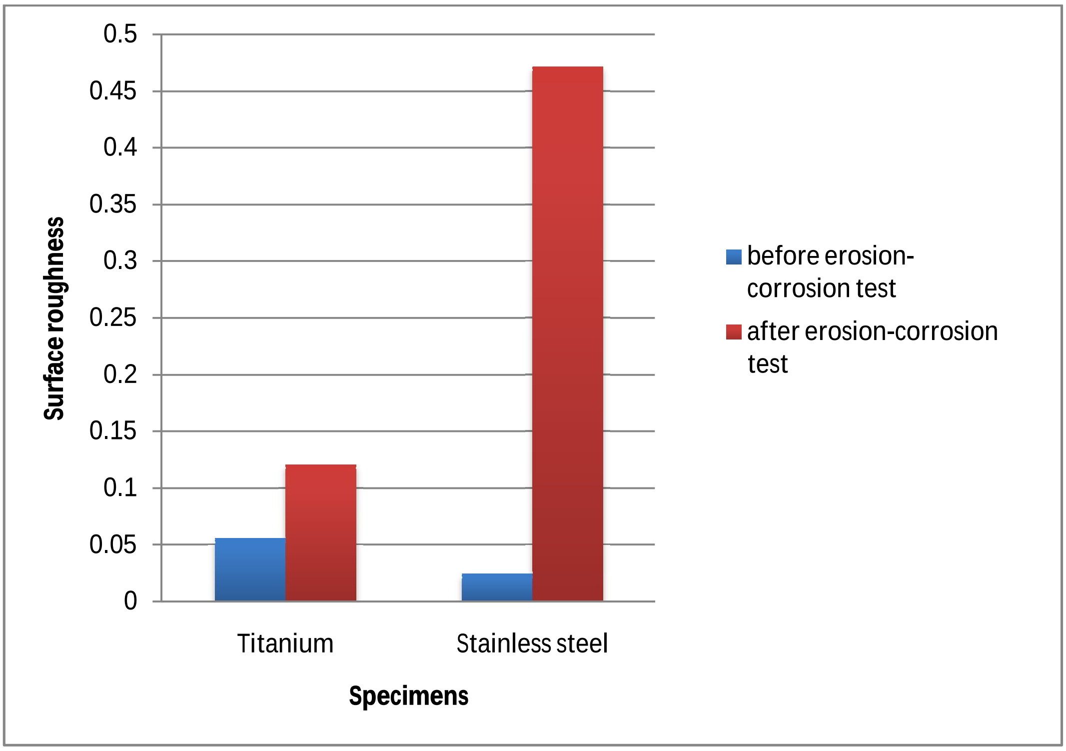


Figure 4.5: Graph surface roughness of specimens before and after erosion corrosion test

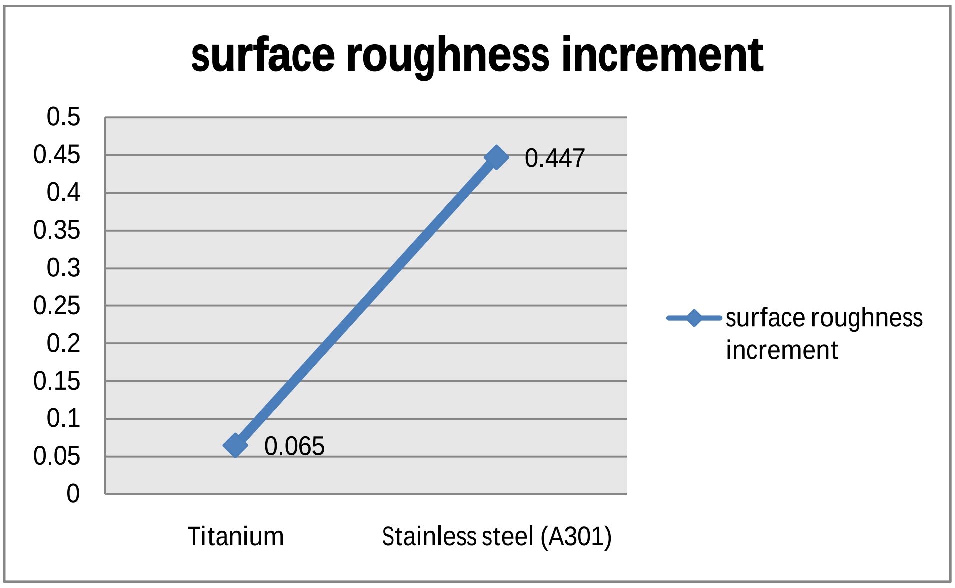


Figure 4.6: Surface roughness increment of Titanium and Stainless steel

From Table 4.2 and Figure 4.5, we can see increasing of surface roughness for Titanium and Stainless steel before and after erosion corrosion test. From Figure 4.6, increment of surface roughness for Stainless steel is higher than Titanium. In previous research, the order of roughness increment after the tests for Titanium and Stainless steel as the following, AISI 304L > AISI 316L > Ti (Maria-Dolores Bermudez, Francisco J. Carrion, Gines Martinez-Nicolas, Rosa L´opez, 2003).

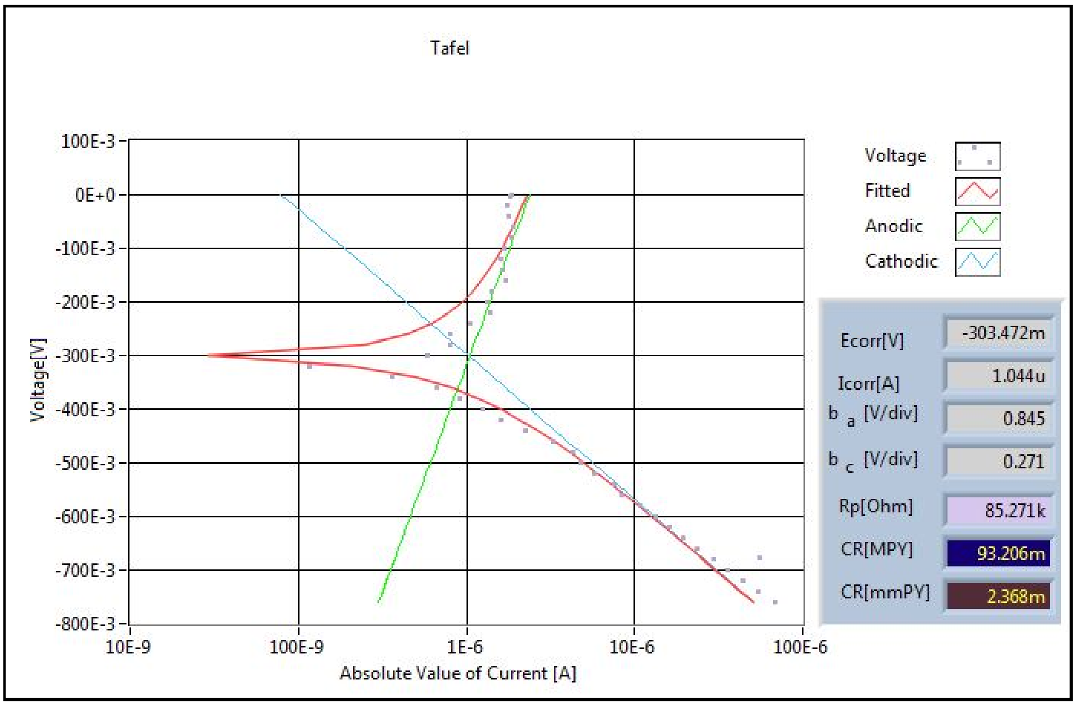
Surface roughness increase due to formation of pitting or scar on specimen’s surface. The pitting and scar is form when passive film of Titanium and Stainless steel is removing by collision with sand particles. Due to lower hardness and lower corrosion resistance of Stainless steel compare to Titanium, this lead to form more and large pitting diameter on Stainless steel surface.

4.5 EROSION-CORROSION TEST ANALYSIS

This test basically uses principal of chemical reaction to produce corrosion on the specimens. These chemical reactions involve two electrochemical reactions which are an oxidation and a reduction process. Oxidation here is actually the corrosion process that we consider as the result from corrosion process.

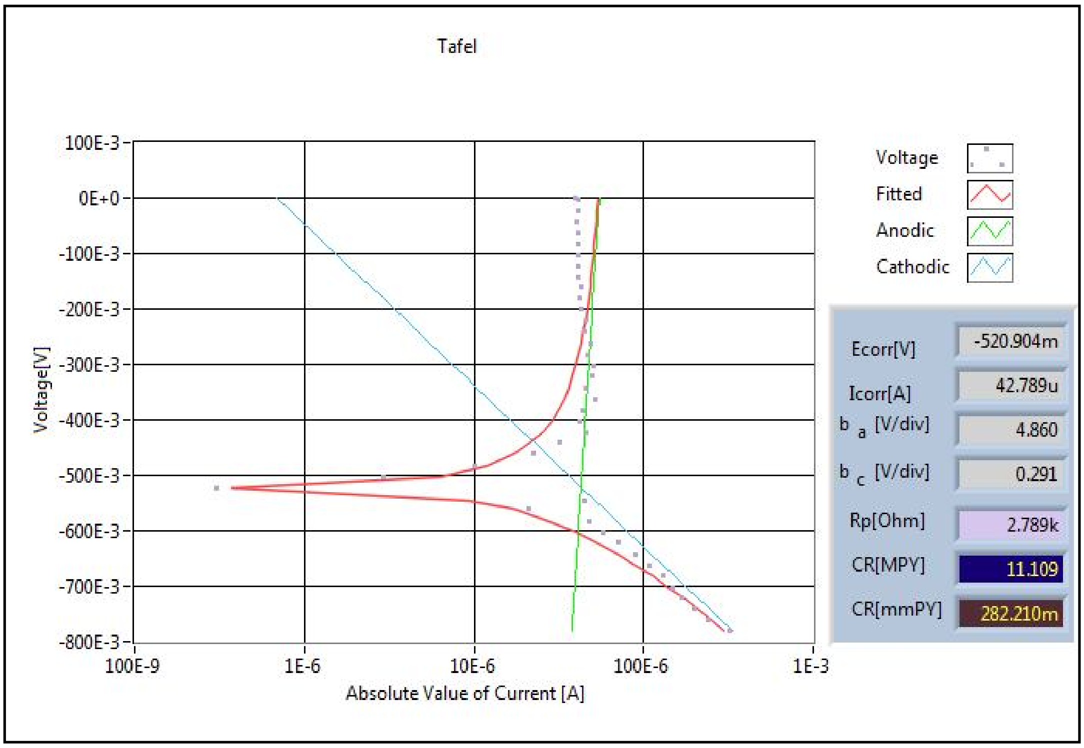
In addition, the experiment conducts in the slurry consist of 3.5 % NaCl solution with 10wt% sand added. The purpose of the slurry is to run the specimens in real application which imply in marine condition. Seawater is fastest medium that accelerate corrosion rate both of Titanium and Stainless steel and corrosion rate of both specimen are compare.

Figure 4.7 show that tafel analysis to measure corrosion rate for Titanium and Stainless steel.



Ecorr[V] -303.472m
Icorr[A] 1.044u
b a [V/div] 0.845
b c [V/div] 0.271
Rp[Ohm] 85.271k
CR[MPY] 93.206m
CR[mmPY] 2.368m

Figure 4.7: Tafel analysis of corrosion rates for Titanium



Ecorr[V] -520.904m
Icorr[A] 42.789u
b a [V/div] 4.860
b c [V/div] 0.291
Rp[Ohm] 2.789k
CR[MPY] 11.109
CR[mmPY] 282.210m

Figure 4.8: Tafel analysis of corrosion rates for Stainless steel

Data collected from the tafel analysis in Figure 4.7 and 4.8 by using IVMan software was collected and was summarized in Table 4.3.

Table 4.3: Corrosion rates determine by Tafel Extrapolation Method

Sample	**Ecorr (V vs SCE)**	**Icorr (µA/cm²)**	***B*a (V/dec**	***B*c (V/dec)**	**Rp(ohm)**	**Corr Rate (mm/year)**
A(Titanium)	-0.3035	0.000001044	0.845	0.271	85271	0.002368
B(Stainless steel)	-0.5209	0.000042789	4.860	0.291	2789	0.28221

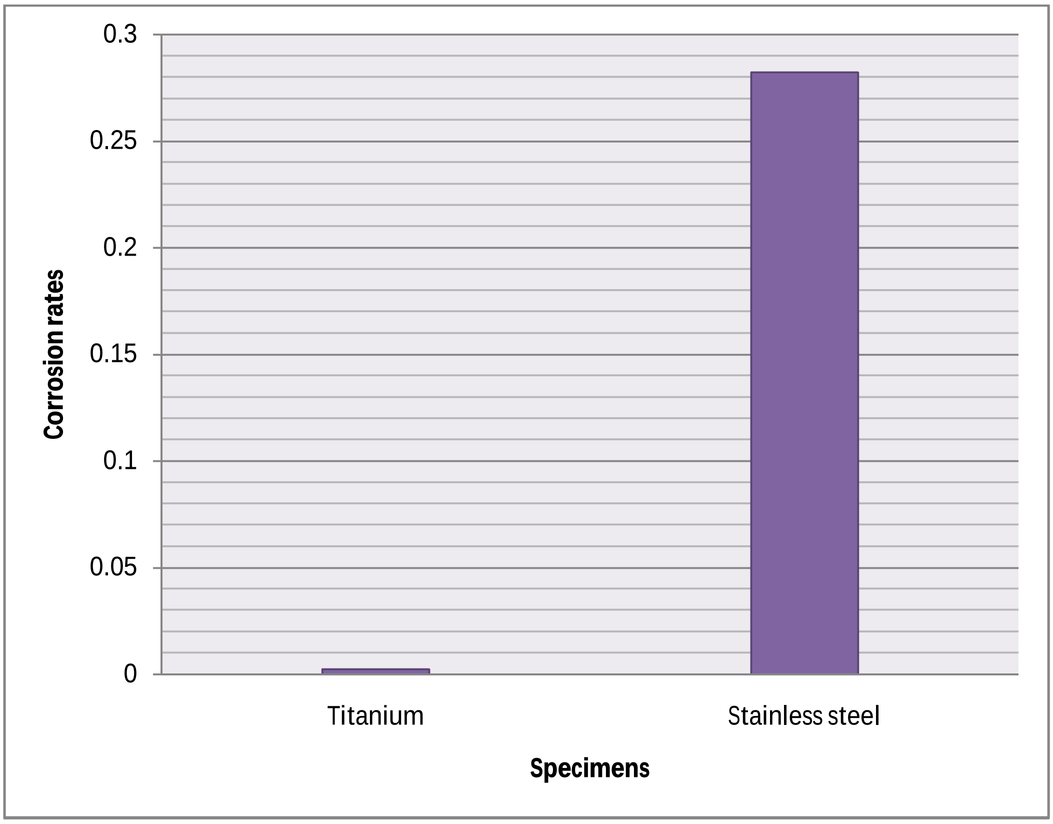


Figure 4.9: Graph corrosion rates for Titanium and Stainless steel

From Table 4.3 and graph 4.9, we get that corrosion rate (mm/year) for Stainless steel is higher than corrosion rate (mm/year) of Titanium. This show that Stainless steel is corrodes faster in seawater compare to Titanium. This is also can relate to high hardness of Titanium that slows the corrosion process and increase corrosion resistance.

In natural seawater, the risk of corrosion is high for most stainless steels. This is due to the effects of the bacterial slime layer that is usually formed in this environment. On stainless steels and other relatively corrosion-resistant materials in seawater a microbiological slime layer is usually formed, and below 30–40°C this slime layer may have a dramatic effect on the cathodic properties (Einar Bardal, 2003).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

Erosion corrosion test analysis, surface roughness analysis and surface image analysis had been carried out to differentiate corrosion rate with different type material which are Titanium and Stainless steel in 3.5% NaCl slurry with 10 % weight sand added.

5.2 CONCLUDING REMARKS

Erosion corrosion usually occurs in marine application such as impeller, turbine, piping system and others. Due to this problem, material selection such as Titanium and Stainless steel is important factor which of the best that can give long life in marine application. The following conclusions can be drawn from this study:

i) Corrosion rate for Titanium is lower than corrosion rates for Stainless steel. This due to hardness of Titanium which higher than the hardness of Stainless steel that gives effect to corrosion resistance.

ii) Pitting form on surface of Stainless steel is larger and clear compare to pitting form on surface of Titanium. More pitting form on surface, so value of Ra will be large which indicate surface roughness of the material.

5.3 RECOMMENDATIONS

The investigation and study about effect of erosion corrosion for Stainless steel and Titanium in different parameters that effect to erosion corrosion need to be continued.

i) Using different velocity rate in erosion corrosion test for Stainless steel and Titanium. This is to study effect on different rate of velocity to erosion corrosion behaviour for both materials.
ii) Using different rate of NaCl solution to compare with the percentage on seawater.
iii) Using a various size of sand particle to see their effect on surface morphology and their corrosion rate.
iv) Use other material to compare with Titanium and Stainless steel and analyze corrosion rate for different material.

In order to get accurate result, test and experiment need to conduct in proper method and tool use is in good condition. Each parameter should be study and control due to objective of the project.

REFERENCES

A. Neville, B.A.B. McDougall, Erosion and cavitation-corrosion of titanium and its alloys, Wear 250 (2001) 726–735.

ASM Handbook, Friction, Lubrication and Wear Technology, vol. 18, 1992.

Batchelor AW, Lam LN, Chandrasekaran M. Materials Degradation and Its Control by Surface Engineering. Singapore: Imperial College Press/World Scientific Publishing, 1999; 189–197, 43.

Corrosion & Protection, Einar Bardal (2003).

Corrosion Tables of Stainless Steels. Stockholm: Jernkontoret, 1979 (in Swedish).

Corrosion handbook: Stainless Steels. Sandviken, Sweden: Sandvik Steel & Avesta Sheffield, 1994.

Efird KD. Effects of fluid dynamics on the corrosion of copper–base alloys in seawater. Corrosion, 33, 1977: 3–8.

Fontana MG Greene ND. Corrosion Engineering. New York: McGraw-Hill, 1978, 1986.

G.T. Burstein, K. Sasaki, Effect of impact angle on the slurry erosion–corrosion of 304L stainless steel, Wear 240 (2000) 80–94.

Gemmel G, Nording S. Monit and 904L – two high alloy stainless steels for seawater applications. Symp. Advanced Stainless Steels for Seawater Applications. Ass. Italiana de Metallurgia – Climax Mo. Co. 1980. (after Coit RL. Inco Power Conference, Lausanne. 1967.)

Metals Handbook. 9th Ed. Vol.13 Corrosion. Ohio: ASM International, 1987.ASTM G15 86. Definition of terms relating to corrosion and corrosion testing, ASTM Annual Book of Standards, Vol. 03.02, 1987, pp. 134–138.

Ijsseling FP. Survey of Literature on Crevice Corrosion (1979–1998). London: The Institute of Materials, 2000

M.G. Fontana, "Corrosion Engineering," McGraw-Hill Book Company,(1986) 282,41.

M.M. Stack, Mapping tribo-corrosion processes in dry and aqueous conditions: some new directions for the new millenium, Tribol. Int. 35 (2002) 681–689

Novak P, Macenauer A. Erosion–corrosion of passive metals by solid particles. Corros Sci 1993;35(1-4):635–40.

Neville A, Reyes M, Hodgkiess T, Gledhill A. Mechanisms of wear on a Co-base alloy in liquid–solid slurries. Wear 2000;238:138–50

Nestor Perez.2004.Electrochemistry and corrosion science.

Pludek VR. Design and Corrosion Control. London: The Macmillan Press, 1977.

Roberge PR Handbook of Corrosion Engineering. New York: McGraw-Hill, 1977

R.W. Schutz, Utilizing Ti to successfully handle chloride process environments, Can. Min. Metall. Bull. 95 (2002) 84–88

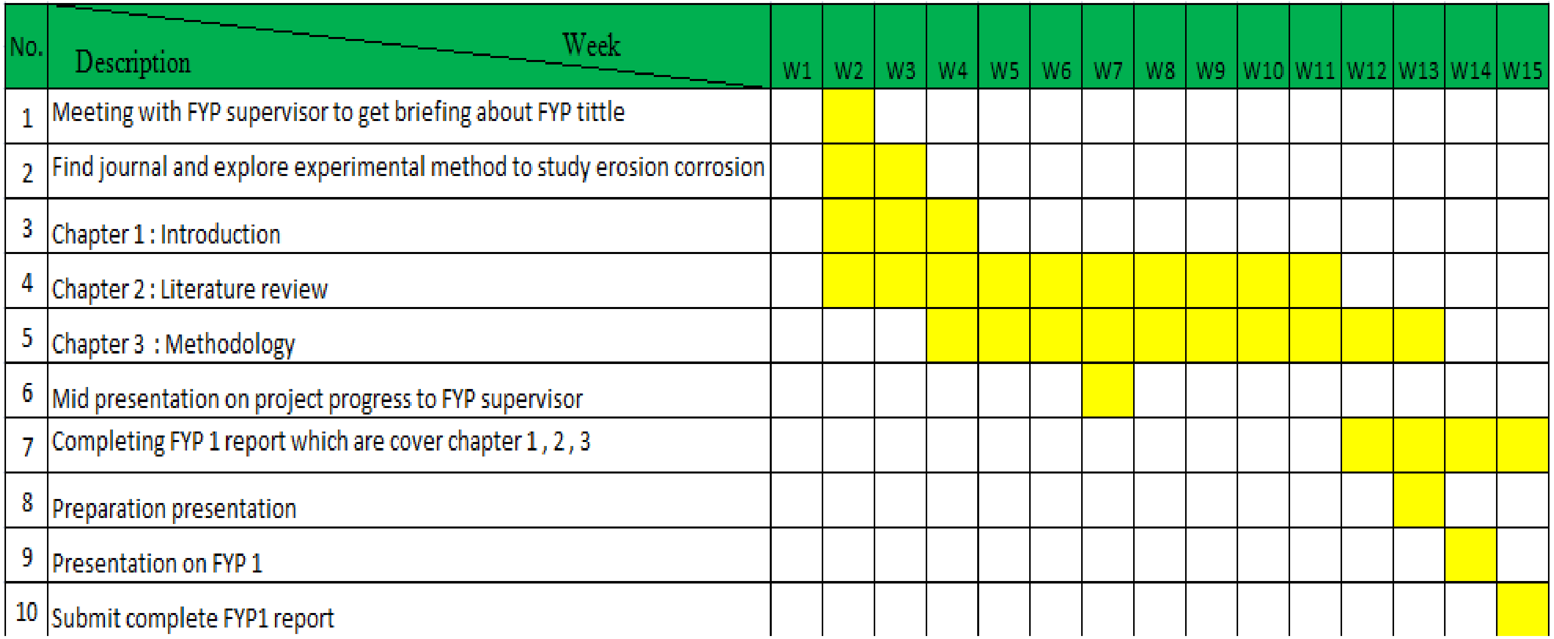
R. Norling, I. Olefjord, Erosion–corrosion of Fe- and Ni-based alloys at 550 ◦C, Wear 254 (2003) 173–184.

Weber J. Flow induced corrosion: 25 years of industrial research. Br Corros J 1992; 27(3):193–9

X.Q. Yu, M. Fan, Y.S. Sun, The erosion–corrosion behavior of some Fe3Al-base alloys at high temperatures, Wear 253 (2002) 604–609.

APPENDIX A1

GANTT CHART FYP1

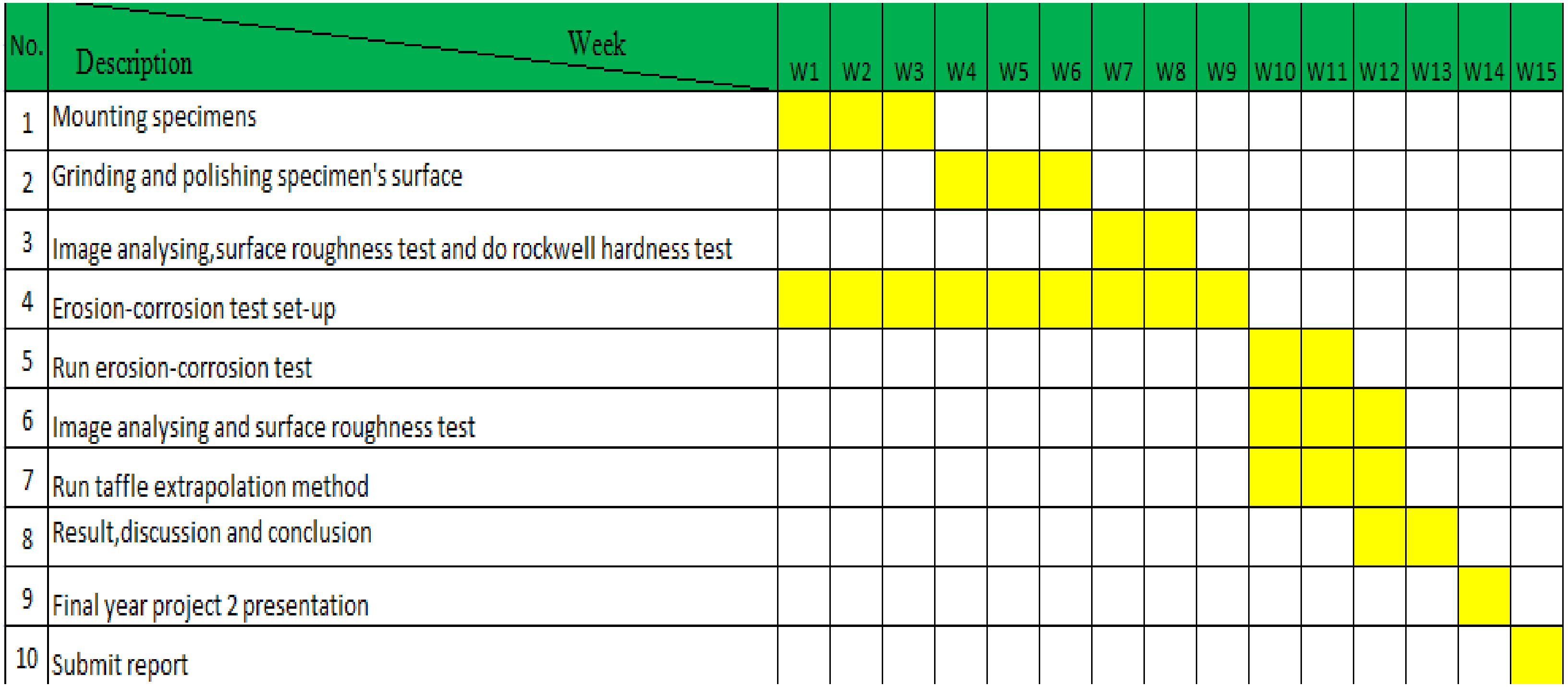


No.	Week Description	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
1	Meeting with FYP supervisor to get briefing about FYP tittle		🟨													
2	Find journal and explore experimental method to study erosion corrosion		🟨	🟨												
3	Chapter 1 : Introduction		🟨	🟨	🟨											
4	Chapter 2 : Literature review		🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨				
5	Chapter 3 : Methodology				🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		
6	Mid presentation on project progress to FYP supervisor							🟨								
7	Completing FYP 1 report which are cover chapter 1 , 2 , 3												🟨	🟨	🟨	🟨
8	Preparation presentation													🟨		
9	Presentation on FYP 1														🟨	
10	Submit complete FYP1 report															🟨

Figure 6.1: Gantt chart for FYP 1

APPENDIX A2

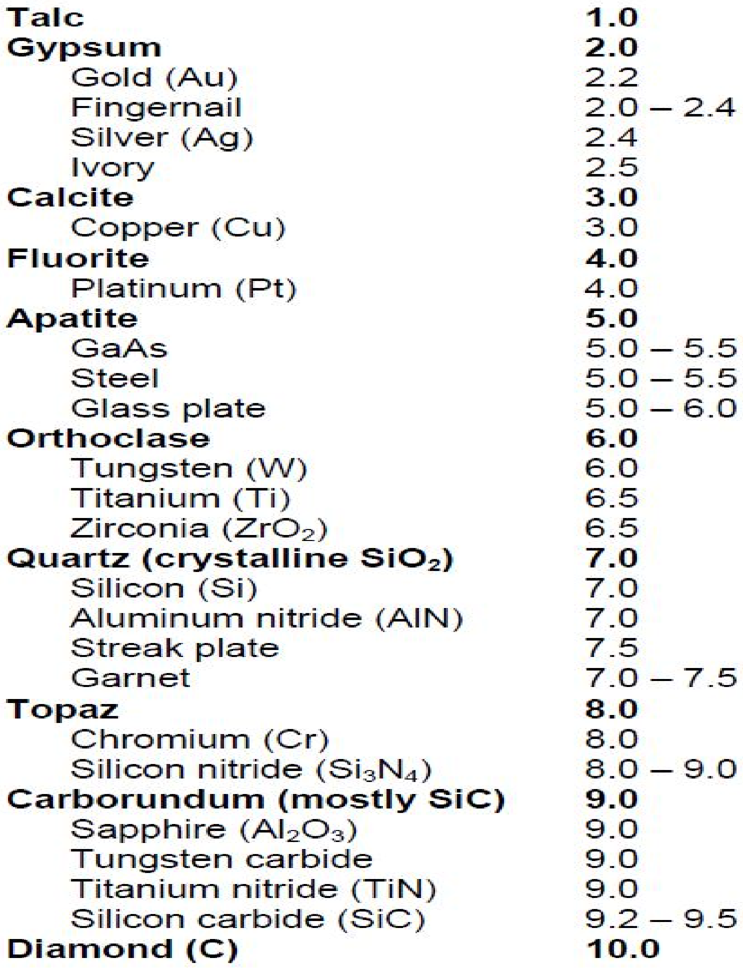
GANTT CHART FYP2



No.	Week Description	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
1	Mounting specimens	🟨	🟨	🟨												
2	Grinding and polishing specimen's surface				🟨	🟨	🟨									
3	Image analysing,surface roughness test and do rockwell hardness test							🟨	🟨							
4	Erosion-corrosion test set-up	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨						
5	Run erosion-corrosion test										🟨	🟨				
6	Image analysing and surface roughness test										🟨	🟨	🟨			
7	Run taffle extrapolation method										🟨	🟨	🟨			
8	Result,discussion and conclusion												🟨	🟨		
9	Final year project 2 presentation														🟨	
10	Submit report															🟨

Figure 6.2: Gantt chart for FYP 2

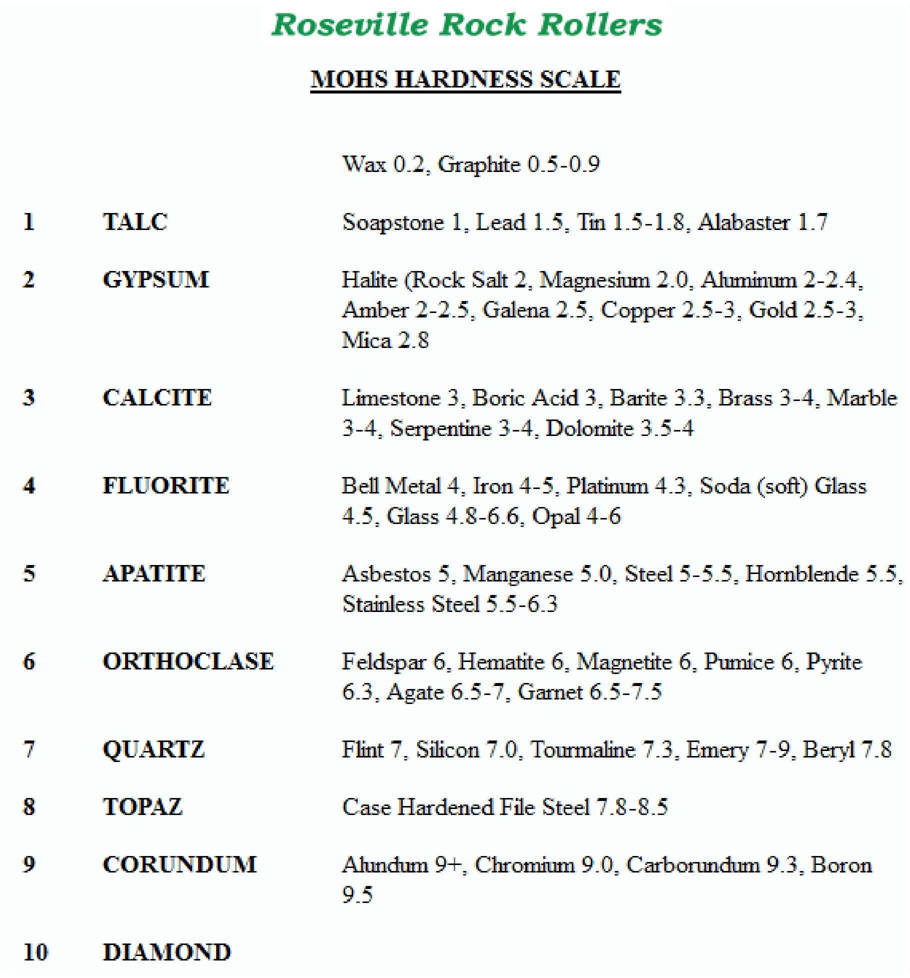
APPENDIX B



Talc	**1.0**
Gypsum	**2.0**
Gold (Au)	2.2
Fingernail	2.0 – 2.4
Silver (Ag)	2.4
Ivory	2.5
Calcite	**3.0**
Copper (Cu)	3.0
Fluorite	**4.0**
Platinum (Pt)	4.0
Apatite	**5.0**
GaAs	5.0 – 5.5
Steel	5.0 – 5.5
Glass plate	5.0 – 6.0
Orthoclase	**6.0**
Tungsten (W)	6.0
Titanium (Ti)	6.5
Zirconia (ZrO_2)	6.5
Quartz (crystalline SiO_2)	**7.0**
Silicon (Si)	7.0
Aluminum nitride (AlN)	7.0
Streak plate	7.5
Garnet	7.0 – 7.5
Topaz	**8.0**
Chromium (Cr)	8.0
Silicon nitride (Si_3N_4)	8.0 – 9.0
Carborundum (mostly SiC)	**9.0**
Sapphire (Al_2O_3)	9.0
Tungsten carbide	9.0
Titanium nitride (TiN)	9.0
Silicon carbide (SiC)	9.2 – 9.5
Diamond (C)	**10.0**

Figure 6.3: Hardness of Titanium in Mohr's Hardness scale

APPENDIX C



Roseville Rock Rollers

MOHS HARDNESS SCALE

		Wax 0.2, Graphite 0.5-0.9
1	**TALC**	Soapstone 1, Lead 1.5, Tin 1.5-1.8, Alabaster 1.7
2	**GYPSUM**	Halite (Rock Salt 2, Magnesium 2.0, Aluminum 2-2.4, Amber 2-2.5, Galena 2.5, Copper 2.5-3, Gold 2.5-3, Mica 2.8
3	**CALCITE**	Limestone 3, Boric Acid 3, Barite 3.3, Brass 3-4, Marble 3-4, Serpentine 3-4, Dolomite 3.5-4
4	**FLUORITE**	Bell Metal 4, Iron 4-5, Platinum 4.3, Soda (soft) Glass 4.5, Glass 4.8-6.6, Opal 4-6
5	**APATITE**	Asbestos 5, Manganese 5.0, Steel 5-5.5, Hornblende 5.5, Stainless Steel 5.5-6.3
6	**ORTHOCLASE**	Feldspar 6, Hematite 6, Magnetite 6, Pumice 6, Pyrite 6.3, Agate 6.5-7, Garnet 6.5-7.5
7	**QUARTZ**	Flint 7, Silicon 7.0, Tourmaline 7.3, Emery 7-9, Beryl 7.8
8	**TOPAZ**	Case Hardened File Steel 7.8-8.5
9	**CORUNDUM**	Alundum 9+, Chromium 9.0, Carborundum 9.3, Boron 9.5
10	**DIAMOND**	

Figure 6.4: Hardness of Stainless steel in Mohr's Hardness scale