SYSTEMATIC TESTING AND ANALYSIS OF CORROSION AT ORGANIC
MATRIX COMPOSITE AND 6061-T6 ALUMINUM INTERFACES

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ABSTRACT

The basic purpose of our research was to study the corrosion of 6061-T6 aluminum when coupled to different types of organic matrix composites. The different types of organic matrix composites included graphite/epoxy composite with the fibers in parallel (0°) and perpendicular (90°) directions, E-glass/epoxy composite, [E-glass, graphite/epoxy] hybrid composite, [E-glass, graphite, E-glass/epoxy] hybrid composite, silicon carbide/epoxy composite, and 3M alumina/epoxy composite. The 6061-T6 Al and composites were coupled using Ti-6Al-4V hex nuts and bolts except in a special case where non-conducting nylon bolts and nuts were used. The galvanic current and voltage profiles between the 6061-T6 aluminum and graphite/epoxy composite with the fibers in parallel and perpendicular direction and as well as Ti-6Al-4V were measured using the zero resistance ammeter technique in 3.15 wt% NaCl, 0.5M Na₂SO₄, ASTM seawater, and actual seawater in aerated and de-aerated conditions. The same types of electrolytes were also used for the accelerated corrosion experiments in the laboratory. The accelerated corrosion experiments consisted of exposure in the humidity chamber and immersion in the electrolytes for a period of 90 days. Weight loss data was observed and the corrosion rates were determined. SEM and EDAX analysis were done to examine the film formation on the composite surfaces in certain cases. Outdoor exposure tests were conducted at six different sites in Oahu at Coconut Island, Manoa, Waipahu, Kahuku, Campbell Industrial Park, and Ewa Nui. The sites were selected for their climatically diverse environments. Weight loss data was observed and the corrosion rates were determined.
FTIR analysis using ATR technique was conducted on the organic matrix composites to study the environmental degradation of the matrix when exposed at the outdoor sites. Similar studies were also conducted to study the effect of 3.15 wt% NaCl in the accelerated corrosion experiments in the laboratory.
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Chapter 1

INTRODUCTION

1.1 Purpose of Research

Composite materials made from glass and carbon/graphite fibers are widely used in space, aviation, automobile, and recreation industries where they are fastened or rigidly bonded to metals such as the 6061-T6 aluminum alloy which is a very versatile material with wide-ranging applications from aircraft fittings to bicycle frames [1, 2]. Advanced composites have comparatively superior strength and stiffness over that of conventional metals. The high strength-to-weight ratio of the composites relative to other materials gives composites a significant edge [2, 3]. When graphite fibers form the structural component in an organic matrix composite, graphite exhibits the electrochemical characteristics of a noble metal, tending to be cathodic to most metals when galvanically coupled [4]. Glass and graphite/epoxy composites are widely used in various applications depending upon the specific criteria and requirements. Epoxy resin systems are extensively used in the manufacturing of these composites [2]. The SiC/epoxy and alumina/epoxy composite laminates also have high mechanical strength and stiffness [2]. The research was primarily focused on the compatibility of 6061-T6 aluminum when coupled to a variety of organic matrix composites under different conditions. Since the composites range from insulators to excellent conductors including semi-conductors, the results generated from the research represent a broad spectrum of data. The 6061-T6 aluminum was also coupled to two types of hybrid composites.
1.2 Research Objectives

The basic objective of this research was to study the compatibility of 6061-T6 aluminum - organic matrix composite couples and a three pronged approach was adopted to conduct this research. The first method of approach was to determine the galvanic corrosion rate between the conducting graphite/epoxy composite electrodes and 6061-T6 aluminum in four different electrolytes such as 3.15 wt% NaCl, 0.5 M Na$_2$SO$_4$, ASTM sea water, and real sea water by the zero resistance ammeter technique. Graphite/epoxy composite electrodes were prepared with two different fiber orientations (i.e. parallel and perpendicular) to understand whether the fiber orientations had any significant influence in the galvanic corrosion rate between the metal and the composite. Few electrochemical experiments were also conducted to determine the galvanic corrosion rate between conducting Ti-6Al-4V electrodes, which was the material used in the fasteners and 6061-T6 aluminum in 3.15 wt% NaCl and ASTM sea water. All the experiments were conducted under both aerated and de-aerated conditions.

The second method of research was to conduct two types of accelerated corrosion experiments in the laboratory where 6061-T6 aluminum coupons were coupled to various organic matrix composites like graphite/epoxy composite with the fibers in parallel and perpendicular directions, E-glass/epoxy composite, E-glass, graphite/epoxy hybrid composite, E-glass, graphite, E-glass/epoxy hybrid composite, silicon carbide/epoxy composite, and 3M alumina/epoxy composite. The couples were treated with 3.15 wt% NaCl, 0.5 M Na$_2$SO$_4$, ASTM sea water, and real sea water and exposed in the humidity chamber in one case and immersed in the electrolytes in the other case.
The last method was to determine the corrosion rate in natural environments for 6061-T6 aluminum when coupled to various organic matrix composites like graphite/epoxy composite with the fibers in parallel and perpendicular directions, E-glass/epoxy composite, E-glass, graphite/epoxy hybrid composite, E-glass, graphite, E-glass/epoxy hybrid composite, silicon carbide/epoxy composite, and 3M alumina/epoxy composite. Six different sites on Oahu were selected to broadly represent the various micro-climates of the island. The couples were exposed at a rainforest environment at Lyon arboretum, Manoa, an industrial environment at Campbell industrial park, an agricultural environment at Ewanui, a typically dry environment at Waipahu, and two marine environments at Kahuku and Coconut Island. The corrosion rate at each site was determined and compared. FTIR analysis was conducted to analyze the degradation of the epoxy matrix of the composites when they were exposed to different conditions both in the accelerated corrosion experiments and as well the outdoor experiments and the spectra were compared to that of the virgin specimens.

1.3 Thesis Format

A general literature review on the galvanic corrosion between 6061-T6 aluminum and organic matrix composites is given in chapter 2. The fabrication and the manufacturing of the test coupons are discussed in chapter 3. The different types of couples that were used in the various laboratory and outdoor experiments are also listed in the same chapter. Chapter 4 covers the DC electrochemical experiments conducted to understand the galvanic corrosion behavior of 6061-T6 aluminum when coupled to graphite/epoxy
composites and Ti-6Al-4V in various electrolytes under aerated and de-aerated conditions. Cathodic polarization of the graphite/epoxy composite with the fibers in the perpendicular direction is also briefly discussed. The accelerated corrosion experiments are covered in chapter 5. The experiments conducted at the six different outdoor sites are discussed in the chapter 6. Chapter 7 covers the FTIR analysis of the degradation of the organic matrix composites. An overall conclusion is given in chapter 8.
Chapter 2

LITERATURE SURVEY

2.1 Galvanic Corrosion between 6061-T6 Aluminum and Organic matrix composites

When graphite fibers form the structural component in an organic matrix composite, graphite exhibits the electrochemical characteristics of a noble metal, tending to be cathodic to most metals when galvanically coupled [4, 5, and 6]. Merlin and Ralph conducted their galvanic corrosion tests in 3.5% NaCl to determine the corrosion rate of 6061-T6 aluminum coupled to graphite/epoxy composites and after one week of immersion in the electrolyte they found that severe corrosion occurred when aluminum was coupled to graphite/epoxy composite [4]. Similar corrosion experiments were conducted by Miller and Lee in aerated neutral 3.5% NaCl solutions where aerospace alloys were coupled to graphite/epoxy composites at 22°C to study the acceptability of a particular alloy based on the magnitude of its galvanic current density [7]. Fischer and DeLuccia determined corrosion current densities from electrochemical tests by coupling graphite/epoxy composites to aluminum alloy and Ti-6Al-4V in neutral 3.5% NaCl solution and found that aluminum was more reactive [8]. Electrochemical studies on graphite/epoxy-alloy couples and uncoupled graphite/epoxy composites were conducted by Johnston and co-workers to determine the galvanic profiles in aerated 3.5% NaCl solution [9]. Brown and Coomber studied the corrosion behavior of the graphite/epoxy-aluminum alloy couple in aqueous 5% NaCl solution [10]. D. E. Prince studied and compared the corrosion behavior of
unprotected aluminum and Ti-6Al-4V fasteners that come into contact with graphite/epoxy composites [11]. Corrosion of metals when coupled to graphite/epoxy composites is a usual process due to galvanic effects but the damages caused to the composites were also significant [4, 12, 13]. The electrical compatibility of the graphite/epoxy composites with metallic alloys especially at the joints is a very important aspect of component design in aerospace industry. Some of the galvanic aluminum alloy – graphite/epoxy composite couples were exposed to aerated 3.5% NaCl solution and Bellucci and Capobianco found that corrosion rates were proportional to the ratio of the cathodic/anodic areas [14]. The structural interaction of graphite-fiber reinforced composites which are widely used in various structural applications with metals will possibly initiate corrosion due to the formation of a galvanic couple as the graphite fibers tend to be electrochemically noble [15]. Sloan and Talbot determined the galvanic corrosion rates of 6061-T6 aluminum when coupled with graphite/epoxy composites electrochemically. Thick film formation on the composites immersed in sea water significantly decreased the corrosion rates. The protective nature of the deposits on the surface can be attributed to the presence of CaCO₃ and Mg(OH)₂ primarily. Damages in the polymer matrix were then evaluated using infrared spectroscopy [16]. Martin widely used Zero resistance ammeter (ZRA) measurements in his corrosion studies and the ZRA currents were compared to those of the laboratory corrosion experiments [17].
Chapter 3

MANUFACTURING AND FABRICATION OF TEST COUPONS

3.1 6061-T6 Aluminum Alloy

3.1.1 Fabrication of Test Coupons

The 6061 Al bars of 0.12 inch thickness were dry sanded with 180 Grit Al₂O₃ oxide grinding paper and then cut using an abrasive cutter into uniform 2 x 2 inches squares. The squares were drilled in the center to make a 0.25 inch diameter hole for coupling to the various organic matrix composites.

3.2 Organic Matrix Composites

3.2.1 Manufacturing of composites*

Five different composite plates were manufactured. 1) Graphite/epoxy plates with two different thicknesses, 2) E-glass/epoxy, 3) Hybrid graphite/epoxy with one layer of E-glass on the top and one layer of E-glass on the bottom, 4) Hybrid graphite/epoxy with only one layer of E-glass on the bottom, and 5) Silicon carbide/epoxy.

*With the help of Dr. Richard Russ, AMML, Dept. of Mechanical Eng. UH Manoa
3.2.1.1 Graphite/epoxy and E-Glass/epoxy Composite Plates

Two types of graphite/epoxy composite plates with different thicknesses were fabricated. The thinner plate was manufactured from fourteen layers of F3584-42"-F155 with standard width of 42 inches and eight-harness satin prepreg with epoxy resin. The thickness of one graphite/epoxy ply before curing was 0.56 mm (0.0225 in) and the thickness after curing was 0.42 mm (0.0164 in). The dimensions of the thinner graphite/epoxy plate were 356 x 356 x 5.3 mm (14 x 14 x 0.21 in). The dimensions of the thicker graphite/epoxy plate were 356 x 356 x 25.4 mm (14 x 14 x 1.0 in) and 56 plies were used in the fabrication of the thicker plate. E-glass/epoxy composite plates were manufactured using twenty-two plies of 7781-38"-F155 with standard width of 38 inches and eight satin prepreg with epoxy resin. The thickness of one E-glass/epoxy ply before curing was 0.35 mm (0.0125 in) and the thickness after curing was 0.254 mm (0.01 in). The dimensions of the E-glass/epoxy plates were similar to the thin graphite/epoxy composite plates. Two types of hybrid plates were also manufactured, first using fourteen plies of graphite/epoxy composite with one E-glass/epoxy ply on the top and bottom and the second hybrid plate with only one ply of E-glass/epoxy on the bottom. Figure 1 shows the graphite/epoxy composite plates with different thicknesses. Smaller samples of required dimensions were cut from these plates using a diamond wheel saw. The edges were trimmed to remove regions of porosity due to edge effects during processing.
3.2.1.2 Procedures for Manufacturing Composite Plates

The following steps were performed in order to manufacture a composite plate.

3.2.1.3 Surface Preparation

An aluminum plate of dimensions 431 x 431 x 6.4 mm (17 x 17 x 1/4 in) was used as a base plate on top which the layers of composite were laid. The aluminum plate was sanded to get a clean and uniform surface. Acetone was used to degrease the sanded surface and to remove the dirt particles from the surface as shown in Figure 2.
Highland 2727 masking tape was applied to the edges of the aluminum base plate, which was later peeled off and replaced with the sealing tape used for vacuum bagging. High temperature mold release was applied with sponge applicator to the surface. The plate was then let to dry after which it was wiped off with a clean piece of cloth to provide a smooth and shiny surface. Dry lubricant release agent was then sprayed on the surface.

3.2.1.4 Manufacturing process

The thickness of the composite plate will specify the number of plies to be laid on the top of each other. Each consecutive layer was flipped over in the opposite direction to preserve
the symmetric configuration of the eight-harness satin prepreg fabric. Each layer was compressed using a pin roller as shown in Figure 3 to prevent air bubbles and voids formation within the laminates. The aluminum base plate was rotated in a clockwise direction after laying down each layer to have uniform thickness everywhere.

Figure 3. Graphite/epoxy composite prepregs and pin roller

Highland 2727 masking tape was peeled off and replaced by sealing vacuum tape. A smaller aluminum plate with dimensions of 381 x 381 x 6.4 mm (15 x 15 x 1/4 in) and with the same surface preparations was placed on the top of the composite plate. A layer of
peel ply, a layer of bleeder (fiberglass), and a layer of breather were placed on the top of the smaller aluminum plate as shown in the figure 4.

![Figure 4. Peel ply, bleeder and breather over the plies](image)

This set-up was covered with a vacuum bag. The vacuum bag was put under 100 psi pressure and the set-up was heated up to 260°F for one hour and forty minutes in an autoclave to cure the composite layers as shown in the figure 5.
3.2.1.5 Procedures for Manufacturing Silicon Carbide Composite Plate

The silicon carbide (SiC) plates were manufactured from twenty layers of ceramic grade plain weave Nicalon cloth with no coating and no epoxy resin with plate dimensions of 25.4 x 25.4 x 0.508 cm (10 x 10 x 0.2 in). In order to manufacture a SiC plate, liquid resin epoxy D. E. R 331 manufactured by The Dow Chemical Company was chosen as the matrix material and Ancamine 1771 hardener was used as the curing agent. The gel time of the mixture of resin and hardener was 88 minutes with a 4:1 volume ratio for the mixture. The curing cycle to complete polymerization was two hours at 176°F plus two more hours at 300°F under 100 psi pressure. Each SiC layer was soaked completely in epoxy using a paintbrush, and squeegee to remove the excess epoxy as shown in Figure 6.
Figure 6. Excess epoxy removed from a SiC ply

A \( \frac{3}{4} \)" thick aluminum base plate was used. The wet SiC layers were laid down on the aluminum base plate on top of each other and compressed by squeegee as shown in Fig. 7.
Finally a smaller 381 x 381 x 6.4 mm (15 x 15 x 1/4 in) aluminum plate was laid down on the top of the SiC composite. A layer of peel ply, a layer of bleeder (fiberglass), and a layer of breather were placed on the top of the smaller aluminum plate. The set-up was covered with a vacuum bag and then placed in an autoclave as shown in Figure 8. The autoclave was programmed to apply pressure of 100 psi and temperature to complete the polymerization was 150°C.
3.2.2 Fabrication of Organic Matrix Composite Test Coupons

All of the OMCs were ‘wet sanded’ with 80 Grit Al₂O₃ oxide grinding paper until the fibers were exposed sufficiently. The coupons were then cut into uniform squares of 0.875 x 0.875 inch with a diamond tipped cutter for maximum precision. Two types of cylindrical diamond coated drill cores (2.270 and 2.295) were used for making holes in the center of each coupon. The 6061-T6 aluminum coupons were coupled using ¼"Titanium or Nylon bolts and nuts.
3.3 Types of Couples used in the Experiments

The OMC coupons were fastened to the 6061-T6 Al coupons with torques of 10 and 100 in-lbs for the nylon and Ti-6Al-4V fasteners, respectively. The different types of OMC coupons were coupled to the 6061-T6 Al coupons in such a way to analyze the compatibility of each material with different combinations taking into account the conductivity of the composites and the fasteners in each couple. Figure 9 shows a non-conducting E-glass/epoxy composite coupled to 6061-T6 aluminum and fastened using a Ti-6Al-4V bolt and nut at a torque of 100 in-lbs.

Figure 9. E-glass/epoxy composite coupled to 6061-T6 aluminum

Figure 10 shows a conducting graphite/epoxy composite with the fibers in the parallel direction (0°) coupled to 6061-T6 aluminum and fastened using a Ti-6Al-4V bolt and nut at a torque of 100 in-lbs.
Figure 10. Graphite/epoxy composite (0°) coupled to 6061- T6 aluminum

Figure 11 shows a conducting graphite/epoxy composite with the fibers in the perpendicular direction (90°) coupled to 6061- T6 aluminum and fastened using a Ti-6Al-4V bolt and nut at a torque of 100 in-lbs.

Figure 11. Graphite/epoxy composite (90°) coupled to 6061- T6 aluminum
Figure 12 shows a non-conducting silicon carbide/epoxy composite coupled to 6061-T6 aluminum and fastened using a Ti-6Al-4V bolt and nut at a torque of 100 in-lbs.

Figure 12. SiC/epoxy composite coupled to 6061- T6 aluminum

Figure 13 shows a non-conducting 3M alumina/epoxy composite coupled to 6061-T6 aluminum and fastened using a Ti-6Al-4V bolt and nut at a torque of 100 in-lbs.

Figure 13. 3M Alumina/epoxy composite coupled to 6061- T6 aluminum
3.3.1 Special OMCs Coupled to 6061-T6 Al

Figure 14 shows an E-glass epoxy/G/E (0°) with non-conducting E-glass layer facing the metal sample. The G/E (0°) is still galvanically coupled to 6061-T6 Al through the Ti-6Al-4V fastener.

![Figure 14. E-glass/epoxy – graphite/epoxy hybrid composite coupled to 6061-T6 aluminum](image)

Figure 15 shows an E-glass epoxy/G/E (0°)/E-glass epoxy hybrid composite with insulating top and bottom E-glass layers fastened with a Ti-6Al-4V bolt that was insulated using a rubber heat shrink sleeve to eliminate all possible galvanic effects.
Figure 15. E-glass/epoxy – graphite/epoxy – E-glass/epoxy hybrid composite coupled to 6061-T6 aluminum with an insulated Ti bolt

Figure 16 shows graphite/epoxy (0°) fastened with non-conducting nylon bolt torqued to 10 in-lbs to contrast the effect of the conducting Ti-6Al-4V fastener in a couple.

Figure 16. Graphite/epoxy composite (0°) coupled to 6061-T6 aluminum with a non-conducting nylon bolt and nut
DETERMINATION OF CORROSION OF 6061-T6 ALUMINUM COUPLED TO GRAPHITE / EPOXY (0° & 90°) COMPOSITES AND Ti-6Al-4V USING DC ELECTROCHEMICAL TECHNIQUES

4.1 General Background

The galvanic current and potential between the 6061-T6 aluminum and graphite/epoxy composites with the fibers in parallel and perpendicular direction were measured using the zero resistant ammeter technique in 3.15 wt% NaCl, 0.5M Na₂SO₄, ASTM sea water, and actual sea water in aerated and de-aerated conditions. The galvanic current and potential between 6061-T6 aluminum and Ti-6Al-4V used for fastening the couples were also measured using the same technique in aerated and de-aerated 3.15 wt% NaCl and ASTM sea water.

4.2 Fabrication of Samples and Electrolytes

Graphite/epoxy electrodes (Figure 17) having surface area of 1 cm² (1 cm x 1 cm) with the fibers in the parallel and perpendicular directions were fabricated. The samples were cut using a Buehler-Isomet™ low-speed diamond saw. The cut composite samples were ultrasonically cleaned and dried. Conductive silver paint was applied on one side of the sample, forming an electrical connection between the graphite/epoxy sample and a copper wire. The copper wire was enclosed in a glass tube and sealed with epoxy.
adhesive to isolate the copper wire from the solution. All sides of the composite sample were sealed in epoxy except the face which was ground and polished. The 6061-T6 Al and Ti-6Al-4V electrodes were also fabricated similarly.

Figure 17. Graphite/epoxy composite (0°) electrode fabricated for ZRA experiment

The surface of all the planar electrodes was ground on a variable speed Buehler Ecomet 6 - grinder/polisher using the 120, 180, 320, and 400 grit SiC grinding paper and polished to a 0.3 μm finish with gamma alumina powder. The surfaces were kept wet and rinsed with 18 MΩ cm ultra pure water before being used in the experiment [18]. Neutral solutions of 3.15 wt% NaCl, 0.5 M Na₂SO₄, and ASTM sea water were prepared from 18 MΩ cm ultra pure water and respective analytical grade chemicals [18]. Real sea water was acquired from the Waikiki Aquarium on Oahu.
4.3 Experiment Procedure, Conditions, and Set-up

The ZRA (Zero Resistance Ammeter) experiments were conducted with the setup shown in the Figure 18.

Figure 18. Experiment set-up for the zero resistant ammeter technique experiments

The galvanic current ($I_{\text{Galv}}$) and potential ($E_{\text{Galv}}$) were measured with a zero resistant ammeter-ZA 100 and electrometer-EM002, respectively. The electrolytes either were de-aerated with pre-purified $N_2$ gas or aerated using pre-purified air. The $I_{\text{Galv}}$ value was measured between the two working electrodes and $E_{\text{Galv}}$ was measured between the 6061-T6 metal electrode and standard calomel reference electrode. The temperature was
maintained at 30°C±0.1°C with a Fisher Scientific Isotemp refrigerated circulator-Model 9500. The current and voltage data were recorded every 15 seconds using Madgetech Volt 101 data loggers. Each experiment was conducted for a period of 5 days and an average of three experiments in each case was plotted against time for both the aerated and de-aerated conditions. The flow rate of the air in the aerated experiments was maintained at 320 ml/min.

The cathodic polarization of the composite was conducted in an aerated condition at 30°C and the scan rate was 0.1 mV/sec. The polarization experiments were conducted in aerated 3.05 wt% NaCl and ASTM sea water. The average values of three experiments in each electrolyte were plotted and the results are presented in the next section. EG & G Princeton Applied Research Potentiostat/Galvanostat Model 273 A was used to conduct the polarization experiment. A standard calomel electrode and platinum counter electrode were used.
4.4 Results

4.4.1 ZRA – Aerated Condition

The average galvanic current and voltage profiles are shown for 6061-T6 aluminum against the graphite/epoxy (0°) composite (Figures 19 to 26) and against the graphite/epoxy (90°) composite (Figures 27 to 34) exposed to aerated 3.15 wt% NaCl, 0.5M Na₂SO₄, ASTM sea water, and real sea water. The average galvanic current and voltage profiles are shown for 6061-T6 aluminum against Ti-6Al-4V (Figures 35 to 38) exposed to 3.15 wt% NaCl, and ASTM sea water. The comparison of the aerated galvanic current and voltage profiles of 6061-T6 aluminum versus G/E (90°), G/E (0°), and Ti-6Al-4V are shown in figures 39-40, 41-42, and 43-44 respectively.
4.4.1.1  Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 3.15 wt% NaCl

![Graph showing galvanic current profile](image)

Figure 19.  Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 3.15 wt% NaCl
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0\(^{0}\)) composites in aerated 3.15 wt\% NaCl

Figure 20. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0\(^{0}\)) composites in aerated 3.15 wt\% NaCl
4.4.1.2 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 0.5M Na$_2$SO$_4$

Figure 21. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 0.5M Na$_2$SO$_4$
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 0.5M Na$_2$SO$_4$

![Graph showing galvanic voltage profile.](image)

Figure 22. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 0.5M Na$_2$SO$_4$.
4.4.1.3 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated ASTM sea water

Figure 23. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated ASTM sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated ASTM sea water

Figure 24. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated ASTM sea water
4.4.1.4 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated actual sea water

Figure 25. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated actual sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated actual sea water

Figure 26. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated actual sea water
4.4.1.5 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 3.15 wt% NaCl

Figure 27. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 3.15 wt% NaCl
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 3.15 wt% NaCl

Figure 28. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 3.15 wt% NaCl
Figure 29. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 0.5M Na₂SO₄

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Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 0.5M Na₂SO₄

Figure 30. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 0.5M Na₂SO₄
4.4.1.7 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated ASTM sea water

Figure 31. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated ASTM sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated ASTM sea water

![Galvanic voltage profile graph](image)

Figure 32. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated ASTM sea water
4.4.1.8 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated actual sea water

Figure 33. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated actual sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated actual sea water

Figure 34. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated actual sea water
4.4.1.9 Galvanic current profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated 3.15 wt% NaCl

Figure 35. Galvanic current profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated 3.15 wt% NaCl
Galvanic voltage profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated 3.15 wt% NaCl

![Graph showing the galvanic voltage profile](image)

Figure 36.  Galvanic voltage profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated 3.15 wt% NaCl
4.4.1.10 Galvanic current profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated ASTM sea water

Figure 37. Galvanic current profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated ASTM sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated ASTM sea water

Figure 38. Galvanic voltage profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated ASTM sea water
4.4.1.11 Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 3.15 wt% NaCl, 0.5M Na$_2$SO$_4$, ASTM sea water, and real sea water.

![Graph showing galvanic current profiles comparison](image)

Figure 39. Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 3.15 wt% NaCl, 0.5M Na$_2$SO$_4$, ASTM sea water, and real sea water.
4.4.1.12 Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water

Figure 40. Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water
4.4.1.13 Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water

Figure 41. Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water
4.4.1.14 Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water.

Figure 42. Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water.
4.4.1.15 Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated 3.15 wt% NaCl and ASTM sea water

Figure 43. Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated 3.15 wt% NaCl and ASTM sea water
Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated 3.15 wt% NaCl and ASTM sea water

Figure 44. Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to Ti-6Al-4V in aerated 3.15 wt% NaCl and ASTM sea water.
4.4.2 ZRA – Deaerated Condition

The average galvanic current and voltage profiles are shown for 6061-T6 aluminum against the graphite/epoxy \((0^\circ)\) composite (Figures 45 to 52) and against the graphite/epoxy \((90^\circ)\) composite (Figures 53 to 60) exposed to deaerated 3.15 wt% NaCl, 0.5M \(\text{Na}_2\text{SO}_4\), ASTM sea water, and real sea water. The average galvanic current and voltage profiles are also shown for 6061-T6 aluminum against Ti-6Al-4V exposed to deaerated 3.15 wt% NaCl, and ASTM sea water are shown in the Figures 61 to 64. The comparison of the de-aerated galvanic current and voltage profiles of 6061-T6 aluminum versus G/E \((90^\circ)\), G/E \((0^\circ)\), and Ti-6Al-4V are shown in figures 65-66, 67-68, and 69-70 respectively.
4.4.2.1 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 3.15 wt% NaCl

Figure 45. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 3.15 wt% NaCl
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy
($0^\circ$) composites in de-aerated 3.15 wt% NaCl

Figure 46. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite /
epoxy ($0^\circ$) composites in de-aerated 3.15 wt% NaCl
4.4.2.2 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 0.5M Na₂SO₄

Figure 47. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 0.5M Na₂SO₄
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 0.5M Na₂SO₄

Figure 48. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 0.5M Na₂SO₄
4.4.2.3 Galvanic current profile of 6061-T6 Aluminum coupled to graphite/epoxy ($0^\circ$) composites in de-aerated ASTM sea water

Figure 49. Galvanic current profile of 6061-T6 Aluminum coupled to graphite/epoxy ($0^\circ$) composites in de-aerated ASTM sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated ASTM sea water

Figure 50. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated ASTM sea water
4.4.2.4 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated real sea water

Figure 51. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated real sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy ($0^\circ$) composites in de-aerated real sea water

Figure 52. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy ($0^\circ$) composites in de-aerated real sea water
4.4.2.5 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated 3.15 wt% NaCl

Figure 53. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated 3.15 wt% NaCl
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated 3.15 wt% NaCl

![Graph showing galvanic voltage profile](image)

Figure 54. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated 3.15 wt% NaCl
4.4.2.6 Galvanic current profile of 6061-T6 Aluminum coupled to graphite/epoxy (90°) composites in de-aerated 0.5M Na$_2$SO$_4$

Figure 55. Galvanic current profile of 6061-T6 Aluminum coupled to graphite/epoxy (90°) composites in de-aerated 0.5M Na$_2$SO$_4$
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated 0.5M Na₂SO₄

Figure 56. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated 0.5M Na₂SO₄
4.4.2.7 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated ASTM sea water

![Galvanic current profile](image)

Figure 57. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated ASTM sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated ASTM sea water

Figure 58. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated ASTM sea water
4.4.2.8 Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated real sea water

![Galvanic current profile graph](image)

Figure 59. Galvanic current profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated real sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated real sea water

Figure 60. Galvanic voltage profile of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated real sea water
4.4.2.9 Galvanic current profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated 3.15 wt% NaCl

Figure 61. Galvanic current profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated 3.15 wt% NaCl
Galvanic voltage profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated 3.15 wt% NaCl

Figure 62. Galvanic voltage profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated 3.15 wt% NaCl
4.4.2.10 Galvanic current profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated ASTM sea water

Figure 63. Galvanic current profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated ASTM sea water
Galvanic voltage profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated ASTM sea water

Figure 64. Galvanic voltage profile of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated ASTM sea water
4.4.2.11 Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water.

Figure 65. Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water.
4.4.2.12 Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water

Figure 66. Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to graphite / epoxy (0°) composites in de-aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water
4.4.2.13 Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to graphite / epoxy (90\°) composites in de-aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water

![Graph showing comparison of galvanic current profiles](image)

Figure 67. Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to graphite / epoxy (90\°) composites in de-aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water
4.4.2.14 Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water.

Figure 68. Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to graphite / epoxy (90°) composites in de-aerated 3.15 wt% NaCl, 0.5MNa₂SO₄, ASTM sea water, and real sea water.
4.4.2.15 Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated 3.15 wt% NaCl, and ASTM sea water

Figure 69. Comparison of galvanic current profiles of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated 3.15 wt% NaCl, and ASTM sea water
Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated 3.15 wt% NaCl, and ASTM sea water

Figure 70. Comparison of galvanic voltage profiles of 6061-T6 Aluminum coupled to Ti-6Al-4V in de-aerated 3.15 wt% NaCl, and ASTM sea water
4.4.3 Cathodic polarization of graphite / epoxy (90°) composites in aerated 3.05 wt% NaCl and ASTM sea water

Figure 71. Comparison of cathodic polarization profiles of G/E (90°) composite in aerated 3.05 wt% NaCl and ASTM sea water
4.5 Discussions

4.5.1 ZRA – Aerated Condition

Table 1. Avg. Steady state $i_{Galv}$ (mA/cm$^2$) values of 6061-T6 Aluminum

<table>
<thead>
<tr>
<th>Versus</th>
<th>0.5 M Na$_2$SO$_4$</th>
<th>3.15 wt% NaCl</th>
<th>ASTM seawater</th>
<th>Real seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td>G/E (0°)</td>
<td>0.0330</td>
<td>0.0937</td>
<td>0.0073</td>
<td>0.0107</td>
</tr>
<tr>
<td>G/E (90°)</td>
<td>0.0307</td>
<td>0.1337</td>
<td>0.0096</td>
<td>0.0057</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>-</td>
<td>0.1194</td>
<td>0.0085</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Avg. Steady state $E_{Galv}$ (V SCE) values of 6061 T6 Aluminum

<table>
<thead>
<tr>
<th>Versus</th>
<th>0.5 M Na$_2$SO$_4$</th>
<th>3.15 wt% NaCl</th>
<th>ASTM seawater</th>
<th>Real seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td>G/E (0°)</td>
<td>-0.598</td>
<td>-0.729</td>
<td>-0.770</td>
<td>-0.770</td>
</tr>
<tr>
<td>G/E (90°)</td>
<td>-0.560</td>
<td>-0.738</td>
<td>-0.685</td>
<td>-0.766</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>-</td>
<td>-0.740</td>
<td>-0.753</td>
<td>-</td>
</tr>
</tbody>
</table>

The comparative analysis of the $i_{Galv}$ values of both 6061-T6 Al versus graphite/epoxy composite with the fibers in parallel direction (0°) and 6061-T6 versus graphite/epoxy composite with the fibers in perpendicular direction (90°) showed that the current in the latter case was greater in aerated 3.15 wt% NaCl and ASTM seawater and the trend was reverse in aerated 0.5 M Na$_2$SO$_4$ and real sea water. The fiber orientation did not significantly affect the corrosion rates because the grinding of the composite exposes the internal fiber structure of both the 0° and 90° cases. The highest $i_{Galv}$ value was observed in the case of 3.15 wt% NaCl when coupled to G/E (90°) because of the presence of the Cl$^-$ ions in the electrolyte while the lowest was in the case of real sea water when coupled to G/E (90°) which could be...
due to the formation of precipitates on the cathodic surfaces. The $i_{\text{Galv}}$ values of 6061-T6 Al coupled to Ti-6Al-4V in the case of 3.15 wt% NaCl were more or less similar to that of those coupled to the graphite epoxy composite electrodes. The primary reaction that occurs in an aerated condition is oxygen reduction at the cathodic surface and the diffusion limited current is independent of the substrate.

4.5.2 ZRA – Deaerated Condition

<table>
<thead>
<tr>
<th>Versus</th>
<th>$0.5 \text{ M Na}_2\text{SO}_4$</th>
<th>3.15 wt% NaCl</th>
<th>ASTM seawater</th>
<th>Seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td>G/E (0°)</td>
<td>7.518</td>
<td>1.260</td>
<td>0.113</td>
<td>0.062</td>
</tr>
<tr>
<td>G/E (90°)</td>
<td>8.117</td>
<td>3.751</td>
<td>0.622</td>
<td>0.080</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>-</td>
<td>1.695</td>
<td>0.045</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Versus</th>
<th>$0.5 \text{ M Na}_2\text{SO}_4$</th>
<th>3.15 wt% NaCl</th>
<th>ASTM seawater</th>
<th>Seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td>G/E (0°)</td>
<td>-1.335</td>
<td>-1.171</td>
<td>-0.992</td>
<td>-0.975</td>
</tr>
<tr>
<td>G/E (90°)</td>
<td>-1.220</td>
<td>-1.069</td>
<td>-1.005</td>
<td>-0.960</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>-</td>
<td>-1.291</td>
<td>-0.955</td>
<td>-</td>
</tr>
</tbody>
</table>

The comparative analysis of the $i_{\text{Galv}}$ values of both 6061-T6 Al versus graphite/epoxy composite with the fibers in parallel direction and 6061-T6 versus graphite/epoxy composite with the fibers in perpendicular direction showed that the current in the latter case was greater in all the four electrolytes, while the trend was slightly different in the aerated case. While the highest $i_{\text{Galv}}$ of 6061-T6 Al was observed in the case of 0.5M Na$_2$SO$_4$ when coupled to G/E (90°), the lowest was in the case of real sea water when coupled
to G/E (0°) which could be due to the formation of precipitates on the cathodic surfaces. The primary reaction that occurs in a deaerated condition is hydrogen evolution at the cathodic surface and the activation-limited current may vary according to the fiber orientation.

4.5.3 Cathodic polarization

There was no significant difference between the Log i values observed in two different electrolytes (Figure 71). But the galvanic current decreases steeply in ASTM sea water after about 10 hours as observed from the earlier ZRA experiments whereas the polarization experiments were run for only about 5 ½ hours. The precipitation on the cathodic surface took more than 10 hours to sufficiently to limit the current and hence the polarization results were not conclusive.

4.6 Conclusions

The $i_{\text{Galv}}$ values of 6061-T6 Al clearly indicated higher corrosion rates when coupled to graphite/epoxy composite with the fibers in perpendicular direction (90°) than in the parallel direction in aerated and de-aerated conditions in most cases except in aerated 0.5 M $\text{Na}_2\text{SO}_4$ and real sea water. The precipitation of a film on the cathodic surfaces in ASTM seawater and real seawater had significantly limited the current. The precipitation of the film is discussed in detail in the following chapter. The $i_{\text{Galv}}$ values of 6061-T6 Al when coupled to G/E (0° & 90°) and Ti-6Al-4V measured in aerated environments were 2 to 3 orders of magnitude higher than that of those in the de-aerated environments in all the electrolytes.
Chapter 5

ACCELERATED CORROSION EXPERIMENTS IN THE LABORATORY

5.1 Humidity Chamber Experiment

5.1.1 General Background

Accelerated corrosion experiments of dissimilar materials could be very helpful in identifying a general trend of corrosion [19]. The basic objective was to conduct accelerated experiments under different conditions in the laboratory and compare the results with those obtained at the outdoor sites, to see if any trend in the type of corrosion phenomenon could be observed among the different couples. The electrolytes were selected for the accelerated experiments to understand the effects of the distinct chemical composition of each electrolyte on the corrosion of 6061-T6 aluminum.

5.1.2 Samples and Electrolytes

The 6061-T6 aluminum coupons were coupled to the following organic matrix coupons (OMC) and the couples were treated with the different electrolytes. The respective rates of corrosion of 6061-T6 aluminum in each case was later determined. The various OMCs coupled to 6061-T6 aluminum and the electrolytes used are listed here.
OMCs

1. E-glass/epoxy
2. Graphite / epoxy (0°)/Ti
3. Graphite / epoxy (0°)/Nylon
4. Graphite / epoxy (90°)
5. E-glass / G/E(0°)
6. E-glass / G/E(0°) / E-glass
7. SiC / epoxy
8. 3M Alumina / epoxy

Electrolytes

1. 3.15 wt% NaCl
2. 0.5 M Na₂SO₄
3. ASTM sea water
4. Real sea water

5.1.3 Experiment procedure, Conditions, and Set up

Figure 72. OMC/6061-T6 Couples exposed in the Humidity Chamber
The seven different OMC couples that were treated with 3.15 wt% NaCl, 0.5M Na₂SO₄, ASTM seawater, and actual seawater were exposed in a humidity chamber (Figure 72) at 85% RH and 30°C for a period of 3 months. The 6061-T6 aluminum coupons were degreased with acetone, dried, and weighed before the experiment. The 6061-T6 aluminum coupons were weighed in a calibrated METLER AE 163 digital balance to four decimal places. The temperature was controlled by Digi-Sense Model-2186-20 temperature controller; whereas, the humidity was controlled by Electrotech Model 514 Auto-Humidity Controller. The OMC/6061-T6 Al couples were fitted in specimen holders and treated with the respective electrolytes. The OMC/6061-T6 Al couples were dipped in their respective electrolytes for a uniform period of 1 min before being placed in the humidity chamber. Each set contained three similar couples and the average weight loss of 6061-T6 aluminum in each case of three couples was considered for calculations.

At the end of the experiment period of 90 days, the specimens were uncoupled. The exposed 6061-T6 aluminum coupons were cleaned according to international standard procedure ISO 8407:1991(E) C.1.1 by immersion for about 10 minutes in a boiling (80°C - 90°C ) solution containing 2% chromium tri-oxide and 5% phosphoric acid (by weight). Jenway 1103 Digital Hotplate/Stirrer fitted with temperature probe was used for the chemical cleaning of the exposed metal coupons. The chemically cleaned coupons were then ultrasonically cleaned in de-ionized water for 5-10 minutes. The cleaned coupons were dried and weighed. The weight loss data was recorded and the corrosion rate was determined.
5.2 Immersion Experiment

5.2.1 General Background

Immersion in electrolytes was the other type of accelerated corrosion experiment conducted in the laboratory to identify and analyze the different trends of corrosion. The couples were immersed in similar electrolytes that were used to treat the couples exposed in the humidity chamber experiment so that both the results can be compared.

5.2.2 Samples and Electrolytes

The 6061-T6 aluminum coupons were coupled to the following organic matrix coupons (OMC) listed below on the left and the couples were immersed in the different electrolytes listed below on the right and the respective rates of corrosion of 6061-T6 aluminum in each case was later determined.

**OMCs**

1. E-glass/epoxy
2. Graphite / epoxy (0°)/Ti
3. Graphite / epoxy (0°)/Nylon
4. Graphite / epoxy (90°)
5. E-glass / G/E(0°)
6. E-glass / G/E(0°) / E-glass
7. SiC / epoxy
8. 3M Alumina / epoxy

**Electrolytes**

1. 3.15 wt% NaCl
2. 0.5 M Na2SO4
3. ASTM sea water
4. Real sea water
5.2.3 Experiment procedure, Conditions, and Set up

The seven different OMC couples were immersed for three months in 600 ml glass beakers containing 3.15 wt% NaCl, 0.5M Na₂SO₄, ASTM seawater, and actual seawater. The beakers were attached to the base of an aquarium using adhesives. The 30” x 12” x 12” aquariums were then filled with water up to three fourths the height of the beakers. The temperature of the water bath was maintained at 30°C using an AQUA automatic aquarium heater. The water bath was also circulated for temperature uniformity. The metal coupons were cleaned and weighed before the experiment. Finally, at the end of three month’s time, the specimens were again weighed after cleaning according to international standard procedure ISO 8407:1991(E) C.1.1. as mentioned earlier. The corrosion rates were calculated using the formula, Corrosion rate (g/md) = \{Weight Loss (g)\} / \{Interface area (m²) x Exposure period (days)\}.

5.3 Results

5.3.1 Results - Humidity chamber experiments

The corrosion of the 6061-T6 Al primarily occurred at the interface between the metal and the composite (See Figure 73 for an example). Hence, the corrosion rates were calculated based on the interface area between 6061-T6 aluminum and the composite. The average corrosion rate and standard deviations of each set of three similar couples has been tabulated in table 5.

Figure 73. Corrosion at the interface when 6061-T6 Al was coupled to G/E (0°) and treated with 3.15 wt% NaCl and exposed in the Humidity chamber
Figure 74. Legend for the OMC couples exposed in the Humidity Chamber

Table 5. Exposure in Humidity Chamber – Corrosion rates (g/m²d)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Description of couple</th>
<th>0.5 M Na₂SO₄ Avg rate</th>
<th>0.5 M Na₂SO₄ SD</th>
<th>3.15 wt% NaCl Avg rate</th>
<th>3.15 wt% NaCl SD</th>
<th>ASTM sea water Avg rate</th>
<th>ASTM sea water SD</th>
<th>Actual sea water Avg rate</th>
<th>Actual sea water SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>E Glass / Al / Ti</td>
<td>0.068</td>
<td>0.021</td>
<td>0.439</td>
<td>0.121</td>
<td>0.457</td>
<td>0.126</td>
<td>0.681</td>
<td>0.079</td>
</tr>
<tr>
<td>B</td>
<td>Carbon 0° / Al / Ti</td>
<td>0.131</td>
<td>0.089</td>
<td>0.719</td>
<td>0.091</td>
<td>0.545</td>
<td>0.116</td>
<td>1.016</td>
<td>0.070</td>
</tr>
<tr>
<td>C</td>
<td>Carbon 0° / Al / Nylon</td>
<td>0.136</td>
<td>0.073</td>
<td>0.625</td>
<td>0.023</td>
<td>0.609</td>
<td>0.163</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Carbon 90° / Al / Ti</td>
<td>0.220</td>
<td>0.024</td>
<td>0.843</td>
<td>0.041</td>
<td>0.806</td>
<td>0.080</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Carbon 0° / E Glass / Al / Ti</td>
<td>0.149</td>
<td>0.051</td>
<td>0.565</td>
<td>0.054</td>
<td>0.483</td>
<td>0.085</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>E Glass / Carbon 0° / E Glass / Al / Ti</td>
<td>0.143</td>
<td>0.032</td>
<td>0.607</td>
<td>0.127</td>
<td>0.600</td>
<td>0.039</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>SiC / Al / Ti</td>
<td>0.138</td>
<td>0.039</td>
<td>0.488</td>
<td>0.032</td>
<td>0.439</td>
<td>0.083</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>3M Alumina / Al / Ti</td>
<td>0.118</td>
<td>0.038</td>
<td>0.645</td>
<td>0.161</td>
<td>0.589</td>
<td>0.068</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Comparison of corrosion rates in Humidity chamber (90 days)

Weight Loss observed at Interface only

- 0.5 M Sodium sulfate
- 3.15 wt% NaCl
- ASTM Sea water
- Real sea water

Figure 75. Comparison of corrosion rates at the interface when 6061-T6 Al was coupled to OMCs and exposed in the Humidity Chamber
5.3.1.1 SEM and EDAX Analysis

The electron microprobe used for the analysis was CAMECA SX-50 with Kevex EDS system attached to it. The composite specimens that were coupled to 6061-T6 Al and exposed to the humidity chamber were ultrasonically cleaned with 18 MΩ-cm ultrapure water. The specimens were carbon coated before analysis. Film formation was observed on the surface of the G/E (90°) composites that faced the metal coupons in the case of the couples treated with ASTM sea water and exposed in the humidity chamber whereas the ED spectrum rather suggested the formation of an oxide film probably (Fig 76, 77).

Figure 76. SEM photograph of G/E (90°) treated with ASTM sea water showing film formed when coupled with 6061-T6 Al and exposed in Humidity chamber
Figure 77. ED spectrum of G/E (90°) treated with ASTM sea water showing film formed when coupled with 6061-T6 Al and exposed in Humidity chamber
5.3.2. Results – Immersion experiment

The corrosion of the 6061-T6 Al primarily occurs at the interface between the metal and the composite as evident in Figure 78. Therefore, the corrosion rates were based only on the interface area between the OMC and metal. The average corrosion rate and standard deviations of each set of three similar couples has been tabulated.

Figure 78. Corrosion at the interface when 6061-T6 Al was coupled to G/E (90°) and immersed in ASTM sea water

<table>
<thead>
<tr>
<th></th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>E Glass</td>
</tr>
<tr>
<td>B</td>
<td>G/E-0° Ti</td>
</tr>
<tr>
<td>C</td>
<td>G/E-0° Ny</td>
</tr>
<tr>
<td>D</td>
<td>G/E-90°</td>
</tr>
<tr>
<td>E</td>
<td>E Glass/G/E-0°</td>
</tr>
<tr>
<td>F</td>
<td>E Glass/G/E-0° /E Glass</td>
</tr>
<tr>
<td>G</td>
<td>SiC</td>
</tr>
<tr>
<td>H</td>
<td>3M-Alumina</td>
</tr>
</tbody>
</table>

Figure 79. Legend for the OMC couples immersed in the electrolytes
Table 6. Immersion in electrolytes – Corrosion rates (gmd)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Description of couple</th>
<th>0.5 M Na$_2$SO$_4$</th>
<th>3.15 wt% NaCl</th>
<th>ASTM sea water</th>
<th>Actual sea water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Avg rate</td>
<td>SD</td>
<td>Avg rate</td>
<td>SD</td>
</tr>
<tr>
<td>A</td>
<td>E Glass / Al / Ti</td>
<td>0.604</td>
<td>0.060</td>
<td>1.708</td>
<td>0.101</td>
</tr>
<tr>
<td>B</td>
<td>Carbon $0^\circ$ / Al / Ti</td>
<td>0.719</td>
<td>0.028</td>
<td>2.866</td>
<td>0.1582</td>
</tr>
<tr>
<td>C</td>
<td>Carbon $0^\circ$ / Al / Nylon</td>
<td>1.212</td>
<td>0.023</td>
<td>1.463</td>
<td>0.014</td>
</tr>
<tr>
<td>D</td>
<td>Carbon $90^\circ$ / Al / Ti</td>
<td>0.794</td>
<td>0.016</td>
<td>2.821</td>
<td>0.056</td>
</tr>
<tr>
<td>E</td>
<td>Carbon $0^\circ$ / E Glass / Al / Ti</td>
<td>0.599</td>
<td>0.018</td>
<td>3.371</td>
<td>0.026</td>
</tr>
<tr>
<td>F</td>
<td>E Glass / Carbon $0^\circ$ / E Glass / Al / Ti</td>
<td>1.124</td>
<td>0.067</td>
<td>2.214</td>
<td>0.123</td>
</tr>
<tr>
<td>G</td>
<td>SiC / Al / Ti</td>
<td>0.523</td>
<td>0.064</td>
<td>2.572</td>
<td>0.142</td>
</tr>
<tr>
<td>H</td>
<td>3M Alumina / Al / Ti</td>
<td>0.625</td>
<td>0.063</td>
<td>2.411</td>
<td>1.053</td>
</tr>
</tbody>
</table>

Avg. rate – Average corrosion rate (gmd)

SD – Standard Deviation
Comparison of corrosion rates
in Immersion experiment
(90 days)

Weight Loss observed at Interface only

- 0.5 M Sodium sulfate
- 3.15 wt% NaCl
- ASTM Sea water
- Real sea water

![Graph showing comparison of corrosion rates](image)

Figure 80. Comparison of corrosion rates at the interface when 6061-T6 Al was coupled to OMCs and immersed in the electrolytes
5.3.2.1 SEM and EDAX Analysis

The qualitative identification of the constituents of the film formed on the cathodic surfaces using ED spectrometer revealed that magnesium was the most abundant ion present, probably in the form of Mg(OH)$_2$ in the case of couples immersed in ASTM sea water [20, 21] (Fig 81, 82). Very few crystals of calcium containing compounds that were probably calcium carbonate were also found (Fig 83, 84).

Figure 81. SEM photograph of G/E (90°) showing film formed when coupled with 6061-T6 Al due to immersion in ASTM sea water
Figure 82. ED spectrum of G/E (90°) showing presence of Magnesium compounds when coupled with 6061-T6 Al due to immersion in ASTM sea water
Figure 83. SEM photograph of G/E (90°) showing calcium containing crystals when coupled with 6061-T6 Al due to immersion in ASTM sea water
Figure 84. ED spectrum of G/E (90°) showing calcium containing crystals when coupled with 6061-T6 Al due to immersion in ASTM sea water
5.4 Discussions

5.4.1 Discussions - Humidity chamber experiments

Corrosion rates of 6061-T6 aluminum coupled to OMCs and treated with ASTM sea water and 3.15 wt% NaCl were similar but relatively higher than that of those treated with 0.5M Na$_2$SO$_4$. Corrosion rates in the galvanic couples were observed to be slightly higher than that of non-galvanic couples. No significant difference in corrosion rates were observed between the G/E (0°)-6061-T6 couples fastened with Ti-6Al-4V and Nylon. The corrosion rate of the 6061-T6 Aluminum treated with 3.15 wt% NaCl and ASTM sea water were the highest when coupled to G/E (0°) and G/E (90°) composites respectively. The corrosion rate of 6061-T6 Al coupled to the totally insulated sandwich (E-glass, graphite, E-glass epoxy) composite was lower than those coupled with G/E (0°) and G/E (90°) composites but otherwise mostly similar to the partially insulated and non-galvanic couples.

5.4.2 Discussions - Immersion experiments

Highest corrosion rates of the 6061-T6 Al were observed when the couples were immersed in 3.15 wt% NaCl. The corrosion rate was much lower in ASTM seawater when compared to that of 3.15 wt% NaCl for all the couples. A magnesium-rich layer formed on the cathodic graphite/epoxy composite surfaces immersed in ASTM sea water. Crystals containing calcium were also detected in selected regions on top of the magnesium-rich layer on the G/E (90°) OMC immersed in ASTM sea water. In 3.15 wt% NaCl, the highest corrosion rates of 6061-T6 Al were observed when coupled to the G/E composites using the Ti-6Al-4V bolts and the orientation of fibers did not affect the corrosion rates to a great
extent. The corrosion rate was relatively lower when the G/E(0°) composite was coupled using the nylon bolt in comparison to those coupled using the Ti bolt. The corrosion rate of 6061-T6 Al coupled to the totally insulated sandwich (E-glass, graphite, E-glass epoxy) composite was lower than those coupled with G/E(0°) and G/E(90°) composites fastened with Ti-6Al-4V but slightly higher to the case where the G/E(0°) composite was coupled using the nylon bolt.

5.5 Conclusions

Significant corrosion was observed in case of galvanic couples especially with those treated with 3.15 wt% NaCl solution. The type of fastener did not affect the corrosion rate to a great extent. The presence of conducting graphite fibers in the composite (i.e. the galvanic couples) appear to be the primary reason for higher corrosion rates. The formation of Mg rich layer on immersion in ASTM sea water had a significant effect in lowering the corrosion rate. Lower corrosion rates were observed in the case of nylon bolted couples immersed in 3.15 wt% NaCl solution and the orientations of the graphite fibers in OMCs did not affect the corrosion rate greatly. The corrosion rates in the immersion experiments were higher than that of the humidity chamber because the samples were constantly in interaction with the electrolytes in the case of immersion which was not the case in the humidity chamber experiment.
Chapter 6

CORROSION EXPERIMENTS CONDUCTED AT OUTDOOR SITES IN OAHU

6.1 General Background

The spatially diverse climatic conditions of Hawai’i make it an ideal corrosion test field. Six different locations were selected to represent each of the diverse climatic conditions available in the island of Oahu. Seven different types of 6061-T6 aluminum and organic matrix composite couples were exposed at these test sites.

6.2 Corrosion Test Racks and Coupons

The corrosion test racks were fabricated from Trex wood which is a recycled wood and plastic composite. Trex composite wood has excellent resistance to harsh weather conditions and resists moisture, insects, and sunlight. The test racks were designed and built by George Hawthorn of the Hawaii Corrosion Laboratory. The test racks were built with ten horizontal slats each of 84” width. The height was 30” and 50.5” in the front and rear respectively. The distance between front and rear legs was 35.5”. The test racks were painted in white. The specimens were mounted at an angle of 30° to the horizontal [22]. The location of each of the six test sites (Figure 85) and their respective significances (Tables 7-12) are covered in the next section.
6.3 Location and Significance of Test Sites

*Courtesy: George Hawthorn, Hawaii corrosion lab

*Figure 85. Test Site Locations at Oahu*

The test sites at Lyon arboretum (Manoa) and Coconut Island are located on University of Hawaii at Manoa property; whereas, the other four sites are located on Hawaiian Electric Company, Inc. property.
Figure 86. Test Site at Lyon arboretum, Manoa*

Table 7. Significance of the Test Site at Lyon arboretum, Manoa

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude *</td>
<td>21° 19’ 58” N</td>
</tr>
<tr>
<td>Longitude *</td>
<td>157° 48’ 12” W</td>
</tr>
<tr>
<td>Type of Environment</td>
<td>Rain forest</td>
</tr>
<tr>
<td>Rainfall recorded (For 90 days) *</td>
<td>61.99 inches</td>
</tr>
<tr>
<td>Elevation from sea level *</td>
<td>520 ft</td>
</tr>
</tbody>
</table>

*Courtesy: George Hawthorn, Hawaii corrosion lab
Figure 87. Test Site at Coconut Island*

Table 8. Significance of the Test Site at Coconut Island

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude *</td>
<td>21° 26' 09'' N</td>
</tr>
<tr>
<td>Longitude *</td>
<td>157° 47' 15'' W</td>
</tr>
<tr>
<td>Type of Environment</td>
<td>Marine</td>
</tr>
<tr>
<td>Distance from the ocean</td>
<td>10 meters</td>
</tr>
<tr>
<td>Rainfall recorded (For 90 days) *</td>
<td>10.03 inches</td>
</tr>
<tr>
<td>Elevation from sea level *</td>
<td>10 ft</td>
</tr>
</tbody>
</table>

*Courtesy: George Hawthorn, Hawaii corrosion lab
Table 9. Significance of the Test Site at Campbell Industrial Park

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude *</td>
<td>$21^\circ 18' 00''$ N</td>
</tr>
<tr>
<td>Longitude *</td>
<td>$158^\circ 06' 00''$ W</td>
</tr>
<tr>
<td>Type of Environment</td>
<td>Industrial</td>
</tr>
<tr>
<td>Major pollutant in atmosphere</td>
<td>SO$_2$</td>
</tr>
<tr>
<td>Rainfall recorded (For 90 days) *</td>
<td>4.05 inches</td>
</tr>
<tr>
<td>Elevation from sea level *</td>
<td>80 ft</td>
</tr>
</tbody>
</table>

*Courtesy: George Hawthorn, Hawaii corrosion lab

**Courtesy: Ryan Sugamoto, Hawaii corrosion lab
Figure 89. Test Site at Ewa Nui **

Table 10. Significance of the Test Site at Ewa Nui

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude *</td>
<td>$21^\circ 24' 00''$ N</td>
</tr>
<tr>
<td>Longitude *</td>
<td>$158^\circ 00' 00''$ W</td>
</tr>
<tr>
<td>Type of Environment</td>
<td>Agricultural</td>
</tr>
<tr>
<td>Rainfall recorded (For 90 days) *</td>
<td>2.18 inches</td>
</tr>
<tr>
<td>Elevation from sea level *</td>
<td>200 ft</td>
</tr>
</tbody>
</table>

*Courtesy: George Hawthorn, Hawaii corrosion lab

**Courtesy: Ryan Sugamoto, Hawaii corrosion lab
Figure 90. Test Site at Kahuku **

Table 11. Significance of the Test Site at Kahuku

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude *</td>
<td>21° 42' 00&quot; N</td>
</tr>
<tr>
<td>Longitude *</td>
<td>157° 54' 00&quot; W</td>
</tr>
<tr>
<td>Type of Environment</td>
<td>Marine</td>
</tr>
<tr>
<td>Direction of the trade winds</td>
<td>North-East</td>
</tr>
<tr>
<td>Rainfall recorded (For 90 days) *</td>
<td>19.4 inches</td>
</tr>
<tr>
<td>Elevation from sea level *</td>
<td>80 ft</td>
</tr>
</tbody>
</table>

* Courtesy: George Hawthorn, Hawaii corrosion lab
** Courtesy: Ryan Sugamoto, Hawaii corrosion lab
Table 12. Significance of the Test Site at Waipahu

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude *</td>
<td>21° 24' 00&quot; N</td>
</tr>
<tr>
<td>Longitude *</td>
<td>158° 00' 00&quot; W</td>
</tr>
<tr>
<td>Type of Environment</td>
<td>Dry</td>
</tr>
<tr>
<td>Rainfall recorded (For 90 days) *</td>
<td>11.58 inches</td>
</tr>
<tr>
<td>Elevation from sea level *</td>
<td>130 ft</td>
</tr>
</tbody>
</table>

*Courtesy: George Hawthorn, Hawaii corrosion lab

**Courtesy: Ryan Sugimoto, Hawaii corrosion lab
6.4 Experiment procedure, Conditions, and Set up

The 6061-T6 aluminum coupons were coupled to the following organic matrix coupons (OMC) and the couples were exposed at the different sites. The corrosion rates of corrosion of 6061-T6 aluminum for each case was later determined.

**OMCs**

1. E-glass/epoxy
2. Graphite / epoxy ($0^\circ$)/Ti
3. Graphite / epoxy ($0^\circ$)/Nylon
4. Graphite / epoxy ($90^\circ$)
5. E-glass / G/E($0^\circ$)
6. E-glass / G/E($0^\circ$)/ E-glass
7. SiC / epoxy
8. 3M Alumina / epoxy

**Outdoor Sites**

1. Lyon arboretum, Manoa
2. Coconut Island
3. Waipahu
4. Campbell Industrial Park
5. Kahuku
6. Ewanui

6.5 Results

The corrosion of the 6061-T6 Al primarily occurred at the interface between the metal and the composite as evident from the Figure 92. Therefore, the corrosion rates were calculated based on the total area and the interface area (Section 5.2.3 Pg. 88). The average and standard deviation of the corrosion rate of three samples for each of the couples at the test sites are shown in table 13.

![Figure 92. Corrosion at the interface when 6061-T6 Al was coupled to G/E ($90^\circ$) and exposed at Lyon arboretum, Manoa](image)
Table 13. Exposure at outdoor sites – Corrosion rates (gmd)

(Weight Loss based on the Total Surface Area)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Manoa</th>
<th>Coconut Island</th>
<th>Waipahu</th>
<th>Campbell</th>
<th>Ewanui</th>
<th>Kahuku</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg rate</td>
<td>SD</td>
<td>Avg rate</td>
<td>SD</td>
<td>Avg rate</td>
<td>SD</td>
</tr>
<tr>
<td>A</td>
<td>0.004</td>
<td>0.001</td>
<td>0.011</td>
<td>0.004</td>
<td>0.006</td>
<td>0.001</td>
</tr>
<tr>
<td>B</td>
<td>0.024</td>
<td>0.001</td>
<td>0.018</td>
<td>0.002</td>
<td>0.009</td>
<td>0.002</td>
</tr>
<tr>
<td>C</td>
<td>0.023</td>
<td>0.004</td>
<td>0.015</td>
<td>&lt;1e⁻³</td>
<td>0.008</td>
<td>&lt;1e⁻³</td>
</tr>
<tr>
<td>D</td>
<td>0.026</td>
<td>0.005</td>
<td>0.026</td>
<td>0.006</td>
<td>0.012</td>
<td>&lt;1e⁻³</td>
</tr>
<tr>
<td>E</td>
<td>0.021</td>
<td>&lt;1e⁻³</td>
<td>0.018</td>
<td>0.004</td>
<td>0.008</td>
<td>&lt;1e⁻³</td>
</tr>
<tr>
<td>F</td>
<td>0.006</td>
<td>0.001</td>
<td>0.006</td>
<td>0.005</td>
<td>0.004</td>
<td>0.003</td>
</tr>
<tr>
<td>G</td>
<td>0.006</td>
<td>&lt;1e⁻³</td>
<td>0.005</td>
<td>&lt;1e⁻³</td>
<td>0.005</td>
<td>0.002</td>
</tr>
<tr>
<td>H</td>
<td>0.011</td>
<td>0.001</td>
<td>0.006</td>
<td>0.001</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>0.002</td>
<td>0.001</td>
<td>0.004</td>
<td>&lt;1e⁻³</td>
<td>0.004</td>
<td>&lt;1e⁻³</td>
</tr>
</tbody>
</table>

Avg. rate – Average corrosion rate (gmd)

SD – Standard Deviation
Table 14. Exposure at outdoor sites – Corrosion rates (gmd)

(Calculations based on relative corrosion rates primarily due to the composites)

<table>
<thead>
<tr>
<th>S.No</th>
<th>Manoa Avg rate</th>
<th>SD</th>
<th>Coconut Island Avg rate</th>
<th>SD</th>
<th>Waipahu Avg rate</th>
<th>SD</th>
<th>Campbell Avg rate</th>
<th>SD</th>
<th>Ewanui Avg rate</th>
<th>SD</th>
<th>Kahuku Avg rate</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.030</td>
<td>0.013</td>
<td>0.083</td>
<td>0.055</td>
<td>0.033</td>
<td>0.020</td>
<td>0.021</td>
<td>0.015</td>
<td>0.055</td>
<td>0.015</td>
<td>0.090</td>
<td>0.051</td>
</tr>
<tr>
<td>B</td>
<td>0.273</td>
<td>0.023</td>
<td>0.174</td>
<td>0.029</td>
<td>0.067</td>
<td>0.050</td>
<td>0.041</td>
<td>0.023</td>
<td>0.075</td>
<td>0.003</td>
<td>0.155</td>
<td>0.076</td>
</tr>
<tr>
<td>C</td>
<td>0.268</td>
<td>0.053</td>
<td>0.144</td>
<td>0.004</td>
<td>0.053</td>
<td>0.005</td>
<td>0.095</td>
<td>0.049</td>
<td>0.126</td>
<td>0.085</td>
<td>0.101</td>
<td>0.003</td>
</tr>
<tr>
<td>D</td>
<td>0.303</td>
<td>0.066</td>
<td>0.280</td>
<td>0.087</td>
<td>0.107</td>
<td>0.003</td>
<td>0.146</td>
<td>0.049</td>
<td>0.133</td>
<td>0.030</td>
<td>0.199</td>
<td>0.013</td>
</tr>
<tr>
<td>E</td>
<td>0.235</td>
<td>0.006</td>
<td>0.178</td>
<td>0.056</td>
<td>0.053</td>
<td>0.011</td>
<td>0.075</td>
<td>0.010</td>
<td>0.114</td>
<td>0.023</td>
<td>0.084</td>
<td>0.003</td>
</tr>
<tr>
<td>F</td>
<td>0.054</td>
<td>0.023</td>
<td>0.022</td>
<td>0.017</td>
<td>0.030</td>
<td>0.013</td>
<td>0.016</td>
<td>0.011</td>
<td>0.048</td>
<td>0.007</td>
<td>0.022</td>
<td>0.002</td>
</tr>
<tr>
<td>G</td>
<td>0.050</td>
<td>0.006</td>
<td>0.012</td>
<td>0.006</td>
<td>0.085</td>
<td>0.006</td>
<td>0.032</td>
<td>0.010</td>
<td>0.039</td>
<td>0.006</td>
<td>0.114</td>
<td>0.042</td>
</tr>
<tr>
<td>H</td>
<td>0.011</td>
<td>0.017</td>
<td>0.025</td>
<td>0.018</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Avg. rate – Average corrosion rate (gmd)

SD – Standard Deviation
6.5.1 Comparison of corrosion rates at outdoor sites

Figure 93. Legend for OMC couples at outdoor sites

<table>
<thead>
<tr>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  E Glass</td>
</tr>
<tr>
<td>B  G/E-0° Ti</td>
</tr>
<tr>
<td>C  G/E-0° Ny</td>
</tr>
<tr>
<td>D  G/E-90°</td>
</tr>
<tr>
<td>E  E Glass/G/E-0°</td>
</tr>
<tr>
<td>F  E Glass/G/E-0° /E Glass</td>
</tr>
<tr>
<td>G  SiC</td>
</tr>
<tr>
<td>H  3M-Alumina</td>
</tr>
<tr>
<td>I  6061-T6 Al</td>
</tr>
</tbody>
</table>

Figure 94. Comparison of corrosion rates at outdoor sites

Comparison of corrosion rates at six Oahu sites (90 days)

Weight loss observed at both sides
6.5.2 Discussions

The 6061-T6 Al coupled to G/E (90°) recorded the highest corrosion rate at all the sites. The corrosion rates of 6061-T6 Al in non-galvanic (E-glass/epoxy composite, E-glass epoxy/graphite epoxy/E-glass epoxy hybrid composite, and SiC/epoxy composite) couples were much lower when compared to those of the galvanic couples. The presence of
graphite fibers in the organic matrix composites coupled to the metal was primarily the reason for the corrosion of the galvanic couples. The different types of fasteners e.g. (Ti-6Al-4V & Nylon) did not affect the corrosion rate of the 6061-T6 Al coupled to G/E (0°) to a great extent. The corrosion rate of 6061-T6 Al coupled to the totally insulated sandwich (E-glass, graphite, E-glass/epoxy hybrid) composite was nearly one third that of the galvanic couples.

6.5.3 Conclusions

The results from the field tests at the six different sites showed that the corrosion rates were very high in the galvanic couples compared to the non-galvanic couples, and similar to the results observed in the laboratory corrosion experiments. Different types of fasteners did not affect the corrosion rate greatly. The corrosion rate in the case of 6061-T6 Al coupled to G/E (90°) were relatively higher than that of those coupled to G/E (0°). The corrosion rates observed at the highly humid rainforest environment at Manoa, marine environment at Coconut Island, and at Kahuku facing the north east trade winds were higher compared to the other three sites. The chloride content in the atmosphere was very high at the two marine sites at Coconut Island and Kahuku which was one of the major factors for the higher corrosion rates observed. A similar trend of higher corrosion rates in the case of 6061-T6 Al coupled to G/E (90°) was also observed in the accelerated corrosion experiments conducted in the laboratory.
Chapter 7

FTIR ANALYSIS OF ENVIRONMENTAL DEGRADATION OF ORGANIC MATRIX COMPOSITES

7.1 General Background

The composites used for the research have an epoxy matrix, which are generally superior to many other resin types in their mechanical properties and resistance to degradation. Epoxy is a polymer-based chemical group where oxygen and two carbon atoms bond in a unique manner [23]. However, the composite materials undergo certain amount of environmental degradation even though they are not vulnerable to aqueous corrosion due to their chemical stability. Moisture absorption could be a significant cause of degradation of composite materials [24, 25]. Moist environments can severely degrade the mechanical properties of glass reinforced epoxy composites [26]. The composites that were coupled to the metal coupons and exposed in the accelerated corrosion experiments and at the outdoor sites were analyzed for the degradation due to different environments. Fourier transform infrared (FTIR) spectroscopy was performed on the surfaces of the composites to analyze the degradation due to the exposure in various environmental conditions. The organic matrix composites analyzed were E-glass/epoxy, graphite/epoxy (0° and 90°), silicon carbide/epoxy, and 3M alumina/epoxy. The spectra were compared to that of the unexposed virgin samples. The peaks were identified.
7.2 Instrument and Technique

Continuum infrared microscope manufactured by Thermo Electron Corporation was used in the analysis. A very effective technique for both qualitative and quantitative analysis called as Attenuated Total Reflection (ATR) was adopted. The salient features of this technique are

- Easy, Fast and Non-destructive
- Flexibility of samples
- Excellent for Quantitative analysis
- Surface studies
- Crystal type can be changed

The surfaces of all the composite samples were flat and polished. The samples were ultrasonically cleaned in 18 MΩ-cm ultra pure water and dried before they were analyzed under the infrared microscope using ATR technique. A silicon crystal ATR lens was used to analyze the degradation of the epoxy matrix in the composites. The microscope is fitted with a contact alert system to monitor the pressure applied to the sample because excess pressure can damage the crystal. Hence optimum pressure is applied and the spectra are generated by setting the experiment parameters. A background was taken before each spectrum. The sides facing the metal coupon and the side facing the environment were analyzed. Three spectra were taken for each of the composite samples. Figures 96 to 99 are the spectra of unexposed virgin composite samples that will be later compared to that of the exposed samples to analyze the effect of the environment.
OMNIC FTIR software was used in the entire analysis. Figure 101 is the comparison of all the virgin spectra.

7.3 FTIR Spectra of Virgin Composite Samples

![FTIR spectrum of a virgin E-glass/epoxy composite](image)

**Figure 96.** FTIR spectrum of a virgin E-glass/epoxy composite
Figure 97. FTIR spectrum of a virgin graphite/epoxy (0°) composite
Figure 98. FTIR spectrum of a virgin graphite/epoxy (90°) composite
Figure 99. FTIR spectrum of a virgin Silicon carbide/epoxy composite
Figure 100. FTIR spectrum of a virgin 3 M Alumina/epoxy composite
7.3.1 Discussion - FTIR Spectra of Virgin Composite Samples

The common peaks that were identified among the different composites are discussed in this section. The spectra of virgin E-glass/epoxy and graphite/epoxy (0°) looked very identical (Figure 96-97) as they were made of the same epoxy matrix. Some common peaks
were observed among the four types of composites. Certain new peaks in the case of the SiC/epoxy and 3M alumina/epoxy composites were also identified. All the identified peaks in A, B, C, and D have been approximately grouped together and listed in the table 16 [27]. The legends used to denote the various spectra of the different composites are classified in table 15.

Table 15. Legends for spectra of different composites exposed in the accelerated corrosion experiments and virgin samples

<table>
<thead>
<tr>
<th>Description</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface of virgin E-glass/epoxy composite</td>
<td>A</td>
</tr>
<tr>
<td>Surface of virgin graphite/epoxy (0°) composite</td>
<td>B</td>
</tr>
<tr>
<td>Surface of virgin SiC/epoxy composite</td>
<td>C</td>
</tr>
<tr>
<td>Surface of virgin 3M alumina/epoxy composite</td>
<td>D</td>
</tr>
<tr>
<td>Surface of E-glass/epoxy composite facing 6061-T6 Al in the couple</td>
<td>A&lt;sup&gt;M&lt;/sup&gt;</td>
</tr>
<tr>
<td>Surface of E-glass/epoxy composite facing solution</td>
<td>A&lt;sub&gt;S&lt;/sub&gt;</td>
</tr>
<tr>
<td>Surface of graphite/epoxy (0°) composite facing 6061-T6 Al in the couple</td>
<td>B&lt;sup&gt;M&lt;/sup&gt;</td>
</tr>
<tr>
<td>Surface of graphite/epoxy (0°) composite facing solution</td>
<td>B&lt;sub&gt;S&lt;/sub&gt;</td>
</tr>
<tr>
<td>Surface of graphite/epoxy (90°) composite facing 6061-T6 Al in the couple</td>
<td>E&lt;sup&gt;M&lt;/sup&gt;</td>
</tr>
<tr>
<td>Surface of graphite/epoxy (90°) composite facing solution</td>
<td>E&lt;sub&gt;S&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
Table 16. Identification of peaks of virgin composite spectra

<table>
<thead>
<tr>
<th>Wave numbers (cm(^{-1}))</th>
<th>Composites</th>
<th>Approx. Fragment and Type [27]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3300 up to 3400</td>
<td>A, B, C &amp; D</td>
<td>N-H stretching vibration</td>
</tr>
<tr>
<td>2920 up to 2930</td>
<td>A, B, C &amp; D</td>
<td>C-H stretching vibration</td>
</tr>
<tr>
<td>2130 up to 2175</td>
<td>A &amp; B</td>
<td>CN stretching vibrations</td>
</tr>
<tr>
<td>1730 up to 1780</td>
<td>A, B, C &amp; D</td>
<td>C=C stretching vibration</td>
</tr>
<tr>
<td>1600 up to 1620</td>
<td>A, B, C &amp; D</td>
<td>Amide C=O stretching vibration</td>
</tr>
<tr>
<td>1510 up to 1510</td>
<td>A, B, C &amp; D</td>
<td>N=N stretching vibration</td>
</tr>
<tr>
<td>1450 up to 1480</td>
<td>A, B, C &amp; D</td>
<td>C-H sym. deformation vibration</td>
</tr>
<tr>
<td>1290 up to 1300</td>
<td>A, B, C &amp; D</td>
<td>C-H in-plane deformation vibration</td>
</tr>
<tr>
<td>1220 up to 1245</td>
<td>A, B, C &amp; D</td>
<td>C-H deformation vibration</td>
</tr>
<tr>
<td>1025 up to 1050</td>
<td>A, B, C &amp; D</td>
<td>C-O stretching vibration</td>
</tr>
<tr>
<td>1170 up to 1190</td>
<td>A, B, C &amp; D</td>
<td>CH(_3) rocking vibration</td>
</tr>
</tbody>
</table>
7.4 FTIR Spectra of Composite Samples exposed in the Humidity Chamber and the Immersion Experiments

7.4.1 Comparison of Spectra

The effect of 3.15 wt% NaCl on the E-glass/epoxy and graphite/epoxy (0° & 90°) composites coupled to 6061-T6 Al in the accelerated corrosion experiments was analyzed in detail. Three spectra were taken for each case to check for consistency. Spectra on the surfaces facing the metal and the solution/environment were taken to contrast and compare with the spectra of the respective virgin samples. Figure 101 show the comparison of spectra taken on the two surfaces of the E-glass/epoxy composite (i.e. metal facing and environment facing) that was coupled to 6061-T6 Al, treated with 3.15 wt% NaCl, and exposed in the humidity chamber with that of the virgin spectra. Similarly figures 102 and 103 show the respective comparisons of graphite/epoxy (0°) and graphite/epoxy (90°) composites in the humidity chamber experiments. Figure 104 show the comparison of spectra taken on the two surfaces of the E-glass/epoxy composite (i.e. metal facing and solution facing) that was coupled to 6061-T6 Al, immersed in 3.15 wt% NaCl with that of the virgin spectra. Similarly figures 105 and 106 show the respective comparisons of graphite/epoxy (0°) and graphite/epoxy (90°) composites in the immersion experiments.
7.4.2 Results – Humidity chamber

Figure 102. Comparison of FTIR spectra of E-glass/epoxy composite facing 6061-T6 Al (AM) and environment (AS) treated with 3.15 wt% NaCl in the Humidity chamber with the spectrum of the virgin composite.

The intensity of the peak at ~2170 cm\(^{-1}\) very slightly decreased in AS and at ~1735 cm\(^{-1}\) in AM. Variations of intensities of the peaks at ~1183 cm\(^{-1}\) and ~1111 cm\(^{-1}\) in AM and A respectively were found in AS.
Figure 103. Comparison of FTIR spectra of graphite/epoxy (0°) composite facing 6061-T6 Al (B^M) and solution (B_s) treated with 3.15 wt% NaCl in the Humidity chamber with the spectrum of the virgin composite

It was observed that B_s was mostly similar to that of B except for the slight variation of intensity of peak at ~1735 cm\(^{-1}\). All the peaks between 1000 cm\(^{-1}\) and 1400 cm\(^{-1}\) were found flattened in B^M. The spectra B^M looks different due to the difficulty in positioning the ATR crystal on the surface of the composite due to the interference of the fibers.
Figure 104. Comparison of FTIR spectra of graphite/epoxy (90°) composite facing 6061-T6 Al (E\textsuperscript{M}) and solution (E\textsubscript{s}) treated with 3.15 wt% NaCl in the Humidity chamber with the spectrum of the virgin composite.

It was rather very difficult to obtain a clear spectrum on E\textsuperscript{M} due to the interference of the graphite fibers but the comparison of the spectra shows the slight variation of intensity of peak at \( \sim 1740 \text{ cm}^{-1} \) on the exposed composites.
7.4.3 Discussion – Humidity chamber

The slight variation of intensities in the region 1155 up to 1175 cm$^{-1}$ in $A_S$ could be due to O-C stretching vibration. The spectra for the E-Glass composites did not show any significant variations in intensities after exposure [27].
Figure 105. Comparison of FTIR spectra of E-glass/epoxy composite facing 6061-T6 Al ($A^M$) and solution ($A_s$) immersed in 3.15 wt% NaCl with the spectrum of the virgin composite

The relative intensities at $\sim$1570 cm$^{-1}$ and $\sim$1605 cm$^{-1}$ in $A$ have slightly changed in $A^M$ and $A_s$. 

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Figure 106. Comparison of FTIR spectra of graphite/epoxy (0°) composite facing 6061-T6 Al (BM) and solution (BS) immersed in 3.15 wt% NaCl with the spectrum of the virgin composite.

Similar to the earlier case, the intensity of the peak at ~1570 cm⁻¹ in B slightly decreased in BM and BS.
Figure 107. Comparison of FTIR spectra of graphite/epoxy $(90^\circ)$ composite facing 6061-T6 Al $(E^M)$ and solution $(E_S)$ and solution immersed in 3.15 wt% NaCl with the spectrum of the virgin composite

The spectra obtained in this case were not distinct to analyze the differences in detail due to the possible interference of the fibers while positioning the ATR crystal on the surface.
7.4.5 Discussions – Immersion

Other than the slight variations in intensities in the region 1555 up to 1575 cm\(^{-1}\) which could be due to N=N stretching vibration, there were no significant differences in the relative spectra obtained after immersion [27].

7.4.6 Conclusions

The spectra of the E-Glass and graphite epoxy composites exposed in humidity chamber and immersion experiments did not show any significant degradation of the epoxy matrix.

7.5 FTIR Spectra of Composites exposed at the Outdoor Sites
7.5.1 Comparison of Spectra

The environmental effect on the organic matrix composites coupled to 6061-T6 Al at the six different sites was analyzed in detail. Three spectra were taken for each case to check for consistency. The five different type of composites analyzed were E-glass/epoxy, graphite/epoxy (0°), graphite/epoxy (90°), SiC/epoxy, and 3M alumina/epoxy composite. The first four types were exposed at all the six sites mentioned earlier but 3M alumina/epoxy composites were exposed only at Manoa and Coconut Island. Spectra on the surfaces facing the metal and the environment were taken to contrast and compare with the spectra of the respective virgin samples. Figures 107 to 110 show the comparison of spectra taken on the two surfaces of the composites exposed at Waipahu with that of the virgin spectra. Figures 111 to 114 show the comparison of spectra taken on the two surfaces of the composites exposed at Campbell Industrial Park with that of the virgin spectra. Figures 115 to 118 show the comparison of spectra taken on the two surfaces of the composites exposed at Kahuku with that of the virgin spectra. Figures 119 to 122 show the comparison of spectra taken on the two surfaces of the composites exposed at Ewanui with that of the virgin spectra. Figures 123 to 127 show the comparison of spectra taken on the two surfaces of the composites exposed at Lyon arboretum, Manoa with that of the virgin spectra. Figures 128 to 132 show the comparison of spectra taken on the two surfaces of the composites exposed at Coconut Island with that of the virgin spectra.

The legends used to denote the various spectra of the different composites are classified in table 17.
Table 17. Legends for spectra of different composites exposed at the outdoor sites and virgin samples

<table>
<thead>
<tr>
<th>Description</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface of virgin E-glass/epoxy composite</td>
<td>A</td>
</tr>
<tr>
<td>Surface of virgin graphite/epoxy (0°) composite</td>
<td>B</td>
</tr>
<tr>
<td>Surface of virgin graphite/epoxy (90°) composite</td>
<td>E</td>
</tr>
<tr>
<td>Surface of virgin SiC/epoxy composite</td>
<td>C</td>
</tr>
<tr>
<td>Surface of virgin 3M alumina/epoxy composite</td>
<td>D</td>
</tr>
<tr>
<td>Surface of E-glass/epoxy composite facing 6061-T6 Al in the couple</td>
<td>A&lt;sup&gt;M&lt;/sup&gt;</td>
</tr>
<tr>
<td>Surface of E-glass/epoxy composite facing environment</td>
<td>A&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>Surface of graphite/epoxy (0°) composite facing 6061-T6 Al in the couple</td>
<td>B&lt;sup&gt;M&lt;/sup&gt;</td>
</tr>
<tr>
<td>Surface of graphite/epoxy (0°) composite facing environment</td>
<td>B&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>Surface of graphite/epoxy (90°) composite facing 6061-T6 Al in the couple</td>
<td>E&lt;sup&gt;M&lt;/sup&gt;</td>
</tr>
<tr>
<td>Surface of graphite/epoxy (90°) composite facing environment</td>
<td>E&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>Surface of SiC/epoxy composite facing 6061-T6 Al in the couple</td>
<td>C&lt;sup&gt;M&lt;/sup&gt;</td>
</tr>
<tr>
<td>Surface of SiC/epoxy composite facing environment</td>
<td>C&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>Surface of 3M alumina/epoxy composite facing 6061-T6 Al in the couple</td>
<td>D&lt;sup&gt;M&lt;/sup&gt;</td>
</tr>
<tr>
<td>Surface of 3M alumina/epoxy composite facing environment</td>
<td>D&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

7.5.2 Results - Waipahu

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Figure 108. Comparison of FTIR spectra of E-glass/epoxy composite facing 6061-T6 Al ($A^M$) and the environment ($A_E$) at Waipahu with the spectrum of the virgin composite

At ~1700 cm$^{-1}$ in $A_E$, a steep shoulder emerges in the spectrum. Similarly, variations in intensities were observed between 1500 and 1180 cm$^{-1}$ in $A_E$. 
Figure 109. Comparison of FTIR spectra of graphite/epoxy (0°) composite facing 6061-T6 Al (B^M) and the environment (B_E) at Waipahu with the spectrum of the virgin composite

A steep shoulder emerges in the spectrum at ~1700 cm\(^{-1}\) in B_E as observed in the earlier case.
Figure 110. Comparison of FTIR spectra of graphite/epoxy (90°) composite facing 6061-T6 Al (E^M) and the environment (E_E) at Waipahu with the spectrum of the virgin composite.

A valid spectrum of the epoxy matrix could not be obtained due to the interference of the graphite fibers. The epoxy used was identical in both 0° and 90° orientations.
Figure 111. Comparison of FTIR spectra of SiC/epoxy composite facing 6061-T6 Al (C^M) and the environment (C_E) at Waipahu with the spectrum of the virgin composite

Variation of intensity at ~1700 cm\(^{-1}\) in C_E was observed with the emergence of a small shoulder.
7.5.2.1 Discussions – Waipahu

The commonly observed trend was the emergence of a steep shoulder around 1700 cm\(^{-1}\) in the spectra of the E-glass and graphite epoxy composites on the surfaces exposed to the environment which could be due to C=O stretching vibration. Similar trend was seen in the spectra of the exposed surface of the SiC epoxy composite but the intensity was relatively lesser [27].
7.5.3 Results – Campbell Industrial Park

Figure 112. Comparison of FTIR spectra of E-glass/epoxy composite facing 6061-T6 Al ($A^M$) and the environment ($A_E$) at Campbell Industrial Park with the spectrum of the virgin composite

A significant change in the spectrum was observed at ~1700 cm$^{-1}$ in $A_E$ due to the emergence of the steep shoulder.
Figure 113. Comparison of FTIR spectra of graphite/epoxy ($0^\circ$) composite facing 6061-T6 Al ($B^M$) and the environment ($B_E$) at Campbell Industrial Park with the spectrum of the virgin composite

It was just the similar trend as in the earlier case with E-Glass epoxy composite.
Figure 114. Comparison of FTIR spectra of graphite/epoxy (90°) composite facing 6061-T6 Al (E_M) and the environment (E_E) at Campbell Industrial Park with the spectrum of the virgin composite.

A valid spectrum of the epoxy matrix could not be obtained due to the interference of the graphite fibers. The epoxy used was identical in both 0° and 90° orientations.
Figure 115. Comparison of FTIR spectra of SiC/epoxy composite facing 6061-T6 Al (C_M) and the environment (C_E) at Campbell Industrial Park with the spectrum of the virgin composite

Slight variations in intensities were observed in the range between 1500 cm\(^{-1}\) and 1600 cm\(^{-1}\) in C_E.
7.5.3.1 Discussions – Campbell Industrial Park

The commonly observed trend was the emergence of a steep shoulder around 1700 cm\(^{-1}\) in the spectra of the E-glass and graphite epoxy composites on the surfaces exposed to the environment which could be due to C=O stretching vibration. The spectra of the exposed surface of the SiC epoxy composite did not show any variations of intensities as observed earlier [27].
7.5.4 Results – Kahuku

Figure 116. Comparison of FTIR spectra of E-glass/epoxy composite facing 6061-T6 Al (AM) and the environment (AE) at Kahuku with the spectrum of the virgin composite

A significant change in the spectrum was observed at ~1700 cm\(^{-1}\) in AE due to the emergence of the steep shoulder.
Figure 117. Comparison of FTIR spectra of graphite/epoxy (0°) composite facing 6061-T6 Al (B^M) and the environment (B_E) at Kahuku with the spectrum of the virgin composite

A steep shoulder emerges in the spectrum at \( \sim 1700 \text{ cm}^{-1} \) in B_E as observed in the earlier case.
Figure 118. Comparison of FTIR spectra of graphite/epoxy (90°) composite facing 6061-T6 Al (Eₘ) and the environment (Eₑ) at Kahuku with the spectrum of the virgin composite

A valid spectrum of the epoxy matrix could not be obtained due to the interference of the graphite fibers. The epoxy used was identical in both 0° and 90° orientations.
Figure 119. Comparison of FTIR spectra of SiC/epoxy composite facing 6061-T6 Al (C_M) and the environment (C_E) at Kahuku with the spectrum of the virgin composite.

A small shoulder emerges in the spectrum at ~1700 cm\(^{-1}\) in C_E.
7.5.4 Discussions – Kahuku

The commonly observed trend was the emergence of a steep shoulder around 1700 cm$^{-1}$ in the spectra of the E-glass and graphite epoxy composites on the surfaces exposed to the environment which could be due to C=O stretching vibration. Similar trend was seen in the spectra of the exposed surface of the SiC epoxy composite but the intensity was relatively lesser [27].
7.5.5 Results - Ewanui

![Figure 120. Comparison of FTIR spectra of E-glass/epoxy composite facing 6061-T6 Al (A_M) and the environment (A_E) at Ewanui with the spectrum of the virgin composite](image)

In this case intensity variations were observed at ~1715 cm\(^{-1}\) in A_E. The spectra for A_M and A_E show some noise due to different scan rates that were applied.
Figure 121. Comparison of FTIR spectra of graphite/epoxy (0°) composite facing 6061-T6 Al (B⁸) and the environment (Bₑ) at Ewanui with the spectrum of the virgin composite

In this case slight variations in intensities of the peaks at ~1641 cm⁻¹ and ~1232 cm⁻¹ were found in Bₑ with the emergence of a small shoulder at 1700 cm⁻¹.
Figure 122. Comparison of FTIR spectra of graphite/epoxy ($90^\circ$) composite facing 6061-T6 Al (E$^M$) and the environment (E$^E$) at Ewanui with the spectrum of the virgin composite.

A valid spectrum of the epoxy matrix could not be obtained due to the interference of the graphite fibers. The epoxy used was identical in both $0^\circ$ and $90^\circ$ orientations.
Figure 123. Comparison of FTIR spectra of SiC/epoxy composite facing 6061-T6 ($C^M$) and the environment ($C_E$) at Ewanui with the spectrum of the virgin composite

Slight variations in peak intensities at $\sim 1700$ cm$^{-1}$ were found in $C_E$. The noise observed in $C_E$ and $C^M$ is due to higher resolution settings.
The common trend observed was the emergence of a steep shoulder around 1700 cm\(^{-1}\) in the spectra of the E-glass and graphite epoxy composites on the surfaces exposed to the environment which could be due to C=O stretching vibration. Similar trend was seen in the spectra of the exposed surface of the SiC epoxy composite but the intensity was relatively lesser. The variations in peak intensities at \(\sim 1645\) and 1240 cm\(^{-1}\) in the exposed graphite/epoxy spectra could be due to C=C stretching and C-H deforming vibration respectively [27].
7.5.6 Results – Manoa

Figure 124. Comparison of FTIR spectra of E-glass/epoxy composite facing 6061-T6 Al (A_M) and the environment (A_E) at Manoa with the spectrum of the virgin composite

In this case a shoulder was found emerging at ~1700 cm⁻¹ A_E similar to the other sites.
Figure 125. Comparison of FTIR spectra of graphite/epoxy (0°) composite facing 6061-T6 Al (B_M) and the environment (B_E) at Manoa with the spectrum of the virgin composite

In this case a steep shoulder was found emerging with significant variations in intensities at ~1700 cm^{-1} A_E similar to the other sites.
Figure 126. Comparison of FTIR spectra of graphite/epoxy (90°) composite facing 6061-T6 Al (E_M) and the environment (E_E) at Manoa with the spectrum of the virgin composite.

A valid spectrum of the epoxy matrix could not be obtained due to the interference of the graphite fibers. The epoxy used was identical in both 0° and 90° orientations.
Figure 127. Comparison of FTIR spectra of SiC/epoxy composite facing 6061-T6 Al (CM) and the environment (CE) at Manoa with the spectrum of the virgin composite

In this case the intensity variations were limited in both CM and CE.
Figure 128. Comparison of FTIR spectra of 3M Alumina/epoxy composite facing 6061-T6 Al ($D_M$) and the environment ($D_E$) at Manoa with the spectrum of the virgin composite.

In this case intensities of the peaks between 1050 cm$^{-1}$ and 1200 cm$^{-1}$ were found varying in $D_E$. 
7.5.6.1 Discussions – Manoa

The common trend observed was the emergence of a steep shoulder around 1700 cm\(^{-1}\) in the spectra of the E-glass and graphite epoxy composites on the surfaces exposed to the environment which could be due to C=O stretching vibration. The variations in peak intensities between 1050 and 1200 cm\(^{-1}\) in the exposed 3M Alumina/epoxy spectra could be due to C-O stretching vibration [27].
7.5.7 Results – Coconut Island

Figure 129. Comparison of FTIR spectra of E-glass/epoxy composite facing 6061-T6 Al (AM) and the environment (AE) at Coconut Island with the spectrum of the virgin composite

In this case new variations of peak intensities at $\sim 1700 \text{ cm}^{-1}$ were found in AE with the emergence of a steep shoulder.
Figure 130. Comparison of FTIR spectra of graphite/epoxy (0°) composite facing 6061-T6 Al (B^M) and the environment (B_E) at Coconut Island with the spectrum of the virgin composite.

In this case a similar variation of peak intensity at ~1700 cm⁻¹ was found in B_E.
Figure 131. Comparison of FTIR spectra of graphite/epoxy (90°) composite facing 6061-T6 Al (EM) and the environment (EE) at Coconut Island with the spectrum of the virgin composite.

A valid spectrum of the epoxy matrix could not be obtained due to the interference of the graphite fibers. The epoxy used was identical in both 0° and 90° orientations.
Figure 132. Comparison of FTIR spectra of SiC/epoxy composite facing 6061-T6 Al (C_M) and the environment (C_E) at Coconut Island with the spectrum of the virgin composite

In this case peak intensities varied between \( \sim 1600 \text{ cm}^{-1} \) and \( \sim 1700 \text{ cm}^{-1} \) in C_E and a appearance of a small shoulder at the latter range can be observed.
Figure 133. Comparison of FTIR spectra of 3M Alumina/epoxy composite facing 6061-T6 Al ($D^M$) and the environment ($D_E$) at Coconut Island with the spectrum of the virgin composite

In this case an emerging shoulder was observed at $\sim1700 \text{ cm}^{-1}$ in $D_E$. 
7.5.7.1 Discussions – Coconut Island

The common trend observed was the emergence of a steep shoulder around 1700 cm\(^{-1}\) in the spectra of the E-glass, graphite/epoxy, SiC/epoxy composite, and 3M Alumina/epoxy composites on the surfaces exposed to the environment which could be due to C=O stretching vibration [27].

7.5.8 Conclusions

Most of the variations in the intensities of peaks that were observed in the spectra were typically on the surface facing the environment of the E-glass/epoxy, graphite/epoxy (0\(^{th}\)), and SiC/epoxy composites and the most common trend observed was the steep shoulder emerging at \(\sim 1700\) cm\(^{-1}\) in the spectra of the composite surfaces facing the environment, which could be due to effect of the sunlight. The physical appearance of the E-glass/epoxy composite drastically changed from pale yellow to dirty brown after exposure at the outdoor sites and it was severe especially at Kahuku (marine environment facing north-east trade winds), at Manoa (highly humid rainforest environment), and at Coconut Island (test racks are located very close to the ocean). The epoxy matrix of the graphite/epoxy composites was also discolored to the “dirty” brown appearance.
Chapter 8

CONCLUSIONS

8.1 Overall comparison of all the corrosion rates determined from three experiments

The corrosion rates calculated from the various experiments were compared and analyzed to understand the trend of the corrosion phenomenon for 6061-T6 aluminum coupled to organic matrix composites. The galvanic corrosion rates observed in the zero resistance ammeter experiments showed that the \( i_{\text{Galv}} \) values were higher in the case of the graphite/epoxy (90°) composites coupled to the metal when compared to the graphite/epoxy (0°) composites. The highest galvanic corrosion rates were observed in aerated 3.15wt% NaCl solution. The galvanic corrosion rates were low in seawater due to precipitation of a magnesium rich film on the graphite/epoxy composite.

The trend of corrosion observed in accelerated corrosion experiments which include immersion and exposure in the humidity chamber and in outdoor exposure tests are shown in the tables 18-20. The basic objective of this comparison was to understand of the trend of the galvanic couples over the non-galvanic couples, the effect of the fiber-orientation in the graphite/epoxy composites, the effect of the partial and total insulation of the conducting graphite/epoxy composite in the couple, and the difference due to conductivities of the composites coupled to 6061-T6 aluminum.
A) Corrosion rates in the Humidity Chamber

Table 18. Trend of corrosion in the Humidity chamber

<table>
<thead>
<tr>
<th>Galvanic</th>
<th>Non-galvanic</th>
</tr>
</thead>
<tbody>
<tr>
<td>G/E(0°)-Ti</td>
<td>G/E(0°)-Nylon</td>
</tr>
<tr>
<td>Totally insulated</td>
<td>Partially insulated</td>
</tr>
</tbody>
</table>

Legend

- High
- Low
B) Corrosion rates in the Immersion experiment

Table 19. Trend of corrosion in the Immersion experiment

<table>
<thead>
<tr>
<th>Galvanic</th>
<th>Non-galvanic</th>
</tr>
</thead>
<tbody>
<tr>
<td>G/E(0°)-Ti</td>
<td>G/E(0°)-Nylon</td>
</tr>
<tr>
<td>Partially insulated</td>
<td>Uncoupled Aluminum</td>
</tr>
</tbody>
</table>

Legend

- High
- Medium
- Low
- Very Low
C) Corrosion rates in the Outdoor experiments

Table 20. Trend of corrosion at the outdoor sites

<table>
<thead>
<tr>
<th>Galvanic</th>
<th>Non-galvanic</th>
</tr>
</thead>
<tbody>
<tr>
<td>G/E(0(^0))-Ti</td>
<td>G/E(0(^0))-Nylon</td>
</tr>
<tr>
<td>Partially insulated</td>
<td>Uncorrupted Aluminum</td>
</tr>
</tbody>
</table>

Legend

- High
- Low
- Very Low
The environmental degradation of the organic matrix composites was analyzed using FTIR microscope and the peaks were identified for each spectrum. The change in color of the E-glass/epoxy composites when exposed in the outdoor sites was drastic that it changed from pale yellow to dark brown and it was further substantiated by some interesting differences in the spectra that were obtained after the exposure. Similar color change was also noted on the exposed graphite/epoxy composites.
REFERENCES


11. D. E. Prince, Corrosion behavior of Metal Fasteners in Graphite/epoxy Composites, Air
   Force Materials Laboratory, TR-75-53, 1975
    1990, pp 93
13. W. C. Tucker, Crystal Formation on Graphite Polymer Composites, Journal of
    Sons, Inc., 1985, 428
17. R. L. Martin, Corrosion, Vol. 51, No. 6, June 1995, Pg 482-484
    and Materials, 1976, pp. 20-21
    Vol. 45, 2000, Pg 1837-1845
    Pg 853

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