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Corrosion of Steel

Dissertation

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Corrosion of steel (Dissertation)

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1 Chapter 1: Introduction

1.1 Abstract

This project involves a thorough study on different types of corrosion that attack metals especially steel. The different types are studied extensively in order to understand how they form, why they form and where they are likely to form. It is important to understand how corrosion mechanism works in order to build strong basis in coming up with better methods for improving corrosion resistance. The main target for this project is corrosion in steel. This is because steel is one of the most utilized metal in a wide range of application from construction of buildings and bridges to making utensils. It has found most interest since it has good mechanical properties, cheap and good corrosion resistance. However due to the iron presence in steel it is at high risk of facing various types of corrosion attacks which result in diverse effects. The project will also be investigating how mechanical properties of steel changes under corrosion. An immersion test in 5% sodium chloride will be carried out to establish the rate of corrosion for different steel components (ss316, ss430 and SS304). A tensile test will be performed on the specimens to determine effects of corrosion on mechanical properties of steel materials. The information from the extensive study of corrosion and experimental analysis will be used to inform new corrosion resistance method.

1.2 Back ground

Corrosion of steel can be defined as the irreversible destruction or deterioration of the material which have a significant impact on its vital properties which is a result of the chemical or electrochemical reaction of the metal surface to the surroundings which may include acids, water, air (oxygen) and moisture. The process of steel corrosion is mainly facilitated through electrolysis process in which the steel surface emits electrons to the available electrolyte which can either be a layer of moisture, water with oxygen presence. The phenomenon of the metals tendency to return to their natural state is the drive towards the occurrence of electrochemical reaction (Rokuro et al. 2012). This is manifested by the iron in steel tendency to return to its original state of iron oxide. Therefore, it reacts with the oxygen in the environment to form iron oxide in the form of rust.

According to Gretchen A. Jacobson, 2015, the most commonly used metals include steel and iron. The two metals are selected due to their advantageous properties such as ease of fabrication, low cost, and structural strength. 85% of engineering material used worldwide annually constitutes of carbon steel which is used in a variety of applications such as marine applications, transportation, pipelines, chemical processing, mining, nuclear power, chemical processing as well as metal processing equipment. However, they have a limitation in their resistance to corrosion. They experience different modes of corrosion from different media including most outdoor atmospheres. Corrosion is manifested in the rate at which the metal is lost due to rust. All steels and low alloy steels experience a magnificent amount of corrosion due to rusting when exposed to moist atmospheres

Research by Gerhardus Koch et al., 2001, reviewed that the cost of steel corrosion experienced in worldwide is very high amounting to hundreds of millions of dollars due to the failure of equipment, accidents, replacements, and repairs. According to a current study it reviewed that 25% of the steel produced worldwide is used exclusively to amend the corroded structures. Since carbon steels represent the largest single class of alloys that is widely used both in terms of total cost and tonnage, it can be easily understood that steel corrosion is a problem enormous practical importance. Therefore, there is need to deeply research on ways to provide protective systems for corrosion in steel and iron.

A study by Bastidas and Scantlebury, 1986, reviewed that the rate of corrosion in steel is affected external factors such as the presence of vapor, humidity chemical fumes, and ambient temperature. For the cases where the steel structure or pipe is buried, the soil composition, moisture content, and temperature contribute to the rate of steel corrosion as well as its impact. Corrosion has diverse effects on the microstructure of steel which impacts the mechanical properties of steel in that it makes it brittle and flaky. The steel ends up losing its elasticity and strength which reduces the useful life of steel which lead

to unexpected failures resulting in severe curtailments. In order to prevent unexpected failures due to corrosion of steel, corrosion of steel need to be curbed. The available means available means corrosion prevention for steel such as protective coating and converting to alloys are effective under normal conditions. But, at high temperature and pressure with exposure to radiations, the behavior of steel is different. So, corrosion of steel is required to be studied thoroughly.

2 Chapter 2: Literature review

2.1 Corrosion phenomena in metals

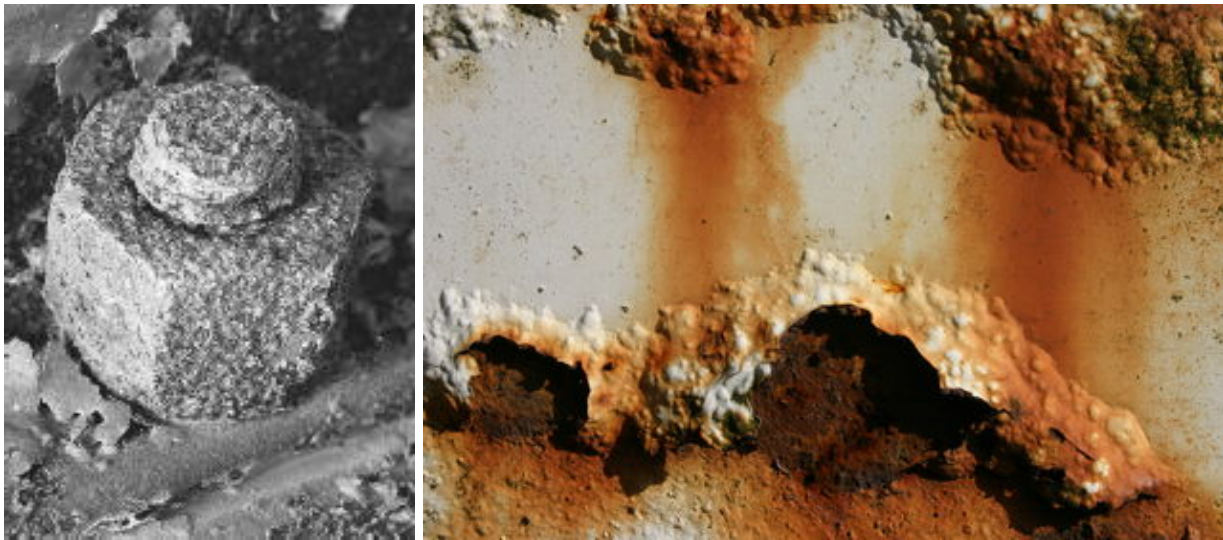


Figure 1: Cases of steel corrosion (Terence, 2017)

2.1.1 Uniform corrosion

All metals are prone to corrosion due to the method utilized for manufacturing and their nature (their constituents). In the manufacturing process, high amount of heat energy is transferred to the metal which affects the microstructure of them metal during the cooling process. Once the metal is altered microscopic areas of difference are created. For iron which is the main constituent of steel, the microstructure include the pearlite and ferrite. The two microstructure contributes to electrolyte reactions between the two microstructure which result in eating away of the ferrite and rust formation on pearlite (Roberge Pierre, 2000).

The rate of corrosion is equivalent to the electron current flowing between the anode and the cathode of the corrosion cell. The manner in which the cathodic and anodic cells are distributed on a steel/iron surface is a determinant factor of what type of corrosion will occur. However mainly the cells are very small, numerous and randomly distributed along the surface of the metal. Thus the resultant corrosion effect is experienced in a uniform attack (Fontana, 1986). The rate of this kind of corrosion depends on the balance between the rates of cathodic and anodic reaction essential in sustaining the electro-neutrality and the reaction that occurs least readily control the corrosion rate.

Metals exhibit active corrosion when they are immersed in the corrosive solution. However, there are a few engineering alloys that carry a stable solid corrosion product film (mostly is an oxide). The rate of metal dissolution is limited to the rate at which the metal ions can penetrate the film, (usually is a factor

of 10^3 - 10^6 times less than the rate at which unfilmed metals experience) if the film has excellent cohesive strength and adhesion to the metal and has low ion conductivity. This phenomenon is referred to as passivity and is exhibited by stainless steel and nickel alloys.

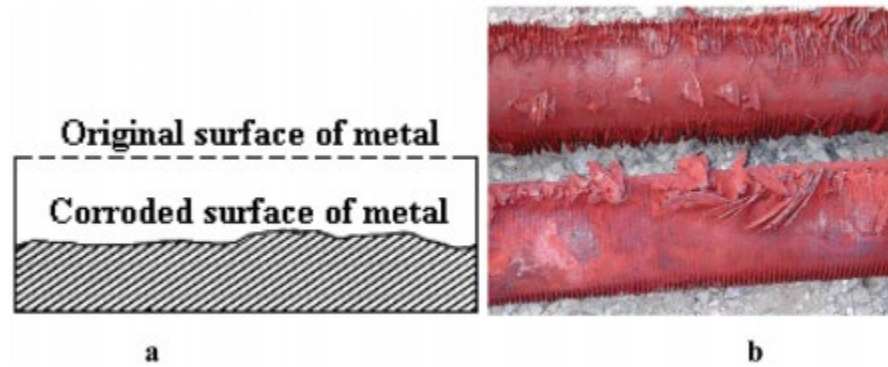
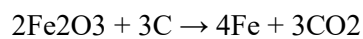


Figure 2: Uniform corrosion. (a) Scheme of the corroded surface of the metal; (b) carbon steel tubes after uniform corrosion in the furnace.

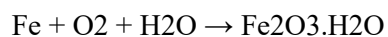
Despite uniform corrosion being responsible for most of the occurrences and destruction of structural materials it is not a major cause for concern. The rate of attack by this phenomenon is easily measurable using simple tests and the life of structures experiencing this kind of corrosion phenomenon can be confidently predicted.

Steel uniform corrosion reaction

Basic corrosion reaction process



(Conversion to iron)



(Change back to Ore-like state)

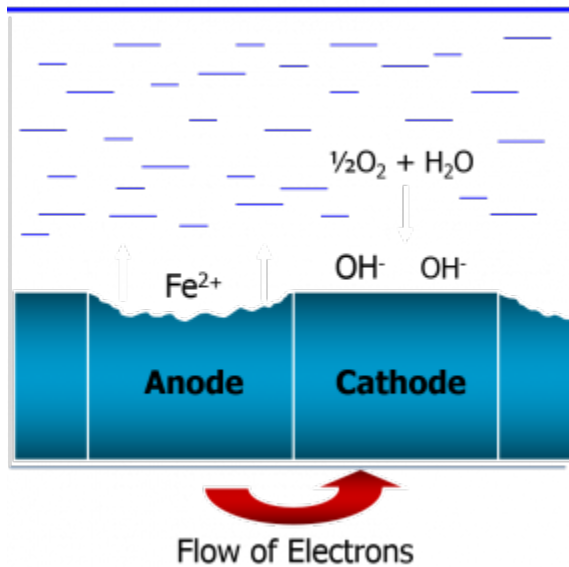
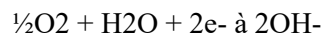
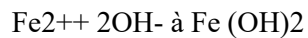


Figure 3: uniform erosion (Gretchen, 2015)

Cathodic Reaction:



Combined Reaction:



Ferrous Hydroxide

Oxidises to $\text{Fe}_2\text{O}_3(\text{H}_2\text{O})$

Hydrated Ferric Oxide – Red Rust

Carbon steels alloys include the addition of other elements in small percentages usually less than 2% of the total weight. Mostly these levels of addition do not necessarily produce desirable changes to curb corrosion behavior. However, there are exceptions where the addition of certain elements produces remarkable results on corrosion reduction in certain environments. These metals include chromium, copper, phosphorous and nickel.

2.1.2 Atmospheric corrosion

There are three classifications of atmospheres which include rural, marine or industrial and nature rural environments can vary in terms of yearly temperature, mean temperature, rainfall patterns and acidic rain. These phenomena make extrapolation from past event less reliable. According to Roberge Pierre, 2000, corrosion in steel in aqueous and atmospheric environments is easily understood a film formation and brake down perspective. This is due to the fact that iron is thermodynamically unstable in the presence of oxygen and water. The presence of an electrolyte is required since corrosion of iron and steel in the atmospheric environment is an electrolytic process. Therefore for the corrosion to take place the surface of steel must be awash in water (Terence, 2017).

At the time of exposure of the steel, it spends some portion of the time immersed in rain water and a portion awash with the absorbed water film. The time spent covered depends on the relative humidity at the exposure site. Time of exposure to the metallic surface is also presumed to influence the rate of corrosion. Rusting of iron solely depends on time of exposure and the site relative humidity. The rate of corrosion is found to increase significantly in atmospheres with the addition of SO₂ (as low as 0.01%). The presence of oxides of nitrogen in the atmosphere accelerates the rate of steel corrosion. Additionally, any gaseous constituent that is capable of strong electrolytic activity is also capable of increasing the rate of corrosion on steel (Fontana, 1986).

2.1.3 Aqueous corrosion

Carbon steels are in various situations used for while submerged in water or used in water transportation. There are different states/conditions of exposure through which the pipes can be exposed to while offering the mentioned services. These conditions may include varying PH, temperature or flow rate which may influence the rate of corrosion. The most important factor of the mentioned is the relative acidity of the water. When the PH of the water or the solution that is being transported, there evolution of hydrogen which eliminates the formation of the protective film, therefore, the rate of corrosion is enhanced since the corrosion continues by the alkaline solutions (Rokuro et al. 2012). Corrosion is adversely hindered by the formation of the protective film. If the alkalinity is very high, the rate of attack on steel is hindered.

In the cases where the solution in consideration is neutral, other factors that contribute to corrosion include aeration and electrical conductivity. Aeration increases the rate of corrosion in both seawater, and freshwater since as mentioned earlier corrosion is an electrolytic process that requires both oxygen and electrolyte. However, seawater experiences increased the rate of corrosion due to increased electrical conductivity compared to fresh water. Steel immersed in seawater experiences increased pitting (corrosion). An alternate exposure to atmospheric air and total immersion has increased corrosion in the

form of pitting than continuous immersion (Fontana, 1986). Effects of alloying addition and exposure conditions is summarized in the table below

Table 1: Effects of alloying addition and exposure conditions (Rothwell. 2000)

Effects of alloy selection, chemical composition and alloy additions	Sea air	Freshwater	Alternately wet with seawater or Spray and dry	Continuously wet with seawater
Ferrous alloys	Pockmarked	Vermiform on cleaned bars	Pitting, particularly on bars with scale	Pitting, particularly on bars with scale
Wrought iron versus carbon steel	Steel superior to wrought and ingot irons	Iron and steel equal in low-moor areas	Low-moor iron superior to carbon steel	Low-moor iron superior to carbon steel
Sulfur and phosphorus content	Best results when S and P are low	Best results when S and P are low	Best results when S and P are low	Apparently little influence
Addition of copper	Beneficial: Effect increasing with copper content	Beneficial: 0.635% Cu almost as good as 2.185% Cu	Beneficial: 0.635% and 2.185% Cu much the same	0.635% Cu slightly beneficial: 2.185% Cu somewhat less so
Addition of nickel	3.75% Ni superior even to 2% Cu; 36% Ni almost perfect after 15-year exposure	3.75%Ni superior even to 2%Cu; 36%Ni excellent resistance	3.75%Ni beneficial usually more so than Cu: 36%Ni the best metal in the set	3.75% Ni slightly beneficial and slightly superior to Cu: 36% Ni the best metal in the set
Addition of 13.5% Cr	Excellent resistance to corrosion: cold blast metal perfect after 15-year exposure: equal to 36% Ni steel	Excellent resistance to corrosion: equal to 36% Ni steel	Subject to severe localized corrosion that virtually destroys the metal	Subject to severe localized corrosion that virtually destroys the metal
Behavior of cast irons	Excellent resistance to corrosion: cold blast metal superior to hot: no graphitic corrosion	Undergoes graphitic corrosion	Undergoes graphitic corrosion	Undergoes graphitic corrosion

Steel immersed in seawater is not affected by geographical location and mean temperature as well do not play a very significant role whatsoever. However, the rate of corrosion in steel immersed in seawater is seen to be further affected by factors such as marine organisms (algae and barnacles).

2.1.4 Soil corrosion

Corrosion of steel buried in soil varies according to the composition of the soil (nature of the soil) as well as environmental factors such as the availability of oxygen and moisture. These factors can lead to extreme variation in the rate of the attack. In some extreme cases, buried vessels can get perforated in a within a period of one year. Some soils can preserve iron material for a very long time as well for example archaeologists have discovered iron tools in arid deserts that have been buried for over a hundred years. It has been found that soils the poses an increased rate of corrosion to steel immersed in them have properties such as high acidity, high electrical conductivity, high dissolved salts, high moisture content and high electrical conductivity (Roberge Pierre, 2000). As opposed to water, poorly aerated soils are highly corrosive since it exhibits accelerated attack by sulfate-reducing anaerobic bacteria (Zuo, Örnek, et al., 2004).

2.1.5 Galvanic (Bimetallic) Corrosion

It is a phenomenon which occurs when two dissimilar metals are immersed in a conducting a solution they tend to develop different corrosion potentials. In cases where the metals are in contact, the potential difference provides a driving force for increased corrosion. The more active (less noble) metal corrodes more readily while the other less active corrodes less. The less noble is also referred to as the anode or the sacrificial metal. For galvanic corrosion to occur certain conditions must exist which include

- Electrochemically dissimilar metals must be present
- The metals must be in electrical contact, and
- The metals must be exposed to an electrolyte



Figure 4: Galvanic corrosion (Gretchen, 2015)

2.1.6 Crevice Corrosion

According to Fontana & Greene, 1967 crevice form of corrosion is a localized form of corrosion such that corrosion is localized on a single metal which happens when the environmental conditions can develop non-uniformly over the surface. The existence of crevices due to either design or manufacturing defect can lead to occluded regions in which oxygen is replenished. Oxygen is the usual cathodic reactant. A place where at a time both anodic and cathodic reaction occurred uniformly, after a short period the only reaction remaining in the crevice may be the anodic reaction, balanced by cathodic action outside the crevice. The resulting crevice corrosion is most serious in active/passive materials where a sequence of events may follow leading to significant and irreversible changes in the environment within the crevice. The rate of crevice corrosion is increased by factors such as the presence of acidic condition or oxygen in the crevice.



Figure 5: Crevice corrosion between a 316 stainless steel tube and stainless steel tube sheet of heat exchanger in a sea water desalination plant (Breakell, 2005)

2.1.7 Pitting corrosion

Pitting is also another form of extremely localized attack where the metal can be extremely damaged with a negligible loss on the overall metal. It is mainly facilitated by the action of chlorine ions. However other ions such as hypochlorites, and bromides are sometimes responsible. It mainly occurs in environments that are almost able of protecting the alloy except for occasional fluctuations in conditions. It is serious in alloys that can cause major changes of the environment within the pit when an autocatalytic increase in corrosion rate can occur (Shreir, Jarman, and Burstein, 1994).

A study by Rothwell, 2000, reviewed that pitting results in the formation of holes. These holes vary in diameter they could be relatively small large. The pits could be isolated or be close together making the surface of the metal appear rough. Pitting is one of the most destructive and insidious forms of corrosion. It results in a lot of equipment failure due to perforations with only a small percentage weight loss of the entire structure. Pits are difficult to detect since they are of small size and mainly they are covered with corrosion products (Fontana, 1986). It is difficult to measure quantitatively and compare the extent of pitting due to their varying depth and numbers. It is also difficult to predict pitting through laboratory tests.



Figure 6: cross section of pitting corrosion (Gretchen, 2015)

2.1.8 Intergranular Attack

Intergranular corrosion is an electrochemical attack on the grain boundaries of a metal and is mainly due to the presence of impurities in the metal which tend to be concentrated near the grain boundaries. Grain

boundaries are slightly more reactive than the matrix of an alloy. Intergranular attacks are mainly as a result of improper treatment. For example, considering austenitic stainless steels, it may be susceptible to intergranular attack if they are heated in the temperature range of 500-800 °C. Chromium carbide is precipitated at grain boundaries, and the removal of a large amount of chromium renders the adjacent boundary susceptible to attack (Chandrasekaran, Batchelor, Loh Nee, 2012). Chromium alloy steel may experience such attacks in areas that are heat-affected especially zones adjacent to welds. Presence of impurities in the grain boundaries, enrichment of one of the alloying element or depletion of one of the alloying elements in the grain boundary area may result in intergranular corrosion. In other metals such as aluminum, small amounts of iron have been seen to cause intergranular corrosion since iron's solubility is low. Depletion of chromium in the grain-boundary regions results in intergranular corrosion of stainless steels (Fontana & Greene, 1967).

2.1.9 Stress corrosion

Stress corrosion is the most serious corrosion phenomena since it involves a combination of both mechanical and corrosive environmental factors. Stress corrosion refers to apparently brittle failure of a number of alloys in very specific environments, under tensile stresses which may be significantly lower than the tensile strength of the material and frequently lower than the yield strength (Shreir, Jarman, and Burstein, 1994). During stress-corrosion cracking the alloy is virtually unattacked over most of its surface, while fine cracks grow through it. Detecting stress corrosion while it happens is extremely difficult therefore the failure that occurs is mainly unexpected and very catastrophic at times (Fontana, 1986).

During stress-corrosion cracking, the metal or alloy is virtually unattacked over most of its surface, while fine cracks progress through it. This cracking phenomenon has serious consequences since it can occur at stresses within the range of typical design stress. Exposure to boiling MgCl_2 at 310°F (154°C) is shown to reduce the strength capability to approximately that available at 1200°F (Rothwell, 2000).

The two classic cases of stress-corrosion cracking are "season cracking" of brass and the "caustic embrittlement" of steel. Both of these obsolete terms describe the environmental conditions present which led to stress-corrosion cracking (Rothwell, 2000). Season cracking refers to the stress-corrosion cracking failure of brass cartridge cases. During periods of heavy rainfall, especially in the tropics, cracks were observed in the brass cartridge cases at the point where the case was crimped to the bullet. It was later found that the important environmental component in season cracking was ammonia resulting from the decomposition of organic matter (Terence, 2017).

Many explosions of riveted boilers occurred in early steam-driven locomotives. Examination of these failures showed cracks or brittle failures at the rivet holes. These areas were cold-worked during riveting operations, and analysis of the whitish deposits found in these areas showed caustic, or sodium hydroxide, to be the major component (Fontana, 1986). Hence, a brittle fracture in the presence of caustic resulted in the term caustic embrittlement. While stress alone will react in ways well known in mechanical metallurgy (i.e., creep, fatigue, tensile failure) and corrosion alone will react to produce characteristic dissolution reactions; the simultaneous action of both sometimes produces the disastrous results.

2.1.10 Hydrogen embrittlement

Commonly engineers have categorized hydrogen embrittlement as a form of stress corrosion despite their mechanistically being quite distinct. Hydrogen embrittlement is a mode of low ductility fracture which may be induced in ferritic and martensitic steels at high strength levels and in titanium alloys by the introduction of hydrogen. The difference between stress corrosion and hydrogen embrittlement can be easily distinguished using simple laboratory test. However, separating the mechanisms in practical failure situation with high-strength materials is not easy.

2.1.11 Corrosion fatigue

It is described as a reduction in resistance to fatigue due to the action of the corrosive environment.

Corrosion fatigue is therefore determined by the loss of mechanical properties rather than by a particular mechanism of failure appearance.

2.1.12 Erosion corrosion

Erosion corrosion is the increase in the rate of metal deterioration which is as a result of relative movement between the metal surface and the corrosive fluid. The evidence of this form of corrosion is manifested by the formation of grooves, waves, gulleys, and rounded holes which usually exhibits a directional pattern. These features are produced due to the velocity of the corrosive fluid and the mechanical removal from the metal surface (Fontana & Greene, 1967). Most metals even those that depend on the formation of the protective films are susceptible to erosion corrosion. Erosion corrosion in these metals occurs when the protective film is damaged by the flow, and therefore the alloys are attacked at a higher rate (Rothwell, 2000).

2.1.13 Microbial corrosion

This type of corrosion is termed as microbiologically influenced corrosion (MIC) which is a corrosion phenomenon caused by micro-organisms (chemoautotrophs). This type of corrosion can take place in both presence and absence of oxygen. In the absence of oxygen sulfate-reducing bacteria act upon the metal producing hydrogen sulfide which results in sulfide stress cracking (Zuo, Örneke, et al., 2004). In oxygen presence, some bacteria directly oxidize iron to iron oxides or hydroxides while other bacteria oxidize

other elements such as sulfur to produce sulfuric acid which result in sulfide corrosion (Fontana & Greene, 1967).

According to Breakell et al., 2005, steel pipes immersed in seawater near low tides are mainly affected by the accelerated low water corrosion which is a very aggressive form of microbially influenced corrosion. It is characterized by a sludge which mainly orange in color which produces a hydrogen sulfide odor when treated with acid. The corrosion rate is unpredictable such that it can be very high exceeding design corrosion allowances which may result in unexpected failure of steel pipes (Breakell et al., 2005).

2.1.14 High-temperature corrosion

High-temperature corrosion is a chemical deterioration of a material (steel metal) due to heating. It is a form of non-galvanic corrosion that occurs when a metal is exposed to a hot atmosphere containing elements such as sulfur, oxygen and other oxidizing compounds (Leonard c. Rowe, 2015). Products with high-temperature corrosion can be considered advantageous in engineering since the formation of oxides such as in stainless steel can provide a protective layer preventing further atmospheric corrosion (Chandrasekaran, Batchelor, Loh Nee, 2012).

2.2 Common corrosions in metals (iron)

2.2.1 Rust

Rust is a mainly an oxide of iron which is usually red in color and is formed by a redox reaction between iron and oxygen in the presence of an electrolyte in most cases water or air moisture. There are several forms of rust that exist and are distinguishable from one another either visually or through spectroscopy, and they also form under different circumstances. Rust comprises of two different compounds which include iron (III) hydroxides ($\text{FeO}(\text{OH})$, $\text{Fe}(\text{OH})_3$) and iron (III) oxides ($\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$).

In an environment with sufficient oxygen and water, with adequate time any mass of iron will entirely convert to rust and eventually disintegrate. Unlike other surface corrosion like the formation of patina on copper surfaces that protects the underlying metal, surface rust is friable and flaky such that it is incapable of protecting the iron underneath. For iron and alloys of iron such as steel, rusting is the most common form of corrosion. There are however other forms of rust that exist such the resultant reactions of iron and chloride that is manifested in iron mainly immersed in water deprived of oxygen. The resultant rust is mainly green in color. Despite rusting being the most negative aspect of iron metal, there is a particular form of rusting referred to as stable rust that has its advantage since it makes the iron develop a thin coating of rust which if kept in low humidity acts a protective layer that prevents the underlying iron from corrosion.

2.2.2 Chemical reaction for the formation of rust

Rust is generally an oxide of iron, therefore, its formation requires the presence of oxygen, moisture, and iron mass or an alloy of iron such as steel. It is also of the essence to this reaction. It takes a considerable amount for the formation of rust. With the right amount of time oxygen combines with the iron metal at atomic level where a new compound is formed (iron oxide) which weakens the metallic of iron metal. According to Gräfen, Horn, ESchlecker, & Schindler, 2000, rust is more than just an oxidation process as most people refer it to, this because not all oxidation forms rust especially with other metal other than iron. Other metals can also corrode similarly as iron but may not form the red oxide.

Rusting process main catalyst is water. Iron and its alloys are solids, but water molecules can penetrate the microscopic pits and cracks in any exposed metal. The hydrogen atoms in water can also combine with other elements to form acids which will cause more metal to be exposed. For example in the case of seawater which has chloride ions present, the Hydrogen in water combine with the chloride ion forming hydrochloric acid which speeds up the corrosion process. As this process continues (reaction of iron with the oxygen and the acids) they weaken the metal which results in the structure becoming brittle and crumbly



Figure 7: Heavy rust on iron/iron alloys (Gräfen, Horn, ESchlecker, & Schindler, 2000)



Figure 8: Light rust formation which acts as protection allowing the structure to retain its structural properties (Gräfen, Horn, ESchlecker, & Schindler, 2000)

According to Ankersmit, Griesser-Stermscheg, Selwyn, Sutherland, 2016, iron can also rust when sprayed by slat based sprays with some parts exposed to atmospheric oxygen especially when the spray coating is flaking. The salt speeds up the rate of corrosion as a result of electrochemical reactions as shown in Figure 9: Flaking coating exposing sections of the iron surface to rust. Pure water or dry oxygen has no effect on iron metal. The light-protective rust layer (passivation layer) is usually a ferrous oxide. This protective layer can be converted to rust from the combined action of two agents usually water and oxygen and can be facilitated by some degrading solutions such as sulfur oxide and carbon oxide in water. In such conditions, iron hydroxide compounds maybe formed. Iron hydroxides do not adhere to the surface of the iron metal as compared to iron oxides. Therefore as they form they flake off the surface exposing the underneath fresh iron metal to further corrosion. This process continues until the entire metal is consumed or the water, oxygen and sulfur dioxide in the system are depleted. In cases where the oxide or the hydroxide formed is more than the original volume of the metal expansion happens. Sometimes the

expansion can generate an enormous amount of forces damaging the structure as shown in Figure 7:
Heavy rust on iron/iron alloys (Gräfen, Horn, ESchlecker, & Schindler, 2000). This form of corrosion can sometimes result in catastrophic events.



Figure 9: Flaking coating exposing sections of the iron surface to rust

2.2.3 Catastrophic Structural failure caused by rust



Figure 10: Collapsed silver bridge in West Virginia (1967) collapsed in less than a minute killing 46 people



Figure 11: Collapsed Kinzua Bridge in Pennsylvania was blown away by a tornado since its central bolts had been eaten away by rust leaving the bridge anchored by gravity

2.3 Effect of high temperature and pressure on the corrosive behavior of steel

According to John, 1999, high temperature and pressure corrosion is a form of corrosion that does not require the presence of liquid electrolyte. In this mechanism the metals react directly with the gaseous atoms in the atmosphere rather than ions in the electrolyte. This type of corrosion is referred to as dry corrosion or scaling. Steel alloys depend on the oxidation reaction to develop a stable protective scale. This protective film is able to resist corrosion such as carburization, sulfidation and other forms of corrosion (John, (1999)). In reducing environments where oxygen concentration is limited are more susceptible to high temperature and pressure corrosion.

High temperature results in increased rate corrosion process. Most of the corrosion reaction will increase with increase in temperature therefore speeding up the corrosion reaction. Where steel material is exposed to high temperatures it experiences an extensive corrosion resistance that tends to penetrate to the scale structures. Increase in temperature increases the penetration extent of the corrosive agents through the deposits and the scales (Kawahara, 2002). High temperatures have been seen to result in destruction of the protective film that appears in most of steel materials. High temperatures play a role in increasing the scaling factor and sometime results in breaking and peeling off of the protective film which will expose fresh uncorroded elements to the corrosive environment rapidly increasing the rate of corrosion (John, 1999).

3 Chapter 3: Methodology

3.1 Experimental methodology on Corrosion in steel

There are various types of corrosion that can produce adverse effects on steel components. Steel material have a wide range of applications which means the components may be exposed to a variety of corrosive environment. When the steel material is exposed to corrosive environment it undergoes a step wise corrosion process which is time relative. Theoretically, corrosion increases with increase in exposure time. The aim of the project is to study the corrosive behavior of steel under various corrosive environments. The experiment involved visual inspection of corrosion of steel and factors affecting corrosion process according to factors such as:

- To study and analyze the corrosion mechanism in steels
- To analyze various factors that affect the rate of corrosion in steels
- To study the behavioral changes in corrosion with change in environment
- To find methods of slowing down corrosion such as barrier corrosion
- To find out the effect of corrosion on steel properties such as strength

To achieve these objectives, standard test methods for evaluating the Corrosion Resistance of Stainless Steel Powder Metallurgy (PM) Parts/Specimens by Immersion in a Sodium Chloride Solution following the ASTM B895 standards. Salt immersion is a method that is used to evaluate corrosion resistance in two methods. First the steel specimens are examined periodically and the end point of the examination is marked by the appearance of the first staining or rust. The second method involves a continuous exposure of the steel specimens to sodium chloride solution monitoring the corrosion as a function of time. The experiment will be carried out in three different types of steels since there are various types of steel. Steel specimens are made of SS304, SS430 and SS316 steel. Corrosion testing of the three materials (SS316, SS304 and SS430) was conducted under the auspices of MPIF standards committee (Gavriljuk, Berns, 1999).

3.1.1 Composition of the material used in the experiment

3.1.1.1 SS316 chemical composition

Carbon (C)	0.12%max
Manganese (Mn)	2.00%
Silicon (Si)	0.75%
Phosphorous (P)	0.045%
Nitrogen (N)	0.10%

Sulphur (S)	0.03%
Molybdenum (Mo)	2-3%
Chromium (Cr)	16-18%
Nickle (Ni)	10-14%max

3.1.1.2 Mechanical properties of SS316

Grade	Tensile Stress (MPa) minimum	Yield Stress 0.2% Proof (MPa) minimum	Elongation (% in 50 mm) minimum	Hardness	
				Rockwell B (HR B) max	Brinell (HB) max
316	515	205	40	95	217
316L	485	170	40	95	217
316H	515	205	40	95	217

SS316 stainless steel are known for its excellent corrosion resistance in chloride environment that are at temperatures of below 60 °C such that they do not experience any surface corrosion except mere stains. It also has excellent corrosion temperature at high temperatures of up to 860 °C. they hardened through annealing and they have excellent weldability and machinability.

3.1.1.3 SS 430 steel chemical composition

Carbon (C)	0.12%max
Manganese (Mn)	1.00%
Silicon (Si)	1.00%
Phosphorous (P)	0.04%
Sulphur (S)	0.03%
Chromium (Cr)	16-18%
Nickle (Ni)	0.75%max

3.1.1.4 Mechanical properties of SS 430

Tensile strength 515-600 mpa, yield strength of 205-305 mpa, elongation of 40%-60%, Hardness (brinell) of 170 and endurance (fatigue) limit of 240 mpa.

3.1.1.5 SS 304 chemical composition

Element	Type 304 (%)
Carbon	0.08 max.
Manganese	2.00 max.
Phosphorus	0.045 max.

Sulfur	0.03 max.
Silicon	0.75 max.
Chromium	18.00-20.00
Nickel	8.00-12.00
Nitrogen	0.10 max.
Iron	Balance

3.1.1.6 SS304 Stainless Physical Properties:

Density: 0.803g/cm³, Thermal conductivity: 16.2 W/m-k (100°C), Modulus of Elasticity (MPa): 193 x 10³ in tension, and Melting Range: 2550-2650°F (1399-1454°C)

Yield Strength 270 MPa, and Tensile Strength 465 MPa hence SS304 has excellent properties of high Durability, toughness, and corrosion resistance

3.1.1.7 Method (immersion experiment procedure)

Immersion method also referred to as ASTM B895 as mentioned earlier comprises of two methods for evaluating the ability of the three materials to resist corrosion in an aqueous solution of sodium chloride (5% NaCl).

3.1.2 Specimen preparation

The specimen of the three materials were prepared specially to ensure that they comprise of similar properties. Each material was sintered to appropriate temperature (i.e. between 752-1112°F for all the specimens). Since the experiment is to be done to other four specimens, sintering the material was important to make sure the specimens bear same properties (mechanical and chemical) to facilitate repeatability of the experiment. Repeatability allows there to be an ease of comparison establishment on the results. The specimens are cut in similar dimensions as well (Gavriljuk, Berns, 1999).

3.1.3 Specimen cleaning

After the specimen preparation follows the cleaning process. Cleaning process is a standard procedure to be followed before exposing the specimen to the experimental corrosive environment. It helps in the removal of any contamination (such as grease process called degreasing) on the surface of the specimen to get rid of any ambiguity. The specimens are cleaned in the following procedure

- ❖ Degreased in a n organic solvent or hot alkaline cleaner however hot alkaline cleaner is not very much preferred since it may attack the metal the most preferred method is ultrasonic cleaning.

- ❖ Pickling is considered for some metals that does not undergo localized corrosion. The metal is pickled in an appropriate oxide solution.
- ❖ Abrade with an abrasive paper to remove burrs
- ❖ The specimen is then rinsed thoroughly in hot dry air and stored in a desiccator

3.1.4 Experimental setup

The different specimens are placed each in its own glass beaker/jar containing 5% NaCl solution. The solution must fully cover the specimen so that the specimen would be fully immersed in the solution. The solution was maintained at 5 times in mass more than the specimen itself. The distance between the top surface of the immersed specimen and the top surface of the solution was maintained at least 25mm. The ratio of air volume to the sodium chloride solution volume was maintained between 1:2 to 1:3. Glass pellets could be included at the bed of the beaker/jars where the specimen will lay. The solution had to be shake/stirred thoroughly and gently to remove any air bubbles. The beakers/jars containing the experimental specimen and solution were then closed and time recording started. The experiment was carried out at room temperature. After the experimental setup and start of the experimental time is recorded at varying intervals i.e. ½hr, 1hr, 2hr, 4hr, 8hr, and 28hr.

3.1.4.1 Method 1

This method examines the corrosion life of the different specimen which is the time taken for the specimen to first show corrosion attack. The set specimens were keenly observed of their first signs of corrosion attack in terms of rust or stain. The time when the rust or stain first shows was recorded and marks the end point of the test (Davis, 1994).

3.1.4.2 Method 2

In this method the level of corrosion is evaluated in percentiles such that the level of corrosion is divided into various levels from partial corrosion to complete corrosion. The corrosion level is measured to the amount of surface area that has been corroded. The experiment continues even after the appearance of the first appearance of the rust. After the appearance of the first stain the time is recorded at intervals of corrosion degree i.e. at 0%, 1%, 25% and Over 25% surface coverage by stain/rust.

The specimens are then ranked according to their degree of corrosion such that

A completely free from any rust /stain

B when the first sign of corrosion was seen or corroded region can be characterized as being less than or equal to 1% of the surface

C corroded region covers between 1% and 25% of total surface area

D corroded region covers more than 25% of the total surface area

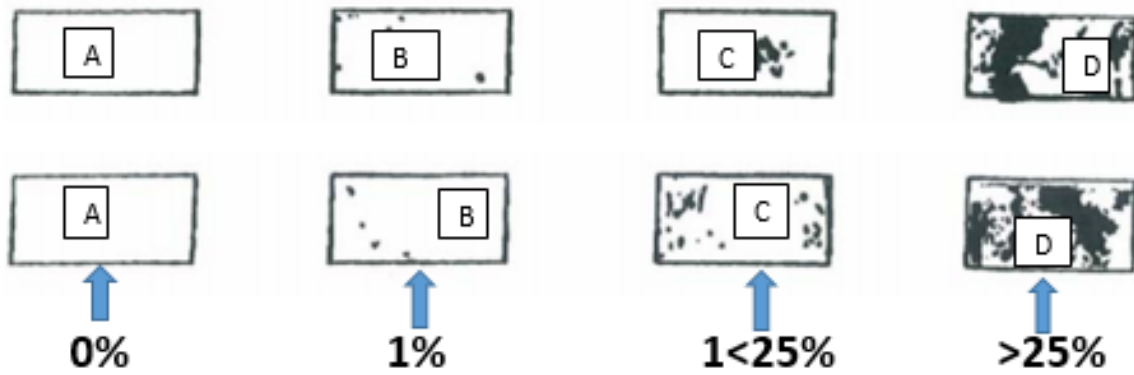


Figure 12: Different corrosion degrees

4 Chapter 4: Results

The results of salt immersion test of method 1 illustrating the time taken for various specimens to show first corrosion stain is as tabulated below

Table 2: Method 2 results

Material	Specimen 1	Specimen 2	Specimen 3	Specimen 4
SS430 steel	30min	45min	30min	45min
SS304 steel	1hr	1hr	45min	80min
SS316	2hr	2hr30min	3hr	2hr45min

Method results showing various ranks of the specimen and time taken to achieve various degrees of corrosion are tabulated as follows

4.1 Rating results for Method 2

SS316 specimen rating

Material = SS316 steel						
	½ hr	1 hr	2 hr	4 hr	6 hr	8 hr
Specimen 1	A	A	B	B	C	C
Specimen 2	A	A	A	B	B	C
Specimen 3	A	A	A	B	B	B
Specimen 4	A	A	A	B	B	C
A holdings	100%	100%	80%	–	–	–
B holdings	–	–	20%	100%	80%	20%
C holdings	–	–	–	–	20%	80%
D holdings	–	–	–	–	–	–
Material = SS430 steel						
Specimen 1	A	B	C	C	D	D
Specimen 2	A	B	B	C	C	D
Specimen 3	A	B	C	C	D	D
Specimen 4	A	B	C	C	D	D
A holdings	100%	–	–	–	–	–
B holdings	–	100	20%	–	–	–
C holdings	–	–	80%	100%	20%	–

D holdings	–	–	–	–	80%	100%
Material = SS304 steel						
	½ hr	1 hr	2 hr	4 hr	6 hr	8 hr
Specimen 1	A	A	B	B	C	D
Specimen 2	A	B	B	C	D	D
Specimen 3	A	A	B	B	D	D
Specimen 4	A	B	B	C	D	D
A holdings	100%	50%	–	–	–	–
B holdings	–	50%	100%	50%	–	–
C holdings	–	–	–	50%	20%	–
D holdings	–	–	–	–	80%	100%

4.1.1 Sample results at deferent degree of corrosion

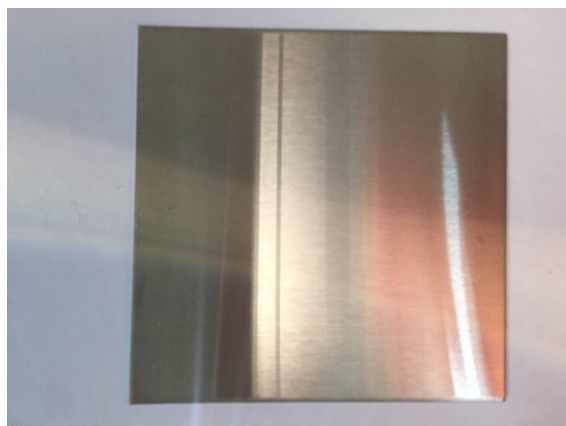


Figure 13: Initial state before corrosion and Class A (1% when the first stain appeared)

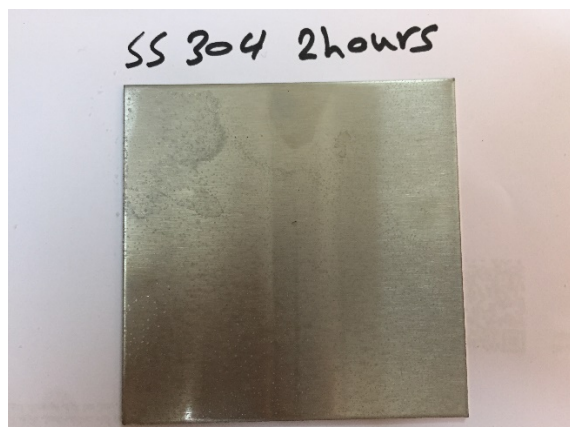


Figure 14: Class B (1%>25% corrosion level) and Class C (1%>25% corrosion level)



Figure 15: Class D (>25% corrosion level)

4.2 Mechanical strength test

The specimens obtained from the salt emersion experiment were further tested for strength properties.

The tensile strength of the specimens was tested to determine the effect of corrosion on load bearing capacity of the material. Tensile test was carried out on these specimens and the results compared to the actual tensile strength of the material. To carry out the test, the resultant corroded specimen obtained at different time intervals were first cleaned and prepared for tensile testing.

A tensile testing machine was used to measure for the changes in tensile strength of the various specimens from different materials (SS316, SS430 and SS304 stainless steel). The specimens were fixed on the tensile testing machine jaws and tensile load applied to allow the specimen to deform uniform until it fractures. Yield load and ultimate tensile loads were noted and recorded. Since the specimens were only exposed to the corrosive environment for very short time, the change in tensile and ultimate tensile load will not differ by much.



Figure 16: Tensile test machine and specimen set up

Tensile test is an experiment designed for testing the mechanical properties of materials to determine how they perform under controlled loading conditions. When the specimens are clamped to the tensile test machine, they are exposed to axial load to elongate the specimen gradually till fracture.

After the tensile test was carried out the results were compared. The specimens that underwent the test are the uncorroded specimen and a specimen exposed to corrosion for 20hrs. specimen exposed to corrosion period of 1/2hr to 4hrs may not result any significant effect to the tensile test of the material hence we

selected the specimen that had the highest exposure time. This specimen had class D level of corrosion except for SS316 specimens. The tensile test results are as presented in the graph and results table below

Table 3: Summary of yield and ultimate tensile loads

Material = SS304 stainless steel		
	Yield strength	Ultimate tensile test
Uncorroded Specimen	2813.333	4203.333
20hrs of exposure to corrosion	2708.333	3976.667
Material = SS430 stainless steel		
Uncorroded Specimen	2575.000	3916.667
20hrs of exposure to corrosion	2666.667	4678.333
Material = SS316 stainless steel		
Uncorroded Specimen	2626.667	4080.000
20hrs of exposure to corrosion	2658.333	4053.333



Figure 17: Graph of tensile for against displacement for SS316 material at different exposure times

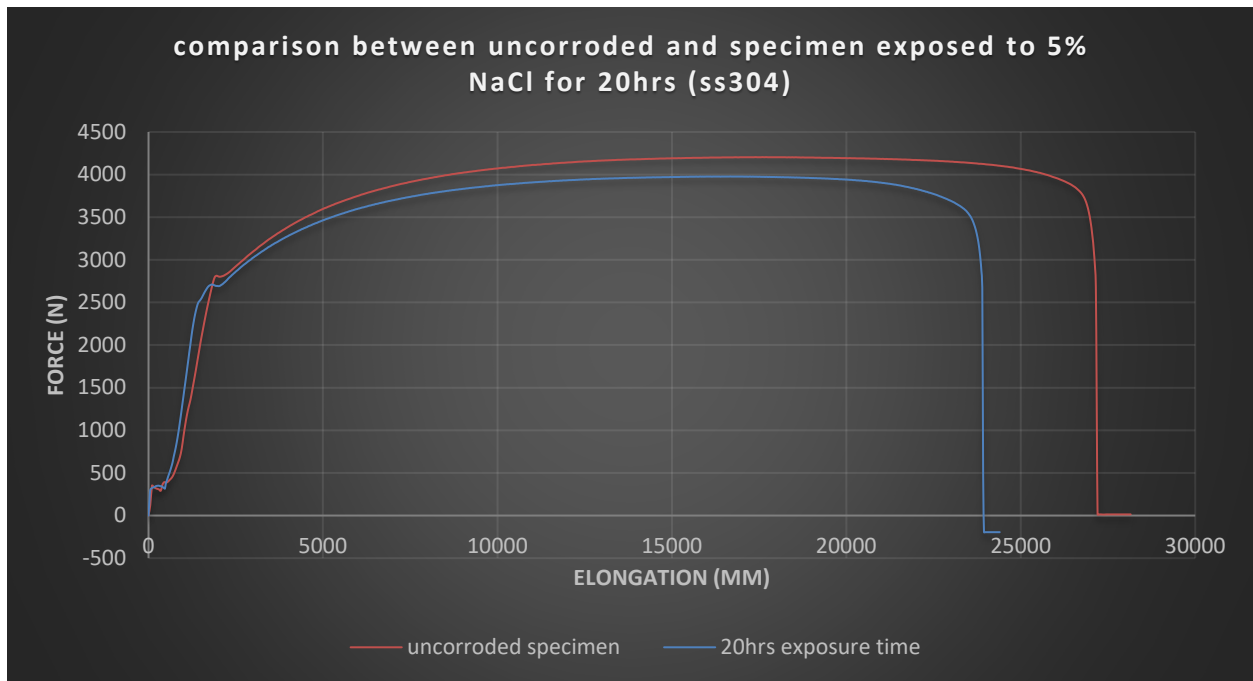


Figure 18: Graph of tensile for against displacement for SS304 material at different exposure times

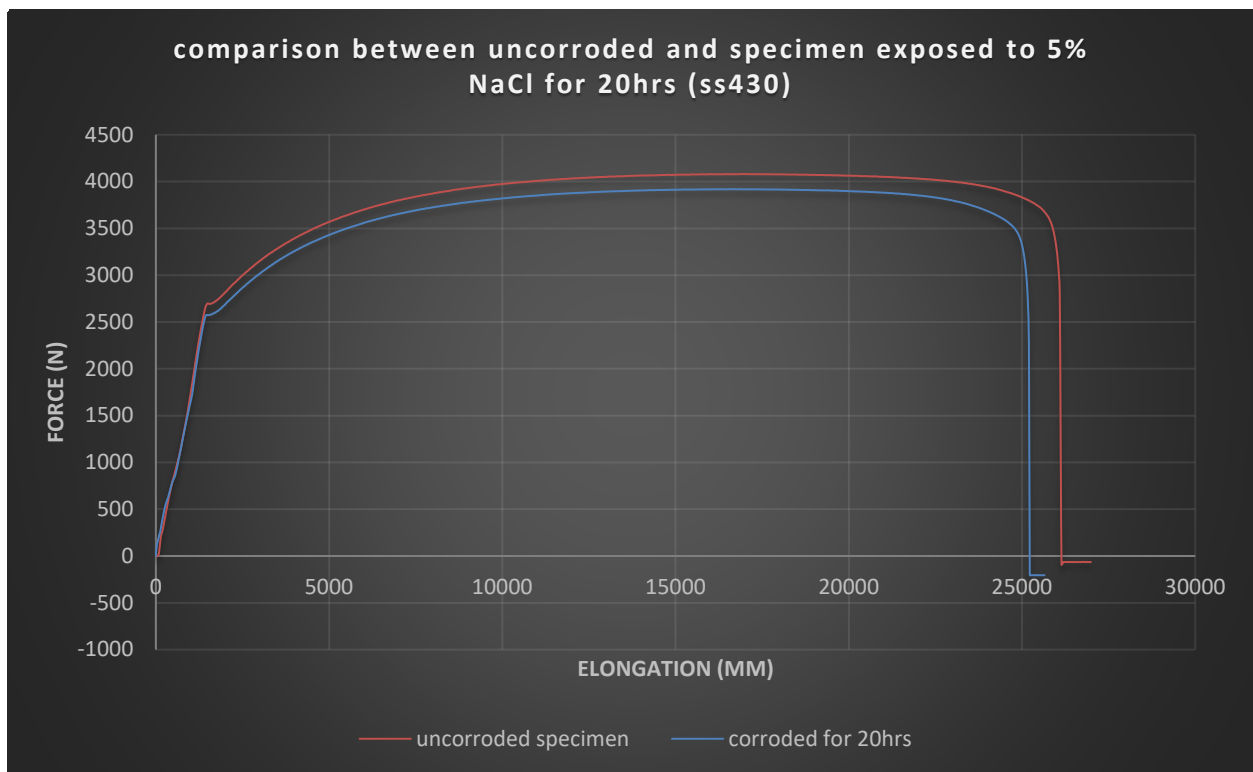


Figure 19: Graph of tensile for against displacement for SS430 material at different exposure times

From the results it can be observed that the yield strength of the different materials reduces infinitely with increase in exposure time to the corrosive environment. However, SS 304 has a higher yield strength than stainless steel. The change is minimal with SS316 since it is slightly affected by NaCl corrosive solution. It however has the highest resistance to corrosion.

5 Chapter 5: Discussion

Corrosion resistance in stainless steel material, which was used as specimen in this project following the immersion in 5% sodium chloride solution method, was found to vary with time. The corrosion rates in the early stages of the test are found to be high and rapid which decreases with increase in corrosion time. The rate of formation of rust between 1% and 25% is very rapid compared to the rate of formation of the rest of the rust. This is due to the fact that at the early stages of corrosion, the surface is free from contaminants. Rust forms with the readily available free iron ions and at the points where the protective film is not fully developed. After the formation of rust, it hinders further corrosion hence reducing the rate of corrosion with time.

As observed from the salt immersion test it can be seen that SS316 steel specimens have a higher tolerance to corrosion than both SS304 and SS430 specimens. The corrosion rate increases gradually with increase in exposure time for all the materials. SS430 stainless steel shows the signs of stain i.e. corrosion sign which faster than the they show in both SS316 and SS304 stainless steel as seen in the salt immersion method one which tests the corrosion life. The method measures the time it takes for the first corrosion signs to show. This illustrates the rate at which the corrosion on material occurs. The material that forms corrosion first is more susceptible to corrosion. As observed SS430 steel was found to be more vulnerable to corrosion than SS304 steel. SS316 was the least affected since even after exposure for over 8hrs only few stains were seen on the surface of the metal. It was found to have the best resistance to corrosion by 5% sodium chloride solution at room temperature.

SS316 stainless steel is usually regarded as the standard marine grade stainless steel since it has excellent resistance to corrosion in a range of atmospheric corrosive environments. It has a high resistance to corrosion in sea water as it does not exhibit surface corrosion. However, it is subject to crevice, pitting and stress corrosion cracking when exposed to warm marine water of about 60 °C and the corrosion appear as brown staining.

It is resistance to high temperature oxidation at average temperatures of 870 °C and 925 °C. SS316L can be continuously used in temperatures between 425 and 860 °C since it has higher resistance to carbide precipitation. At elevated temperature, SS316H maintains its higher strength hence it finds application in places requiring high structural and pressure containing at high temperature of 500 °C.

SS316 has excellent manufacturability considering weldability and machinability. It has excellent welding abilities by using methods such as fusion method with or without filler metal. However, for 316H additional post weld annealing is required to in heavy welded regions to improve corrosion resistance. It provides reduced tool wear in most machining operations and higher machining rates. SS316 is heat

treatable through annealing (solution treatment) at temperature between 1010-1020 °C and rapidly cool. Thermal treatment does not harden this type of steel.

The reason behind the difference in corrosion resistance of the materials is the difference in chemical composition. Every alloying element that makes up the materials i.e. stainless steel SS316, SS430 and SS304 contributes to physical and mechanical properties of the material. The element responsible for improving corrosion resistance in steel is mainly chromium and Molybdenum for SS316. Nickel is responsible for the improvement of ductility, manganese responsible for workability properties, aluminum improves scaling resistance and carbon strengthens the material.

5.1 Elements that improve resistance of stainless steel

Material that contribute to the non-corrosive features of stainless steel are briefly discussed below.

5.1.1 Chromium

Chromium is the main element that contributes to the corrosion resistance of steel alongside other minor element such as nickel, molybdenum and nitrogen. Chromium element contributes to the formation of an invisible, rough, adherent oxide film on the steel surface which is responsible for resisting corrosion. Chromium composition exceeding 1.1% results in formation of protective film on the surface of the material. This chromium oxide film also improves scaling resistance of steel at high temperatures. Chromium element in steel also allows for the formation of a self-healing film if chemically or mechanically harmed. Self-healing process is dependent on oxygen availability to oxidize the fresh chromium element exposed during the chemical or mechanical corrosion process. It should be noted that excessive addition of chromium element reduces ductility hence care should be taken to add the correct composition of material (Potgieter & Van Der Lingen, 2016).

5.1.2 Nickel

Nickel is the other element that contributes largely in improving the resistance of steel material. It works such that it steadies the austenitic structure and builds up ductility making the stainless steel easier to form. It also raises high temperature strength and corrosion resistance mostly in industrial and marine environments, chemical, food and textile processing industries (Potgieter & Van Der Lingen, 2016).

5.1.3 Silicon

Silicon improves scaling resistance by creating a tight initial scale which will tolerate cyclic temperature changes. Small amounts of silicon are added to all grades of stainless for deoxidizing.

5.1.4 Manganese

Manganese promotes the stability of austenite at or near room temperature and improves hot working properties. It is a mild deoxidant which acts as a steel cleanser by taking out Sulphur and oxygen of the melt during slag. It is responsible for improving the materials harden ability and tensile strength however it decreases ductility. Most of steels have at least 0.3% but the amount can be increased up to 1.5% with accordance to the use of the material (Potgieter & Van Der Lingen, 2016).

5.1.5 Molybdenum

Molybdenum increases corrosion resistance, strength at high temperatures and increases the range of passivity and lessens the susceptibility to pit formation/corrosion and crevice corrosion certainly in chloride and Sulphur containing environments. This why SS316 is not greatly affected by NaCl solution.

5.1.6 Aluminum

Aluminum lowers the hardenability, and improves scaling resistance

5.1.7 Titanium

Titanium provides carbide stabilization for material that will undergo welding. Alloying steel with titanium forms titanium carbides with carbon which are very stable and hard to penetrate which contributes in minimizing occurrence of intergranular corrosion. For best results the content of alloying titanium should be between 0.25%-0.6%.

5.1.8 Carbon

Iron cannot be strengthened by heat treatment hence it is alloyed with carbon to obtain steel metal hence carbon strengthens and promotes the expansion of precipitates harmful to corrosion resistance. High amount of carbon in steel is undesirable especially if the metal is to be used in high temperature (eg welding) due to carbide precipitation.

5.1.9 Copper

Despite copper being normally present in stainless steel as a residual element it is added in small amounts to enhance resistance to corrosion especially in chloride environments and sulphuric acid. Copper also produces a precipitation hardening property to steel.

5.1.10 Nitrogen

It increases the austenitic stability of stainless steel and it also improves the yield strength of stainless material. Nitrogen also improves resistance to pitting corrosion in stainless steel.

As observed the main alloying elements responsible for corrosion resistance are chromium, molybdenum and nickel therefore increasing the composition of these elements will result in improvement of corrosion

resistance of steel. The elements also have an added advantage of improving tensile strength. For elements to be used in harsh chloride and sulphuric corrosive environments such as marine environment, or high temperature chemical environments alloying stainless steel produces the best results.

There are various types of corrosion in metals especially in steel material. However, the main corrosion attacking most materials is rust (oxidation reaction with oxygen) which results in formation of iron oxide. This is achieved by the tendency of iron need to return to its original stable state that is iron oxide. Rust is a mainly an oxide of iron which is usually red in color and is formed by a redox reaction between iron and oxygen in the presence of an electrolyte in most cases water or air moisture. Other corrosion attacks that steel is susceptible to include Uniform, Atmospheric, aqueous, soil, galvanic, pitting, intergranular, crevice, erosion, microbial and high temperature corrosion. Corrosion can result in catastrophic event such as collapsing of building and bridges which results in great losses in terms of life, and properties (Parshutin, 2012). It is therefore important to understand corrosion and device new ways to curb corrosion to prevent such catastrophes from happening.

Several tests were performed on different types of steel to determine the rate of corrosion, how corrosion affects the strength of materials and understand how to improve materials to withstand corrosion. It was discovered that corrosion reduces strength of material with respect to exposure time to corrosive environment (Parshutin, 2012).

Several elements have been seen to improve greatly the corrosion and strength of materials, these materials include Chromium, nickel, molybdenum, silicon, copper, carbon and manganese. Understanding steel constituents to the element level is important in order to know the best way of improving corrosion resistance of steel. From the discussion above, it can be deduced that in order to improve steel resistance to corrosion chromium need to be used as the alloying agent at a composition of between 18 and 20% since further increase in composition could raise corrosion resistance but reduce the ductility of the material. Depending on the use of the material the chromium composition can be altered accordingly (Potgieter & Van Der Lingen, 2016). Nickel builds on the ductility of the material as well as corrosion resistance it should be added between 8% to 12% composition. Molybdenum also contributes largely in preventing corrosion in chloride and sulphuric environments such as marine environment and chemical facilities. It is also a main constituent of corrosion resisting element and should constitute 10% for best results. However, for more improved corrosion resistance, other elements can be added such as carbon = 0.08% max, Molybdenum = 10%, Manganese = 2.00% max, phosphorous = 0.045% max, sulfur = 0.03% max, silicon = 0.75% max, and Nitrogen = 0.10% max.

5.2 Corrosion reduction

5.2.1 Reducing atmospheric corrosion

Most of the carbon steels do not have large differences in their rate of atmospheric corrosion since they are not highly alloyed. Alloying can significantly reduce the rate of atmospheric corrosion of carbon steels. The alloying elements that can contribute the reduction of corrosion in steels include silicon, nickel, phosphorous, copper and chromium. However, from the mentioned elements, copper is the most appropriate material added at a proportion of between 0.01 – 0.05%. It reduces the corrosion rate by a factor of two to three. Adding a combination of the mentioned elements is more effective than adding either of them singly (Terence, 2017).

5.2.2 Reduction of soil corrosion

Research by Bradford, Samuel A. 1993, shows that's alloying of carbon steel with various elements to have little to no significant contribution to the reduction of soil corrosion. Some experimental tests have shown that alloying steel with copper a proportion ranging from 1% to 2.5% in combination with nickel can have some significant benefits to influence the reduction of soil corrosion (Yuan, Wen, and Shen, 1992).

5.2.3 Reduction of intergranular attack

According to Chandrasekaran, Batchelor, Loh Nee, 2012, intergranular attack is reduced through proper heat treatment of the steels. It can as well be reduced by another method that involves the reduction of carbon level of the steel below 0.03% or by stabilizing the carbon by addition of strong carbide-formers (alloying). The strong carbide formers elements include titanium or niobium. The strong carbide formers elements make carbon no longer available for chromium carbide precipitation.

5.2.4 Reduction of microbial corrosion

Research by Jones, Denny A. 1996, reviewed that this form of corrosion can be reduced through the coating and cathodic protection during the time of construction. This because coating and cathodic protection prevent the exposure of the pipes to accelerated low water corrosion. The pipes that are unprotected during installation can utilize the local installation sacrificial anodes to the affected regions to inhibit the corrosion. For long-term purposes, a complete retrofitted sacrificial anode system can be installed. Affected areas can also be treated using cathodic protection, using either sacrificial anode or applying current to an inert anode to produce a calcareous deposit. The produced deposit helps in shielding the metal from further attack (Fontana & Greene, 1967).



Figure 20: Sacrificial anode attached to prevent corrosion (Gretchen, 2015)

5.2.5 Reduction of pitting and crevice corrosion

Alloying stainless steel with a high percentage of Molybdenum increases resistance to pitting and crevice corrosion especially in sea water environment. Molybdenum content of about 10% provides the best result in resisting crevice and pitting corrosion.

5.2.6 Cathodic modification

Cathodic modification is an anodic reaction retardation resulting from the enhanced capability of alloys to undergo passivation through the active introduction in the alloy. It is one method that allows production of alloys that are resistant to corrosion since the alloys' resistance from electrochemical attack is enhanced. Cathodic modification is typically seen with alloying titanium and stainless steel with certain metals such as the platinum group (Potgieter, Heyns, & Skinner, 1990).

For various corrosion attacks there are several ways in which alloys to form and enhance alloys that are resistance to corrosion or resistance to electrochemical attack which include the following

- Increased thermodynamic stability
- Kinetic retardation involving the anodic process
- Kinetic retardation involving the cathodic process
- Generation of passivating and stable oxide layers

Steel containing chromium as an alloying agent can have their thermodynamic stability improved by alloying them with molybdenum and nickel. Retardation of cathodic reaction can be achieved by eradication of active positive impurities and increasing cathodic process overvoltage. This can be achieved by alloying steel with elements such as manganese, antimony or arsenic (Ujiro, Satoh, Staehle and Smyrl, 2001). Passivating layers can be achieved through the addition of chromium, which is less stable relative to iron in terms of thermodynamics. Stainless steel technically derives its resistance to corrosion to the passivating oxide layers on top of the steel. Meanwhile, anodic reactions can be slowed down in many ways, like alloying nickel and iron steels with metals like chromium. This can also be

achieved by the introduction of active cathodes into the alloy. One good example is alloying titanium and stainless steel with platinum-group metals (PGMs) (Potgieter, Heyns, & Skinner, 1990). This technique is referred to as cathodic modification.

For cathodic modification to be achieved there are various requirements that need to be followed as mentioned below

- ❖ Base alloy should contain critical density
- ❖ The potential base metal for passivation must be negative to allow for cathodic component to modify the corrosion potential
- ❖ For broader passive range, the base transpassive potential for the base alloy must be electropositive
- ❖ The cathodic alloying material should have lower overvoltage and higher current density and must be resistant to corrosion under the situation.

6 Chapter 6: Conclusion

Corrosion is a major issue in applications of steel metal. There are various forms of corrosion however the main corrosion types that affects steel material is rust which occurs in presence of oxygen and an electrolyte contain. From the study it has been found that the main method of improving corrosion of steel is by alloying with elements such as chromium molybdenum and nickel. They are the major elements that contributes to the largest portion of improving resistance of steel to corrosion.

Chromium need to be added as an alloying element at 18% and 20% composition. Past that composition it will introduce undesirable characteristic to the material such reduced ductility. 10% of molybdenum and a maximum of 12% of Nickel will produce excellent results in improving the resistance of steel. Nickel also improves ductility of steel. A combination of chromium and nickel will produce best result since as higher amounts of chromium lowers ductility of steel nickel on the other hand improves it. Other alloying elements include carbon = 0.08% max, Manganese = 2.00% max, phosphorous = 0.045% max, sulfur = 0.03% max, silicon = 0.75% max, copper = 2.5% max, Titanium = 0.6max and Nitrogen = 0.10% max.

Apart from alloying other new method that would contribute largely in improving corrosion resistance of steel is cathodic modification. Cathodic modification is an anodic reaction retardation resulting from the enhanced capability of alloys to undergo passivation through the active introduction in the alloy. It is a method that produces elements with high resistance to electrochemical corrosion. It is mainly achieved by alloying with titanium.

7 Chapter 7: References

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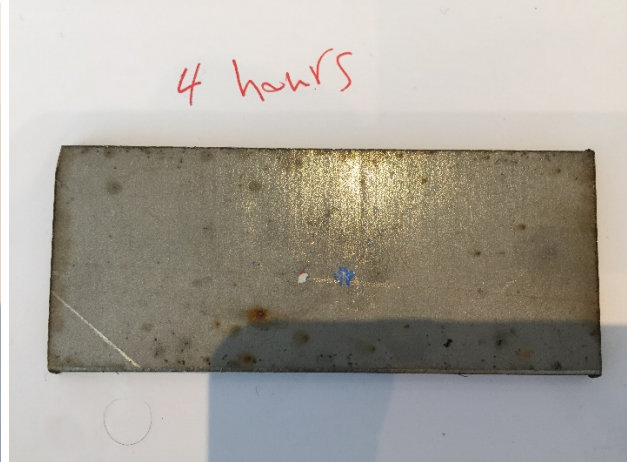
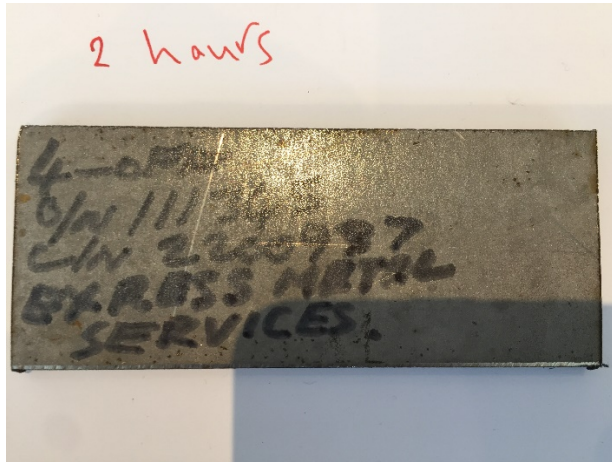
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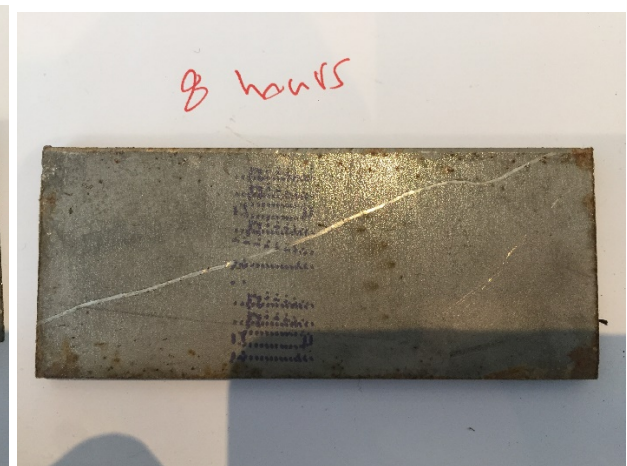
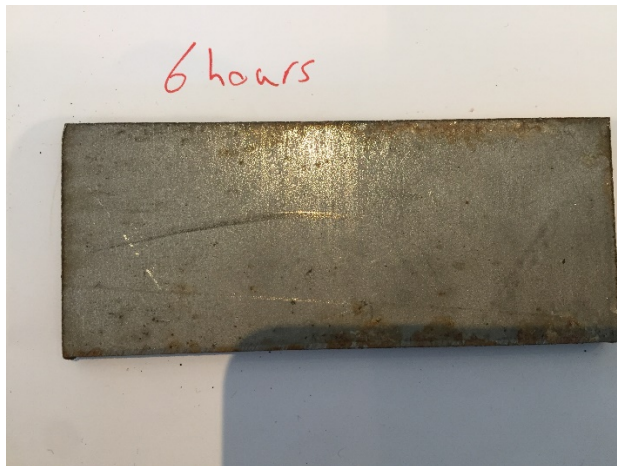
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8 Chapter 8: Appendices

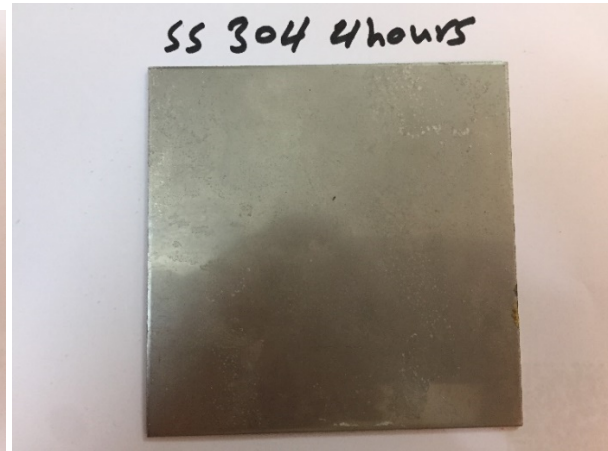
Appendix 1: Method 2 results for SS316 at 2hrs and 4hrs time intervals



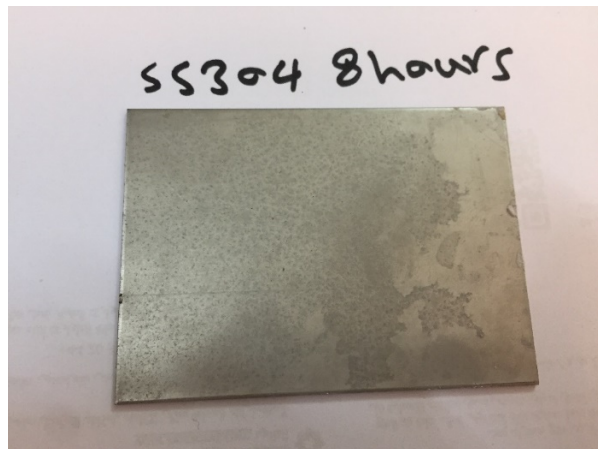
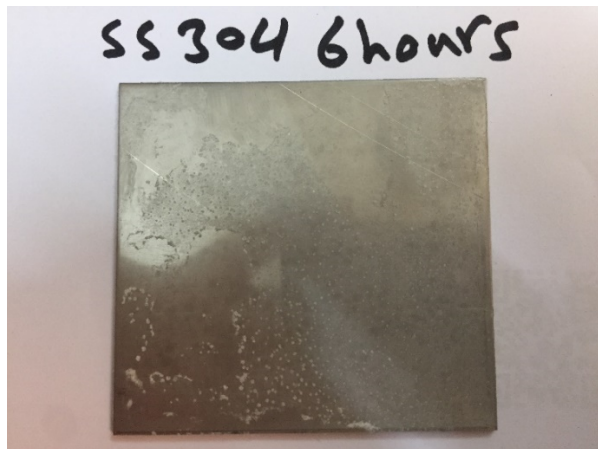
Appendix 2: Method 2 results for SS316 at 6hrs and 4hrs time intervals



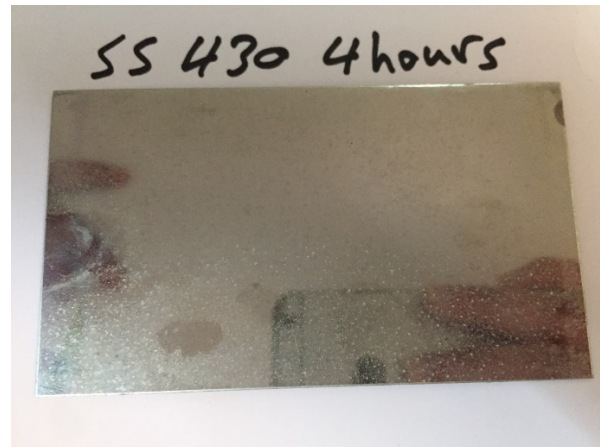
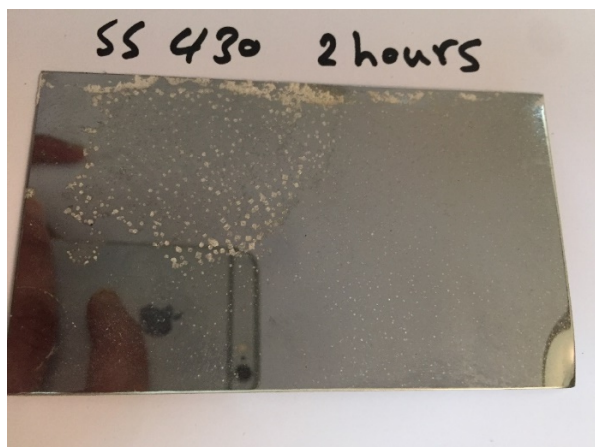
Appendix 3: Method 2 results for SS304 at 2hrs and 4hrs time intervals



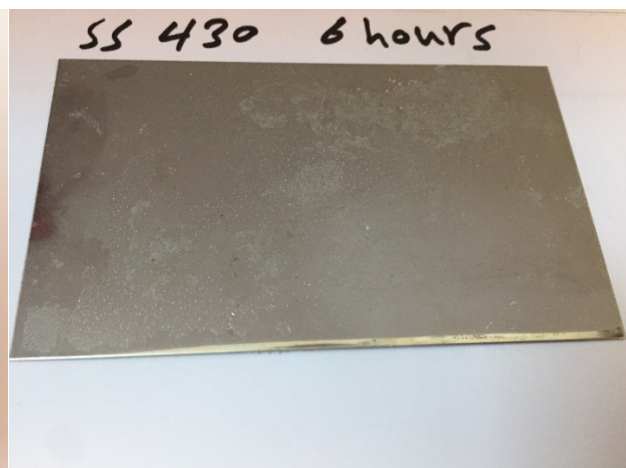
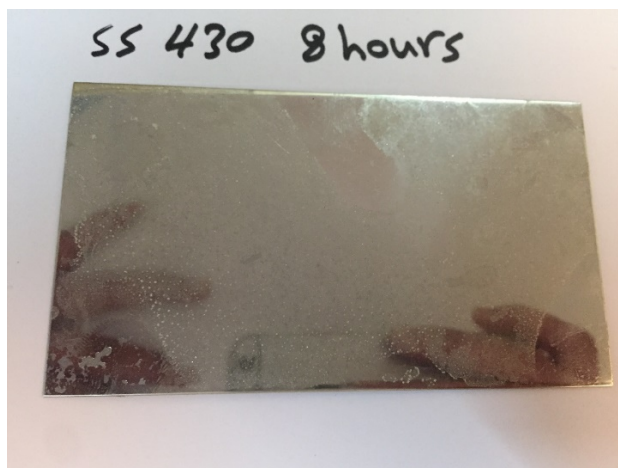
Appendix 4: Method 2 results for SS304 at 6hrs and 8hrs time intervals



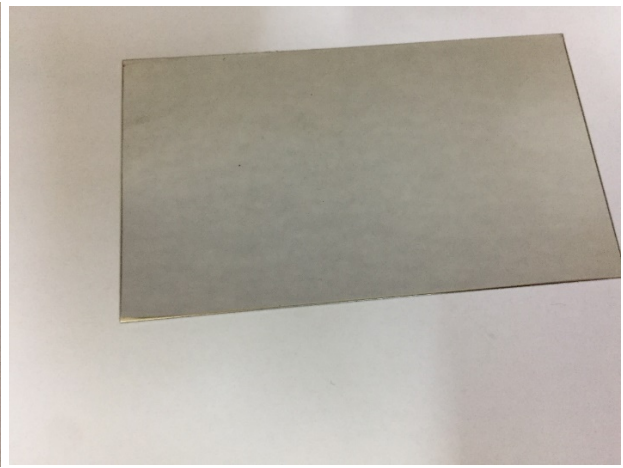
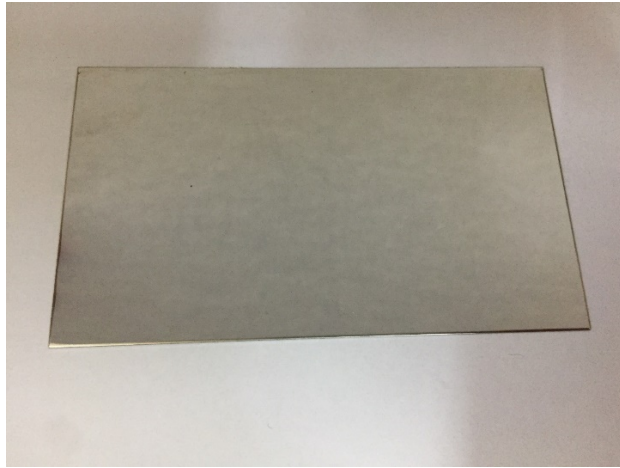
Appendix 5: Method 2 results for SS430 at 2hrs and 4hrs time intervals



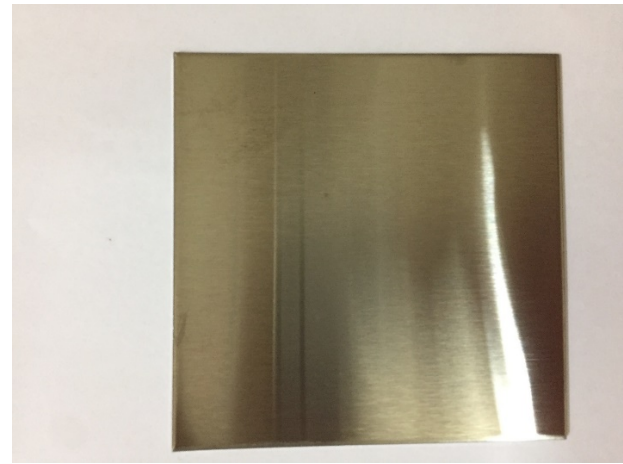
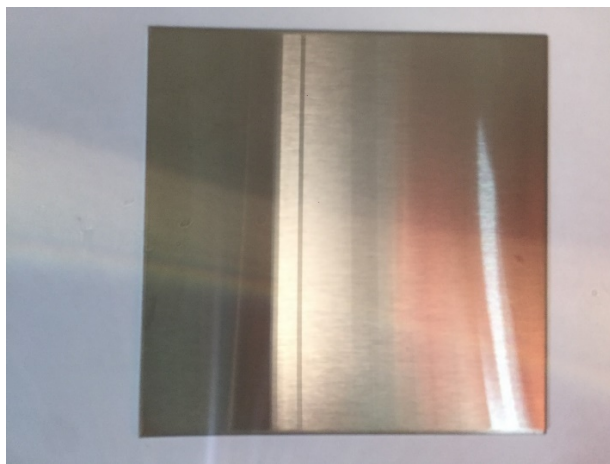
Appendix 6: Method 2 results for SS430 at 6hrs and 8hrs time intervals



Appendix 7: Method 1 results for SS430 and SS304 for first since of corrosion rust



Appendix 8: prepared specimen before introduction to corrosive environment



Appendix 9: specimen and salt immersion test set up

