QUANTIFICATION OF CORROSION
IN 7075-T6 ALUMINUM ALLOY

by

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ABSTRACT

High strength aluminum alloys, such as 7075-T6, are widely used in aircraft structures due to their high strength-to-weight ratio, machinability, and low cost. However, due to their compositions, these alloys are susceptible to corrosion. Corrosion is a major concern involving the structural integrity of aircraft structures. Corrosion has been shown to reduce the life expectancy of these structures considerably. Aircraft, during normal operation, are subjected to natural corrosive environments due to temperature, humidity, rain, and seawater.

The objective of this research was to analyze the effects of corrosion on the static strength and fatigue life of 7075-T6 aluminum alloy. Test specimens were cut from flat sheets of aluminum and covered with masking material to restrict corrosion to a confined area. The corrosion process was accelerated by use of a galvanic corrosion cell. After corrosion, specimens were tested in tension and fatigue.

The effect of corrosion on the tensile strength resulted in a large initial drop in strength, then a linear reduction in strength as mass loss increased. The tensile strength was observed to reduce significantly at low mass loss levels. The reduction of fatigue life due to corrosion tended to follow an inverse exponential reduction as mass loss increased. Even small amounts of corrosion reduced the fatigue life of the aluminum alloy drastically.

An investigation was made of the specimen thickness after corrosion versus fatigue life. The thickness of the fatigue samples was measured at the thinnest area of the fracture surface using digital calipers. The thickness was also calculated assuming

uniform corrosion of the exposed area, therefore uniform reduction in thickness. The results were plotted for both means of thickness measurement. The fatigue life was found to reduce exponentially as thickness decreased similar to the trend observed from the mass loss analysis.

In addition to mechanical testing, a microstructure analysis was performed on samples cut from the corroded areas of untested and fatigue tested specimens. This analysis showed that corrosion existed in localized areas below the visible corrosion surface and may have been a factor in the formation of cracks. The topology of the pits, and the related subsurface damage produced areas of high stress concentration resulting in the immediate reduction of ultimate tensile strength and fatigue life.

Finite element analysis was investigated as an alternative means of quantification. Specimens were modeled and analyzed using I-Deas Master Series 7. Corrosion pits were modeled as elliptical voids on the surface of the specimen. The results of the finite element analysis showed that the modeled pits produced areas of high stress concentration as expected. Furthermore, the resulting stress concentration was found to be a function of the location of the pits within the gage area of the specimen.

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CHAPTER I

INTRODUCTION

1.1 Background

1.1.1 Galvanic Corrosion

Galvanic corrosion is a process involving two dissimilar metals in electrical contact with each other in an electrolytic solution. Corrosion is promoted by the potential difference that exists between the two metals, which produces a reduction-oxidation reaction (Chang, 1991). The more noble metal acts as the cathode, where it is reduced by some oxidizing specie, while the more active metal behaves as the anode and is the metal which corrodes. In addition, this corrosive process can be accelerated by applying an external voltage across the coupled metals which essentially increases the flow of electrons between the metals.

The galvanic corrosion experiment under investigation consists of 7075-T6 aluminum alloy in electrical contact with graphite submerged in an electrolytic seawater solution. The graphite acts as the cathode while the aluminum alloy behaves as the anode, and hence, corrodes. It should be noted that aluminum alloys are generally stable due to a thin protective oxide film or passivation layer which forms on the surface of the metal. This passivation layer reforms rapidly when the metal is scratched or damaged. However, in certain environments, such as seawater, this protective film may dissolve (Baboian, 1995). For seawater, the passivation layer breaks down due to the chloride ions present in the seawater and, as a result, will expose the aluminum and alloying elements to corrosion.

Constituent particles also play an important role in the process of corrosion. Constituent particles have been shown to behave either cathodic or anodic relative to the parent aluminum matrix. Anodic particles themselves corrode leaving a pit in the material where the element existed. On the other hand, cathodic elements induce corrosion of the surrounding aluminum. Corrosion of the aluminum continues until the cathodic element is separated from the aluminum matrix. As a result, for the same size element, a cathodic element will produce a larger pit than an anodic element.

1.1.2 Tensile Test Analysis

Tensile testing is a procedure in which a specimen is loaded quasi-statically to the point of fracture. During testing, the load applied to the specimen and the deformation experienced in the gage area of the test specimen are measured and recorded. Tensile tests are typically performed to determine specific properties of materials. The primary objective of the static tensile test is to obtain a stress-strain curve for the material being tested. Stress and strain are calculated from values recorded during testing. From the stress-strain curve many important properties can be obtained such as the modulus of elasticity, ultimate tensile strength, yield strength, fracture strength, and others (Smith, 1993).

1.1.3 Fatigue Test Analysis

Fatigue tests are performed to determine the number of cycles a material can withstand when subjected to a repeated loading generally below the yield strength of the material. Fatigue test can be performed by applying completely reversed stresses or by

tension-tension loading. A completely reversed stress is obtained when equal loads are applied in tension and compression, thus resulting in stresses equal in magnitude but opposite in sign. In addition, fatigue test may be performed by applying two different levels of tension. Typically, the results of fatigue tests are presented as a graph of alternating stress (S) versus number of cycles to failure (N) called an S-N curve (Bannantine, 1990). According to the S-N curve, materials can be designed to last a certain number of cycles, or they can be designed to last indefinitely.

1.2 Literature Review

A large amount of literature is available on the topics of corrosion detection in aluminum alloys, corrosion of aluminum alloys, and corrosion fatigue testing of aluminum alloys. A small sample of recent publications of research and developments in these areas will be discussed.

Early detection of corrosion in components and structures which experience fatigue is essential to prevent premature failure. This issue has been studied by many industries but most intensely in the aerospace industry.

Testing methods that are most attractive to the aerospace industry are nondestructive evaluation (NDE) techniques that reduce the down time of aircraft. This goal is achieved by minimizing disassembly at the time of scheduled maintenance checks. Green (1998) presented a review of emerging technologies for the NDE of aging aircraft. The author, among others, also outlined in situ NDE techniques that could be used to continuously monitor aging aircraft structures. He noted that NDE, due to their improving accuracy, will play a crucial role in the future. Recently, Crispim and

da Silva (1998) demonstrated that neutron radiographic images, produced with a suitable contrasting agent, have potential as an essential tool in the maintenance of aging aircraft in the future. A holistic approach on the maintenance of aging aircraft is presented by Feinberg *et al.* (1994). In the latter paper, the authors proposed a flexible framework to administer reliability-guided maintenance corrosion programs. This framework was developed for the corrosion simulation of aging aircraft which could be applied to structural failure prediction with some degree of certainty. Alodan and Mnyrl (1998) presented a method of employing confocal laser scanning microscopy in an in situ fluorescence mode to investigate localized corrosion of aluminum alloys. The authors used fluorescein dye to indicate pH changes and surface chemistry over and around active sites.

Among the different forms of corrosion, pitting is the form that is prevalent in aging aircraft, and is the main factor in most corrosion failures. Frankel (1998) offered a detailed review on the factors that play a crucial role in the onset of pitting corrosion of metal. The author presents a concise outline of the phenomenology and stages of pitting. Through investigation it has been shown that constituent particles play a significant role in the corrosion process of aluminum alloys. For example, Chen *et al.* In 1996, identified two types of constituent particles in the corrosion of 2024 T3 Aluminum in a 0.5 M NaCl Solution. Particles containing Al, Cu, Fe and Mn were found to act in a cathodic manner and promote matrix dissolution. Conversely, particles containing Al, Cu, and Mg displayed anodic behavior and dissolved showing preferential dissolution of Mg and Al. Liao *et al.* (1998) extended the investigation of constituent particles through in situ monitoring of the corrosion process of the same

aluminum alloy in the same aqueous solution. This study confirmed the importance of intermetallic constituent particles in the initiation and growth of pits. In addition, the formation of occluded cells under corrosion product domes over severe pits was observed. This observation was incorporated into modeling the process of pitting corrosion of aluminum alloys. Building on the previous research, Harlow and Wei (1998) presented a probabilistic model for the growth of corrosion pits in aluminum alloys in aqueous environments. The authors' purpose was to estimate the cumulative distribution function for the size of corrosion pits at a given time for use in multi-site damage and crack growth analyses.

There have also been numerous studies on the impact of corrosion on the fatigue properties of aircraft materials. The influence of corrosion on the fatigue life is central to the issues of aging aircraft. In studying the impact of corrosion on the fatigue properties of 7075-T6 aluminum alloy Du *et al.* (1998) demonstrated the extent of synergistic activity between corrosion and fatigue effects. In their study, the authors used the surface roughness as a revealing parameter in corrosion-fatigue interaction. Ma and Hoepfner (1994) addressed the issues pertaining to pitting formation and shape as it relates to crack nucleation. Fisher *et al.* (1998) extended the understanding of the impact corrosion has on crack development and fatigue life of structures. The function of the corrosion phenomena on the integrity of structural elements was outlined.

Among aircraft aluminum alloys, 7075-T6 is widely used due to its comparatively high strength per unit weight and high fracture toughness. However, due to its composition, this aluminum alloy is susceptible to corrosion. There have been several studies on the corrosion and corrosion fatigue of aircraft aluminum alloys. Chen

et al. (1994) presented an overview of such a comprehensive program. The authors presented tools that could be applied in formulating approaches for service life prediction. In a separate effort, Chen *et al.* (1996) investigated the transition from pitting to fatigue crack growth. The nucleation of fatigue cracks was found to be a competition between the rate of pitting and crack growth rate. Pitting was found to dominate the early stages until reaching a critical stress intensity factor after which corrosion fatigue crack growth dominates. [Recently, Lin and Yang (1998) carried out a study of the corrosion fatigue characteristics of 7050 aluminum alloy at various tempers. The authors demonstrated that higher tempers depicted a higher corrosion-fatigue-cracking resistance and stress-corrosion-cracking resistance.] Similarly, Chandhuri *et al.* (1994) compared the corrosion fatigue properties of different aircraft aluminum alloys. Intergranular corrosion was shown to be a factor in the fatigue life of the materials.]

In this thesis, the effects of corrosion on the static strength and fatigue life of 7075-T6 aluminum alloy are quantified on the basis of mass loss. In contrast to other research found in literature, this effort investigates the results of pre-existing corrosion, not the simultaneous interaction of corrosion and fatigue. The samples were first corroded, then removed from the corrosive environment and tested in fatigue and tension in air.

1.3 Motivation

As evident from the vast amount of information available, corrosion of aluminum alloys is an area of intense study and research. This is due largely in part to the fact that high strength aluminum alloys are widely used in the aircraft industry and in recent years many aircraft fleets are approaching, or exceeding, their design service life limit.

Among the issues facing aging aircraft, corrosion in combination with fatigue is extremely undesirable. Corrosion can reduce the life expectancy of aircraft structures considerably. Corrosion on aircraft can be attributed to natural environmental factors such as humidity, rain, temperature, and salt water. Because of this impact on the life of aging aircraft, there is a need to understand, quantify, and monitor the corrosion process, particularly as it relates to structural fatigue life.

There is need to quantify the effects of corrosion on the mechanical properties of AL 7075-T6. The quantification of mass loss, due to pitting corrosion, as a function of static strength and fatigue life could be a useful measure in the maintenance of aging aircraft. Funding for this research was provided by Raytheon Aircraft Integration Systems in Waco, TX. Raytheon performs maintenance and modifications on both military and commercial aircraft, therefore they face the problems of corrosion inherent with aging aircraft.

1.4 Objectives

The objective of this experiment was to quantify the effects of corrosion, based on mass loss, on the static strength and fatigue life of 7075-T6 aluminum alloy. To

obtain this objective, test specimens were cut from flat sheets of aluminum and covered with masking material to restrict corrosion to a confined area. The corrosion process was accelerated by use of a galvanic corrosion cell. After corrosion, specimens were tested in tension and fatigue. Specimens were corroded to mass loss levels of 0, 5, 10, 15, 20, 25, and 30%. Tensile and fatigue tests were performed on the corroded and uncorroded samples and the results were interpreted.

CHAPTER II

EXPERIMENTAL PROCEDURE

2.1 Corrosion of Specimens

2.1.1 Masking Selection

This experiment required only a small rectangular area on one side of the specimens to be corroded. Therefore, it was necessary for the remainder of the specimen to be protected from the corrosive environment by means of masking.

Many options were tested to find a suitable masking to protect the area of the specimens which was to remain uncorroded during immersion in the galvanic corrosion cell. The first material tested was Plasti Dip Spray-On Heavy Duty Flexible Rubber Coating. Samples were tested with several coats of Plasti Dip, but they all leaked around the edge of the exposed area on the sample.

Next, Nyalic polymer resin coating was tested, and also failed but in a different manner than the rubber coating. Nyalic failed in localized areas throughout the sample, whereas, the failure of the plastic coating was concentrated at the edge of the exposed area.

After several samples coated with Nyalic were tested and failed, corrosion resistant spray paint was tested. The corrosion resistant paint failed at the sharp edges of the samples and leaked at localized areas similar to the Nyalic coating.

The next masking tested was epoxy paint, which also failed by leaking at the edges of the exposed area. Finally, 3-M Corrosion Resistant Tape was tested and found to work well. The tape leaked slightly after long periods of submersion, but the leakage

only resulted in discoloration of the samples and no detectable corrosion beyond the specified area. Therefore, 3-M Corrosion Resistant Tape was used as the masking material.

2.1.2 Application of Masking

After the corrosion resistant tape was selected as the masking material to be used, a procedure for applying the masking to the samples was developed. Some difficulty was encountered in finding a suitable method of applying the tape to the sample.

First, the tape was applied in separate pieces which overlapped each other to produce the desired exposed area. This was found to induce leakage at the exposed area where the tape overlapped. Also, the top of the specimens were left unmasked to allow the connection of an alligator clip to connect the specimen to the power supply, which induced the voltage for galvanic corrosion. Since the top of the sample was not submerged, it was thought to be safe from corrosion, but this was proven to be false.

To correct the problems, the area to be exposed was cut out of the middle of the tape previous to applying it to the specimen, and the tape was extended to cover the whole specimen. The alligator clips were attached before the masking was applied, and the masking covered the alligator clips as well. This method of application corrected the previous problems.

The only remaining problem was the fact that some leakage occurred around the edge of the exposed area after long periods of submersion. The leakage did not result in corrosion but only in discoloration of the sample; therefore, the results were acceptable.

The area to be exposed was cut out of the tape by precisely measuring and marking the area on the tape and on the specimen. The area was then cut out of the center of the tape. The cut piece of tape was then applied to the front of the specimen, and the cut area of the tape was matched to the marked area on the specimen to ensure accuracy. Next, a continuous piece of tape was applied to the back of the specimen. The pieces of tape used were larger than the specimen in all directions. Since both pieces of tape overlapped they were adhered to each other thereby sealing the specimen from the corrosive environment. An example of a masked specimen can be seen in Figure 2.1.

2.1.3 Galvanic Corrosion Cell

Corrosion of the samples was accelerated by use of a galvanic corrosion cell. The corrosion cell consisted of 19-gallon plastic containers, salt water, a power supply, an anode, and a cathode as shown in Figure 2.2. The aluminum samples were used as the anode, graphite rods as the cathode, and salt water as the electrolyte to complete the cell. The salt water was produced by mixing Instant Ocean aquarium salt to distilled water. One-half cup of salt was added for each U.S. gallon of water. This resulted in water which closely simulated actual seawater. The specific gravity of the salt water was measured using an Aquarium System – Sea Test specific gravity meter. For each experiment, the specific gravity was found to be between 1.023 and 1.026, which correlates closely with natural seawater.

Figure 2.1 – Masked Specimen Showing Exposed Area to Be Corroded

(a)

(b)

Figure 2.2 – Galvanic Corrosion Cell: (a) Top View (b) Front View

The masked specimens were submerged vertically in the salt water and connected to the positive lead of the power supply. The graphite rods were submerged and connected to the negative lead. The power supply was used to apply an induced voltage across the corrosion cell, which varied from 750 to 850 mV. The setup is shown in Figure 2.2

2.1.4 Corrosion Rate Determination

In order to predict the time required to achieve target mass loss levels, several test samples were corroded for varying amounts of time and with different currents applied. The current and time of the samples were recorded for each test sample. These test samples were corroded previous to the corrosion of the specimens to be tested. The test samples used were small samples (2 inch by 6 inch) cut from the material supplied for the experiment and were not tested after corrosion. The test samples were used to test masking candidates as well as determine corrosion rates.

2.1.5 Corrosion

The specimens were submerged and allowed to corrode in the galvanic corrosion cell. Sixteen specimens were corroded at a time in four separate corrosion cells. This allowed for two control samples to be removed early from each cell to ensure mass loss rates experienced matched those predicted. During the corrosion process, the current supplied to each specimen was recorded daily to determine the mass loss rate.

As a result of corrosion, the graphite cathode experienced a buildup of material on the surface. This material was removed with a wire brush periodically to increase

current flow between the anode and cathode. The aluminum specimens themselves also experienced a buildup of material and were gently shaken periodically to remove the buildup. The buildup of material on both the anode and cathode was examined using X-ray diffraction in an effort to identify their compositions. X-ray diffraction showed the buildup material on both surfaces to be amorphous therefore no insight was gained as to the materials composition. It is speculated that the material at the anode surface is aluminum chloride and that the material at the cathode surface is aluminum hydroxide; however, further analysis is needed to verify this.

After a predicted amount of time, depending on the mass loss desired, the specimens were removed from the corrosion cell and were cleaned.

2.1.6 Cleaning

After removing the samples from the corrosion cell, the samples were unmasked and cleaned using a plastic bristle scrub brush to remove loose corrosion products. Next, the samples were cleaned by applying nitric acid, as specified by ASTM standards, ASTM G1 (1990), to the corroded area to further remove corrosion products. After cleaning, the samples were dried using a hair dryer and were then weighed.

2.1.7 Weighing

The samples were weighed using a Sartorius Analytic scale, model A 210P, with precision of 1/10000 of a gram. The weight of the samples was recorded before and after the corrosion process to obtain the difference in mass which was used in the calculation of percent mass loss. Prior to corrosion the samples were marked for

identification using a metal stamp. The specimens were stamped in the area to be gripped during testing, therefore the marking procedure did not affect the mechanical properties of the specimen in the tested region.

2.1.8 Percent Mass Loss Calculations

The percent mass loss for the samples was calculated using the difference in the uncorroded and corroded sample masses and the calculated mass of the original volume of exposed aluminum. The original mass of the exposed aluminum was calculated from the volume of the exposed area and the density of the 7075 T6 alloy. The following equation was used to determine the original mass of the exposed area:

$$M_o = (L * w * t) * \rho \quad (2.1)$$

where: M_o = original mass

L = length of exposed area

w = width of exposed area

t = thickness of exposed area

ρ = density of 7075 T6 aluminum (2.80 g/cm³ [Boyer, 1985]).

The percent mass loss was calculated by the following equation:

$$\% \text{Mass Loss} = (\Delta M / M_o) * 100 \quad (2.2)$$

Where: ΔM = change in mass

M_o = original mass.

2.2 Manufacturing of Specimens

2.2.1 Specimen Dimensions

As specified by Raytheon Systems, the test specimens were dog bone specimens 12 inches in length and 3 inches in width, with a gage area of 2.5 inches in length and 2 inches in width at the center as shown in Figure 2.3. The exposed corrosion area was to be 2.5 inches in length and 1.8 inches in width centered in the gage area on one side of the specimen. Samples were produced for 0, 5, 10, 15, 20, 25, and 30% mass losses. Fourteen samples were produced for each mass loss level. The specimens were further divided into seven tensile specimens and seven fatigue specimens for each mass loss level. A total of 98 samples were tested.

Figure 2.3 – Test Specimen Dimensions

2.2.2 Machining of Specimens

The materials used to manufacture the samples were 12 by 24 by 0.063 inch sheets of 7075 T6 aluminum alloy. First, each sheet was cut into eight rectangles, 12 inches by 3 inches. Next, the samples were stamped for identification, and the original weight was measured and recorded. After the samples were corroded to the desired mass loss and the corroded weight was measured and recorded, they were machined to the test size specified by Raytheon using a HAAS VF-3 Computer Numeric Control Mill (HAAS Automation, Inc. L.A., CA).

The reason for manufacturing the final shape after the corrosion process is due to masking requirements. As discussed earlier, the masking chosen was 3M Corrosion Resistant Tape; in order for the tape to have adequate adhesion to the sample around the exposed area, the extra space was needed between the exposed area and the edge of the sample. Had the specimens been machined first, there would have been only 1/10 inch space between the exposed area and the edge of the specimen which was found to be inadequate for proper masking adhesion. Prior to machining, there was a space of 3/5 inch on the sides of the exposed area, which provided adequate area for adhesion of the masking.

2.3 Tensile Test of Specimens

2.3.1 Setup

Tensile testing of the specimens was performed using a servo hydraulic material testing machine. The machine consisted of an MTS load frame (Minneapolis, MN) with Instron grips and hydraulics (Canton, MA). The testing system was controlled using a

desktop PC. The software used for signal control and data acquisition was Wavemaker- Runtime (Ver. 5.1) developed by Instron. In order to achieve quasistatic loading a slow rate of displacement, one millimeter per minute, was used. The values for the load, and strain were recorded for each test. The load was measured using an MTS load cell model 661.21A-02. The strain was acquired by means of an Instron extensometer attached to the gage area of the specimen during testing. The values recorded during the testing of the samples were used to generate stress strain curves for each of the samples tested.

2.3.2 Parameters

The samples were tested to failure for each level of mass loss. The uncorroded samples were tested to determine the ultimate tensile strength of the material. The tensile strength of the undamaged specimens was used in comparison with that of the corroded samples to determine the effects of corrosion on the reduction in tensile strength of the material.

2.3.3 Ultimate Strength Calculations

The ultimate tensile strength of the specimens was calculated using two area approximations. First, the ultimate tensile strength was calculated by dividing the maximum force obtained in the tensile test by the original cross sectional area of the specimen. Next, the ultimate tensile strength was calculated by dividing the maximum force by the effective cross sectional area of the specimen. The effective area of the

corroded specimens was approximated by assuming uniform corrosion of the exposed area and therefore uniform reduction in thickness as shown in Figure 2.4.

Figure 2.4 Corroded Specimen Effective Cross Sectional Area

The effective area of the corroded specimens was calculated using Equation 2.3:

$$A_e = (0.2 * t) + (M_o - \Delta M) (L * \rho) \quad (2.3)$$

where: A_e = effective area

t = thickness of specimen at uncorroded regions

M_o = original mass

ΔM = change in mass

L = length of exposed area

ρ = density of 7075 T6 aluminum (2.80 g cm³ [Boyer, 1985]).

The ultimate strength was then calculated using the following equations:

$$\sigma_{ut_o} = F_{max}/A_o \quad (2.4)$$

$$\sigma_{ut_a} = F_{max}/A_e \quad (2.5)$$

where: σ_{ut_o} = Ultimate strength assuming original cross sectional area

σ_{ut_a} = Ultimate strength assuming effective cross sectional area

F_{max} = Maximum force recorded during testing

A_o = Original cross sectional area

A_e = Effective cross sectional area.

2.4 Fatigue Test of Specimens

2.4.1 Setup

The material testing machine used for tensile testing, described earlier, was also used to conduct fatigue test. The same software was used for signal control and data acquisition. The fatigue tests were conducted at 10Hz with a range in load varying from 2000 lbf to 200 lbf. Using the control software, a load was applied first to a mean force level of 1100 lbf as a ramp function, then a sine wave function was applied with an amplitude of ± 900 lbf, which resulted in the desired range of 2000 to 200 lbf.

2.4.2 Parameters

Fatigue tests were first conducted on undamaged specimens. As specified by Raytheon, the undamaged samples were required to last a minimum of 3 million cycles.

All undamaged specimens lasted longer than necessary but were stopped soon after the maximum number of cycles was reached due to time constraints. Corroded samples were tested in order starting with 5% mass loss up to 30% mass loss. The machine used for tensile and fatigue testing of the samples is shown in Figure 2.5.

Figure 2.5 – Material Testing Machine

2.5 Thickness Measurement

After the samples were corroded it was noticed that the bottom edge of the specimens experienced the most severe corrosion. During testing, failure occurred most often at the bottom edge due to the fact that it had the thinnest cross sectional area. This prompted an investigation of fatigue life vs. thickness. The thickness was determined by two methods: direct measurement, and calculations based on mass loss. In order to determine the thickness by direct measurement, the corrosion product on the specimen was scraped away from a small spot on the fracture surface, and the resulting thickness was measured using vernier calipers. Thickness was also calculated by assuming uniform corrosion on the exposed surface and therefore a uniform reduction in thickness as seen in Figure 2.4. The estimated thickness was calculated using Equation 2.6:

$$t_{\text{calc}} = (M_o - \Delta M) / (w * L * \rho) \quad (2.6)$$

where: t_{calc} = effective thickness,

M_o = original mass

ΔM = change in mass

w = width of effective area.

L = length of exposed area

ρ = density of 7075 T6 aluminum (2.80 g/cm³ [Boyer, 1985]).

2.6 Microstructure Analysis

In order to investigate the grain structure of the material tested and subsurface damage due to corrosion, several specimens were prepared for metallurgical examination. Two specimens to be viewed were cut from the corroded area of untested samples. One section was cut along the X (horizontal) axis and one along the Y (vertical) axis as indicated in Figure 2.6. This was done to get a better picture of the pit topology. The samples were then mounted in a polymer resin such that the thickness could be viewed. Next, the samples were sanded and polished to a 0.1 micron finish using silicon carbide (SiC) sand paper and Lev Alumina abrasive particles. The samples were etched using Keller's reagent (2ml 48% HF, 3ml HCL, 5ml HNO₃, 190ml H₂O). The samples were then viewed using a metallograph, and photomicrographs were made of the samples for comparison and analysis. Next, a section was cut from a specimen that failed in fatigue. The sample was cut so that the length of the fracture surface could be viewed. The sample was prepared in the same manner as described previously, and a photomicrograph was made for analysis.

Figure 2.6 – Corroded Specimen Showing Reference Axes

CHAPTER III

RESULTS AND DISCUSSION

3.1 Mass Loss Results

The mass loss for each specimen was compared to the average current measured during corrosion multiplied by the time required for corrosion. The reason for multiplying the current by the time of corrosion is due to the difference in current for each specimen. Since the current varied for each specimen, the time required to obtain the same mass loss also varied. Multiplying the current by the time gave a consistent basis of comparison. The results are shown in Figure 3.1 and the tabulated data is included in Table A.1 in Appendix A. As seen from Figure 3.1, mass loss increases linearly as the product of current and time increases. This result was used to predict the time required to corrode test specimens to target mass loss levels.

Figure 3.1 Mass Loss versus (Current * Time)

3.2 Tensile Test Results

The tensile test results of samples tested at different mass loss levels due to corrosion are shown in Figure 3.2. In addition to Figure 3.2, the experimental data is included in Table A.2 and A.3 in Appendix A. The ultimate strength curves were calculated using the original non-corroded cross sectional area and the calculated effective cross sectional area, A_e . A comparison of the two curves shows that the values for the ultimate strength obtained from the effective area were higher than the strengths obtained from the original area calculations which is due to the fact that the effective area is smaller than the original area. As seen in this figure, there is a large initial drop in strength from the undamaged specimens to the 5% mass loss. For example, based on

original area, the difference in mean strength between the undamaged and 5% mass loss samples is approximately 20 Kpsi; and the difference between the 5 and 10% mass loss is approximately 4 Kpsi. After the 5% mass loss, the strength of the aluminum tends to reduce linearly with increasing mass loss. Table 3.1 shows the mean value and standard deviation for mass loss and ultimate strength at each percent corrosion level.

Figure 3.2 – Tensile Test Data

Table 3.1 – Tensile Test Summary

	% Mass Loss		Ultimate Strength (psi)			
			Original Area		Effective Area	
	<i>Mean</i> (%M.L.)	<i>Std Dev.</i> (%M.L.)	<i>Mean</i> (psi)	<i>Std Dev.</i> (psi)	<i>Mean</i> (psi)	<i>Std Dev.</i> (psi)
7S-00	0	0	87900	700	87900	700
7S-05	4.95	0.8	67750	2056	70905	2314
7S-10	9.58	1.1	63698	1836	69708	2288
7S-15	14.94	1.6	55154	2290	63731	1675
7S-20	20.53	2.4	42900	2779	52591	2325
7S-25	24.91	1.4	39899	1724	52073	1765
7S-30	30.13	1.8	36146	1731	49619	1926

During testing, it was noticed that the static samples failed most often along the bottom edge of the exposed corrosion area. This is thought to be due to the more severe corrosion, therefore thinner cross sectional area, observed at that location. This effect is more evident at higher mass losses which may be due to the increased exposure time required during corrosion.

3.3 Fatigue Test Results

The results of the fatigue test conducted on samples of different mass loss due to corrosion are shown in Figures 3.3, 3.4, and 3.5. The experimental data is also included in Table A.4 in Appendix A. As seen in Figure 3.3 the fatigue life of 7075-T6 reduces drastically beginning at low mass loss levels of 5%.

To further investigate the reduction of fatigue life, the results of the corroded samples were plotted without the presence of the results from the undamaged specimens, this is shown in Figure 3.4. As illustrated by Figure 3.4, the effect of corrosion tends to

follow an inverse exponential trend. More specifically, the difference in average cycles to failure from 5 to 15% mass loss is approximately 46000; whereas the difference in average cycles from 20 to 30% mass loss is approximately 3000.

To further illustrate the effects of corrosion on the reduction in fatigue life, a plot was made of the percent reduction in fatigue based on a safe fatigue life of 3 million cycles. The result of this comparison is presented in Figure 3.5. As indicated by Figure 3.5, as the mass loss increases the percent reduction in fatigue life increases Table 3.2 shows the mean value and standard deviation of mass loss and fatigue life for each percent corrosion level.

Figure 3.3 – Fatigue Test Data
(Undamaged and Corroded Specimens)

Figure 3.4 – Fatigue Test Data (Corroded Specimens Only)

Figure 3.5 – Percent Reduction in Fatigue Life Due to Corrosion

Table 3.2 – Fatigue Test Summary

	% Corrosion		Fatigue Life (cycles)	
	<i>Mean Value</i>	<i>Standard Deviation</i>	<i>Mean Value</i>	<i>Standard Deviation</i>
7F-00	0.00	0.0	3000801	531
7F-05	5.48	0.8	58904	20162
7F-10	10.52	1.1	47682	17553
7F-15	15.37	1.3	12685	7343
7F-20	21.12	1.5	6835	3731
7F-25	24.91	1.2	4148	1123
7F-30	30.13	1.2	3802	906

Small amounts of corrosion reduced the fatigue life of the aluminum drastically. For example, the average life of samples tested with 5% mass loss was 58904 cycles

which corresponds to approximately a 98% reduction in fatigue life compared to the undamaged samples which lasted 3 million cycles. This is a significant reduction in fatigue life even though the undamaged specimens were stopped soon after 3 million cycles and not tested to failure.

A trend observed from both the fatigue and tensile tests was that the specimens tended to fail along the bottom edge of the corrosion area. It was noticed that the bottom edge of the samples appeared to have the most severe corrosion. This trend prompted an investigation of fatigue life versus thickness. The thickness of the specimens was measured at the fracture surface. In addition, the thickness was calculated based on the mass loss as described previously. A plot was made of the cycles to failure versus thickness as shown in Figure 3.6. The X axis of Figure 3.6 begins at 0.063, the thickness of the specimen, and continues to 0.0. A thickness of 0.063 would indicate an undamaged specimen, or no reduction in thickness. (Tabulated results are included in Appendix, Table A.5.)

The measured thickness was consistently smaller than the calculated thickness. This is due to the fact that the calculated thickness was based on an average thickness across the width of the corroded area, while the measured thickness was taken at the edges of the fractured surface with the exfoliated surface removed before measurement. Nonetheless, the two curves still appear to follow a similar trend of inverse exponential decrease in fatigue life with decreasing thickness. These curves are consistent with Figure 3.4, which also shows an inverse exponential decrease in fatigue life with increasing mass loss.

Figure 3.6 – Failure versus Thickness Data

3.4 Microstructure Analysis Results

As described earlier, specimens were prepared for metallurgical examination. The resulting images of the samples cut from corroded areas of untested specimens are shown in Figures 3.7 (a) and (b). These figures show that the corrosion penetrates into the thickness of the metal deeper than can be seen at the surface. The resulting subsurface corrosion creates areas of high stress concentration and results in the reduction of strength and fatigue life. The section cut from the Y (vertical) axis shows an internal crack believed to be induced by corrosion in combination with residual stresses present in the test material. A detailed examination of the crack shows that it is

running along the grain boundaries and not across them. This observation indicates that this crack is corrosion induced.

(a)

(b)

Figure 3.7 – Microstructure of Corrosion Samples:
(a) Horizontal cut (100X); (b) Vertical Cut (200X)

The resulting image from the sample cut from the fracture surface of a fatigued specimen can be seen in Figure 3.8. A fatigue induced crack such as the one in Figure 3.8 runs across the grains and looks very different than the crack seen in Figure 3.7 (a).

Figure 3.8 – Microstructure of Fracture Surface (100X)

CHAPTER IV

FINITE ELEMENT ANALYSIS

4.1 Introduction

As stated previously, the objective of this research was to quantify the effects of corrosion on the mechanical properties of 7075 T6 aluminum. This was investigated experimentally on the basis of mass loss. However, as seen from the results, quantifying the effects of corrosion on the basis of mass loss is difficult.

It was noticed during the course of this research that most fatigue failures initiated at one large pit or a combination of pits, then propagated across the width of the specimen. The loss of material due to pitting creates an area of localized stress concentration. Due to these observations it is believed that pit depth, geometry and interaction are a factor in the reduction in static strength and fatigue life of the aluminum alloy. In order to model this phenomenon the use of finite element analysis was employed. In this research a "first step" was made in the development of a finite element model to study the stress concentrations due to pit location, depth, geometry, and interaction.

4.2 Software and Parameters

The software used for modeling and finite element analysis was I-Deas Master Series 7. Using the modeling function of the software, the test specimens were created according to dimensions reported earlier.

Corrosion pits were modeled as elliptical voids on the surface of the specimen. The pits were produced by creating an ellipse on the surface of the specimen and revolving it about its major axis to cut an elliptical void out of the surface. Due to this method of creation, the depth of the pits was equal to $\frac{1}{2}$ the minor axis of the ellipse. The pit size was determined according to this factor. The depth of the pit desired was $\frac{1}{4}$ of the thickness of the specimens tested (0.01575 in), thus the minor axis of the pits were $\frac{1}{2}$ the thickness of the specimen (0.0315 in). The ratio of major to minor axes used was 2 to 1; therefore, the major axis of the pit was equal to the thickness of the specimen (0.063 in).

The pits were arranged within the gage area of the specimen in several configurations in order to determine the effects of location on the resulting stress concentration induced by the pit(s). First, a single pit was modeled in the center of the gage area. This was done for simplicity and used as a reference for comparison. Next, a specimen was created with a pit at an off-center location.

In addition, a specimen was modeled having two pits of the same size to further investigate the dependence of pit location on stress concentration. The two pits were placed at random locations in the gage area of the specimen. It should be noted that all pits were arranged such that their major axis was perpendicular to the loading axis. This orientation results in the greatest stress concentration experienced by the pit.

After the modeling of the specimens was complete, a finite element analysis was performed to calculate the stress concentration of the modeled pits. Using the finite element function of I-Deas, the appropriate boundary conditions were applied, the volume was meshed, and the resulting solutions were calculated.

The boundary conditions applied to the specimen were modeled to simulate the loading experienced by the specimens during actual tensile and fatigue testing. To accomplish realistic loading, one surface perpendicular to the loading axis was constrained in all directions (fixed), while a negative pressure was applied to the other surface perpendicular to the loading axis. A total force of 2000 lbf tension was applied to the surface which resulted in a pressure of approximately -10.6 Kpsi. The pressure applied to the surface was negative in order to load the specimen in tension. The total force, 2000lbf, was selected because it was the maximum force experienced in fatigue testing.

After boundary conditions were applied, the sample was meshed. A volume mesh was selected in order to obtain the stress variation throughout the thickness of the specimen. A parabolic tetrahedron element was used in order to give accurate results. An element length of 0.25 in. was selected for the meshing procedure to provide a fine enough mesh to yield accurate results. I-Deas allowed only limited control of the meshing process; therefore, the number, depth, and location of pits was restricted to those found to mesh without error.

4.3 Results and Discussion

The results of the finite element analysis performed on specimens with various pit locations and configurations are shown in Table 4.1. The stress variations of the specimens analyzed are also illustrated in Figures 4.1 through 4.8. As mentioned previously, the load applied to the specimens was 2000 lbf. This resulted in a theoretical

stress of approximately 15.9 Kpsi in the gage area of the specimens, not accounting for stress concentrations.

Table 4.1 – Finite Element Stress Analysis Results

Pit Orientation	Stress Calculated	von Mises Stress	Sigma X
No Pits	Max in Specimen	18.5	19.1
1 Pit (Center)	Max in Specimen	18.5	18.7
	Max at Pit	17.1	17.4
		15.8	16.1
1 Pit (Off Center)	Max in Specimen	18.4	18.6
	Max at Pit	17.1	17.4
		15.8	16.3
2 Pits	Max in Specimen	19.9	18.9
	Max at Pit 1	19.9	21.9
		18.4	20.4
	Max at Pit 2	16.9	17.5
		15.4	16

As seen from Table 4.1, the difference in maximum stress observed for the specimen with one centrally located pit does not differ significantly from the specimen with a pit off center. However, since only a range of stresses is known for the elements, it is not possible to determine if there is indeed a difference between the actual values of the elements. On the other hand, there is a noticeable difference in the values of the maximum stress observed in the specimen modeled with two pits. The difference between pit one and pit two is definite since the range of the maximum stress for pit one does not overlap the range of maximum stress for pit two in either the von Mises stress or the sigma X stress results. Due to this fact, it is concluded that the stress concentration induced by the pit is dependent on its location in the gage area.

Figure 4.1 – F. E. A. of Specimen With no Flaw
 von Mises Stress Results (Isometric View)

Figure 4.2 – F. E. A. of Specimen With no Flaw
Sigma X Stress Results (Isometric View)

Figure 4.3 – F. E. A. of Specimen With Central Flaw
 von Mises Stress Results (Enlargement of Gage Area)

Figure 4.4 – F.E.A. of Specimen With Central Flaw
 Sigma X Stress Results (Enlargement of Gage Area)

Figure 4.5 – F.E.A. of Specimen With Off Center Flaw
 von Mises Stress Results (Enlargement of Gage Area)

Figure 4.6 - F. E. A. of Specimen With Off Center Flaw
 Sigma X Stress Results (Enlargement of Gage Area)

Figure 4.7 – F.E.A. of Specimen With Two Flaws
 von Mises Stress Results (Enlargement of Gage Area)

Figure 4.8 – F.E.A. of Specimen With Two Flaws
 Sigma X Stress Results (Enlargement of Gage Area)

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions were found:

1. Corrosion reduced the ultimate strength of the aluminum alloy considerably, even at low mass loss.
2. After corrosion is initiated there appears to be a linear decrease in strength with increasing mass loss.
3. The fatigue life appears to follow an inverse exponential reduction in life as mass loss increases.
4. Similarly, the fatigue life decreases in an inverse exponential fashion with decreasing thickness.
5. Small amounts of corrosion reduce the fatigue life of the aluminum alloy significantly.
6. Specimens tended to fail more often at the bottom edge of the exposed area in fatigue and tension due to more severe corrosion, which resulted in a thinner cross sectional area, experienced at that location. This was more evident at higher mass losses.
7. Localized areas of corrosion existed below the visible corrosion surface.
8. The finite element analysis of specimens with pits modeled as elliptical voids showed evidence of the resulting stress concentration to be location dependent.

5.2 Improvements and Recommendations

The following improvements and recommendations are suggested for further investigation:

1. Due to the dramatic reduction in fatigue life resulting at 5%, further investigations of the effects of corrosion should be restricted to mass loss ranges less than 5%.
2. Investigating other types of accelerated corrosion may produce more uniform corrosion and not result in increased corrosion at the edges of the exposed area as seen in this experiment. However, other types of accelerated corrosion may yield different results.
3. Mass measurements may be inaccurate due to the fact that an exfoliation layer existed even after chemical cleaning. Investigating a different method of calculating mass loss may produce more precise results.
4. Pre-test (static and or fatigue) micro-structural examination of some corroded samples should be preformed to study further possibility of sub-surface fracture due to the corrosion process.
5. An investigation should be made to determine the role of residual stresses, in combination with pitting, in the formation of subsurface cracks.
6. Further development of the finite element model should be made. Using a more flexible finite element package would allow better modeling and analysis of pit depth, geometry and interaction.

REFERENCES

1. ASM Handbook, Vol. 13 *Corrosion*, 1987. ASM International, U.S.A.
2. ASTM G 1-90 Standard. 1994. *Standard Practice for Preparing Cleaning, and Evaluating Corrosion Test Specimens*. American Society for Testing and Materials, Philadelphia, PA.
3. ASTM G 31-72. Standard. 1994. *Standard Practice for Laboratory Immersion Corrosion Testing of Metals*. American Society for Testing and Materials, Philadelphia, PA.
4. Agarwala, V. S., and Ugiansky, G. M., (Ed.). 1992, *New Methods for Corrosion Testing of Aluminum Alloys*. American Society for Testing and Materials, Philadelphia, PA.
5. Askeland, D. R., 1994, *The Science and Engineering of Materials*. 3rd Edition. PWS Publishing Company. Boston, MA.
6. Baboian, R., (Ed.). 1995. *Corrosion Tests and Standards: Application and Interpretation*, ASTM Manual Series: MNL 20, American Society for Testing and Materials, Philadelphia, PA.
7. Bannantine, J. A., Comer, J. J., and Handrock, J. L., 1990, *Fundamentals of Metal Fatigue Analysis*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
8. Boyer, H. E., and Gall, T. L., (Ed.), 1985. *Metals Handbook: Desk Edition*, American Society for Metals, Metals Park, Ohio.
9. Callster, W. D. Jr., 1997. *Materials Science and Engineering an Introduction*. 4th Edition. John Wiley & Sons, Inc., New York.
10. Chang, R., 1991. *Chemistry*. 4th Edition. McGraw-Hill Inc., New York.
11. Chaudhuri, J., Tan, Y. M., Gondhalekar, V., and Patni, K. M., 1994, "Comparison of Corrosion-Fatigue Properties of Precorroded 6013 Bare and 2024 Bare Aluminum Alloy Sheet Materials," *Journal of Materials Engineering and Performance*. Vol.3 pp. 371-377.
12. Chen, G. S., Gao, M., and Wei, R. P., "Microconstituent – Induced Pitting Corrosion in Aluminum Alloy 2024-T3," *The Journal of Science and Engineering – Corrosion*. Vol. 52, No.1, pp.8-15.

13. Chen, G. S., Wan, K. C., Gao, M., Wei, R. P., and Flournoy, T. H., 1996, "Transition from pitting to fatigue crack growth – modeling of corrosion fatigue crack nucleation in a 2024-T3 aluminum alloy." *Materials Science and Engineering. A. Structural Materials: Properties, Microstructure and Processing*, Vol. 219, No.1-2, pp. 126-132
14. Chen, G. S., Gao, M., Harlow, D. G., and Wei, R. P., 1994, "Corrosion and Corrosion Fatigue of Airframe Aluminum Alloys," *NASA Conference Publication*, No. 3274/P1, pp. 157-173.
15. Crispim, V. R., and da Silva, J. J., G., 1998, "Detection of Corrosion in Aircraft Aluminum Alloys," *Applied Radiation and Isotopes*, Vol. 49, No. 7., pp. 779-782.
16. Crooker, T.W., and Leis, B.N., (Ed.), 1983, *Corrosion Fatigue – Mechanics, Metallurgy, Electrochemistry, & Engineering*, ASTM, Baltimore, MD.
17. Du, M. L., Chiang, F. P., Kagwade, S. V., and Clayton, C. R., 1998, "Influence of Corrosion on the Fatigue Properties of Al 7075-T6," *Journal of Testing and Evaluation*, Vol. 26, No. 3, pp. 260-268.
18. Du, M. L., Chiang, F. P., Kagwade, S. V., and Clayton, C. R., 1998, "Damage of Al 2024 alloy due to sequential exposure to fatigue, corrosion and fatigue," *International Journal of Fatigue*, Vol. 20, No. 10, pp. 743-748.
19. Elboujdaini, M., Shehata, M. T., and Ghali, E., 1998, "Stress Corrosion Cracking and Corrosion Fatigue of 5083 and 6061 Aluminum Alloys," *Microstructural Science*, Vol. 25, pp. 41-49.
20. Feinberg, A. A., Gibson, G. J., White, J. V., and Briggs, R. E., 1994, "A Corrosion Simulation Environment for Maintenance of Aging Aircraft," *Proceedings – Institute of Environmental Sciences*, Vol. 40, pp. 198-210.
21. Fisher, J. W., Kaufmann, E., and Pense, A. W., 1998, "Effect of Corrosion on Crack Development and Fatigue Life," *Transportation Research Record*, No. 1624, pp. 110-117.
22. Frankel, G. S., 1998, "Pitting Corrosion of Metals," *Journal of the Electrochemical Society*, Vol. 145, No.6, pp. 2186-2198.
23. Green, R. E., 1998, "Emerging Technologies for NDE of Aging Aircraft Structures," *Materials Research Society Symposia Proceedings*, Vol. 503, pp. 3-14.

24. Hack, H. P., (Ed.). 1988, *Galvanic Corrosion*. American Society for Testing and Materials, Philadelphia, PA.
25. Harlow, D. G., and Wei, R. P., 1998, "A Probability Model for the Growth of Corrosion Pits in Aluminum Alloys Induced by Constituent Particles," *Engineering Fracture Mechanics*, Vol. 59, No. 3 pp. 305-325.
26. Liao, C. M., Olive, J. M., Gao, M., and Wei, R. P., "In-Situ Monitoring of Pitting Corrosion in Aluminum Alloy 2024," *The Journal of Science and Engineering - Corrosion*, Vol. 54, No. 6, pp. 451-458.
27. Lin, C. K., and Yang, S. T., 1998, "Corrosion Fatigue Behavior of 7050 Aluminum Alloys in Different Tempers," *Engineering Fracture Mechanics*, Vol. 59, No. 6, pp. 779-795.
28. Ma, L., and Hoepfner, W., 1994, "The Effects of Pitting on Fatigue Crack Nucleation in 7075-T6 Aluminum Alloy," *NASA Conference Publication*, No. 3274/P1, pp. 425-440.
29. Maher, A. A., and Smyrl, W. H., 1998, "Detection of Localized Corrosion of Aluminum Alloys Using Fluorescence Microscopy," *Journal of Electrochemical Society*, Vol. 145, No. 5, pp.1571-1577.
30. Mansfeld, F., (Ed.), 1987, *Corrosion Mechanisms*, Marcel Dekker, Inc. New York
31. Marcus, P., and Oudar, J., (Ed.), 1995, *Corrosion Mechanisms in Theory and Practice*, Marcel Dekker, Inc., New York.
32. Patton, G., Rinaldi, C., Brechet, Y., Lormandi, G., and Fourgeres, R., 1998, "Study of fatigue damage in 7010 aluminum alloy," *Materials Science and Engineering. A. Structural materials properties, microstructure and processing*, Vol. 254, No. 1, pp. 207-218
33. Smith, W. F., 1993, *Foundations of Materials Science and Engineering*, 2nd Edition, McGraw-Hill Inc., New York.
34. Wang, L., Chow, W. T., Kawai, H., and Atluri, S. N., 1998, "Predictions of Widespread Fatigue Damage Thresholds in Aging Aircraft," *ALAA Journal*, Vol. 36, No. 3, pp. 457-464.
35. West, J. M., 1986, *Basic Corrosion and Oxidation*, 2nd Edition., John Wiley & Sons, New York.

APPENDIX – TABULATED DATA

Table A.1 – Mass Loss, Current and Time Data

mass loss (%)	current (A)	time (hrs)	current*time (A*hrs)
13.99	0.0126	284	3.5784
16.62	0.016	288	4.608
14.49	0.0115	284	3.266
15.96	0.0119	284	3.3796
16.63	0.0141	288	4.0608
13.49	0.0148	216	3.1968
16.39	0.0156	288	4.4928
19.19	0.0148	284	4.2032
19.68	0.0169	282	4.7658
22.06	0.0174	288	5.0112
20.1	0.0172	288	4.9536
21.79	0.0182	288	5.2416
23	0.0137	280	3.836
22.08	0.0219	238	5.2122
23.04	0.0192	288	5.5296
24.3	0.0198	288	5.7024
24.64	0.0215	288	6.192
26.88	0.0253	238	6.0214
25.59	0.0253	238	6.0214
25.3	0.0258	238	6.1404
24.59	0.0256	238	6.0928
31	0.0255	288	7.344
28.53	0.0257	288	6.8256
30	0.0252	288	7.2576
30.05	0.0119	619	7.3661
32.06	0.0134	594	7.9596
30.15	0.0108	688	7.4304
29.11	0.0107	689	7.3723
15.38	0.0124	284	3.5216
12.16	0.0101	284	2.8684
13.63	0.0104	284	2.9536
15.45	0.0138	284	3.9192
16.66	0.0138	284	3.9192
16.74	0.0149	288	4.2912
21.31	0.026	193	5.018
17.74	0.0146	288	4.2048
22.74	0.0227	238	5.4026
22.92	0.023	238	5.474
17.04	0.0101	283	2.8583
19.52	0.0239	238	5.6882
22.37	0.0227	238	5.4026
24.33	0.0198	288	5.7024
23.95	0.0202	288	5.8176
24.12	0.0198	288	5.7024
24.33	0.0249	238	5.9262
27.36	0.0264	238	6.2832
26.29	0.0261	238	6.2118
23.98	0.0237	238	5.6406
28.37	0.0226	288	6.5088
28.52	0.0244	288	7.0272
29.76	0.0123	595	7.3185
31.41	0.0131	594	7.7814
30.69	0.0127	595	7.5565
33.23	0.0139	593	8.2427

Table A.2 – Tensile Test Data: Original Area

7S-00				7S-20			
<i>Specimen</i>	<i>% Corrosion</i>	<i>Ult. Strength</i>	<i>Mod. of Elasticity</i>	<i>Specimen</i>	<i>% Corrosion</i>	<i>Ult. Strength</i>	<i>Mod. of Elasticity</i>
7S-00-01	0	88600	N/A	7S-20-01	21.31	43392	7260000
7S-00-02	0	87200	N/A	7S-20-02	17.74	47857	8670000
7S-00-03	0	87900	N/A	7S-20-03	22.79	41278	8540000
7S-00-04	N/A	N/A	N/A	7S-20-04	22.92	40437	7280000
7S-00-05	N/A	N/A	N/A	7S-20-05	17.04	45265	8640000
7S-00-06	N/A	N/A	N/A	7S-20-06	19.52	41423	7980000
7S-00-07	N/A	N/A	N/A	7S-20-07	22.37	40650	10600000

7S-05				7S-25			
<i>Specimen</i>	<i>% Corrosion</i>	<i>Ult. Strength</i>	<i>Mod. of Elasticity</i>	<i>Specimen</i>	<i>% Corrosion</i>	<i>Ult. Strength</i>	<i>Mod. of Elasticity</i>
7S-05-01	4.76	71340	9260000	7S-25-01	24.33	39684	7900000
7S-05-02	4.21	68743	9840000	7S-25-02	23.95	42435	8430000
7S-05-03	4.92	66153	9130000	7S-25-03	24.12	38367	7910000
7S-05-04	3.8	65935	9480000	7S-25-04	24.33	40586	7650000
7S-05-05	5.2	65913	8950000	7S-25-05	27.36	37149	9110000
7S-05-06	5.33	67073	10100000	7S-25-06	26.29	40259	8150000
7S-05-07	6.4	69092	9650000	7S-25-07	23.98	40816	7370000

7S-10				7S-30			
<i>Specimen</i>	<i>% Corrosion</i>	<i>Ult. Strength</i>	<i>Mod. of Elasticity</i>	<i>Specimen</i>	<i>% Corrosion</i>	<i>Ult. Strength</i>	<i>Mod. of Elasticity</i>
7S-10-01	9.09	60548	8710000	7S-30-01	28.37	37621	6770000
7S-10-02	10.85	62470	8550000	7S-30-02	28.52	37501	7370000
7S-10-03	9.86	64488	8740000	7S-30-03	29.76	33857	7180000
7S-10-04	9.49	63516	9040000	7S-30-04	31.41	34155	6830000
7S-10-05	10.49	65145	8780000	7S-30-05	30.69	36420	7250000
7S-10-06	7.54	63566	8780000	7S-30-06	33.23	35322	7100000
7S-10-07	9.72	66153	10600000	7S-30-07	28.9	38148	7580000

7S-15			
<i>Specimen</i>	<i>% Corrosion</i>	<i>Ult. Strength</i>	<i>Mod. of Elasticity</i>
7S-15-01	14.57	55424	8020000
7S-15-02	15.38	54325	8470000
7S-15-03	12.16	59511	12000000
7S-15-04	13.63	56204	9030000
7S-15-05	15.45	53970	N/A
7S-15-06	16.66	52201	7760000
7S-15-07	16.74	54446	7820000

Table A.3 – Tensile Test Data: Effective Area

7S-00				7S-20			
<i>Specimen</i>	<i>Corrosion</i>	<i>Eff. Area</i>	<i>Ult. Strength</i>	<i>Specimen</i>	<i>Corrosion</i>	<i>Eff. Area</i>	<i>Ult. Strength</i>
	%	in ²	psi		%	in ²	psi
7S-00-01	0	0.126	88600	7S-20-01	21.31	0.102	53691
7S-00-02	0	0.126	87200	7S-20-02	17.74	0.106	56948
7S-00-03	0	0.126	87900	7S-20-03	22.79	0.100	51932
7S-00-04	N/A	N/A	N/A	7S-20-04	22.92	0.100	50944
7S-00-05	N/A	N/A	N/A	7S-20-05	17.04	0.107	53468
7S-00-06	N/A	N/A	N/A	7S-20-06	19.52	0.104	50253
7S-00-07	N/A	N/A	N/A	7S-20-07	22.37	0.101	50899

7S-05				7S-25			
<i>Specimen</i>	<i>Corrosion</i>	<i>Eff. Area</i>	<i>Ult. Strength</i>	<i>Specimen</i>	<i>Corrosion</i>	<i>Eff. Area</i>	<i>Ult. Strength</i>
	%	in ²	psi		%	in ²	psi
7S-05-01	4.76	0.121	74534	7S-25-01	24.33	0.098	50808
7S-05-02	4.21	0.121	71452	7S-25-02	23.95	0.099	54096
7S-05-03	4.92	0.120	69216	7S-25-03	24.12	0.099	49007
7S-05-04	3.8	0.122	68269	7S-25-04	24.33	0.098	51966
7S-05-05	5.2	0.120	69150	7S-25-05	27.36	0.095	53846
7S-05-06	5.33	0.120	70451	7S-25-06	26.29	0.096	52739
7S-05-07	6.4	0.119	73266	7S-25-07	23.98	0.099	52048

7S-10				7S-30			
<i>Specimen</i>	<i>Corrosion</i>	<i>Eff. Area</i>	<i>Ult. Strength</i>	<i>Specimen</i>	<i>Corrosion</i>	<i>Eff. Area</i>	<i>Ult. Strength</i>
	%	in ²	psi		%	in ²	psi
7S-10-01	9.09	0.116	65831	7S-30-01	28.37	0.093	50754
7S-10-02	10.85	0.114	69288	7S-30-02	28.52	0.094	50450
7S-10-03	9.86	0.115	70771	7S-30-03	29.76	0.092	46242
7S-10-04	9.49	0.115	69447	7S-30-04	31.41	0.090	47614
7S-10-05	10.49	0.114	71933	7S-30-05	30.69	0.091	50320
7S-10-06	7.54	0.117	68195	7S-30-06	33.23	0.088	50392
7S-10-07	9.72	0.115	72494	7S-30-07	28.9	0.093	51559

7S-15			
<i>Specimen</i>	<i>Corrosion</i>	<i>Eff. Area</i>	<i>Ult. Strength</i>
	%	in ²	psi
7S-15-01	14.57	0.109	63972
7S-15-02	15.38	0.109	63053
7S-15-03	12.16	0.112	66828
7S-15-04	13.63	0.111	64062
7S-15-05	15.45	0.108	62685
7S-15-06	16.66	0.107	61412
7S-15-07	16.74	0.107	64108

Table A.4 – Fatigue Test Data

7F-00			7F-20		
<i>Specimen</i>	<i>% Corrosion</i>	<i>Cycles</i>	<i>Specimen</i>	<i>% Corrosion</i>	<i>Cycles</i>
7F-00-01	0	3001015	7F-20-01	19.12	10389
7F-00-02	0	3001000	7F-20-02	19.68	13510
7F-00-03	0	3000056	7F-20-03	22.06	5635
7F-00-04	0	3001285	7F-20-04	20.1	3923
7F-00-05	0	3000055	7F-20-05	21.79	3275
7F-00-06	0	3001305	7F-20-06	23	6050
7F-00-07	0	3000893	7F-20-07	22.08	5065

7F-05			7F-25		
<i>Specimen</i>	<i>% Corrosion</i>	<i>Cycles</i>	<i>Specimen</i>	<i>% Corrosion</i>	<i>Cycles</i>
7F-05-01	5.5	35764	7F-25-01	23.04	4194
7F-05-02	4.91	46709	7F-25-02	24.3	5851
7F-05-03	4.77	66632	7F-25-03	24.64	4023
7F-05-04	6.59	51410	7F-25-04	26.88	4320
7F-05-05	6.51	75825	7F-25-05	25.59	2243
7F-05-06	4.95	92360	7F-25-06	25.3	4907
7F-05-07	5.15	43630	7F-25-07	24.59	3500

7F-10			7F-30		
<i>Specimen</i>	<i>% Corrosion</i>	<i>Cycles</i>	<i>Specimen</i>	<i>% Corrosion</i>	<i>Cycles</i>
7F-10-01	9.76	72440	7F-30-01	31	4858
7F-10-02	10.37	41350	7F-30-02	28.53	3858
7F-10-03	12.4	28340	7F-30-03	30	3718
7F-10-04	9.01	59594	7F-30-04	30.05	2284
7F-10-05	9.91	64055	7F-30-05	32.06	3000
7F-10-06	11.16	38297	7F-30-06	30.15	4540
7F-10-07	11.05	29695	7F-30-07	29.11	4353

7F-15		
<i>Specimen</i>	<i>% Corrosion</i>	<i>Cycles</i>
7F-15-01	14	1659
7F-15-02	16.62	9610
7F-15-03	14.49	18658
7F-15-04	15.96	16729
7F-15-05	16.63	9612
7F-15-06	13.49	23524
7F-15-07	16.39	9002

Table A.5 – Corroded Thickness of Fatigue Specimens

<i>Specimen</i>	<i>Fatigue Life</i>	<i>Corroded Thickness</i>	
		<i>Measured Average, in</i>	<i>Calculated, in</i>
7F-05-01	35764	0.0440	0.0595
7F-05-02	46709	0.0450	0.0599
7F-05-03	66632	0.0485	0.0600
7F-05-04	51410	0.0475	0.0589
7F-05-05	75825	0.0500	0.0590
7F-05-06	92360	0.0510	0.0599
7F-05-07	43630	0.0445	0.0598
7F-10-01	72440	0.0445	0.0570
7F-10-02	41350	0.0320	0.0567
7F-10-03	28340	0.0353	0.0553
7F-10-04	59594	0.0485	0.0574
7F-10-05	64055	0.0445	0.0568
7F-10-06	38297	0.0375	0.0560
7F-10-07	29695	0.0285	0.0560
7F-15-01	1659	0.0315	0.0542
7F-15-02	9610	0.0320	0.0525
7F-15-03	18658	0.0360	0.0539
7F-15-04	16729	0.0318	0.0529
7F-15-05	9612	0.0323	0.0525
7F-15-06	23524	0.0363	0.0545
7F-15-07	9002	0.0280	0.0527
7F-20-01	10389	0.0283	0.0510
7F-20-02	13510	0.0287	0.0506
7F-20-03	5635	0.0253	0.0491
7F-20-04	3923	0.0247	0.0503
7F-20-05	3275	0.0250	0.0493
7F-20-06	6050	0.0270	0.0485
7F-20-07	5065	0.0213	0.0491
7F-25-01	4194	0.0270	0.0485
7F-25-02	5851	0.0260	0.0477
7F-25-03	4023	0.0268	0.0475
7F-25-04	4320	0.0268	0.0461
7F-25-05	2243	0.0260	0.0469
7F-25-06	4907	0.0248	0.0471
7F-25-07	3500	0.0265	0.0475
7F-30-01	4858	0.0233	0.0435
7F-30-02	3858	0.0237	0.0450
7F-30-03	3718	0.0245	0.0441
7F-30-04	2284	0.0208	0.0441
7F-30-05	3000	0.0220	0.0428
7F-30-06	4540	0.0233	0.0440
7F-30-07	4353	0.0300	0.0447

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