THE OHIO STATE UNIVERSITY

Use of laboratory accelerated cyclic corrosion test for predicting on-road corrosion behavior of AA6xxx coupled to carbon fiber reinforced plastics

Priyanka Adapala, Dr. Gerald S. Frankel

Fontana Corrosion Center

Department of Materials Science and Engineering, The Ohio State University

This work is submitted to Corrosion Journal for a publication

Acknowledgements

- This work was supported by **the U.S. Department of Energy** with the award DE-EE0007760, in a joint collaboration including PPG Industries, Ford Motor Company and the Ohio State University.

- **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

  Ohio State University – Gerald Frankel, Jenifer Locke, Katrina Catledge

- **Center for Electron Microscopy and Analysis** (CEMAS), OSU

Project Background

Relevance

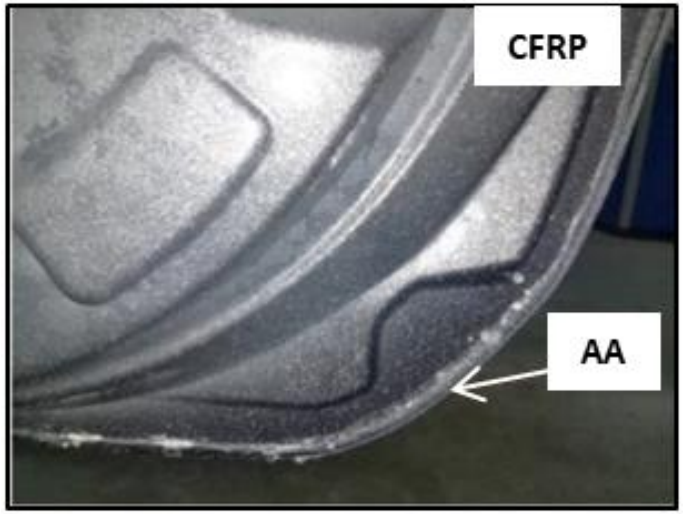
- Ever-growing concerns of fuel usage and green house emissions are addressed by automotive industry through vehicle light weighting.[1,2]
- Conventional steel body parts are replaced with Al, Mg, composite materials etc.[3]

Objectives

- Evaluation and application of carbon fiber reinforced plastics (CFRP)/aluminum alloy (AA) structures in automobile closure panels such as doors, deck lids, lift gates, which have inner and outer components joined by hem flanges.

Aim of the current work:

- To establish an accelerated laboratory corrosion testing for CFRP-AA couples.
- To understand the galvanic corrosion behavior of CFRP-AA couples under laboratory conditions that might allow prediction of performance in real environments.



CFRP inner-AA outer joined by hem flange in a car door. Image provided by Ford Motor Company

1. Mascarin et al., “Vehicle Lightweighting: 40% and 45% Weight Savings Analysis: Technical Cost Modeling for Vehicle Light weighting,” 2015.
2. L. W. Cheah et al., “Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S.,” *Engineering*,2010.
3. R. W. Revie, *Uhlig’s Corrosion Handbook*. 2011.

Test Materials

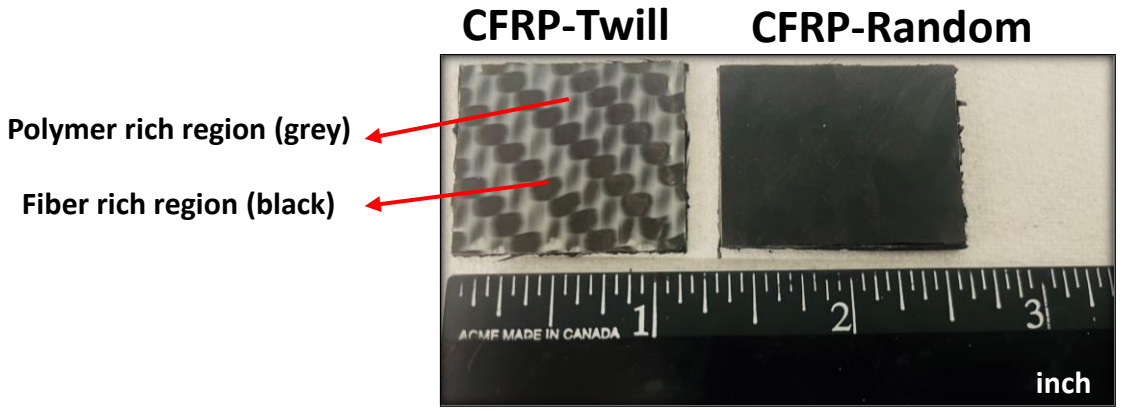
❖ **Aluminum Alloys (AA):** 6xxx Aluminum alloys are AlMgSi wrought alloys

Alloy/Element %	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	Balance
6022	0.52	0.13	0.05	0.07	0.61	0.03	0.01	0.02	Balance

Elemental analysis data of AA6111, 6022 using ICP-MS

❖ **Carbon Fiber reinforced polymer composites (CFRP):**

1. Twill - 55 wt.% polyacrylonitrile based carbon fiber bundles alternately braided in epoxy matrix,
2. Random - 40 wt.% polyacrylonitrile based carbon fiber bundles randomly dispersed in vinyl ester matrix.

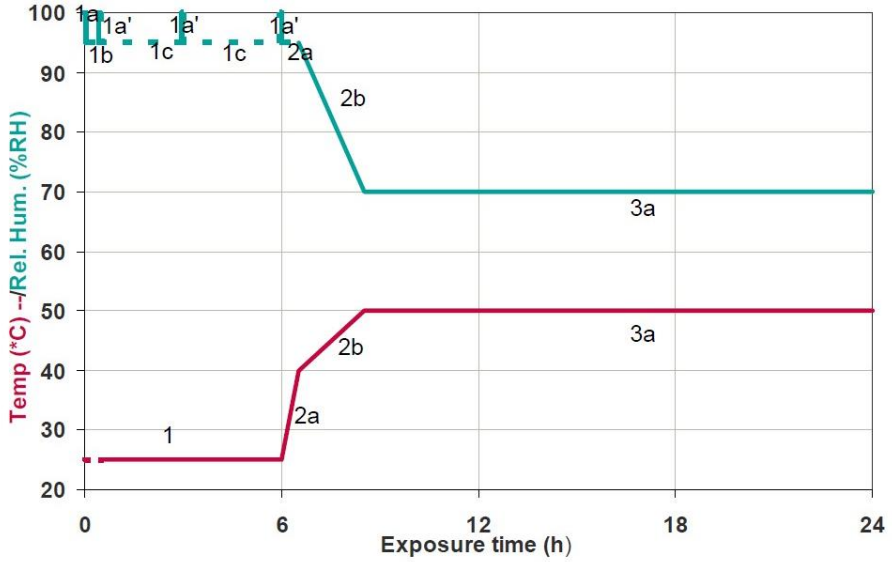


Laboratory Accelerated Cyclic Corrosion Test

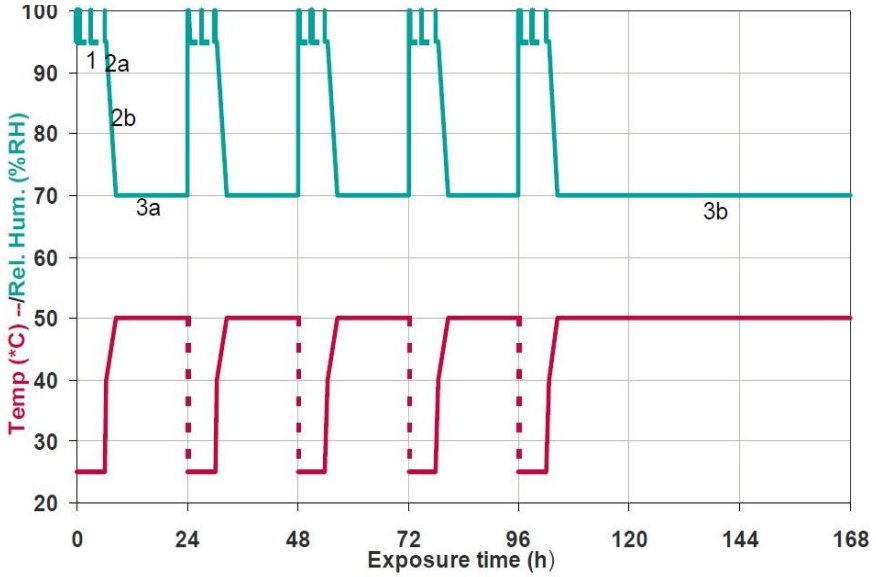
CETP-00.00-L-467

- Designed by Ford Motor Company
- Used to study conditions such as salt load/climatic variations during in-service exposure.
- Solution used was 0.5 wt.% NaCl.

Controlled Relative Humidity Cyclic Corrosion Tester, facility at FCC



Workday (Mon-Friday) test cycle.



Complete weekly program

Field performance test

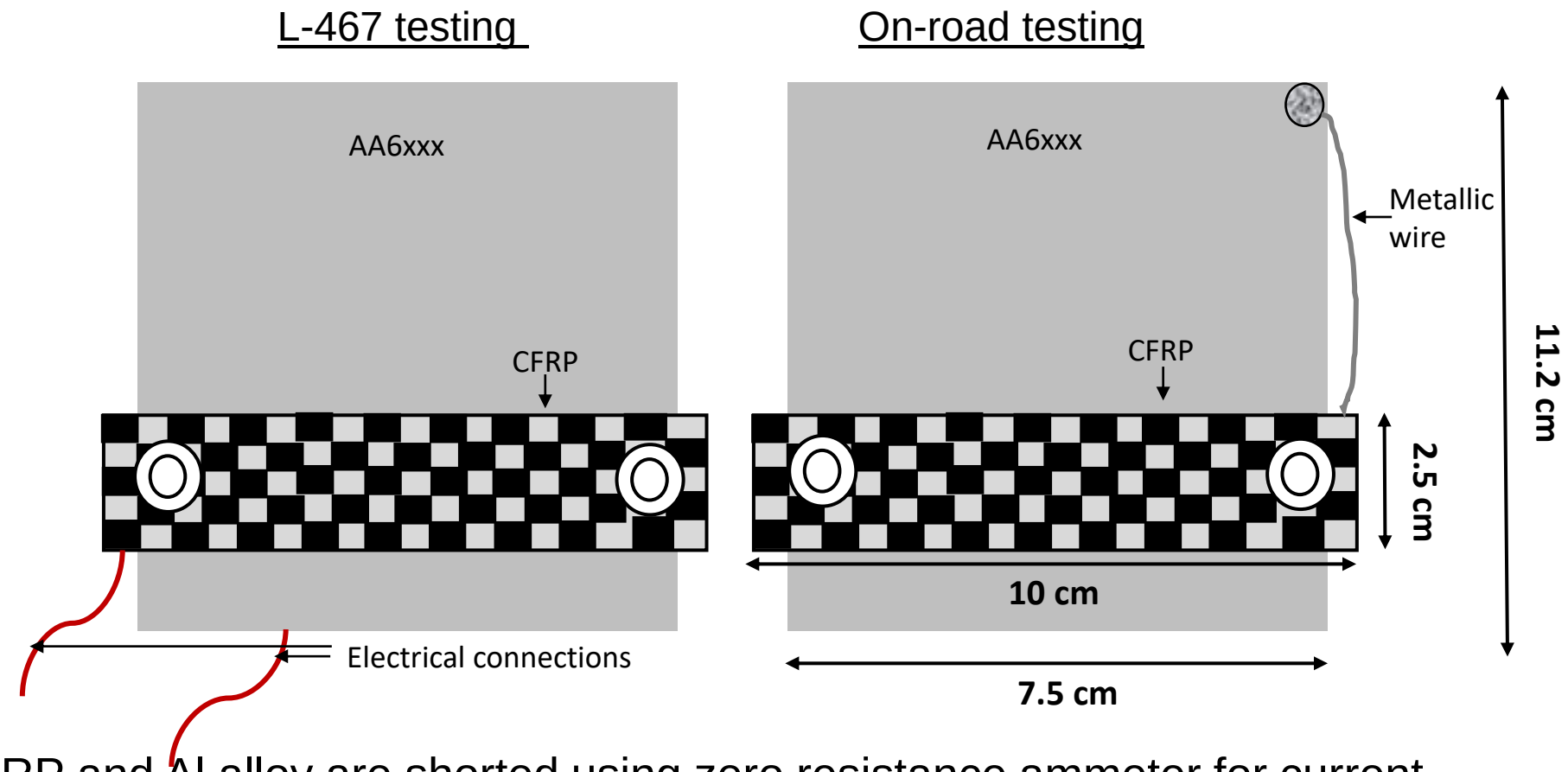
On-road testing of CFRP-AA materials on OSU busses

- To understand the corrosion behavior of CFRP-AA materials under natural road conditions including de-icing salts during winter, mud and other environmental pollutants and varying weather conditions.
- Materials were fixed onto the undersides of busses that circulated the campus for 1 year.

OSU bus onto which materials were mounted

Test Samples

- Actual hem flange geometry is too complex to study, so a simplified galvanic test coupon was devised:



- CFRP and Al alloy are shorted using zero resistance ammeter for current measurement during L-467 testing, and directly shorted with wire for on-road testing.

Nomenclature

##	X	Y
Aluminum (**61**11 or **60****22**)	CFRP (**R**andom or **T**will)	Testing (**L**ab or **B**us)

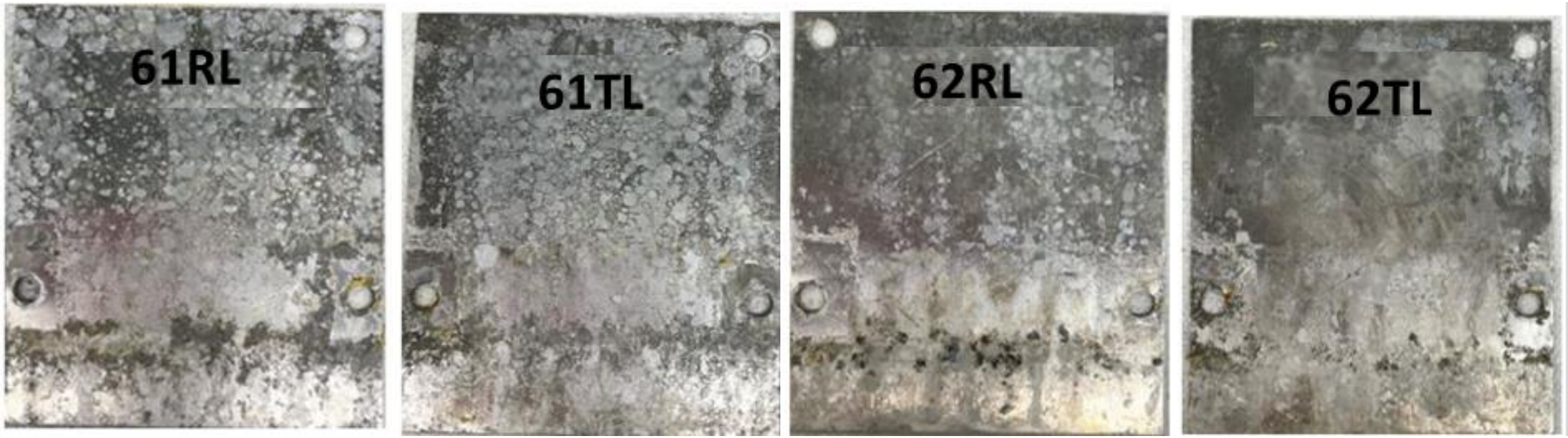
Corrosion Test	Coupon Combinations	Coupon Designations (##XY)
L-467	AA6111-CFRP random	61RL
	AA6111-CFRP twill	61TL
	AA6022-CFRP random	62RL
	AA6022-CFRP twill	62TL
On-bus testing	AA6111-CFRP random	61RB
	AA6111-CFRP twill	61TB
	AA6022-CFRP random	62RB
	AA6022-CFRP twill	62TB

Testing & Analysis

Feature	L-467 testing	On-bus testing
Time of exposure	12 weeks	1 year
Galvanic current measurements	Yes	No
Test Results Correlation Analysis		
Volumetric material loss	Optical Profilometry (OP)	
Surface analysis	Scanning Electron Microscopy (SEM)	
Cross-sectional analysis	Optical Microscopy (OM)	

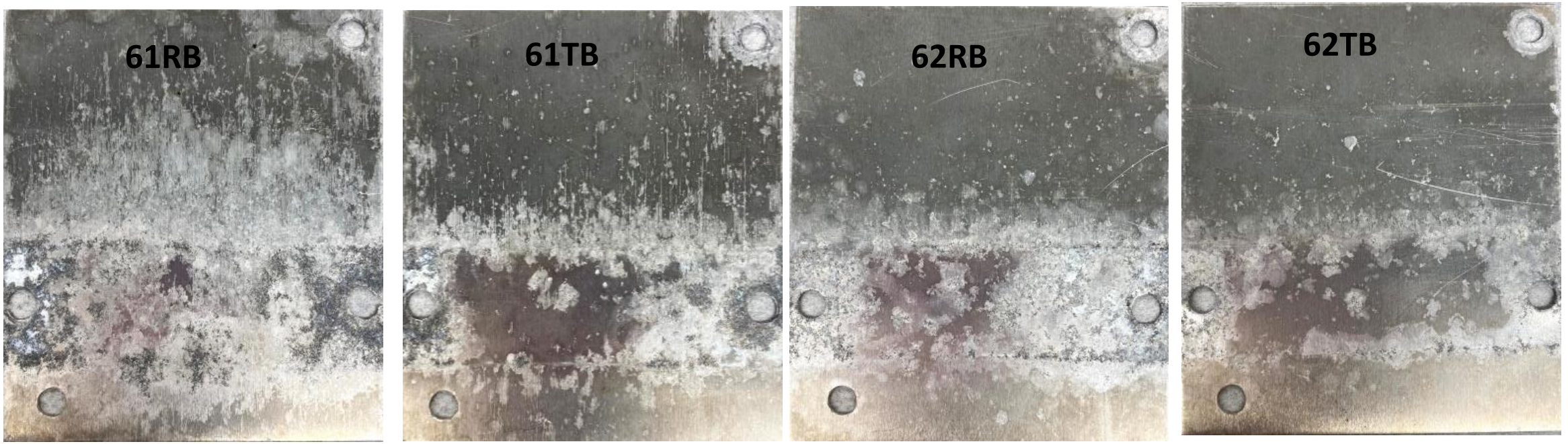
- Differences between both the tests were evaluated based on visual inspection, OP, SEM and OM analyses.

Visual Inspection of L-467 tested Coupons



- Visual inspection of coupons depict **highest** extent of corrosion on **61RL** whereas **lowest** on **62TL**.
- Trend in corrosion susceptibilities among other coupons isn't clear.

Visual Inspection of On-bus tested Coupons



- Visual inspection of coupons depict **highest** extent of corrosion on **61RB** whereas **lowest** on **62TB**.
- Trend in corrosion susceptibilities among other coupons isn't clear.

Comparison between L-467 and on-road testing:

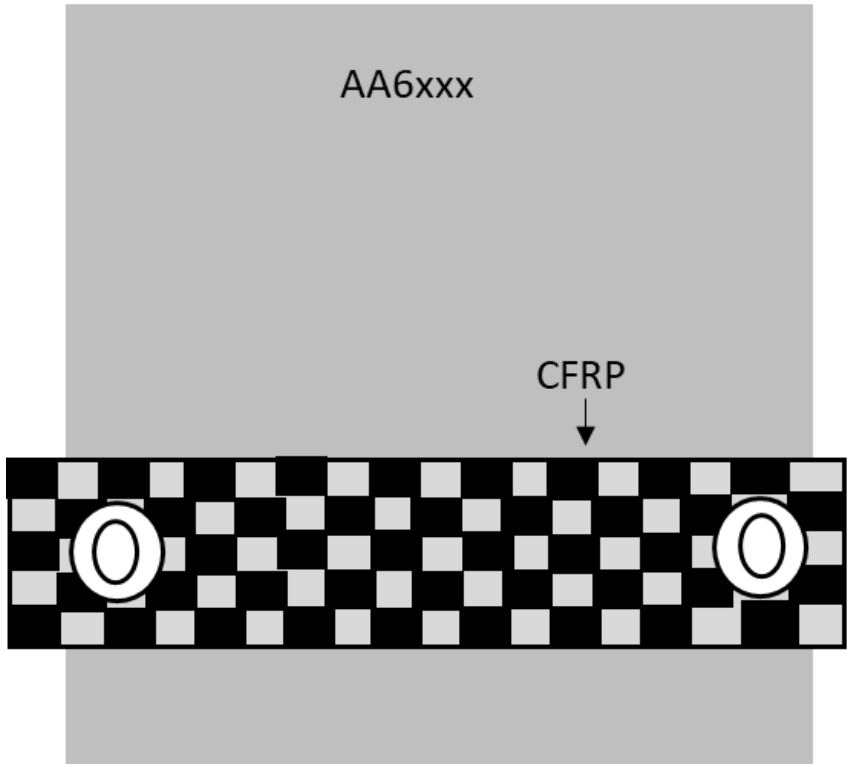
a) Optical Profilometry

b) Surface morphology by SEM

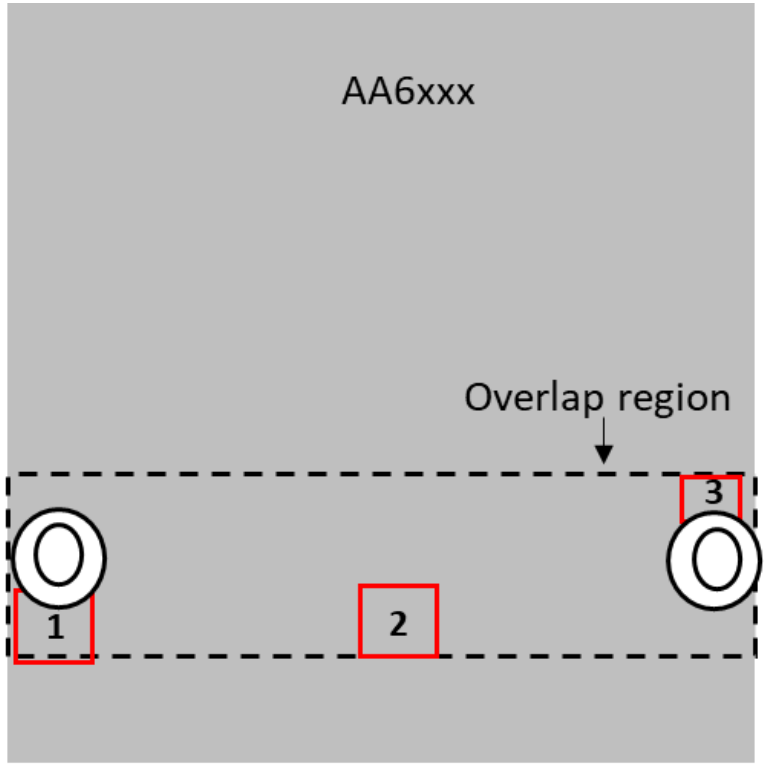
c) Cross-sectional analysis: Optical Microscopy

Representation for corroded surface analysis

CFRP-AA coupon



AA panel after CFRP removal



Comparison between L-467 and on-road testing:

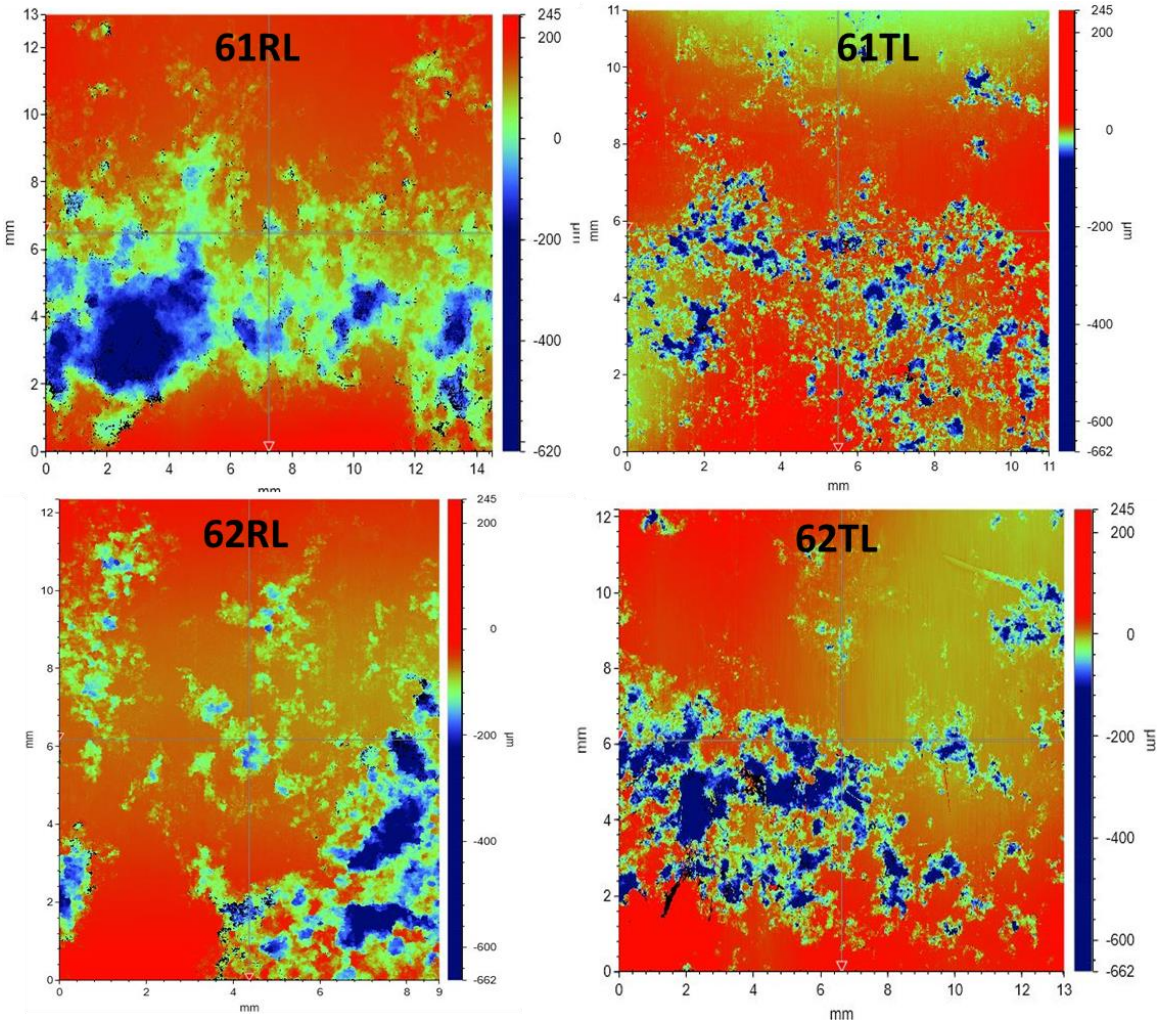
a) **Optical Profilometry**

b) **Surface morphology by SEM**

c) **Cross-sectional analysis: Optical Microscopy**

Topographical Maps – Optical Profilometry (L-467)

Optical Profilometry performed on three representative areas to determine AA volume losses using Vision64 image Analysis software.

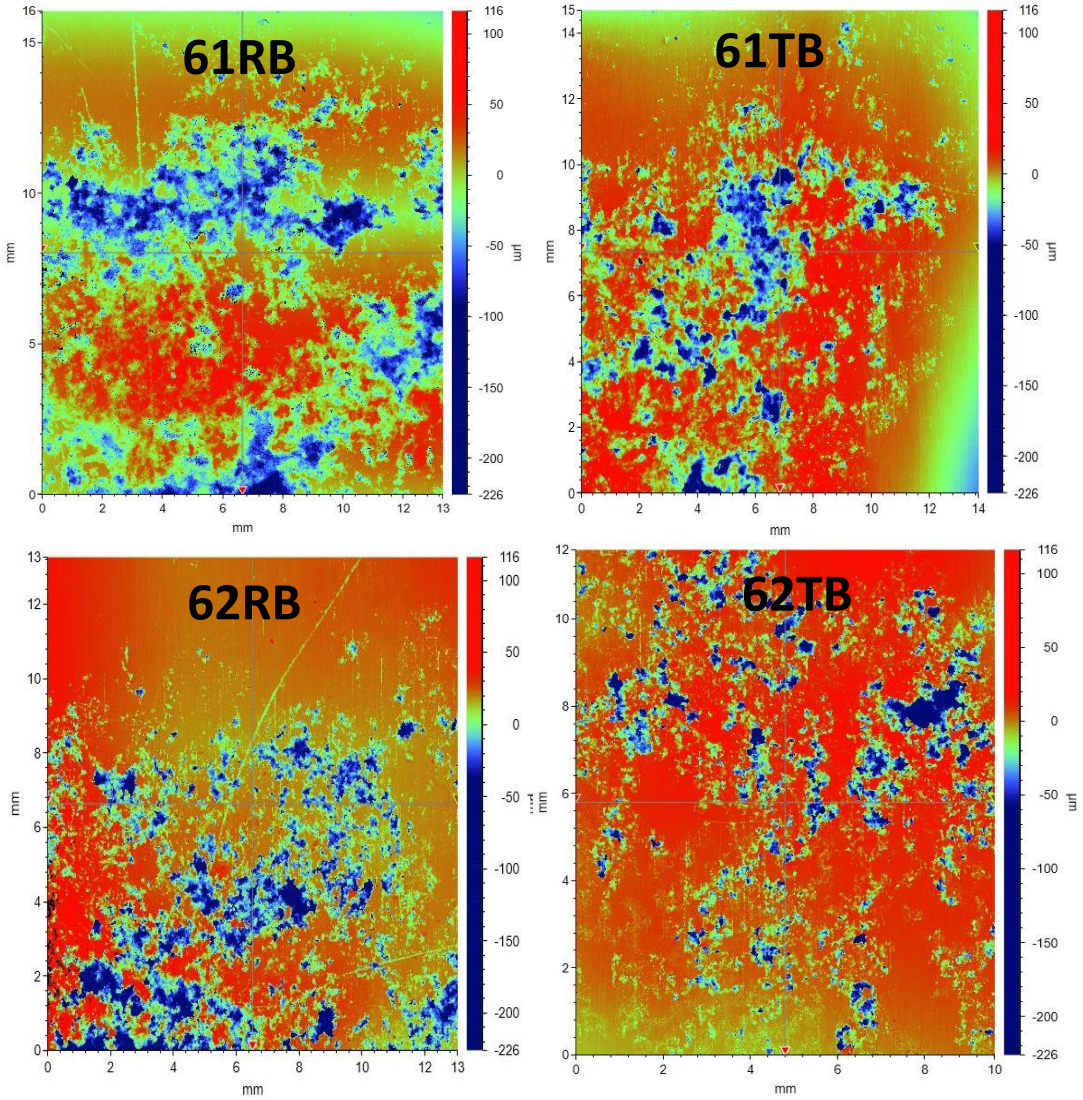


Topographical maps of representative area 1

Average volume losses of material of coupons after L-467 testing

Coupon Designation	Volume loss/ Unit area, (µm³/ µm²)			Average Volume loss, (µm³/ µm²)
	Area 1	Area 2	Area 3	
61RL	15.6	20.2	9.97	15.3 ± 4.2
61TL	3.5	3.23	4.02	3.6 ± 0.32
62RL	6.7	8.35	7.22	7.4 ± 0.68
62TL	2.9	1.98	1.74	2.21 ± 0.5

Topographical Maps – Optical Profilometry (on-road testing)

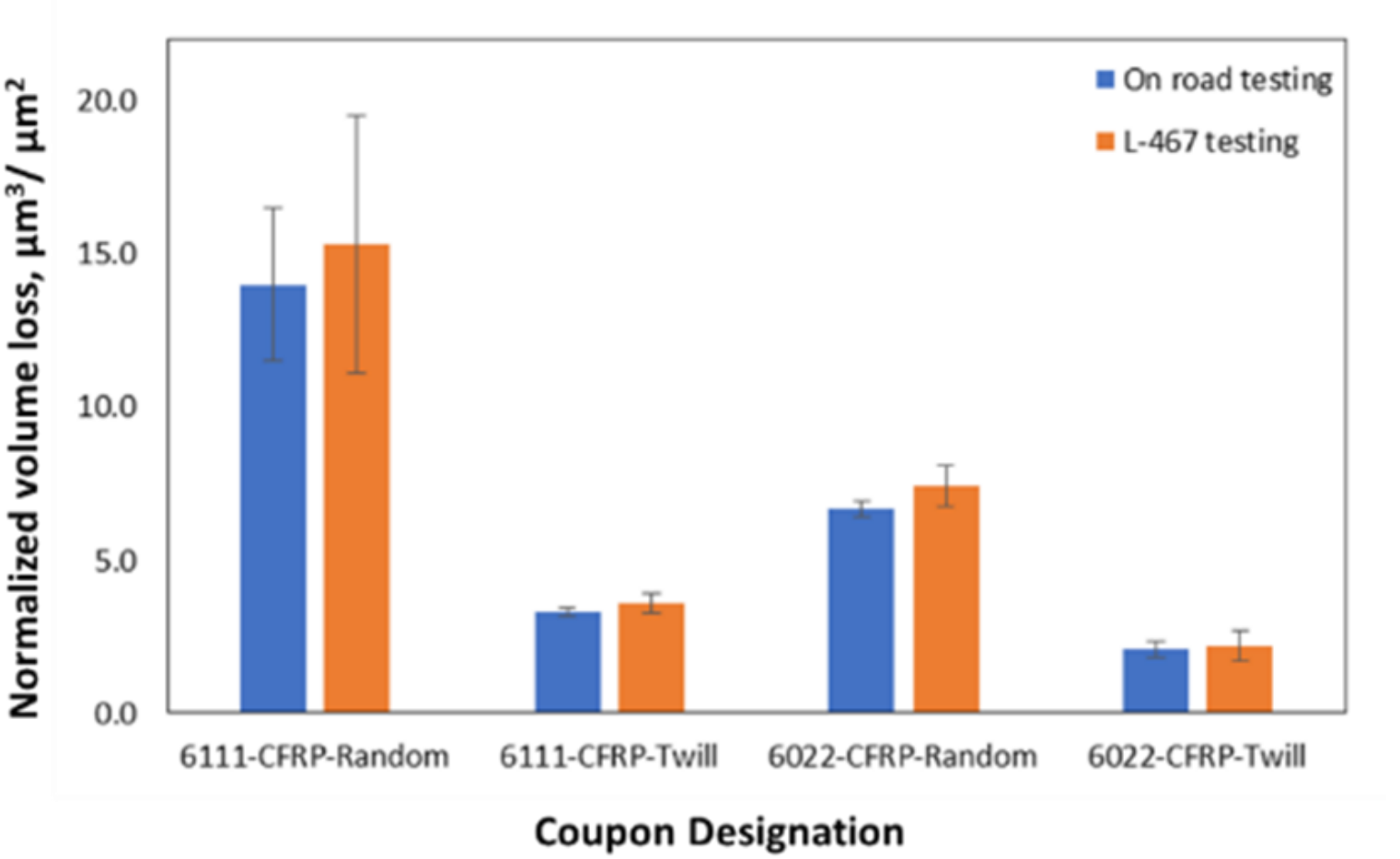


Topographical maps of representative area 1

Average volume loss of material of coupons after on-road testing.

Coupon Designation	Volume loss/ Unit area, (µm³/ µm²)			Average Volume loss, (µm³/ µm²)
	Area 1	Area 2	Area 3	
61RB	12.63	11.89	17.61	14 ± 2.5
61TB	3.34	3.06	3.41	3.27 ± 0.15
62RB	6.89	6.72	6.39	6.67 ± 0.27
62TB	2.42	2.02	1.79	2.07 ± 0.26

Summary of OP analysis



- Volume losses of AA panels coupled with CFRP-Random are higher than CFRP-Twill.
- AA6111 exhibited larger extent of corrosion than AA6022.
- More corrosion was observed in coupons subjected to L-467 testing than on-bus testing.
- Order of corrosion attack: 61R> 62R> 61T> 62T in both the tests.

Comparison between L-467 and on-road testing:

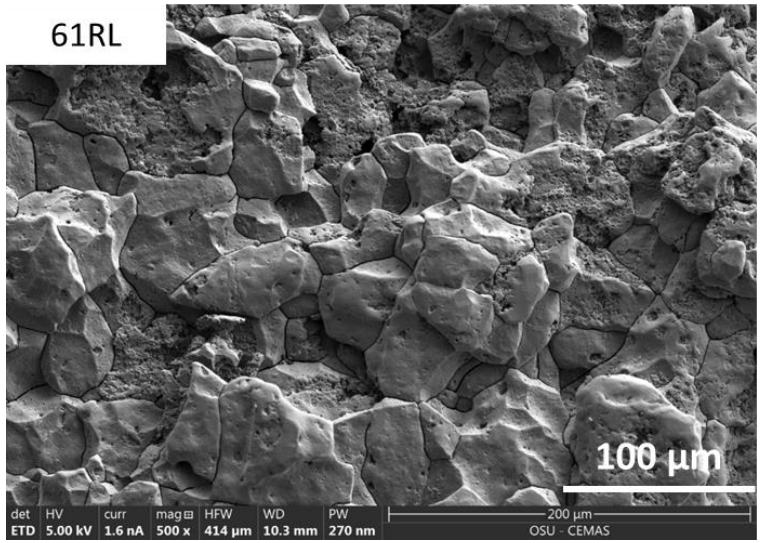
a) Optical Profilometry

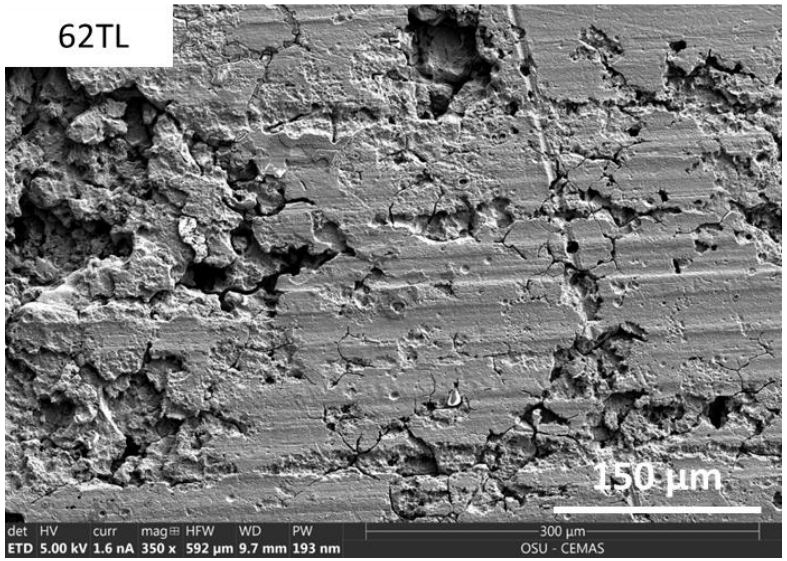
b) Surface morphology by SEM

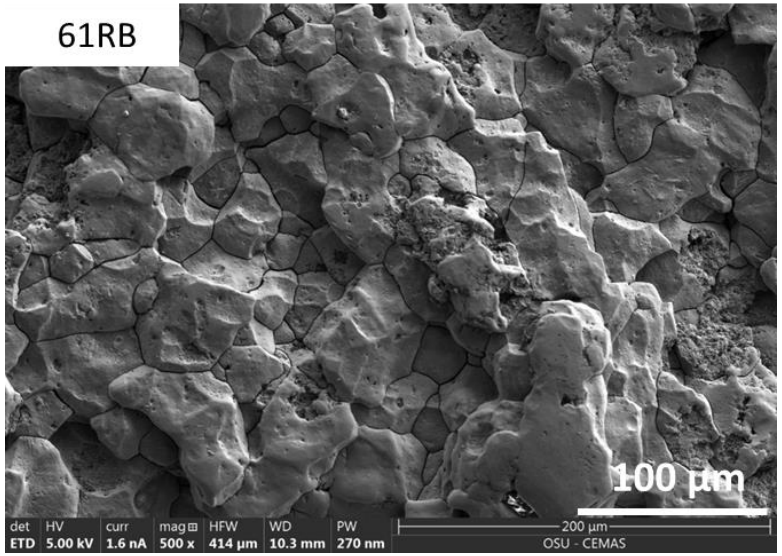
c) Cross-sectional analysis: Optical Microscopy

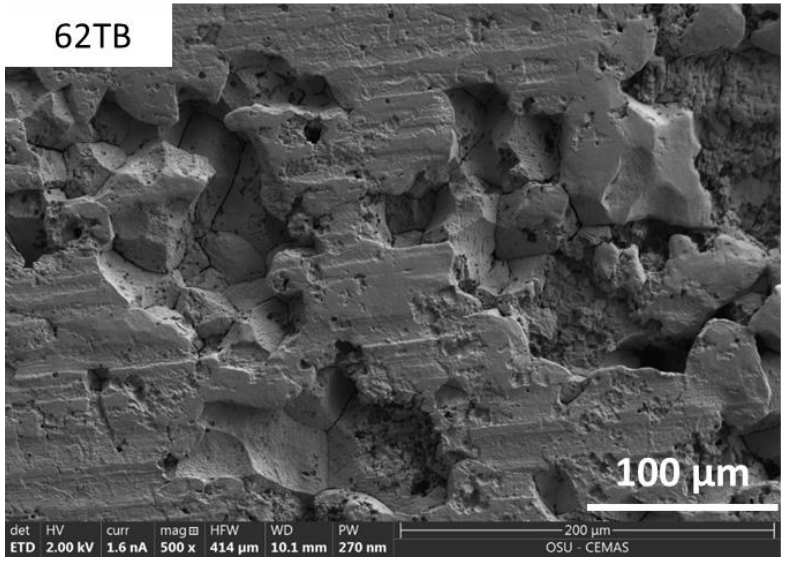
Morphology: Top surface SEM

Scanning Electron Micrographs









- In both 61RL and 61RB, the whole surface is severely attacked, whereas in 62TL and 62TB, un attacked pristine regions exist.
- Severe and deeper IGC in 61RL and 61RB.
- Regions of grains fall out can be observed in all the AA.

Comparison between L-467 and on-road testing:

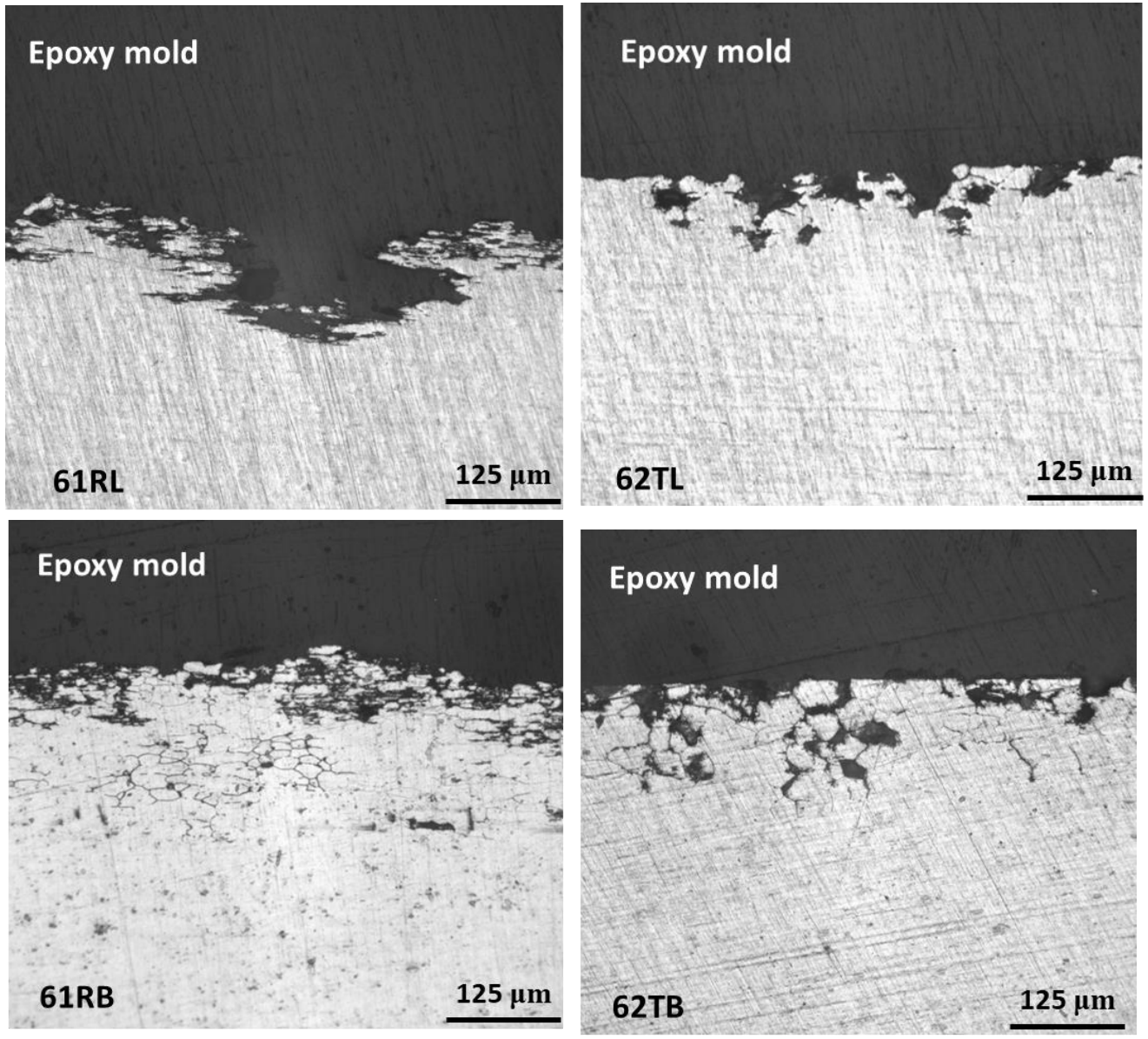
a) Optical Profilometry

b) Surface morphology by SEM

c) Cross-sectional analysis: Optical Microscopy

Cross-sectional analysis

Optical micrographs



- Localized attack and IGC extended deeper in 61RL and 61RB which led to the whole surface being attacked unlike the attack in 62TL and 62TB wherein pristine surface exists.
- Grains fall out can be seen closer to the surface.
- Average gage losses were 48, 25, 30 and 15% in 61RL, 62TL, 61RB and 62TB respectively, as determined using average pit depths.

Conclusions

- AA6111 exhibited higher corrosion susceptibility than AA6022 in both L-467 and on-bus tests.
- As a cathode, CFRP-Random exhibited higher electrochemical activity than CFRP-Twill, leading to an accelerated attacked of AA coupled with it.
- Trends in corrosion susceptibilities observed in CFRP-AA coupons exposed to CETP-00.00-L-467 test conditions for 12 weeks were similar to those found for 13-month exposure to on-road conditions in Columbus, OH.

CETP-00.00-L-467 can be considered as suitable accelerated test to evaluate CFRP-AA structures for automobile applications.

Questions and comments

adapala.3@osu.edu