The Cost of Going Green?  
Filiform Corrosion of Powder-Coated Aluminum on the Gulf Coast

By Richard Burgess and Kenneth B. Tator, KTA-Tator, Inc.

Thousands of linear feet of aluminum hand railing have been powder coated by electrostatic spray in the shop and installed on balconies of condominiums along the Atlantic and Gulf Coasts. Over the past five years, the writers have investigated several premature failures of such railings from Orange Beach, AL, to Florida's Marco Island and Ft. Lauderdale area.

The failure typically propagates as bubbles and blisters in the coating. They result from under-film corrosion, which commonly begins as small, localized bubbles or bumps along crevices or thread-like tracks of filiform corrosion. Should the initial conditions go unnoticed, film distortion becomes larger and progresses to delamination, cracking, and peeling. Premature failure typically occurs within a few months after installation but may go unnoticed for a year or longer.

Three failure cases involving extruded aluminum are briefly described in this article. A failure mechanism common to them was filiform corrosion, but the case histories suggest the outcomes should have been quite different. Filiform corrosion developed even when it appeared that everything was done "correctly." Although condominium buildings are not considered industrial structures, the aggressive environment described is common to many industrial structures. Moreover, because of the environmentally friendly, i.e., "green," advantages of powder over liquid coatings, newer powder coating applications for industrial use are developing. Lessons from these railings, therefore, can also benefit the protective coatings industry.

### Background

The aluminum alloy (AA) used in each case was reported to be 6xxx, Al-Mg-Si, series (6063-T5/T52 or 6061-T6) for extruded bar, tube, plate, and sheet.

For each case, a different manufacturer supplied the powder coatings.

- **Case 1:** Polyester TGIC (triglycidyl isocyanurate), "a weather resistant powder coating for interior and exterior applications." Recommended coating thickness, 2.5 to 3.5 mils.
- **Case 2:** TGIC-Free Polyester coating having "...superior weatherability compared to standard polyester powder coatings." Recommended coating thickness, 1.5 to 4.0 mils.
- **Case 3:** Fluoropolymer, "...for high performance architectural applications." Recommended coating thickness, 1.5 to 2.5 mils.

After surface cleaning and preparation, the thermoset powder coating products were applied to the aluminum railing sections. The powders were cured by heating the pieces to the temperature-time curing cycle, as recommended by the powder manufacturer.

In Cases 1 and 2, project specifications called for coatings to meet the requirements of American Architectural Manufacturers Association (AAMA) 603-98, Voluntary Specification, Performance Requirements and Test Procedures for Pigmented Organic Coatings on Aluminum Extrusions and Panels. For surface preparation, AAMA 603-98 says only that "cleaning and metal preparation shall be to ensure compliance with the performance requirements." When the metal in Case 1 was prepared (in 2003), AAMA 603-98 had been superseded by AAMA

### Table 1: Summary of the Powder Coating Thickness on Aluminum Hand Rails (mils)

<table>
<thead>
<tr>
<th>Case 1 Surfaces</th>
<th>Average</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>Top Rail</td>
<td>3.5</td>
<td>1.8 to 5.1</td>
</tr>
<tr>
<td>Post</td>
<td>2.7</td>
<td>1.3 to 5.4</td>
</tr>
<tr>
<td>Picket</td>
<td>3.3</td>
<td>1.8 to 4.5</td>
</tr>
<tr>
<td>Bottom Rail</td>
<td>3.7</td>
<td>1.8 to 6.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case 2 Surfaces</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Rail</td>
<td>3.2</td>
<td>2.5 to 6.1</td>
</tr>
<tr>
<td>Post</td>
<td>2.5</td>
<td>1.1 to 3.9</td>
</tr>
<tr>
<td>Picket</td>
<td>2.3</td>
<td>1.1 to 3.3</td>
</tr>
<tr>
<td>Bottom Rail</td>
<td>3.7</td>
<td>1.8 to 6.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case 3 Surfaces</th>
<th>Average</th>
<th>Maximum</th>
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</thead>
<tbody>
<tr>
<td>Bottom Rail</td>
<td>3.0</td>
<td>1.4 to 3.7</td>
</tr>
<tr>
<td>Mid-Rail</td>
<td>2.5</td>
<td>1.9 to 3.3</td>
</tr>
<tr>
<td>Posts and Spindles</td>
<td>2.6</td>
<td>1.4 to 4.1</td>
</tr>
</tbody>
</table>

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2603-02, which calls for a multi-stage pretreatment and conversion coating of the metal before coating the aluminum. However, the Case 1 applicator may have followed AAMA 603-98 as given in the project specification. Only glass bead blast cleaning was performed to prepare the substrate. In Case 2, the applicator employed a multi-stage pretreatment process as described below. Product performance certifications were not available for the investigations of Case 1.

(It should be noted that of the AAMA’s three voluntary performance specifications for coating work, 2603-02 is the least rigorous and addresses “Pigmented Organic Coatings.” AAMA 2604-02 addresses “High Performance Organic Coatings.” AAMA 2605-02 addresses “Superior Performing Organic Coatings” and contains the most rigorous performance protocols. As in AAMA 2603-02, AAMA 2604-02 and AAMA 2605-02 state that a multi-stage pretreatment and conversion coating application should be performed before coating aluminum.)

In Case 1, the manufacturer’s product data sheet (PDS) did not contain claims that the powder coatings comply with any AAMA standards. In Case 2, the manufacturer’s PDS stated that the high-gloss series meets AAMA 2603-02 requirements.

There were no project specifications provided for Case 3. However, the applicator reported that a fluoropolymer-based powder coating, considered superior to the products in Cases 1 and 2, was selected due to project warranty requirements. The manufacturer’s PDS included data demonstrating the fluoropolymer-based powder coating met test requirements in AAMA 2605.

For surface preparation, each manufacturer’s PDS stated that aluminum substrates require multiple cleaning/treatment steps before applying powder coatings. As noted above, the aluminum substrate in Case 1 was prepared by (glass) bead blast cleaning. The substrates in the Cases 2 and 3 underwent multi-step cleaning and preparation processes, described by the powder coaters as follows.

Case 2: Cleaning and Preparation
- Alkaline cleaner (90 – 120 F)
- Fresh water rinse
- Back-up rinse
- Chrome-free pretreatment
- High-temperature drying (250 – 350 F)
- Automated electrostatic powder coat application
- Transport through a baking oven (400 – 425 F for 15 minutes)

Case 3: Cleaning and Preparation
- Alkaline cleaning, pH 11.0, 120 F
- Acidic water rinse (pH 4.5 – 5.0)
- Hydrofluoric acid cleaning, pH 2.0 – 3.0, ambient temperature 2 minutes
- Transported through baking (400 – 430 F).

The applicators supplied no quality control or performance test data for the aluminum alloy or powder coatings in any of the cases.

Field Investigation

The field examination included visual examinations, coating thickness measurements (Table 1, p. 11), adhesion testing, sample removal for laboratory analysis, and substrate examination.

Observations from Case 1

The coating failure included filiform corrosion; blisters of differing size; and split, delaminated films (Fig. 1). The origin of

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the filiform strands was associated with edges and seams, most commonly where aluminum pickets passed through the lower railing.

Blister clusters and split coatings were present without indication that filiform corrosion was the initiating mechanism (Fig. 2, p. 13). The aluminum top rails exhibited occasional blister clusters at the ends, while adjacent rails were unaffected.

Observations from Case 2
- Filiform corrosion was the principal mode of corrosion at edges and seams, most commonly where aluminum pickets passed through the bottom and mid rails (Figs. 3 and 4, p. 13).
- Distinct individual blisters were present in otherwise intact coating, as were clusters of smaller, irregular blisters.

Observations from Case 3
- The aluminum substrate exhibited filiform corrosion, crevice corrosion, and probable galvanic corrosion at stainless steel screw penetrations (Fig. 5). Corrosion was primarily limited to edges and connections.
- The products of aluminum corrosion created blisters (bub

### Table 2: Typical Seven-Step Aluminum Pre-Treatment Process

<table>
<thead>
<tr>
<th>Step</th>
<th>Process</th>
<th>Description</th>
<th>Time</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clean</td>
<td>Alkaline or acid uniform mild etching to remove surface soils</td>
<td>1-5 minutes</td>
<td>140-180 F</td>
</tr>
<tr>
<td>2</td>
<td>Rinse</td>
<td>Tap water, overflowing</td>
<td>30 seconds</td>
<td>Ambient</td>
</tr>
<tr>
<td>3</td>
<td>Deoxidize (optional)</td>
<td>Acid treatment to remove natural oxide film</td>
<td>1 minute</td>
<td>Ambient</td>
</tr>
<tr>
<td>4</td>
<td>Rinse</td>
<td>Tap water, overflowing</td>
<td>45 seconds</td>
<td>Ambient</td>
</tr>
<tr>
<td>5</td>
<td>Conversion Coating*</td>
<td>Amorphous Chromium Phosphate or Amorphous Chromate**</td>
<td>45 seconds</td>
<td>100-120 F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>45 seconds</td>
<td>75-90 F</td>
</tr>
<tr>
<td>6</td>
<td>Rinse</td>
<td>Tap water, overflowing</td>
<td>30 seconds</td>
<td>Ambient</td>
</tr>
<tr>
<td>7</td>
<td>Final Rinse (and oven dry)</td>
<td>Acidulated rinse or water (TDS, 300 ppm)</td>
<td>15 seconds</td>
<td>Ambient***</td>
</tr>
</tbody>
</table>

* Coatings weight range: 30 to 100 mg/ft²
** Applies to AAMA 2605 only. Chrome or chrome free can be used for AAMA 2603 and AAMA 2604
*** May be heated to 150 F to facilitate drying

### Table 3: Comparison of Voluntary Specification Performance Requirements for Organic Coatings Applied to Aluminum Extrusions and Panels

<table>
<thead>
<tr>
<th>Voluntary Specification</th>
<th>AAMA 2603</th>
<th>AAMA 2604</th>
<th>AAMA 2605</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretreatment System</td>
<td>Chrome (30 mg/SF) or Non-chrome (per mfg)</td>
<td>Chrome or Non-chrome</td>
<td>Chrome, 40 mg/SF</td>
</tr>
<tr>
<td>Dry Film Thickness Minimum (mils)</td>
<td>0.8</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Outdoor Exposure</td>
<td>1 Year, South Florida</td>
<td>5 Years, South Florida</td>
<td>10 Years, South Florida</td>
</tr>
<tr>
<td>Chalking Resistance</td>
<td>1 Year, Slight Chalk</td>
<td>5 Years, Chalk = 8</td>
<td>10 Years, Chalk = 8</td>
</tr>
<tr>
<td>Accelerated Corrosion Resistance</td>
<td>1500 Hours</td>
<td>3000 Hours</td>
<td>4000 Hours</td>
</tr>
<tr>
<td></td>
<td>Salt Spray</td>
<td>Salt Spray</td>
<td>Salt Spray</td>
</tr>
<tr>
<td></td>
<td>1500 Hours</td>
<td>3000 Hours</td>
<td>4000 Hours</td>
</tr>
<tr>
<td></td>
<td>100% Humidity</td>
<td>100% Humidity</td>
<td>100% Humidity</td>
</tr>
<tr>
<td>Gloss Retention</td>
<td>None specified</td>
<td>5 years, 30%</td>
<td>10 Years, 50%</td>
</tr>
<tr>
<td>Erosion Retention</td>
<td>None specified</td>
<td>5 Years, 10% loss</td>
<td>10 Years, 10% loss</td>
</tr>
<tr>
<td>Color Uniformity</td>
<td>Excellent color uniformity of all finishes is required. Final color approval should be made with applicator-prepared production line samples for all finish specifications.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warranty*</td>
<td>1–5 Years</td>
<td>5–10 Years</td>
<td>10–20 Years</td>
</tr>
</tbody>
</table>

* Varies by manufacturer
bles) in the coating film on extruded pieces (Fig. 6). However, the blistered coating was not split or ruptured.

**Commonalities and Uniqueness**

Factors common to all three cases were the use of powder coatings, extruded aluminum alloys suitable for marine (coastal) environments, and the presence of filiform corrosion and blisters. Apart from surfaces with under-film corrosion, adhesion was good, the substrate appeared clean, and the coating appeared durable. Filiform corrosion in all cases originated at edges, penetrations, and similar locations where the coating was not continuous.

In each case, adhesion was tested in accordance with ASTM D3359 and ASTM D6677 and by subjective probing around blisters and bubbles. For all intact coating, adhesion was excellent. Wherever the coating film was failing, the underside showed white corrosion products.

Unique factors included the type of powder coat resin, surface cleaning and preparation methods, and degree of failure observed. Case 1 had the least rigorous preparation, a TGIC polyester powder coat, and the most extensive failure. Case 2 had several surface cleaning and preparation steps, a TGIC-free polyester powder coat, and less extensive failure than Case 1. Case 3 had the most thorough surface cleaning and preparation, a high grade (fluoropolymer) powder coat, and the least degree of failure.

**Research**

Research into the failures began with investigation into proper surface preparation. Among documents reviewed was ASTM D 1730, Standard Practices for Preparation of Aluminum and Aluminum-Alloy Surfaces for Painting, which, simply summarized, says that unless the service environment is interior (ambient) or very mild, chemical treatment or anodizing should be employed. Research of applicable powder coat manufacturers’ PDS and literature consistently showed that some measure of chemical treatment was necessary. Voluntary specifications and other published AAMA information were reviewed. This included an article4

![Fig 6: (Case 3) Intact coating blisters on a railing section prior to removal of the coating (left) and the appearance of the substrate (right) with confined spots of corrosion product.](image)

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that described a “typical” pre-treatment process for aluminum fenestration products (Table 2, p. 14). Table 3 (p. 14) briefly compares the three AAMA Voluntary Specifications named above.

Corrosion mechanisms common to aluminum were also investigated with particular emphasis on filiform corrosion as an initial corrosion form and a likely predecessor to crevice corrosion and many of the blisters.

Filiform corrosion occurs on coated aluminum under particular conditions—temperature (70–105 F), relative humidity (75%–95%), beneath thin films (e.g., 3–4 mils)—and is not observed when coatings are not applied. The presence of soluble salts (e.g., chloride) is also contributory. The driving force of filiform corrosion is the “head,” which serves as the corrosion cell anode and which pushes the filament forward. Humidity and salts provide the electrolyte. The aluminum behind the head where the corrosion products are deposited is (relatively) cathodic. The corrosion products include hydrated forms of aluminum hydroxide and aluminum oxide. The expanded volume of the corrosion products deforms the coating. Without conditions conducive to filiform corrosion, it does not develop. It is the opinion of some that a breach and/or initiating contaminant must be present to result in filiform corrosion progression.

Not surprisingly, the environment along saltwater coasts is conducive to filiform corrosion. During the course of a calendar year, typical average daily relative humidity ranges from 70% to 93% and daily average temperature can range from 47–85 F. The service environment is classified as Corrosion Class 3; in the vicinity of open water and near the coast.

Conclusions

The aluminum alloys selected were suited to the environment, so the substrate selection appears appropriate.

In Case 1, the surface preparation was not appropriate for the service environment. No reports or data were presented to demonstrate the powder coating would meet the specified performance requirements (AAMA 603), making the coating selection suspect.

In Case 2, the surface preparation was insufficient. The process included cleaning and a conversion coating (non-chromate) but did not include the (optional) deoxidizing acid step. The powder manufacturer recommends a minimum five-step chrome phosphate treatment (or equivalent). No reports or data were presented to demonstrate the powder coating would meet the specified performance requirements (AAMA 603), again making the coating
Resistance to filiform corrosion should also be a performance criterion. Research in Europe, where powder coatings have had longer and more diverse applications, shows that while the use of conversion coatings reduces the potential for filiform corrosion, such surface treatments are not 100% effective. Although chromate-containing compounds have demonstrated better performance than non-chromate formulations, the use of chromates is diminishing due to environmental and health concerns with hexavalent chromium toxicity. Anodizing before coating has been recommended as an alternative surface preparation process. (The pressure to replace conversion coatings based on hexavalent chromium is also present in the U.S.)

In Case 3, the surface preparation was appropriate. A non-chromate treatment was used, which is allowed by AAMA 603 (and AAMA 2603). For aluminum in a marine environment, the fluoropolymer powder coating was considered superior to the polyesters, and the manufacturer showed test data meeting many requirements of AAMA 2605. But AAMA 2605 requires a chromate treatment, not a non-chromate treatment. Failure at penetrations, including crevice corrosion, suggests that coating coverage was too thin or not complete, that contaminants were present, and/or that non-chromate treatments are not equivalent to chromate treatments.

Coating aluminum extrusions requires detailed surface cleaning and preparation and a continuous film. Electrostatic deposition has high transfer efficiency but the electrical fields formed in channels, boxes, and bends (Faraday cage effect) can yield incomplete coverage or coating films (whether liquid or powder) that are too thin. This effect sets the stage for the failures observed.

**Discussion**

Applicators have argued that AAMA 2605-compliant products should be specified for marine (coastal) applications and that specifying lesser materials will naturally shorten the coating service life. Arguments have also been made that numerous AAMA 2603-specified projects on the Gulf Coast have been successful. Both arguments merit investigation. If the AAMA Voluntary Specifications are to be used, the industry would benefit if documentation were available demonstrating which powder (and liquid) coatings, when applied to aluminum, have passed the requisite tests.

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(ESTCP) has issued Non-Chromate Aluminum Pretreatments® (NCAP) Phase I and Phase II Reports. A chromate product was used as a control (reference), and non-chrome and trivalent chrome products were tested. While some of the test products showed adequate performance in some applications, the chromate control performance was superior over a wider array of service environments and alloys. One test was for resistance to filiform corrosion. No such specific test is identified in the AAMA Voluntary Specifications but would be a significant addition.

ASTM D2803-03, Standard Guide for Testing Filiform Corrosion Resistance of Organic Coatings on Metal, contains three methods for exposing coated and scribed test specimens to a corrosive environment before placing them in temperature and humidity conditions conducive to filiform corrosion. The standard does not provide a uniform filiform corrosion rating system. However, the NCAP Phase I report used and described two techniques for rating filiform corrosion.

The first rating method assigned two numbers, one based on filament length and one based on relative filament density along the scribe. The second technique required stripping the coating from half of the test panel; placing a standard, transparent template of a grid of squares on the surface of a scribe leg; and counting the squares without filament corrosion.

Further Considerations
Among the many aluminum handrail coating failure investigations performed or reviewed, the writers have not encountered similar failures where liquid coatings were applied. One manufacturer reports that liquid coatings, particularly the fluoropolymer resins, simply outperform currently available powder coating formulations, a significant advantage for coastal applications. Liquid coatings are reported to meet AAMA 2605 requirements while powder coating products simply do not.

Perhaps aluminum substrates in marine environments represent a unique situation where powder coatings and (non-chrome) surface treatments require further evolution to meet or exceed the performance of chromate treatments and liquid coatings. Performance issues might be mitigated with consideration of the European experience and more transparent performance testing. Without equivalency performance on aluminum, one side effect of going green may be accepting lesser performance. In the meantime, powder coating failures on aluminum in coastal environments may continue.
# Training & Certification – November 2009

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<td>Pasadena, TX</td>
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<td>November 2-6</td>
<td>Planning &amp; Specifying Coatings Projects</td>
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<td>Protective Coatings Inspector</td>
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Notes
6. Corrosion Class 3 is defined as an environment in densely populated areas or near industrial areas; in the vicinity of open water and near the coast.
7. The Environmental Security Technology Certification Program (ESTCP) was established as a program of the DoD in December 1993. The ESTCP is managed by the Office of the Deputy Undersecretary of Defense for Environmental Security (DUSD-ES). The ESTCP demonstrates and validates laboratory-proven technologies that target the DoD’s most urgent environmental needs. These technologies provide a return on investment through reduced environmental, safety, and occupational health (ESOH) risks; cost savings; and improved efficiency.
8. ESTCP selected the NCAP project, led by Naval Air Systems Command (NAVAIR) and coordinated with JG-PP, to assist in the mitigation of the significant ESOH risks that are associated with the use of chromate conversion coatings.

Richard Burgess, a senior coatings consultant with KTA-Tator, Inc. (Pittsburgh, PA), is the editor of the F-Files series.

Ken Tator has been Chairman of the SSPC Research Committee and numerous other SSPC and NACE committees; a member of SSPC’s first Board of Directors; Director of NACE; and writer for JPCL, SSPC, NACE, and ASM.
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