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Benefits of Aluminum: Comparing the Common Materials in the Bar Grating Industry

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Benefits of Aluminum: Comparing the Common Materials in the Bar Grating Industry

Honors Project

Jonathan Geiser

April 11th, 2018

Benefits of Aluminum

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Executive Summary

This paper presents several characteristics of aluminum that make it the product of choice in the grating industry. Aluminum's material and mechanical properties make it most desirable, as it has a density one third that of steel. Even with its lightweight characteristic, it can withstand the same or higher amount of force than steel can before it begins to deform permanently, depending on the alloy. When compared to glass fiber reinforced plastic (GFRP), aluminum is almost identical in density, and in applied force withstood until failure, but is five times stiffer than GFRP. These comparisons show the benefits of aluminum.

Aluminum sets itself apart from other metals by its resistance to corrosion. This paper outlines why aluminum exhibits corrosion resistance (a spontaneously occurring oxide film). In addition, this paper gives a generalization of the environments in which aluminum will be resistant to corrosion, as shown in **Figure 6**. It also presents a list of the chemicals that have little to no corrosive effects on aluminum equipment, shown in **Figure 7**. The most important part is the summarization of the experimental data on the corrosion rates of aluminum. In this data, the assessment of a 40 year industrial atmospheric exposed aluminum showed the maximum size reduction of all aluminum wires was 11% due to corrosion. It was also predicted that there would only be a 20% decrease of the tensile strength of the aluminum strands over 50 years of service life. This study concludes that aluminum has an excellent corrosion rate and strength retention, making it a highly sought after product.

This paper looks at the aluminum alloys used in the grating industry. It explains the mechanical properties of aluminum. It also gives an explanation of what corrosion is and how it happens, then applies that understanding specifically to aluminum. In addition, it presents a summary of various corrosion testing results to display the long life expectancy of aluminum. This paper gives a comparison of the overall product value of the various materials used in grating. Other advantages of aluminum discussed include its non-sparking property and its recyclability. Through all the various aspects of aluminum discussed, it is shown aluminum has many benefits making it a valuable product.

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Introduction

According to the Aluminum Association, 22 million pounds of aluminum were consumed in the United States in 2014.¹ Aluminum is widely used in numerous industries, from automotive to electrical, and from firearms to bar grating. Aluminum is one of the most abundant metals on earth in ore form. Once it has been processed into a useable form, it has some very competitive material and mechanical properties, including strength, weight, and stiffness. A strong characteristic of aluminum is its high resistance to corrosion, due to its naturally occurring aluminum oxide film that does not corrode readily. The material properties are important to understand, but the cost, weight, and deflection of aluminum make it a valuable product. Aluminum's non-sparking property is advantageous in many applications, and once it reaches the end of its service life, aluminum can be completely recycled. These many engineering considerations demonstrate the benefits of aluminum and why it is one of the most reliable materials that can be used in the grating industry.

Literature Review on Properties of Aluminum

Hugh P. Godard, the author of the Aluminum section in the "Corrosion of Light Metals" said, "It is generally true that the higher the degree of purity of aluminum, the greater the corrosion resistance."² However, the addition of alloying elements enables other characteristics to be increased, including yield strength, modulus of elasticity, and fabricability, including the ease of forming, welding, and other mechanical operations. The most common aluminum alloys used in the grating industry are ASTM-B221 6061, 6063, and 6105.³ The alloy 6061 was introduced in America about 1932 and has been used ever since in large quantities for structural members and plate.² The 6000 alloy series, with the main alloying elements of magnesium and silicon, are a widely used medium-strength aluminum alloy. The unique thing about this alloy is "when magnesium and silicon are both present, a stoichiometric second phase constituent, magnesium silicide (Mg_2Si) is formed. The alloys are termed balanced when the magnesium and silicon contents are in the correct proportion to form Mg_2Si and unbalanced when the silicon content exceeds the amount of magnesium that forms Mg_2Si . In general, balanced alloys have slightly better corrosion resistance than unbalanced alloys."² In addition, this magnesium silicide increases the heat treatability and also the weldability of the material. **Figure 1** shows the weight percentage of the different alloying elements in a few of the 6000 series alloys.

AA number	% Mg	% Si	% Cr	% Cu	% Mn	% Fe
6061	1.0	0.6	0.25	0.25	0.15	0.7
6063	0.6	0.4	0.1	0.1	0.1	0.35
6105	0.8	1.0	0.1	0.1	0.15	0.35

Figure 1: Weight percent of alloying elements, adopted from ASTM-B221M.²³

Aluminum is a competitive material from a properties standpoint when compared to other materials commonly used in the grating industry. The most distinctive characteristic of aluminum is its lightweight material property due to its low density. A mechanical property of aluminum is it has about the same yield strength as that of steel, depending on the alloy. *Yield strength* is the maximum force applied where the material returns to original dimensions after the force is removed. The *tensile strength* of a material is the maximum force a material can withstand before failing. While the tensile strength of aluminum is only a little over half that of steel depending on the alloy, it can still withstand a high amount of force before failure. Another mechanical property that is taken into account when looking at material selection is the Modulus of Elasticity, sometimes called the Young's Modulus, which is a measure of the stiffness of a material. The *Modulus of Elasticity* is the ratio of the stress, calculated from the applied force, to the strain, calculated from the elongation experienced, of a material until the yield strength is achieved. The Modulus of Elasticity of aluminum is about one third that of steel, which

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means that aluminum will elongate more under the same applied force. **Figure 2** shows a summary of the Density, Yield Strength, Tensile Strength, and Modulus of Elasticity for the materials used in grating.

Material	Density (lbs./ft ³)	Yield Strength (kpsi)	Tensile Strength (kpsi)	Modulus (Gpsi)
Aluminum 6061 ³	168.48	35	38	10
Aluminum 6063 ³	168.48	25	30	10
Aluminum 6105 ²⁵	167.62	39.9	45	10
Aluminum 5083 ²⁶	166.06	33	46	10
Low Carbon Steel ³	490.75	30	53	29
Stainless 316L ³	501.12	25	70	28
Stainless 304L ³	501.12	25	70	28
GFRP: Molded ²⁴	106.10	21.5	21.5	2.25
GFRP: Pultruded ²⁴	119.92	30	30	2.8

Figure 2: Summary of mechanical properties for standard materials.

Metals referenced from NAAMM Engineering Design Manual.

GFRP: Molded referenced from Molded Fiber Glass companies, compression polyester, high glass.

GFRP: Pultruded referenced from Molded Fiber Glass companies, polyester pultruded.

Literature review on fundamentals of Aluminum Corrosion

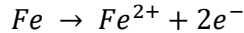
According to Mars G. Fontana, the pioneer of corrosion as an academic study, “Corrosion is defined as the destruction or deterioration of a material because of reaction with its environment. Some of the deleterious effects of corrosion are appearance, maintenance and operating costs, plant shutdowns, contamination and loss of product, effects on safety and reliability, and product liability.”⁴ In order to understand the corrosion resistance of aluminum and the possible effects of corrosion, an understanding of what corrosion is must be established.

Looking at the academic definition of corrosion, it can be understood that a chemical reaction takes place in order for corrosion to occur. The chemical reaction that takes place when corrosion occurs is called an electrochemical reaction. An electrochemical reaction, or cell, consists of two simultaneous chemical reactions in which electrons are transferred from a material in one reaction (*oxidation reaction*) and to another material in the other reaction (*reduction reaction*). Each of these individual reactions are often referred to as *half-cell reactions*. The site at which electrons are transferred from is called the *anode*. The site at which electrons are transferred to is called the *cathode*. When writing out the reactions, an oxidation reaction can be changed to a reduction reaction by changing the direction in which the reaction proceeds. In an electrochemical cell, both the oxidation and reduction reaction are always present, and occur simultaneously at the same rate.

There are four things that are needed for the corrosion reaction to take place: anode, cathode, electron path, and ion path. The anode and cathode defined were defined in the previous paragraph. The *electron path* is a way for the negatively charged electrons produced at the anode to flow to the cathode. This electron path can exist as direct contact between the anode and the cathode sites. The *ion path* is a way positively charged ions developed at the anode transfer to the cathode. This ion path is called an *electrolyte*, which exists as liquid, soil, concrete, and other types of suspended liquid. An example of how a corrosion reaction takes place in the real world is shown by the following example taken from Fontana to explain how iron corrodes in the presence of water and oxygen: ⁴

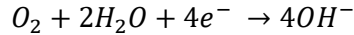
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Consider what happens when iron is immersed in water which is exposed to the atmosphere. Corrosion occurs. The oxidation reaction at the iron anode is:

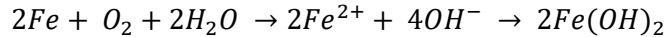


Since the medium is exposed to the atmosphere, it contains dissolved oxygen.

Water is nearly neutral, and thus the reduction reaction at the cathode is:



The overall corrosion reaction can be obtained by adding the oxidation and reduction reactions, in which the electrons cancel and are not shown, is:



The final product of this reaction is ferrous hydroxide.

Now that it is understood how a corrosion reaction happens, the question must be asked what causes these half-cell reactions to take place. Not all metallic materials oxidize to form ions with the same degree of ease. An electric potential difference, or voltage, exists between any two half-cell reactions. When an electrical path is present, electrons generated at the anode flow to the cathode causing this measurable electric potential difference.⁵ From a standard reference point of the hydrogen reduction at 1 atm and 25°C, an *electromotive force (EMF) series* is created by coupling the half-cell reactions for various metals with the reference point.⁵ **Figure 4** is an EMF of all reduction reactions.

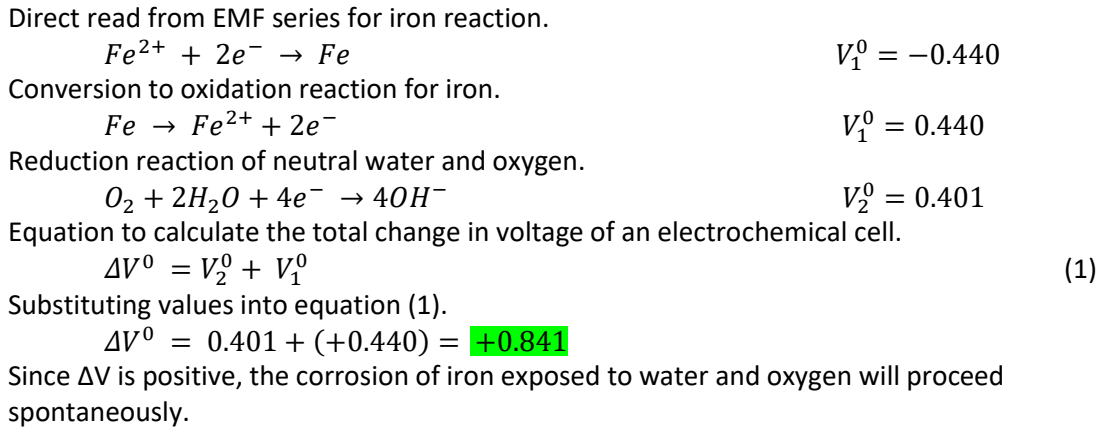
	<i>Electrode Reaction</i>	<i>Standard Electrode Potential, V⁰ (V)</i>
	$\text{Au}^{3+} + 3e^{-} \longrightarrow \text{Au}$	+1.420
	$\text{O}_2 + 4\text{H}^{+} + 4e^{-} \longrightarrow 2\text{H}_2\text{O}$	+1.229
	$\text{Pt}^{2+} + 2e^{-} \longrightarrow \text{Pt}$	~ +1.2
	$\text{Ag}^{+} + e^{-} \longrightarrow \text{Ag}$	+0.800
	$\text{Fe}^{3+} + e^{-} \longrightarrow \text{Fe}^{2+}$	+0.771
↑ Increasingly inert (cathodic)	$\text{O}_2 + 2\text{H}_2\text{O} + 4e^{-} \longrightarrow 4(\text{OH}^{-})$	+0.401
	$\text{Cu}^{2+} + 2e^{-} \longrightarrow \text{Cu}$	+0.340
	$2\text{H}^{+} + 2e^{-} \longrightarrow \text{H}_2$	0.000
	$\text{Pb}^{2+} + 2e^{-} \longrightarrow \text{Pb}$	-0.126
	$\text{Sn}^{2+} + 2e^{-} \longrightarrow \text{Sn}$	-0.136
	$\text{Ni}^{2+} + 2e^{-} \longrightarrow \text{Ni}$	-0.250
	$\text{Co}^{2+} + 2e^{-} \longrightarrow \text{Co}$	-0.277
	$\text{Cd}^{2+} + 2e^{-} \longrightarrow \text{Cd}$	-0.403
	$\text{Fe}^{2+} + 2e^{-} \longrightarrow \text{Fe}$	-0.440
	$\text{Cr}^{3+} + 3e^{-} \longrightarrow \text{Cr}$	-0.744
↓ Increasingly active (anodic)	$\text{Zn}^{2+} + 2e^{-} \longrightarrow \text{Zn}$	-0.763
	$\text{Al}^{3+} + 3e^{-} \longrightarrow \text{Al}$	-1.662
	$\text{Mg}^{2+} + 2e^{-} \longrightarrow \text{Mg}$	-2.363
	$\text{Na}^{+} + e^{-} \longrightarrow \text{Na}$	-2.714
	$\text{K}^{+} + e^{-} \longrightarrow \text{K}$	-2.924

Figure 4: An Electromotive force series, adopted from Callister.⁵

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The EMF series in **Figure 4** is very useful in understanding the electrical nature of the half-cell reactions that are involved in the corrosion process. As **Figure 4** describes, the more positive a measured standard potential is, the better the corrosion resistance of the material, meaning the more likely the reduction reaction will occur. Conversely, the more negative a measured standard potential is, the more likely it is for corrosion to occur on that material. This means it is more likely for the opposite direction of the reduction reaction (the oxidation reaction) to occur. When trying to determine which half-cell reaction is the oxidation reaction, it will always be the half-cell reaction with the lower standard potential.

This EMF series is useful in determining if a total electrochemical reaction would happen spontaneously. In order to determine this, the total change in standard voltage, ΔV , needs to be calculated, which is shown in equation (1). If the calculated total change in voltage is positive, the reaction proceeds spontaneously to the product side. If the change is negative, the reaction proceeds spontaneously to the reactants side.⁵ Since the EMF series gives the reduction reaction, to obtain the oxidation form, the direction of the reaction and the sign of the voltage are reversed.⁵ Below is the example of how iron corrodes in water and oxygen from Fontana, in which the total change in voltage is calculated using the EMF series:



While the EMF series is very useful for determining the direction of a reaction at ideal conditions, the environment has a large impact on corrosion. A better representation of the general corrosion resistance of a metal is called a *Galvanic Series*. This represents the relative reactivity of a number of metals and commercial alloys. The alloys near the top are cathodic and unreactive, whereas those at the bottom are anodic and most reactive.⁵ No voltages are provided in order to standardize the results and to show a more general relationship of the corrosion resistance of different metals. See **Figure 5** for the Galvanic Series.

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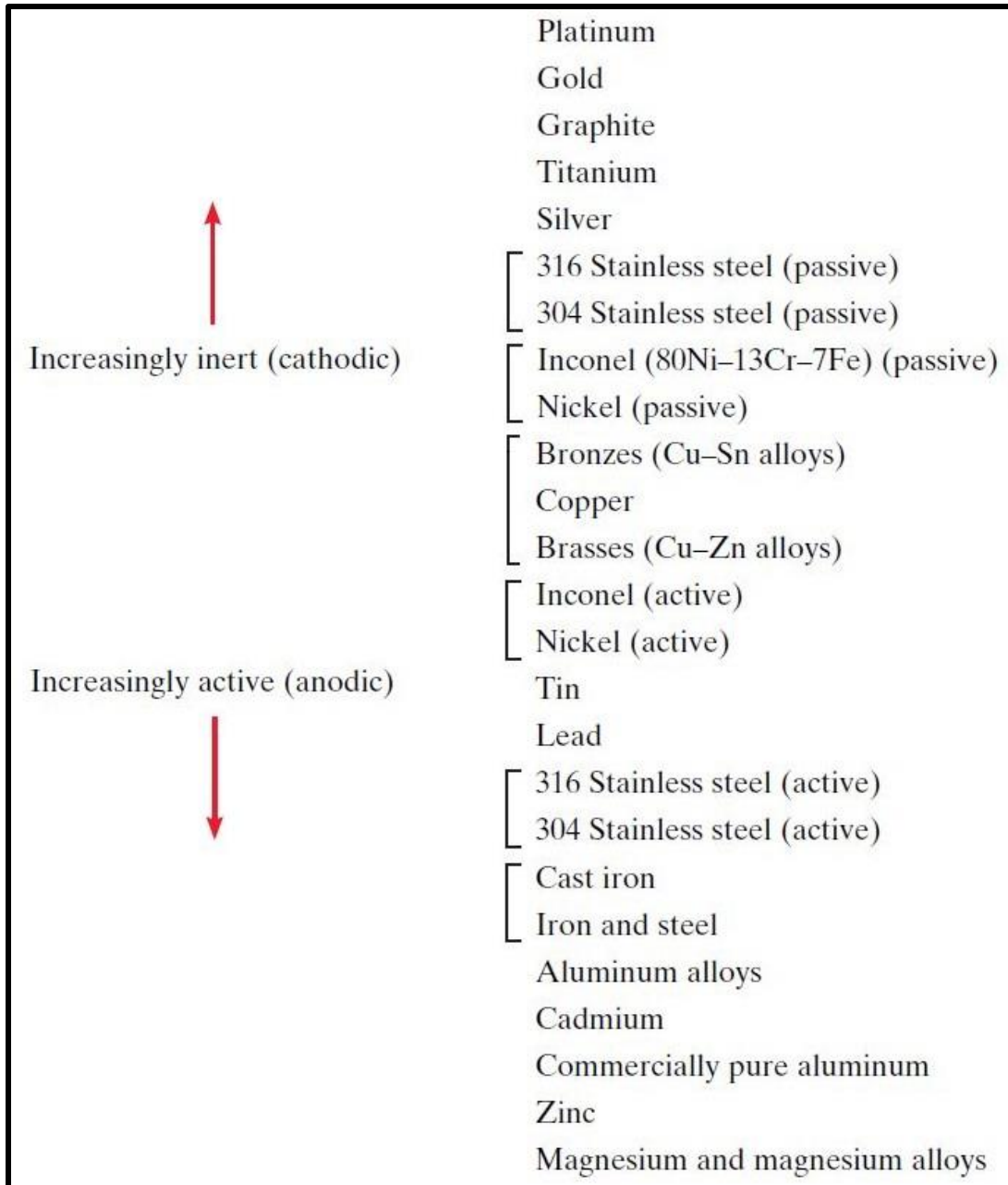


Figure 5: Galvanic Series, adopted from Callister.⁵

As seen on the Galvanic Series in **Figure 5**, stainless steel is an example of a material that has two different places on the series. The more anodic placement has the description of active, while the more cathodic placement has the description passive. What does this description mean? “*Passivity* is the phenomenon that under particular environmental conditions, some normally active metals and alloys, lose their chemical reactivity and become extremely inert. This behavior results from the formation of a highly adherent and very thin oxide film on the metal surface, which serves as a protective barrier to further corrosion.”⁵ Although aluminum does not have this description of passive or active, it is this oxide film that increases the corrosion benefits of aluminum.

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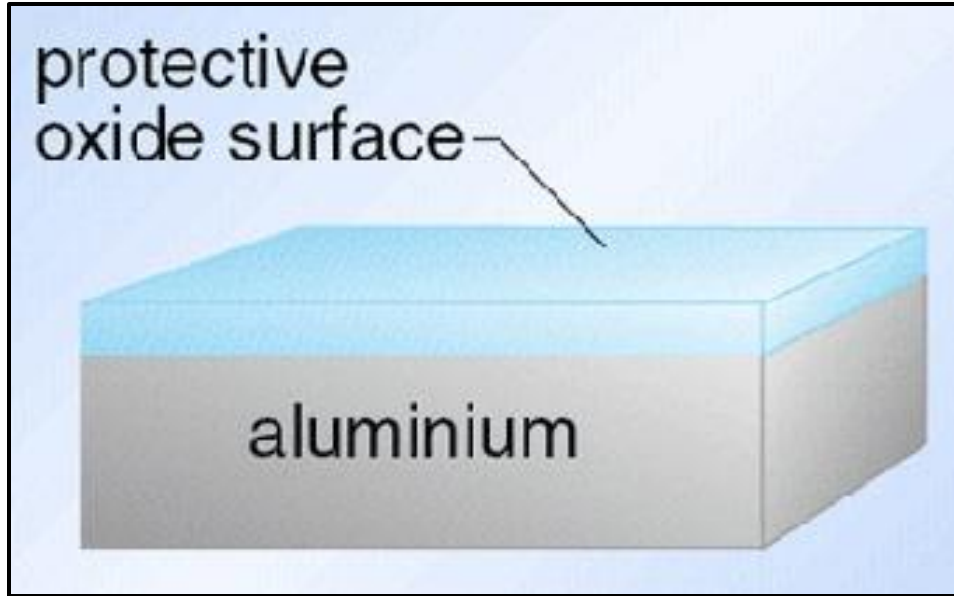


Figure 6: Model of the aluminum oxide film, adopted from Window & Façade Magazine.²²

Now that a general understanding of corrosion has been established, a specific look at the corrosion resistance of aluminum needs to be discussed. According to the Aluminum Company of Canada, “Corrosion resistance’ is not a property of a metal per se as is specific gravity, tensile strength, etc., but depends on the environment. A metal may be very resistant to one chemical but have little or no resistance to another. Aluminum and its alloys have excellent corrosion resistance in environments that do not seriously attack the natural protective oxide film.”⁶ From this statement, it can be understood that the corrosion resistance of aluminum in various environments is a result of a naturally occurring aluminum oxide (Al_2O_3) film, shown in **Figure 6**.

Godard says that when talking about the corrosion behavior of aluminum, the discussion should start with “the surface film of aluminum oxide, for it is the properties of this film that provide aluminum with its resistance to corrosion. When a fresh aluminum surface is created and exposed to air, it oxidizes rapidly, and acquires a compact, adherent, protective film of aluminum oxide which tends to resist further oxidation. Aluminum oxide is relatively inert chemically, and it is on this inactivity that the good corrosion resistance of aluminum depends.”² The EMF series that was discussed previously can be used to understand how this aluminum oxide film spontaneously forms, which is shown below.

Aluminum reduction reaction from **Figure 5**.



Conversion to oxidation reaction for Aluminum.



Reduction reaction from the dissertation of Pradyumna Singh.⁷



Calculating ΔV from equation (1).

$$\Delta V^0 = -0.284 + (+1.662) = +1.378 \qquad (4)$$

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Since the result of equation (4) is positive, the total reaction between aluminum and oxygen will proceed spontaneously. The reduction potential of the half-cell in equation (3), called superoxide (O_2^-) ion, has been referenced from the doctoral dissertation of Pradyumna Singh. However, that specific reaction is only part of the reaction in which the aluminum oxide film is formed. Singh states, "Addition of another electron to superoxide will yield (O_2^{2-}), the peroxide ion. A further addition of two more electrons into peroxide ion would completely cleave the O-O bond, forming ($2O^{2-}$)."⁷ There is no available reduction potential for the formation of ($2O^{2-}$) from O_2 , which is why the super oxide ion standard potential is used. The process of the superoxide ion conversion to ($2O^{2-}$) is summarized by the following reactions.

Summary of the Singh discussion of superoxide conversion.

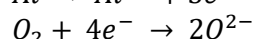
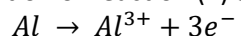


Summation of (3), (4), and (5), the intermediate steps being cancelled.



When these individual equations from Singh's dissertation are added together, equation (6) is the result. Equation (7) is the balanced summation of equation (2) and (6), which is the formation of the aluminum oxide film.

Summation of reaction (2) and (6).



Balanced summation, with cancelation of electrons.



This aluminum oxide film spontaneously forms when aluminum comes in contact with oxygen and attributes to the passivity of aluminum. However, it is understood that passivity of any metal (specifically aluminum) depends on the environment. The easiest indicator of the environment is to look at the pH of a fluid. Since the nature of corrosion is electrochemical, the reduction potential also needs to be considered when looking at an environment. The best way to understand theoretical environments and how aluminum will react within them is called a *Pourbaix Diagram*. In such diagrams, "the reduction potential of a corroding system is plotted on the vertical axis and the pH on a horizontal axis. These diagrams are constructed from calculations based on Nernst equations and solubility data for metal and its species."⁸ **Figure 7** shows a Pourbaix Diagrams for aluminum.

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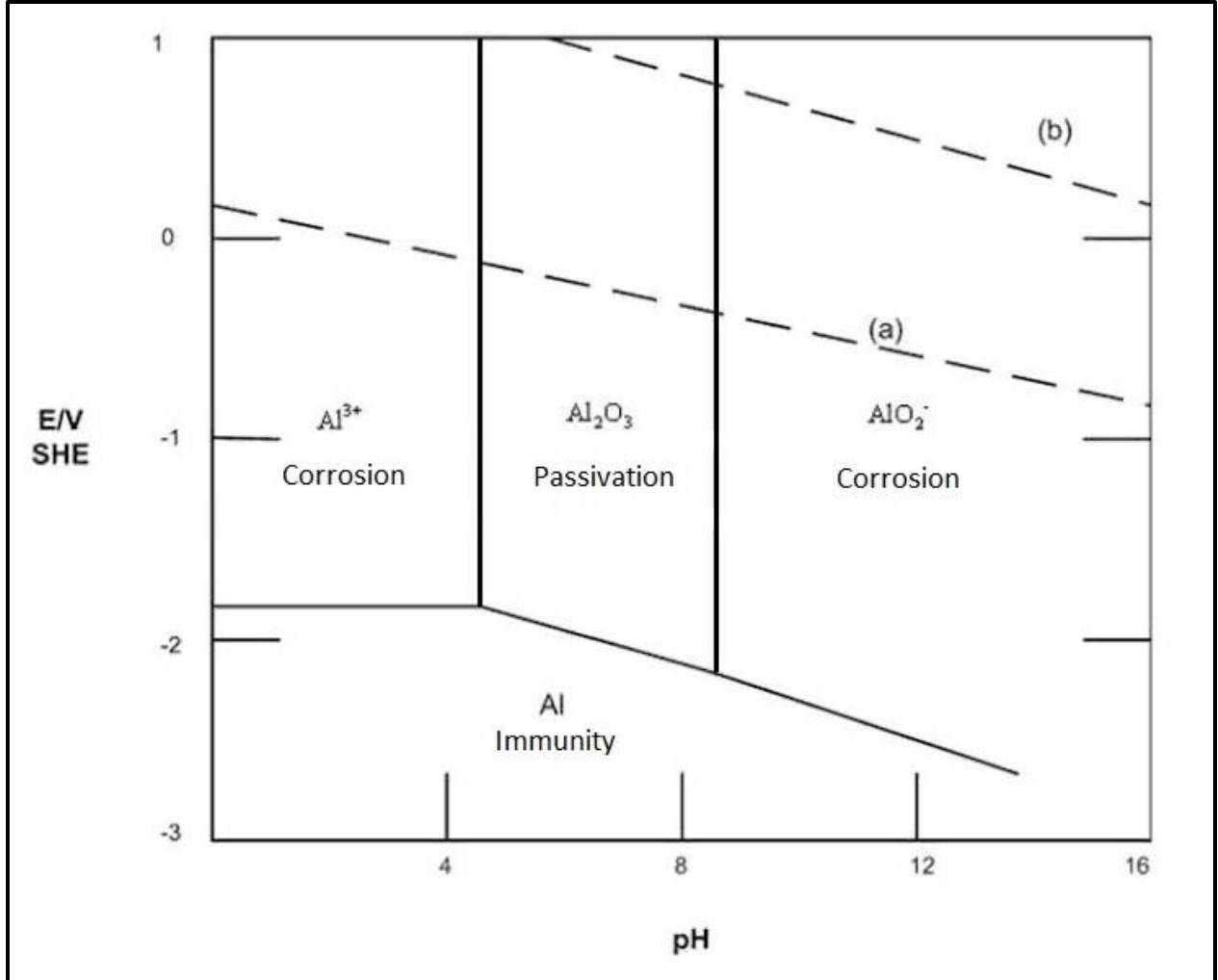


Figure 7: Pourbaix Diagram of Aluminum – water system at 25°C, adopted from Ahmad.⁸
Water is stable between regions (a) and (b).

Because the Pourbaix Diagram is based on the Nernst equation, it has some limitations and should never be used to predict the velocity of a reaction, as stated by Dr. Pourbaix, the developer of the diagram, when he first proposed the diagram for the use of understanding the environmental effects on corrosion.⁴ Pourbaix's diagram is useful for understanding a general situation in which aluminum will display corrosion resistance. In addition to the environment, Godard has compiled a list of bulk chemicals that are commonly handled in aluminum equipment, including heat exchangers, pressure vessels, condensers, rotary dryers, tanks, valves, and piping^[2]. This list of bulk chemicals is useful in understand what specific chemicals aluminum is resistant to. This bulk chemical list is shown in **Figure 8**.

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Acetaldehyde	Cyclopentane	Naphthalene	Propionic
Acetic Acid	Cyclopropane	Naphthenic acids	anhydride
Acetic anhydride	Dextrin	Naval stores	Propyl alcohol
Acetone	Dextrose	Nitric acid	Propylene glycol
Acrolein	Dichloro difluoro	(fuming - above 82%)	Pyridine
Acrylonitrile	Methane	Nitrocellulose	Ricinoleic acid
Adipic acid	Dichlorobenzene	Nitrogen fertilizer	Rosin
Alcohols	Easter gum	solutions	Salicyclic acid
Aldol	Essential oils	Nitroglycerine	Shellac
Ammonia	Ethyl acetate	Nitrous oxide (dry)	Sodium bicarbonate
Ammoniated ammonium	Ethyl acetoacetate	Nylon salts	Sodium chlorate
nitrate solutions	Ethyl alcohol	Oils, edible	Sorbitol
Ammonium nitrate	Ethylene glycol	Oils, essential	Starch
Ammonium	Fatty acids	Oils, fuel, lube	Stearic acid
thiocyanate	Formaldehyde	Oils, transformer	Styrene monomer
Aniline	Furfural	Oleic acid	Styrene polymer
Benzaldehyde	Gasoline	Oxygen	Sugar
Benzene	Glucose	Paraldehyde	Sulphur
Benzoic acid	Glycerin	Pentaerythritol	Sulphur dioxide
Butyl acetate	Helium	Pentaerythritol	Tall oil
Caprylic acid	Hydrocyanic acid	tetranitrate	Tar
Carbon dioxide	Hydrogen	Pentane	Toluene
Carbon disulfide	Hydrogen peroxide	Perchloroethylene	Triacetin
Carbonic acid	Iso-butyric acid	Petroleum gas	Trichlorobenzene
Castor oil	Lacquer solvents	Phthalic acid	Trichloroethylene
Cellulose acetate	Lacquers	Phthalic	Titanium
Cement	Linseed oil	anhydride	tetrachloride
Cod-liver oil	Maple syrup	Picric acid	Urea
Creosote	Methyl ethyl ketone	Potassium	Vinyl acetate
Cresol	Methyl salicylate	nitrate	Vinyl chloride
Crotonaldehyde	Mono-chloro-difluoro	Propane	Water
Cyclohexane	methane	Propionic acid	Xylene

Figure 8: Typical Bulk Chemicals Handled in Aluminum Equipment ^[2].

While the aluminum oxide film is very protective, the process of anodizing has been developed to thicken and harden this film. The term anodizing is related to the anodic and cathodic sites of the electrochemical reactions. In the process, the aluminum becomes anode in an electrochemical cell causing the aluminum oxide film to grow. A detailed process of anodizing will not be discussed, but the advantageous effects of anodizing will be covered.

Possibly the biggest advantage of anodizing is the increased thickness of the oxide film. The naturally occurring oxide film on freshly rolled aluminum sheet is extremely thin, about .0001 mils, and a mil is 1/1000th of an inch ^[2]. Depending on the application, the anodic coating thickness is in a range of 0.1-1.0 mils ^[20]. This anodized film is the same chemical formula as the naturally occurring oxide film. Since it is the same film chemically, it exhibits all the same traits: a stable pH range and adherence. The oxide film has been described as a very hard, tough, abrasion resistant protective coating, consisting of a

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thin barrier layer of about 0.02 mils, then a porous layer of about 0.4-0.9 mils which is sealed with different colors.²⁰ Anodizing is used because this thicker coating slows down the attack of chemicals that are detrimental to aluminum. A cross section of the unsealed anodized coating is shown in **Figure 9**.

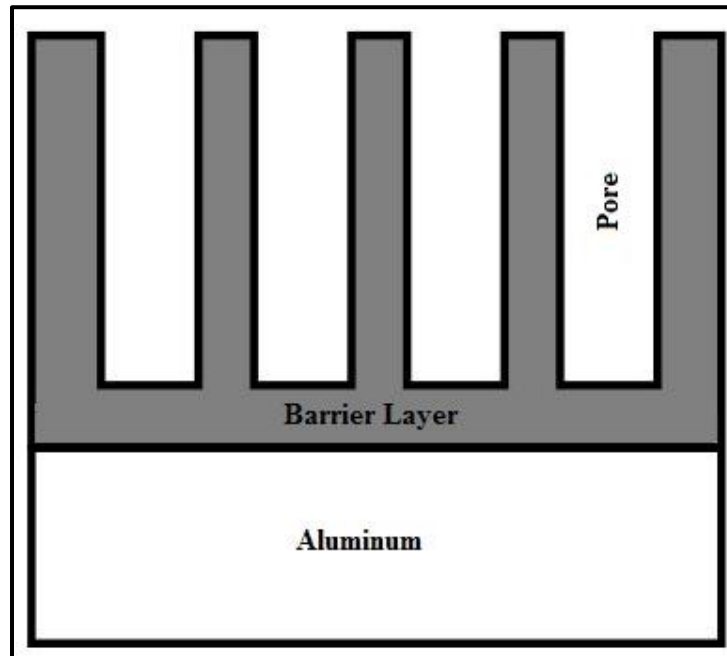


Figure 9: Cross section of an unsealed anodic coating, adopted from Caswell.²⁰

Galvanic Corrosion

Even though aluminum is highly resistant to corrosion, as with any material, there are some areas in which aluminum is susceptible to corrosion. The Galvanic Series (**Figure 5**) has a two-fold utilization. First, it shows the general corrosion resistance of a metal in comparison to other metals and second, it helps to determine when two metals are coupled together, which of the metals will become the anode and which will become the cathode. This process of coupling two dissimilar metals leads to a phenomenon called *galvanic corrosion*. Fontana explains galvanic corrosion as “an electric potential difference usually exists between two dissimilar metals when they are immersed in a corrosive or conductive solution, an electrolyte. If these metals are placed in contact, this electric potential difference produces electron flow between them. Corrosion of the less resistant metal is usually increased and the attack of the more resistant metal is decreased, as compared with the behavior of them when they are not in contact.”² Galvanic corrosion is needed in order for batteries to function. This corrosion is shown in **Figure 10**.

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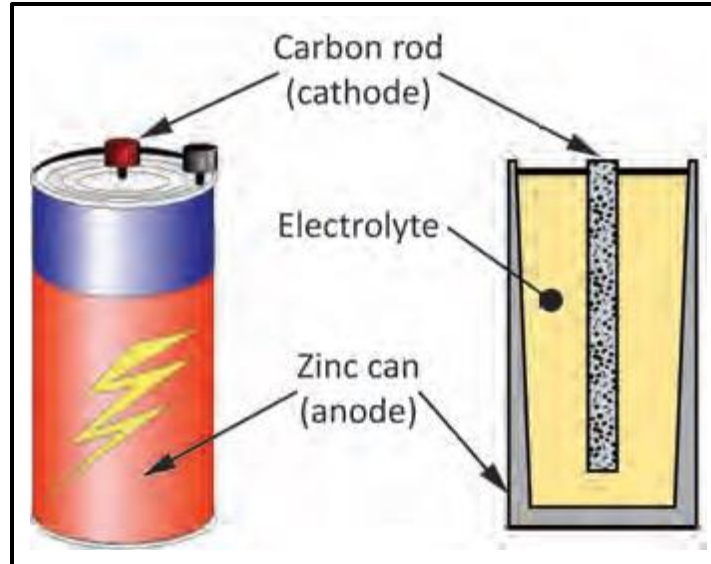


Figure 10: A battery cell which depicts galvanic corrosion, adopted from NACE.⁹

In the example of the battery, the carbon rod is higher on the galvanic series making it the cathode. The zinc can is lower on the galvanic series making it the anode. In **Figure 10**, the yellow solution is the electrolyte which enables the flow of ions. The electron path is made by the connecting the battery terminals to a device. The electrons transferred from the Zinc can flow through the device to power it, then back to the carbon rod to be used in the reduction reaction.

When looking specifically at aluminum, it can be seen that aluminum is relatively low on the Galvanic Series (**Figure 5**), when compared to other metals. Consequently, aluminum will corrode before (preferentially) another metal that is higher on the Galvanic Series when placed in electrical contact with the other metal. However, many structural materials like steel, stainless steel, and copper, are higher than aluminum on the Galvanic Series.

How does one eliminate the possibility of galvanic corrosion of aluminum? Three things are needed for galvanic corrosion to occur: potential difference between metals, an electrolyte for the ions to flow through, and electrical connections of metals for the electrons to flow through. If one of these elements needed for corrosion is eliminated, then the corrosion will not happen. While this is a simple concept, it can be relatively difficult to engineer. In order to eliminate a potential difference between metals, an entire structure would have to be built out of the same material, which is unfeasible due to strength requirements. In order to eliminate the presence of an electrolyte, a structure would have to be completely absent from all mediums that can transfer electrons. This is almost impossible as earth's atmosphere has water vapor in it, which condensate and then enable the transfer of ions. By deduction, this leaves eliminating electrical connections between the two metals. From an engineering standpoint, this can be done by adding a barrier coating. The barrier coating can be as simple as a neoprene gasket, powder coating, or bituminous paint. All barrier coatings serve the same purpose, they act as a non-conductive material that is physically placed between two dissimilar metals to break the electrical connection and inhibit the flow of electrons.

Corrosion in Concrete

The corrosive effect of concrete on aluminum is a complex issue. Godard said that "Contrary to popular belief, aluminum alloys are not seriously corroded by long-term embedment in Portland-cement. Slight superficial etching of the aluminum takes place during the period when these products are setting, but unless there is frequent intermittent wetting and drying, no appreciable corrosion takes place" ^[2]. However, there are some factors that increase the corrosion rates of aluminum when embedded in concrete, which includes Portland-cement. The effects of corroding aluminum can

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decrease the strength of the concrete because of the cracking caused by expanded aluminum corrosion products.

The first factor that can affect the corrosion of aluminum in concrete is the composition of the concrete. Concrete is a composite building material made up of cement, sand and gravel (aggregate), and water. The water is added to the cement and aggregate to allow the ensuing mixture to be poured, shaped, and molded. In concrete, the water and cement react chemically to form a new compound that bonds the concrete components together.⁹ While these are the main elements of concrete, and most of them are non-corrosive, some additives in concrete facilitate the corrosion of aluminum. Kiran Majmudar said in his master's thesis that, "the admixture calcium chloride used in concrete results in earlier set and increased strength at early ages. But the use of the calcium chloride in concrete structures that have aluminum embedded in them has proved to be detrimental to the concrete, as in the aluminum will corrode in the presence of calcium chloride."¹⁰ What makes the addition of calcium chloride corrosive to embedded aluminum? The calcium chloride dissociates into ions of calcium and chloride in the presence of water. The chloride ions then attack the aluminum material taking aluminum ions away causing corrosion. Chloride ions also reduce the electrical resistivity of concrete, and thus stimulate galvanic corrosion.² Other factors causing corrosion on aluminum are increased by the addition of calcium chloride in the concrete mixture.

The second factor that can affect the corrosion of embedded aluminum is the presence of embedded steel due to the galvanic coupling in which steel is more inert on the galvanic series. Godard explains that it was found that calcium chloride increases the corrosion of embedded steel and tends to stimulate galvanic corrosion of aluminum that is in contact with steel; however that rate decreases with distance from the point of contact between the two metals up to 6 inches, after which galvanic corrosion is negligible.² Majmudar said that in one case study, corrosion was found to be particularly severe near a steel wire that tied the aluminum conduit to the reinforcing steel.¹⁰ **Figure 11** shows the mass loss results of aluminum when coupled with steel embedded in concrete for seven days.

Test	Fe:Al surface ratio	Contact	Mass loss (mg)
1	3:1	No	0.09
2	3:1	Yes	0.23
3	12:1	Yes	2.40

Figure 11: Mass loss data from Iron and aluminum couple in concrete, adopted from Majmudar.¹⁰

The final, and possibly most detrimental, factor that increases the corrosion of embedded aluminum in concrete, is the presence of stray electric currents. Stray currents happen when electrical systems have improper grounding to the embedded aluminum, which then flows to the embedded steel. Stray currents may flow from certain points on the aluminum through the concrete to ground via the reinforcing steel and can cause corrosion of the aluminum at the point of leaving.² The effects of these stray currents can be understood because of the electrochemical nature of the corrosion reactions. When the electric current passes through the aluminum, it passes through in the form of the transfer of electrons. This transfer of electrons enables the corrosion reaction, as stated throughout this paper. The most detrimental part of the stray currents in concrete is the synergistic effect of all the previously mentioned factors that lead to the corrosion of aluminum. Majmudar summarized it best by saying that calcium chloride in concrete, in the presence of stray current when structural steel is in close proximity, is highly corrosive to aluminum. The corrosion products formed cause serious cracks by reducing the limited tensile strength of concrete.¹⁰

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There are ways to inhibit the corrosion of aluminum embedded in concrete. The most prevalent way is to add a barrier coating to the aluminum. This barrier coating protects the electrons from leaving the aluminum in the presence of chlorine ions and disrupts the electrical contact made between aluminum and the structural steel, thereby inhibiting the effects of galvanic corrosion. The inhibiting effect of the barrier coating to galvanic corrosion is also utilized in the presence of stray currents. While bare aluminum can corrode in concrete causing a loss of strength, the addition of a barrier coating to the aluminum diminishes the corrosive effects of the concrete.

Literature review on Life Expectancy Data

One of the greatest attributes of aluminum is its life expectancy, which is directly related to its corrosion resistance. There is a lot of data available to show that aluminum has a reliable life expectancy. From an engineering viewpoint, the rate of penetration is used to predict the life of a given component and is the industry standard for the measurement of corrosion. The expression of *mils per year* (mpy) is the most desirable way of expressing corrosion rates.⁴ A mil in the standard of measurement is actually milli-inches, or 1/1000th of an inch. All the following data has been converted into mpy for consistency. The chart in **Figure 12** provides a characterization of corrosion rate of aluminum.

Rate (mpy)	Characterization
< 0.5	Excellent
0.5 - 2.0	Good
2.0 - 5.0	Fair
5.0 - 10.0	Poor
> 10.0	Unacceptable

Figure 12: Characterization of corrosion rates for aluminum, adopted from Association of Water Technologies.¹¹

While it is difficult to give an exact value for life expectancy of or to pinpoint the exact environment that aluminum will be exposed to, the corrosion rate is an easily measured and expressed value. This paper will reflect several different corrosion rates from various environments that show aluminum is a versatile material and can exhibit various characterizations of corrosion resistance, which is color coded in **Figure 12**.

Surface Roughness Data

The first testing data to be looked at is titled “Effect of Surface Roughness on Corrosion Behavior of Aluminum Alloy 6061 in Salt Solution (3.5%NaCl)” by Almansour, Azizi, Jersi, and Entakly^[12]. In this research, they obtained samples of aluminum with varying surface roughness. The varying roughness was obtained by the use of emery papers, Al₂O₃ powder, and diamond powder. The specific process of obtaining different roughness was not given. The roughness was measured by a roughness machine tester TR110, produced by TIME HOLLND. The samples were then immersed in a solution of 3.5% NaCl for 8 days. There were three solutions with varying pH of 2, 7, and 12 in which corrosion was measured. The pH of 2 was obtained by adding Hydrochloric Acid, and pH of 12 was obtained by adding Sodium Hydroxide. Corrosion rates were calculated from mass loss measurements. The results of the experiment are shown in **Figure 13**.

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	pH 2	pH 7	pH 12
Roughness	Corr Rate	Corr Rate	Corr Rate
0.64	0.088	0.042	0.667
1.83	0.307	0.045	0.763
2.06	0.333	0.053	0.810
3.48	0.347	0.069	0.865
7.04	0.351	0.089	0.871

Figure 13: Effects of pH and surface roughness.¹²

The results of this experiment shows two different trends. The first trend is the effect of pH on the corrosion of aluminum, the corrosion rate was smallest when the pH was neutral. In addition, there was a lower corrosion rate at a pH of 2 than at a pH of 12, which is consistent with the Pourbaix Diagram of Aluminum. This shows that aluminum is more corrosion resistant at a lower pH than at a higher pH. The second trend this research establishes is that with increasing surface roughness, the corrosion rate increases. While this trend is extremely important, it is beyond the scope of this paper and will not be discussed further. The important thing to note about these results is that, even with varying pH and varying surface roughness, the corrosion rate of aluminum never exceeds 1 mpy. These rates meet the excellent or good corrosion characterizations, which show that aluminum has a long life expectancy.

Deformation Effects Data

The next experiment to be looked at is titled “Effect of Deformation Processes on Corrosion Behavior of AA6061 in Salt Solution (3.5% NaCl)” by Almansour, Azizi, Jersi, and Entakly.¹³ To test the effects of deformation, the samples of aluminum were tested with percent elongation, % ΔL, of 0, 14, 22, and 30. In addition, each of these elongations were tested at a pH of 2, 7, and 12. The pH of 2 was obtained by adding Hydrochloric Acid, and pH of 12 was obtained by adding Sodium Hydroxide. Corrosion rates were calculated from the linear polarization curves obtained for each of the samples. **Figure 14** shows the results of the experiment.

	pH 2	pH 7	pH 12
% ΔL	Corr Rate	Corr Rate	Corr Rate
0	19.69	3.94	39.37
14	28.66	19.92	70.87
22	59.06	30.83	105.43
30	90.55	83.46	124.41

Figure 14: Effects of deformation and pH.¹³

The trends shown in the results are comparable to that of the Surface Roughness Data. The results show that aluminum exhibits lower corrosion rates in neutral environments than in acidic, and lower rates in acidic environments than in basic. Another trend shown by this data is that increasing deformation of the material increases the corrosion rate of the material. With the increase in the degree of deformation, the hardness increased because of dislocations that formed and the structure became fine because of participates that broke. This may have increased the free energy and created a potential energy for corrosion.¹³ The important thing to understand about these results is the corrosion rate is best in a neutral pH with no deformation.

Fatigue Life Data

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The third experimental data is from a master's thesis titled "The Effect of Surface Corrosion Damage on the Fatigue Life of Extruded Aluminum Alloy 6061-T6" by Weber.¹⁴ The scope of this project focused more on the adverse effects of corrosion to the mechanical property of fatigue life. Fatigue data is collected from multiple stress states with the first specimens being tested at high stress, usually at about ninety percent of the yield strength. The fatigue test was done by a rotational tester. Specimens were corroded by immersion in a solution of 3.5% NaCl at a pH of 2, which was obtained by adding Hydrochloric Acid to the solution. The specimens were corroded for 0, 2, 24 days then cycled to failure at 90% and 50% of the yield strength. The results were adopted to show the percentage of number of cycles to failure in comparison to 0 days corroded, shown in **Figure 15**.

% of Yield	Days corroded	% Failure Of 0 days corroded
90	0	100.00
	2	85.19
	24	85.91
50	0	100.00
	2	13.43
	24	14.75

Figure 15: Effects of corrosion on Fatigue life.¹⁴

The results prove the concept that corrosion decreases the fatigue life of a material. However, it is interesting to note that the percent failure of un-corroded specimens increased, although minutely, from 2 days to 24 days of corrosion. The 2-day corroded specimens exhibit small diameter pit openings around 1-2 μm and appear unaffected by general corrosion. The 24-day corroded specimens have broad, scalloped pits with coincident and overlapping borders.¹⁴ This difference in corrosion cross section can influence effects of fatigue of the specimen. Because the 24 day corrosion has more overlapping pits, they are less likely to propagate failure and can withstand more cycles than the 2 day corroded specimens. Another important thing to note about this experiment is at high percent of yield, the corroded specimens exhibit a higher percentage of cycles than at a lower percent of yield. The most important thing to understand about this experiment is that regardless of the time corroded, the fatigue at 90% of the yield strength was about 85% of the un-corroded specimen, which is extremely high. This means that aluminum keeps to a high percentage of its material properties even under the influence of corrosion.

Long-Term Exposure Data

The last, and possibly most important data about the life expectancy of aluminum is a report titled "Evaluation of Corrosion of Long-Term Exposed Aluminum Conductor" by Kreislova, Jaglova, Turek, and Koukalova^[15]. This report is an assessment of electric power transmission lines after they have been decommissioned after 40 years of service. The cables were used in the North Bohemia region of the Czech Republic, which is an industrial atmosphere. In this industrial atmosphere, the dominant corrosion stimulator was an in-air Sulphur concentration of 100 $\mu\text{g}/\text{m}^3$. The powerlines are called Aluminum Conductor galvanized Steel-Reinforced cable (ACSR), which are made up of four different layers. The outer three layers are made of aluminum in varying diameters. The center layer is galvanized steel and will not be considered in the data. The cross section of the cable is shown in **Figure 16**.

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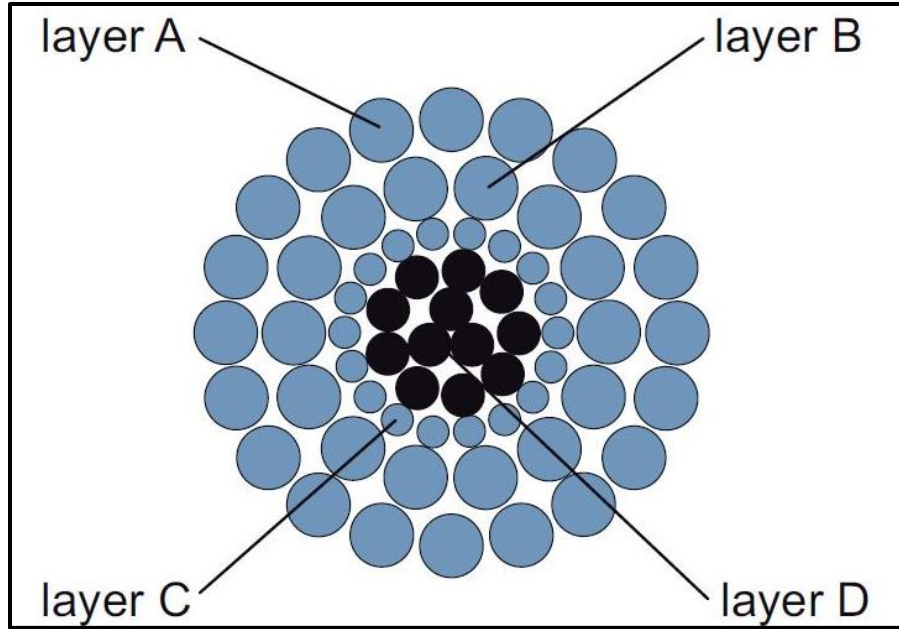


Figure 16: Cross section of ACSR cable.¹⁵

The assessment of the ACSR cable showed 2 different types of corrosion in the aluminum wires. The first type of corrosion that the wires experienced is called *pitting corrosion*, which is a form of localized attack that results in holes in the metal.⁴ The other type of corrosion experienced by the wire is called *exfoliation corrosion*, which is localized attack at and adjacent to grain boundaries causing thin fiber-like strands of metal to disconnect from the main material.⁵ The maximum value of depth for each type of corrosion was stated in the paper and that depth was over a 40 year period. Consequently, the corrosion rate was calculated and is summarized in **Figure 17**.

Layer	Diameter (mm)	Wires	Pit rate	Exfo Rate
A	3.75	20	0.20	0.05
B	3.75	14	0.15	0.20
C	1.9	18	0.05	0.00

Figure 17: Pit rate and Exfoliation rate in mpy of aluminum wires in ACSR.¹⁵

The results prove that aluminum has a very good life expectancy. The corrosion rates, regardless of the type of corrosion, showed excellent corrosion rate characterizations. The authors summarized the results by saying, "Considering the maximum corrosion determined on aluminum wires after 40 years of exposure the total reduction of all aluminum wires was 11%. It was also predicted that there would only be 20% decrease of the tensile strength of the aluminum strands over 50 years of service in highly corrosive environment."¹⁵ The exposure assessment demonstrates that aluminum expresses excellent corrosion resistance in an industrial atmosphere with a minimal decrease in strength.

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Literature review on Environmental impact of Aluminum

It is well known that aluminum does not spark when it is struck or ground by another material. However, steel sends off bright orange sparks when it is struck or ground by another material. So what causes this difference? It is due to the pyrophoric material property. *Pyrophoric materials* are substances that instantly ignite when exposed to oxygen at ambient temperatures.²¹ Iron, the main element in steel, is pyrophoric when it is exposed to oxygen because the reaction between iron and oxygen produces large amounts of heat. This property is displayed as those bright orange sparks when steel is struck or ground, which is freshly exposed iron that has broken away from the main material. The reason that large pieces of steel do not ignite is that the amount of heat given off relative to the total area of the material is too small to be significant.

Aluminum is not a pyrophoric material and does not give off any of these sparks when it is struck or ground by another material. The main reason for this property is due to the naturally occurring aluminum oxide film, which has already been discussed. The reaction between aluminum and oxygen to form this film does not give off heat. Additionally, this hard film inhibits the exposure of fresh aluminum when the material is struck or ground. Furthermore, if this film is broken, it rapidly reforms but the reformation does not give off heat. As a result, even when aluminum is struck or ground, the freshly exposed aluminum forms this film and does not ignite. This is why aluminum is often characterized as a non-sparking material.

While no one wants to talk about a product's end of service life, it is bound to happen for any material. Recyclability is a positive attribute of aluminum. A detailed explanation of the recycling process will not be provided, however, the available data about the recycling of aluminum will be discussed. All of the available data has been extracted from a paper from The Council for Aluminum in Building. Aluminum is different from other materials in that it is completely recyclable. This means that all the aluminum in the product can be extracted and reused to make a new product. This differs from other common materials. Both carbon and stainless steel can be recycled, but some of the base material is lost. Glass Fiber Reinforce Plastic (GFRP) cannot be recycled at all, since it is a thermosetting plastic, meaning it cannot be melted and reformed. In addition, the glass, which is normally recyclable, cannot be separated out of the GFRP to be recycled. One of the most outstanding facts of the current aluminum is that 75% of all aluminum produced since the 1880's is still in use.¹⁹ Not only does the recycling of aluminum save raw material from being mined, the re-melting of aluminum requires little energy, which saves up to 95% of the energy required for primary aluminum production.¹⁹ In 2006, there were 50 million tons of aluminum produced worldwide. Of that 50 million tons, 16 million tons (or 32%) was produced from recycled products.¹⁹ The last fact about aluminum recycling is that end-of-life collection rates for aluminum in the building sector are from 92% to 98%.¹⁹ This data is summarized in **Figure 18**. All of this data shows that aluminum is the most environmentally friendly material available for use in the grating industry.

- **75%** of all aluminum produced since the 1880's is still in use.
- **95%** of the energy required for primary aluminum production is saved by the re-melting process.
- **32%** of all the aluminum produced worldwide was made from recycled products in 2006.
- **92-98%** of aluminum in the building sector is collected at the end of its service life.

Figure 18: Summary of data about aluminum recycling.
Adopted from the Council for Aluminum in Building.¹⁹

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Experimental Procedure

For a more direct comparison of the corrosion behavior of the main metals used in the grating industry, a potentiodynamic polarization test in 0.6 M NaCl solution was done on Aluminum 6061, Aluminum 5083, Low carbon Steel, and Stainless Steel 304. First, a sample of each materials was obtained for a raw material provider.

The sample preparation is as follows. The sample was polished by hand using silicon carbide sandpaper, using grits od 60, 180, 240, 400, and 600. The sample was then cleaned with ethanol to remove allow polishing medium. The sample was then cleaned with deionized water.

The samples were mounted in a testing celling with a luggin capillary. The cell was filled with 0.6 M NaCl, a saturated calomel electrode was used as a reference, and the platinum counter electrode was used. The experiment was performed with a Bio-logic instrument using EC-lab software on the computer. Each material was tested twice. The test was run with an open circuit potential allowed to stabilize for one hour. **Figure 19** shows the polarization setting that were used for the experiment.

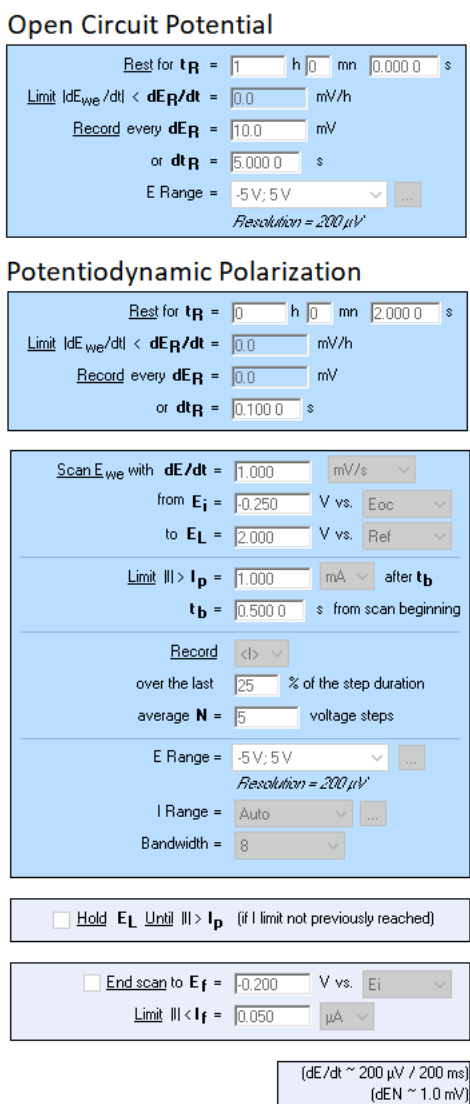


Figure 19: Screen capture of the EC-Lab setting for the polarization test.

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Result and Discussion

Figures 20-25 show the Potential versus Log |Current|, also known as a Tafel plot, for each of the materials tested. These figures show the general corrosion behavior of the material and does not consider some of the special forms of corrosion that have been discussed previously.

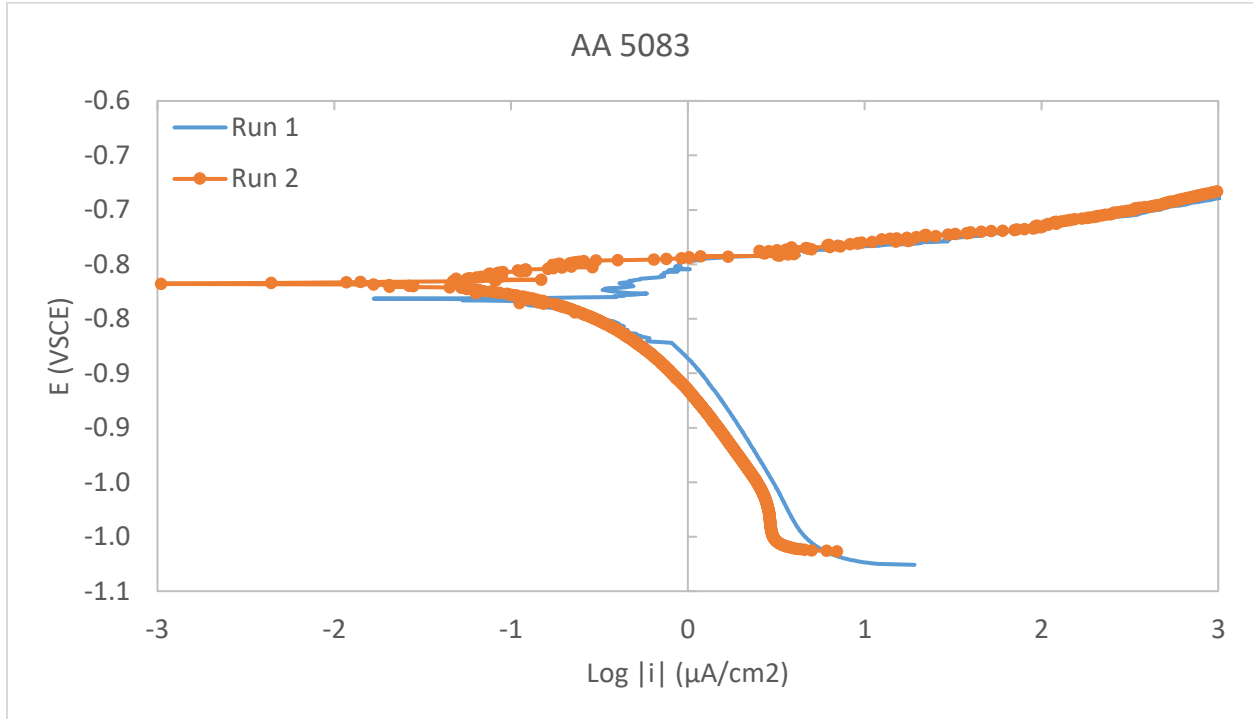


Figure 20: Tafel plot for Aluminum 5083.

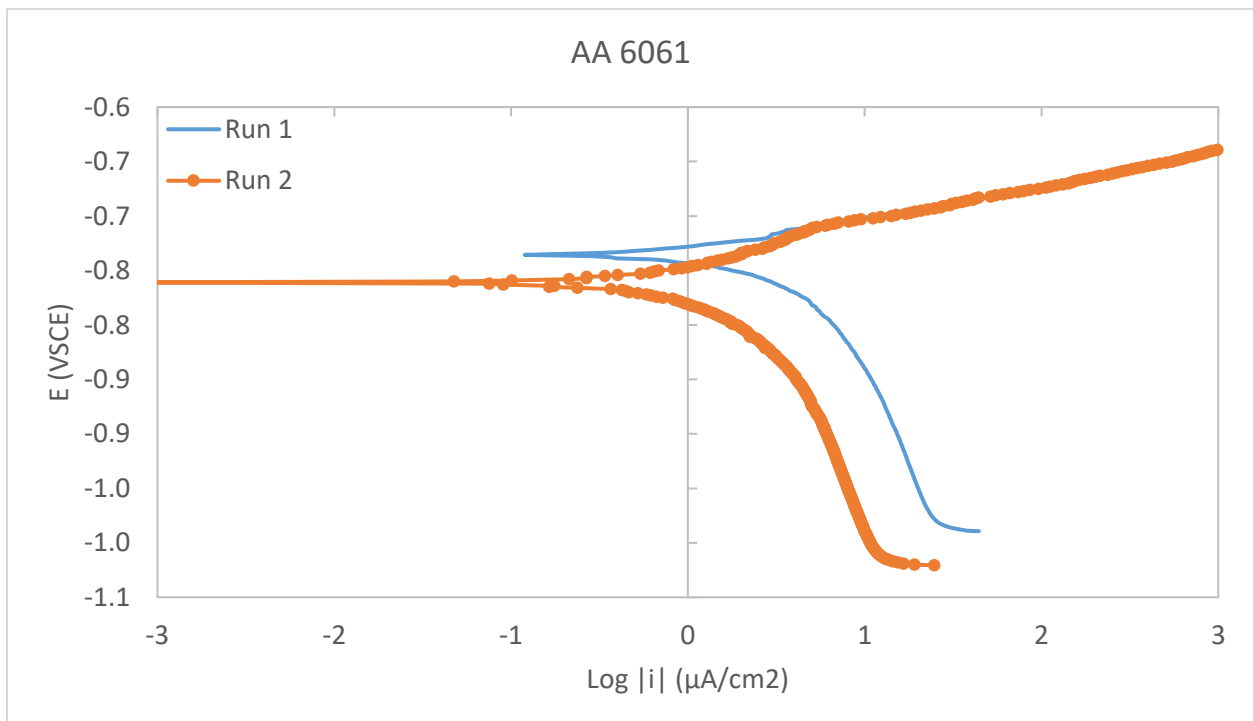


Figure 21: Tafel plot for Aluminum 6061.

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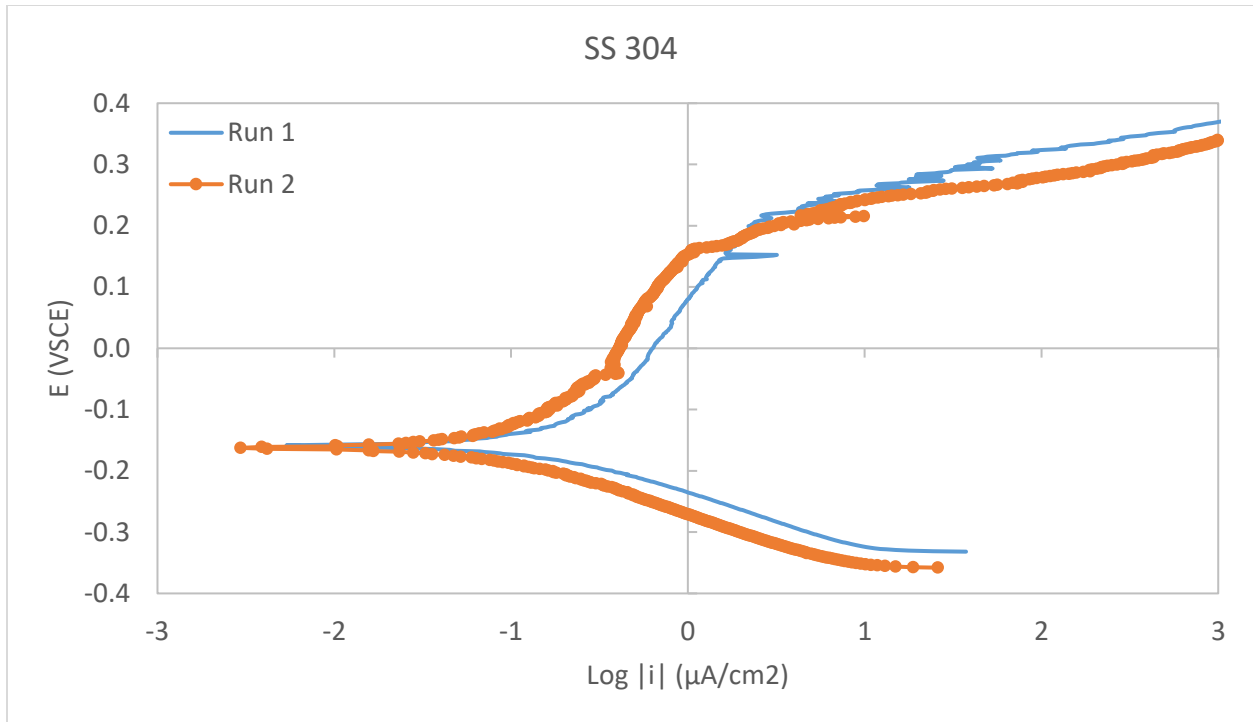


Figure 22: Tafel plot for Stainless Steel 304.

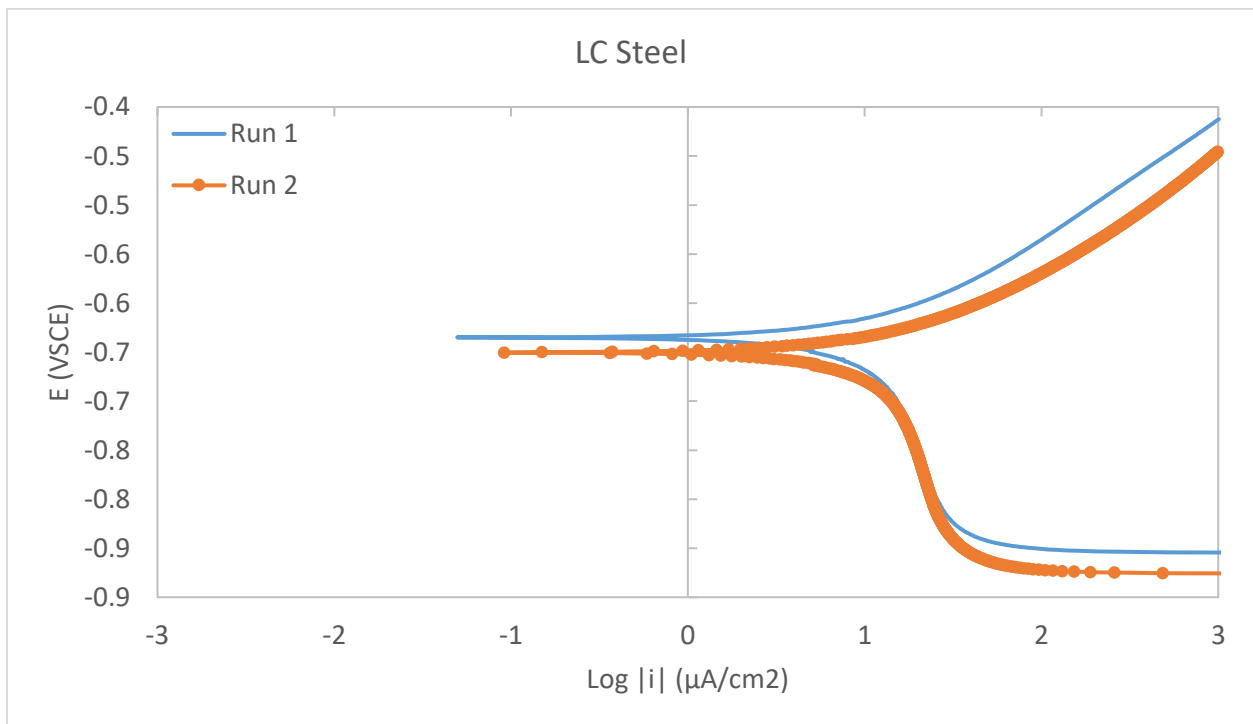


Figure 23: Tafel plot for Low Carbon Steel.

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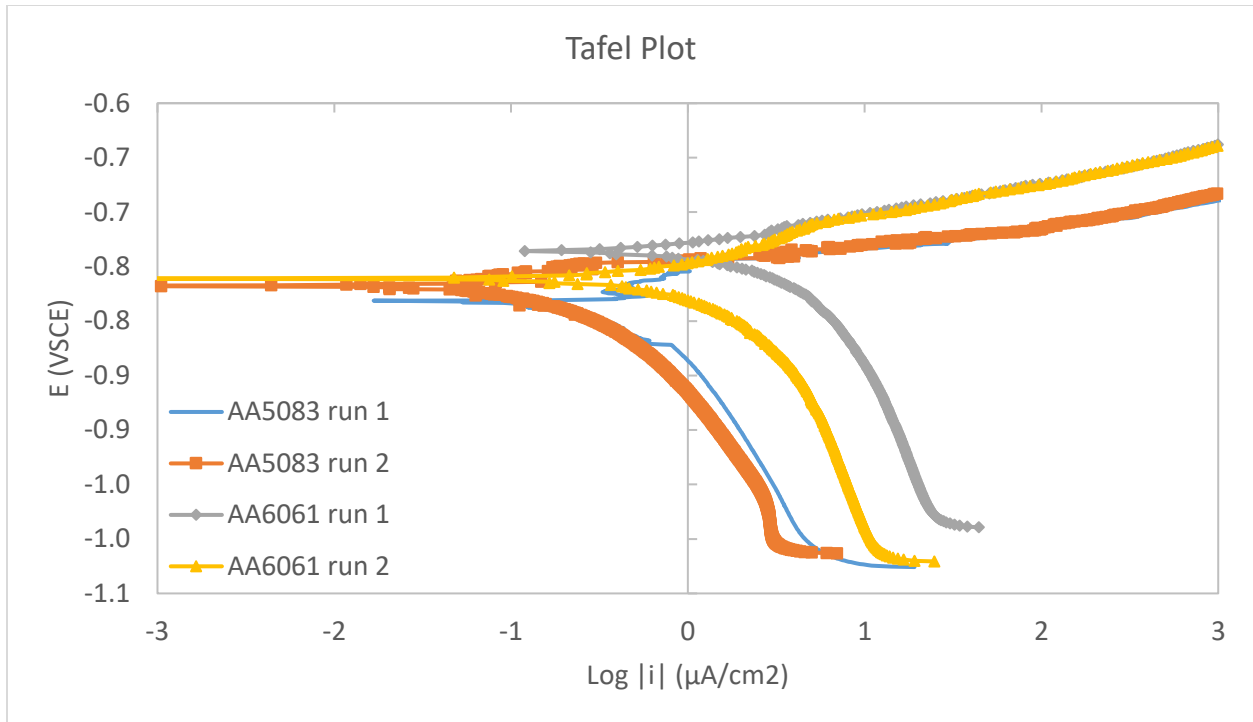


Figure 24: Tafel plot for both aluminum alloys.

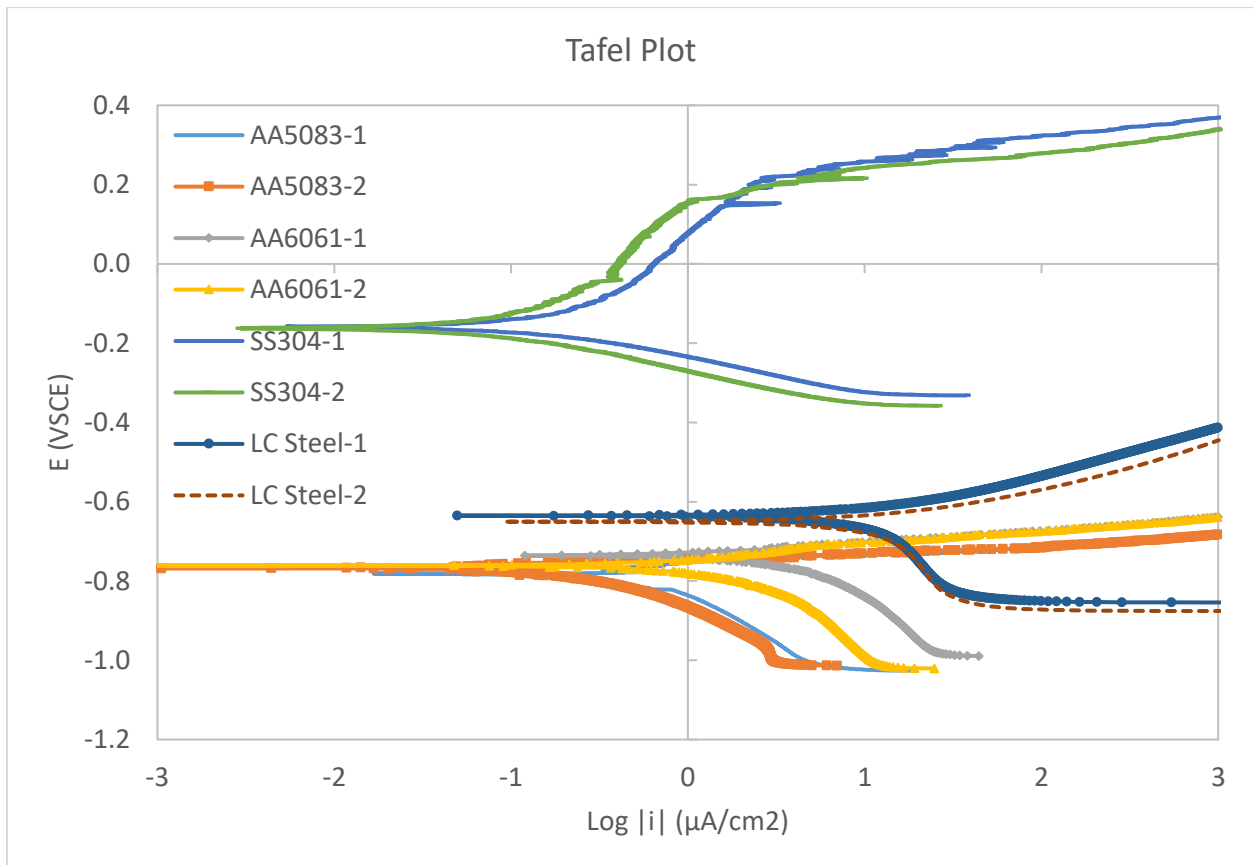


Figure 25: Tafel plot for all materials.

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There is a lot of qualitative analysis that can be determined from the comparison of the Tafel plots for each of the materials. The first comparison of the Tafel plots should be to look at the potential for each material, specifically where the current is smallest for the whole plot. This potential shows the relative activity of each of the metals. This can generally be used to determine which materials will be more likely to corrode, with the material that has a lower potential being more likely to corrode. In this case, the aluminum alloys have the lowest potential where the current is smallest, which means that they have the highest likelihood of corrosion.

However, the magnitude of the current is more directly related to the overall thickness loss. The corrosion current of a material is determined from a Tafel plot by determining the current where currents on the graph change from decreasing to increasing with change in potential. This is done by extrapolating the slope of the region where the current is decreasing with increasing potential and finding the intersection of the extrapolated slope from the region where current is increasing with increasing potential. The lower the current value of the intersection point, the less thickness loss of the material. When comparing these materials, it is obvious that stainless steel has the lowest corrosion current, almost an order of magnitude lower than that of aluminum and steel. However, it is also obvious that the aluminum alloys both have a lower corrosion current than that of steel. The last observation about the corrosion current is that aluminum 5083 has a lower current than aluminum 6061.

Conclusion

Aluminum is one of the most versatile engineering materials available for the grating industry. It is one of the most lightweight materials available. Even though it is lightweight, it exhibits an extremely good strength and can withstand large loads before experiencing permanent deformation. Possibly the most beneficial property of aluminum is its corrosion resistance. Aluminum spontaneously reacts with oxygen in the atmosphere to form a thin protective oxide film on the surface. This film is the reason for aluminum's corrosion resistance in many environments. Although there are a few environments in which aluminum does corrode, the available data shows that even when corrosion happens, the corrosion rate is low so that it still has a long life expectancy. The non-sparking characteristic of aluminum makes it sought after for highly flammable environments. In addition, once aluminum reaches the end of its use, it can be completely recycled. The experimental testing performed has also proven that aluminum has an overall lower corrosion current, which related to a lower thickness loss, than that of steel. In conclusion, the material and mechanical properties, corrosion resistance, and the recyclability of the material make aluminum the product of choice in the grating industry.

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