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Use of Global Electrochemical Techniques to Characterize Localized Corrosion Behavior on Aluminum Alloys

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Abstract

Precipitated intermetallic phases strengthen aluminum aircraft alloys; these inclusions also establish localized electrochemical environments, significantly influencing the bulk corrosion behavior of such alloys. To gain insight on the effects of intermetallic phases on the bulk corrosion behavior, two established forms of electrochemical characterization techniques were used, polarization scans and impedance spectroscopy. This effort was undertaken to:

- Provide a statistical body of electrochemical data for aluminum alloys,
- Provide fundamental electrochemical parameters to aide in a continuum scale modeling effort,
- Validate the effect of solution chemistry on bulk corrosion behavior,
- Determine the influence of precipitated intermetallic phases on the bulk corrosion behavior,
- Decouple the metal-coating interface behavior from bulk corrosion behavior in continuing tests on coated aluminum.

Disciplines

Materials Science and Engineering

Use of Global Electrochemical Techniques to Characterize Localized Corrosion Behaviors on Aluminum Alloys

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BOISE STATE UNIVERSITY
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ADVANCED MATERIALS LAB

Abstract

Precipitated intermetallic phases strengthen aluminum aircraft alloys; these inclusions also establish localized electrochemical environments, significantly influencing the bulk corrosion behavior of such alloys. To gain insight on the effects of intermetallic phases on the bulk corrosion behavior, two established forms of electrochemical characterization techniques were used, polarization scans and impedance spectroscopy. This effort was undertaken to:

- Provide a statistical body of electrochemical data for aluminum alloys,
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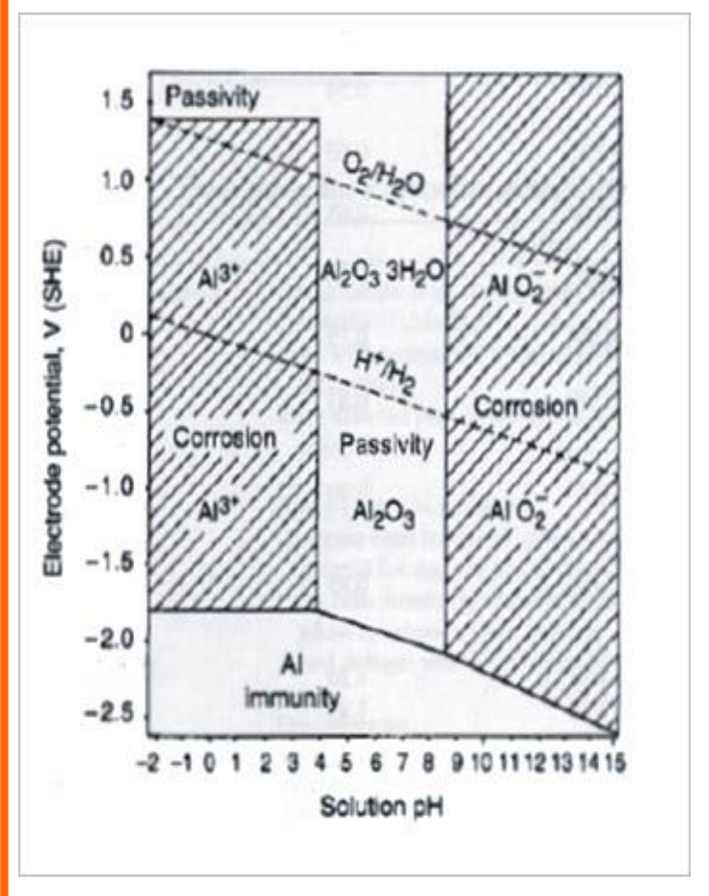
Introduction

The precipitated intermetallic phases in AA2024-T3 form localized galvanic couplings in the form of precipitate-matrix coupling, close-range precipitate-precipitate couplings in clusters, and long-range precipitate-precipitate couplings via conductive grain boundaries. Dealloyed particles result in a high Cu^{2+} ion concentration in the bulk solution. Ions reduced on the surface of the metal, or on the surface of other precipitates, result in the production of OH^- ions, and thus a local solution of high pH[1,2,3,4,5]. The specific interactions are as follows:

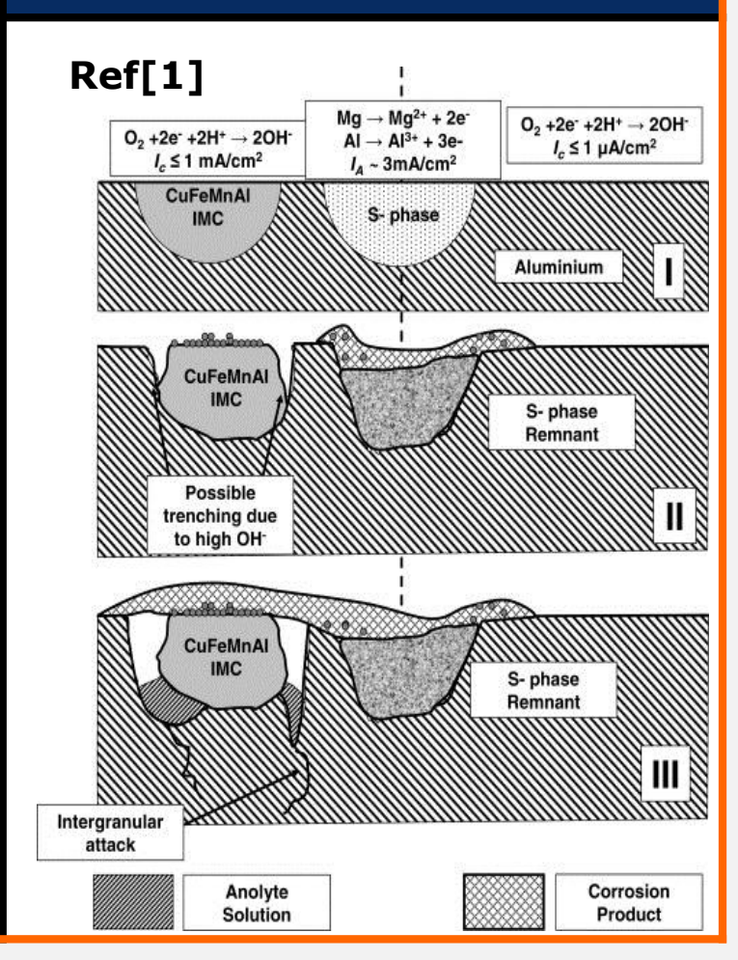
- Al-Cu and Al-Cu-Fe-Mn Precipitates
  - Form "blocky" particles cathodic to the matrix
  - Coupling of Cu-depleted matrix and Cu-rich particle establishes local potential, driving anodic trenching[2,3,4]
- Al-Cu-Mg (S-phase) Precipitates
  - Form spherical particles anodic to the matrix
  - most active, account for 60% of precipitated particles
  - Large cathode to anode ratio preferentially dealloys these particles
  - Reduction of Cu2+ ions drive surface pitting, grain boundary attack and cathodic trenching[2,3,4]

Corrosion Behavior of Aluminum Alloys

Pourbaix Diagram



IMC Schematic

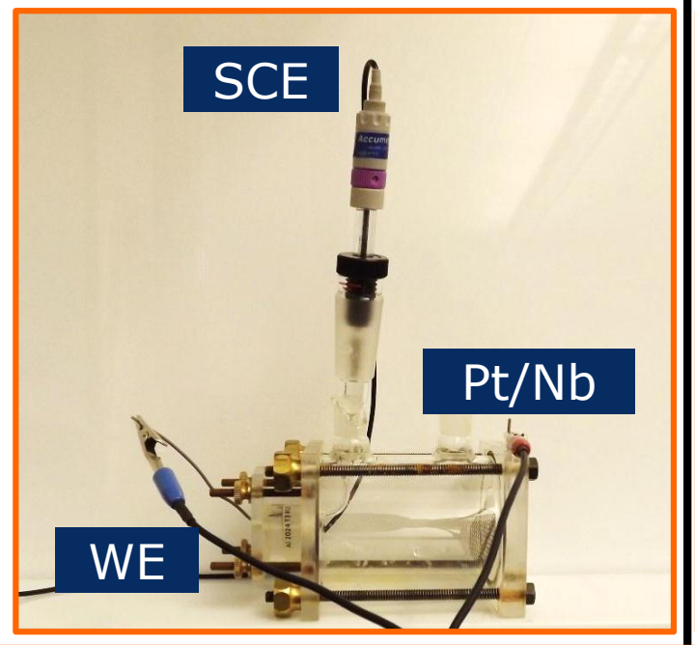


Experimental

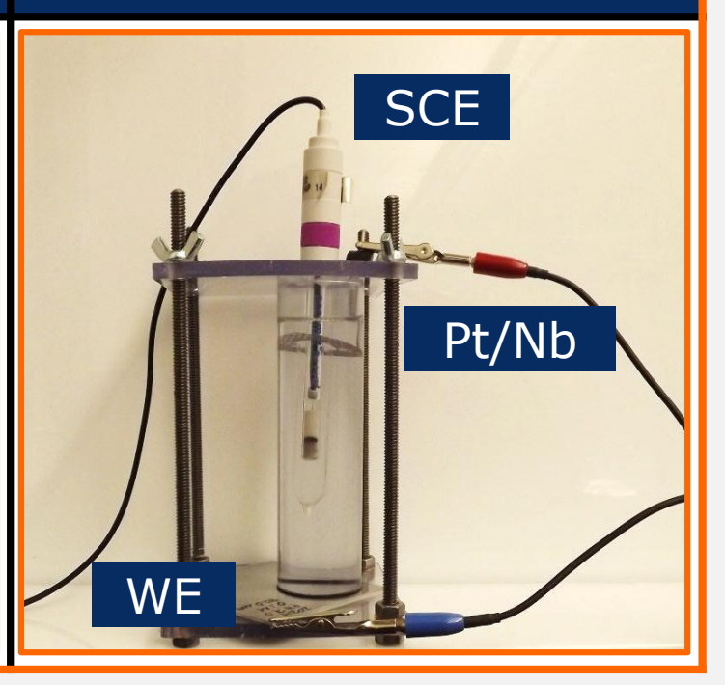
Polarization scans (DC) provided fundamental parameters such as open circuit potential, corrosion current density and Tafel slopes. Impedance spectroscopy (AC) provided parameters such as polarization resistance for extended durations. The test shown on the right were conducted in the setups shown below.

Electrochemical Test Cells

Flat Cell - DC



Vertical Cell - AC



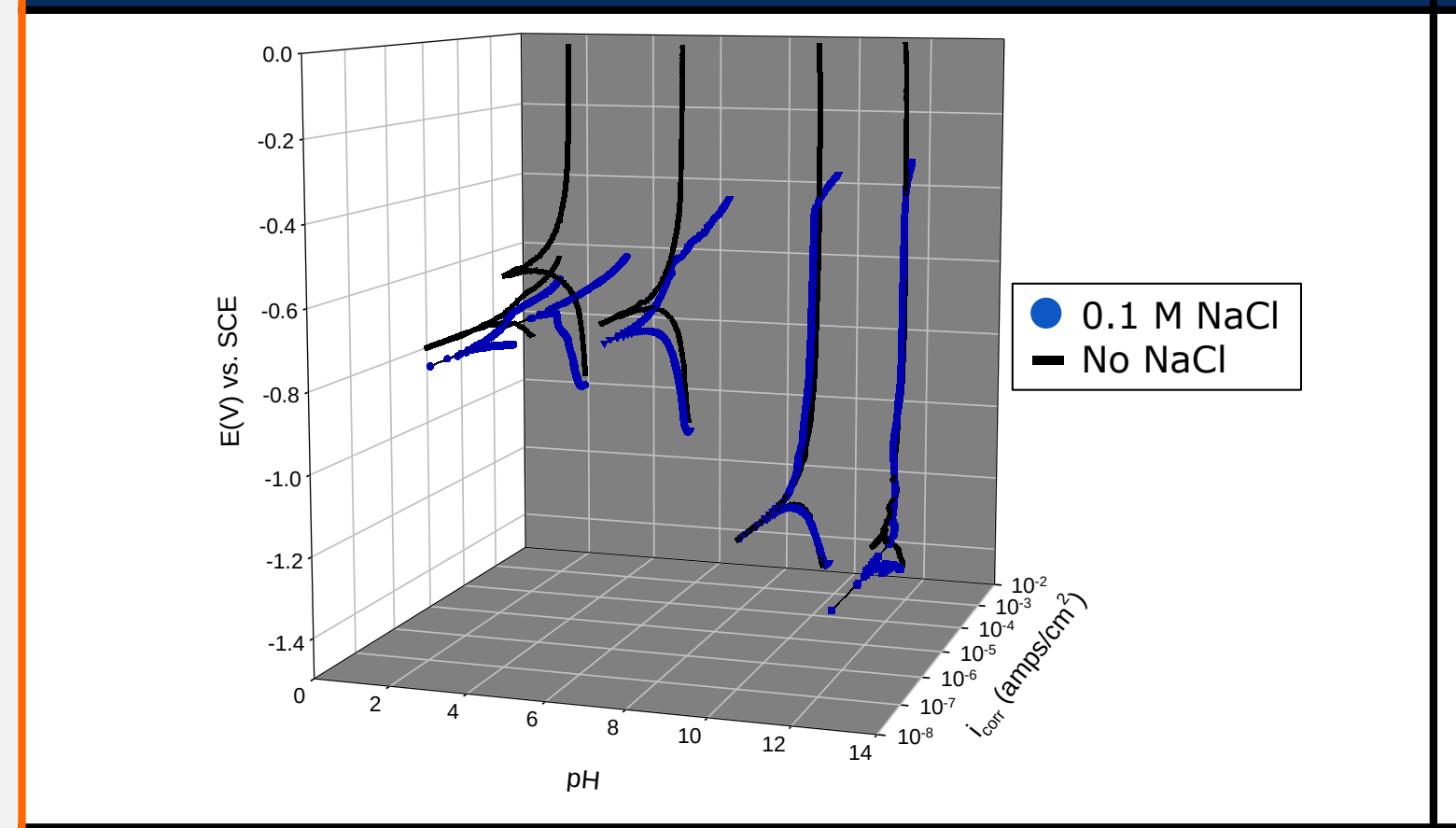
Experimental Design Matrix

Alloy	Electrochemical Test	Solution Chemistry	
Al 1100 • 99.0% Al min • 0.95% Fe max • 0.2% Cu max • 0.05% Mn	Anodic Polarization Scan • -20mV vs. OCP • 10^{-3} A/cm2 turn-around	pH	2.0, 4.0, 7.0, 10.0, 12.0
		[Cl-]	0.0M, 0.1M
	Cathodic Polarization Scan • +20mV vs. OCP • 10^{-3} A/cm2 turn-around	pH	2.0, 4.0, 7.0, 10.0, 12.0
		[Cl-]	0.0M, 0.1M
	Electrochemical Impedance • ±10mV vs. OCP, • 0.01Hz ≤ f ≤ 1.0MHz	pH	2.0, 4.0, 7.0, 10.0, 12.0
		[Cl-]	0.01M, 0.1M
Al 2024 – T3 • 4.60% Cu • 1.50% Mg • 0.65% Mn • 0.16% Fe	Anodic Polarization Scan • -20mV vs. OCP • 10^{-3} A/cm2 turn-around	pH	2.0, 4.0, 7.0, 10.0, 12.0
		[Cl-]	0.0M, 0.1M
	Cathodic Polarization Scan • +20mV vs. OCP • 10^{-3} A/cm2 turn-around	pH	2.0, 4.0, 7.0, 10.0, 12.0
		[Cl-]	0.0M, 0.1M
	Electrochemical Impedance • ±10mV vs. OCP, • 0.01Hz ≤ f ≤ 1.0MHz	pH	2.0, 4.0, 7.0, 10.0, 12.0
		[Cl-]	0.01M, 0.1M

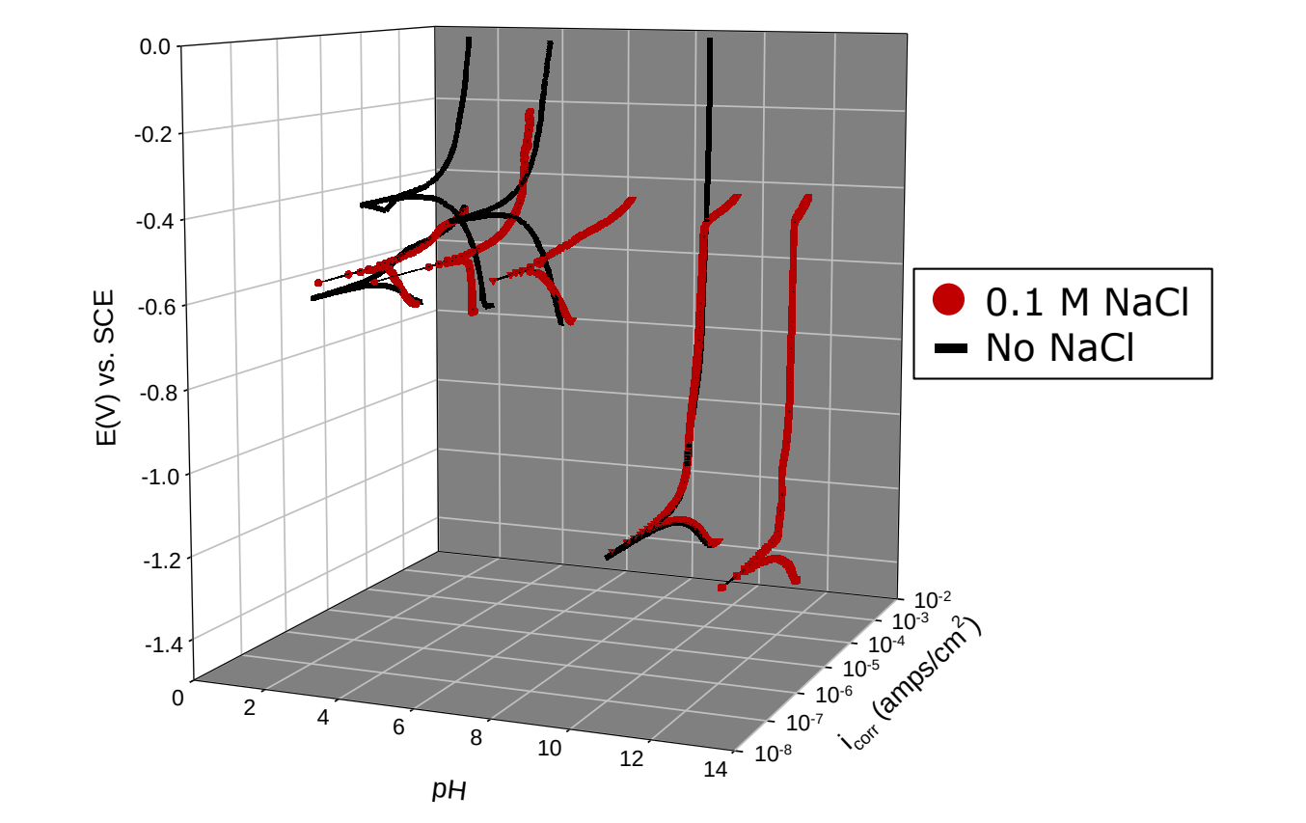
Results

Polarization Scans – DC Method

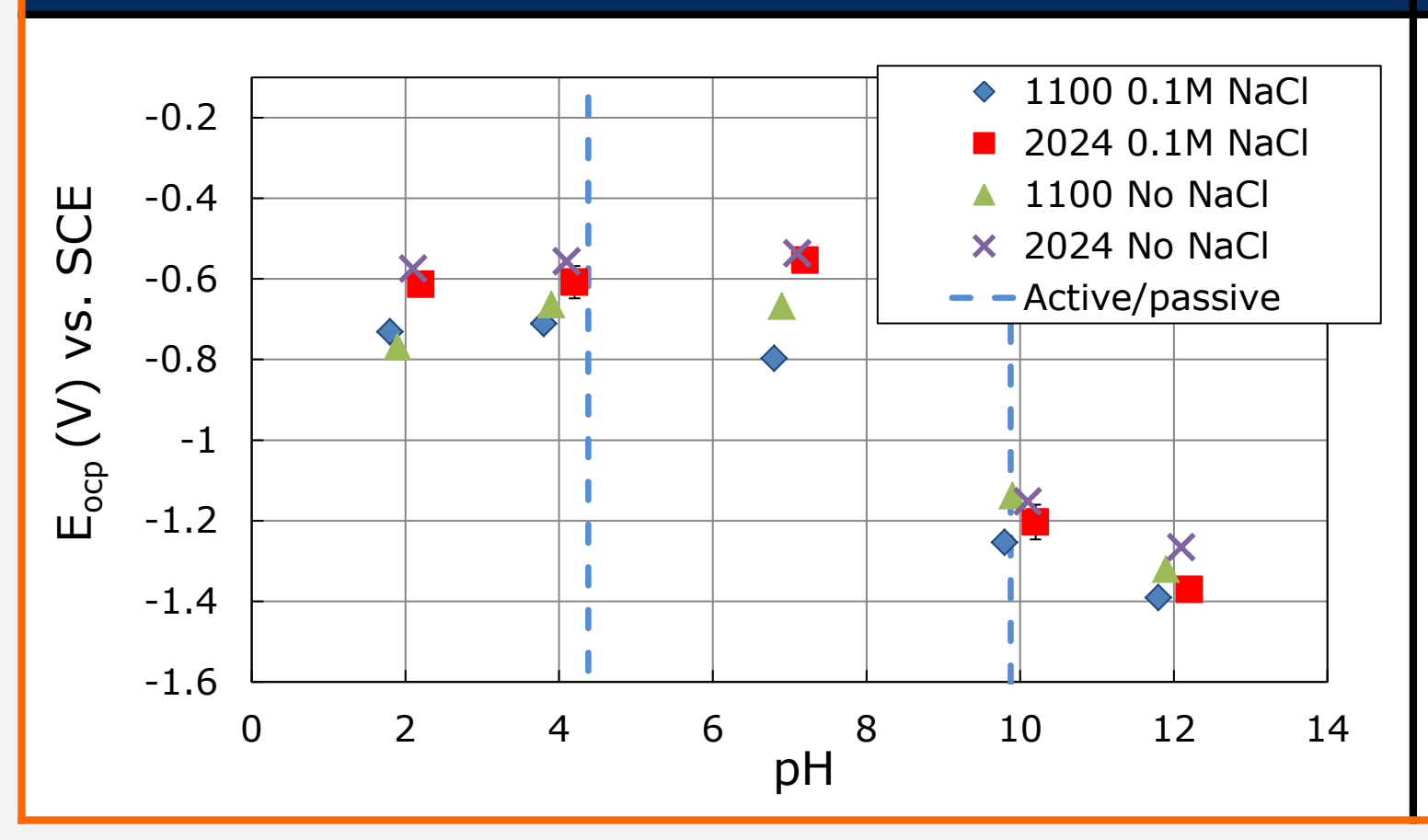
AA1100 Summary



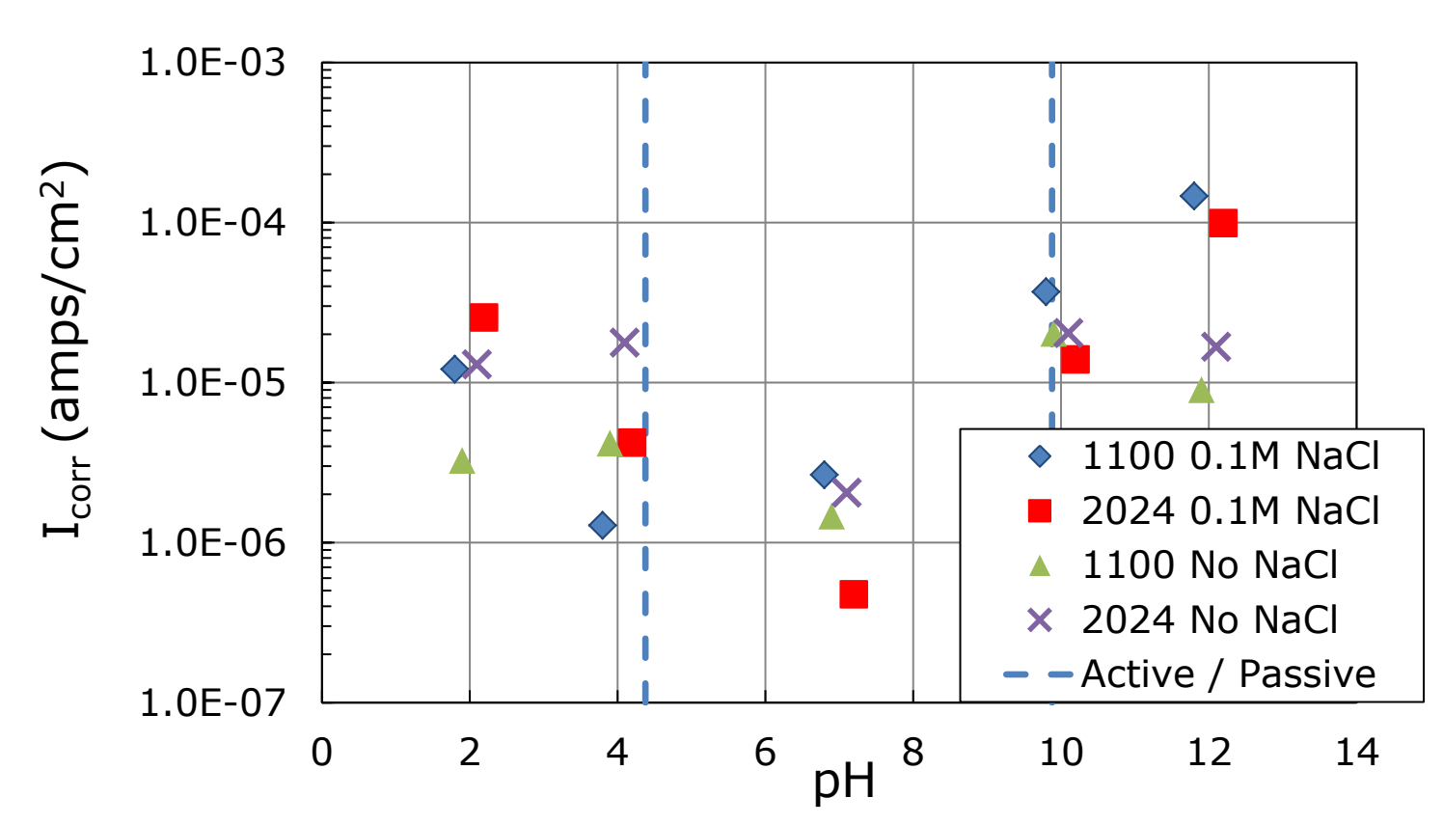
AA2024-T3 Summary



Corrosion Potential

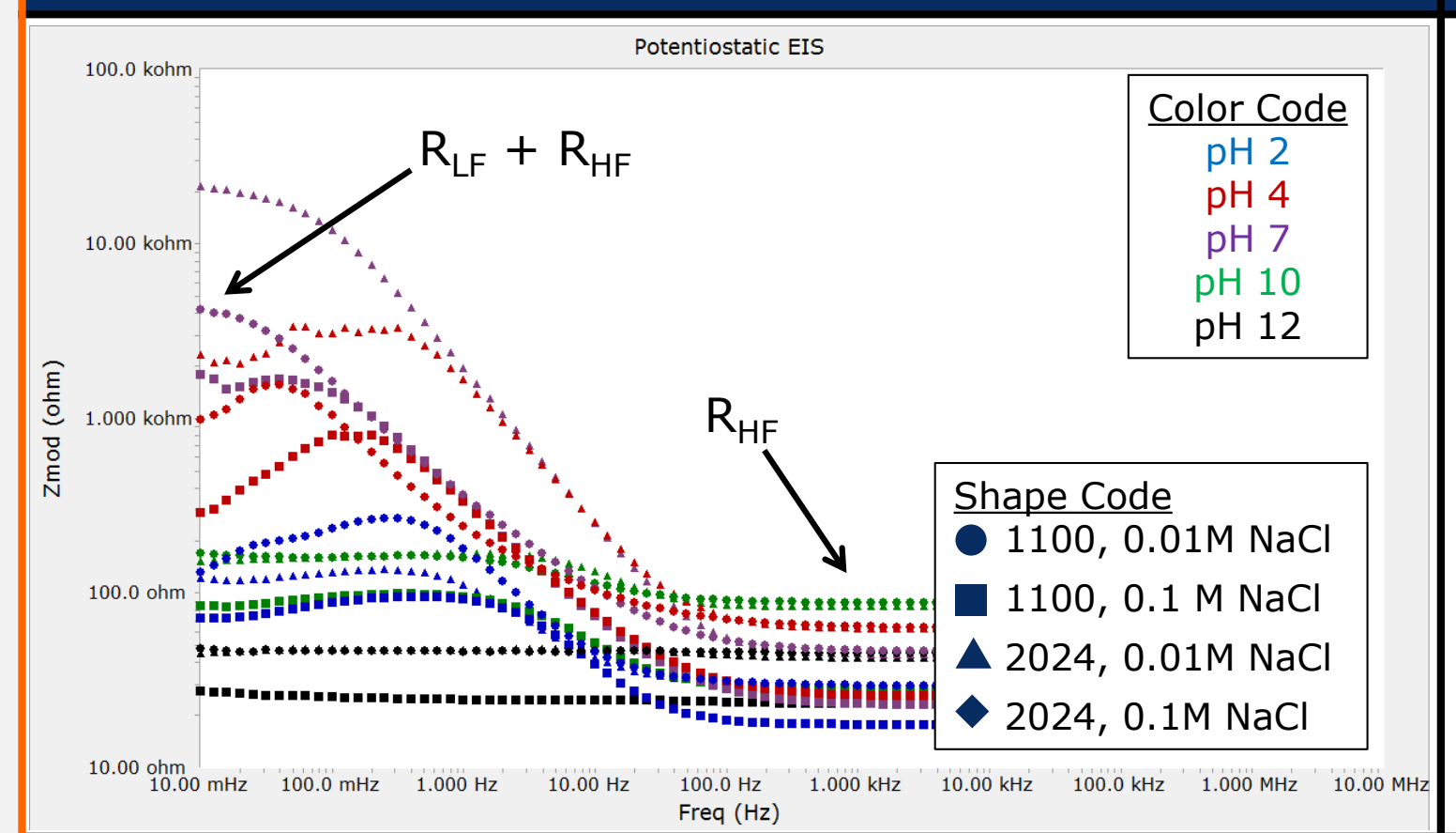


Corrosion Current Density

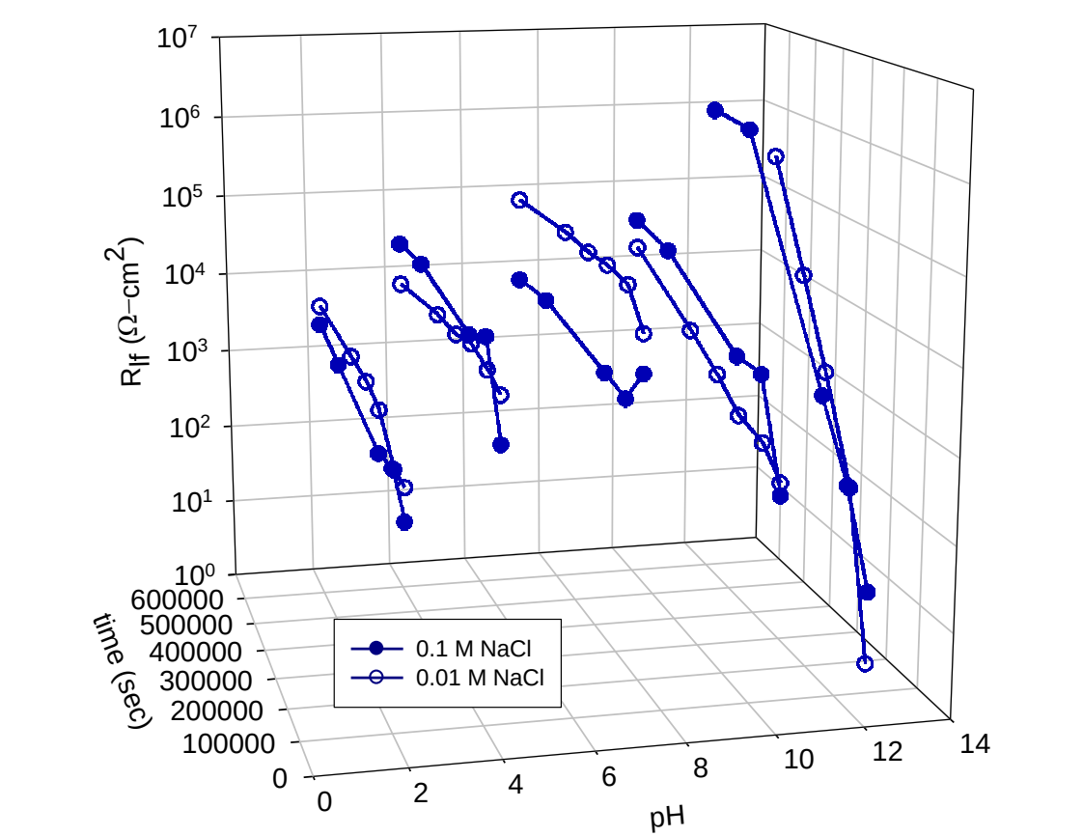


Electrochemical Impedance – AC Method

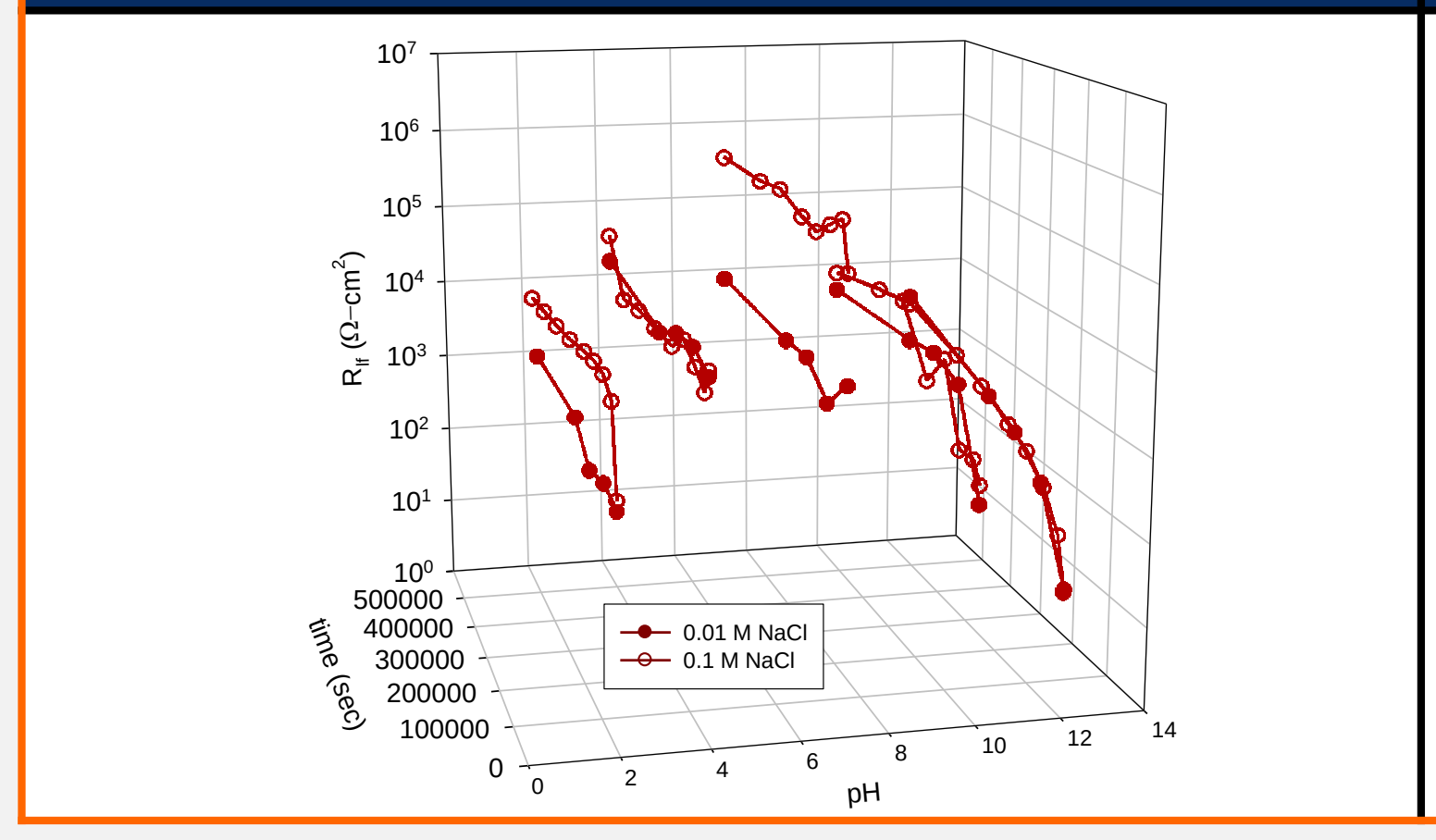
EIS Summary



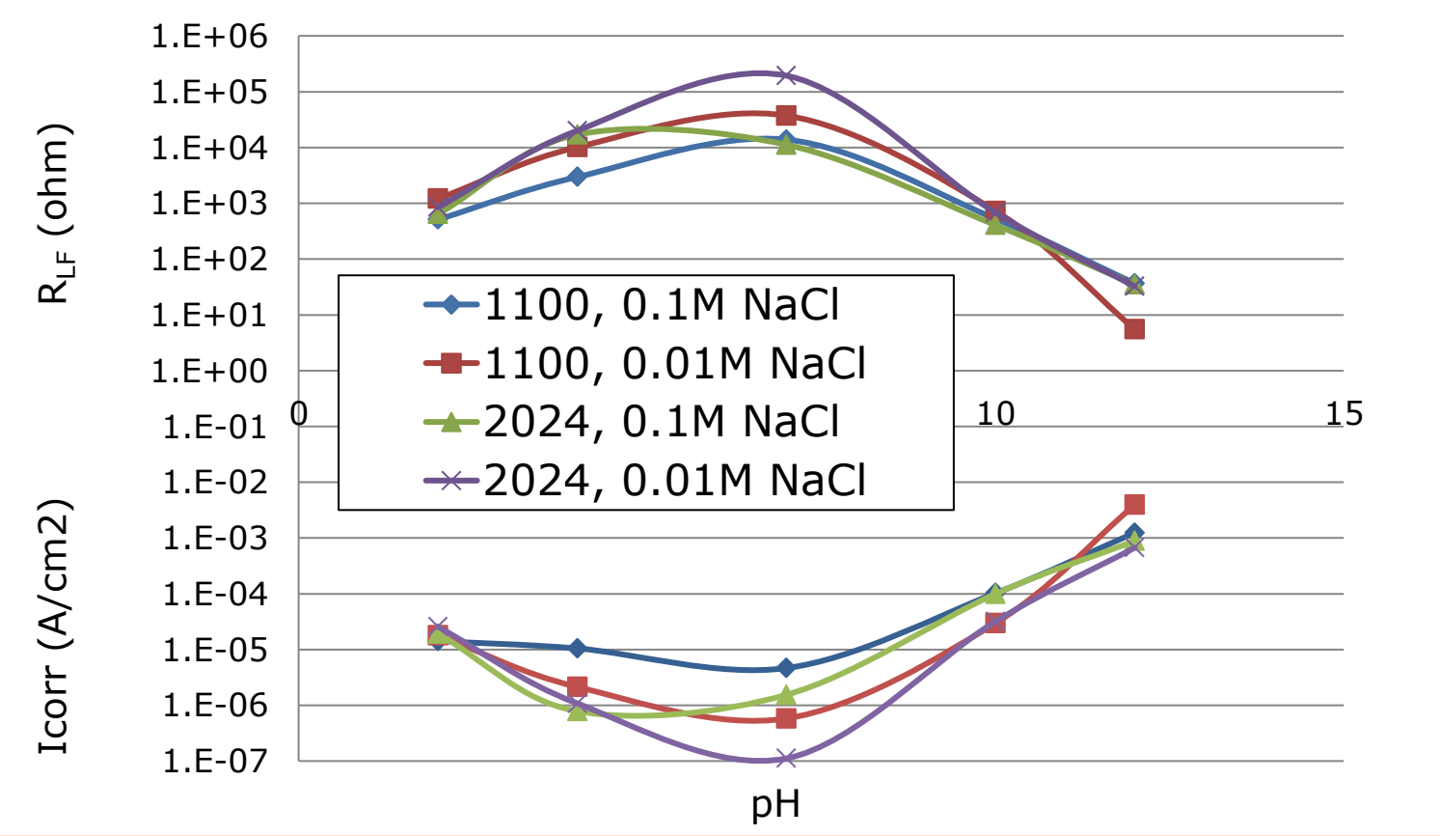
AA1100 - R_{LF} vs. Time



AA2024T3 - R_{LF} vs. Time



Relationship of R_{LF} and I_{CORR}



Experimental results, and the extracted parameters, can be seen in the series of plots at left, highlighting the polarization and impedance scans, the open circuit potentials, corrosion current densities, as well as the high and low frequency (R_{HF}, R_{LF}) resistance. Impedance spectroscopy was used to get R_{LF} as a function of time. The corrosion current densities and low frequency resistances are related as follows, where βa and βc are the anodic and cathodic Tafel slopes.

$$R_{LF} = \frac{\beta_a \beta_c}{2.3 i_{corr} (\beta_a + \beta_c)}$$

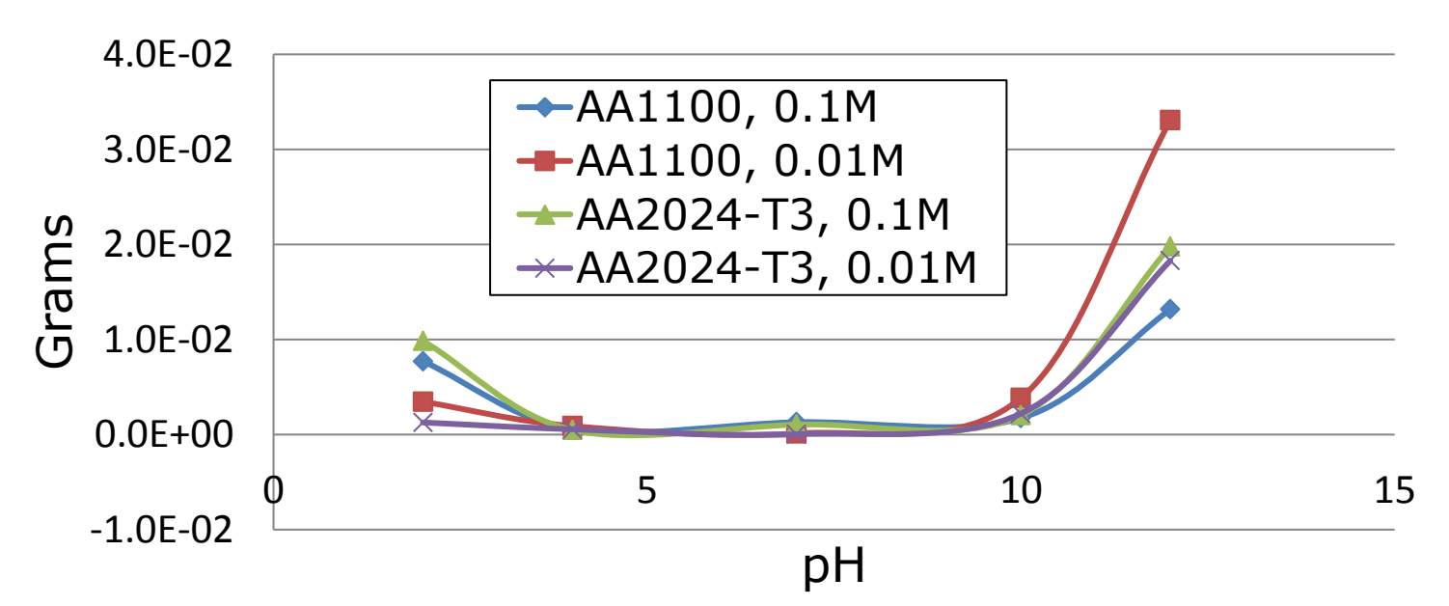
Converting R_{LF}(time) to I_{corr}(time), the mass lost to corrosion can then be calculated as follows, where *a* is the atomic weight of the corroding species, *n* is equivalents per reaction and *F* is Faraday's constant.

$$m = \frac{I_{corr}(t)\, t\, a}{nF}$$

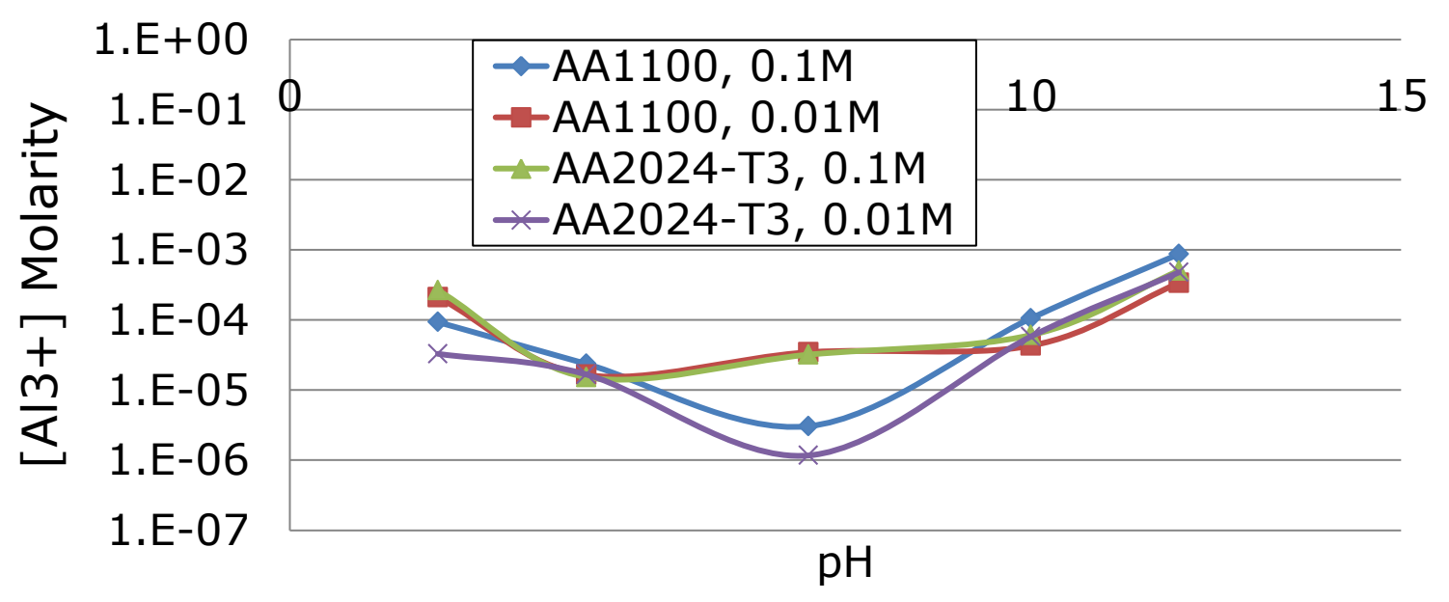
One can then predict a final solution concentration of dissolved ions after a specific time of exposure. Inductively coupled plasma mass spectrometry (ICP-MS) was used to analyze the solution concentration of dissolved species following solution exposure for the duration of impedance scans, shown below. Measured results match closely with the predicted concentration of Al^{3+}.

Something about calculated results

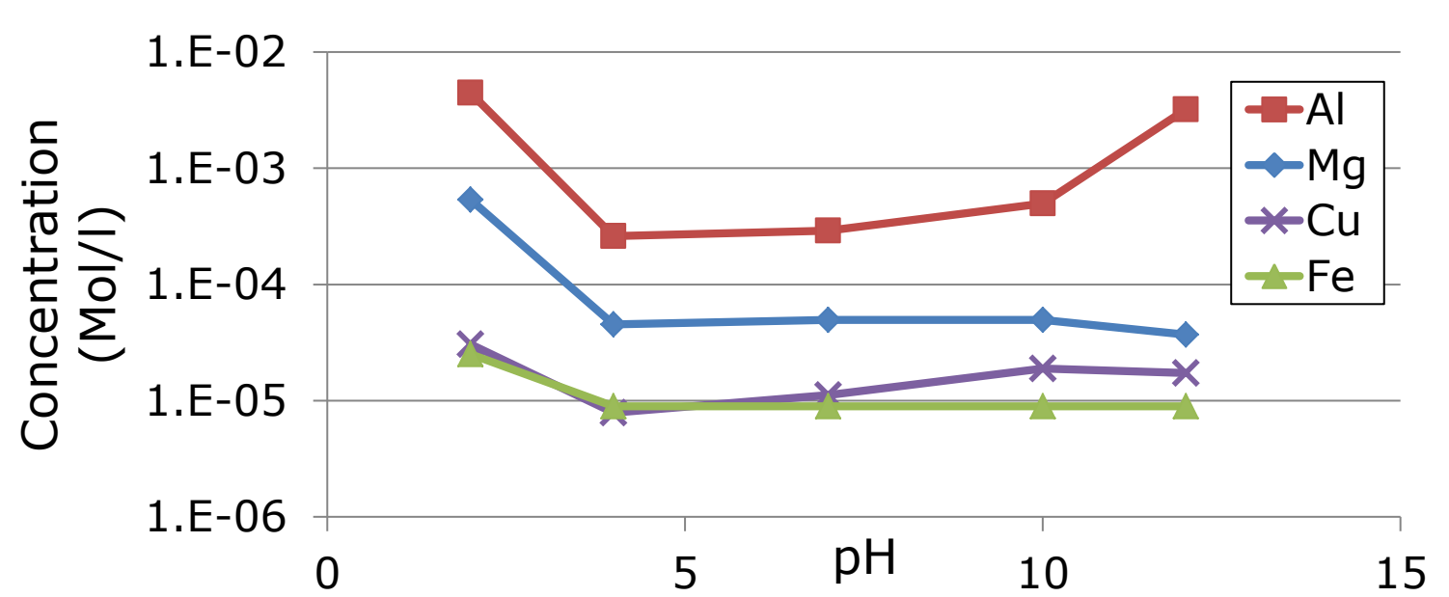
Calculated Mass Lost to Dissolution of Al^{3+}



Predicted Solution Concentration After 7 Days



ICP-MS AA2024T3, 0.1M NaCl

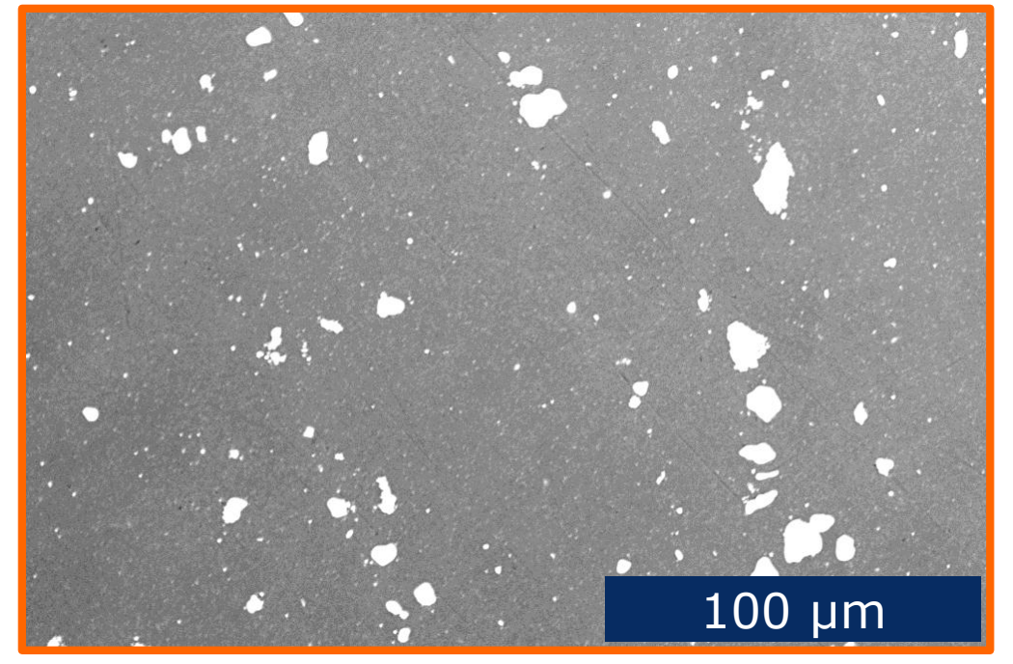


*The values at pH 2 have been inflated by an artificially induced corrosion potential.

Discussion

Precipitated Phases

Backscattered SEM of AA2024-T3



Binary Image

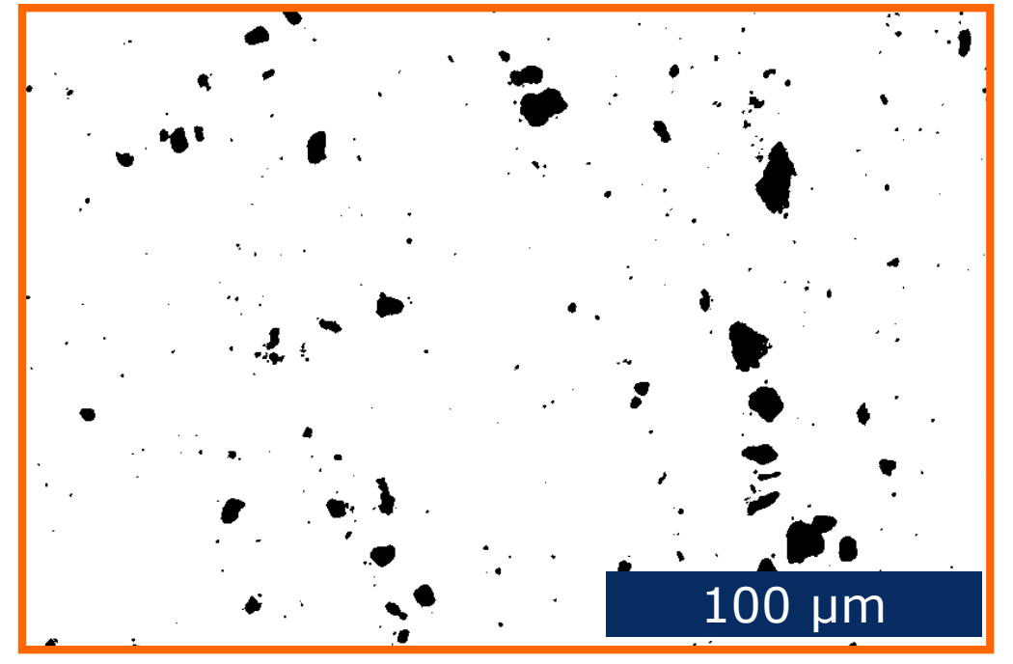
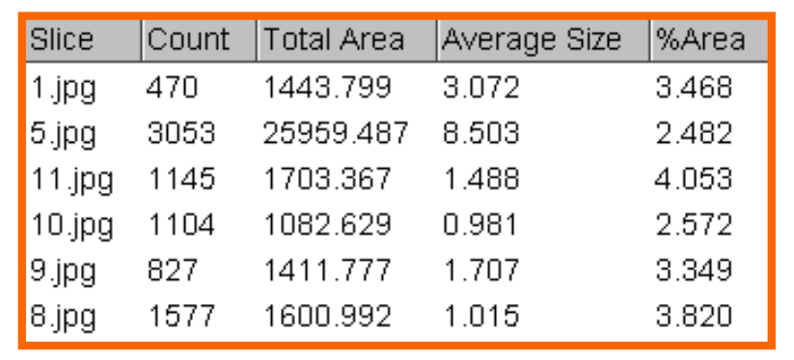


Image Analysis Results



Slice	Count	Total Area	Average Size	%Area
1.jpg	470	1443.799	3.072	3.468
5.jpg	3053	25959.487	8.503	2.482
11.jpg	1145	1703.367	1.488	4.053
10.jpg	1104	1082.629	0.981	2.572
9.jpg	827	1411.777	1.707	3.349
8.jpg	1577	1600.992	1.015	3.820

Surface particle analysis using ImageJ software suggests that approximately 3.5% of the exposed surface of AA2024-T3 is composed of precipitated phases.

Particle Contributions

The corrosion rates of select phases[1]

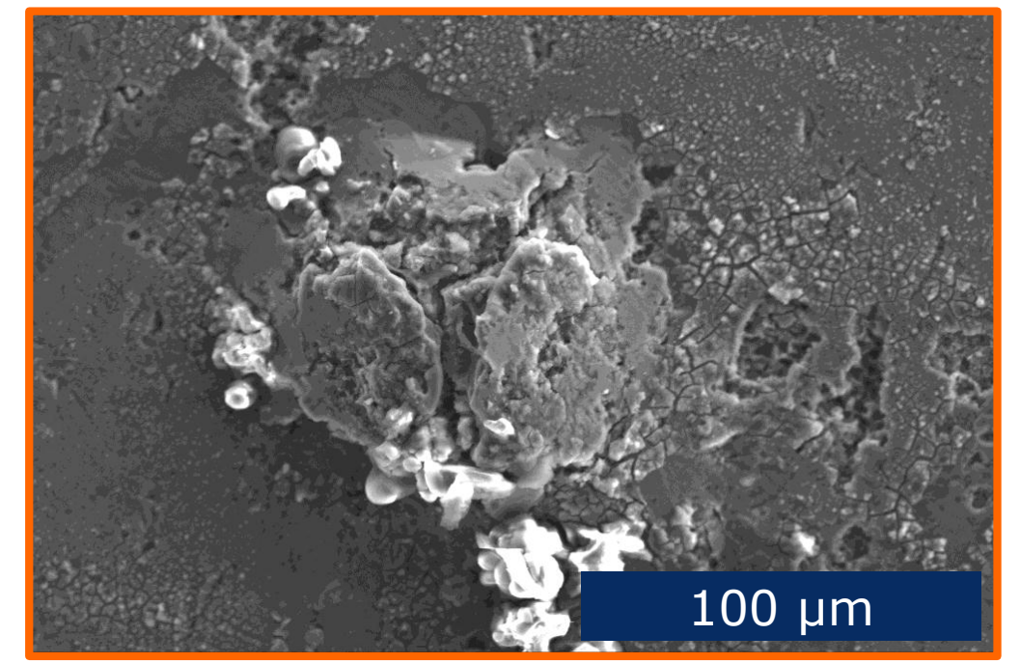
Phase	OCP (mV) 0.1M NaCl	I_{CORR} A/cm² @2024 OCP	I_{CORR} A/cm² @own OCP
Al_2CuMg	-830 (a)	9.3E-3	1.1E-5
Al_7Cu_2Fe	-640 (a)	3.8E-4	6.8E-5
AA2024-T3	**-555**	**6.7E-6**	**6.7E-6**
Al_2Cu	-484 (c)	2.5E-6	3.5E-6

And contribution to total current[5]

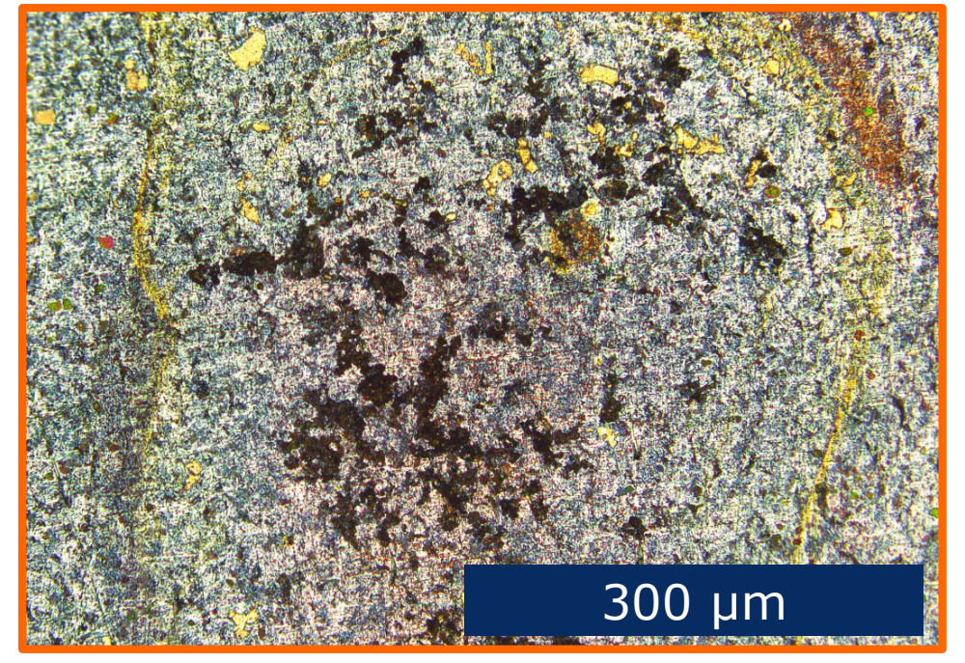
Steady State Dissolution	Al	Cu	Mg
Current Density (μA/cm²)	2039	0.48	47.5
Contribution (%)	Bal.	0.023	2.3

Particle Influenced Corrosion

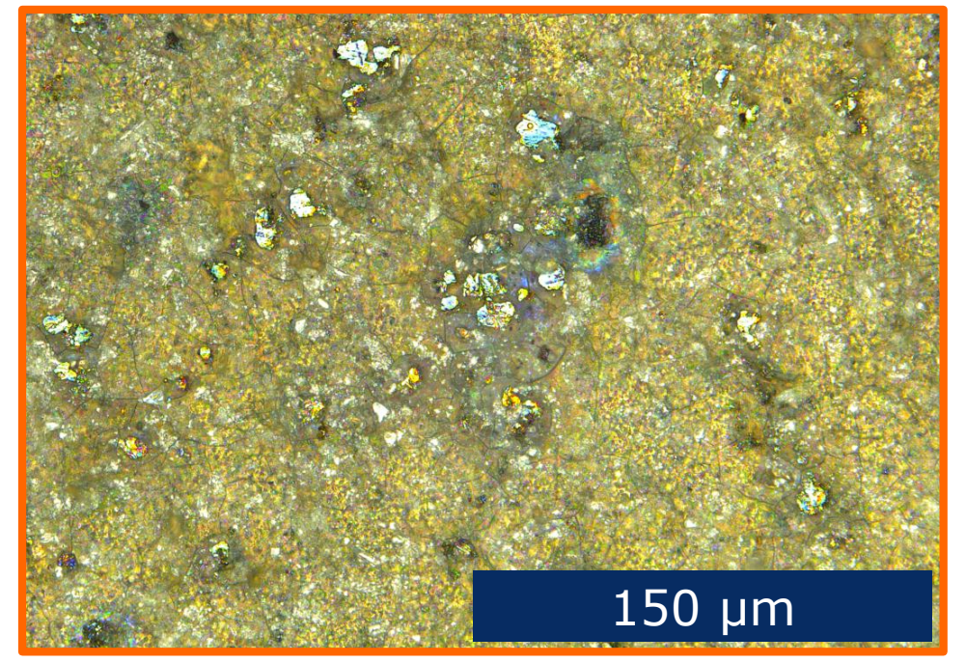
Corrosion Product Wedging - pH 7



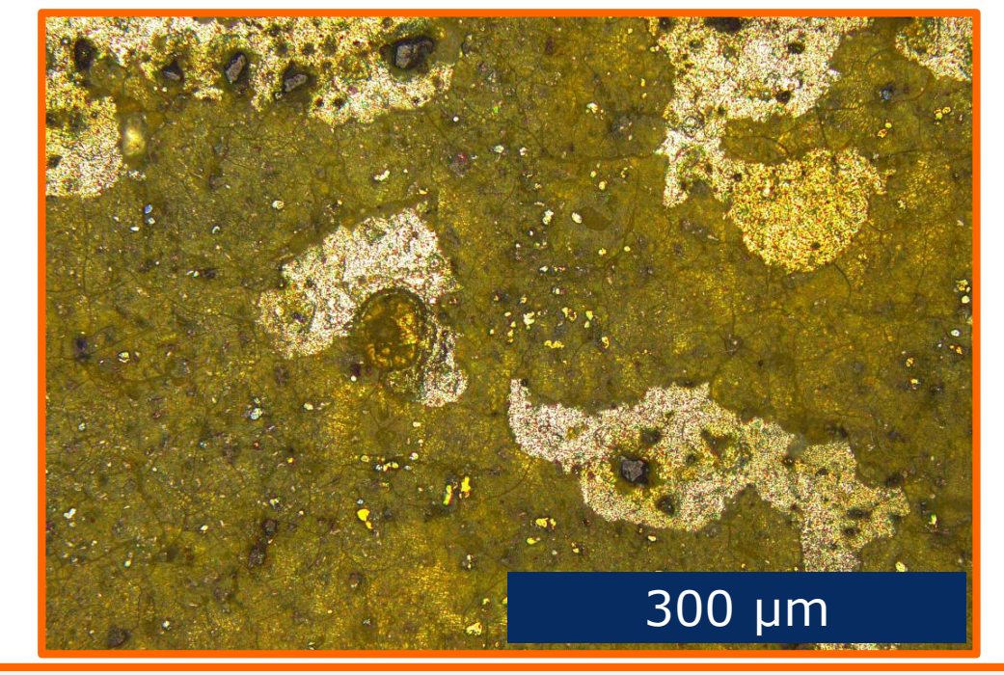
Particle Induced Pitting – pH 4



Corrosion Product – pH 2



Corrosion Product – pH 12



Corrosion of aluminum is dictated first by environmental exposure, and then influenced by microchemistry. Interactions of the matrix and precipitated phases in strengthened aluminum alloys result in localized methods of corrosion. Corrosion can lead to premature mechanical failure as a result of fatigue cracks initiating at pits, or cross-sectional reduction in area due to grain boundary etch-out. Coating failure can also be attributed to corrosion in the form of anodic undercutting, corrosion product wedging, cathodic delamination, a chemically induced loss of adhesion and osmotic effects.

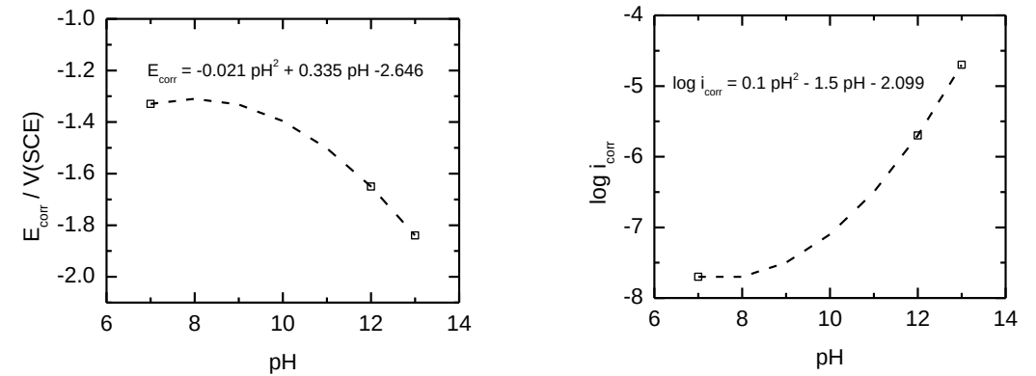
This work set out to establish the effects of localized corrosion mechanisms on the bulk corrosion behavior. The exposed surface fraction of precipitated phases was determined to be approximately 3.5% using binary image analysis techniques on high-contrast, backscattered SEM images. Energy dispersive X-ray spectroscopy (EDS) confirmed the compositions of the "blocky" precipitates are of the Al-Cu and Al-Cu-Fe-Mn phases, and the spherical precipitates are of the Al-Cu-Mg, S-phase.

The specific dissolution rates of these particles[1] and their contribution to the overall current density[5] have been presented in literature and are in agreement with the values measured using ICP-MS. The observed mechanisms of corrosion influenced by the precipitated phases are also in agreement with those presented in literature[1,2,3,4,5].

The fundamental parameters extracted from these data can be used in the equations governing the corrosion behavior of aluminum. With a thorough understanding of this behavior, the corrosion of bare and coated aluminum alloys can be modeled in a range of environments.

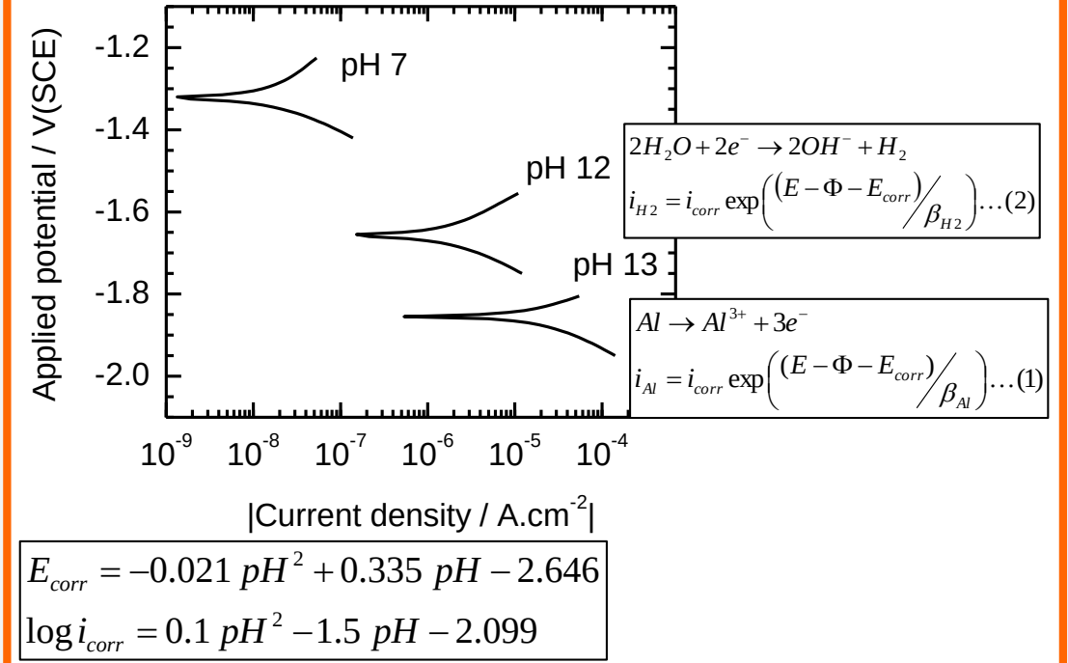
Corrosion Modeling

E_{CORR} and I_{CORR} as Functions of pH



Parameter	pH 7	pH 12	pH 13
E_{CORR} (V)	-1.33	-1.65	-1.84
I_{CORR} (A/cm²)	2.0E-8	2.0E-6	2.0E-5
$β_{Al}$(mV.dec⁻¹)	733	93	78
$β_{H2}$(mV.dec⁻¹)	43	52	55

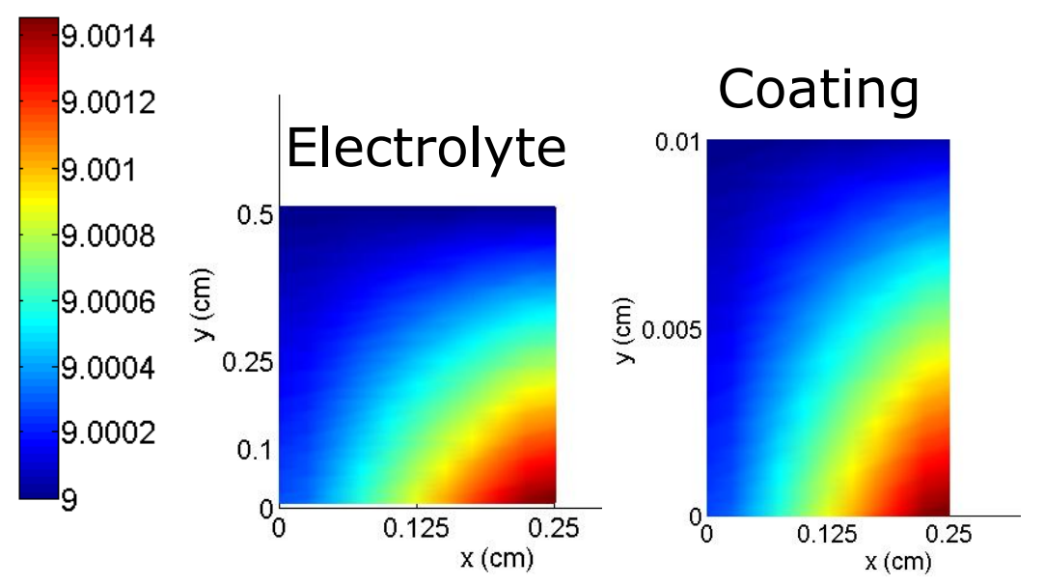
Simulated Polarization Curves



$$2H_2O + 2e^- \rightarrow 2OH^- + H_2$$
$$i_{H2} = i_{corr} \exp\left(\left(E - \Phi - E_{corr}\right)/\beta_{H2}\right) \ldots (2)$$
$$Al \rightarrow Al^{3+} + 3e^-$$
$$i_{Al} = i_{corr} \exp\left(\left(E - \Phi - E_{corr}\right)/\beta_{Al}\right) \ldots (1)$$

$$E_{corr} = -0.021\, pH^2 + 0.335\, pH - 2.646$$
$$\log i_{corr} = 0.1\, pH^2 - 1.5\, pH - 2.099$$

Coating and Electrolyte pH



Modeling Commentary

1. Fundamental parameters derived from experimental data build expressions for corrosion behavior as a function of pH
2. Polarization scans can be simulated from expressions
3. Localized corrosion can be modeled in a variety of systems

Conclusions

- This work has provided a statistical body of electrochemical data to the open literature for aluminum alloys 1100 and 2024-T3
- The fundamental parameters determined by this work will aide in the modeling of corrosion on a continuum scale
- The effect of solution chemistry was verified on the bulk corrosion behavior of aluminum, and corrosion rates for a comprehensive set of solutions was provided
- The localized corrosion mechanisms influenced by the presence of precipitated intermetallic phases was shown to influence the bulk corrosion behavior, and can be measured with a globalized test
- This work will aide in a modeling effort to decouple the metal-coating interface behavior from bulk corrosion behavior in continuing tests on coated aluminum alloys

Acknowledgements

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- A special thanks to Erik Sapper and the Boeing Research and Technology department for their enthusiastic encouragement
- Our gratitude to Anthony Brown of the Boise State department of Geosciences for providing ICP-MS analysis

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