EXTRINSIC INFLUENCE OF ENVIRONMENT ON
TENSILE RESPONSE, IMPACT TOUGHNESS AND FRACTURE BEHAVIOR OF
FOUR METALS: FERROUS VERSUS NON FERROUS

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EXTRINSIC INFLUENCE OF ENVIRONMENT ON TENSILE RESPONSE, IMPACT TOUGHNESS AND FRACTURE BEHAVIOR OF FOUR METALS: FERROUS VERSUS NON FERROUS

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ABSTRACT

In this thesis report an attempt is made to present and briefly discuss the specific influence of exposure, by way of immersion, to four different environments, pH+Salt, salt, pH and distilled water, for four chosen time period of one-week, two-weeks, three-weeks, and eight-weeks on the static (uni-axial tensile) and dynamic (impact) properties of two ferrous metals [i.e., 304L stainless steel, and alloy steel 4340 CF] and two non-ferrous metals [i.e., aluminum alloy 6061-T651 and aluminum alloy 7075]. Test specimens for both tensile tests and Charpy V-Notch impact tests on the as-provided material were precision machined and conformed to standards specified by the American Society for Testing Materials (ASTM). The pH and conductivity were measured using a pH meter and a conductivity meter. The pH and conductivity were measured in an attempt to establish the acidity-level or alkalinity-level of the chosen mediums. The impact toughness response and resultant fracture behavior of the four chosen metals, subsequent to their exposure, by way of immersion, for chosen time periods were studied over the temperatures range -180°C to +170°C. The tensile tests were performed in the room temperature (25°C), laboratory air (RH 55 pct.) environment. Final fracture behavior of the chosen metals was determined at both the macroscopic and fine microscopic levels. This was made possible following careful examination in a scanning electron microscope. After analyzing the data obtained it was observed that Salt medium was more corrosive among all the four environments and Distilled water was corrosion resistant medium. Steel was more corrosion resistant compared to Aluminum.
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CHAPTER I
INTRODUCTION

There are very few events which exert a devastating effect from the structural, economical and human casualties’ point of view as corrosion. Virtually any metallic material is subjected to corrosion even in humid air. Structures are continuously attacked and sometime even completely demolished by corrosion. It is certainly a very complex and multi-sided phenomenon that can be hardly tied to a single parameter theory [1].

Corrosion damage has been a major problem from the day metal has been produced. Recent study showed that cost of corrosion prevention currently represent 2.5% of Gross domestic product in United States of America [2]. Corrosion is deterioration of the metal which is initiated by the electronic transfer. Many types of corrosion have been studied to include the following: atmospheric corrosion, galvanic corrosion, crevice corrosion, pitting corrosion etc. The effect of corrosion on metals such as steel, aluminum, titanium and iron may take many different forms. In order to have an insight on the corrosion process and its control it is important to identify the different forms of corrosion [3].

Uniform Corrosion: It is the most common form of corrosion. It is an even rate of metal loss over the exposed surface. It is kind of corrosion which is easily predictable and can be easily measured. General corrosion rate of less than 3 mils per year (mpy) are often considered to be acceptable for many chemical process and structures,
While a corrosion rate of 20 to 50 (mpy) [4] may be economically justifiable in severe environment. Uniform corrosion represents the greatest destruction of metal on a tonnage basis. However, this form of corrosion is not of great concern from a technical standpoint because the life of equipment can be accurately estimated on the basis of simple immersion tests [4].

Galvanic Corrosion: Galvanic corrosion The Coupling of two or more dissimilar metals, Metals with electron conductive non-metals are highly susceptible to corrosion when: (a) the materials are in electrical contact, (b) the materials are exposed in the same electrolyte or if the potential difference has to exist between the different materials. Under these conditions the material coupling represents a galvanic cell where the material which has a more negative electrode potential forms the anode and the corrosion can take place at an accelerated speed therefore [5]. Galvanic corrosion is generally experienced in old homes where modern copper tubing often connected to much older existing carbon steel water lines. There are many factors which influence galvanic corrosion such as: spacing, anode – cathode area ratio, temperature etc [6].

Pitting corrosion: Pitting corrosion is defined by Szklarska as a localized dissolution of metals which occurs because of breakdown of protective passive film. It can also occur during active dissolution if certain section of the samples are more susceptible and dissolves faster than the rest of the surface [7]. It is associated with high loss of metals and does affects materials, such as: (a) stainless steel, (b) aluminum, (c) copper alloys etc. In cases where environment is one where repassivation of the damage film can be made many shallow pits tend to form but initiation of new sites occurs on a regular basis. The localized nature of pitting attack can be associated with (a) component
geometry, (b) mechanism of corrosion process, and (c) imperfection in the material chosen. The growth of pits once initiated is closely related to one other mechanism of corrosion i.e. crevice corrosion [8].

Crevice corrosion: Crevice corrosion is another form of “localized” corrosion of a metal or alloy surface at or immediately adjacent to the gap between the two surfaces. This type of corrosion can be formed between two metals or between a metallic and a non-metallic material. It can result either from the deposition of dirt, dust, mud and deposits on a metallic surface or result from the existence of voids, gaps and cavities between adjoining surfaces. Crevice corrosion is initiated by a difference in concentration of some chemical constituents, usually oxygen, which sets up an electrochemical concentration cell [9].

Intergranular corrosion: This particular corrosion attacks those sites where individual grain within a metallic material touch each other. Based on the alloy system and the corrodent, corrosion attack may initiate at these sites due to attack of the surrounding matrix or preferential attack of the secondary phase, which is dealloyed during formation of the secondary phase. A gradual progress in the attack results in separation of individual grains from the matrix which results in more porous surface layer [3]. Intergranular corrosion (IGC) is a serious problem when exposed to aggressive environments, which could result in unexpected failures and often lead to huge losses. One of the major reasons for these forms of corrosion is the grain boundary sensitization. The surface texture will be grainy or powdery leading to a rapid loss of the metals in severe cases [10].
Stress Corrosion Cracking: Stress Corrosion Cracking (SCC) is a form of failure of material having specific characteristics. It is caused by cooperative and simultaneous action of tensile stress, susceptible microstructure and environment. Microstructure depends upon the manufacturing methods and chemical composition. In few cases residual stress may exceed the tensile stress, which results in worsening of Stress corrosion cracking susceptibility of the material [11]. Stress corrosion cracking is most often rapid and unpredictable. Failure can occur in a short time as a few hours or take years and decades to happen. Extensive cracking can be generated within few hours in severe cases like 304 stainless steel in a boiling magnesium chloride solution [3, 12].

Corrosion plays a critical role in determining safety, life-cycle performance, and cost of engineering products. Successful application of corrosion understanding already saves billions of dollars annually in these endeavors. Studies upon corrosion have concluded that wider application of our understanding of corrosion phenomenon or process can reduce the cost of corrosion. It will impact materials differently, one material might get corroded in no time whereas one might take weeks to get corroded after the exposure. Corrosion of the material depends to a large extent on composition of the material [13]. The most common alloying elements used in stainless steel are chromium, nickel, carbon, nitrogen, molybdenum, silicon and manganese. Manganese is present in almost all stainless steels in concentrations of 1-2% whereas silicon is present in the concentrations of 0.2-0.7%. There are other materials, which are also are used for various purposes but the above mentioned five elements are the most common alloying elements. Ferritic steels have high chromium and virtually no nickel content relative to martensitic steels. This is in contrast to austenitic steels which always have nickel and comparatively
high chromium content. Duplex steel falls between ferritic steel and austenitic steel as they have high chromium content but less nickel content when compared to austenitic steels. The use of nitrogen is restricted exclusively to austenitic steels and duplex steels [14].

The low yield strength but high ductility of the austenitic steels are apparent as are the high yield strength and tensile strength but the low ductility of the martensitic steels. Ferritic and duplex steels both lie somewhere between the extremes. Austenitic steels have slightly lower yield strength when compared to ferritic steels, whereas duplex steels have much higher yield strength when compared to both austenitic steels and ferritic steels. [14]. Austenitic stainless steel is most widely stainless steel in construction industry and are based on 17-18 % chromium and 8 – 11 % nickel addition, but when it comes to duplex stainless steel, they have a mixed austenitic/ferritic microstructure and are based on 22-23 % chromium and 4-5% nickel additions. Duplex stainless steel have a higher corrosion resistance when compared to austenitic because of the higher content of chromium and presence of molybdenum and nitrogen [15].

By virtue of the elements used, a substantial number of aluminum alloys have been developed resulting in a sufficient number of Al alloy series with each having its own set of custom properties [16]. It is convenient to divide alloy of aluminum into two categories: (a) cast aluminum alloys and (b) wrought aluminum alloys. The division is based upon the composition and mechanism used for property development. There are many alloys, which successfully respond to thermal treatment depending upon their composition and other factors, such as phase solubilities and this treatment involves quenching, solution heat treatment, hardening, precipitation heat treatment etc. Therefore,
such alloys which can be either wrought or cast alloys are described as heat treatable [17].

As a general average, 75 to 80% of the aluminum alloy are used for wrought products, e.g. (a) rolled plate (6mm thickness), (b) sheet (0.15–6mm), (c) foil (0.15mm), (d) extrusions, (e) rod, (f) bar, and (g) wire. Wrought aluminum alloys are generally classified into two categories (a) heat treatable and (b) non-heat treatable alloys. Heat treatable alloys possess their strength from solutionizing and subsequent age hardening, whereas the non-heat treatable alloys derive their strength from a combination of dispersion hardening or solid solution strengthening and can be further strengthened using cold working or strain hardening [18].

Naturally, the cast alloys may not be strain hardened but they are heat treatable. The strength of cast aluminum alloys is lower when compared to the wrought alloys. Cast and wrought alloys have different nomenclatures. The alloy identification system employs different nomenclature for wrought and cast alloys, but divides alloys into families for simplification. For the case of wrought alloys, a four digit system is used to produce a list of wrought composition families. When it comes to cast alloys, they are described using a three digit system followed by a decimal value [12, 14].

Aluminum alloy are a good conductor of electricity and also very ductile. The structure of aluminum is face-centered cubic and similar to few other metallic metals such as: (a) copper, (b) nickel, (c) gold etc. Alloys of Aluminum are important subject of research primarily because it is abundant in nature, easy to handle, and represents an important category of material due to high technological value coupled with wide range of industrial applications, especially in aerospace and household industries. [19].
CHAPTER II

OBJECTIVES OF THIS RESEARCH STUDY

The focus of this study was to determine the effect of four different mediums on the chosen test materials for different span of time and to publish the results. The objectives of the research were to determine how pH and conductivity can vary over a time period for eight weeks due to the addition of both salt and acid. The variation of pH and conductivity for the four different mediums was compared to evaluate how different aqueous environment can influence the corrosion behavior and resultant mechanical properties of a metal. The test materials chosen were subjected to tensile and the impact tests and the results were recorded. Duplicates samples from each medium were tested in order to provide a valuable evidence of material behavior. The values of strength were compared with typical values documented in the published literature in order to record any observable difference in structural behavior. The tensile tests and impact test were conducted on test samples to establish the difference between the samples, which were immersed in different mediums and the time of immersion or exposure to the environment affected the mechanical properties of the chosen materials. The deformed failed samples were then examined in a Scanning electron micrograph [SEM] to understand the fracture behavior of the chosen material and any changes as a consequence of exposure of the materials to the different environments.
CHAPTER III

REVIEW OF LITERATURE

3.1 What is a Corrosion

Corrosion is an electrochemical process that can be measured, predicted and controlled under specific conditions. As it is governed by reaction at an atomic level, it can act on uniform surface area, isolated regions and can lead to microscopic damage. In the context of hydrothermal and supercritical water processes, corrosion includes all reactions of components of an aqueous reaction mixture within the walls of an equipment of experimental or production size facility, such as, pipes, valves, fittings, and autoclaves [20].

When steel is exposed to industrial atmosphere it reacts to form rust having the composition Fe$_2$O$_3$·H$_2$O. Since the rust is loosely adhered to the surface it does not form a protective layer, which can isolate the metal from the environment. This leads to reaction at a linear rate until the metal is completely consumed. On the other hand, the vessel constructed from titanium in hot 40% H$_2$SO$_4$ with formation of Ti$^{4+}$ aqueous cations conforms both the definitions of corrosion. However, a thin adherent protective film of Titanium dioxide (TiO$_2$) is formed, which can isolate the metal from the acid resulting in a decreased rate of corrosion [21].
These examples lead to the conclusion that any reaction of the metal with the environment must be regarded as a corrosion process regardless of initial or subsequent stages of reaction or extent of the reaction. Therefore, it is important to have a better understanding of the corrosion process.

Corrosion process: In its simplest definition, it is a process of a material returning to its natural thermodynamic state [3]. The changes that occur during the return are electrochemical reactions, which follow the laws of thermodynamics. It helps in understanding why corrosion processes are temperature dependent and time dependent. It also explains why some reactions are reversible or controllable and thermodynamics can be used to establish corrosion reactions. The most basic corrosion reaction involves oxidation of the chosen metal when exposed to a strong acid. An example is the reaction of pure iron when placed in hydrochloric acid. The chemical reaction is expressed as [3]:

\[ \text{Fe} + 2\text{HCl} \rightarrow \text{FeCl}_2 + \text{H}_2 \uparrow \]  

(1)

There is also exchange of electrons taking place at the electrochemical level

\[ \text{Fe} + 2\text{H}^+ + 2\text{Cl}^- \rightarrow 2\text{Fe}^{2+} + 2\text{Cl}^2^- + \text{H}_2 \uparrow \]  

(2)

As shown in equation (2) iron is converted to ferrous ions by giving up two electrons which were picked by the hydrogen ions. Hydrogen ions are reduced to hydrogen gas after gaining two electrons. This transfer of electrons is taking place on the surface of the metal. The locations where electrons are given up is identified as “anodes”. The site where electrons are being absorbed are identified as cathodes. A complete electric circuit is developed since a difference in electrical potential exists between these two areas. Positively charged hydrogen ions in the solution flow towards the cathode to
complete circuit and negatively charged electron flow in the direction of anode to cathode. Current flow is directly proportional to rate of corrosion or dissolution of metals. The sites of cathodes and anodes can easily change locations on the surface. This happens generally when the general corrosion takes place with the metal surface being covered uniformly with the anodic areas.

Anodic reactions during metal corrosion are such that the metal is oxidized to a higher valence state. This results in the formation of metallic ions of the alloying elements. During the corrosion process metals, which are capable of exhibiting multiple valence state, may go through many stages of oxidation.

When it comes to cathodic reaction they are more difficult to predict but can be categorized into one of the five different types of reduction reactions [3]:

Hydrogen evolution

\[ 2H^+ + 2e \rightarrow H_2 \uparrow \] (3)

Reduction of oxygen into acids

\[ O_2 + 4H^+ + 4e \rightarrow 2H_2O \] (4)

Reduction of oxygen – Neutral solutions

\[ O_2 + 2H_2O + 4e \rightarrow 4OH^- \] (5)

Metal ion reduction

\[ M^{3+} + e \rightarrow M^{2+} \] (6)

Deposition of the metal
3.2 Corrosion behavior of stainless steels: Role of Environment

Stodart and Faraday (1820) from England published a report on corrosion resistance of various alloys. It was the first report in which chromium and iron alloys were described. In 1821, Berthier whose attention was drawn to the work of Stodart and Faraday found that iron alloyed with chromium had more resistance to acids when compared to the unalloyed iron [22]. They were brittle with high carbon content and were of no value for structural materials. Although a variety of chromium-iron alloys were produced during subsequent years, the resistance against corrosion of the alloys was not observed due to high carbon content, which resulted in impaired corrosion resistance. In 1904, Guillet from France produced low-carbon chromium alloys overlapping the passive composition range. Guillet studied mechanical properties and metallurgical structure of the Cr-Fe and Cr-Fe-Ni alloys, which are now known as austenitic stainless steel [22].

The corrosion resistance of stainless steel not only varies with composition but is also influenced by heat treatment, fabrication procedures, and condition of the surface. All the parameters may vary the thermodynamic activity of the surface, which therefore does affect the corrosion resistance [23]. The corrosion resistance of stainless steels are attributed to the thin passive film that forms spontaneously on the surface of the stainless steels in oxidizing environments if the chromium content in the steel is minimum. Stainless steels are used in wide variety of corrosion-resistant applications. Stainless steels are often susceptible to many localized forms of corrosion, such as: (a)
intergranular, (b) crevice, (c) pitting, or (d) general corrosion. Factors, such as: chemical environment, pH, temperature, surface finish, product design, fabrication method, contamination and maintenance procedures will tend to influence the corrosion behavior of stainless steels and the type of corrosion that can occur [23].

The basis for the various stainless steels is the binary Fe–Cr system. The properties of which are modified by the addition of several major alloying elements such as Nickel, Molybdenum and Manganese as well as minor ones. The Fe–Cr–Ni alloys are the most predominantly used austenitic stainless steels. Carbide precipitation and the time at temperature greatly influences the corrosion performance. Reduction in the “local” chromium content caused by the precipitation of chromium rich at the grain boundaries does affect passivity of the grain boundary area and this is known as sensitization. It is also lowers the resistance to other form of corrosion, such as pitting, crevice, stress-corrosion cracking [24, 25].

Sigma phase can be formed because of precipitation during heat treatment or during the course of service exposure. It generally occurs in highly alloyed stainless steels that form rapidly at a temperature of 650-925°C and this formation makes the stainless steel susceptible to intergranular corrosion. Intergranular corrosion can be avoided by adding vanadium, titanium, and niobium. Addition of these elements can also improves the creep strength of these alloys by encouraging the precipitation of fine intragranular carbides [26]. The amount of time spent in this temperature is critical for formation of the sigma phase. Therefore, it is clear that any precipitate, which extracts important corrosion resisting elements from the solution or produces a phase which is
anodic or cathodic to the matrix, has the potential to decrease corrosion resistance of the chosen stainless steel [24].

There are many environments, which have different influences on stainless steels or into which a stainless steel can be successfully introduced. Atmospheric corrosion on stainless steel, which is affected with humidity and natural and/or man-made pollutants. There have been test samples, which have been exposed to a rural atmosphere for as long as 50 years without any measurable deterioration. Despite the extraordinary corrosion resistance in various media, the austenitic stainless steels in a chloride-containing environments can undergo pitting corrosion. The aggressiveness and ability of Cl\(^{-}\) ions to initiate this type of corrosion is well known [25, 27].

In general, applications of stainless steel in chemical environments should be evaluated for all forms of corrosion, the impurities associated with the stainless steel, and the degree of aeration in the environment. Organic acids are basically less aggressive when compared to mineral acids but they can be corrosive depending upon the impurities associated with the chosen stainless steel. Oxidizing agents can help in reduction of corrosion rates in the absence of chlorides. It is generally agreed that with stainless steel tanks used in the subsurface, one of the most important factors is the chloride ion (Cl\(^{-}\)) concentration in the soil and the soil moisture, which can contain different dissolved species such as sulphate ions (SO\(_{4}\)^{2-}). Chloride ions are harmful, as they participate directly during pitting initiation of stainless steels and their presence tends to decrease the soil resistivity. In principle, stainless steels should be in the passive state in soils, but the presence of water and aggressive chemical species, such as: (a) chloride ions, (b) sulphates and (c) types of bacteria and stray current, can cause localized corrosion. This
probability increases with increasing chloride ion content and higher redox potential. Chloride ions can be a primary problem, because specific ions affect pitting corrosion. Negative impact of Cl\(^-\) is not only limited to stainless steel in contact with the soil. Cl\(^-\) in solution (in tanks/pipes) or vapor (gas) in stainless steel structure can also induce corrosion. [24, 28].

At lower temperatures most of the stainless steel will tend to resist chlorine or fluorine gas if the gas is completely dry, the presence of small amount of moisture will result in corrosion, especially pitting corrosion or stress-corrosion cracking. When it comes to a strong oxidizing environment, stainless steel is resistant to oxidation. However, corrosion attack can occur if sulfur compounds or vapor are present in the gas.

At higher temperatures, the stainless steel is protected by the gaseous oxidation film of chromium oxide that is produced due to interaction of chromium and oxygen in the substrate. Microstructural changes in form of precipitation of various kind of phases occur in nitrogen austenitic stainless steel at high temperatures [29]. At lower temperatures, passivity of the stainless steel can be explained through the formation of a protective layer on the surface of the metal. This film forms naturally in an oxidizing environment, but will not degrade in a reducing environment. Some stainless steel compositions are better suited for the reducing agent [24].

3.3 Corrosion Behavior of Aluminum Alloys: Role of Environment

Aluminum was initially produced in the year 1825 by Hand Christian in impure form, in the pure form by Friedrich Wohler by 1827 [14]. The first commercial preparation of aluminum alloys was in 1855 in France when Henry Etienne reduced aluminum chloride with sodium. Having been discovered in early 1800’s aluminum and
its alloys have a short history. However the key to its extensive use today is corrosion resistance and versatility, which makes it suitable for many purposes [14].

Alloys of Aluminum exhibit diverse range of properties that can be safely matched for a specific application depending upon the required choice of composition, mode of fabrication, and temper. In addition to being corrosion resistant, aluminum and its alloys have several other important properties to offer like good specific strength, reasonable formability, good conduction of electricity, lighter than most other non-ferrous alloys except magnesium and beryllium [16].

Aluminum–magnesium–silicon (Al–Mg–Si) alloys denoted as 6xxx series are medium strength heat treatable alloys that have excellent formability and good corrosion resistance characteristics. They are of particular interest in aerospace and automotive industries because of their combination of properties [30]. These materials can be heat treated to enable precipitation to various levels and/or degrees. A common method for increasing the strength of the 6xxx alloys is T6 heat treatment which involves solution heat treatment, quenching and artificial aging. The Al–Mg–Si series alloys generally have lower formability than the Al–Mg alloys (5XXX series), but provide higher strength subsequent to paint baking [31].

In this series, AA6061 is one of the most widely chosen and used alloys. It is an age-hardened aluminum alloy originally developed in 1935 to satisfy the need for a medium-strength aluminum alloy that has with high toughness coupled with weldability. It can be tempered to various conditions including the T6 design. Alloy 6061 is often used in welded structures such as: pipelines, railroads, and cars. The good mechanical and corrosion behavior of aluminum alloy 6061, coupled with its low density, make an
attractive choice for the structural applications in an automotive. The presence of 0.2% of chromium makes the alloy resistant to corrosion. The presence of excess silicon improves age hardening response, while concurrently reducing ductility and preventing intergranular embrittlement, as a consequence of segregation of excess silicon to the grain boundaries. In fact AA 6061 is a popular choice and is preferred as a matrix for many aluminum alloy based MMCs. Aluminum alloy (6061) is well-known for its superior mechanical properties, such as high strength to weight ratio and good ductility, excellent weldability, good corrosion resistance, and an immunity to stress corrosion cracking [32].

The Al–Mg–Cu based alloys like AA2024, are susceptible to corrosion. The corrosion process that occurs on the surface of these aluminum alloys when exposed to NaCl solution is a localized alkaline corrosion of the aluminum matrix surrounding the solution of Al(Mn, Fe, Cr) cathodic intermetallic [33].

The 7xxx series alloys, they are heat treatable. These alloys are regularly used with riveted constructions as they cannot be easily welded using commercials processes. A common application for these alloys is in the aerospace industry where fracture critical design provided the impetus for higher toughness alloys. In these alloys the Iron and Silicon are believed to improve the combination of strength and fracture toughness. The atmospheric corrosion resistance of 7xxx series alloy is not as high as the 5xxx series and the 6xxx series due to which 7xxx series alloys are generally coated prior to use. There have been special tempers created in order to improve their resistance to corrosion. Generally, they have a tensile strength ranging from 32,000 to 88,000 psi [34].
The high strength precipitation hardenable 7075 (Al Mg Zn Cu) aluminum alloy is widely used in the aerospace industry, due to its useful properties of (a) high specific strength ($\frac{\sigma}{\rho}$), (b) ductility, (c) toughness and, (d) fatigue resistance, (e) low density [35]. Corrosion resistance of aluminum alloy AA7075 is related to the presence of many different intermetallic phases like Al$_7$Cu$_2$Fe, (Al,Cu)$_6$(Fe,Cu), Al$_{23}$CuFe$_4$, Al$_2$CuMg, Al$_{12}$(Fe,Mn)$_3$Si, Mg$_2$Si. Phases consisting of aluminum, zinc and magnesium are anodic, while those containing Copper, Iron and Manganese are cathodic, relative to the aluminum alloy matrix. This situation promotes the formation of corrosion micro-cells and initiates the “local” corrosion process. Alloys in T6 temper have high mechanical strengths coupled with good machinability characteristics that makes them useful for many engineering applications. These properties are usually achieved after homogenizing the cast 7075 at 450°C for several hours, followed by aging at 120°C for 24 hours [36, 37].

Aluminum is quite a reactive metal having a high affinity for oxygen. However, it can develop a thin oxide layer in dry and non-salty environments, which could restrain their further corrosion [38]. This film is stable in natural in the absence of chloride and provides natural corrosion resistance to the metal. Nonetheless, this film has insufficient barrier properties for long term corrosion prevention of the underlying metal substrate, even after being further coated by organic protective coatings [39]. The corrosion process specific to aluminum alloys is influenced by factors, such as: solution nature, hydrodynamics, temperature as well as aluminum purity and several environmental factors, such as: salinity, oxygen content, and solution flow, as well as the geometry of the corroding system and time of exposure etc [40].
The corrosion resistance of aluminum alloys is dependent on the formation of an oxide or passive film, which naturally develops on the alloy surface under normal atmospheric conditions. The oxide film that is formed on the surface is not uniform but thin and non-coherent. Therefore, it tends to impart a certain level of protection under normal conditions [14, 41].

Alloys of aluminum are also commonly chosen for marine applications. It has the additional advantage of superior resistance to corrosion, since it tends to corrodes over 100 times slowly than conventional structural carbon steel that are used to build ships. There will be no immediate effect of corrosion on aluminum and its alloys in neutral waters and it can give satisfactory service if both cleaning and drying can occur on a regular basis. The 5xxx series and 6xxx series aluminum alloys are commonly used in marine applications where low density materials, good mechanical properties and better resistance to corrosion are desired. The oxide film that is formed on an aluminum alloy surface is non-uniform, thin and non-coherent. Therefore, it tends to impart a certain level of protection under normal conditions. When exposed to environments containing halide ions, of which the chloride (Cl⁻) ion is the most frequently encountered in service, the oxide film breaks down at specific points resulting in the formation of pits on the surface of the aluminum alloy. This type of corrosion is known as pitting corrosion. [14, 42]

When it comes to chemical environments most acids are corrosive to aluminum alloys. Aluminum alloys, when compared to 304l stainless steel shows advantage at acid concentration of more than 95%; however if the acid concentration falls below 80% or if the temperature increases above 40°C, higher corrosion rate can be expected [43]. Boric acid has little to no effect on an aluminum alloys whereas, a mixture of chromic and
phosphoric acid can be used for the removal of corrosion debris from an aluminum alloy without having any appreciable influence on the metal. Dissolution of aluminum alloys in phosphoric acid is lower when compared to hydrochloric acid or sulfuric acid, but it does corrode aluminum and its alloys. Organic acids usually have a low rate of attack on an aluminum alloy but this excludes organic acids like formic acid, oxalic acid etc [44]. Alkali are corrosive to an aluminum alloy. Mild alkali, such as: sodium carbonate is moderately corrosive and certainly not used for washing aluminum hallo-wares. Alloys containing magnesium or silicon are more resistant to the alkali medium when compared to other aluminum alloys. The corrosion rate in potassium and sodium hydroxide decreases with an increase in purity of the metal However, when it comes to ammonium hydroxide a reverse process tends to occur [14].

The corrosion of an aluminum alloy in soils is an important issue primarily because of the application of an aluminum alloy as: (a) cable for electricity, (b) water and gas distribution grids, (c) embedding of street lamps and, (d) other support structures [45]. The Nature of the soil varies as a function of depth, while nature of successive layers depends on the “local” geology. Aluminum and its alloys, when placed beneath the ground, will undergo surface attack, whose intensity depends on nature of the soil. The overall corrosion resistance of the metal when it comes to soil depends upon factors like: (a) water content, (b) the structure of the soil, (c) resistivity of the soil, which itself depends on the water content and concentration of inorganic salts, (d) concentration of dissolved oxygen which depends on depth and, (e) structure of the soil. When it comes to soil unprotected aluminum alloy can exhibit corrosions such as: (a) pitting, (b) galvanic, and (c) corrosion by stray current. Severe galvanic corrosion is observed if either a totally
or partially embedded structure is earthed with a copper strap. Experience with aluminum alloy tubes in irrigation installations revealed that the corrosion in contact with soil is generally very superficial [46].

The spontaneous degradation of metals when exposed to an atmosphere is a growing problem that has an impact on industrialized societies. The presence of chemical species in the atmosphere has quite an effect on atmospheric corrosion. Aluminum and its alloys are often exposed to various atmospheric environments and their behavior can be influenced by different forms of atmospheric corrosion like pitting corrosion, intergranular corrosion and even exfoliation corrosion. Alloys of Aluminum have often been chosen for use in the outdoors, such as: (a) transportation, (b) aircraft, (c) aerospace, (d) electrical engineering, etc. Gases, such as: (a) hydrogen sulphide (H₂S) and, (b) carbon dioxide (CO₂) will not have a great effect on corrosivity of the chosen aluminum alloys [47]. Alloys like the copper bearing alloys and medium strength Al-Zn-Mg alloys tend to have additional protection, such as painting, to avoid the risk of intercrystalline corrosion when used in a severe environment. In general, a longer exposure time to the environment of an aluminum alloy can result in high pit density and pit depth. The magnitude of pit depth greatly depends on composition of the “local” environments. A linear relationship can be established from both pit depth and density from the pollutant concentrations namely, Cl⁻ ions and SO₂ [48].

The melting point of aluminum is 660 ºC while that of zinc and magnesium is 419 ºC and 650 ºC [46]. Since the temperature exceeds 660 ºC in practice, they tend melt but not burn. The linear expansion coefficient of an aluminum alloy is twice when compared
to that of steel and is directly proportional to test temperature. The same trend is followed for thermal conductivity and mass thermal capacity.

It is difficult to ignite an aluminum alloy because of the natural oxide film, which tends to block the reaction of metal with air or oxygen. Among the alloying elements and additives used, only magnesium can significantly change the fire resistance of an aluminum alloy. The Alloys containing more than 10% magnesium can ignite at 550 °C [46] primarily because magnesium can burn at the chosen temperature. Water is often sprayed on molten aluminum. A small quantity of the water will tend to decompose since the metal’s reactivity leads to decrease as a consequence of the formation of a natural oxide film [46, 49].
CHAPTER IV
THE TEST MATERIAL CHOSEN

The test materials chosen were Stainless steel 304L, alloy steel 4340 and Wrought aluminum alloys 6061 and 7075. Test materials 304L stainless steel and, 6061 aluminum alloy were used for the tensile test whereas, alloy steel 4340 CF Steel and aluminum alloy 7075-T651 were used for the impact tests.

The two major potential components of a stainless steel scale are the $\text{M}_2\text{O}_3$ rhombohedral phase and $\text{M}_3\text{O}_4$ spinel phase. Austenitic stainless steels are a group of steels that contain nominally 19% [Cr] chromium and 9% nickel [Ni]. They typically contain more than 12% Cr which provides resistance to corrosion by formation of a tenacious, spontaneously regenerating surface layer of chromium oxide [50]. Other alloying elements such as nickel, manganese and molybdenum [Mo] are often added to achieve a specific purposes needed for the application. This group of steels exhibit a highly attractive combination of high strength, good ductility, excellent corrosion resistance and a reasonable weldability [51]. Alloy steel 4340 is representatives of medium carbon alloy steel with low alloy steel content. Due to its strength, toughness and wear resistance it is chosen for large number of structural components. AISI 4340 high strength steel is also used in aeronautical applications. This alloy steel is susceptible to stress corrosion cracking [52].
Aluminum alloy - 6061 is an Al-Mg-Si alloy. The aluminum–magnesium–silicon (Al–Mg–Si) alloys denoted as 6XXX series, are medium strength heat treatable alloys that offer excellent formability coupled with good corrosion resistance characteristics. Magnesium [Mg] and Silicon [Si] are the major alloying elements: they help in increasing strength of the alloy by precipitation hardening [53]. Thus 6061 is an age hardenable alloy, the mechanical properties of which can be controlled by the hardening precipitates contained in the material [54]. In addition, this alloy finds application in artificial ageing condition (-T6). The T6 treatment involving solution heat treatment, quenching and subsequent artificial aging method that is used to increase strength of the alloy [55].

AA 7075 is an Al-Zn-Mg-Cu alloy that is chosen for use in the aerospace industry for the fabrication of structural components [56]. Aluminum alloy 7075 can be formed by wrought manufacturing process which results in high strength. However, in order to obtain high strength in this alloy, heat treatment is a key process that can be used to improve mechanical properties subsequent to the forming process. T6 heat treatment schedule for wrought 7075 Al alloy includes a solution heat treatment in the temperature range of 465–490 °C and artificial aging temperature in the range of 120°C [57]. Al-7075 alloy possesses a microstructure having finer grain size due to the occurrence of dynamic recrystallization and dynamic recovery during thermo-mechanical treatment. The 7075 aluminum alloy contains a variety of second-phase particles distributed either in the grain interior or along grain boundaries [58].

The chemical composition of all the four metals used are shown in the tables 4.1 and 4.2 below:
Table – 4.1 Nominal chemical composition of 304L stainless steel and 4340 Cold finish alloy steel [59]

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>304L stainless steel</td>
<td>&lt; 0.03</td>
<td>18 to 20</td>
<td>&lt; 2</td>
<td>8 to 12</td>
<td>&lt; 0.045</td>
<td>&lt; 0.03</td>
<td>&lt; 1</td>
<td>–</td>
</tr>
<tr>
<td>4340 CF Steel Alloy</td>
<td>0.37 to 0.43</td>
<td>0.7 to 0.9</td>
<td>0.6 to 0.8</td>
<td>1.65 to 2</td>
<td>0.035</td>
<td>0 to 0.04</td>
<td>0.15 to 0.30</td>
<td>0.2 to 0.3</td>
</tr>
</tbody>
</table>

Table – 4.2 Nominal chemical composition of ALUMINUM ALLOYS 6061 T6 and 7075 T651 [60]

<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Ti</th>
<th>Zn</th>
<th>Cr</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061 T6 Aluminum Alloy</td>
<td>95.8 - 98.6</td>
<td>0.15 - 0.4</td>
<td>&lt; 0.7</td>
<td>0.8 - 0.12</td>
<td>&lt; 0.15</td>
<td>&lt;</td>
<td>0.04 - 0.35</td>
<td>0.4 - 0.8</td>
</tr>
<tr>
<td>7075 T651 Aluminum Alloy</td>
<td>87.1 - 91.4</td>
<td>1.2 - 2</td>
<td>&lt; 0.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.18 - 0.28</td>
<td>–</td>
</tr>
</tbody>
</table>
CHAPTER V

PREPARATION OF TEST SAMPLES

5.1 Impact test specimens

Charpy-V Notch test specimens of Aluminum Alloy 7075 T651 and Alloy Steel 4340 were prepared in accordance with specifications outlined in ASTM E-23 (American Society for Testing Materials, 2012) [61]. The notched impact test specimens measured 55 mm in length, 10 mm in width and 10 mm in height. The notch was machined at the center, and which had a depth of 2 mm and an angle of 45 degrees. The dimensions of impact test specimens are shown in Figure 5.1.
5.2 Samples for Tensile tests

The flat tensile test specimens were prepared in accordance with ASTM standards for the materials chosen [62]. The overall length of the tensile specimen was 290 mm and having a gage length of 50.8 mm. The length of the shoulder of a test sample was measured to be 100 mm(+). To minimize the effects of surface irregularities, the gage sections of all test specimens were mechanically grounded using progressively finer grades of silicon carbide (SiC) impregnated emery paper and then finish polished, to a mirror-like finish, using an alumina-based polishing compound. The primary purpose of polishing was to remove of all circumferential scratches and surface machining marks.
The samples were then placed in their respective jars for a specified amount of time. The jars in which the samples were placed contained four different solutions: (a) pH +Salt, (b) pH, (c) Salt, and (d) Distilled water. Sodium chloride was added to the solution with respect to the content of the salt and sulfuric acid was added for the content of the pH.

The key dimensions of a machined test specimen are shown in the Figure 5.2.

![Figure 5.2: A schematic of the cylindrical test specimen used for mechanical testing (Tensile).](image)

- L - Overall length 11.5±0.05in
- B – Length of shoulder 4.00±0.01in
- C – Grip length of the sample 0.70±0.01in
- G – Gage Length 50.8±0.01in
- W – Length of reduced section 12.7±0.01in
CHAPTER VI
EXPERIMENTAL TEST PROCEDURES

6.1 Initial Microstructure Characterization

Initial characterization of microstructure of the as-provided materials was done by low magnification optical microscope. Test Samples were cut according to the requirement from the received material i.e. stainless steel and aluminum alloy and then mounted in epoxy. The mounted samples were then subsequently polished using a series of silicon carbide impregnated emery paper (240 grit, 320 grit, 400 grit and 600 grit) using copious amount of water acting as both a lubricant and a coolant. Subsequently, the surface of the samples were mechanically polished using five-micron alumina solution and one-micron alumina solution. Fine polishing to a perfect mirror-like finish of the surface of all samples was achieved by using a alumina solution as the lubricant. The polished samples were subsequently etched using their respective reagents (i.e. Viella’s reagent for stainless steel 304L, and Keller’s reagent for the aluminum alloys). The polished and etched surface of the samples was observed in an optical microscope and they were photographed using standard bright field illumination technique.

6.2 Choice of environments

The four environments which were used for the tensile specimen were:

1) pH+Salt, 2) Salt, 3) pH, 4) Distilled water.
The medium of pH+salt was made by using a combination of sulfuric acid and sodium chloride. The salt and pH mediums were made by the addition of required amount of salt and acid. Sulfuric acid was added until the initial pH reached a value of 3.5, while NaCl was added to a concentration of 35ppt. The initial values for pH and Conductivity were 3.06 and 24 ms/cm for pH+Salt medium, for salt medium pH was 5.25 and conductivity was 29.3 ms/cm for pH medium initial value of pH and conductivity were 3.04 and 0.238ms/cm and in case of distilled water medium initial values were 4.5 and 0.00374ms/cm. In the same way impact test samples were immersed in two different mediums:

(a) Acid+salt, and (b) Salt

The acid and salt used was the same as that used for the tensile samples. Upon immersing the samples in the medium for required amount of time, both pH and conductivity of the solution were measured using, a pH meter of Fisher Science and, a conductivity meter of Mettler Toledo. Initially the two meters where calibrated. The calibration was carried out with an initial pH of 7. Subsequent to calibration the probe was immersed in the solutions and their respective pH and conductivity values were displayed on the meter. The probe was then washed using distilled water and continuous readings were taken by dipping it in the different solution. In case of salt medium the initial value of pH was 8.49 and conductivity was above detection limit, whereas in Acid+Salt medium initial values of pH and conductivity were 3.05 and 31.2ms/cm.

6.3 Impact toughness test

Charpy V-Notch specimens were prepared in conformance with specifications outlined in ASTM E-23. [61] Two duplicate samples were tested at each of the six
selected test temperatures. Test specimens were brought to the desired temperature by dipping in environments of:

(a) Liquid nitrogen (T = -180°C)
(b) Dry ice (T = -55°C)
(c) Ordinary ice (T = 0°C)
(d) Room temperature (T = 25°C)
(e) Boiling water (T = 98°C)
(f) Furnace (T = 170°C).

The samples were immersed in a specific environment for full 30 minutes prior to initiation of the testing. Specimens evaluated at the higher test temperature (T = 170°C) were placed in a Blue-M Moldatherm box furnace and allowed to soak at the temperature for full 30 minutes prior to testing. The specimens were removed from the respective environments and quickly placed in the test fixture of the impact test machine (Model: Tinius-Olsen) with a capacity of 300 ft-lbs. This was followed by a quick release of the impact hammer, i.e., the pendulum. The total energy absorbed or hardness of the sample to failure was read from the graduated scale on the test machine.

6.4 Mechanical test (Tensile)

Uniaxial tensile tests were conducted on an INSTRON-8500 Plus which is a closed-loop, fully programmed servo-hydraulic mechanical test machine with a 100 kN load cell. The tests were did at room temperature (298 K) and in the laboratory air environment were relative humidity of 55 pct. The steel test specimens deformed at a constant strain rate of 0.0001/sec. An axial 12.5-mm gage-length clip-on extensometer was attached to the test specimen, with the help of rubber bands, to deliver a measure of
the strain during uniaxial stretching. The stress and strain measurements, which were parallel to the load line, were recorded on a PC-based data acquisition system (DAS).

6.5 Fractography and Failure-damage analysis

Fracture surfaces of completely deformed and failed samples under uniaxial loading and impact loading were studied comprehensively in a scanning electron microscope (SEM). This is done to govern fracture mode the material at a macroscopic level and also characterize the fine scale topography and features on the fracture surface. This study helps in finding the microscopic mechanisms governing fracture during the tensile deformation and offers useful information related to the same.

The difference between the macroscopic mode and microscopic fracture mechanisms is built on the magnification level at which the micrographs were taken. The general nature of failure is referred to as the macroscopic mode while failure processes occurring at the “local” level is referred to as microscopic mechanisms, such as, (a) microscopic void formation, (b) microscopic void growth and eventual coalescence, and (c) nature, intensity (i.e. number) and strictness of the fine microscopic cracks and macroscopic cracks. The samples for observation in the scanning electron microscope (SEM) were obtained from the deformed and failed tensile specimens and test specimens by segmenting parallel to the fracture surface [63, 64].
CHAPTER VII
RESULTS AND DISCUSSION

7.1 Part A: Immersion tests: Variation of conductivity with pH

The pH obtained in the pH+salt medium for aluminum alloy 6061 was observed to increase from week # 1 to week # 8, where pH for week one was 4.4 and for week eight it was 7.04 which explains the influence of the medium, which with increase in time of immersion of the test sample the solution becomes more alkaline. The conductivity was plotted along with the pH and it was observed to decrease with an increase in exposure time due to precipitation from solution that rested on bottom of jar. However, the conductivity failed to show a trend just like the pH which increased from week one to week eight. The observed decrease in conductivity during the later weeks explains the formation of ions in eight-week solution which, was noticeably less when compared to the initial few weeks.

The conductivity for the pH medium ranged from 0.005 to 0.9ms/cm for all the eight weeks and gradually decreased from Week # 2 to Week # 8. The solution was acidic during the span of first seven weeks and then became neutral in the eight week explains that the effect of medium was decreasing as the time was decreasing. The sample being acidic in the initial weeks explains their corrosion in the chosen medium. The conductivity for the salt medium followed a similar trend that was followed in the
pH+Salt medium where it revealed a decrease from the first week (28.9ms/cm) to the final week of immersion (2.05ms/cm). This rationalizes the conduction of current in the final weeks to be lower when compared to conduction in the initial few weeks of immersion because the conductivity can be measured from the solution only, but as the time progressed precipitate was observed to settle at the bottom of the jar. The solution were slightly acidic during the entire span of eight weeks and have had a similar effect on the specimen for all eight weeks of immersion causing thereby greater degree or extent of corrosion due to the presence of the NaCl.

As expected conductivity for distilled water ranged from 0.00084 to 2.07ms/cm and did not follow the trend shown by above mentioned environments. The solution was moderately acidic during the initial few weeks of immersion and subsequently alkaline in the later weeks of immersion.
Figure 7.1: Variation of pH and conductivity for tensile samples of aluminum alloy 6061, which were immersed in the pH+Salt medium for eight weeks.

Figure 7.2: Variation of pH and conductivity for tensile samples of aluminum alloy 6061 that were immersed in the salt medium for eight weeks.
Figure 7.3: Variation of pH and conductivity for tensile samples of aluminum alloy 6061 that were immersed in the pH medium for eight weeks.

Figure 7.4: Variation of pH and conductivity for tensile samples of aluminum alloy 6061 that were immersed in distilled water for eight weeks.
The pH+salt medium for the 304L stainless steel was acidic throughout the span of eight weeks. The acidic nature of the solution containing (sulfuric acid+ NaCl) was relatively less for the eight weeks. The conductivity for the same solution was ranged from 0.017 to 27.93ms/cm. Its ability to transmit the electric charge was greater for the initial weeks and gradually decreasing during the final weeks of immersion explaining the settlement of the precipitation at the bottom of the jar.

The salt solution had an acidic influence on the test specimen which was seen in tensile test results. The pH values are ranged from 5.5 to 6.3 showing acidic nature of the solution while at the same time conductivity of the solution was maximum for the first two weeks and subsequently lower during the following weeks of continued immersion. The effect of the solution was seen explicitly in strength of the materials too, where salt medium samples had the least strength.

The trend followed by the pH medium for 304L stainless steel was similar to the trend shown by aluminum alloy 6061, where the solution was completely acidic during the first seven weeks of immersion and became neutral during eight week of immersion explaining the reduction in influence of the medium. Maximum conductivity was observed in the eight week and sixth week of immersion because of an increase in the formation of ions during those weeks. Distilled water was found to be neutral for the first seven weeks where the pH ranged from 6.5 to 8.5 and the conductivity was maximum during the first week of immersion and decreased during the following weeks. The pH and the conductivity obtained for the four different medium are shown in Figures 7.5 to Figures 7.8 below.
Figure 7.5: Variation of pH and conductivity for tensile samples of 304L stainless steel that were immersed in the pH+Salt medium for eight weeks.

Figure 7.6: Variation of pH and conductivity for tensile samples of 304L stainless steel that were immersed in a salt-containing medium for eight weeks.
Figure 7.7: Variation of pH and conductivity for tensile samples of 304L stainless steel that were immersed in a pH medium for eight weeks.

Figure 7.8: Variation of pH and conductivity for tensile samples of 304L stainless steel that were immersed in distilled water for eight weeks.
For the aluminum alloy samples, conductivity was found to be above detection limit. The pH gradually increased for all the six weeks by almost 10 to 20% relative to the initial pH. The conductivity was found to be maximum for the sixth week of immersion and was found to be minimum for the fifth week. The pH for the acid+salt medium was less when compared to the salt medium where it was recorded to be 3.05 and the conductivity was measured to be 31.2ms/cm. The acidic nature of the medium was due to the addition of sulfuric acid. The pH then followed an increasing trend where the maximum pH was observed following eight weeks of immersion. The conductivity measured was too high during the first week and third week of immersion and was seen to be maximum following eight week of immersion. A trend similar to salt the medium.

The salt solution in which alloy steel 4340 was immersed had a pH of 8.6. pH was relatively similar for all the six weeks of immersion with a maximum pH recorded in the third week of immersion. Conductivity was maximum during the sixth week of immersion similar to the salt medium for the aluminum alloy samples explaining the formation of the ions following eight weeks. Similar to the salt medium, the conductivity was observed to be maximum in eight week immersion even in acid+salt medium with a pH for this medium ranging from 7.2 to 8.3. The graph for pH and conductivity have been shown below.
Figure 7.9: Variation of pH and conductivity of the impact test samples of aluminum alloy 7075 that were immersed in an Acid + Salt medium for eight weeks.

Figure 7.10: Variation of pH and conductivity for the impact test samples of aluminum alloy 7075 that were immersed in a salt medium for six weeks.
Figure 7.11: Variation of pH and conductivity for the impact test samples of alloy steel 4340 CF that were immersed in an acid + salt medium for eight weeks.

Figure 7.12: Variation of pH and conductivity for the impact test samples of alloy steel 4340 CF that were immersed in a salt medium for six weeks.
7.2 Part B: Impact toughness behavior

Variation of energy absorption with respect to temperature to which the samples of 4340 CF steel and aluminum alloy 7075 were treated prior the testing is described below

7.2.1 Influence of environment on impact toughness response and/or properties.

Results of the impact tests on the two metals 4340 CF Steel and aluminum alloy 7075 reveals the influence of temperature on toughness of the two metals. Increase in energy absorbed with an increase in temperature explains the validity of test since the metal is brittle at lower temperature and ductile at the higher temperature regardless of time of immersion in the medium in which the metal was immersed. At the higher test temperature the two metals showed evidence of plastic deformation prior to catastrophic failure, while at lower temperature the two metals exhibited little to no plastic deformation and failed in a brittle manner. The energy absorbed by the 4340 CF steel at the higher temperatures is noticeably more when compared to energy absorbed by the aluminum alloy at the same temperature. Also alloy steel 4340 CF is far more ductile at the higher temperature when compared to aluminum alloy 7075. There was not much change observed in the energy absorbed by aluminum alloy 7075 at the different temperature. It reveals a trend, where a decrease in the energy absorbed by the metals following 8 weeks of immersions when compared to immersion for 4 weeks due to the effect of corrosion on the metals. Also, the same time the variation in toughness or energy absorbed is not much. At lower temperatures, alloy steel 4340 CF is brittle when observably compared to aluminum alloy 7075, which is seen in the energy absorbed as a function of test temperature Comparing the influence of environment it is observed that the effect of medium did exert an influence on the aluminum alloy 7075. There was a
decrease in the energy absorbed at all temperatures in the salt medium when compared to that of acid+salt medium which explains the salt medium to be more corrosive on aluminum alloy 7075. This trend is seen for 4340 CF alloy steel with certain irregularities. There was an influence of the salt (NaCl) environment on the metal that led to an increase in corrosion of the chosen metals.

There was an increase in toughness or energy absorbed, with an increase in temperature for alloy steel 4340 CF, which is due localized to microplastic deformation. The high energy absorption during the later stages in the steel is due to the fracture by ductile tearing. The toughness of aluminum alloy 7075 and alloy steel 4340 CF is relatively similar in the temperature range (-180 to 23) but at the higher test temperatures the toughness, or energy absorption, of alloy steel 4340 CF in the two chosen mediums, is higher which shows the metal to have better impact fracture toughness when compared to aluminum alloy 7075.

The toughness of aluminum alloy 7075 T651 and alloy steel 4340 CF when compared to the energy absorption by, identical samples which were not associated with either of the chosen medium and were not immersed for 4 or 8 weeks, was relatively lower over the range of temperatures studied. This revealed that the medium and time of immersion did have a significant influence on the samples, and also explains the extent to which the samples were corroded as a consequence of exposure to the medium coupled with time of immersion in the environment.
Figure 7.13: Influence of temperature on impact toughness of aluminum alloy 7075 T651 that was exposed to two environments: Acid + salt and Salt for a time span of 4 weeks and 8 weeks.
Figure 7.14: Influence of temperature on impact toughness response of alloy steel 4340 CF when exposed to the environments of Acid + salt and Salt for a time span of 4 weeks and 8 weeks.
Figure 7.15: A comparison of the energy absorbed response of alloy steel 4340 CF and aluminum alloy 7075 that was exposed to Acid + Salt environment for time span of 4 weeks.

Figure 7.16: A comparison of the energy absorbed response of alloy steel 4340 CF and aluminum alloy 7075 that was exposed to the salt environment for time span of 4 weeks.
Figure 7.17  A comparison of the energy absorbed response of alloy steel 4340 CF and aluminum alloy 7075 that was exposed to an Acid + Salt environment for time span of 8 weeks

Figure 7.18  A comparison of the energy absorbed response of alloy steel 4340 CF and aluminum alloy 7075 that was immersed in a salt environment for time span of 8 weeks
Table 7.1 - The impact toughness properties of aluminum alloy 7075 and 4340 Cold finish alloy steel immersed in two different environment for four and eight weeks respectively

<table>
<thead>
<tr>
<th>Material</th>
<th>Environment</th>
<th>Liquid Nitrogen (-190°C) (N-m)</th>
<th>Dry ice (-70°C) (N-m)</th>
<th>Ordinary ice (-45°C) (N-m)</th>
<th>Room Temp (23°C) (N-m)</th>
<th>Boiling water (90°C) (N-m)</th>
<th>Furnace (190°C) (N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7075 T651 Aluminum Alloy</td>
<td>Acid+Salt (4weeks)</td>
<td>17.63</td>
<td>20.33</td>
<td>23.05</td>
<td>21.69</td>
<td>25.76</td>
<td>31.18</td>
</tr>
<tr>
<td></td>
<td>Salt(4weeks)</td>
<td>14.91</td>
<td>17.62</td>
<td>20.33</td>
<td>18.98</td>
<td>23.05</td>
<td>28.47</td>
</tr>
<tr>
<td></td>
<td>Acid+Salt (8weeks)</td>
<td>17.62</td>
<td>21.01</td>
<td>22.37</td>
<td>21.69</td>
<td>26.43</td>
<td>29.15</td>
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<tr>
<td></td>
<td>Salt(8weeks)</td>
<td>13.56</td>
<td>16.27</td>
<td>18.3</td>
<td>17.63</td>
<td>20.34</td>
<td>21.7</td>
</tr>
<tr>
<td>4340 CF Alloy Steel</td>
<td>Acid+Salt (4weeks)</td>
<td>13.56</td>
<td>14.03</td>
<td>16.27</td>
<td>42.03</td>
<td>94.55</td>
<td>98.96</td>
</tr>
<tr>
<td></td>
<td>Salt(4weeks)</td>
<td>13.56</td>
<td>18.98</td>
<td>16.95</td>
<td>40.67</td>
<td>96.26</td>
<td>94.91</td>
</tr>
<tr>
<td></td>
<td>Acid+Salt (8weeks)</td>
<td>11.52</td>
<td>12.2</td>
<td>18.98</td>
<td>42.7</td>
<td>75.92</td>
<td>98.97</td>
</tr>
<tr>
<td></td>
<td>Salt(8weeks)</td>
<td>10.84</td>
<td>13.56</td>
<td>21.69</td>
<td>33.89</td>
<td>68.46</td>
<td>88.12</td>
</tr>
</tbody>
</table>
7.2.2 Impact fracture behavior

Impact fracture of Aluminum Alloy 7075 - T651

The fracture surface features of 7075 T651 alloy which was immersed in the medium containing a combination of Acid+salt for a time span of 8 weeks, and tested at a temperature 190°C which is the highest temperature used in the CVN impact tests for a pH of 8.54 and conductivity of be 32.7ms/cm is shown in the Figure 7.19. The overall morphology of the test sample revealed a major part of the sample to be rough and minor part to be smooth which features reminiscent of globally brittle behavior [Figure 7.19 (a)]. At higher magnification of (a) it reveals the rough surface covered with heavy population of voids and dimples. At the next higher allowable magnification of the scanning electron microscope regions of the micrograph shown in (b) reveal the morphology, which is surrounded with the voids and dimples. When the Figure(c) was seen at higher magnification, the region of overload was covered with the sizeable population of dimples indicative of locally dominating ductile failure mechanism.

At room temperature Aluminum Alloy 7075 – T651 was immersed in the salt medium for a time span of 8 weeks, where the pH and conductivity of the metal was measured to be 9.69 and 2.11ms/cm respectively. The scanning electronic micrographs of the samples which were tested at 190°C are shown in Figure 7.20. Overall morphology of the test sample shows the locally rough and smooth surfaces. Higher magnification of the figure 7.20 (a) reveals a microscopically rough fracture surface that is inlaid with an observable population of macroscopic cracks. Figure 7.20(c) which is taken at higher magnification of the fracture surface showed in (b) reveals dimples and voids of varying size along with a macroscopic cracks. These dimples populate the region adjacent to a
macroscopic crack. The region of overload revealed a sizeable population of dimples inter-dispersed with a good number of macroscopic cracks, which is reminiscent of both brittle and ductile failure is shown in the Figure (d).

At room temperature 7075 T651 was immersed in the environment of salt where pH and conductivity were measured to be 9.69 and 2.11 ms/cm. Overall morphology of the specimen as observed in an scanning electron micrographs is shown in the Figure 7.21(a). Over all morphology revealed the surface to be rough. High magnification observation revealed a microscopically rough fracture surface that contained an observable population of macroscopic cracks. At higher magnification revealed both macroscopic cracks along with fine microscopic cracks, which are intermingled with the pockets of dimples. The region of overload revealed a sizeable number of shallow dimples along with the cracked second phase particles.
Figure 7.19 Scanning electron micrographs of the impact fracture surface of test specimen of aluminum alloy 7075 that was immersed in an environment of pH plus salt having a measured pH of 8.54 and a conductivity of 32.7 ms/cm following exposure to temperature of 190 C, showing
(a) Overall morphology of failure
(b) High magnification observation of (a) showing microscopically rough fracture surface and an a population of voids of varying sizes intermingled with dimples
(c) High magnification observation of (b) showing non-linear nature of macroscopic crack surrounded by an array of fine microscopic cracks.
(d) The region of overload showing a sizeable population of dimples of varying size indicative of locally dominating ductile failure mechanisms.
Figure 7.20  Scanning electron micrographs of the impact fracture surface of test specimen of aluminum alloy 7075 that was immersed in an environment of salt having a measured pH of 9.69 and a conductivity of 2.11 ms/cm following exposure to temperature of 190 C, showing

(a) Overall morphology of failure
(b) High magnification observation of (a) showing microscopically rough fracture surface inlaid with observable of macroscopic cracks
(c) High magnification observation of (b) showing an observable population of dimples of varying size immediately adjacent to the macroscopic crack.
(d) The region of overload showing a sizeable population of dimples, and macroscopic cracks reminiscent of both locally ductile and brittle failure mechanisms.
Figure 7.21  Scanning electron micrographs of the impact fracture surface of test specimen of aluminum alloy 7075 that was immersed in an environment of salt having a measured pH of 9.69 and a conductivity of 2.11 ms/cm deformed at room temperature [25°C], showing
(a) Overall morphology of failure
(b) High magnification observation of (a) showing microscopically rough fracture surface containing an array of macroscopic cracks
(c) High magnification observation of (b) showing both macroscopic cracks, fine microscopic cracks intermingled with pickets of dimples.
(d) The region of overload showing cracked second-phase particles surrounded by a sizeable number of shallow dimples.
Impact fracture of alloy steel 4340 Cold Finish

The fracture surface features of alloy steel 4340 CF, which was immersed in a medium containing a combination of Acid+salt for a time span of 8 weeks, and tested at a temperature of 190°C, which is the highest temperature used in the CVN impact tests, at the end of eight weeks pH was 7.16 and the conductivity was measured to be 34.2ms/cm is shown in the Figure 7.22. The Figure 7.22 (a) reveals dimples covering the surface. It supports the observation of an increase in energy absorbed by the alloy steel 4340 with an increase in test temperature. Higher magnification reveals the nature and shape of the dimples. It revealed dimples interdispersed with the fine microscopic cracks. The dimples and voids, of varying size and shape are more explicitly seen in Figure 7.22 (c). The dimples intermingled with voids provides the evidence for mechanism of “locally” operating ductile failure.

Scanning electron micrographs of the test samples deformed from the cryogenic temperature, i.e., -180°C and furnace temperature of 180°C are shown from Figure 7.23 and Figure 7.24. Scanning electron micrographs of the alloy steel 4340, which was immersed in a medium which is a combination of both acid and salt at the lowest temperature used in the CVN impact tests where the pH was 7.16 and the conductivity was measured to be 34.2 ms/cm is shown in the Figure 7.23. Overall morphology of failure is shown in Figure (a) and reveals very little information. It is flat and essentially featureless at low magnification. At higher magnification fine microscopic cracks covering the transgranular fracture surface was seen. Careful observation at higher magnification revealed fine microscopic cracks to be intermingled with pockets of cleavage facets, indicative of “locally” occurring brittle failure mechanisms. At higher
magnification the region of overload revealed fine macroscopic cracks and faceted features indicative of locally occurring brittle failure.

Figure 7.24 which shows the failure behavior of the alloy steel 4340 at the furnace temperature which was immersed in the salt environment and pH was measured to be 9.48 and the conductivity was measured to be 34.1 ms/cm. The overall morphology of failure is shown in the Figure 7.24 (a) which explains that the surface to be both rough and smooth. Higher magnification reveals the nature of the surface to be microscopically rough and inlaid with number of many macroscopic cracks. Figure (c), which is the higher magnification of the (b) reveals the nature of cracking. The cracks were seen covering the surface. The observed cracks are a combination of both microscopic and fine macroscopic. Higher magnification of (c) is seen in (d) which reveals a population of dimples of varying size covering the transgranular fracture surface.

The fracture surface features of alloy steel 4340 deformed at the cryogenic temperature (-190°C) are shown in Figure 7.25. A vast majority of the fracture surface was covered with a population of microscopic cracks. The overall morphology of the test sample was essentially smooth with an observable number of macroscopic cracks and other features reminiscent of globally brittle behavior as seen in the figure 7.25 (a). At the higher allowable magnification of the scanning electron microscope regions of the micrograph shown in (b) revealed clearly the nature of the cracks to be microscopic covering the surface. Cracking occurred around the second phase particles in the region of overload. The region of was covered with microscopic cracks. At higher magnification of (c) faceted features were easily observed and separated by the fine microscopic cracks.
Figure 7.22 Scanning electron micrographs of the impact fracture surface of the test specimen of alloy steel 4340 that was immersed in an environment of pH plus salt having a measured pH of 7.16 and a conductivity of 34.2 ms/cm following exposure to 190 °C, showing

(a) Dimples covering the fracture surface
(b) Showing nature, shape and morphology of the dimples interdispersed with fine microscopic cracks.
(c) Dimples of varying size and shape intermingled with fine microscopic Voids indicative of locally operating ductile failure mechanisms.
Figure 7.23  Scanning electron micrographs of the impact fracture surface of test specimen of alloy steel 4340 that was immersed in an environment of pH plus salt having a measured pH of 7.16 and a conductivity of 34.2 ms/cm following exposure to temperature of -190 C, showing
(a) Overall morphology of failure, flat and near featureless at low magnification
(b) Fine microscopic cracks covering the transgranular fracture surface
(c) cleavage facets inlaid with fine microscopic cracks indicative of locally brittle failure mechanisms.
(d) The region of overload showing fine microscopic cracks and faceted Features.
Figure 7.24 Scanning electron micrographs of the impact fracture surface of test specimen of alloy steel 4340 that was immersed in an environment of salt having a measured pH of 9.48 and a conductivity of 34.1 ms/cm following exposure to temperature of 180 C, showing:

(a) Overall morphology of failure taken at low magnification
(b) High magnification observation of (a) showing fracture surface to be microscopically rough and inlaid with sizeable number of macroscopic cracks
(c) High magnification observation of (b) showing nature of macroscopic cracking
(d) High magnification observation showing sizeable number of dimples covering the transgranular fracture surface.
Figure 7.25 Scanning electron micrographs of the impact fracture surface of test specimen of alloy steel 4340 that was immersed in an environment of salt having a measured pH of 9.48 and a conductivity of 34.1 ms/cm following exposure to temperature of -190 C, showing:

(a) The transgranular fracture surface at low magnification showing an array of microscopic cracks

(b) High magnification observation of (a) showing the nature of microscopic crack.

(c) Cracking around second phase particle and fine microscopic cracks in the region of overload.

(d) High magnification observation of (c) showing faceted features separated by fine microscopic cracks indicative of locally brittle failure mechanisms
The presence of few yet isolated population of fine microscopic cracks provides evidence of “locally” brittle failure mechanisms.

7.3 Part C Tensile response

Tensile test on samples of aluminum alloy 6061 T651 and 304L stainless steel were conducted and the observation obtained have been explained below along with the failure mechanism of the samples.

7.3.1 Influence of environment exposure on tensile response and/or properties

The salt medium and the time of the immersion had a considerable influence on the tensile properties of Aluminum alloy 6061 T651. The tensile properties of 6061-T651 are shown in the Table 7.2. The results summarized in the table are the average values based up on the duplicates test samples.

The yield strength of the metal was relatively similar for the first three weeks of immersion in the salt medium, which ranged from 205 to 222 Mpa, and showed a decreasing trend from week # 1 of immersion to week # 3 of immersion. The yield strength of 6061 T651 at room temperature, when it is not associated with any medium or immersion time, is 276 Mpa. There was decrease of 19% for the first week and around 25% for the following two weeks. It shows that there have been certain effect of the medium chosen and the time of immersion as a consequence of which there was been decrease in yield strength of alloy 6061 T651. There was a substantial decrease in yield strength when it was immersed in the salt medium. The yield strength obtained following exposure of eight weeks to the salt medium was 147.85 MPa, which is 46% less when compared to the yield strength of the same material in the normal condition.
The ultimate strength also followed a similar trend with the strength being relatively similar for the first three weeks of immersion and there was a decrease in the eight week. The tensile strength obtained for the first three weeks ranged from 285 to 295 MPa. The ultimate strength of 6061 T651 at room temperature which is not associated with any medium is 310Mpa. The ultimate strength obtained from the samples that was immersed for 8 weeks was 166MPa, which is about 46% less when compared to ultimate strength of the same metal under normal condition.

The ductility, quantified by elongation over 2 inch (50.8 mm) gage length, is around 12.75% for the first week immersion, 14.9% for the second week, and around 15.7% for the third week. The elongation for the eight week immersion was 19.2%. The elongation was relatively similar when compared to the sample that was deformed under normal condition and not associated or exposed to any medium. The reduction in test specimen cross-section area, a direct measure of ductility, was relatively similar for first, second, and third week and a the minimum reduction was observed in the eight week samples

The engineering stress versus engineering strain curve for 6061 T651 sample which was immersed in the salt medium containing(NaCl) for a span of one week, two weeks, three weeks and eight weeks respectively, is shown in the Figure 7.26 below. The samples chosen for the stress versus strain figures were based up on the duplicates in the same medium.

There was certain effect of the medium that is combination of salt and pH on the tensile properties of aluminum alloy 6061- T651. The tensile properties of 6061- T651 have been summarized in table 7.3. The results provided in this table are the average
values based on the duplicates of the test samples. The elastic modulus of the samples for four different weeks was identical and ranged from 60 to 65GPa. The yield stress followed the same trend which was followed in the salt medium, and decreased from week # 1 to week # 3. The yield strength of the samples, which were exposed to the medium for 8 weeks is 38% less when compared to yield strength in normal condition. The yield strength of the samples which were exposed to the medium for eight weeks is 20% less when compared to yield strength of the samples which were exposed for three weeks. Ultimate tensile strength followed a similar trend seen in the salt medium, where strength did reveal a decreasing trend. The ultimate tensile strength of the week 8 sample is 165Mpa which is 47% less than tensile strength of the 6061 T651 under normal conditions. The tensile strength obtained was relatively identical for the first three weeks and 6% less than the tensile strength under normal condition. The ultimate strength of the samples following 8 weeks of exposure to the environment was around 40% less when compared to ultimate strength of the samples following first three weeks of immersion.

The elongation, over 2 inch (50.8 mm) gage length, was approximately similar when compared to elongation in the salt medium. The elongation for the first, second, third and eight week was 12.5%, 15.2%, 15.1% and 15% respectively. The elongation for eight week of exposure to the medium was minimum, which explains brittle behavior of the sample due to the medium and time of the immersion associated with aluminum alloy 6061 T6. The specimen had similar reduction in area for the first three weeks whereas the reduction in area was minimum for eight week sample when compared to the first three weeks of exposure to the medium. This is due to the less elongation obtained in eight week samples.
The engineering stress versus engineering strain curve for 6061 T651 sample, which was immersed in the salt+pH medium for the span of one, two, three and eight weeks respectively is shown in the figure 7.27 below. The effect of pH medium on the samples for one, two, three and eight weeks was relatively similar to salt and pH+Salt, where elastic modulus was in the range of 60 to 70GPa, and yield strength ranged from 130 to 200 Mpa, and was lowest for 8 week samples 52% less when compared to yield strength under normal conditions. The yield strength for the first three weeks, was identical around 27% less when compared to yield strength under normal conditions. Thus Ultimate strength followed a similar trend that was seen in above mentioned environments. The Ultimate tensile strength was lowest for the eight week samples that was exposed to the medium and 40% less when compared to ultimate tensile strength under normal conditions. The Ultimate strength for the 8 weeks sample was 42% less than the strength following first three weeks of exposure to the medium.

The elongation of the samples over 2 inch (50.8 mm) gage length, associated with the pH medium was less compared to the above mentioned environment. The elongation of the samples following the first week was around 13.25%, for the second week it was 15.4%, for the third week elongation was 12.7%, and elongation observed for the samples, which were immersed in the pH medium for eight weeks was 14%. The effect of medium on the samples was similar for the first three weeks, where the elongation was relatively similar during this period of immersion.

The reduction in test specimen cross-section area, a direct measure of ductility, was highest for the samples, which were immersed in the medium for one week and two
weeks. The reduction in cross section area was noticeably less for the third week samples and eight week of exposure to the environment due to failure of the samples.

The engineering stress versus engineering strain curve for the 6061 T651 aluminum alloy sample which was immersed in the pH medium for a time span of one week, two weeks, three weeks and eight weeks is shown in the Figure 7.28. The Modulus of elasticity was ranged from 59 Gpa to 66 Gpa in the distilled aqueous medium of distilled water for all of the four weeks [i.e. one – week, two – weeks, three – weeks and eight weeks]. There occurred a drastic decrease in yield stress for eight weeks of immersion when compared to the three week of exposure and the same trend was observed for ultimate strength. The tensile strength obtained was 47% less than the tensile strength under normal conditions of laboratory temperature and no exposure to the medium.

The ductility quantified by elongation over 2 inch (50.8 mm) gage length ranged from 14.6% to 17.55% for the first three weeks samples and elongation was around 18% for eight week immersion. The trend followed here is quite similar to what was observed other mediums where the elongation was less following the eight week exposure to the chosen environment when compared to the samples that were immersed for one week, two weeks, three weeks and eight weeks. A similar trend was seen for the samples, which were immersed in distilled water where the reduction in cross section area was maximum for one week and two week exposure to the medium and reduction in cross section was less for the sample that was exposed to the distilled water medium for eight weeks. It explains about corrosion which lead to the early failure of the samples since they were immersed in the chosen medium for a longer duration of time.
The engineering stress versus engineering strain curve for 6061 T651 sample which was immersed in the distilled water medium for the span of one week, two weeks, three weeks and eight weeks respectively is shown in the Figure 7.29. The tensile properties of the samples are summarized in Table 7.5.
Figure: 7.26  Engineering stress versus strain curve for aluminum alloy 6061 that was immersed in a salt medium for time span of four different weeks at room temperature
Figure: 7.27  Engineering stress versus strain curve for aluminum alloy 6061 that was immersed in a pH+salt medium for time span of four weeks at room temperature
Figure 7.28 Engineering stress versus strain curve for aluminum alloy 6061 that was immersed in pH medium for time span of four weeks at room temperature
Figure 7.29  Engineering stress versus strain curve for aluminum alloy 6061 that was immersed in distilled water medium for time span of four weeks at room temperature
Table 7.2: Compilation of room temperature tensile properties of 6061 aluminum alloy, which was immersed in salt medium for four different weeks

<table>
<thead>
<tr>
<th>Time</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 1</td>
<td>69</td>
<td>221</td>
<td>288</td>
<td>12</td>
<td>27</td>
</tr>
<tr>
<td>Week 2</td>
<td>66</td>
<td>208</td>
<td>287</td>
<td>14</td>
<td>29</td>
</tr>
<tr>
<td>Week 3</td>
<td>65</td>
<td>206</td>
<td>292</td>
<td>15</td>
<td>29</td>
</tr>
<tr>
<td>Week 8</td>
<td>35</td>
<td>147</td>
<td>165</td>
<td>19</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 7.3: Compilation of room temperature tensile properties of 6061 aluminum alloy, which was immersed in pH+salt medium for four different weeks

<table>
<thead>
<tr>
<th>Time</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 1</td>
<td>66</td>
<td>194</td>
<td>292</td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td>Week 2</td>
<td>60</td>
<td>193</td>
<td>290</td>
<td>15</td>
<td>24</td>
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<tr>
<td>Week 3</td>
<td>62</td>
<td>192</td>
<td>286</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>Week 8</td>
<td>39</td>
<td>143</td>
<td>162</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 7.4: Compilation of room temperature tensile properties of 6061 Aluminum alloy which was immersed in pH medium for four different weeks

<table>
<thead>
<tr>
<th>Time</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation</th>
<th>Reduction In Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks</td>
<td>GPa</td>
<td>MPa</td>
<td>MPa</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Week 1</td>
<td>62</td>
<td>199</td>
<td>291.80</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>Week 2</td>
<td>65</td>
<td>199</td>
<td>286.94</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>Week 3</td>
<td>64</td>
<td>196</td>
<td>291.08</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>Week 8</td>
<td>69</td>
<td>132</td>
<td>164.18</td>
<td>N/A</td>
<td>19</td>
</tr>
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</table>

N/A – Not Available

Table 7.5: Compilation of the room temperature tensile properties of 6061 aluminum alloy, which was immersed in distilled water medium for four different weeks.

<table>
<thead>
<tr>
<th>Time</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation</th>
<th>Reduction In Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks</td>
<td>GPa</td>
<td>MPa</td>
<td>MPa</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Week 1</td>
<td>66</td>
<td>197</td>
<td>293</td>
<td>14</td>
<td>26</td>
</tr>
<tr>
<td>Week 2</td>
<td>64</td>
<td>203</td>
<td>295</td>
<td>17</td>
<td>27</td>
</tr>
<tr>
<td>Week 3</td>
<td>63</td>
<td>192</td>
<td>284</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>Week 8</td>
<td>59</td>
<td>153</td>
<td>162</td>
<td>18</td>
<td>22</td>
</tr>
</tbody>
</table>

The engineering stress versus engineering strain curve for aluminum alloy 6061 T651 samples that was immersed in the four chosen mediums for one full week is shown in the Figure 7.30. The elastic modulus of the sample ranged from 60 Gpa to 70 GPa. The yield stress was maximum for the sample, which was immersed in the salt medium and was around 221 Mpa. The tensile stress of the samples was in the range of 288 Mpa to 297 Mpa which is similar to the tensile stress under normal conditions of temperature and...
laboratory air. There was a slight variation in elongation of the samples which are ranged from 12.5% to 14.6% for a gage length of 50.8 mm. The reduction in cross section area was maximum for the salt medium where it reduced up to 27.49%. There was no substantial influence of the chosen mediums over a time span of one week immersion in the chosen environment. There was a 6% reduction in tensile strength of the samples. The tensile strength and the elongation were maximum for the sample immersed in distilled water which projects that there was slight influence of both acid (H₂SO₄) and salt (NACl) on the samples. A similar was seen for the samples which were immersed in the four chosen mediums for 2 weeks. The elastic modulus ranged from 64 Gpa to 66 Gpa, whereas yield strength of the samples ranged from 194 Mpa to 208 Mpa. The tensile strength was maximum for samples exposed by way of immersion in distilled water. The elongation of the samples ranged from 14.9 mm to 17.55 mm over the gage length of 50.8 mm. The elongation was maximum in the Distilled water medium. Reduction in cross section area was maximum for samples exposed to the salt medium, which was similar for the samples that were exposed for one week. The elastic modulus for the samples exposed by way of immersion in to the mediums for one week, two weeks, three weeks ranged from 62 Gpa to 65 Gpa. There was small decrease in yield strength for the samples when compared to two weeks immersion and similar trend was shown by the tensile strength. The elongation was maximum for exposure to the Salt medium which is similar to exposure to the distilled water medium.

The sample of the chosen alloy that was immersed for eight weeks did reveal a substantial influence of the medium and time of the immersion. The yield strength of the sample decreased by 47% when compared to the yield strength under normal conditions.
of testing in laboratory air. The yield strength in distilled water medium was maximum among all the four chosen mediums. There was significant decrease in tensile strength of the medium where reduction was around 47% when compared to tensile strength of the sample under normal condition. There was a decrease in elongation as well when compared to the elongations recorded for one-week, two weeks, and three weeks, exposure. Reduction in cross section area was maximum in the Salt and distilled water medium among all the four mediums. The effect of medium, or environment chosen and the time of the immersion was maximum for samples that were exposed for eight full weeks. There was a small effect for the one week, two weeks, and three weeks in different medium but was very less when compared to the influence of eight week exposure. The engineering stress versus engineering strain curve for 6061 T651 samples which were immersed in the four different medium for eight weeks is shown below in Figure 7.33.
Figure: 7.30 Engineering stress versus strain curve for aluminum alloy 6061 that was immersed in four different medium for time span of one week at room temperature
Figure 7.31  Engineering stress versus strain curve for aluminum alloy 6061 that was immersed in four different mediums for time span of two weeks at room temperature
Figure 7.32  Engineering stress versus strain curve for Aluminum Alloy 6061 which was immersed in four different medium for time span of three weeks at room temperature.
Figure 7.33  Engineering stress versus strain curve for aluminum alloy 6061 which was immersed in four different mediums for time span of eight weeks at room temperature.
Table 7.6: The tensile properties of aluminum alloy 6061 immersed in four different mediums for a time span of one week.

<table>
<thead>
<tr>
<th>Environment Exposed</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt+pH</td>
<td>60</td>
<td>194</td>
<td>292</td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td>Salt</td>
<td>69</td>
<td>221</td>
<td>288</td>
<td>12</td>
<td>27</td>
</tr>
<tr>
<td>pH</td>
<td>62</td>
<td>199</td>
<td>291</td>
<td>13</td>
<td>24</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>66</td>
<td>197</td>
<td>293</td>
<td>14</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 7.7: The tensile properties of aluminum alloy 6061 immersed in four different mediums for a time span of two complete weeks.

<table>
<thead>
<tr>
<th>Environment Exposed</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt+Ph</td>
<td>66</td>
<td>193</td>
<td>292</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>Salt</td>
<td>66</td>
<td>208</td>
<td>287</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>pH</td>
<td>65</td>
<td>199</td>
<td>286</td>
<td>15</td>
<td>29</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>64</td>
<td>203</td>
<td>295</td>
<td>17</td>
<td>26</td>
</tr>
</tbody>
</table>
Table 7.8: The tensile properties of aluminum alloy 6061 immersed in four different mediums for a time span of three complete weeks.

<table>
<thead>
<tr>
<th>Environment Exposed</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPa</td>
<td>MPa</td>
<td>MPa</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Salt+pH</td>
<td>62</td>
<td>192</td>
<td>286</td>
<td>15</td>
<td>24</td>
</tr>
<tr>
<td>Salt</td>
<td>65</td>
<td>206</td>
<td>292</td>
<td>15</td>
<td>29</td>
</tr>
<tr>
<td>pH</td>
<td>64</td>
<td>196</td>
<td>291</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>63</td>
<td>192</td>
<td>284</td>
<td>15</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 7.9: The tensile properties of aluminum alloy 6061 immersed in four different mediums for a time span of eight complete weeks.

<table>
<thead>
<tr>
<th>Environment Exposed</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPa</td>
<td>MPa</td>
<td>MPa</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Salt+pH</td>
<td>59</td>
<td>143</td>
<td>162</td>
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<tr>
<td>Salt</td>
<td>65</td>
<td>147</td>
<td>165</td>
<td>19</td>
<td>24</td>
</tr>
<tr>
<td>pH</td>
<td>69</td>
<td>132</td>
<td>164</td>
<td>14</td>
<td>19</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>59</td>
<td>153</td>
<td>162</td>
<td>18</td>
<td>22</td>
</tr>
</tbody>
</table>

Nature of the chosen environment and time of immersion did have a considerable influence on the tensile properties of 304L stainless steel. The tensile properties of 304L stainless steel in the different mediums are shown in tables 7.10 to 7.13. The results summarized in the tables are the mean values based on duplicate test.

The yield strength of the samples immersed in a medium, which is the combination of salt and pH ranged from 300 Mpa to 307 Mpa for the first three weeks.
and was 201.94 Mpa for the samples which were immersed for full eight weeks. The yield strength obtained for one week, two weeks, and three weeks is 43% more when compared to yield strength under normal laboratory air conditions. For eight weeks of immersion yield strength was 5% less when compared to the yield strength under normal conditions in case of pH+Salt medium. The tensile strength of the samples for the first three weeks of immersion to the environment ranged from 625 to 635 Mpa and for eight weeks of exposure to the environment tensile strength was recorded as 373.20 Mpa. Ultimate strength reduced by 41% from first three weeks of exposure to eight weeks of exposure to the environment. The elongation was observed to be maximum for samples that were exposed for eight weeks samples where it elongated for almost 45%. The elongations for the first three weeks [i.e. one - week, two – weeks, three – weeks] of exposure to the environment ranged from 42% to 45% over the same gage length. The ultimate tensile strength was maximum for the samples which were immersed in the medium for one week revealed a decreasing trend for two weeks, three weeks, and eight weeks. This decrease in tensile strength for the eight week samples is due to the effect of salt NaCl and the acid used for the immersion sulfuric acid. Reduction in area was maximum in the eight weeks samples.

The effect of salt medium over the samples was quite similar to the effects observed in the pH and salt medium. The yield strength of the samples ranged from 298 Mpa to 308 MPa and tensile strength of the samples following eight week exposure was 27.4% less than the ultimate tensile strength under normal conditions. The elongation which directly represents the ductility factor of the samples was maximum for the samples that were immersed for eight week and was 49.8 mm. The elongation of the
eight week sample was 25% more than the elongation for one week two week and three weeks samples. The recorded values explains the samples becoming more ductile in eight weeks of exposure to the chosen environment when compared to first three weeks. A similar trend was shown by the samples in pH medium where yield strength was similar relative to each other for the first three weeks of exposure and ultimate tensile strength for the eight week samples was about 26% less than normal tensile strength. The elongation obtained for the eight week was about 99% for the gage length of 50.8 mm. Reduction in cross-section area was maximum among eight weeks sample for all the four mediums.

There was small deviation seen in the samples which were immersed in distilled water when compared to the other mediums. The tensile strength obtained for these samples was highest among all of the chosen mediums. The Elastic modulus of the samples ranged from 190 Gpa to 200 Gpa. The yield strength of the samples was similar to the yield strength obtained in the other mediums. The elongation of the samples which were immersed for eight full weeks in distilled water, was averaging around 47 mm over the gage length of 50.8 mm. The engineering stress versus engineering strain curves for 304L stainless steel samples, which was immersed in the four different medium for one week, two weeks, three weeks, and eight weeks are shown in Figures. The tensile properties of samples are summarized in Table 7.10 to Table 7.13.
Figure 7.34 Engineering stress versus strain curve for 304L stainless steel that was immersed in a pH+Salt medium for time span of four weeks at room temperature.
Figure 7.35  Engineering stress versus strain curve for 304L Stainless steel that was immersed in a salt medium for time span of four weeks at room temperature.
Figure 7.36: Engineering stress versus strain curve for 304L Stainless steel that was immersed in a pH medium time span of four weeks at room temperature.
Figure: 7.37 Engineering stress versus strain curve for 304L Stainless steel that was immersed in distilled water medium for time span of four weeks at room temperature.
Table 7.10: Compilation of the room temperature tensile properties of 304L Stainless steel which was immersed in pH+salt medium for four different weeks.

<table>
<thead>
<tr>
<th>Time</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks</td>
<td>GPa</td>
<td>MPa</td>
<td>MPa</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Week 1</td>
<td>199</td>
<td>306</td>
<td>634</td>
<td>45</td>
<td>32</td>
</tr>
<tr>
<td>Week 2</td>
<td>193</td>
<td>302</td>
<td>626</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>Week 3</td>
<td>195</td>
<td>300</td>
<td>630</td>
<td>43</td>
<td>34</td>
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<tr>
<td>Week 8</td>
<td>N/A</td>
<td>201</td>
<td>373</td>
<td>98</td>
<td>43</td>
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</tbody>
</table>

N/A – Not Available

Table 7.11: Compilation of the room temperature tensile properties of 304L stainless steel which was immersed in salt medium for four different weeks

<table>
<thead>
<tr>
<th>Time</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks</td>
<td>GPa</td>
<td>MPa</td>
<td>MPa</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Week 1</td>
<td>198</td>
<td>292</td>
<td>620</td>
<td>43</td>
<td>34</td>
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<tr>
<td>Week 2</td>
<td>194</td>
<td>308</td>
<td>631</td>
<td>41</td>
<td>35</td>
</tr>
<tr>
<td>Week 3</td>
<td>196</td>
<td>303</td>
<td>633</td>
<td>43</td>
<td>39</td>
</tr>
<tr>
<td>Week 8</td>
<td>N/A</td>
<td>179</td>
<td>373</td>
<td>98</td>
<td>44</td>
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</table>

N/A – Not Available
Table 7.12: Compilation of the room temperature tensile properties of 304L stainless steel which was immersed in pH medium for four different weeks.

<table>
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<th>Time</th>
<th>Elastic Modulus (GPa)</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks</td>
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<td></td>
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</tr>
<tr>
<td>Week 1</td>
<td>199</td>
<td>300</td>
<td>628</td>
<td>42</td>
<td>34</td>
</tr>
<tr>
<td>Week 2</td>
<td>195</td>
<td>306</td>
<td>628</td>
<td>42</td>
<td>33</td>
</tr>
<tr>
<td>Week 3</td>
<td>194</td>
<td>305</td>
<td>633</td>
<td>45</td>
<td>38</td>
</tr>
<tr>
<td>Week 8</td>
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<td>185</td>
<td>377</td>
<td>99</td>
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</table>

Table 7.13: Compilation of the room temperature tensile properties of 304L stainless steel which was immersed in Distilled water medium for four different weeks.

<table>
<thead>
<tr>
<th>Time</th>
<th>Elastic Modulus (GPa)</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 1</td>
<td>196</td>
<td>312</td>
<td>646</td>
<td>41</td>
<td>39</td>
</tr>
<tr>
<td>Week 2</td>
<td>199</td>
<td>319</td>
<td>646</td>
<td>45</td>
<td>37</td>
</tr>
<tr>
<td>Week 3</td>
<td>199</td>
<td>305</td>
<td>639</td>
<td>44</td>
<td>42</td>
</tr>
<tr>
<td>Week 8</td>
<td>190</td>
<td>186</td>
<td>364</td>
<td>91</td>
<td>46</td>
</tr>
</tbody>
</table>

Comparing the effect of four different medium for the one week samples it is seen that the samples which were immersed in distilled water had the maximum ultimate tensile strength and yield strength. The elastic modulus was ranged from 196 GPa to 199 GPa in all the four chosen mediums. There was 45% elongation over the gage length of 50.8mm in pH+Salt environment, which is maximum among all the four chosen mediums. Ductility which is direct measure for elongation was maximum in the pH+salt environment. Similar trend was followed in the samples, which were immersed in four
chosen mediums for two full weeks. Yield strength and ultimate tensile strength obtained was maximum for chosen samples that were immersed in distilled water. Elongation in the four chosen mediums ranged from 41% to 45% with maximum elongation occurring in distilled water medium. For the samples that were immersed in the four chosen mediums for three full weeks, the elastic modulus ranged from 194 GPa to 199 GPa. A similar trend was seen for three weeks sample with the samples immersed in distilled water having maximum ultimate strength and maximum yield strength. The elongation was recorded to be maximum for the samples immersed in distilled water. There was 75% elongation over the gage length of 50.8 mm. The effect of medium confirming salt and the acid was substantial when compared to distilled water. There was slight variation in the tensile properties of the samples for first three weeks of exposure and the values obtained where quite similar to each other. The samples which were immersed in the medium for full eight week revealed a significant reduction in the tensile and yield strength when compared to one week two weeks and three weeks. The tensile strength was ranged from 364 Mpa to 368 Mpa which was 41% less compared to the first three weeks. A similar reduction was seen in yield strength of the samples immersed in the four chosen medium for eight weeks. The elongation increased by 20% among the samples immersed for eight full weeks explaining the ductility of the material as a direct consequence of exposure to the chosen medium. Reduction in area was maximum in the distilled water medium four all four of weeks immersion. The engineering stress versus strain curves for the samples immersed in chosen mediums for a time span of one week, two weeks, three weeks, and eight weeks are shown in the Figures 7.38 to 7.41. The tensile properties are represented in Table 7.14 to Table 7.17.
Figure 7.38 Engineering stress versus strain curve for 304L stainless steel that was immersed in four different mediums for the span of one complete week at room temperature.
Figure 7.39: Engineering stress versus strain curve for 304L stainless steel that was immersed in four different mediums for a time span of two weeks at room temperature.
Figure 7.40 Engineering stress versus strain curve for 304L stainless steel that was immersed in four different mediums for time span of three weeks at room temperature
Figure 7.41  Engineering stress versus strain curve for 304L stainless steel that was immersed in four different mediums for time span of eight weeks at room temperature
Table 7.14: The tensile properties of 304L stainless steel immersed in the four different mediums for a time span of one full week.

<table>
<thead>
<tr>
<th>Environment Exposed</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation</th>
<th>Reduction In Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPa</td>
<td>MPa</td>
<td>MPa</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Salt + pH</td>
<td>199</td>
<td>306</td>
<td>634</td>
<td>45</td>
<td>32</td>
</tr>
<tr>
<td>Salt</td>
<td>198</td>
<td>298</td>
<td>620</td>
<td>43</td>
<td>34</td>
</tr>
<tr>
<td>pH</td>
<td>199</td>
<td>300</td>
<td>628</td>
<td>42</td>
<td>34</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>196</td>
<td>312</td>
<td>646</td>
<td>41</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 7.15: The tensile properties of 304L Stainless steel which was immersed in the four different mediums for a time span of two complete week

<table>
<thead>
<tr>
<th>Environment Exposed</th>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
<th>Tensile Strength</th>
<th>Elongation</th>
<th>Reduction In Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPa</td>
<td>MPa</td>
<td>MPa</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Salt + pH</td>
<td>193</td>
<td>302</td>
<td>626</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>Salt</td>
<td>194</td>
<td>308</td>
<td>631</td>
<td>41</td>
<td>35</td>
</tr>
<tr>
<td>pH</td>
<td>195</td>
<td>306</td>
<td>628</td>
<td>42</td>
<td>33</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>199</td>
<td>319</td>
<td>646</td>
<td>45</td>
<td>37</td>
</tr>
</tbody>
</table>
Table 7.16: The tensile properties of 304L stainless steel immersed in four different mediums for a time span of three complete week.

<table>
<thead>
<tr>
<th>Environment Exposed</th>
<th>Elastic Modulus GPa</th>
<th>Yield Strength MPa</th>
<th>Tensile Strength MPa</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt+pH</td>
<td>195</td>
<td>300</td>
<td>630</td>
<td>43</td>
<td>34</td>
</tr>
<tr>
<td>Salt</td>
<td>196</td>
<td>303</td>
<td>633</td>
<td>43</td>
<td>39</td>
</tr>
<tr>
<td>pH</td>
<td>194</td>
<td>305</td>
<td>633</td>
<td>45</td>
<td>38</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>199</td>
<td>305</td>
<td>639</td>
<td>44</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 7.17: The tensile properties of 304L stainless steel immersed in four different mediums for a time span of eight complete week.

<table>
<thead>
<tr>
<th>Environment Exposed</th>
<th>Elastic Modulus GPa</th>
<th>Yield Strength MPa</th>
<th>Tensile Strength MPa</th>
<th>Elongation (%)</th>
<th>Reduction In Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt+pH</td>
<td>197</td>
<td>201</td>
<td>373</td>
<td>98</td>
<td>43</td>
</tr>
<tr>
<td>Salt</td>
<td>194</td>
<td>179</td>
<td>373</td>
<td>98</td>
<td>44</td>
</tr>
<tr>
<td>pH</td>
<td>N/A</td>
<td>185</td>
<td>377</td>
<td>99</td>
<td>39</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>196</td>
<td>186</td>
<td>364</td>
<td>91</td>
<td>46</td>
</tr>
</tbody>
</table>

N/A- Not Available

7.3.2 Tensile fracture behavior

The tensile fracture surfaces of the stainless steel 304L and aluminum alloy 6061 which were immersed in four different were examined in a scanning electron microscope (SEM) to provide useful information relating to the specific role of intrinsic microstructural features and microstructural effects on strength, ductility and fracture properties of the metal.
Tensile fracture behavior of aluminum alloy 6061

The fracture surface features of aluminum alloy 6061, which was immersed in the salt medium for the span of 8 weeks where the pH was 5.23 and the conductivity was measured to be 26.4 ms/cm is shown in the Figure 7.42. The overall morphology of the failure is shown in (a). Higher magnification reveals clearly nature of the fracture with the transgranular region covered with dimples on the surface of the sample. The surface is microscopically rough covered with dimples. Higher magnification of the surface revealed an array of fine microscopic cracks. Higher magnification of region of overload revealed a population surface shows the population of voids and dimples. The microscopic voids are interdispersed with the dimples, which indicates the occurrence of ductile failure mechanisms.

The fracture surface features of aluminum alloy 6061, which was immersed in the distilled water medium for the span of 8 weeks where the pH was 4.60 and the conductivity was measured to be 0.0019 ms/cm, is shown in the Figure 7.43 Figure A shows the overall morphology of the surface giving hint about the rough surface of the sample. Higher magnification at (a) the transgranular region of the surface reveals a microscopically rough fracture surface. Higher magnification reveals the presence of dimples, microscopic cracks along with the microscopic voids. The region of overload revealed the cracks and voids to be interdispersed. The voids and dimples of varying sizes which are interdispersed with microscopic provides adequate evidence for the occurrence of locally ductile and brittle failure mechanism.
Figure 7.42  Scanning electron micrographs of the tensile fracture surface of aluminum alloy 6061-T6 sample that was exposed salt environment with a pH level of 5.23 and conductivity of 26.4 ms/cm, showing:
(a) Overall morphology of failure
(b) High magnification observation of the transgranular region showing a sizeable population of dimples and microscopically rough fracture surface.
(c) The region immediately prior to overload showing an array of fine microscopic cracks.
(d) Microscopic voids of varying size interdispersed with dimples on the overload fracture surface indicative of locally operating ductile failure mechanisms.
Figure 7.43. Scanning electron micrographs of the tensile fracture surface of aluminum alloy 6061-T6 sample that was exposed to distilled water environment with a pH level of 4.60 with a conductivity of 0.0019 ms/cm, showing:
(a) Overall morphology of failure
(b) High magnification observation of the transgranular region showing microscopically rough fracture surface.
(c) High magnification observation of (b) showing an array of fine microscopic cracks interdispersed with microscopic voids and dimples in the region of overload.
(d) The region of overload showing voids of varying size interdispersed with dimples and fine microscopic cracks features reminiscent of locally ductile and brittle failure mechanisms.
Tensile fracture behavior of 304L stainless steel

Scanning electron micrographs of the tensile fracture surface of 304L stainless immersed in a combination of pH and salt medium having pH of 3.08 and conductivity of 28 s/cm is shown in Figure 7.44. Scanning electron microscopy observation, conducted with care, caution revealed overall morphology of failure to be normal to far-field stress axis. Higher magnification shows the region of the overload and explains about transgranular failure of the surface. Up on higher permissible of Figure [b], it revealed the tensile fracture surface was covered with population of varying size. Higher magnification revealed that surface is filled with dimples of varying sizes interdispersed with microscopic voids in the region of the overload reminiscent of “locally” ductile failure mechanisms.

Scanning electron micrographs of the tensile fracture surface of 304 L stainless steel sample exposed to pH plus salt environment with a pH level of 3.08 and conductivity of 28 ms/cm is shown in Figure 7.45. Figure [a] revealed overall morphology and the failure normal to be far-field stress axis. Higher magnification revealed surface near overload was microscopically rough. At Higher magnification, presence of the microscopic cracks which are parallel to major stress axis are revealed. Figure (d) which is the higher magnification of (c) shows the presence of macroscopic cracks along with the voids and dimples of varying sizes. Dimples are voids are adjacent to the macroscopic cracks explaining ‘locally’ ductile and brittle failure mechanisms.

Scanning electron micrographs of the tensile fracture surface of 304 L stainless steel sample exposed to distilled water environment with a pH level of 4.43 and conductivity of 0.0055 ms/cm is shown in the Figure 7.46. Figure (a) explains overall
morphology of the sample. Higher magnification revealed presence of macroscopic cracks responsible for the separation of the region of the overload from the transgranular region. The region of tearing or overload failure revealed high population of voids which are of varying size intermingled with pockets of non-uniform size and shear shaped dimples responsible for covering the transgranular fracture region. The features observed at the higher magnifications of the scanning electron microscope, fine microscopic cracks, microscopic voids, and shear shaped dimples covering the overload fracture surface suggest the “locally” operating ductile mechanisms.

Scanning electron micrograph 304L stainless steel immersed in the salt medium where pH was recorded as 5.3 and conductivity was recorded as 33.6ms/cm is shown in Figure 7.47. Figure (a) explains overall morphology of failure normal to stress axis. Higher magnification of the figure (a) revealed the presence of macroscopic cracks responsible for the separation of transgranular region and the region of the overload. Figure (c) reveals the presence of macroscopic cracks surrounded with numerous dimples of varying sizes. Higher magnification reveals the region of overload explaining microscopic void coalescence to form a microscopic crack surrounded by shallow dimples.

Scanning electron micrographs of the tensile fracture surface of 304 L stainless steel sample exposed to pH medium having a pH level of 3.04 and conductivity being above bearing limit is shown in the Figure 7.48. Figure (a) revealed the overall morphology to be essentially transgranular. Higher magnification reveals the presence of dimples and explains about region of transgranular failure which was flat and covered with the distribution of dimples. Higher magnification of (b) reveals presence of dimples
of varying size and shape. Higher magnification is seen in [d], which revealed an adequate number of cracked second-phase particles intermingled between the growth and eventual coalescence of the finer microscopic voids to form a microscopic crack and dimples of varying sizes which covers the overload fracture surface indicating the locally ductile failure mechanism.
Figure 7.44. Scanning electron micrographs of the tensile fracture surface of 304 L stainless steel sample that was exposed to pH plus salt environment with a pH level of 3.08 conductivity of 28 mn/cm, showing:

(a) Overall morphology of failure normal to far-field stress axis
(b) High magnification observation of (a) showing the region of transgranular failure and overload
(c) High magnification observation of the transgranular region showing a sizeable population of shallow dimples of varying size.
(d) Dimples interdispersed with isolated fine microscopic voids in the region of overload reminiscent of locally ductile failure mechanisms
Figure 7.45. Scanning electron micrographs of the tensile fracture surface of 304 L stainless steel sample that was exposed to pH plus salt environment with a pH level of 3.08, conductivity of 28 ms/cm showing:

(a) Overall morphology of failure normal to far-field stress axis
(b) High magnification observation of (a) in the region immediately prior to overload showing microscopically rough fracture surface
(c) High magnification observation of (b) showing macroscopic cracking parallel to the major stress axis.
(d) An observable population of dimples of varying size interdispersed with fine microscopic voids immediately adjacent to macroscopic crack; features reminiscent of locally ductile and brittle failure mechanisms
Figure 7.46. Scanning electron micrographs of the tensile fracture surface of 304 L stainless steel sample that was exposed to distilled water environment with a pH level of 4.43 and conductivity of 0.0055 ms/cm, showing:
(a) Overall morphology of failure
(b) High magnification observation of (a) showing macroscopic crack separating the transgranular region from region of overload.
(c) An observable population of elongated shear-like dimples covering the transgranular fracture region.
(d) Microvoid coalescence and dimples of varying size covering the overload fracture surface reminiscent of locally ductile failure mechanisms
Figure 7.47. Scanning electron micrographs of the tensile fracture surface of 304 L stainless steel sample that was exposed to salt environment with a pH level of 5.3 and conductivity of 33.6 ms/cm, showing:
(a) Overall morphology of failure normal to stress axis.
(b) High magnification observation of (a) showing a macroscopic crack separating the transgranular region from the region of overload.
(c) The transgranular region at high magnification showing isolated macroscopic crack surrounded by an observable population of dimples of varying size and shape.
(d) The region of overload showing microscopic void coalescence to form a microscopic crack surrounded by shallow dimples.
Figure 7.48. Scanning electron micrographs of the tensile fracture surface of 304 L stainless steel sample that was exposed to pH with a pH level of 3.04, showing:

(a) Overall morphology of failure
(b) High magnification observation of (a) showing the region of transgranular failure to be essentially flat and covered with shallow dimples.
(c) High magnification observation of (b) showing the population of dimples to be of varying size and shape.
(d) Macroscopic and fine microscopic voids interdispersed with dimples of varying size covering the overload fracture surface indicative of locally operating ductile failure mechanisms.
CHAPTER VIII

CONCLUSIONS

In the detailed experiment study, pH and conductivity were recorded in two chosen mediums (Acid, Acid+Salt) where initial value of pH was 8.49 and Conductivity was Above detection limit for salt medium, and it was 3.05 and 31.2 ms/cm in case of Acid+Salt medium for aluminum alloy 7075 – T651 and alloy steel 4340 and the following are the key observations.

1) Conductivity level for (Acid+Salt) solution where impact samples of aluminum alloy 6061 were immersed was maximum for samples immersed for eight week and 73% greater than initial conductivity level explaining the formation of ions to be greater in the eighth week. Initial pH was recorded as 3.05 and pH level decreased from week # 1 to week # 8 explaining about the domination of salt in the medium (Acid+Salt) over sulphuric acid. The increase in time of immersion made the solution more alkaline.

2) Conductivity level for Salt medium was recorded to be at the highest for 8th week. Initial conductivity for salt medium was above detection limit to record. pH for the salt medium ranged from 9.4 to 9.7 whereas the initial pH was 8.6 which explains increase in alkalinity of the solution due to the presence of salt, similar to (Acid+salt) medium.
3) The pH level for the (Acid+Salt), where impact samples of alloy steel 4340 were immersed was at maximum in the first week. This implies that solution was acidic in the initial weeks [i.e. first week, second week, third week]. The solution became more alkaline in nature with the increase in time of immersion.

4) pH value obtained for salt medium where impact samples of alloy steel 4340 were immersed explained that influence of salt medium was more on aluminum alloy 7075 T651 samples when compared to alloy steel 4340 samples. Salt solution, where samples of alloy steel 4340 were immersed gave pH values ranging from 8.2 to 9.2 which is less when compared to pH values obtained from the salt solution where samples of aluminum alloy 6061-T6 were immersed.

5) Among the four chosen medium pH+Salt, pH, Salt and Distilled water where tensile samples of aluminum alloy 6061 were immersed. The conductivity was observed to be more in the two medium which had salt in it [i.e. pH+Salt, Salt]. The presence of salt lead to formation of the ions in the solution. At the same time, salt and distilled water mediums were slightly neutral compared to pH and pH+Salt medium. NaCL did not have a significant effect over the solution in which aluminum alloy 6061 tensile samples were immersed due to composition of the metal.

6) Similar results were obtained for solutions in which 304L stainless steel tensile samples were immersed. The solution was acidic throughout the span of 8 weeks in the pH+ Salt and pH medium. The other two solution were slightly acidic.
7) Charpy impact tests on alloy steel 4340 and aluminum alloy 7075 T651 were conducted at temperatures ranging from -190°C to +200°C. Alloy steel 4340 revealed an increase in energy absorbed with test temperature. At a given temperature there was decrease in the energy absorption of alloy steel samples immersed for eight weeks compared to samples immersed for four weeks.

8) At negative temperatures energy absorption of aluminum alloy 7075 was higher when compared to alloy steel regardless of the medium or the time of the immersion. The energy absorption of the aluminum alloy was relatively similar for all the test temperature explaining that there wasn’t any effect of the temperature over it. The energy absorption of aluminum alloy 7075 T651 in acid+salt mediums was higher for all the test temperature when compared to the salt medium for both samples immersed for four weeks and sample immersed for eight week.

9) In 8 weeks immersion alloy steel 4340 had higher energy absorption in acid+salt medium when compared to the salt medium for all the positive temperatures.

10) For a given sample of alloy steel 4340 or aluminum alloy 7075 the macroscopic fracture mode was flat at all of the test temperatures the surfaces were examined in the scanning electron microscope. At progressively higher magnification the fracture surface revealed a sizeable population of dimples which were intermingled with fine microscopic voids of varying shape along with isolated microscopic cracks, features reminiscent of both locally ductile failure mechanisms and brittle failure mechanism.

11) Over the entire range of test temperatures examined the overall fracture surface morphology and intrinsic microscopic features an observation on the fracture surface was found to be nearly identical for both the mediums.
Based on the detailed study aimed at understanding composition and processing influences on microstructural development, tensile properties and fracture behavior of 304L stainless steel and aluminum alloy 6061 T6, the following are the key findings:

12) The elastic modulus for 304L stainless steel ranged from 192 to 205 GPa for all the samples immersed in four chosen solutions for one week, two weeks, three weeks, and eight weeks. The yield strength was similar for the first three weeks and distilled water samples had a slightly higher yield strengths among the four mediums for first three weeks. Similar trend was seen in the ultimate tensile strength, where distilled water samples had higher ultimate tensile strength ranging from 640 to 646 Mpa.

13) The ductility quantified by elongation over 2 inch (50.8 mm) gage length ranged from 41 to 45% for all the samples which were immersed in different mediums for the first three weeks. There was not a significant change observed in the elongation of the samples which were immersed in the chosen medium for one week, two week and three weeks when compared to the samples which were not immersed in any medium for the same amount of time.

14) There was a substantial decrease in yield strength and ultimate tensile strength of the eight week samples in all the four mediums when compared to first 3 weeks samples. The reason being the effect of the corrosion on the samples but at the same time there was increase in the elongation of the eight week samples explaining the increased ductility of the steel samples due to the span of the immersion.

15) The elastic modulus of aluminum alloy 6061 T6 samples were ranging from 59 to 69 GPa. Ultimate tensile strength was marginally similar for first 3 weeks samples.
The yield strength was ranged from 192 to 220 Mpa and ultimate strength ranged from 284 to 295Mpa for the first three weeks samples.

16) There was 12 to 15% elongation for aluminum alloy 6061 T6 samples for the first three weeks comparatively was slightly less to the elongation of the samples which were not immersed in any medium. The elongation of eight weeks sample was slightly higher when compared to the first three weeks samples.

17) There was substantial decrease in the yield strength and the ultimate strength of the samples in the eight week justifying the effect of corrosion over the samples due to the span of the immersion.

18) For a given sample of 304l stainless steel or 6061-T6 aluminum presence of macroscopic voids and fine microscopic voids degrades the actual strain-to-failure associated with ductile fracture. These macroscopic and microscopic crack interdispersed with dimples and voids of varying sizes indicates local ductile failure.

19) Overall results obtained from research were that salt medium was more corrosive over Acid+salt medium. Steel was more corrosive resistant when compared to Aluminum and as expected distilled water medium was more corrosive resistant environment among all the four medium.
REFERENCES

1) P.P Milella, Fatigue and Corrosion in metals, 2013


8) Francois Ropital, Corrosion and degradation of Metallic Materials, IFP Publications, 2010


20) Gerd Brunner, Supercritical Fluid Science and Technology, Corrosion in hydrothermal and supercritical water, Volume-5, 2014.


59) ASM Aerospace specification metals Inc

60) Alstom


APPENDIX

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>196</td>
<td>303.81</td>
<td>635.13</td>
<td>42.04</td>
<td>46.2</td>
<td>39.56%</td>
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</tbody>
</table>

A.1 Engineering stress versus engineering strain curve for Sample # 7 of 304L stainless steel, exposed for 1 week to the medium of pH + salt at a pH level of 3.0
A.2 Engineering stress versus engineering strain curve for Sample #14 of 304L stainless steel sample that was exposed for 1 week to the medium of salt whose pH value was found to be 5.46
A.3 Engineering stress versus engineering strain curve for Sample#43 of 304L stainless steel that was exposed for one full week to environment of distilled water whose pH level was measured to be 5.49.
A.4 Engineering stress versus engineering strain curve for 304L stainless steel sample that was exposed for one full week to distilled water environment whose pH level was measured to be 5.49

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>196</td>
<td>306.77</td>
<td>632.56</td>
<td>43.33</td>
<td>43.75</td>
<td>41.15%</td>
</tr>
</tbody>
</table>
Sample #9

Exposure Time = 2 Weeks
T = 25°C
Medium = pH+Salt
pH = 2.99
Conductivity = ABL

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>195</td>
<td>306.51</td>
<td>625.45</td>
<td>42.24</td>
<td>41.5</td>
<td>39.81%</td>
</tr>
</tbody>
</table>

Engineering stress versus engineering strain curve for Sample #9 of 304L stainless steel sample that was exposed for two full week to a medium of salt+pH whose pH level was measured to be 2.99.
A.6 Engineering stress versus engineering strain curve of Sample # 11 of Stainless steel 304L that was exposed two full weeks to a medium of pH + salt whose pH level was measured to be 2.99.
A.7 Engineering stress versus engineering strain curve for Sample # 13 of Stainless steel 304L that was exposed two full weeks to a medium of salt whose pH level was measured to be 5.72
Engineering stress versus engineering strain curve for Sample # 18 of Stainless steel 304L that was exposed two full weeks to a medium of salt whose pH level was measured to be 5.72.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>190</td>
<td>316.01</td>
<td>643.59</td>
<td>42.93</td>
<td>45.2</td>
<td>38.59%</td>
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</table>

A.8
A.9 Engineering stress versus engineering strain curve for Sample # 23 of Stainless steel 304L that was exposed two full weeks to a medium pH whose pH level was measured to be 3.42
A.10 Engineering stress versus engineering strain curve for Sample # 24 of Stainless steel 304L that was exposed two full weeks to a medium pH whose pH level was 3.42
The stress versus engineering strain curve for Sample # 25 of Stainless steel 304L that was exposed two full weeks to distilled water environment whose pH level was measured to be 6.28.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>199</td>
<td>319</td>
<td>646.53</td>
<td>42.59</td>
<td>45.15</td>
<td>37.63%</td>
</tr>
</tbody>
</table>
Engineering stress versus engineering strain curve for Sample # 26 of Stainless steel 304L that was exposed two full weeks to a distilled water environment whose pH level was measured to be 6.92.
A.13 Engineering stress versus engineering strain curve for Sample # 2 of Stainless steel 304L that was exposed three full weeks to a medium of pH + salt whose pH level was measured to be 2.90
engineering stress versus engineering strain curve for Sample # 12 of Stainless steel 304L that was exposed three full weeks to a medium of pH + salt whose pH level was measured to be 2.91.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>197</td>
<td>309.24</td>
<td>626.56</td>
<td>42.92</td>
<td>41.35</td>
<td>36.36%</td>
</tr>
</tbody>
</table>
A.15 Engineering stress versus engineering strain curve for Sample # 38 of Stainless steel 304L that was exposed three full weeks to a pH medium of pH whose pH level was measured to be 3.37.
Engineering stress versus engineering strain curve for Sample # 40 of Stainless steel 304L that was exposed three full weeks to a pH medium whose pH level was measured to be 3.37.
Engineering stress versus engineering strain curve for Sample # 41 of Stainless steel 304L that was exposed three full weeks to a pH medium whose pH level was measured to be 3.37.

A.17

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>197</td>
<td>303.20</td>
<td>628.64</td>
<td>43.42</td>
<td>44.3</td>
<td>42.26%</td>
</tr>
</tbody>
</table>
A.18 Engineering stress versus engineering strain curve for Sample # 42 of Stainless steel 304L that was exposed three full weeks to a medium pH whose pH level was measured to be 3.37.
Engineering stress versus engineering strain curve for Sample # 06 of Stainless steel 304L that was exposed eight full weeks to a pH+Salt medium whose pH level was measured to be 6.9
Engineering stress versus engineering strain curve for Sample # 32 of Stainless steel 304L that was exposed eight full weeks to a Salt medium whose pH level was measured to be 6.3.
Engineering stress versus engineering strain curve for Sample # 35 of Stainless steel 304L that was exposed eight full weeks to a Salt medium whose pH level was measured to be 6.3

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>10</td>
<td>177.52</td>
<td>374.99</td>
<td>96.03</td>
<td>103.9</td>
<td>43.25%</td>
</tr>
</tbody>
</table>

A.21
A.22 Engineering stress versus engineering strain curve for Sample # 36 of Stainless steel 304L that was exposed eight full weeks to a Salt medium whose pH level was measured to be 6.3
Engineering stress versus engineering strain curve for Sample #05 of Stainless steel 304L that was exposed eight full weeks to a pH+Salt medium whose pH level was measured to be 6.9.
Engineering stress versus engineering strain curve for Sample #27 of Stainless steel 304L that was exposed eight full weeks to a Distilled water environment whose pH level was measured to be 7.14
A.25 Engineering stress versus engineering strain curve for Sample # 02 of aluminum alloy 6061-T651 that was exposed one full weeks to a pH+Salt medium whose pH level was measured to be 4.4
Sample # 3

Exposed Time = 1 Week
Medium = pH+Salt
T = 25°C
pH = 4.4
Conductivity = 22.5 ms/cm

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>60</td>
<td>194.26</td>
<td>292.82</td>
<td>13.94</td>
<td>12.5</td>
<td>25.19%</td>
</tr>
</tbody>
</table>

A.26 Engineering stress versus engineering strain curve for Sample # 03 of aluminum alloy 6061-T651 that was exposed one full weeks to a pH+Salt medium whose pH level was measured to be 4.4
Engineering stress versus engineering strain curve for Sample # 20 of aluminum alloy 6061-T651 that was exposed one full week to a pH medium whose pH level was measured to be 4.69.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>18</td>
<td>200.05</td>
<td>293.42</td>
<td>13.61</td>
<td>12.95</td>
<td>22.17%</td>
</tr>
</tbody>
</table>
Sample# 21

Exposed Time = 1 Week
Medium = pH
T = 25 °C
pH = 4.69
Conductivity = 0.0673ms/cm

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>10</td>
<td>196.26</td>
<td>291.82</td>
<td>13.20</td>
<td>12.9</td>
<td>24.19%</td>
</tr>
</tbody>
</table>

A.28 Engineering stress versus engineering strain curve for Sample # 21 of aluminum alloy 6061-T651 that was exposed for one full week to a pH medium whose pH level was measured to be 4.69.
Engineering stress versus engineering strain curve for Sample # 31 of aluminum alloy 6061-T651 that was exposed one full week to a medium of salt whose pH level was measured to be 6.05.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>62</td>
<td>206.97</td>
<td>290.76</td>
<td>13.40</td>
<td>13.9</td>
<td>29.39%</td>
</tr>
</tbody>
</table>
A.30 Engineering stress versus engineering strain curve for Sample # 33 of aluminum alloy 6061-T651 that was exposed one full week to a medium of salt whose pH level was measured to be 6.05
Engineering stress versus engineering strain curve for Sample # 44 of aluminum alloy 6061-T651 that was exposed one full week to distilled water environment whose pH level was measured to be 6.11.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>19</td>
<td>197.78</td>
<td>293.29</td>
<td>12.80</td>
<td>15.05</td>
<td>24.16%</td>
</tr>
</tbody>
</table>

A.31
A.32 Engineering stress versus engineering strain curve for Sample # 5 of aluminum alloy 6061-T651 that was exposed for two full weeks to medium of pH + salt whose pH level was measured to be 4.63.
53 Engineering stress versus engineering strain curve for Sample # 22 of aluminum alloy 6061-T651 that was exposed two full weeks to a pH medium whose pH level was measured to be 4.62.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>65</td>
<td>199.52</td>
<td>286.94</td>
<td>9.44</td>
<td>11.5</td>
<td>23.48%</td>
</tr>
</tbody>
</table>
Engineering stress versus engineering strain curve for Sample # 35 of aluminum alloy 6061-T651 that was exposed two full weeks to a medium of salt whose pH level was measured to be 6.14.
Engineering stress versus engineering strain curve for Sample # 36 of aluminum alloy 6061-T651 that was exposed for two full weeks to a medium of salt whose pH level was measured to be 6.14.
A.36 Engineering stress versus engineering strain curve for Sample # 7 of aluminum alloy 6061-T651 that was exposed for three full weeks to a medium of salt + pH whose pH level was measured to be 4.54.
A.37 Engineering stress versus engineering strain curve for Sample # 11 of aluminum alloy 6061-T651 that was exposed three full weeks to a medium of salt + pH whose pH level was measured to be 4.54

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>62</td>
<td>192.56</td>
<td>286.26</td>
<td>11.58</td>
<td>15.1</td>
<td>24.93%</td>
</tr>
</tbody>
</table>

Exposed Time = 3 Weeks  
Medium = pH+Salt  
T = 25 °C  
pH = 4.54  
Conductivity = 29.1 ms/cm
Engineering stress versus engineering strain curve for Sample # 12 of aluminum alloy 6061-T651 that was exposed for three full weeks to a medium of salt + pH whose pH level was measured to be 4.54.
Engineering stress versus engineering strain curve for Sample # 37 of aluminum alloy 6061-T651 that was exposed three full weeks to a pH medium whose pH level was measured to be 4.55.
Engineering stress versus engineering strain curve for Sample # 42 of aluminum alloy 6061-T651 that was exposed for three full weeks to a pH medium whose pH level was measured to be 4.55.
A.41 Engineering stress versus engineering strain curve for Sample # 17 of aluminum alloy 6061-T651 that was exposed for three full weeks to a Salt medium whose pH level was measured to be 6.12
Engineering stress versus engineering strain curve for Sample # 18 of aluminum alloy 6061-T651 that was exposed for three full weeks to a Salt medium whose pH level was measured to be 6.12.
Engineering stress versus engineering strain curve for Sample #16 of aluminum alloy 6061-T651 that was exposed for eight full weeks to a Salt medium whose pH level was measured to be 6.84.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>38</td>
<td>142.94</td>
<td>162.61</td>
<td>18.82</td>
<td>19.62</td>
<td>29.03%</td>
</tr>
</tbody>
</table>
A.44 Engineering stress versus engineering strain curve for Sample # 29 of aluminum alloy 6061-T651 that was exposed for eight full weeks in Distilled water environment whose pH level was measured to be 7.31
ing stress versus engineering strain curve for Sample # 41 of aluminum alloy 6061-T651 that was exposed for eight full weeks to pH medium whose pH level was measured to be 7.06

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% yield Stress (MPa)</th>
<th>Tensile Stress (MPa)</th>
<th>Failure Strain (%)</th>
<th>Total Elongation (%)</th>
<th>Reduction in Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>7</td>
<td>248.55</td>
<td>288.08</td>
<td>14.6</td>
<td>15.90</td>
<td>28.76%</td>
</tr>
</tbody>
</table>

Exposed Time = 8 Weeks
Medium = pH
Т = 25°C
pH = 7.06
Conductivity = 0.00627 ms/cm
Engineer stress versus engineering strain curve for Sample # 08 of aluminum alloy 6061-T651 that was exposed for eight full weeks in pH+Salt medium whose pH level was measured to be 7.04
A.47 Engineering stress versus engineering strain curve for Sample # 10 of aluminum alloy 6061-T651 that was exposed for eight full weeks in pH+Salt medium whose pH level was measured to be 7.04
A.48 Engineering stress versus engineering strain curve for Sample # 15 of aluminum alloy 6061-T651 that was exposed for eight full weeks in Salt medium whose pH level was measured to be 6.84