

# UNIVERSITI MALAYSIA PAHANG

## BORANG PENGESAHAN STATUS TESIS

**JUDUL: EFFECT OF VELOCITY IN EROSION CORROSION**

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Saya, **MOHD KHAIRUL NA'IM B MOHD ARIFFIN (890924-08-6375)**

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Alamat Tetap:

**No 12, Taman Manik,  
36000 Teluk Intan,  
Perak Darul Ridzuan**

**NOR IMRAH BT YUSOFF**  
(Nama Penyelia)

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EFFECT OF VELOCITY IN EROSION CORROSION

MOHD KHAIRUL NA'IM BIN MOHD ARIFFIN

Thesis submitted in partial fulfillment of requirements for the award of Bachelor of  
Mechanical Engineering

Faculty Of Mechanical Engineering

UNIVERSITI MALAYSIA PAHANG

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**UNIVERSITY MALAYSIA PAHANG**  
**FACULTY OF MECHANICAL ENGINEERING**

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Signature :

Name : NOR IMRAH BINTI YUSOFF

Position :

Date :

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Signature :

Name : MOHD KHAIRUL NA'IM BIN MOHD ARIFFIN

ID Number : MA 08047

Date :

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## ABSTRACT

The present study has been conducted to investigate the interaction effect of velocity on erosion corrosion of material in aqueous slurries. Tests were performed on stainless steel samples of grade 301. Pure erosion and pure corrosion as well as erosion corrosion impingement tests were carried out at two different impact velocities 500 rpm, 1000 rpm and also without any velocity. The erosion corrosion test was carried out by immersing the specimen in an aqueous 3.5% NaCl solution and presence of sand particles. Electrochemical Erosion Corrosion Test have been conducted and reported in this thesis. The data then analyze using Ivman software to determine the value of corrosion rate. The surface image and surface roughness value was taken before and after the Electrochemical Erosion-Corrosion test. From observation of the result, when the value of velocity increases the corrosion rate also increases. Besides that, the value of surface roughness also increase when the corrosion rate increase due to present of pitting corrosion.

## ABSTRAK

Kajian ini telah dijalankan untuk mengkaji kesan interaksi halaju pada kakisan hakisan bahan di dalam larutan akueus. Ujian telah dijalankan ke atas sampel keluli tahan karat gred 301. Pengaratan hakisan dan kakisan telah dijalankan di dua kesan halaju yang berbeza 500 rpm, 1000 rpm dan juga tanpa halaju. Ujian hakisan kakisan telah dijalankan dengan merendamkan spesimen di dalam larutan akueus 3.5% NaCl dan kehadiran pasir. Ujian elektrokimia kakisan hakisan telah dijalankan dan dilaporkan di dalam tesis ini. Data diperolehi daripada ujian elektrokimia dianalisis menggunakan perisian Ivman untuk menentukan nilai kadar kakisan. Imej permukaan dan nilai kekasaran permukaan telah diambil sebelum dan selepas ujian elektrokimia kakisan hakisan. Daripada pemerhatian keputusan, apabila nilai halaju meningkatkan kadar kakisan juga meningkat. Selain itu, nilai kekasaran permukaan juga meningkat apabila kadar kakisan meningkat disebabkan kehadiran kakisan berbintik.

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**LIST OF ABBREVIATION**

NaCl	Sodium Chloride
Rpm	Rotational Per Minute
Fe	Ferrous
°C	Celsius
$e^-$	Electron
$H_2O$	Water
$O_2$	Oxygen
$OH^-$	Oxide
$Cl^-$	Chlorine
FeCl	Ferrous Chloride
SCE	Saturated Colonel Electrode
E	Potential
V	Volt
$A/cm^2$	Current Density

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 PROJECT BACKGROUND**

Erosion-corrosion actually arises from the combined action of chemical attack and mechanical abrasion or wear as a consequence of fluid motion. Virtually all metal alloys, to one degree or another, are susceptible to erosion corrosion. It is especially harmful to alloys that passivity by forming a protective surface film the abrasive action may erode away the film, leaving exposed a bare metal surface. Relatively soft metals such as copper and lead are also sensitive to this form of attack. Usually it can be identified by surface grooves and waves having contours that are characteristic of the flow of the fluid. Increasing fluid velocity normally enhances the rate of corrosion. Also, a solution is more erosive when bubbles and suspended particulate solids are present.

Erosion–corrosion is commonly found in piping, especially at bends, elbows, and abrupt changes in pipe diameter positions where the fluid changes direction or flow suddenly becomes turbulent. Propellers, turbine blades, valves, and pumps are also susceptible to this form of corrosion. In offshore well systems, the process industry in which components come into contact with sand-bearing liquids, this is an important problem. Materials selection plays an important role in minimizing erosion corrosion damage. Caution is in order when predicting erosion corrosion behavior on the basis of hardness. High hardness in a material does not necessarily guarantee a high degree of resistance to erosion corrosion. Design features are also particularly important.

Erosion-corrosion tests were carried out by immersing the materials in an aqueous solution and presence of sand particles. Combine erosion corrosion effect were

studied by partially protecting the materials from the impact of solid particles during the test. Erosion corrosion mechanisms were determined from micro structural studies by light microscopy.

## **1.2 PROBLEM STATEMENTS**

It is well known that the industries that transport slurries and other particle-laden liquids in pipes for sectors such as offshore and marine technologies spend millions of pounds every year to repair material damage. The typical examples of this kind of material destruction are erosion–corrosion damage to pumps, impellers, propellers, valves, heat exchanger tubes and other fluid handling equipment. In a recent survey, erosion–corrosion was rated in the top five most prevalent forms of corrosion damage in the oil and gas industry (P. McIntyre, 1999). When corrosion and erosion act together the damage mechanism are complex and generally the measured mass losses are higher than the sum of separate material losses due to corrosion and erosion.

So, the erosion corrosion test was carried out by immersing the specimen in an aqueous 3.5% NaCl solution and presence of sand particles. First, the value of roughness is determines. The surface micro structural also was study before start the experiment. It was done without any velocity and by two different rate of velocity which 500 rpm and 1000 rpm where the impact angle of the slurry against the surface is 90° and at the ambient temperature.

## **1.3 PROJECT OBJECTIVE**

To study the surface roughness and corrosion rate of material (stainless steel) in aqueous slurries with different rate of velocity.

## 1.4 SCOPE

The focus area will be done on the following aspect:

- (i) Different rate of velocity where 0, 500 and 1000 rpm.
- (ii) The specimen immersing in an aqueous 3.5% NaCl solution and 10 wt% presence of sand particles.
- (iii) The impact angle of the slurry against the surface is 90°.
- (iv) At ambient temperature 27°C- 30°C.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Introduction

The discussion is limited to the potential effect of fluid velocity on metal loss and the consequence on the erosion velocity. The localized corrosion rate is a function of multiple variable, which include fluid chemistry, tube metallurgy, and accelerating factor of flow rate and sand production. The effect of corrosion on solid particle erosion is to provide a brittle target for the solid particle. The combination process of erosion corrosion has a number of potential effects depending on the relative rates of each of the individual process. If the mechanical action of erosion removes or reduces the thickness of this scale, then the stifling process is reduced or does not occur. This combined process in term erosion-corrosion. It is clear that the rate of the scale growth and the rate of scale thinning govern the total metal loss. When the rate of scale growth is significantly greater than scale thinning, the scale thickness will increase, the rate of metal loses decrease and the total metal loss is due to corrosive action. When the rate of scale thinning is significant greater than the scale growth, the effect is metal loss due to pure erosion. However, the composition of the metal surface have been altered due to corrosive action and if the surface hardness is decrease due to depletion of the alloying element, then the erosion rate is greater than that which would be expected due to pure erosion. The prediction of corrosive damage is an extremely complex issue that does play a role in the erosion-corrosion process. The scale composition, scale mechanical properties, and resulting damage are specific to the chemistry of the following fluid and the metallurgy of the pipe wall. However, for the case with sand present the functional relationship for erosion velocity and sand production is similar to pure erosion even though the magnitude may be greater when corrosion is present. The rate of metal loss is increased with an increase in velocity, but the process is somewhere different.

$$W = \frac{\theta(c_e - c_\infty)}{\left(\frac{1}{k}\right) + (1-f)\left[\left(\frac{1}{h_4}\right) + \left(\frac{d}{D}\right)\right]} \quad (2.1)$$

Where:

W = wear rate

$C_e$  = equilibrium concentration of iron species

$\theta$  = porosity of open area of metal

$h_4$  = mass transfer coefficient

k = A exp, the reaction rate constant

f = fraction of oxidized metal into magnetic at the metal- oxide interface

D = Diffusion coefficient

d = oxide thickness

$C_\infty$  = iron species concentration in the bulk of the fluid

The effect of velocity was to increase the mass transfer coefficient. The conclusion is the flow of condensate increase the rate of arrival of the corrosive species to the metal surface and the rate of removal of the corrosion product from the surface and, therefore increases the rate of corrosion. (Danny M. Deffenbaugh, J. Christopher Buckingham, 1989)

## 2.2 The Mechanisms of Erosion: Brittle versus Ductile

Brittle erosion involves the impact of particles on the surface of the metal which cause cracks to propagate down through the metal surface. These cracks propagate throughout the metal and lead to chunks of metal being chipped away by repeated impact of particles. This type of erosion occurs because the metal has little tendency to strain which causes it to fracture.

As opposed to brittle erosion, ductile erosion involves the impact of particles which plastically deform the surface of the metal. The repeated impact of particles forges hardened platelets on the surface of the metal and this creates a transient response in the erosion process and this process is termed the platelet formation theory of erosion. Work hardening of the metal subsurface occurs for ductile metals undergoing

erosion due to the extensive plastic deformation at the metals surface. This leads to a transient response in the erosion process for a ductile metal at which time the surface of the metal is being work hardened and platelets are being formed. The steady-state response occurs after the platelets are formed.

The process of erosion for a ductile metal, such as carbon steel, occurs by the followings steps. First a single particle is impinged upon the surface of the target metal. This initial impingement creates a crater in the metal surface which removes little to no material. Subsequent impacts on the metal surface forge platelets from the deformations caused by the extrusion process. During this time there is also work-hardening of the metal subsurface occurring.

The impact of the particle on the surface of the metal carries a much greater force than that required to form platelets. This energy is transferred into the subsurface of the metal where the metal is cold worked, creating a less ductile subsurface below the platelet surface. The result of platelet formation is a harder surface which now allows particles to impinge and chip away at the platelets. The mechanism of erosion is dependent on the type of material that is being eroded. Harder metals will tend to erode by brittle erosion mechanisms and softer metals will erode by ductile erosion mechanisms. It should be noted that it is possible to have a metal where both mechanisms are occurring simultaneously. One example of this would be in alloyed metals with very coarse grain structure. It could be that one of the components of the alloy erodes in a ductile manner and one in a brittle manner. (Levy Av, 1995)

### **2.2.1 Particle Impact and Velocity**

It would be expected that as the velocity of the particle increases the greater the erosion damage upon impact and much experimental evidence from researchers such as Levy.(Levy Av, 1995), (Nesic and Postlethwaite, 1993), ( Salama, 2004) have shown this.

$$\text{Kinetic energy} = \frac{1}{2} MV^2 \quad (2.2)$$

Where:

M = mass

V = velocity

The faster a particle moves the more kinetic energy it has based on the equation for kinetic energy equation 2.2. Therefore, it would be expected that as the velocity increases the erosion rate would increase and most likely in non-linear manner. If the erosion rate is proportional to the kinetic energy of the particle then it would be likely that erosion rate is proportional to the square of the velocity. However, only part of the velocity component is lost upon impact on the metal surface because the particle is under constant movement due to flow and therefore not all of the particles energy is transferred to the metal surface (Levy ,1995).It should be noted that increasing the velocity increases the erosion rate for both brittle and ductile metals although they erode by different mechanisms.

Surface analysis for 1018 carbon steel shows that erosion tests using an impingement jet with velocities ranging from 15-130 m/s show that the mechanism of platelet formation occurs over this entire range of velocities. This suggests that the mechanism of erosion does not change with increasing velocity for a ductile metal (Levy, 1995). The corrosion rate on the surface is enhanced as the bare metal is exposed following erosion or the coating adhesion is affected. At higher velocity the crater volume will increase due to the higher particle kinetic energies. The literature also suggests that with increasing velocities the corrosion currents will increase due to the higher mass transfer at such velocities and hence will also enhance the formation of passive films by the transport of oxygen to the reaction site. The frequency of the particles impacting the surface will increase as the velocities increases causing a change in the rate of depassivation and repassivation leading corrosion currents to increase

### **2.2.2 Particle Size**

The reason for this is because as the particle increases in size the surface area of the particle increases as well (Levy, 1995). This means there is more particle surface which will contact the metal surface upon impact which will lead to the force upon

impact being spread out over a wider area (Levy, 1995). This will lead to a shallower depth of penetration and therefore the erosion damage will not significantly change even though the mass and size of the particle is greater. Another reason for this phenomenon is that as particles increase in size there are more particle interactions which may inhibit certain particles from contacting the metal surface. Larger particles at the metal surface may hinder other particles from coming in contact with the surface. Particles less than 175 micron yielded lower erosion rates than those in the range of 175-900 microns given above (Nesis.S and J.postlethwaite, 1993). This is because the smaller particles have less kinetic energy and therefore cause less erosion damage (Levy, 1995).

### 2.2.3 Particle Shape

Sharper particles tend to have higher erosion rates associated with them than duller, more spherical shaped particles. This is because sharper particles can penetrate deeper into the metal surface ( Levy, 1995) ( Nesis.S and J.postlethwaite, 1993). Sharper particles also have a smaller contact area at the metal surface so the force generated is much larger. A spherical shaped particle has little penetration power and the exposed area is greater which means there is the same amount of force exerted as a sharper particle but over a larger area of the metal surface. Although smooth, spherical particles do erode metals, the erosion rates are significantly less than sharper particles such as sand ( Nesis.S and J.postlethwaite, 1993).

### 2.2.4 Metal Loss Rate

The simplest method for measuring the erosion rate of a material is by measuring the weight loss of a metal sample before and after being subjected to an erosive condition (Levy A.V, 1995). In this study the erosion rates will be calculated using the following equation 2.2 .(Jones, Denny A 1996)

$$\text{Metal Loss Rate} = \frac{W}{\rho / A.T} \quad (2.3)$$

Where  $W$  is the weight loss,  $\rho$  is the density of the metal,  $A$  is the exposed area, and  $T$  is time. This calculation can be used for corrosion and erosion weight loss data to determine the metal loss rate.

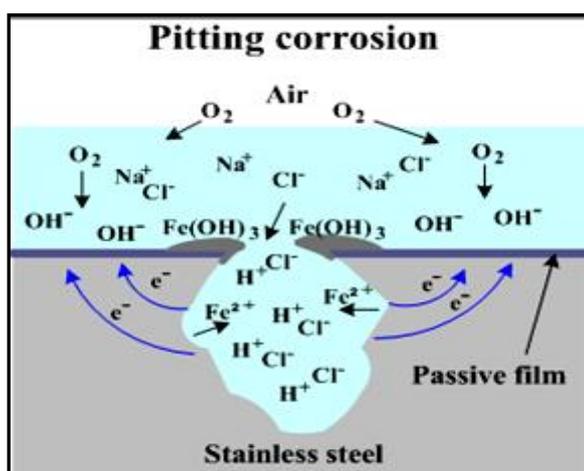
## 2.3 Erosion corrosion mechanism

Corrosion of metals takes place through the action of electrochemical cells. Although this single mechanism is responsible, the corrosion can take many forms. Through an understanding of the electrochemical cell and how it can act to cause the various forms of corrosion, the natural tendency of metals to corrode can be overcome and equipment that is resistant to failure by corrosion can be designed.

The corrosion resistance of stainless steel is achieved through the formation of a thin chromium oxide film layer on the surface of the material (Callister WD, 2007). However, when this material is exposed to erosion-corrosion condition, the mechanical damage of the passive film from the solid particle suspended in the corrosive fluid can lead to passive film breakdown. (Renoult L.Abrasion et al., 1998)

### 2.3.1 Basics of $\text{Fe}^{2+}$ Corrosion

#### a) Pitting Initiation



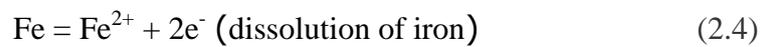
**Figure 2.1:** Pitting Corrosion

(Source: Dr. Dmitri Kopeliovich, 2008)

At the initial pit a film forms on the surface as a passive oxide film. Affect from the scratches it makes a mechanical damage on the passive film then the anodic reaction will expose to the electrolyte. The passivated surrounding will act as the cathode. Particles on a second phase will emerge on the metal surface the particles receiving along the grain boundaries may function as local anodes causing formation of initial pits.

#### b) Pitting Growth

Present the chloride ions will initiate the pitting growing. The anodic reaction inside the pit:



The electron that will be given up by the anode flows to the cathode (passivated surface) where they are discharged in the cathodic reaction:



As a result, this reaction will on the electrolyte enclosed in the pit gain positive electrical charge in contrast to the electrolyte surrounding the pit, which becomes negatively charged. Then the positive charged pit attracts negative ions of chlorine  $\text{Cl}^-$  to increasing acidity of the electrolyte according to the reaction.



From the equation the pH value of the electrolyte inside the pit decreases from 2 until 3 which causes a further acceleration in the corrosion process. Then the corrosion rate will increase because of the large ratio between the anode and cathode. Corrosion products ( $\text{Fe}(\text{OH})_3$ ) form around the pit resulting in further separation of its electrolyte.

### 2.3.2 Measuring Corrosion Rate

The corrosion process can be monitored in order to determine the actual rate of metal loss occurring on the target metal. Electrochemical measurements can be made in order to determine the actual current flowing through the target metal. This current is

called the corrosion current and is directly proportional to the corrosion rate. As the potential between the corroding metal and the cathode gets larger, the corrosion current increases up to a point where the current no longer changes with increasing potential difference. This point is called the limiting current and is limited due to the transfer of charges from the metal to the cathode. When the limiting current is reached there are more electrons at the metal surface than the cathodic specie can consume.( Jones and Denny, 1996)

The corrosion rate can be obtained through the use of a potentiostat. A potentiostat controls the voltage difference between a working electrode and a reference electrode. The working electrode is the metal which is being tested and the potentiostat controls the potential of the metal and measures the current passing through the working electrode. The reference electrode is used to measure the potential of the working electrode. Since potential is relative there needs to be a stable reference electrode that maintains the same potential throughout the experiment. The electrons flow from the working electrode to the counter or auxiliary electrode which completes the circuit. ( Jones and Denny, 1996)

In order to test the corrosion rate of a metal, the corrosion potential of the target metal is tested first. The corrosion potential is the potential of the non-polarized target metal in the corrosive solution. A potentiodynamic sweep polarizes the target metal at a given voltage above and below the corrosion potential. The current is monitored at each incremental change in the potential difference. At potentials lower than the corrosion potential (more negative) the sweep shows the current versus potential curve for the cathodic reactions and at potentials higher than the corrosion potential (more positive) the sweep shows the current versus potential curve for the anodic reaction. The corrosion current can be measured directly from the plot of the potentiodynamic sweep by extending the linear portions of the anodic and cathodic curves until they cross at the corrosion potential. The current at which these two lines intersect is the corrosion current.

When the potential of an electrode is plotted as a function of the logarithm of current density, then this is called a Tafel plot(Jones and Denny, 1996). The straight line

portions of the curves which can be extrapolated to determine the corrosion current are called the Tafel lines (Nesic et al., 2003). The slope of the Tafel lines is defined as the Tafel slope. The equation for each Tafel line is given as :

$$\eta = \frac{2.3 RT}{\alpha n F} \log_0 i - \frac{2.3 RT}{\alpha n F} \log i \quad (2.7)$$

Where  $\eta$  is the over potential, R is the ideal gas law constant, T is temperature,  $\alpha$  is the cathodic electron transfer coefficient, n is the number of equivalents exchanged, and F is Faraday's constant (96,500 coulombs/equivalent),  $i_0$  is the exchange current density, and I is the current at the given over potential. (Jones and Denny, 1996).

As the over potential is shifted more negatively then the cathodic reaction or reactions will be accelerated and the anodic reaction will be decreased (Jones and Denny, 1996). The difference between the increase in the cathodic reduction rate and the decrease in the anodic oxidation rate is equal to the applied current:

$$i_{app,c} = i_c - i_a \quad (2.8)$$

As the cathodic over potential increases there is a point where the anodic current density becomes insignificant when compared to  $i_c$  and therefore the straight line portions of the Tafel plot are seen. This linear behavior at high cathodic over potentials is referred to as Tafel behavior.

Using the polarization resistance method the corrosion current can be directly measured from polarization data. For small deviations in the over potential (up to 20 mV from the corrosion potential) the plot of over potential versus applied current is linear. The slope of this line is the polarization resistance for the electrode. (Jones, Denny A, 1996).

$$R_p = \frac{\Delta E}{\Delta i_{app}} \quad (2.9)$$

The corrosion current can be measured directly from the polarization resistance using the proportionality constant. The proportionality constant is calculated from the anodic and cathodic Tafel slopes,  $\beta_a$  and  $\beta_c$ , from the following equation. (Jones, Denny A, 1996):

$$B = \frac{\beta_a \beta_c}{2.3 (\beta_a + \beta_c)} \quad (2.10)$$

The corrosion current can then be calculated from the proportionality constant and the polarization resistance from the equation :

$$i_{corr} = \frac{B}{R_p} \quad (2.11)$$

### 2.3.3 Correlation Between Current Flow and Weight Loss

For each specific anodic reaction a characteristic number of electrons are produced in the reaction of one metal ions. Thus, all other things being equal, the metal loss is proportional to the number of electrons that are produced. As the electrons produced migrate to cathodic areas through the electron path, the metal loss is proportional to the current flow. In cases where more positively charged ions are produced, more electrons flow for a given number of corroding metal atoms but the current flow remains proportional to the metal loss. (NAVFAC, 1992)

## 2.4 Electrochemical Impedance Spectroscopy (EIS)

In an electrochemical cell there is a solution resistance that creates a voltage drop along the path of the current. Therefore, the potential measured between the reference and working electrode has an error associated with it due to the resistance of the solution. This solution resistance is increased as the reference electrode is moved farther from the working electrode. In corrosion measurement techniques there is always going to be some distance between the reference and working electrode and thus solution resistance will cause an inaccuracy in the corrosion rate measurement. All electrochemical cells have a solution resistance; however, for some testing this solution

resistance may be insignificant when compared to the overall polarization resistance of the working electrode. If the solution resistance is significant then it is subtracted from the polarization resistance measured on the working electrode.

To correct for solution resistance the reference and working electrode can be considered a capacitor with the solution between them acting as the dielectric. When a direct current is passed through an electrochemical cell the resistance through the system is a sum of the solution resistance (capacitance) and the polarization resistance of the working electrode. High frequency alternating currents passed through the electrochemical cell will directly measure the solution resistance of the electrochemical cell by measuring the resistance of the equivalent ohmic resistive element. At very low alternating current frequencies the current is more like a direct current and the resistance measured is once again the sum of the ohmic solution resistance and the polarization resistance. Using a large range of frequencies, the polarization resistance of the working electrode can be determined by taking the difference between the low end alternating frequency currents and the high frequency currents. This procedure for measuring solution resistance is called electrochemical impedance spectroscopy (EIS). (Jones and Denny, 1996):

## **2.5 Microbiological effects on corrosion in seawater**

Seawater is an excellent electrolyte. The presence of a large amount of dissolved salts, sodium chloride (NaCl), that are ionized make it an excellent conductor. The chloride ions are particularly aggressive as it causes a breakdown of passivity. The chloride ion is also particularly aggressive as most chloride compounds are highly soluble, which limits the formation of polarizing anodic films. Seawater also usually contains enough dissolved oxygen for reducing water to be the prevalent cathodic reaction in most cases. (NAVFAC, 1992)

The exposure of any material to natural seawater initiates a series of sequential and parallel biological and chemical events that culminate in the formation of a complex layer of inorganic, organic, and cellular components known as biofouling. The accumulation of bacteria, fungi, and microalgae and their secretions is collectively

termed a biofilm (W.G Characklis and K.C marshall,1990)(L.V. evans Ed et al.,2000). Within two hours of immersion, a non-living organic conditioning film develops on a solid surface. Within the first 1-2 days, a bacterial slime film develops over the conditioning film. A slime film creates a partial barrier to diffusion between the liquid/metal interface and the bulk seawater environment. Speciation within a biofilm has its own growth parameters and there appear to be spatial distributions of growth (E.J.Wentland et al,1996). Biofilms are capable of forming and maintaining environments at biofilm/surface interfaces that are radically different from the bulk fluid in terms of pH, dissolved oxygen, and other organic and inorganic species. Biofilms may facilitate reactions that are not predicted thermodynamically based on the bulk medium chemistries (M.McNeil et al.,1991). Some biofilms introduce new redox reactions available to the corrosion process, particularly to the cathodic reaction. Biofilms have been shown to cause a noble shift, or ennoblement, in the open circuit potential (OCP) of stainless steels, nickel-base, or titanium alloys exposed in marine environments which can lead to accelerated corrosion( B.H.Olesen et al.,2000). Microbiological activity may be the sole accelerant to corrosion, cause no changes, or as an inhibitor to corrosion depending on the active species, the materials, and the specific nutrients and environmental conditions. Microbiological activity may also contribute to other corrosion mechanisms.

## **2.6 Forms Of Corrosion**

It is convenient to classify corrosion according to the manner in which it is manifest. Metallic corrosion is sometimes classified into eight forms: uniform, galvanic, crevice, pitting, intergranular, selective leaching, erosion corrosion, and stress corrosion. The causes and means of prevention of each of these forms are discussed briefly. In addition, we have elected to discuss the topic of hydrogen embrittlement in this section. Hydrogen embrittlement is, in a strict sense, a type of failure rather than a form of corrosion; however, it is often produced by hydrogen that is generated from corrosion reactions.

## 2.6. Uniform attack

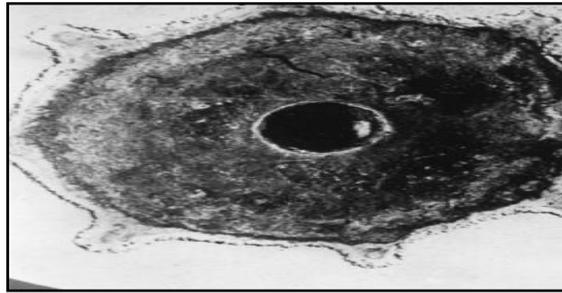
Uniform attack is a form of electrochemical corrosion that occurs with equivalent intensity over the entire exposed surface and often leaves behind a scale or deposit. In a microscopic sense, the oxidation and reduction reactions occur randomly over the surface. Some familiar examples include general rusting of steel and iron and the tarnishing of silverware. This is probably the most common form of corrosion. It is also the least objectionable because it can be predicted and designed for with relative ease.

### 2.6.2 Galvanic corrosion

Galvanic corrosion occurs when two metals or alloys having different compositions are electrically coupled while exposed to an electrolyte. The less noble or more reactive metal in the particular environment will experience corrosion; the more inert metal, the cathode, will be protected from corrosion. For example, steel screws corrode when in contact with brass in a marine environment; or if copper and steel tubing are joined in a domestic water heater, the steel will corrode in the vicinity of the junction. Depending on the nature of the solution, one or more of the reduction reactions. Figure 2.2 shows galvanic corrosion.

A number of measures may be taken to significantly reduce the effects of galvanic corrosion. These include the following:

- i. If coupling of dissimilar metals is necessary, choose two that are close together in the galvanic series.
- ii. Avoid an unfavorable anode-to-cathode surface area ratio; use an anode area as large as possible.
- iii. Electrically insulate dissimilar metals from each other.
- iv. Electrically connect a third, anodic metal to the other two; this is a form of cathodic protection, discussed presently.

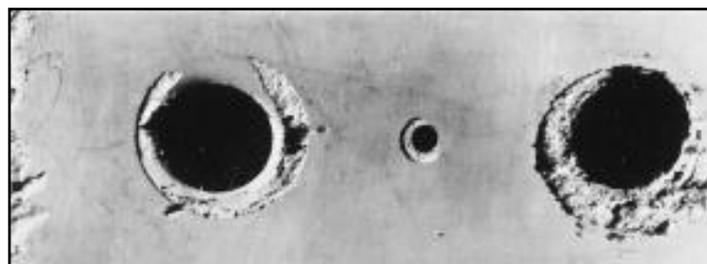


**Figure 2.2:** Galvanic corrosion of a magnesium shell that was cast around a steel core.

(Source: McGraw-Hill ,1986)

### 2.6.3 Crevice corrosion

A good example of this type of corrosion occurs in crevices and recesses or under deposits of dirt or corrosion products where the solution becomes stagnant and there is localized depletion of dissolved oxygen. Corrosion preferentially occurring at these positions is called crevice corrosion figure 2.3. The crevice must be wide enough for the solution to penetrate, yet narrow enough for stagnancy; usually the width is several thousandths of an inch. Crevice corrosion may be prevented by using welded instead of riveted or bolted joints, using nonabsorbent gaskets when possible, removing accumulated deposits frequently, and designing containment vessels to avoid stagnant areas and ensure complete drainage.

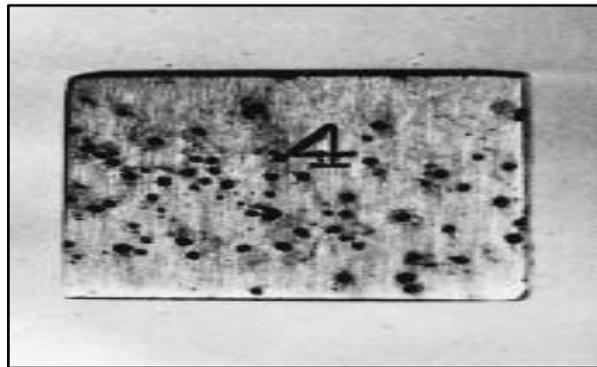


**Figure 2.3:** On this plate, which was immersed in seawater, crevice corrosion has occurred at the regions that were covered by washers.

(Source: McGraw-Hill 1986)

### 2.6.4 Pitting

Pitting is another form of much localized corrosion attack in which small pits or holes form. They ordinarily penetrate from the top of a horizontal surface downward in a nearly vertical direction. It is an extremely insidious type of corrosion, often going undetected and with very little material loss until failure occurs. An example of pitting corrosion is shown in Figure 2.4. The mechanism for pitting is probably the same as for crevice corrosion in that oxidation occurs within the pit itself, with complementary reduction at the surface. It is supposed that gravity causes the pits to grow downward, the solution at the pit tip becoming more concentrated and dense as pit growth progresses. A pit may be initiated by a localized surface defect such as a scratch or a slight variation in composition.



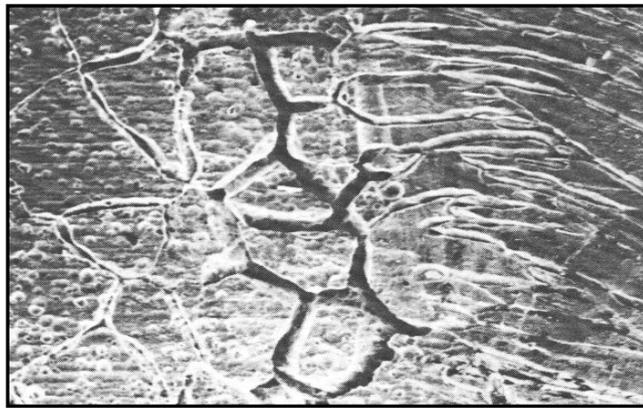
**Figure 2.4:** The pitting of a 304 stainless steel plate by an acid-chloride solution.

(Source: McGraw-Hill 1986)

### 2.6.5 Intergranular corrosion

As the name suggests, intergranular corrosion occurs preferentially along grain boundaries for some alloys and in specific environments. The net result is that a macroscopic specimen disintegrates along its grain boundaries. This type of corrosion is especially prevalent in some stainless steels. When heated to temperatures between 500 and 800\_C (950 and 1450\_F) for sufficiently long time periods, these alloys become sensitized to intergranular attack. It is believed that this heat treatment permits the

formation of small precipitate particles of chromium carbide ( $\text{Cr}_{23}\text{C}_6$ ) by reaction between the chromium and carbon in the stainless steel. Intergranular corrosion is an especially severe problem in the welding of stainless steels, when it is often termed weld decay. Figure 2.5 shows this type of intergranular corrosion. Stainless steels may be protected from intergranular corrosion by the following measures: (1) subjecting the sensitized material to a high-temperature heat treatment in which all the chromium carbide particles are redissolved, (2) lowering the carbon content below 0.03 wt% C so that carbide formation is minimal, and (3) alloying the stainless steel with another metal such as niobium or titanium, which has a greater tendency to form carbides than does chromium so that the Cr remains in solid solution.



**Figure 2.5:** Weld decay in a stainless steel.

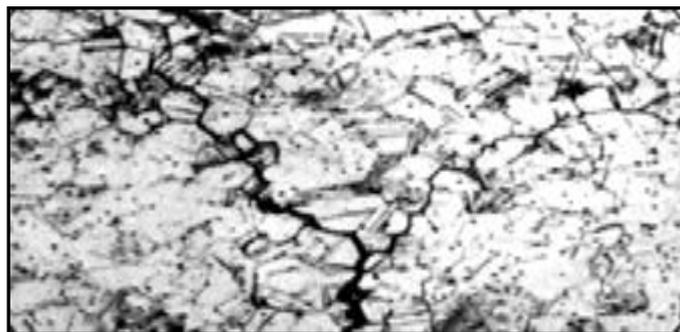
(Source: John Wiley, 1985)

### 2.6.6 Selective leaching

Selective leaching is found in solid solution alloys and occurs when one element or constituent is preferentially removed as a consequence of corrosion processes. The most common example is the dezincification of brass, in which zinc is selectively leached from a copper–zinc brass alloy. The mechanical properties of the alloy are significantly impaired, since only a porous mass of copper remains in the region that has been dezincified. In addition, the material changes from yellow to a red or copper color. Selective leaching may also occur with other alloy systems in which aluminum, iron, cobalt, chromium, and other elements are vulnerable to preferential removal.

### 2.6.7 Stress corrosion

Stress corrosion, sometimes termed stress corrosion cracking, results from the combined action of an applied tensile stress and a corrosive environment; both influences are necessary. In fact, some materials that are virtually inert in a particular corrosive medium become susceptible to this form of corrosion when a stress is applied. Small cracks form and then propagate in a direction perpendicular to the stress (see the chapter-opening photograph for this chapter), with the result that failure may eventually occur. Failure behavior is characteristic of that for a brittle material, even though the metal alloy is intrinsically ductile. Furthermore, cracks may form at relatively low stress levels, significantly below the tensile strength. Most alloys are susceptible to stress corrosion in specific environments, especially at moderate stress levels. For example, most stainless steels stress corrode in solutions containing chloride ions, whereas brasses are especially vulnerable when exposed to ammonia. Figure 2.6 is a photomicrograph in which an example of intergranular stress corrosion cracking in brass is shown. Probably the best measure to take in reducing or totally eliminating stress corrosion is to lower the magnitude of the stress. This may be accomplished by reducing the external load or increasing the cross-sectional area perpendicular to the applied stress. Furthermore, an appropriate heat treatment may be used to anneal out any residual thermal stresses.



**Figure 2.6:** Photomicrograph showing intergranular stress corrosion cracking in brass.

(Source: John Wiley, 1985)

### **2.6.8 Hydrogen embrittlement**

Various metal alloys, specifically some steels, experience a significant reduction in ductility and tensile strength when atomic hydrogen (H) penetrates into the material. This phenomenon is aptly referred to as hydrogen embrittlement; the terms hydrogen induced cracking and hydrogen stress cracking are sometimes also used. Strictly speaking, hydrogen embrittlement is a type of failure; in response to applied or residual tensile stresses, brittle fracture occurs catastrophically as cracks grow and rapidly propagate. In order for hydrogen embrittlement to occur, some source of hydrogen must be present, and, in addition, the possibility for the formation of its atomic species. Some of the techniques commonly used to reduce the likelihood of hydrogen embrittlement include: reducing the tensile strength of the alloy via a heat treatment; removal of the source of hydrogen; “baking” the alloy at an elevated temperature to drive out any dissolved hydrogen; and substitution of a more embrittlement-resistant alloy.

### **2.6.9 Erosion corrosion**

Erosion-corrosion arises from the combined action of chemical attack and mechanical abrasion or wear as a consequence of fluid motion. Virtually all metal alloys, to one degree or another, are susceptible to erosion–corrosion. It is especially harmful to alloys that passivate by forming a protective surface film; the abrasive action may erode away the film, leaving exposed a bare metal surface. The nature of the fluid can have a dramatic influence on the corrosion behavior. Increasing fluid velocity normally enhances the rate of corrosion. Also, a solution is more erosive when bubbles and suspended particulate solids are present. Erosion–corrosion is commonly found in piping, especially at bends, elbows, and abrupt changes in pipe diameter-positions where the fluid changes direction or flow suddenly becomes turbulent. Propellers, turbine blades, valves, and pumps are also susceptible to this form of corrosion. Figure 2.7 illustrates the impingement failure of an elbow fitting.



**Figure 2.7:** Impingement failure of an elbow that was part of a steam condensate line.

(Source: McGraw-Hill, 1986)

## 2.7 Surface roughness test

Surface roughness, often shortened to roughness, is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small the surface is smooth. Roughness is typically considered to be the high frequency, short wavelength component of a measured surface. Roughness plays an important role in determining how a real object will interact with its environment. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces. Roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks or corrosion. Although roughness is usually undesirable, it is difficult and expensive to control in manufacturing. Decreasing the roughness of a surface will usually increase exponentially its manufacturing costs. This often results in a trade-off between the manufacturing cost of a component and its performance in application. By convention every 2D roughness parameter is a capital R followed by additional characters in the subscript. The subscript identifies the formula that was used, and the R means that the formula was applied to a 2D roughness profile. Different capital letters imply that the formula was applied to a different profile. For example,  $R_a$  is the arithmetic average of the roughness profile,  $P_a$  is the arithmetic average of the unfiltered raw profile, and  $S_a$  is the arithmetic average of the 3D roughness.

$$R_a = \frac{1}{n} \sum y_i \quad (2.12)$$

The average roughness,  $R_a$ , is expressed in units of height. In the Imperial (English) system,  $R_a$  typically expressed in "millionths" of an inch. This is also referred to as "microinches" or sometimes just as "micro" (however the latter is just slang). In the metric system,  $R_a$  is typically expressed as "millionths of a meter" also called "micrometers" or "microns". (Mark Malburg, Surface Texture)

## CHAPTER 3

### METHODOLOGY

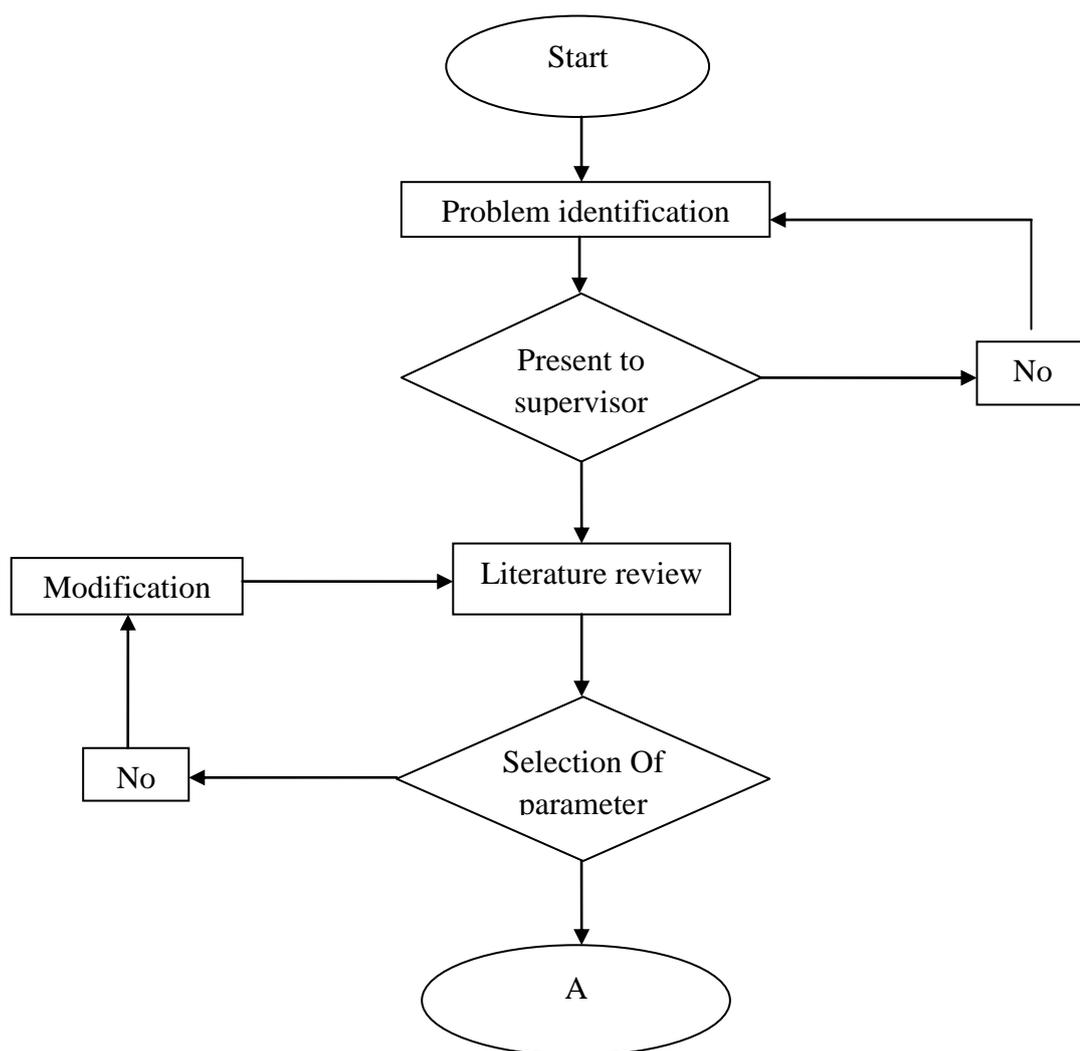
#### 3.1 INTRODUCTION

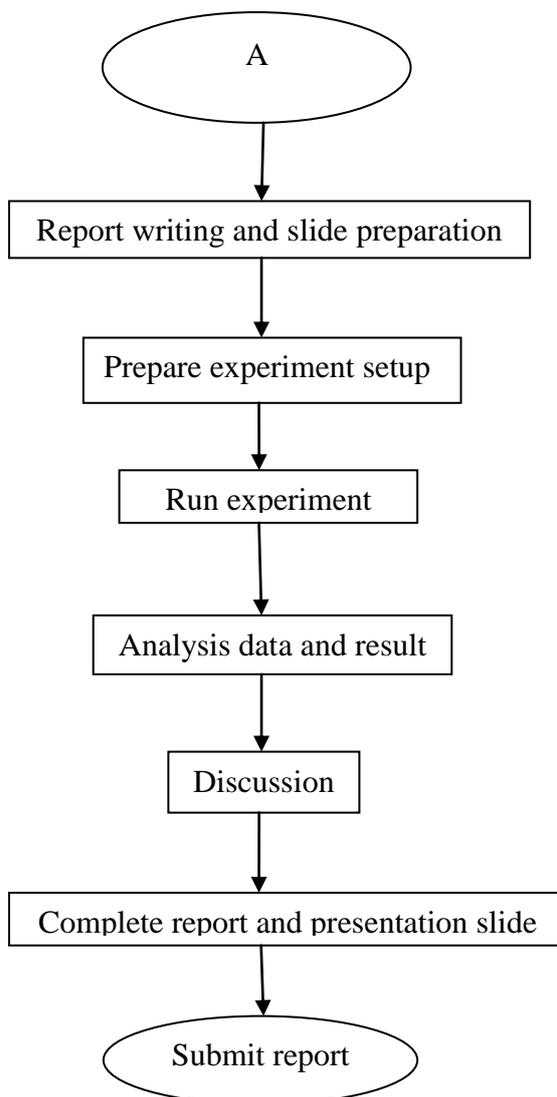
In this project, there were aim in the Corrosion laboratory (erosion corrosion test) and inspection of erosion corrosion parameter before and after the process. Erosion corrosion test were carried out by immersing the specimen in an aqueous 3.5% NaCl solution and presence of sand particles. This project consists an experiments where combined erosion corrosion. This experiment is with present of the velocity and without a velocity where the velocity with 500 and 1000 rpm and the impact angle of the slurry against the surface is 90° at ambient temperature 27°C- 30°C. The erosion corrosion was test only a few minute. The specimen were prepare with electrochemical test 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. The experiment specimen was analyst with the corrosion rate, surface microstructure analysis and roughness test. Before running the project, a flow chart is shown in figure 3.1 which represent the planning for the whole project. Besides that, there is the Gantt chart on the whole project shown in table 3.1

#### 3.2 DESIGN OF EXPERIMENT

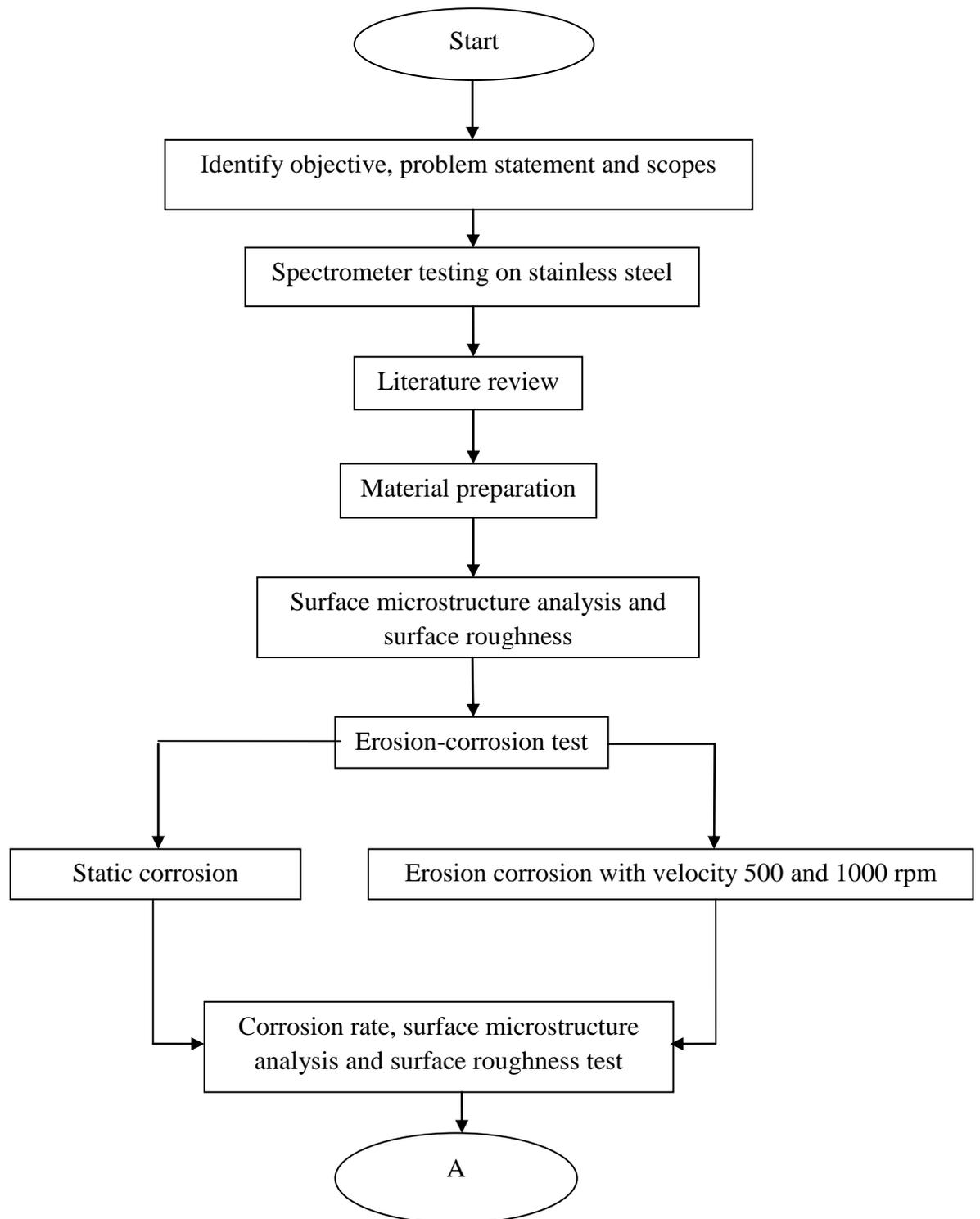
This corrosion laboratory was prepared to investigate the effect of the surface properties and change in microstructure of stainless steel by using corrosion test. In this process it consisted of specimen preparation, composition analysis, corrosion rate and

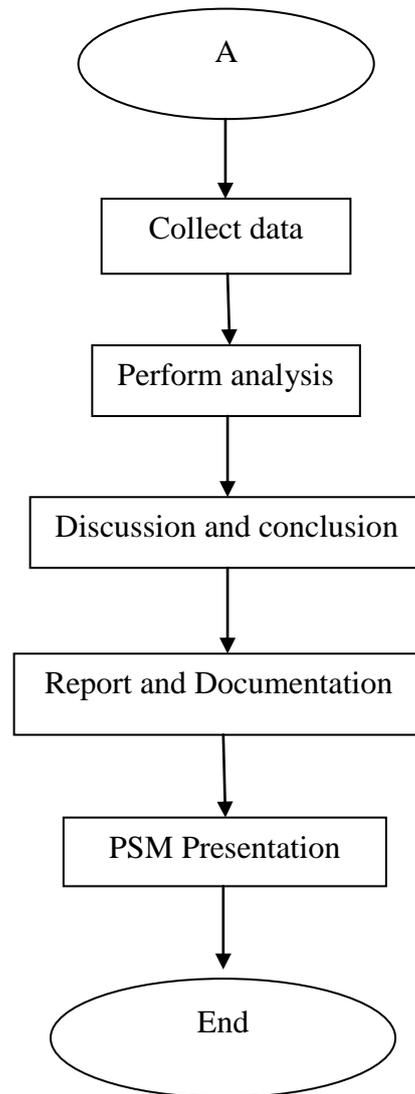
cold mounting process. Before start the experiment, a methodology flow chart of experiment flow was shown in figure 3.2.





**Figure 3.1:** Flow chart PSM





**Figure 3.2:** Experiment setup

### 3.2.1 Specimen preparation

At the first, the material was cut using a band saw machine with a 15mm length and 30mm in diameter. After that, the material was turning and facing using a lathe turning machine to reduce the length and diameter. The size of the specimen that we need is 5mm in length and 15mm diameter. Total number of work piece that need for this experiment a nine. The work piece was dividing by three for different testing. After that, the average value was calculated to get more accuracy result.



**Figure 3.3:** Specimen cutting process

### 3.2.2 Composition analysis

In metal analysis, a spark emission spectrometer was used to analysis the composition of the metal before erosion corrosion test as shown in figure 3.4. The specimen must be flat enough before undergo the testing composition analysis process. Generally, there are two possible that the specimen is not flat which have other element on the surface of specimen such as corrosion and the grinding error during do a finishing. The sparking emission light reflected out from the specimen and this cause the reading taken by spectrometer is not correctly or not accurate. Therefore the entire specimen must undergo the grinding process before the metal analysis.

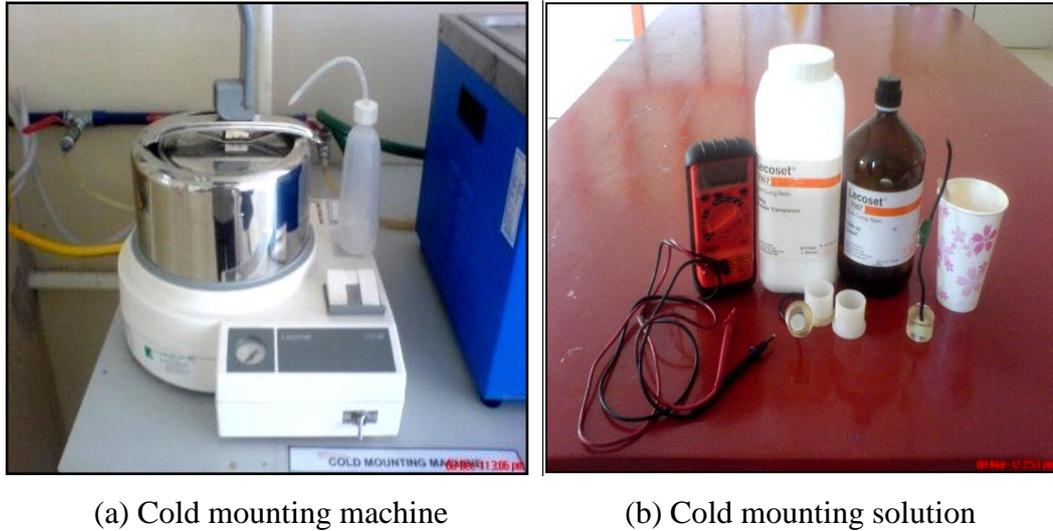


**Figure 3.4:** Spark emission spectrometer

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

### **3.2.3 Cold mounting process**

To avoid another surface open to the slurry, the cold mounting process was do. Figure 3.5a shown the cold mounting machine. The specimen was mounting to an electrical wire as shown in figure 3.5b. Cold mounting is especially suited for mounting specimens that is sensitive to heat or pressure. Additionally, cold mounting does not require an investment in a mounting press and is therefore good for infrequent mounting tasks. 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.



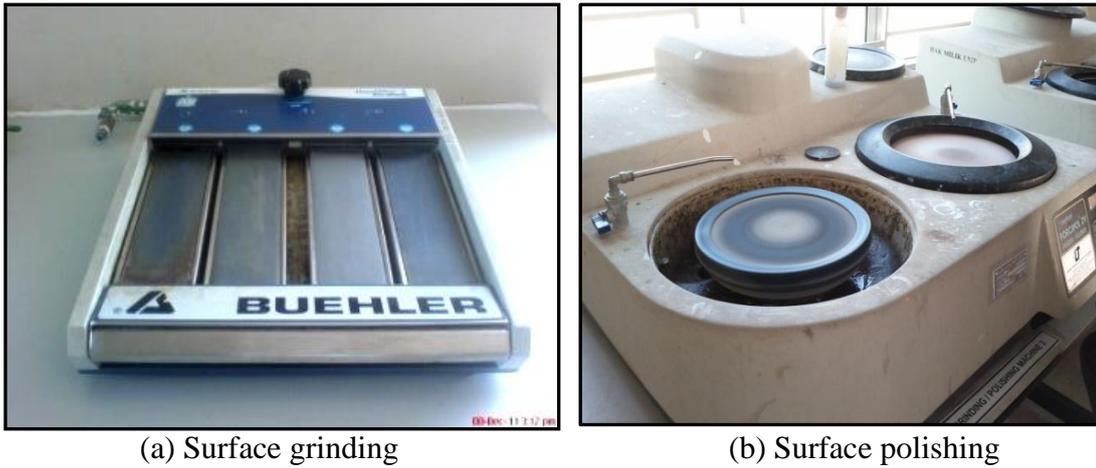
**Figure 3.5:** The cold mounting process

The resin is a mixture of two components where the solution and a powder. Then it was poured over the specimen after it has been placed in a mounting cup. After curing, the specimen can be taken out of the cup and processed.

### 3.2.4 Surface Grinding and Polishing.

To get a smooth surface finish it was following by the vertical grinding machine which has divide into four grade and grid it with follow the order from low grade to the highest grade as shown in figure 3.6a. The grades that involve are 240X, 320X, 400X and 600X. The best integrity grinding method is grinded the specimen only in one direction either is vertically from bottom to top or vertically from top to bottom for each grade for 4 minute.

After that, to make the work piece surface look like a mirror surface a polishing process was doing. There are three steps to do a surface polishing where first with 6  $\mu\text{m}$  in sized, 2<sup>nd</sup> with 1  $\mu\text{m}$  and for the last with 0.5  $\mu\text{m}$ . The specimen then was cleaning with distilled water.



**Figure 3.6:** Surface finishing

### 3.3 INSPECTION OF EROSION CORROSION PARAMETER.

Inspection of erosion corrosion parameter was prepared to observe and determine the material behavior and mechanical properties corresponding to each of the specimen. There were two time of inspection to be done which are before and after the material undergo erosion corrosion test. The test of preparation to check the microstructure inspection, measuring weight, Rockwell hardness test, and surface roughness test.

#### 3.3.1 Microstructure analysis

After the specimen is dried, the microstructure of the specimen is observed by using microscope knows as Image Analyzer as shown in figure 3.7. The microstructure is then capture and saved. Different magnificent power is used to observed and capture the microstructure of the specimen. This step was doing before and after an electrochemical erosion corrosion test to compare their result.



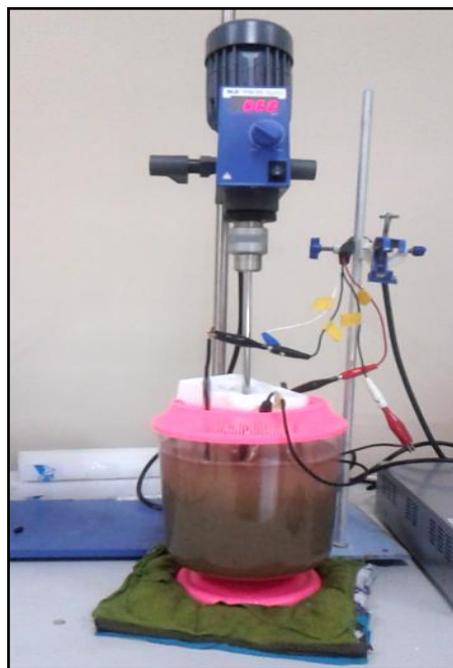
**Figure 3.7:** Image analyzer

### 3.3.2 Electrochemical test

Electrochemical methods shown in figure 3.8 are popular in erosion corrosion studies mainly because these methods are able to provide quantitative and qualitative information on erosion corrosion rates and the corrosion mechanism occurring on the surface. The substrate material was fully isolated from the working fluid by applying cold mounting at the specimen or resin interface. The potentiodynamic polarization test utilized a simple standard three electrode cell where working electrode, counter electrode and reference electrode. The work piece was set as working electrode and it was immersed in sodium chloride. Counter electrode that was use in this experiment graphite and the reference a saturated calomel electrode. The current and reaction was measure between the counter electrode and working electrode. The experiment are carried out without velocity and two different rate of velocity where 500 and 1000rpm. The classified of specimens in this experiment was shown in Table 3.1. Solution for the experiment is sodium chloride with 10 wt% present of sand particle.

**Table 3.1:** Classified of specimen

Specimens	Rpm
1	0
2	500
3	1000

**Figure 3.8:** Electrochemical Erosion Corrosion test.

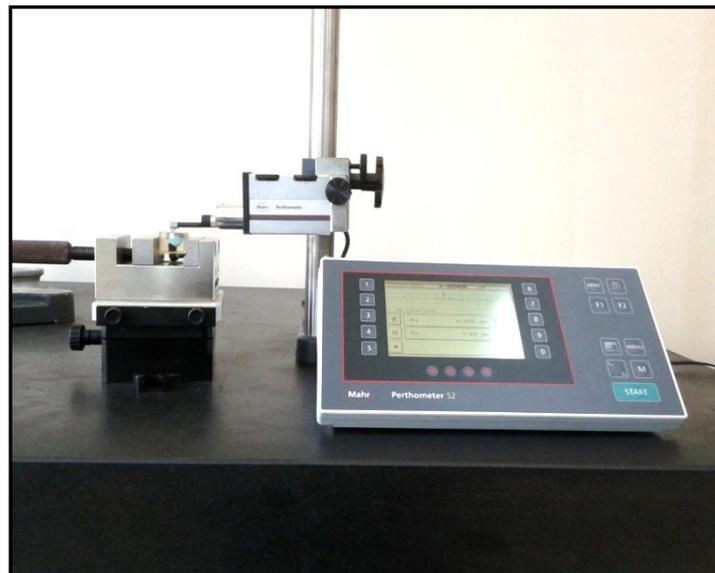
### 3.3.3 Optical Measurement

The function of optical measurement show in figure 3.9 below a in this experiment a quite same as image analyzer but for an optical measurement the magnificent was use a 4 times. The image only takes after the electrochemical erosion corrosion test to see the pitting corrosion. From the image the size and the value of pitting will see clearly. So, the image can analyze clearly with different rate of velocity based on the pitting value and size.



**Figure 3.9:** Optical Measurement

### 3.3.4 Surface roughness test



**Figure 3.10:** Surface Phertometer

After done with the measuring specimen weight, the surface roughness was checked to know the Ra value of the specimen. This test was do before and after at every single experiment or test. Surface roughness, often shortened to roughness, is a measure of the texture of a surface. It is quantified by the vertical deviations of a real

surface from its ideal form. If these deviations are large, the surface is rough; if they are small the surface is smooth. Roughness plays an important role in determining how a real object will interact with its environment. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces. Roughness is often a good predictor of the performance of a mechanical component, since irregularities in the surface may form nucleation sites for cracks or corrosion.

## **CHAPTER 4**

### **RESULT AND DISCUSSION**

#### **4.1 INTRODUCTION**

In this chapter, there is inspection parameter and discussion of the result on stainless steel before and after the erosion corrosion test which includes composition analysis, surface roughness test and surface microstructure analysis. Based on the result there were discussed relationships between effect of the velocity on erosion corrosion corresponding to the surface morphology and surface roughness change. At surface morphology it will be discussed about the relation between corrosion rate and velocity. It will also discuss about how kinetic energy participates on erosion corrosion mechanism.

#### **4.2 COMPOSITION ANALYSIS**

The composition analysis for the raw material was done before the machining and erosion corrosion test. This composition analysis was done to identify and ensure the type of the material, stainless steel as shown in Table 4.1 and figure 4.1 shown the impact of spark emission spectrometer. Because of the relatively of the high chromium content and the other components composition, so the raw material is investigated as stainless steel with grade 301. This type of stainless steel is good resistance in applications involving external exposure to mildly corrosive conditions at ambient temperature.



**Figure 4.1:** Impact of spark emission spectrometer

**Table 4.1:** Composition analysis on raw material stainless steel

Test	Composition analysis of elements						
	Fe	Cr	Ni	Mn	Cu	P	C
<b>1</b>	71.2	17.2	8.16	1.79	0.513	0.0306	0.0341
<b>2</b>	71.1	17.6	8.02	1.76	0.510	0.0414	0.0280
<b>3</b>	71.1	17.5	8.02	1.76	0.518	0.0452	0.0281
<b>Average</b>	71.1	17.5	8.07	1.77	0.513	0.0410	0.0301

### 4.3 Microstructure Analysis

The surface image was taken before and after the electrochemical erosion-corrosion test with different rate of velocity where 0 rpm, 500 rpm and 1000 rpm. The surface morphology of the specimen is observed by using microscope known as Image Analyzer and also with optical measurement only after the erosion corrosion test. Before the electrochemical erosion-corrosion test was conducted, all the specimen was polished until it's turned into mirror-like. Specimens after undergoing electrochemical erosion-corrosion test were cleaned using distilled water.

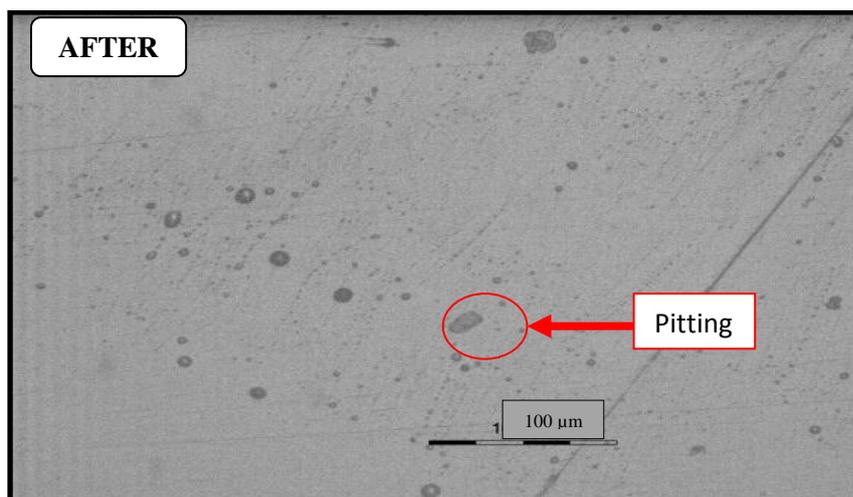
Figure 4.2 until 4.4 below show the visual inspection of the specimen that was revealed before and after the electrochemical erosion-corrosion test with twenty times magnification. The image was taken with different rate of velocity. For figure 4.5 the image was revealed by optical measurement with four times of magnification. The image only shows after the electrochemical erosion-corrosion test with different rate of velocity.

These effects of electrochemical erosion-corrosion test can be analyzed by pitting corrosion. Without any velocity, the surface of the specimen is a little bit smooth compared with the presence of the velocity. Where with the presence of 500 rpm and 1000 rpm velocity shows a difference in their surface morphology. The 1000 rpm of velocity shows more pitting corrosion compared to 500 rpm of velocity.

It was expected that after the electrochemical erosion corrosion test, there will be pitting formation due to the strong anions from the sodium chloride and with the presence of the velocity and also the presence of sand particles. The pit cannot be seen clearly through naked eyes since the pitting is very small in size so it is necessary to do the surface analysis by using microscope image analyzer and optical measurement.

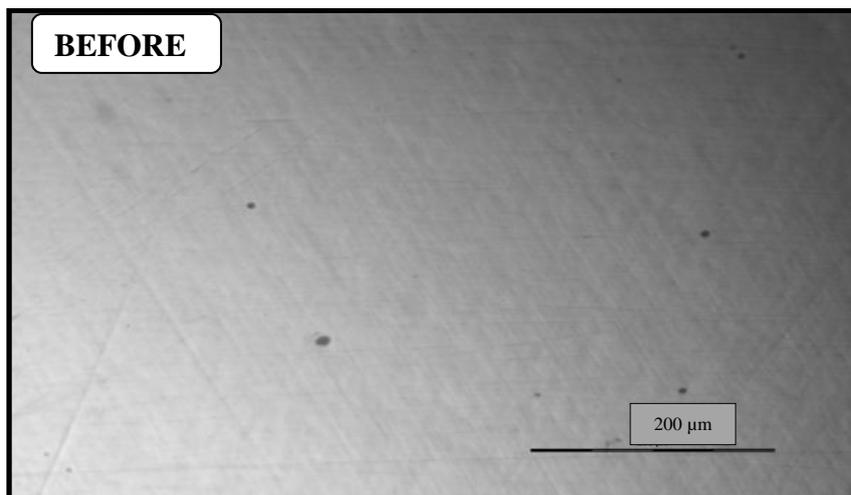


(a) Before electrochemical erosion-corrosion test

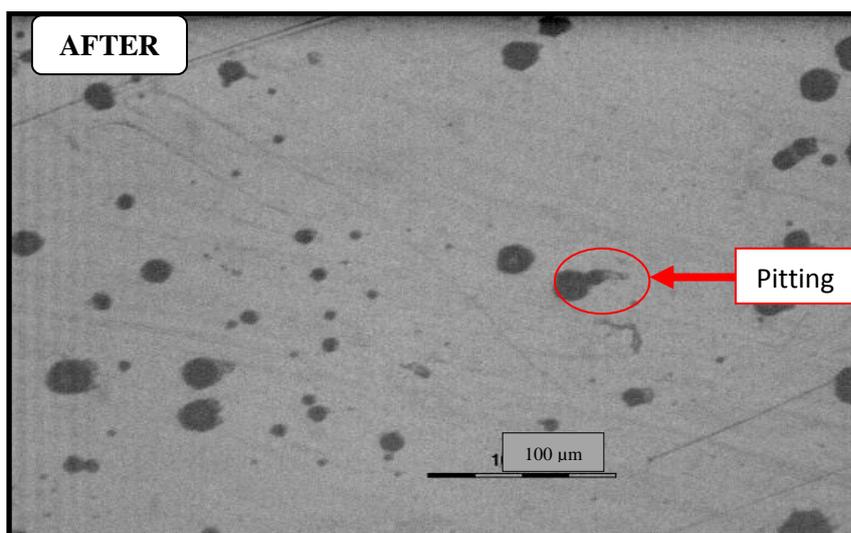


(b) After electrochemical erosion-corrosion test

**Figure 4.2:** Surface morphology of Type 301 Stainless Steel with 0 rpm, 20 x magnifications.

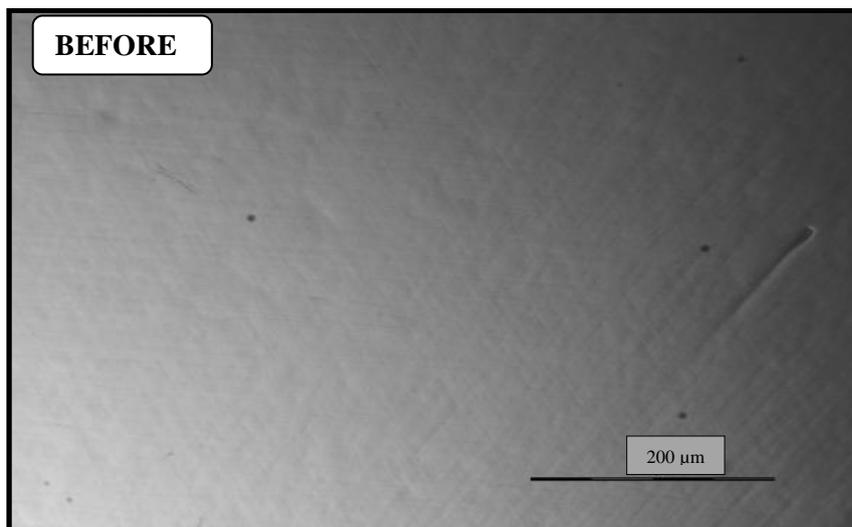


(a) Before electrochemical erosion-corrosion test

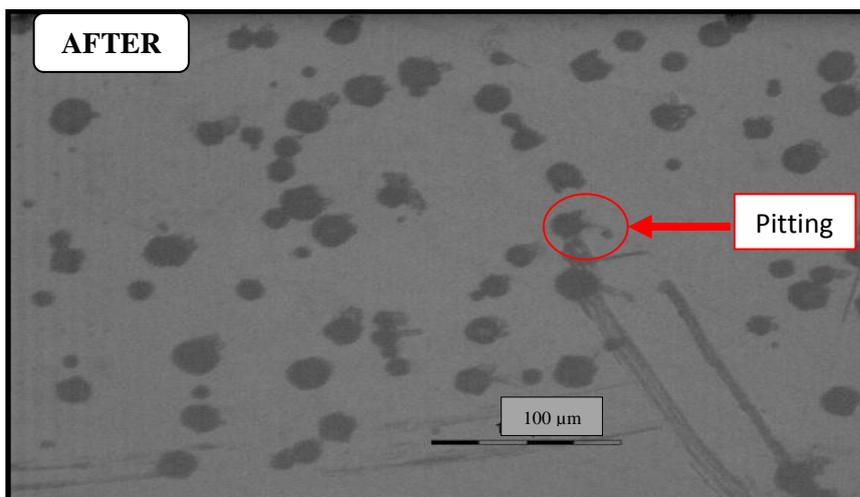


(b) After electrochemical erosion-corrosion test

**Figure 4.3:** Surface morphology of Type 301 Stainless Steel with 500 rpm, 20 x magnifications.

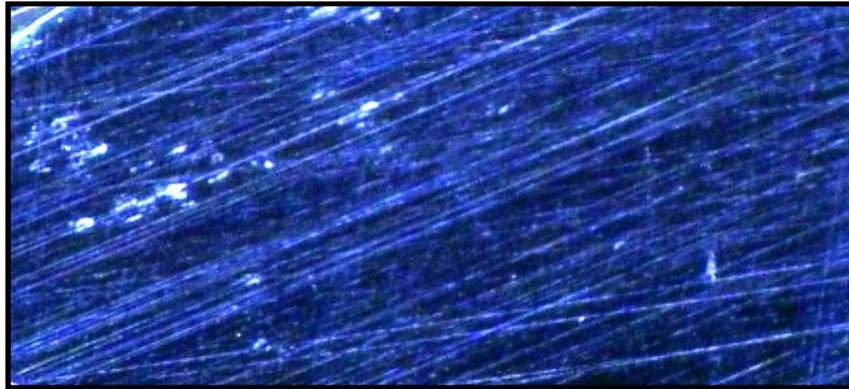


(a) Before electrochemical erosion-corrosion test

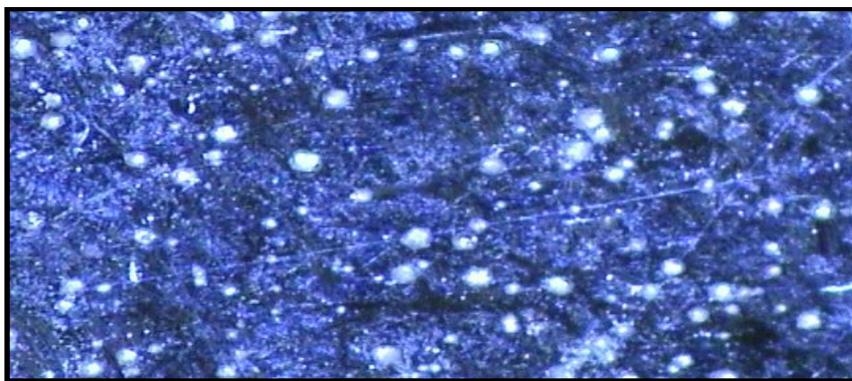


(b) After electrochemical erosion-corrosion test

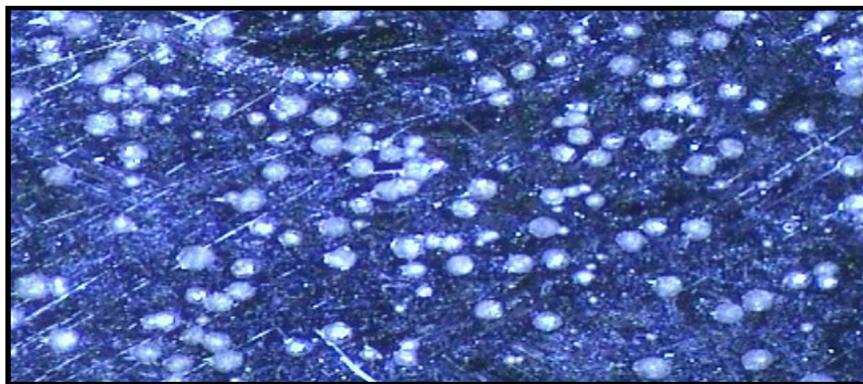
**Figure 4.4:** Surface morphology of Type 301 Stainless Steel with 1000 rpm, 20 x magnifications.



(a) 0 rpm



(b) 500 rpm



(c) 1000 rpm

**Figure 4.5:** Surface morphology of Type 301 Stainless Steel after electrochemical erosion corrosion test using an Optical measurement, 4x magnifications.

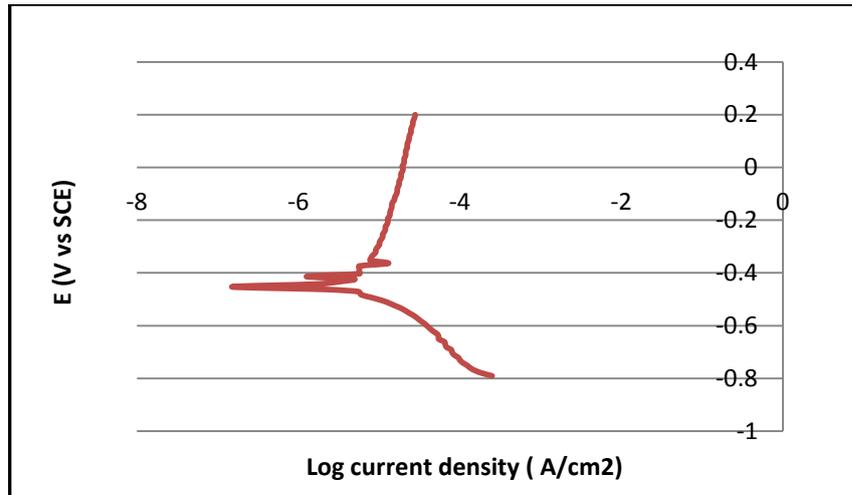
#### 4.4 Potentiodynamic Test

Electrochemical erosion corrosion test was done to study corrosion reaction and its mechanism. It is more to a reaction where the electron is produced by a chemical reaction in one area that travel through a metallic path and are consumed through different chemical reaction in another area. Oxidation and reduction reaction occurs during corrosion at a metal electrolyte interface and it is happen cause of the corrosion due to an electrochemical mechanism.

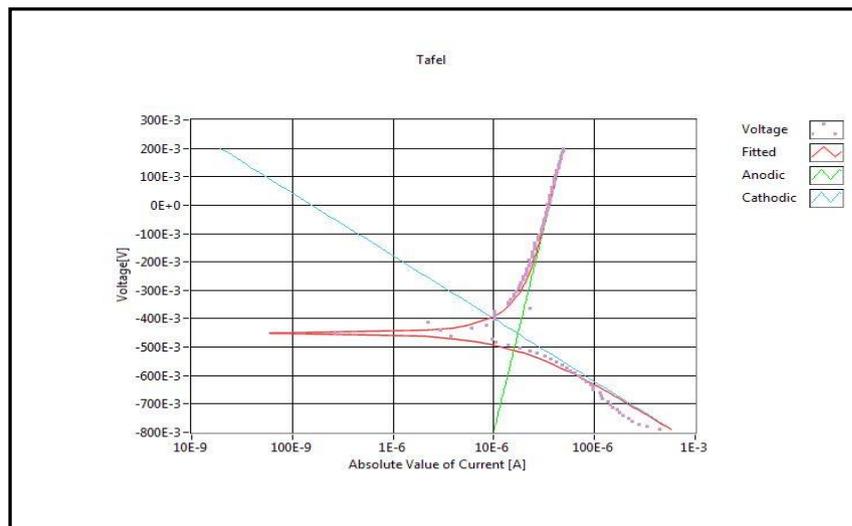
In an electrochemical cell, the anode is the site where electrons are produced through the chemical activity of the metal. The anode is the area where metal loss occurs. The metal loses electrons and migrates from the metal surface through the environment. The electrons remain in the metal but are free to move about in response to voltage gradients. The cathode in an electrochemical cell is the site where electrons are consumed. For each electron that is produced at an anodic site, an electron must be consumed at a cathodic site.

Figure 4.6 until 4.8 show a potentiodynamic polarization curve from erosion corrosion test and the tafel extrapolation curve which can determine a corrosion rate during a erosion corrosion test. From tafel extrapolation diagram the vertical axis is potential and the horizontal axis is the logarithm of absolute current. The theoretical current for the anodic and cathodic reaction are shown as straightline. The curved line is the total current which is the sum of the anodic and cathodic currents. This is the current were measured sweep of the potential of the metal with potentiostat. The sharp point in the curve is actually the point where the work piece starts to passivation.

The experimental Tafel extrapolation plots were analyzed. The cathodic ( $\beta_c$ ) and anodic ( $\beta_a$ ) Tafel slopes, the estimates corrosion current density ( $i_{corr}$ ) and estimated corrosion potential ( $e_{corr}$ ), corrosion resistance (RP) and corrosion rate are tabulated in Table 4.2. The corrosion rates were fairly reproducible and the corrosion rates of the specimen's type were comparable.

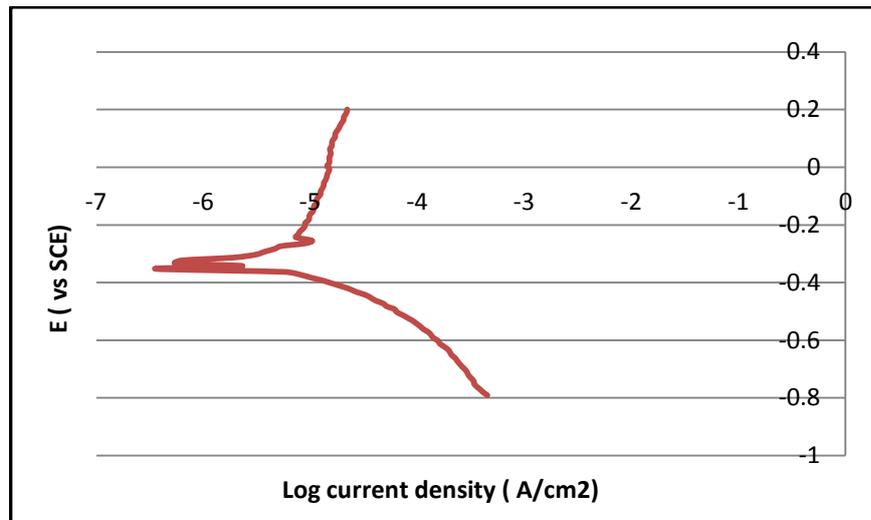


(a) Potentiodynamic polarization curves.

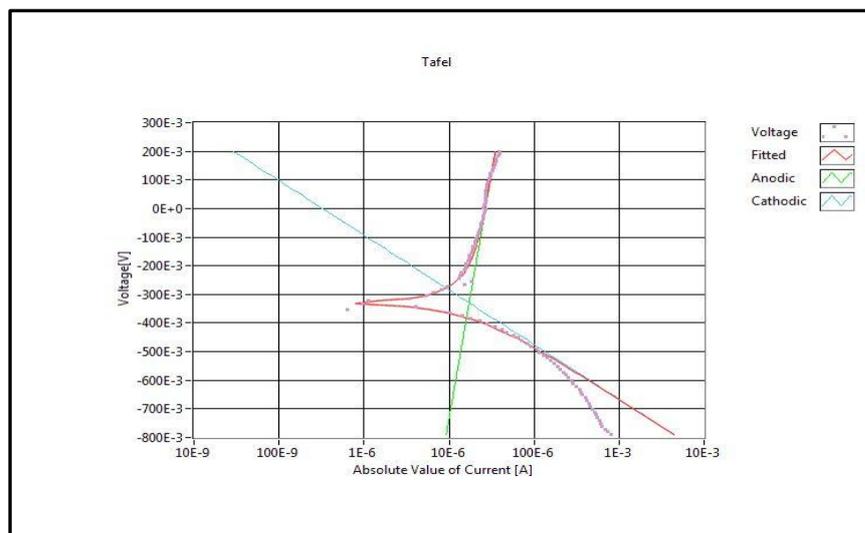


(b) Tafel extrapolation plot

**Figure 4.6:** Type 301 Stainless Steel with 0 rpm.

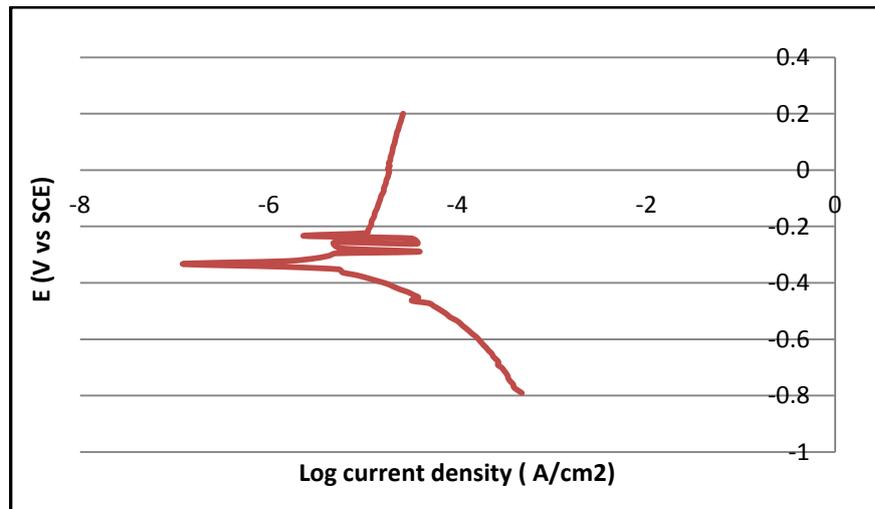


(a) Potentiodynamic polarization curves.

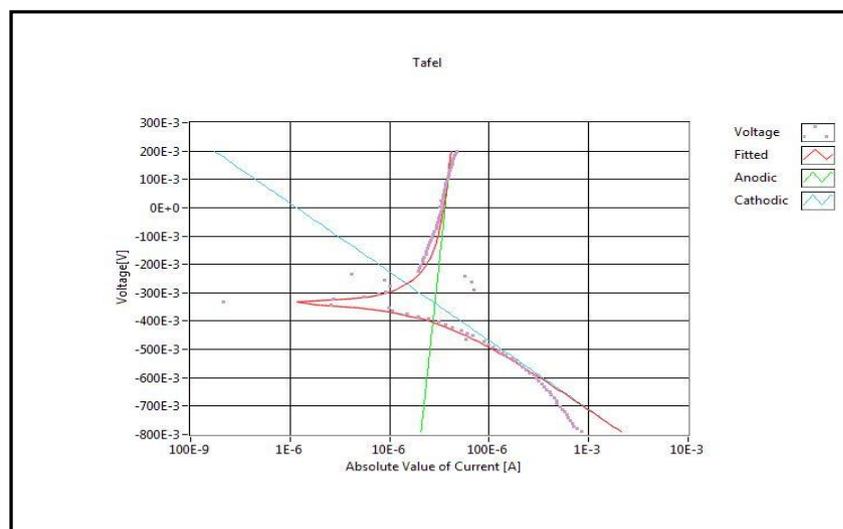


(b) Tafel extrapolation plot

**Figure 4.7:** Type 301 Stainless Steel with 500 rpm.



(a) Potentiodynamic polarization curves



(b) Tafel extrapolation plot

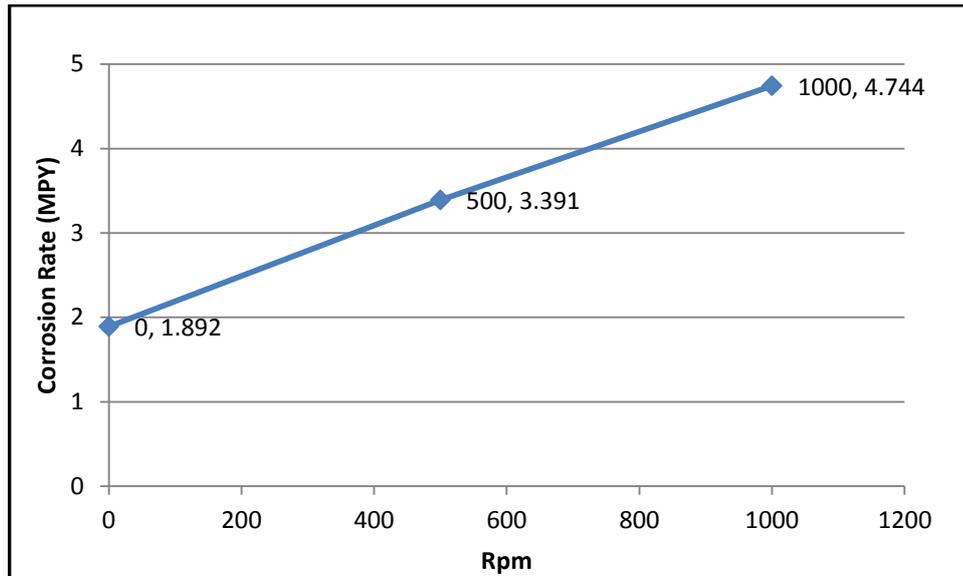
**Figure 4.8:** Type 301 Stainless Steel with 1000 rpm.

**Table 4.2:** Corrosion rates determine by Tafel Extrapolation Method

<b>RPM</b>	<b><math>E_{corr}</math> (V)</b>	<b><math>I_{corr}</math> (A)</b>	<b><math>\beta_a</math> (V/diV)</b>	<b><math>\beta_c</math> (V/diV)</b>	<b><math>R_p</math> (kohm)</b>	<b>Corr Rate (MPY)</b>	<b>Corr Rate (MMPY)</b>
O	-0.4487	7.3160	0.385	0.126	5.642	1.892	0.0482
500	-0.3248	13.110	0.752	0.162	4.406	3.391	0.0862
1000	-0.3304	18.347	1.329	0.198	4.007	4.744	0.1205

From the table 4.2 above the value of corrosion current and rate an increase due to rpm increases from non-velocity until 1000 rpm. The MPY show the millimeter per year and MMPY for mill inches per year. The value of corrosion rate also distribute on the surface roughness. When the oxide layer inhibits further corrosion, the metal is said passivity. In some case, local area of the passive film breaks down allowing significant metal corrosion to occur in a small area. This phenomenon is called pitting corrosion or simply pitting mechanism.

According to the result from the figure 4.2 until 4.5 it was shown the value of pitting are increase due to effect of velocity. The effect of velocity and sand particles a mostly contribute on erosion-corrosion test that will give an effect to the surface. The collision between the surface and particle sand by giving velocity of aqueous, accelerates the mechanical removal rate of the passive film thus accelerating the erosion-corrosion process.



**Figure 4.9:** Graph of corrosion rate versus rotational per minute (rpm).

Figure 4.9 show the increasing value of corrosion rate based on the velocity with present of the sand as impact mechanism particle. The increasing of the corrosion rate is probably result from the combination of mechanism during the passivation process which affected by the chemical reaction near to the work piece surface (Y.Zheng and Z.Yao, 2001). When the velocity increase an additional oxidation then occurs by reaction with the liquid. This alternate oxidation and removal of the film will accelerate the rate of corrosion. The resulting erosive attack will often to produces pitted areas over the surface. Besides that, the crater volume will be increase due to the higher particles kinetic energy at the higher velocity (Y.P Purandare and M.M. Stack, 2006). The faster a particle moves the more kinetic energy it has. According to the equation for kinetic energy:  $\text{kinetic energy} = \frac{1}{2}mv^2$ , where M = mass and V = velocity. Therefore, it would be expected that as the velocity increases the erosion rate would increase and most likely in non-linear manner. If the erosion rate is proportional to the kinetic energy of the particle then it would be likely that erosion rate is proportional to the square of the velocity.

Based on the literature it also said corrosion rate depend on the increasing of the velocity due to the higher mass transfer at such velocity and hence will enhance the formation of the passive film by the transport of oxygen to the reaction site (Y.P

Purandare and M.M Stack, 2005). Based on depassivation and repassivation when the velocity increase it will affected the frequency of the particle impacting the surface and also will leading the corrosion current increase.

#### 4.5 Surface Roughness Test.

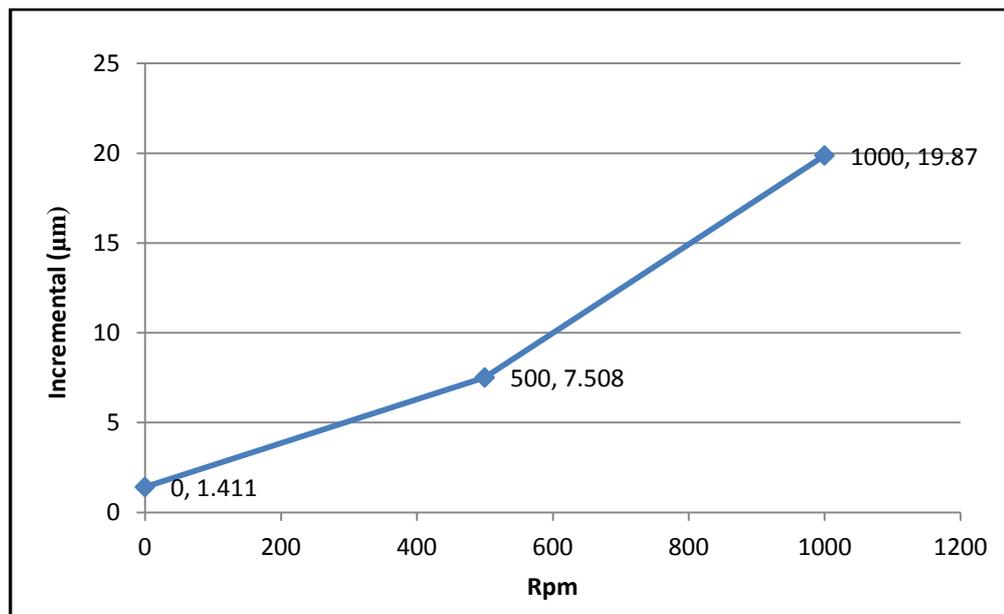
The other way to define the effect of velocity on electrochemical erosion corrosion is using surface roughness test. Table 4.3 shows the different between before and after the electrochemical erosion corrosion test. Before doing a test the work piece surface look like a mirror-like and after the test the surface become rougher. It is actually because present of the sand particle and the pitting corrosion on the surface. Besides that, the result shows the highest Ra value for higher velocity. So, the value of the velocity also contributes on the surface roughness at the surface.

**Table 4.3:** Surface Roughness before and after erosion corrosion test.

Rpm	Before ( $\mu\text{m}$ )	After ( $\mu\text{m}$ )	Incremental
0	0.056	0.135	1.411
500	0.057	0.485	7.508
1000	0.054	1.1270	19.870

##### 4.5.1 Effect on Surface Roughness

The variation of the surface roughness before and after the electrochemical test is actually because of the impact of sand particle and also with present of the pitting corrosion on the work piece surface. Figure 4.10 show, when the velocity increases the value of the surface roughness also increases. Based on the result, the relation between corrosion rate and surface roughness a directly proportional where when the corrosion rate increase the surface roughness also increase.



**Figure 4.10:** Graph Incremental value of roughness versus rotational per minute (rpm) after chemical erosion corrosion test.

## **CHAPTER 5**

### **CONCLUSION AND RECOMMENDATION**

#### **5.1 INTRODUCTION**

This chapter will conclude the research according to the result obtain in chapter 4 and also briefly recommendation that can be applied for the future work. The main objective of this project is to study the effect of the erosion corrosion in aqueous slurries with different rate of velocity. Since the experiment have be done and it was achieved the objective some conclusion and recommendation had suggest concluding this thesis.

#### **5.2 CONCLUSION**

Erosion corrosion is a form of material degradation involving electrochemical corrosion processes and mechanical wear. It is well known that the industries transport slurries and other particle laden liquid in pipes for sector such as offshore and marine technologies that spend a million of ringgit every year to repair a material damage. The typical example of this kind of destruction on erosion corrosion are at the pumps, impellers, propellers, valves, tubes and other fluid that handling equipment. So, one experiment was setup to analyze the effect of velocity in erosion corrosion. The erosion wears of material in aqueous slurries with different rate of velocity was study by do experiment using electrochemical erosion corrosion. This experiments was done with three different rate of velocity where 0 rpm, 500 rpm and 1000rpm. From this experiment several conclusions that can be drawn from the study. According to the equation of kinetic energy when the flow of aqueous slurries increases it will accelerate the removal of thin film and will increase the pitting corrosion. Highest value of velocity will give high value of corrosion rate compare than the lowest. Highest

corrosion rate will give highest value of Ra value for surface roughness due to present of pitting corrosion on the surface.

### **5.3 RECOMMENDATIONS**

The investigation and study about the effect of erosion corrosion of stainless steel type 301 in aqueous solution with different rate of velocity should be continue.

- (i) Using a different of material to compare the value of the corrosion rate with different rate of velocity. Besides that, also try doing a heat treatment for stainless steel.
  
- (ii) Using different angle of impact in aqueous slurries.
  
- (iii) Using a various size of sand particle to see their effect on surface morphology and their corrosion rate.

The test and experiment also should be conduct in a good condition and also with the better equipment that will give a better result. It also must be do with a real life environment to get a relationship with the experiment.

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## APPENDIX A

## GANTT CHART PSM 1

PROJECT ACTIVITIES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Meeting with fyp supervisor	■	■													
Briefing about the project	■	■													
Find journal and explore Experiment method		■	■	■											
State project background objective and project scope			■	■											
Literature review				■	■										
Finding suitable method And design experiment				■	■	■	■	■							
Mid presentation to Supervisor						■									
Methodology						■	■	■							
Completing the Proposal								■							
Preparation for presentation									■	■					
Submit the proposal										■					
Presentation on Proposal											■	■			
Submit proposal report															■

■	Planning Progress
■	Current Progress

## APPENDIX B

## GANTT CHART PSM 2

PROJECT ACTIVITIES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1) Sample preparation.	Planning Progress	Planning Progress													
	Current Progress	Current Progress													
2) Surface morphology before corrosion test.		Planning Progress	Planning Progress	Planning Progress											
		Current Progress													
3) Electrochemical test					Planning Progress	Planning Progress	Planning Progress								
					Current Progress	Current Progress	Current Progress								
4) Surface morphology after corrosion test						Planning Progress	Planning Progress								
						Current Progress	Current Progress	Current Progress							
5) Surface Roughness test.								Planning Progress	Planning Progress						
								Current Progress	Current Progress						
6) Prepare for chapter 4 (result and discussion)									Planning Progress	Planning Progress	Planning Progress				
									Current Progress	Current Progress	Current Progress				
7) Prepare for chapter 5 (conclusion and recommendation)											Planning Progress	Planning Progress	Planning Progress		
											Current Progress	Current Progress	Current Progress		
8) Prepare for presentation													Planning Progress	Planning Progress	
													Current Progress	Current Progress	
9) Project presentation														Planning Progress	Planning Progress
														Current Progress	Current Progress

	Planning Progress
	Current Progress

**APPENDIX C****Potentiodynamic setup parameter**

<b>Parameter</b>	<b>Value</b>
<b>Initial E (V)</b>	-0.8
<b>Final E (V)</b>	0.2
<b>Scan Rate (mV/s)</b>	10
<b>Sampling Time (s)</b>	1
<b>Sample Area (cm<sup>2</sup>)</b>	1.767
<b>Density (gm/cm<sup>3</sup>)</b>	7.87
<b>Equivalent weight</b>	27.92

**APPENDIX D**

**Time Calculation**

$$\begin{aligned} \text{Time} &= \frac{\Delta V}{\text{scan rate}} \times 1000 \\ &= \frac{1}{10} \times 1000 \\ &= 100 \text{ s @ } 1\text{m } 40 \text{ s} \end{aligned}$$

**Velocity Calculation**

$$r = 5\text{cm}$$

$$\text{rpm} = 500$$

$$= 1000$$

$$V = \text{rpm} \times \frac{2\pi}{60} \times r$$

$$\text{Rpm} = 500$$

$$V = 500 \times \frac{2\pi}{60} \times 5$$

$$= 261.8 \text{ cms}^{-1} \text{ @ } 2.62 \text{ ms}^{-1}$$

$$\text{Rpm} = 1000$$

$$V = 1000 \times \frac{2\pi}{60} \times 5$$

$$= 523.60 \text{ cms}^{-1} \text{ @ } 5.23 \text{ ms}^{-1}$$