# Corrosion Control in Carbon Fiber Reinforced Plastic (CFRP) Composite-Aluminum Closure Panel Hem Joints

Project ID: MAT131

Award DE-EE0007760

**Project Team:**

**PPG Industries** – *Brian Okerberg (PI)*, Hyun Wook Ro, Loubna Pagnotti, Reza Rock, Masayuki Nakajima, Egle Puodziukynaite, Scott Benton

**Ford Motor Company** – Mark Nichols, Niamh Hosking, Jeremy Ritchey

**Ohio State University** – Gerald Frankel, Jenifer Locke, Priyanka Adapala, Katrina Catledge

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# Overview

## Timeline

- Project start – 10/1/16
- Project end – 9/30/20*
- Percent complete – 95%*

  *Includes unanticipated COVID-19 delays and extension

## Budget

- Total project funding - $2,950,025
  - DOE share - $2,212,519
  - Contractor share - $737,506
- Funding for FY 2019 through project completion - $637,568

## Barriers addressed[1]

- Corrosion evaluation of mixed material joints
- Predictive corrosion modeling
- High volume use of CFRP materials (automotive line)

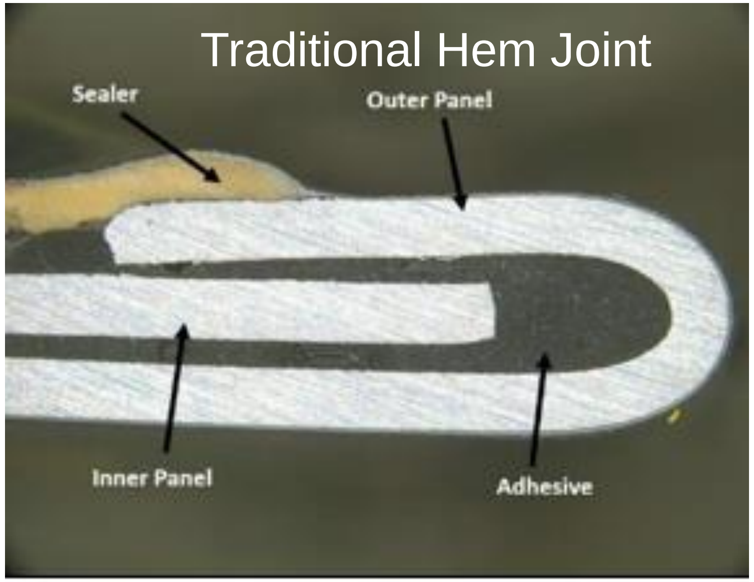
[1] Source: 2017 U.S. Drive MTT Roadmap Report, Section 4.

## Partners

# Relevance & Objectives

## Relevance

- Enable vehicle weight reduction by introducing CFRP
- Identify dissimilar material joining and corrosion protection challenges and predictive models
- Develop novel technologies to enable vehicle lightweighting




## Objectives

- Understand the impact of CFRP on part distortion and corrosion
- Develop low-temperature cure solutions to mitigate CTE mismatch
- Improve understanding of corrosion involving lightweight materials (CFRP/Al), including mechanisms and test methods

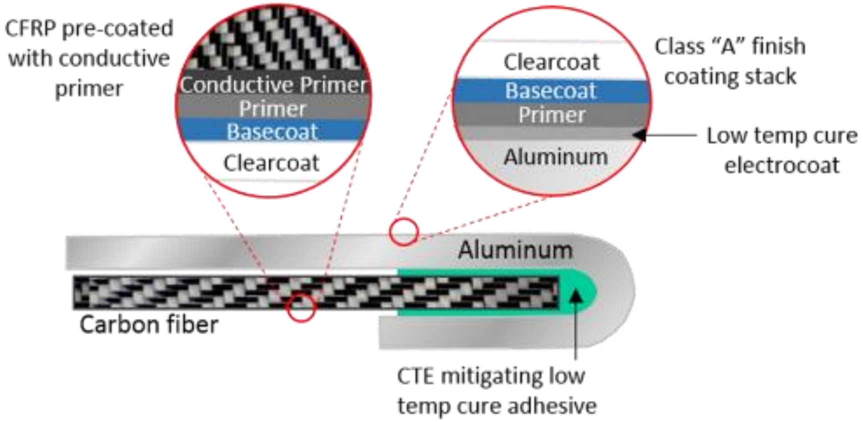
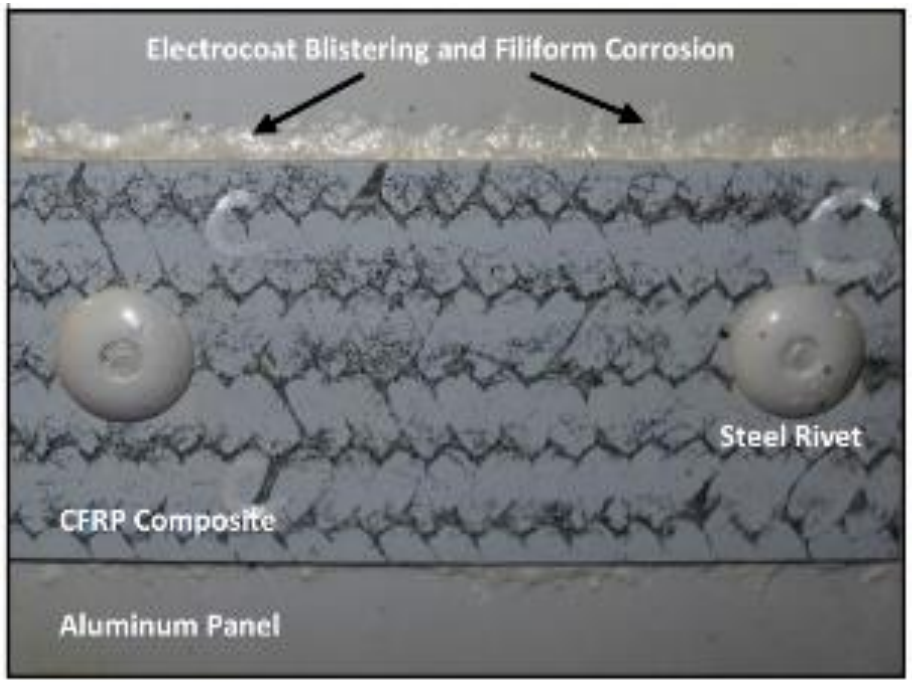



Image provided by Ford Motor Company

# Challenges

- CFRP introduces a potential source of galvanic corrosion
- Thermal expansion mismatch (CTE) between CFRP and Al will impart dimensional stresses and displacement during the paint bake process
- Affordable CFRP matrix materials are not stable at current paint bake oven temperatures
- Conventional automotive coatings and adhesives are not compatible with CFRP or the required lower bake temperatures
- Predictive accelerated corrosion tests for automotive CFRP/aluminum joints have not been determined

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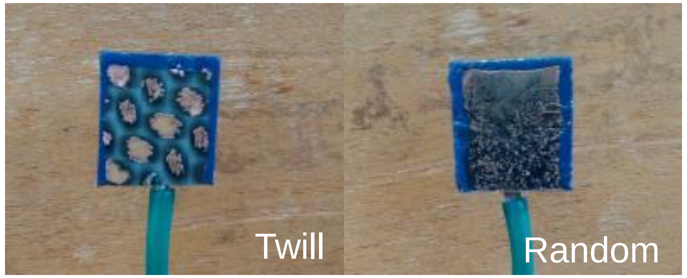
# Milestones & Approach

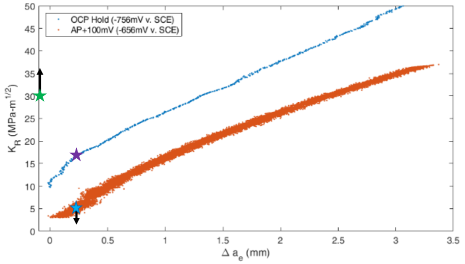
| | |
|---|---|
| **Budget Period 1: Understanding Nature/Extent of Problem** | • Understand the extent of the corrosion problem<br>• Identify the susceptibility to galvanic corrosion and SCC<br>• Balance conductivity for painting/galvanic coupling<br>• Identify pathways to low-cure adhesives and coatings |
| **Budget Period 2: Developing Solutions** | • Develop conductive primers, adhesives, and electrocoats<br>• Identify hem geometries to mitigate corrosion/CTE<br>• Galvanic assessment of CFRP type and joined samples<br>• Accelerated testing of CFRP/Al couples |
| **Budget Period 3: Optimization and Validation** | • Optimize and validate the solutions developed in BP 2<br>• Construct a surrogate aluminum outer/CFRP inner closure<br>• Process through a typical paint shop operation and corrosion test |

# Prior Technical Accomplishments

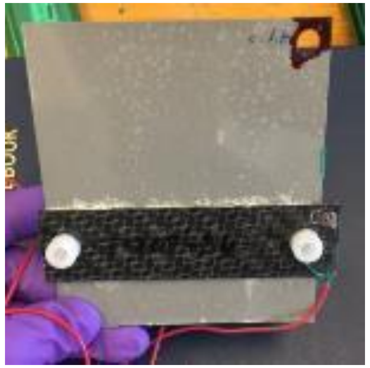
## Substrate Characterization

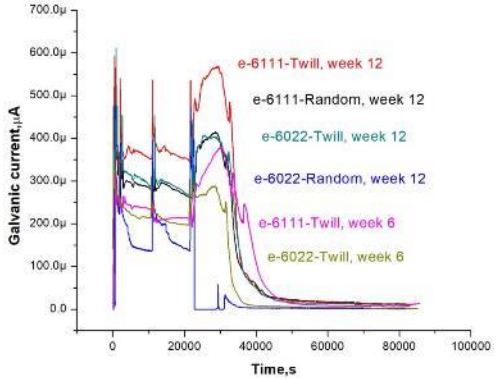



## Galvanic Corrosion & SCC Evaluation

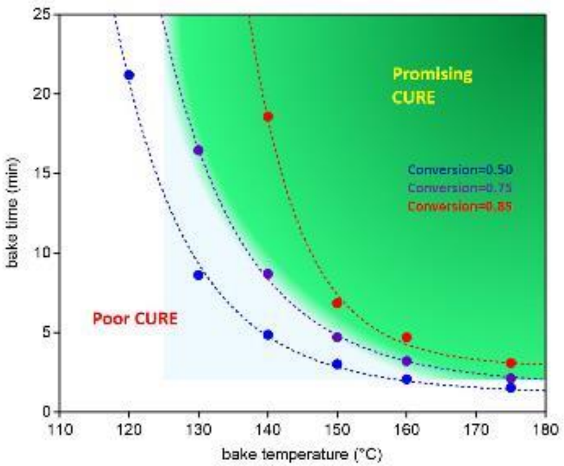



## Electrochemistry of CFRP/Al Coupons



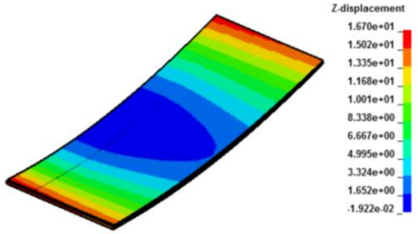



## Low Cure Electrocoat/Adhesive

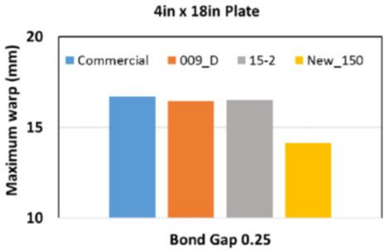



## CTE Mismatch Modeling

Prediction of Deflection

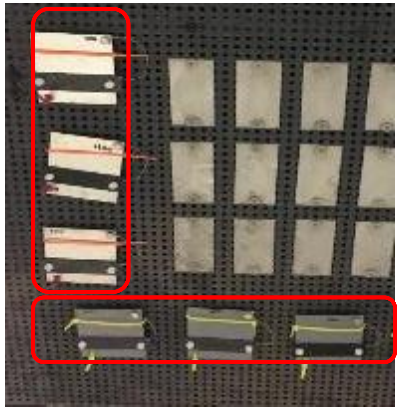


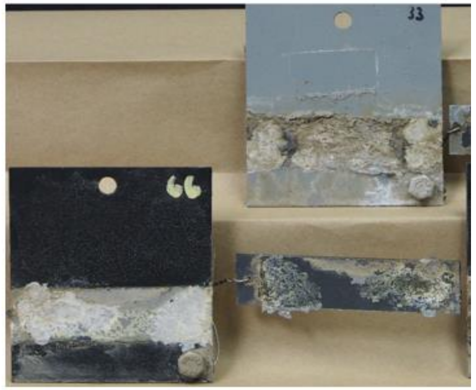

Z Displacement Contour under Room Temperature (mm) (Commercial Material)




Comparison of maximum deflection

## Validation (Bus Testing / Coupon Tests)







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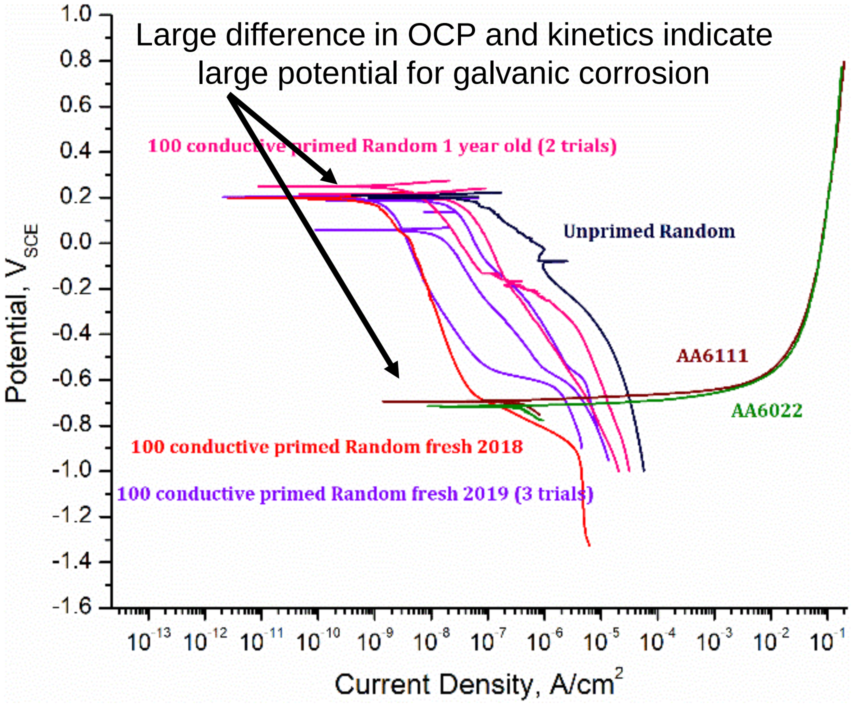
# Accomplishments: Galvanic Corrosion Susceptibility

Fontana Corrosion Center AT THE OHIO STATE UNIVERSITY

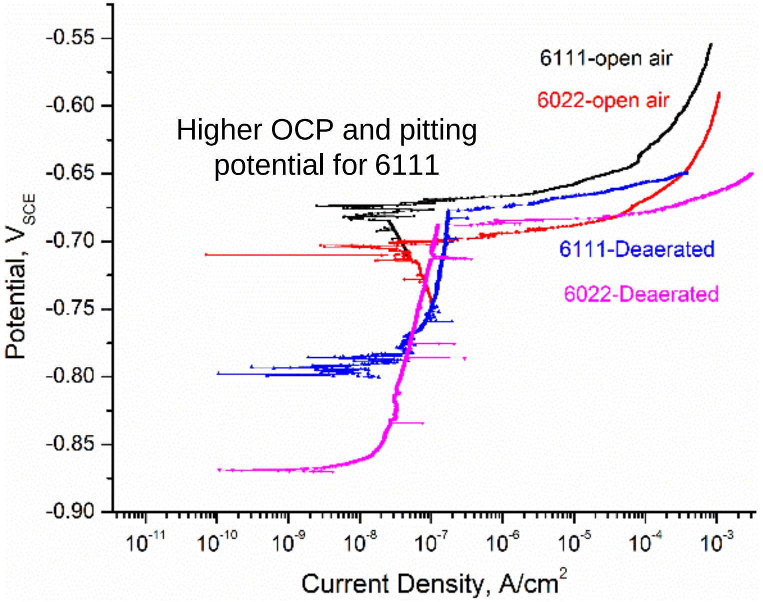
## Galvanic Corrosion Susceptibility




**Potentiodynamic polarization of unprimed CFRP random, fresh 100 conductive primed CFRP, primed CFRP after 1-year storage and Al alloy in 3.5 wt% NaCl**

## Differences between AA6111 and AA6022

| Alloy/Element wt.% | Si | Fe | Cu | Mn | Mg | Cr | Zn | ❖ Ti Others | Al |
|---|---|---|---|---|---|---|---|---|---|
| 6111 | 0.61 | 0.26 | 0.61 | 0.22 | 0.81 | 0.05 | 0.03 | 0.03 | Bal. |
| 6022 | 0.52 | 0.13 | 0.05 | 0.07 | 0.61 | 0.03 | 0.01 | 0.02 | Bal. |




**Anodic polarization in aerated/deaerated conditions**

**Aging of the primed CFRP impacts the galvanic corrosion susceptibility**
**AA6111 has higher OCP/pitting potential but greater corrosion susceptibility in cabinet tests**

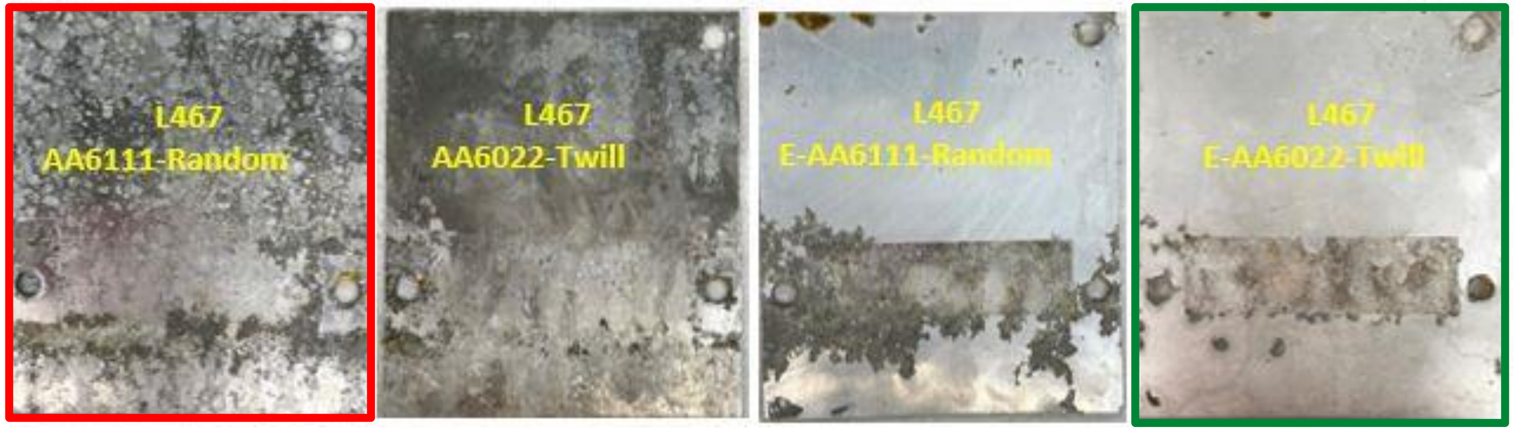
# Accomplishments: Cabinet and On-Road Corrosion Testing

## Accelerated Corrosion Testing

- L-467 accelerated chamber testing: 12 weeks
- On road tests on OSU busses: 13 months from Dec 2018 to Jan 2020

In L-467 testing and on-road testing, the blistering, and corrosion damage were highest for AA6111-CFRP random and minimum for AA6022-Twill

**L467 testing of uncoated, e-coated AA6xxx-CFRP coupons**




**On-road testing of uncoated, e-coated AA6xxx-CFRP coupons**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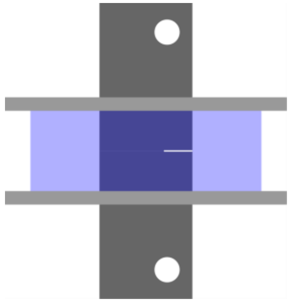
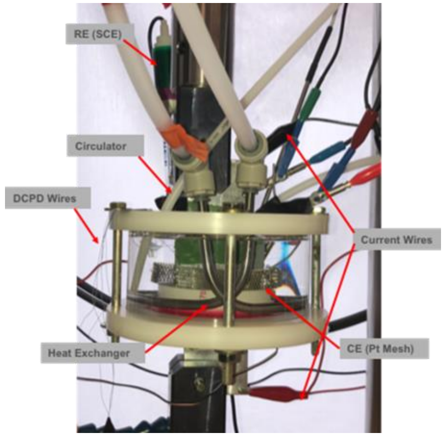
**Excellent correlation between L467 and on-road testing**
**AA6022-CFRP(twill) is the most corrosion resistant combination**

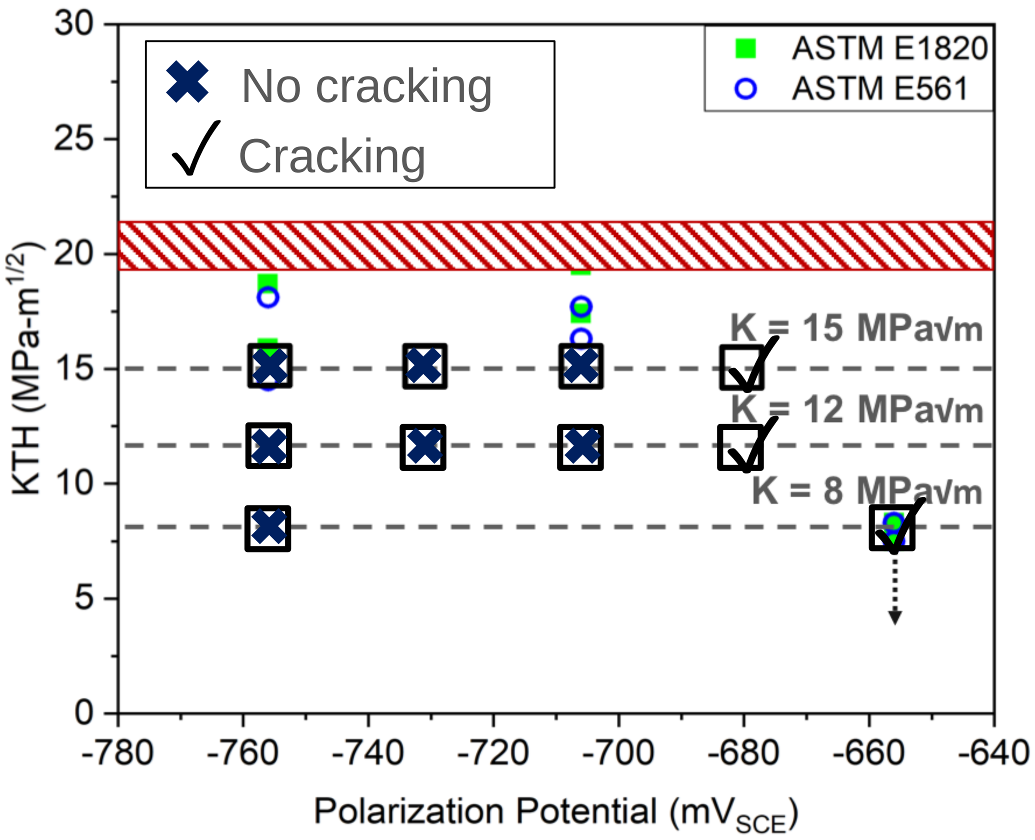
# Accomplishments: AA6111-T8-like SCC Behavior

## Setup






## Test Results




At all tested K:

**-756 $mV_{SCE}$, -731 $mV_{SCE}$, -706 $mV_{SCE}$ :**
Below resolution limit

At K = 15 MPa√m:

**-681 $mV_{SCE}$** : da/dt = 2.8 x $10^{-6}$ mm/s

At K = 12 MPa√m:

**-681 $mV_{SCE}$** : Average
da/dt = 2.3 x $10^{-6}$ mm/s

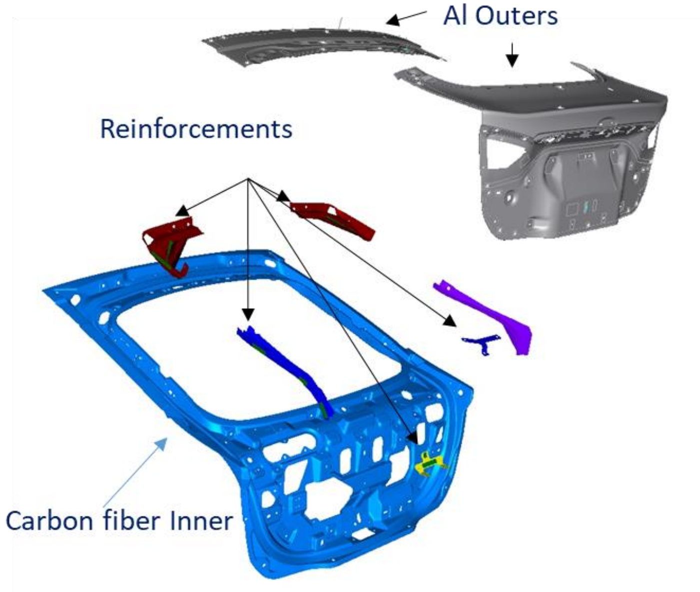
At K = 8 MPa√m:

**-656 $mV_{SCE}$** : Average
da/dt = 7.5 x $10^{-6}$ mm/s

**AA6111 is not highly susceptible to SCC at freely corroding conditions**
**Anodic polarization reduces SCC resistance**

# Accomplishments: Liftgate Demonstration

## Part Design




## Test Matrix

| Material | Standard Component (Control) | Prototype Part 1 | Prototype Part 2 | Prototype Part 3 | Prototype Part 4 |
|---|---|---|---|---|---|
| **Conductivity of Primer** | High | Low | High | Low | High |
| **Conductive Primer Application** | Outside only | Both sides | Outside only | Both sides | Both sides |
| **Adhesive Type** | High Temp | Low Temp | Low Temp | High Temp | Low Temp |
| **E-Coat Type** | High Temp | Low Temp | High Temp | High Temp | Low Temp |

## Assembly & Coating Process

**CFRP Part Production (FORD)** → **CFRP Primer Application (PPG)** → **Adhesive & Ecoat Scale-Up (PPG)** → **Liftgate Assembly (FORD)** → **Pretreatment / Electrocoat (PPG)** → **Topcoat Application (PPG)** → **Corrosion Testing (FORD)**

**Five prototype liftgates prepared according to standard automotive processes**



Images on this page provided by Ford Motor Company

# Accomplishments: Liftgate Demonstration

## Liftgate Assembly

- Inner and outer panels joined with adhesive
- Hem manually created to join CFRP inner and Al outer

## Pretreatment & Electrocoat

- Liftgates pretreated and coated with conventional or low temp electrocoat
- Overlap coupons also prepared

## Topcoat Application

- All liftgates topcoated with conventional topcoat system

**Successful coating of the prototype parts**

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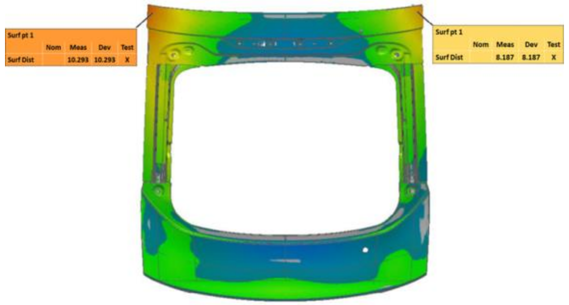
# Accomplishments: Liftgate Demonstration

## Corrosion Testing

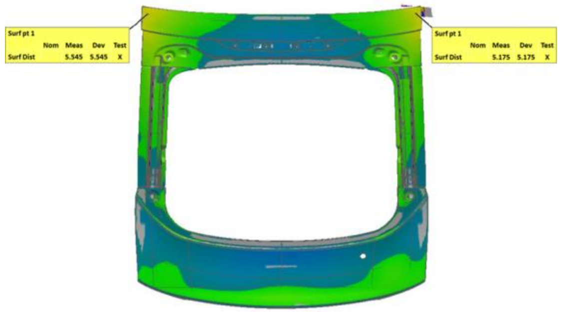

- Mounted in “vehicle position” and subjected to Ford’s full vehicle corrosion test protocol
- Liftgates examined after 6/12 weeks

## Performance Assessment

**Control**




**Low Temperature Cure Ecoat/Adhesive**




Liftgates laser scanned to assess dimensional accuracy after manufacturing

Corrosion assessed at hem joint (CFRP/Al)

**Dimensional stability and corrosion assessed for each liftgate**



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# Prototype Testing Summary

**Adhesion**

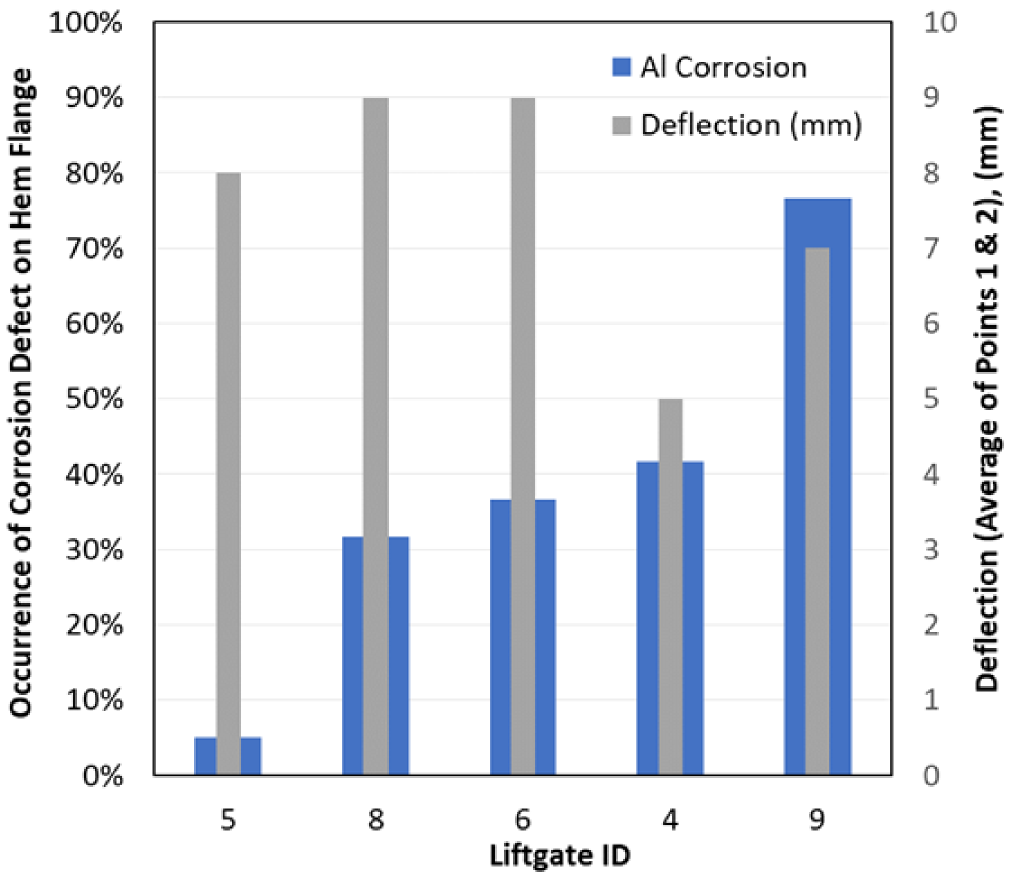
- Difficult to balance adhesion between adhesive/primer and adhesive/substrate interfaces
- More flow observed with conventional adhesive – greater coverage of aluminum substrate and more encapsulation of CFRP possible

**Dimensional Stability**

- *Improved* dimensional stability (less deflection) observed on liftgates with flexible adhesive and low temp cure electrocoat
- Possible indication of separation of CFRP/Al on liftgate 5 (with rigid adhesive), where very low deflection was measured on one side

**Corrosion**

- *More* corrosion observed on liftgates with flexible adhesive and low temp cure electrocoat
- Unexpected result and attributed to:
  - Lower adhesion and less flow with flexible adhesive
  - Less deflection, meaning greater CFRP – aluminum contact, with flexible adhesive
- Both leading to stronger galvanic attack of aluminum by the CFRP cathode



# Responses to Previous Year Reviewers' Comments

- It is not clear what experiments are planned to make the CFRP resin and adhesive withstand the paint bake temperature.
  - The CFRP resin was fixed due to cost constraints for high volume use. The paint and adhesive bake temperatures were reduced to meet the stability requirements of the CFRP.
- Size of the coupon may not be sufficient.
  - The initial CTE mismatch coupons was determined by our OEM partner based on their experience and chosen to enable lab-scale experimentation and adhesive development. Longer coupons were tested in follow-up studies before the prototype build.

# Project Collaboration

## PPG Industries, Inc.

– Project coordination
– Coating test coupons for corrosion evaluation at Ford
– Providing samples of conductive primers to OSU for electrochemical evaluations
– Prototype coating

## Ford Motor Company

– Providing substrate materials for testing
– Conducting track testing of coated samples
– Providing input on electrochemical evaluations
– Modeling adhesive formulation / CTE mismatch
– Prototype development and testing

## The Ohio State University

– Measuring uniformity of conductivity of Ford CFRP substrate
– Conducting electrochemical evaluation of corrosion panels during corrosion testing
– Outdoor exposure of test samples (OSU bus system)
– Understanding of stress-corrosion behavior

# Remaining Challenges and Barriers

- Implementation of this concept would require additional development to develop a *system* of materials that were mutually compatible and possessed all processing performance characteristics of current generation materials:
  - Good adhesion between adhesive and all substrates/coatings
  - Surface preparation procedures
  - Optimized flow and wetting of adhesive
  - Optimized part design to aid in adhesive placement and hemming

# Summary

- **Corrosion Fundamentals**
  - Aging of the primed CFRP impacted the galvanic corrosion susceptibility
  - Al-6111 had a higher OCP/pitting potential but greater corrosion susceptibility
  - AA6022-CFRP(twill) was the most corrosion resistant combination
  - AA6111 was not highly susceptible to SCC at freely corroding conditions but anodic polarization reduced SCC resistance
  - L467 and on-road testing resulted in similar amounts of corrosion
- **Prototype Part Demonstration**
  - Galvanically-accelerated corrosion of aluminum in CFRP/Al closure panels was conclusively demonstrated in coupons and prototype closure panels
  - Mixed material coupon testing demonstrated the benefit of conductive primer with lower conductivity, flexible adhesive, and low temperature cure electrocoat
  - Expected benefit of the new material system was not observed in prototype component testing due to secondary processing issues
  - Processing variability prevented rigorous quantification of results