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Evaluation of silane-doped epoxy coatings for resisting aluminum corrosion by oxalic acid, an *A. Niger* metabolite

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The Williams Honors College

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Executive Summary
Due to the numerous potential financial, environmental, and health and safety impacts of metallic corrosion, there is significant motivation within the research community to develop solutions to this widespread problem. One commonly used method for preventing corrosion in many types of materials – metallic and otherwise – is coating. Many types of coatings exist, including paints, powder coatings, thin-film conversion coatings, and others.
In this study, we investigated the ability of silane-doped epoxy coatings to resist corrosion of aluminum alloy AA 2024-T3 by oxalic acid – one of the most abundant metabolites of the ubiquitous fungus Aspergillus Niger. Epoxy coatings containing various percentages of 3-aminopropyltriethoxysilane were applied to the surface of AA 2024-T3 coupons. After oven drying and curing, the coupons were immersed in an oxalic acid solution of pH = 2.3 (the naturally occurring pH produced by the fungus) for 7 days. Following the test period, the coupons were cleaned of any corrosion products, and the total weight loss was measured. Optical microscopy was also used to observe the extent of pitting corrosion in the samples. Of the coated samples, the coating containing 20% silane performed the best in minimizing uniform corrosion, with a corrosion rate of 350 ± 9 µm/yr – compared to 439 µm/yr in the uncoated control – and the coating containing 5% silane performed the best in reducing pitting, with an average of 154 pits/mm² and an average pit size of 5.48 ± 0.17 µm – compared to 478 pits/mm² and an average pit size of 7.77 ± 0.11 µm in the uncoated control.
In a second experiment, the effect of pH on the efficacy of the coating was investigating by coating all coupons with 20% silane in epoxy, and immersing them in solutions of various pH (pH = 1.16, 2, 3, 4, 11) for 7 days. In this experiment, the coupon in the pH = 2 solution showed the least amount of weight loss and pitting, with a corrosion rate of 284 ± 47 µm/yr and an
average of 171 pits/mm² with an average pit size of 7.53 ± 0.21 µm.

However, while the maxima and minima of uniform corrosion and pitting can be determined in each experiment, statistical analysis shows that a strong conclusion cannot be made as to whether the variables of silane content or pH have an influence on the coating’s ability to prevent corrosion of AA 2024-T3 by oxalic acid, due to the high amount of variance within the data sets. The data does show measurable weight loss and significant pitting across all samples, offering the conclusion that none of the tested coatings offer adequate corrosion protection in this environment.

Based on the results of this research, it is recommended that further study be done into how to enhance the adhesive properties of the coating to prevent delamination from the metal surface, which was observed in multiple trials in the present work. It is also recommended to investigate alternative coating methods to produce a uniform, defect-less coating that is applicable in a larger, commercial scale operation.
Introduction

In their recent 2016 IMPACT study, the National Association of Corrosion Engineers (NACE) has estimated the global cost of corrosion to be around 2.5 trillion dollars, or around 3.4% of the global GDP.[1] Besides this significant economic driver, health, safety, and environmental protection issues consequent from corrosion related material failures strongly incentivize solutions for ameliorating this issue.

One commonly used material for which corrosion can be an issue is aluminum and aluminum alloys, especially due to its prominence as a structural material. Due to several highly desirable characteristics – including high strength-to-weight ratio, a wide range of toughness and ductility between alloys and tempers, high thermal and electrical conductivity, and others – aluminum and its alloys can be found across industries and services. In many cases, aluminum is naturally corrosion resistant under acidic and neutral conditions, as it tends to form a passivating oxide layer (Al₂O₃) in air.[2] However, this does not mean that all aluminum is immune to corrosion – some alloys are more susceptible to corrosion than others, and it has long been documented that issues with pitting, de-alloying, galvanic corrosion, and other forms of corrosion can occur under the proper conditions.[3], [4], [5]

One particular alloy, AA 2024-T3, is commonly used in the aircraft and aeronautics industry as a structural material due to its high mechanical strength and resistance to fatigue-related failures.[7] Previous work has shown that this alloy is subject to pitting corrosion in the presence of a ubiquitous acid producing fungus, Aspergillus niger.[6] Notwithstanding the economic impacts previously mentioned, the huge safety risks involved with a mechanical failure in these particular applications provide strong motivation to address this issue. The purpose of this study is to investigate whether organosilane-doped epoxy-based coatings are capable of protecting AA 2024
in an aqueous environment containing oxalic acid, one of the primary metabolites of the *A. Niger* fungus. The effect of the silane content in the coating on corrosion resistance will first be tested by conducting immersion tests of epoxy-coated AA 2024-T3 coupons in oxalic acid solutions at the concentration and pH naturally created by the *A. Niger* fungus. Additionally, the performance of the coating will then be tested at various other pH to see if it is capable of withstanding slightly altered ambient conditions.

**Background**

*Corrosion of aluminum and aluminum alloys*

The mechanism by which aluminum corrodes depends on the type of alloying and the ambient conditions.[8] However, one typical feature that is commonly observed in aluminum and aluminum alloys – generally when exposed to humid or aqueous environments – is pitting corrosion. This is a result of localized galvanic cells created by differences in electrochemical properties of the alloying materials and the base metal – particularly, sites containing particles of copper, iron, and manganese have been shown to promote dissolution of the surrounding matrix, leading to localized pits.[3] Pitting corrosion can have severe impacts on the structural stability of materials – research has shown that the fatigue life of AA 2024-T3 can be reduced by nearly an order of magnitude due to the pitting caused by spending just ~16 days in a salt solution (0.5 M NaCl).[9] AA 2024-T3 exposed to oxalic acid has been shown to corrode with a similar pitting morphology to that exposed to NaCl, but at a rate of up to 4 times as fast (compared to 3.5 wt% NaCl solution).[6] In applications such as aircraft, where structural elements are exposed to frequent and repeated stress cycles, severe pitting corrosion could bring about significantly premature material failure.
Corrosion protection of aluminum alloys

There are several options that are currently widely used to mitigate corrosion on aluminum alloys. As aforementioned, many aluminum alloys naturally form a passive oxide layer. The corrosion inhibiting ability of this passive layer can be enhanced either chemically or electrolytically (anodization). Another option is to use conversion coatings – specifically, chromate conversion coatings have been used to prevent AA 2024 corrosion.[10] In chromate conversion coatings, chromic acid is applied to the surface which modifies the surface properties by reacting with both the base metal and alloying agents, forming an extremely thin, corrosion resistant surface layer.[11] The most commonly used way of inhibiting corrosion of aluminum, however, is by adding a surface coating, which can take the form of plating (electrochemical deposition of a dissimilar metal to the surface), cladding (bonding of a dissimilar metal to the surface, typically by high pressure), or painting (either liquid paints or powder coatings).

Organic based coatings are one of the most widely used coatings to protect metals from corrosion. However, these coatings are also subject to failure under certain conditions.[12] While the exact mechanisms of failure are not entirely understood, much research has been conducted in recent years regarding how to enhance the coatings resistance to phenomena such as adhesive failure and chemical degradation – commonly surface pre-treatment or coating additives. Recently, the use of organosilanes both as an additive and as a surface pre-treatment for organic coatings has been shown to enhance both the adhesive properties and reduce the water uptake of polymer based coatings, providing superior corrosion resistance.[13]
Silanes and silane incorporated epoxy coatings for corrosion protection

Previous research exists which investigates the corrosion protection offered by several silane-incorporated epoxy coatings to AA 2024 in salt solutions.[13] In their work, Jiang et al. incorporated two different types of silanes into epoxy coatings: an ‘active’ silane, γ-aminopropyltrimethoxy silane (γ-APS), which is capable of reacting chemically with the epoxy via the amino group, and a ‘non-active’ silane, bis-1,2-[triethoxysilyl]ethane (BTSE), which does not contain a reactive functional group. The silanes were incorporated physically, via mixing with epoxy resin, mixed solvents, and a polyamide curing agent. The results of their research showed that both silane incorporated coatings boosted the adhesive properties and reduced the adsorption of water relative to a plain epoxy coating. A follow-up mechanistic study concluded that these enhancements were a result of both silane’s ability to order functional groups on the surface of the coating, as well as impart a “self-healing” property, whereby surface and bulk defects are repaired via condensation of Si-O-Si groups.[14]

The present research seeks to build on those findings – and potentially broaden the possible applications for this coating in industry – by investigating whether this coating resists degradation and offers adequate corrosion protection in an acidic environment as well as saline environments.

Experimental Methods

Materials

Sheets of aluminum alloy 2024 were purchased from McMaster-Carr (AA 2024-T3), containing Si 0.50 wt%, Fe 0.50 wt%, Cu 3.8 – 4.9 wt %, Mn 0.3 – 0.9 wt%, Mg 1.2 – 1.8 wt%, Cr 0.1 wt%, Zn 0.25 wt%, Ti 0.15 wt% and the remainder Al (conforming to ASTM B209-96). Hexane
(ACS grade, mixed isomers), oxalic acid dihydrate (99.0%), and 3-aminopropyltriethoxysilane (99%) were obtained from Sigma-Aldrich. Sodium hydroxide (solid, 99.3%) and nitric acid were obtained from Fisher Scientific. Acetone (ACS grade, 99.5%) was obtained from EMD Chemicals. Ethanol (200 proof) was obtained from Decon Labs. The alkaline cleaning solution was prepared using ZEP Professional Heavy-Duty Alkaline Cleaner (diluted 1:10 in DI water). DI water was prepared in-house. The two part epoxy coating was obtained from a lab at The University of Akron, and consisted of epoxy 828 and Epikure 3295.

**Coupon Preparation**

Sheets of the aluminum 2024 were cut using a sheet metal cutter into 1 cm x 2.5 cm coupons (0.4 mm thickness). The surface of each coupon was cleaned thoroughly via sonication for 10 minutes in each hexane, acetone, and alkaline cleaning. The coupons were rinsed thoroughly with DI water and allowed to air dry overnight.

After drying, the coupons were soaked in a silane pre-treatment solution, prepared by adding 1 wt% silane to absolute ethanol. The coupons were allowed to soak in solution for 2 hours, at which point they were air dried and stored in polystyrene well plates for later use.

**Coating Preparation**

The two-part epoxy-based coating was prepared by first dissolving both components in acetone to 5 wt%. Just before use, the two components were added to a test tube in a 4:1 epoxy-to-cure ratio (80% epoxy, 20% cure). In the silane-doped coatings, silane was then added in various percentages relative to the total epoxy/cure solution weight. The solutions were mixed via swirling for 30 seconds before application.
**Coating Application**

After trying multiple application techniques, it was found that the most consistent coating (uniform thickness, minimal coating defects) was achieved by applying small drops of the coating to the surface of the coupon and allowing them to dry, covered, in a warm environment. Using a micropipette, a 100 μL aliquot of the appropriate solution was dispensed onto the surface of each coupon and allowed to spread to the edges. The coupons were then covered (using a watch glass or glass petri dish lid) and placed in a warm oven (70°C) to dry (3-4 hours). After drying, the cover was removed, and the coating was allowed to cure in a hot oven (~100 °C) overnight.

**Oxalic Acid Solution Preparation**

Oxalic acid solutions were prepared at a concentration of ~0.068 M by dissolving solid oxalic acid dihydrate in the appropriate amount of DI water. In order to tune to pH of these solutions without significantly altering the concentration of the oxalic acid in solution, a concentrated solution (10 M) of sodium hydroxide was prepared by dissolving solid NaOH in DI water. The pH of each oxalic acid solution was measured by removing a small portion into a 20 mL scintillation vial which was then probed using with a pH probe (Apera Instruments PH60 pH Tester). In solutions requiring pH adjustment, the vial contents were returned to the solution bottle and NaOH solution was added in small amounts (~5 – 10 drops). The solution was then thoroughly mixed before the pH was measured again. This process was repeated as necessary to obtain the required solution pH.
**Corrosion Studies**

Corrosion studies were carried out in glass jars at ambient conditions over a period of 7 days. Each coupon’s initial weight was measured and recorded using an electronic analytical balance. Then, the coupons were placed in small glass containers inside the glass jar. Each jar was filled with 100 mL solution (meeting ASTM G31-12a corrosion testing standards). The jars were covered with cling film and left at ambient conditions for 7 days. The jars were occasionally uncovered in order to photograph the coupons as the corrosion progressed. Figure 1 provides images of the experimental setup.

A total of two experiments were carried out, firstly to investigate the effect of silane content on the corrosion resistance of the coating, and secondly to investigate the effect of solution pH on the corrosion resistance of the coating. In the first experiment, coupons were prepared using the following coatings: plain aluminum, silane pre-treatment only, 0% silane in epoxy, 5% silane in epoxy, 10% silane in epoxy, and 20% silane in epoxy. The coupons, in triplicate, were all placed in oxalic acid solutions of pH = 2.3 (the naturally occurring pH of the oxalic acid produced by *A. Niger*)

In the second experiment, all coupons were prepared using 20% silane in epoxy coatings – as this was the best-performing silane-doped coating from the first experiment. Oxalic acid solutions were prepared with pH = 1.16, pH = 2, pH = 3, pH = 4, and pH = 11. The coupons were placed into these solutions in triplicate.
Figure 1: Experimental setup for the immersion tests. Coupons were placed in small glass containers to maximize surface area exposed to the solution. Cling film was placed on top of the jars to prevent excess dust / detritus from getting in.

**Corrosion Product Cleaning Procedure**

After the corrosion studies had concluded, it was necessary to clean any corrosion products from the surface of the coupon which included both mechanical and chemical means (as per ASTM G1-7). After removing the coupons from the oxalic acid, they were first brushed using a nylon brush in 70% ethanol. Afterwards, they were submerged in a 70% nitric acid solution for 3 minutes, followed by a thorough rinsing with DI water and drying under a stream of dry air. After the coupons were completely dry, they were weighed a second time. The coupons were then returned to the well plates and vacuum sealed for long term storage.

**Data and Results**

**Corrosion Rate – Variable Silane Content**

The first measure to determine the effectiveness of the various coatings was a weight loss analysis. An initial weight was measured for each of the coupons before immersion, and then they were weighed again following the cleaning at the conclusion of the test. 6 sets of coupons were tested in triplicate: no treatment (raw aluminum), silane pre-treatment only, epoxy coating
without silane, epoxy with 5% silane, epoxy with 10% silane, and epoxy with 20% silane. Using the weight loss data, a corrosion rate was calculated using the equation $CR = \frac{W}{A\rho t}$, where $W$ is the weight loss, $A$ is the surface area (neglecting edges), $\rho$ is the density of the coupon, and $t$ is the total immersion time. The results are shown in Figure 2. See Appendix A for charts comparing raw weight loss. While it appears that the corrosion rate is decreasing as the silane content increases, the difference does not appear to be statistically significant. A simple linear regression of the data yields a p-value of just over 0.05 (0.073), and a single factor analysis of variance (ANOVA) yields a p-value of 0.265 between groups, suggesting that this data is non-conclusive as to how changes in the silane content of the coating effects on the corrosion resistant properties, at least with respect to corrosion rate or weight loss.

Figure 2: Shows the corrosion rate of each coupon after 7 days in 0.068 M oxalic acid solution at pH = 2.3. Average values are presented, and error bars represent the standard deviation between 3 samples in each set.
**Pitting Quantification – Variable Silane Content**

In addition to measuring the weight loss, the surface topology of the coupons was observed using optical microscopy. Figure 3 provides a comparison of the coupons’ surfaces following the test. In order to quantify the extent of pitting corrosion in the samples, the average number of pits on each coupon was counted (in 242 x 242 µm sections), and the average pit size was calculated. For the purposes of this analysis, a ‘pit’ is defined as a defect greater than 4 µm in size across its longest axis. The microscope images show that, while the raw aluminum showed significant signs of pitting, the size and number of pits on the coupons with any of the coatings, including just the pre-treatment, do not differ significantly from one another, and were only marginally increased over the aluminum that had not been subjected to the immersion test. Table 1 shows the number of pits and average pit size for the different samples.

*Table 1: Shows the extent of pitting corrosion in the various samples. Average # of pits is measured across 3 samples in 242 x 242 µm sections, and average pit size is an average of all pits on each of the 3 samples, +/- the standard error in each set.*

<table>
<thead>
<tr>
<th>Coating</th>
<th>Average # of Pits</th>
<th>Average Pit Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% Silane in Epoxy</td>
<td>12</td>
<td>5.99 ± 0.12</td>
</tr>
<tr>
<td>5% Silane in Epoxy</td>
<td>9</td>
<td>5.48 ± 0.17</td>
</tr>
<tr>
<td>10% Silane in Epoxy</td>
<td>10</td>
<td>6.85 ± 0.25</td>
</tr>
<tr>
<td>20% Silane in Epoxy</td>
<td>18</td>
<td>7.25 ± 0.14</td>
</tr>
<tr>
<td>Pre-Treatment Only</td>
<td>10</td>
<td>6.15 ± 0.18</td>
</tr>
<tr>
<td>Raw Aluminum</td>
<td>28</td>
<td>7.77 ± 0.11</td>
</tr>
</tbody>
</table>
Figure 3: Optical microscope images were taken of the surface of each coupon post-cleaning at 40x magnification. The coatings were as follows:

a.) raw aluminum (before test);
b.) raw aluminum (after test);
c.) pre-treatment only;
d.) 0% silane;
e.) 5% silane;
f.) 10% silane;
g.) 20% silane.
**Corrosion Rate – Variable pH**

Again, weight loss (presented as corrosion rate) was used as the primary measurement to determine the performance of the coating in various pH environments. This test was conducted using the 20% silane coating, as it performed the best of all coatings in the previous test. 5 sets of coupons were tested in triplicate, with pH = 1.16 (natural pH of 0.068 M oxalic acid in water), pH = 2, pH = 3, pH = 4, and pH = 11 (to observe the results of the coating under basic conditions). The results of this test are shown in Figure 4.

![Coupon Corrosion Rate vs. Solution pH](chart.png)

*Figure 4: Shows the corrosion rate of each coupon after 7 days in 0.068 M oxalic acid at various pH. Average values are presented, and error bars represent the standard deviation between 3 samples in each set.*
While the data shows a general trend that one might expect – higher corrosion under more highly acidic conditions – statistical analysis again shows that conclusions cannot be drawn from this data with a high level of confidence. A linear regression results in a high p-value (0.291), as does an ANOVA (p = 0.277), suggesting that too much variance exists in the data to make a sound conclusion.

**Pitting Quantification – Variable pH**

Optical microscope images were also taken of these samples following the immersion test (Figure 5), which show an increase in the size and number of pits for the samples in the lower pH solutions. However, while it is clear that the most significant pitting occurs in the lowest pH sample (pH = 1.16), and that only minor pitting occurs at high pH (pH = 11), there is not a monotonic trend in terms of either number of pits or pit size. Table 2 shows the pitting data for these samples.

*Table 2: Shows the extent of pitting corrosion in the various samples. Average # of pits is measured across 3 samples in 242 x 242 µm sections, and average pit size is an average of all pits on each of the 3 samples, +/- the standard error in each set.*

<table>
<thead>
<tr>
<th>Oxalic Acid pH</th>
<th>Average # of Pits</th>
<th>Average Pit Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.16</td>
<td>20</td>
<td>8.45 ± 0.13</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>7.53 ± 0.21</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>8.23 ± 0.19</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>8.08 ± 0.47</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>5.36 ± 0.12</td>
</tr>
</tbody>
</table>
Corrosion Progression – Visible Results of Corrosion Product Formation

Since weight loss and microscopic images could only be taken at the end of the experiments, the progress of corrosion over the 7 day period was monitored visually. In both experiments, as the corrosion progressed, a noticeable color change occurred as dark spots began to occur on the

Figure 5: Optical microscope images were taken of the surface of each coupon post-cleaning at 40x magnification. The solution pH were as follows:

a.) raw aluminum (before test);

b.) pH = 1.16;

c.) pH = 2;

d.) pH = 3;

e.) pH = 4;

f.) pH = 11
coupons, particularly around the edges. Figure 6 shows images of the coupons as corrosion progressed.

While the phenomenon of surface darkening was observed across all samples, only the 20 wt% silane samples resulted in darkening across the entire surface, whereas in the other samples (0% – 10%), it only progressed to the outer edge as seen in image b.) above. While the exact nature of this corrosion product is not investigated in this study, previous research has confirmed the existence of aluminum oxalates, aluminum oxides, and copper oxides on the surface of AA 2024-T3 in the presence of oxalic acid.[6]

**Discussion**

The purpose of this research was to determine whether organosilane-doped epoxy coatings were capable mitigating corrosion to aluminum alloy 2024-T3 in various environments containing
oxalic acid. After performing the experiments and conducting statistical analysis, a strong conclusion cannot be made. With regards to how the silane content of the coating effects its ability to inhibit corrosion, a regression shows that there is no statistically significant relationship between silane content and corrosion rate – at least, not a linear relationship. Furthermore, an ANOVA indicates that there is not a statistically significant variance between the data sets in the first place. Additionally a quantification of the extent of pitting corrosion does not show a significant difference between samples. So, while it appears that the corrosion rate does decrease as silane content increases from 0% to 20%, a definitive conclusion cannot be made at this time.

The results of the effect of pH on coating performance are similarly inconclusive. A significantly larger standard deviation exists within the data sets, and the p-values from statistical analysis (linear regression p = 0.291, ANOVA p = .278) do not indicate any significant trends in the data. The microscopic images for this set of coupons do indicate a noticeably different surface topology among the samples, where the coupons subjected to a more acidic solution showed noticeably larger and more numerous pits in the surface. However, while a quantification of the pits shows that the most acidic solution produced the most and largest pits, and the basic solution produced the least and smallest pits, there is not a monotonic trend in the data with respect to either number of pits or average pit size.

Besides the numerical evidence being mostly inconclusive, an issue which was pervasive across all experiments which throws into question the validity of the results was the delamination of the coating from the surface of the coupon. In nearly every case (with the outlier being the coupons exposed to the alkaline solution, pH = 11), after the 7 days had concluded, the coating had separated from the surface of the metal (Figure 7). Obviously, in sections where the coating was
no longer attached to the surface, there would be no corrosion protection, though it is not clear to what extent this influenced the results of the experiments.

While the present data does not provide much in the way of understanding how silane content or pH effects the efficacy of the coating, a more generalized conclusion can be made that none of the tested coatings provided reliable corrosion resistance in the acidic environment. While the weight loss in most of the samples was not significant, the extent of pitting present in every sample suggests that the coating was not effective. Even in cases where weight loss is minimal, the localized defects caused by pitting corrosion can have a large impact on the mechanical integrity of a material, leading to structural failure.

While the results of the present research are not particularly consequential, they lay the groundwork for much further experimentation. Research into the cause of – and potential solution to – the problem with adhesion / delamination is an obvious next step. The scope of the current data does not provide any insight into the root cause of the poor adhesion – it could be the particular chemical species present (oxalate), it could be purely the acidic nature of the solution, or any number of other factors. If the cause of the coating delamination were to be
determined, further research could be done into how to mitigate this issue through the use of different chemical additives or a different surface preparation / pre-treatment protocol. Additionally, it may be of value to investigate different coating application techniques. While the dropping method used herein successfully results in a uniform surface with minimal defects in the lab, it is likely not practical for industrial scale processes. Improved variable control should also be considered in future research. In this research, the samples were simply placed at ambient conditions in the lab, and were not controlled for variables like temperature, ambient light, humidity, etc. While any variability in this data from these factors is likely overshadowed by the larger issues previously mentioned, these factors are worth bearing in mind, as conclusive future research in this area is highly desired.

Conclusions

The results from this research do not allow for a conclusion relating to either of the hypotheses – whether silane content or pH have an impact on the efficacy of an epoxy-based coating in resisting corrosion to aluminum alloy 2024-T3. A more general conclusion can be made, however, that none of the tested coatings were successful at completely preventing corrosion over the 7 day test period, as moderate to severe pitting corrosion was observed in all samples. It is recommended that future research investigate ways to improve surface adhesion and prevent delamination of the coating – either through coating additives or surface treatments – as well as look into more practical means of achieving a uniform and defect-less coating.
References


Appendix A – Raw Weight Loss Trends

Figure A: Shows the weight loss of each coupon after 7 days in 0.068 M oxalic acid solution at pH = 2.3. Average values are presented, and error bars represent the standard deviation between 3 samples in each set.

Weight Loss vs. Silane Content of Coating

$y = (-0.039 \pm 0.019)x + (10.1 \pm 0.220)$
Figure B: Shows the weight loss of each coupon after 7 days in 0.068 M oxalic acid at various pH. Average values are presented, and error bars represent the standard deviation between samples in each set.
Appendix B: Implications and Learning Outcomes
As a result of completing this project, I have gained not only a handful of useful technical skills in the lab, but also a greater appreciation for the amount of work that goes into independent research. I have come to appreciate failure as a learning experience, as it is a common phenomenon in research. My confidence in designing, conducting, and analyzing data from my own experiments has increased, which will be valuable in any sort of engineering position I might find myself in down the road. While the results of this research in particular may not be of benefit to society – due to the inconclusive data – future students/researchers can learn from the mistakes and use this as a foundation for their own studies, hopefully leading to consequential advancements in the area of corrosion protection.
Honors Abstract Addendum

The goal of this study was to investigate whether silane-doped epoxy coatings are capable of preventing corrosion of aluminum alloy 2024-T3 by oxalic acid, one of the primary metabolites of the fungus *Aspergillus Niger*. Previous research suggested the success of these types of coatings at preventing AA 2024-T3 corrosion in saline solutions, and this study was meant to build on those findings by investigating the efficacy of the coating in an acidic environment.

Each coating was applied to an AA 2024-T3 coupon by dissolving the epoxy and varying amounts of 3-aminopropyltriethoxysilane in acetone and then dripping the solution onto the surface. After allowing the coating to dry and cure, the coupons were weighed, and then immersed in oxalic acid solution for 7 days.

Two different independent variables were investigated – the silane weight percentage in the coating (0 wt%, 5 wt%, 10 wt%, 20 wt%) and the pH of the oxalic acid solution used in the immersion tests (pH = 1.16, 2, 3, 4, 11).

After analyzing the results, no strong conclusion can be made regarding the proposed hypotheses, as too much variance exists within the data. However, due to significant pitting corrosion observed across all samples, a general conclusion can be made that this coating does not offer adequate corrosion protection in this particular environment.