

Predictive Coating Condition Model for Coating Lifetime Under Environmental Stressors

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ABSTRACT

In this work, laboratory test methodologies that employ the combined environmental stressors of time of wetness and salt loading were used to excite corrosion failure modes of coating systems. Real-time measurements via interdigitated electrodes were correlated with reference panel images to monitor the evolution of coating damage. These data can give insights into the coating degradation process and can be used as parameters for developing a predictive coating condition model. A description of the sensors, electrochemical measurements, and methods for coating testing are reported along with the results of atmospheric tests using a range of conditions to produce coating degradation.

Key words: salt loading, coating degradation, electrochemical measurements, time of wetness, aerospace corrosion

INTRODUCTION

The corrosion of aircraft costs the U.S. Department of Defense billions of dollars annually and accounts for a significant portion of maintenance time and costs.¹ Coatings are the most effective way to protect aircraft, but they have a finite lifetime and must be maintained or replaced before the underlying substrate is damaged by corrosion. Current aircraft maintenance practices call for coating inspections and maintenance based on elapsed time and not on measurements of coating health. Coating lifetime varies depending on the environmental stressors experienced in service, including temperature, humidity, and salt loading.

To enable more effective condition-based maintenance of coated assets, there is a recognized need for predictive coating condition models (PCCMs) to characterize the coating degradation process and make service life predictions in environments of varying severity. A PCCM can be used to manage corrosion protection systems, optimize the timing of maintenance activities to minimize hazardous waste, reduce costs, and increase asset availability. However, model development and validation may be limited by the ability to produce service-relevant failures in well-controlled laboratory tests. Current corrosion test practices rely heavily on operator visual or optical inspections and rating criteria that are applied at the conclusion of an accelerated test or outdoor exposure (ASTM D1654⁽¹⁾, ISO 4628⁽²⁾).^{2,3}

⁽¹⁾ ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA, 19428-2959 USA

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Little to no information on the corrosion kinetics is obtained in conventional tests, and often, knowledge of the impact of galvanic processes and inhibitor exhaustion behavior of coatings is not determined. This makes quantifying interaction effects of environmental stressors to better understand the time-dependent degradation of the coatings and corrosion of the substrate difficult. Real-time evaluation of coating condition using advanced coating evaluation metrics (ACEM) has the potential to significantly improve laboratory and outdoor testing of coatings.

It is hypothesized that once a coating is damaged, inhibitor leaching initiates to protect the exposed metal from corrosion.^{4,5} The amount of corrosion that occurs depends on the inhibitor concentration available to inhibit the surface and the kinetics of the inhibitor release or leach rate. It has been demonstrated that the leach rate and critical concentration for chromate-based coatings is faster and lower than non-chrome praseodymium-based coatings. Recently, it has been proposed that corrosion product formation, rather than the presence of inhibitor, may dominate corrosion currents over long exposure times^{5,6}. However, it is unknown how long the soluble inhibitor and/or corrosion product can maintain corrosion protection in various aggressive environments where the materials are continuously exposed to chloride salts and dilution events such as a dew, rain, or aircraft washes. For simplicity, dilution events can be represented environmentally as time of wetness (TOW). This is defined by ISO as the percent of time above 80% relative humidity (RH).⁷

Salt loading represents the amount of chloride deposited on a surface. Knowledge of the daily salt deposition rate at representative outdoor sites has led to severity classifications for military base locations.⁴ In the laboratory, this process is replicated using periodic dips (immersion) in salt solution. The salt solution concentration required to replicate a particular chloride severity can be calculated from the target salt deposition rate (S), the dip interval (t_s), and the electrolyte film thickness (d) (Equation 1).⁸⁻¹⁰

$$[\text{Cl}^-] = \frac{S * t_s}{d} \quad (1)$$

For the purpose of the experiments described in this paper, the electrolyte film thickness was assumed to be 56 μm . This is based on previous work where the average electrolyte thickness was measured by mass gain on aluminum 7075 (AA7075) substrates exposed to 0.1M and 5M sodium chloride solutions.

Zero resistance ammeter (ZRA) measurements provide *in situ* quantification of galvanic corrosion response on the substrate as the coatings degrade over time. ZRA works by shorting two electrodes using active circuitry on operational amplifiers to supply enough current to maintain a zero-potential difference between two electrodes. By utilizing a known resistance in the feedback loop, the current at each electrode can be measured without affecting impedance. The sensors and measurement techniques used in this work are compliant with ANSI/NACE TM0416-2016 and ISO 22858.^{11,12}

The purpose of this work was to improve understanding of protective coating properties by analyzing the inhibitor responses to multiple environmental stressors. The resulting datasets will inform development of a PCCM. Results are presented that compare the coating response of chromate and non-chrome aerospace primers to reoccurring damage, humidity, temperature, time of wetness, and salt exposure.

EXPERIMENTAL PROCEDURE

The following sections describe the measurement system and samples used in this work, sample preparation procedures, and the environmental test conditions used.

(2) International Organization for Standardization, ISO Central Secretariat, Chemin de Blandonnet 8, CP 401 - 1214 Vernier, Geneva, Switzerland

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Coating Measurement Set Up and Sample Preparation

A commercially available docking platform system* composed of three multi-sensor panels (MSP), a temperature sensor panel (TSP) and environmental sensors were used to measure environmental severity and its effect on the degradation of coatings (Figure 1). The docking platform includes environmental sensors to monitor the air temperature and relative humidity. The TSP records the panel surface temperature and uses an uncoated gold interdigitated electrode (IDE) to collect single frequency impedance-based measurements (10Hz, 25 kHz) which reflect the concentration of contaminants on the surface. The MSP include the same gold IDEs as the TSP, but they are fully coated to measure *in situ* changes in the coating conductance. Each MSP is also equipped with an AA7075 IDE that quantifies free corrosion of the substrate using a low frequency impedance-based measurement (0.5 Hz). Finally, an IDE of AA7075 and SS316 measured the galvanic corrosion rate of the substrate via ZRA.¹³ This paper will focus on the galvanic corrosion rates measured by the AA7075/SS316 IDEs to characterize the effectiveness of coating inhibitor protection against galvanic corrosion in various environments.

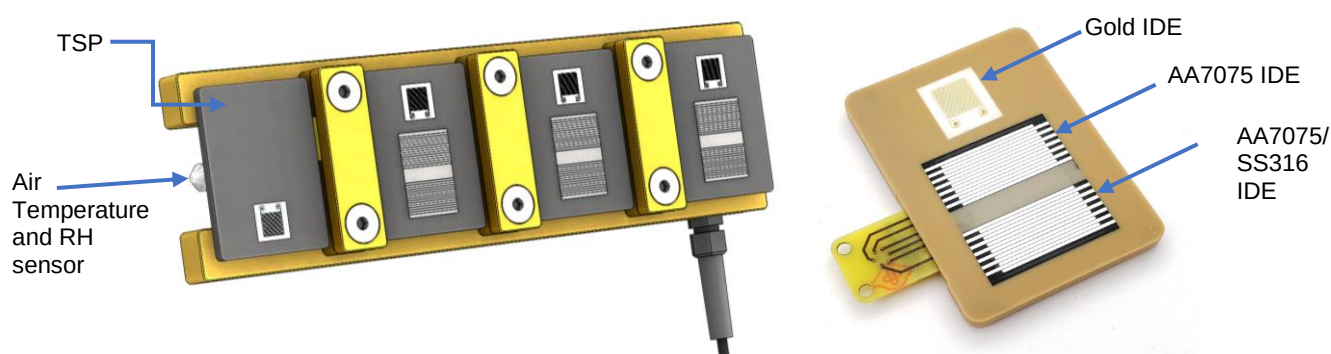


Figure 1: Docking platform system (left) and MSP (right).

Coating Application

Prior to coating application, MSP were wiped clean, acid etched/deoxidized (AA7075 and SS316 only)[†], and treated with an organic film-former pretreatment[‡]. Triplicate MSP were coated with different aerospace primers including: a solvent borne chromate[§], a solvent borne non-chrome^{**}, a water borne non-chrome^{††}, and an uninhibited^{‡‡} primer according to manufacturer recommendations. All MSP were then overcoated with the same glossy, polyurethane topcoat^{§§}. After coating curing, an x-scribe was introduced over the free corrosion and galvanic corrosion IDEs to simulate initial damage to a coating (Figure 2).

* Luna CorRES™

† Henkel Alumiprep 33

‡ Pre-Kote

§ PPG-Deft CA7233

** PPG-Deft 02GN098

†† PPG-Deft 44GN098

‡‡ PPG 45GY005

§§ PPG-Deft CA8202

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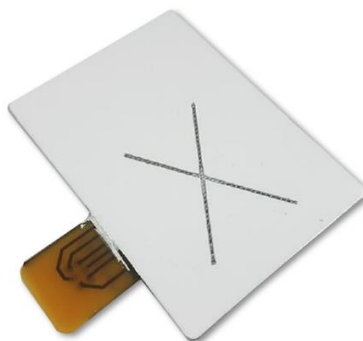


Figure 2: Coated and scribed MSP.

Reference Coupons

Reference coupons were assembled to accompany the coated MSP in each test. The AA7075 coupons were coated with the same coating systems as the MSP and x-scribed before being instrumented with SS316 hardware (Figure 3). The coupons were mounted to inert backing plates, allowing them to be placed in a test panel rack at a slight angle from the vertical during testing (Figure 4).

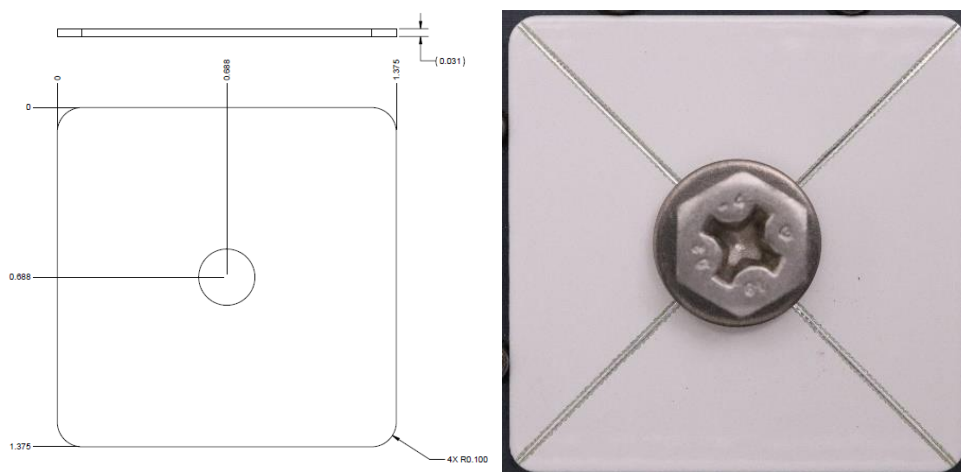


Figure 3: Reference coupon dimensions (inches, left) and coated and assembled photo (right).

Environmental Stressors

Salt Load Comparison Testing

All samples were placed in a controlled temperature and humidity chamber^{***} for testing (Figure 4). Portions of a dynamic environmental severity index (d-ESI) cycle based on summer conditions in Beaufort, South Carolina were selected to create a diurnal cycle that was programmed into the test chamber and repeated over the duration of the test.¹⁴ The simplified cycle consists of a week with a low time of wetness (TOW) of 28% followed by a week of high TOW of 74% (Figure 5).

^{***} Thermotron