



Enhancing Corrosion Resistance in Multimaterial Joints for Automotive Lightweighting Applications

Sridhar Niverty

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Detroit, Michigan



Acknowledgements

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The Pacific Northwest National Laboratory is operated by the Battelle Memorial Institute for the United States Department of Energy under contract DE-AC06-76LO1830.



Auto/Steel
Partnership



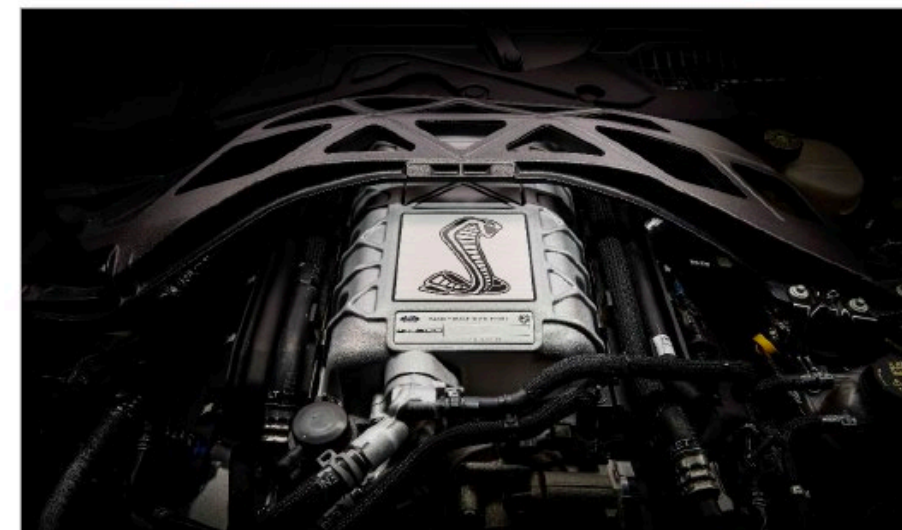
U.S. DEPARTMENT OF
ENERGY

Energy Efficiency &
Renewable Energy

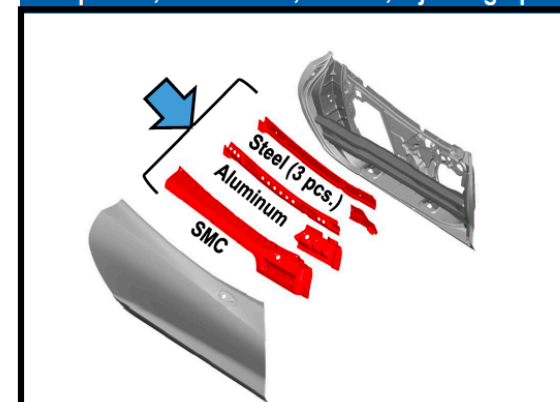
Motivation

- **Vehicle lightweighting, reduced part counts and lowered assembly costs.**
- Lightweight materials applications result in **weight savings of 25-50%.**
 - 10% weight reduction improves fuel economy by 6-8%.
 - Increases driving range by 14% with a 20% weight reduction in EV's
- **Need for improvement in Mechanical Properties and Corrosion Resistance.**
- **Need for improved understanding and predictive modeling understanding of corrosion progress in multimaterial joints.**

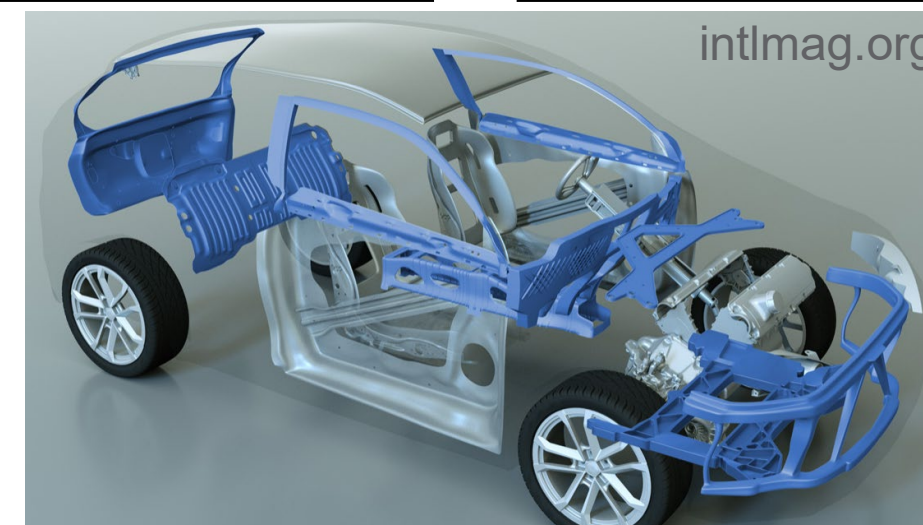
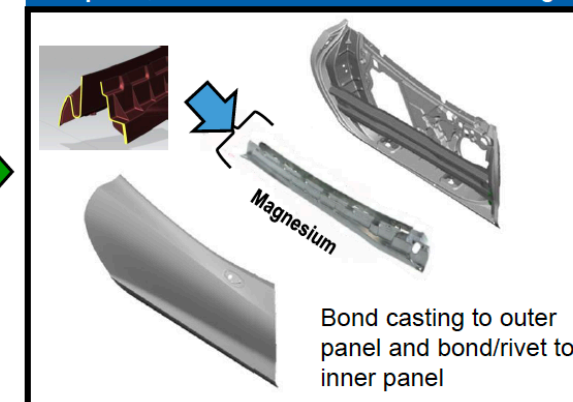
Mg Strut Tower Brace



5 pieces; 3 materials; 5 tools; 3 joining ops



1 piece; Innovative "S" section and ribbing



Goals and Impact

Goals

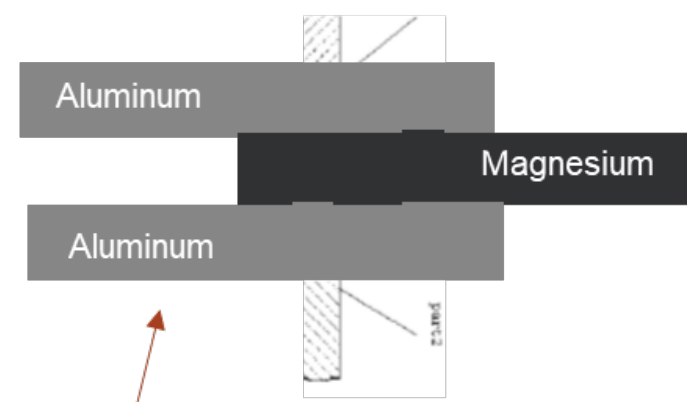
- Develop scalable and cost-effective processing methods to enable joining of Multimaterial configurations. Develop methods to analyze and predict corrosion in such joints.
- Perform selective processing to enhance corrosion resistance and improve the wear resistance to address shortcomings of typical commercial lightweight (in particular Mg) alloy castings.

Impact

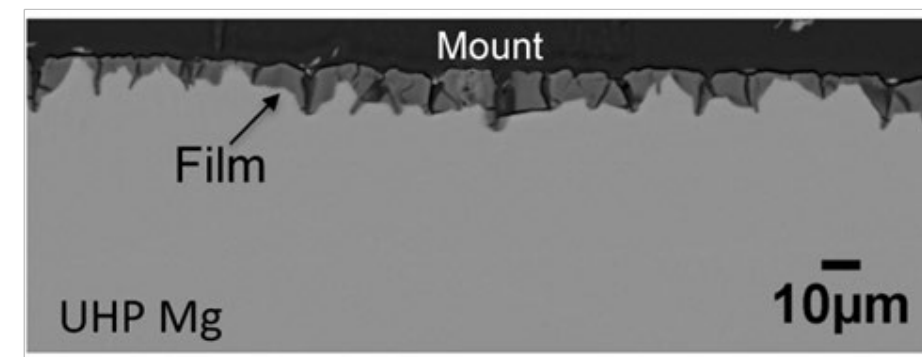
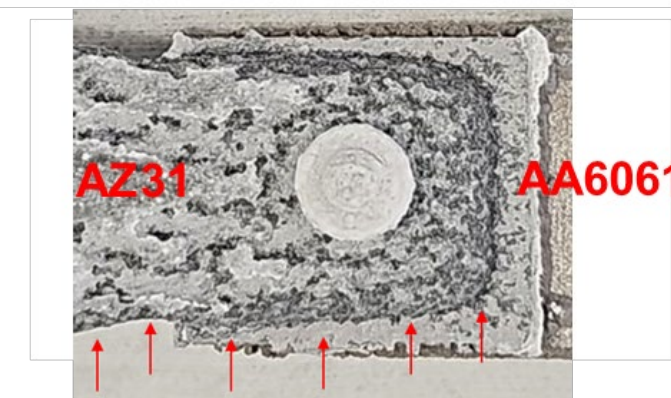
- Improved joint corrosion resistance and reliable damage prediction for enhancing long term performance of multimaterial joints.
- Improved corrosion resistance and wear resistance will aid in the widespread adoption of Mg components to achieve vehicle light weighting goals

Challenges

Additional Materials Added to minimize Galvanic corrosion



Galvanic corrosion of AZ31 when combined with AA6061 and steel rivet



Cross-Section Showing Non-Protective Mg-O-H Scale Formed in Water

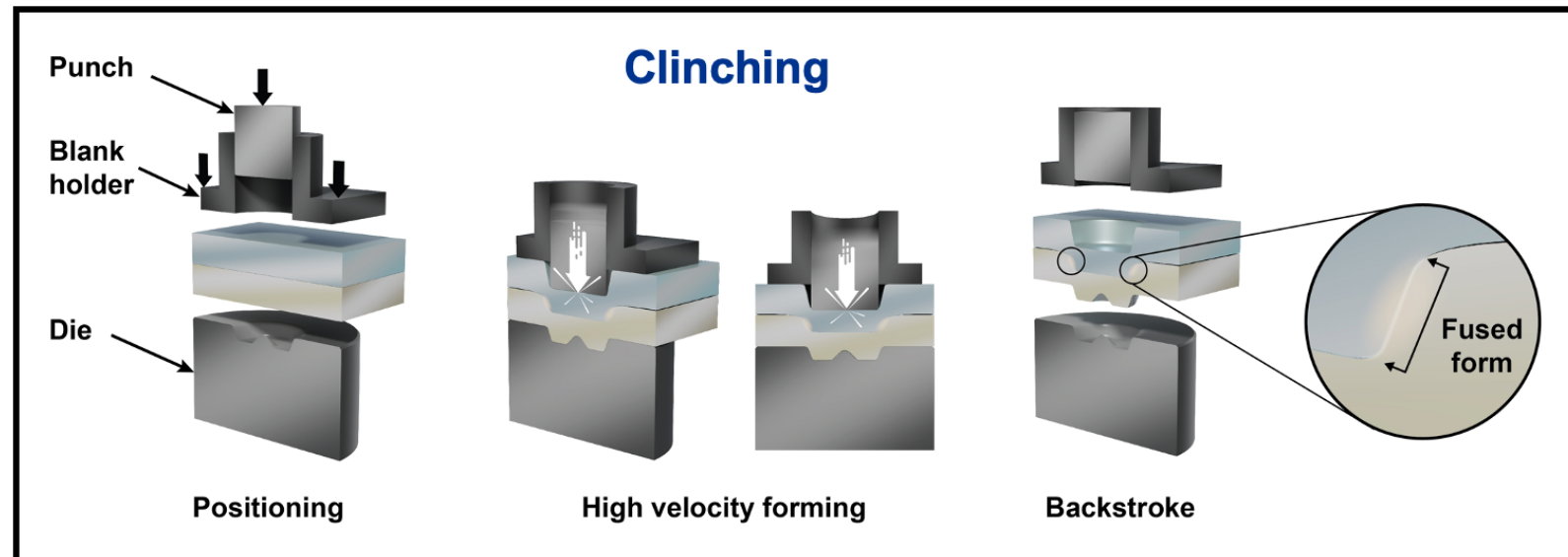
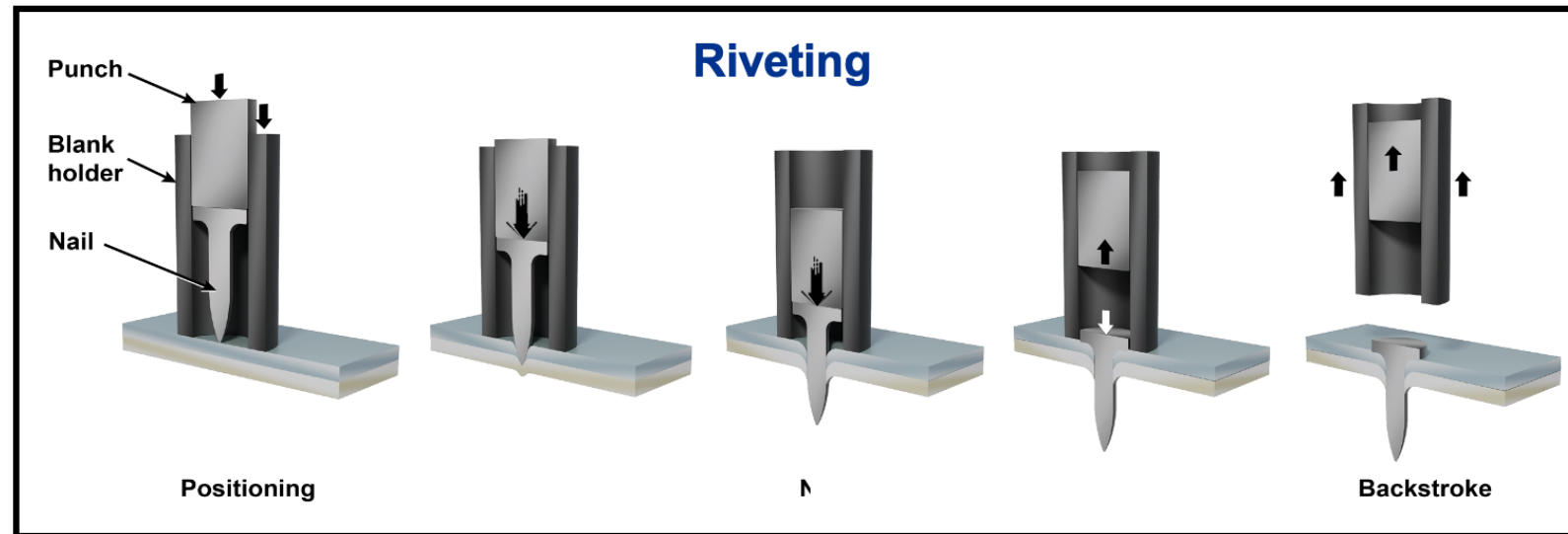
K. A. Unocic et.al,
J. Electrochem.
soc, 2014, DOI
10.1149/2.02440
6jes

Scientific and Engineering Challenges

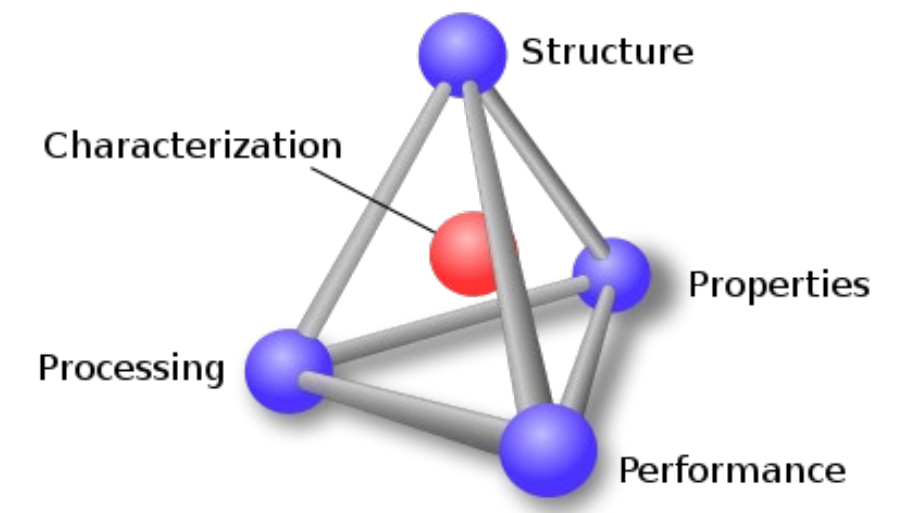
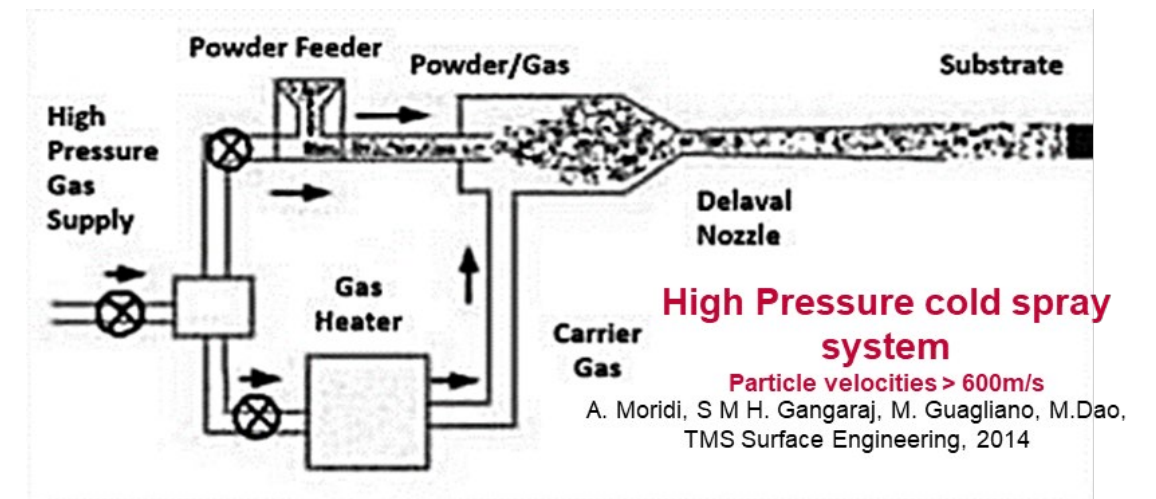
- General and Filiform Corrosion
- Crevice Corrosion
- Macro Galvanic Corrosion
- Micro Galvanic Corrosion

Focus Areas of Dissimilar Materials Joining and Surface Processing for Corrosion Mitigation

Materials Joining and Corrosion



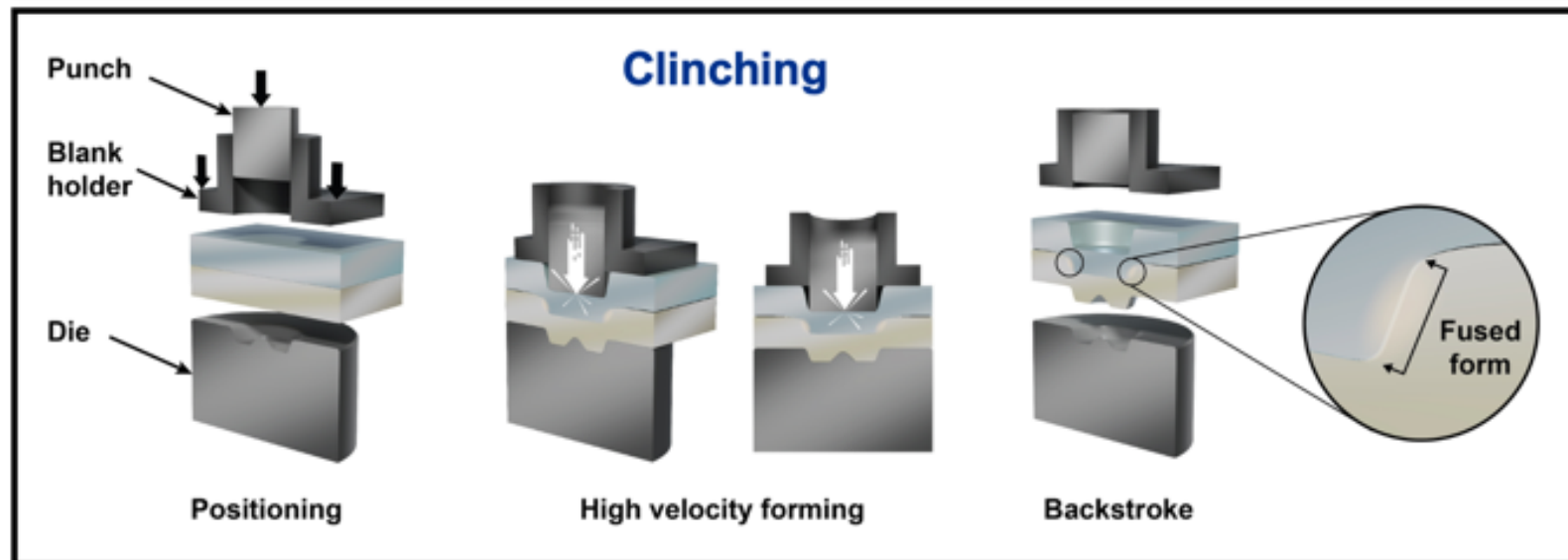
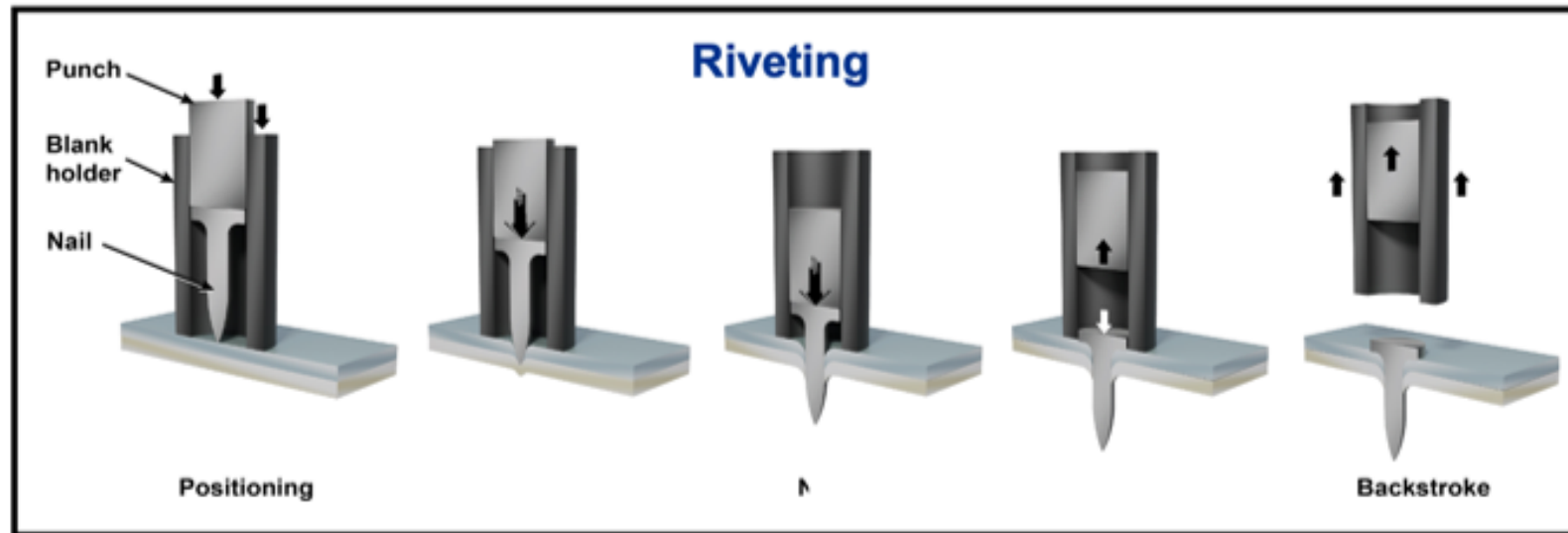
Enhancing Surface Properties



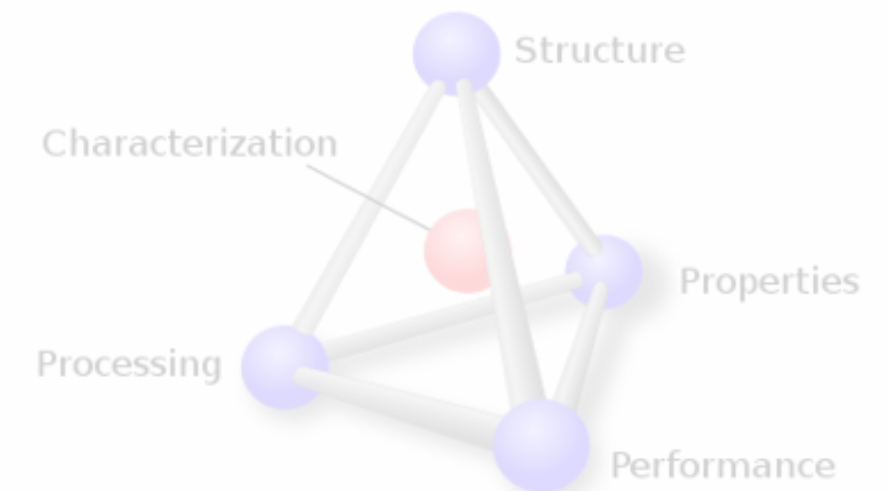
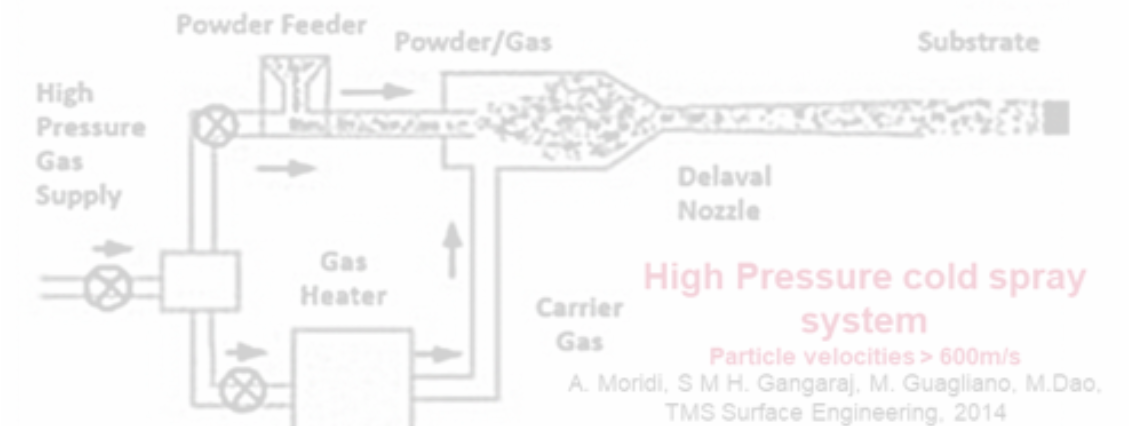
Structure-Processing-Performance Improvement

Focus Areas of Dissimilar Materials Joining and Surface Processing for Corrosion Mitigation

Materials Joining and Corrosion



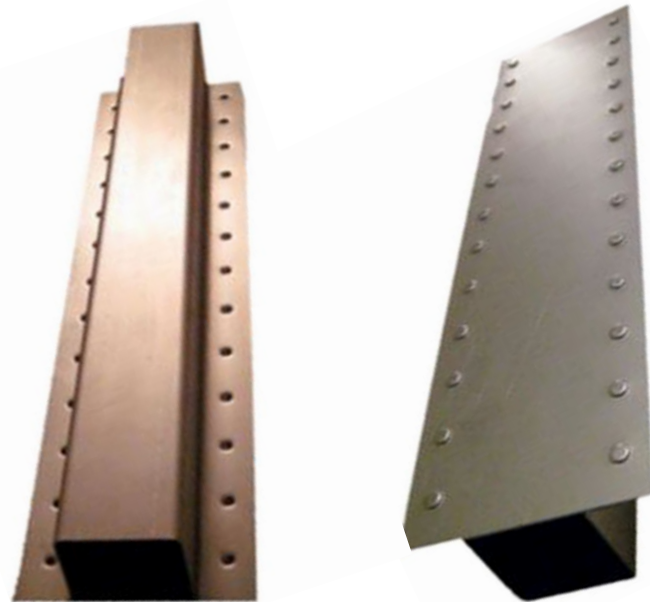
Enhancing Surface Properties



Structure-Processing-Performance Improvement

Designing Corrosion Experiments

Large Area with
multiple joints



Small Area with
single joint

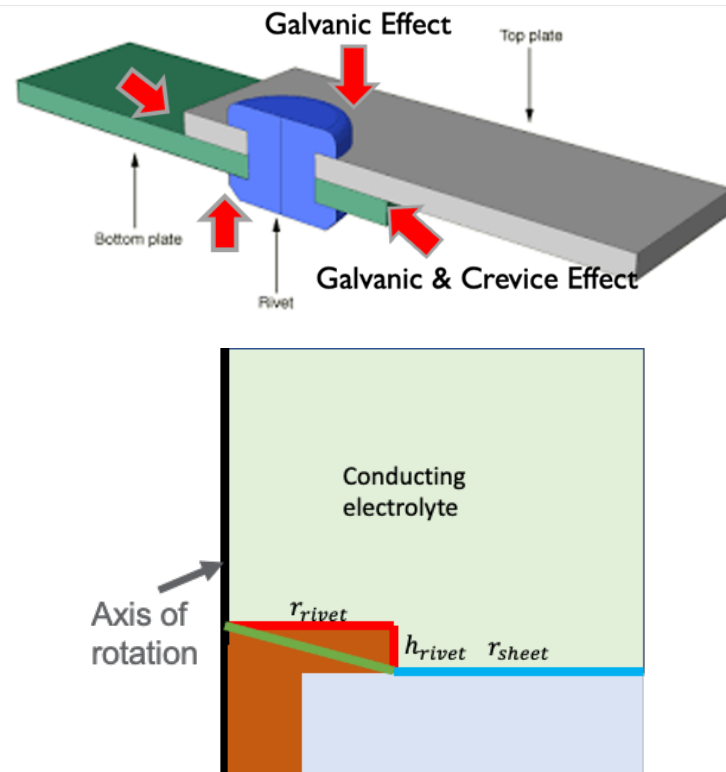


- How do we run corrosion tests that are aggressive enough to accelerate corrosion tests?
- Can they replicate real world long term corrosive behavior?
- Can we predict the role of multimaterial joints and surfaces on the overall corrosion behavior ?
- Identify and vary the most important input variables.
- Develop predictive capability using modeling.
- More models and fewer experiments.

Multiscale Modeling

Employing COMSOL to guide corrosion experiments

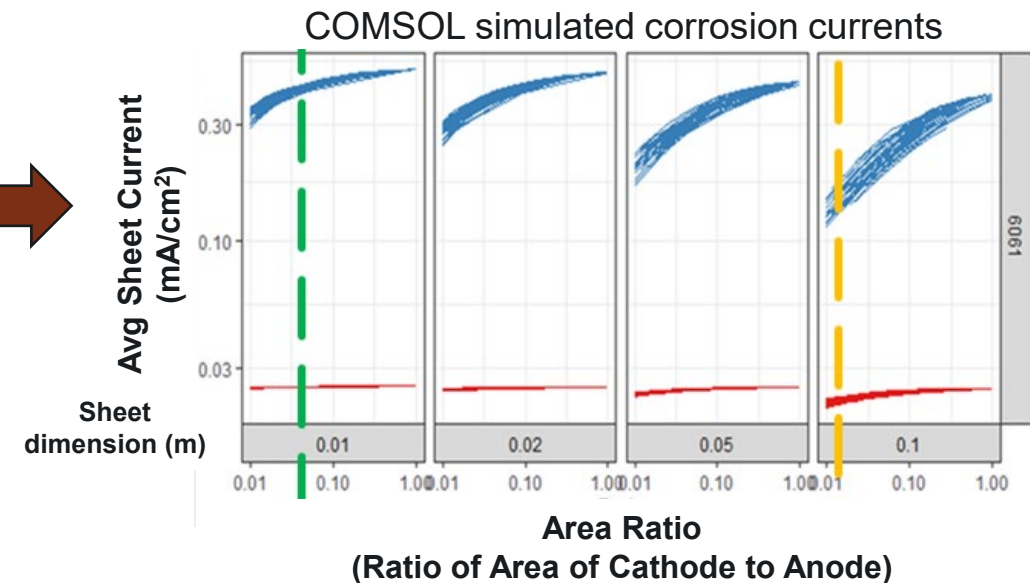
Model Setup



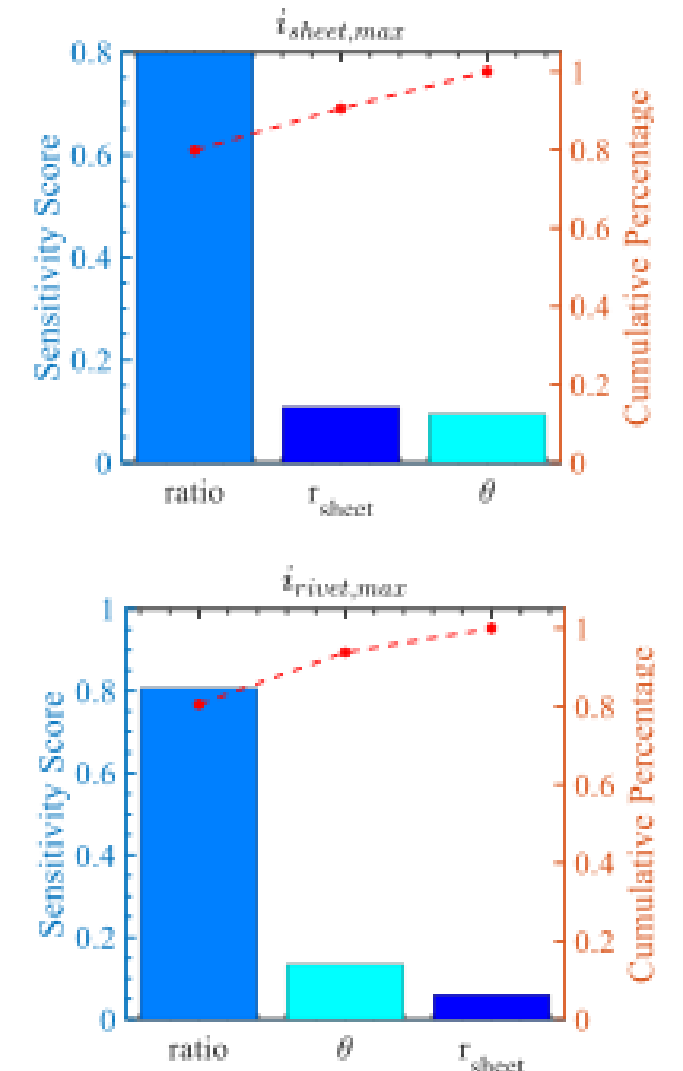
Angle between green and blue is θ , used this for regression goes from 90 to 180 degrees

$$\theta = \pi - \text{atan} \frac{h_{rivet}}{r_{rivet}}$$

Performed over 2000 Simulations to understand the effect of height of rivet, cathode to anode area effects.

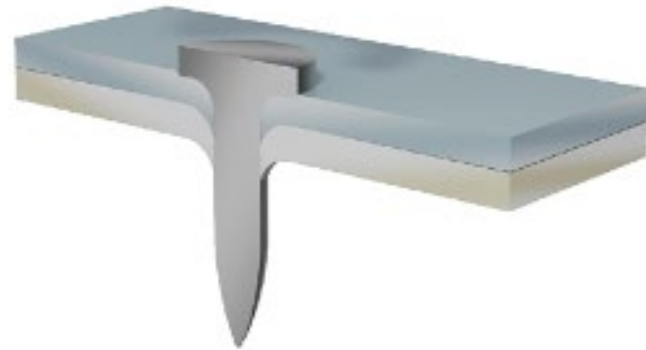


Pareto Plot of Sensitivity Score from Multivariate Adaptive Regression Splines method (MARS)

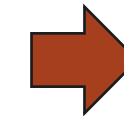
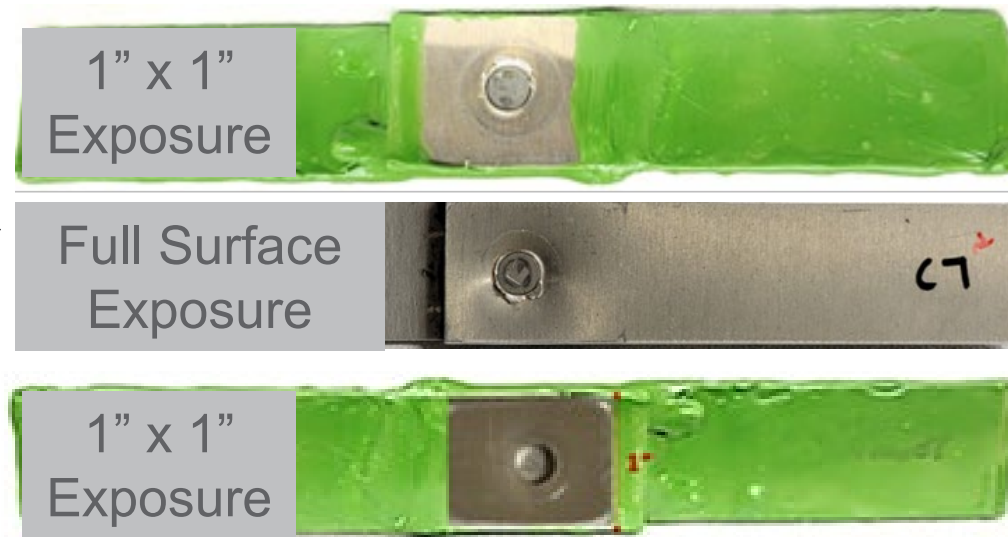


- Cathode to Anode area ratio has largest influence on the results
- r_{sheet} and θ have less influence

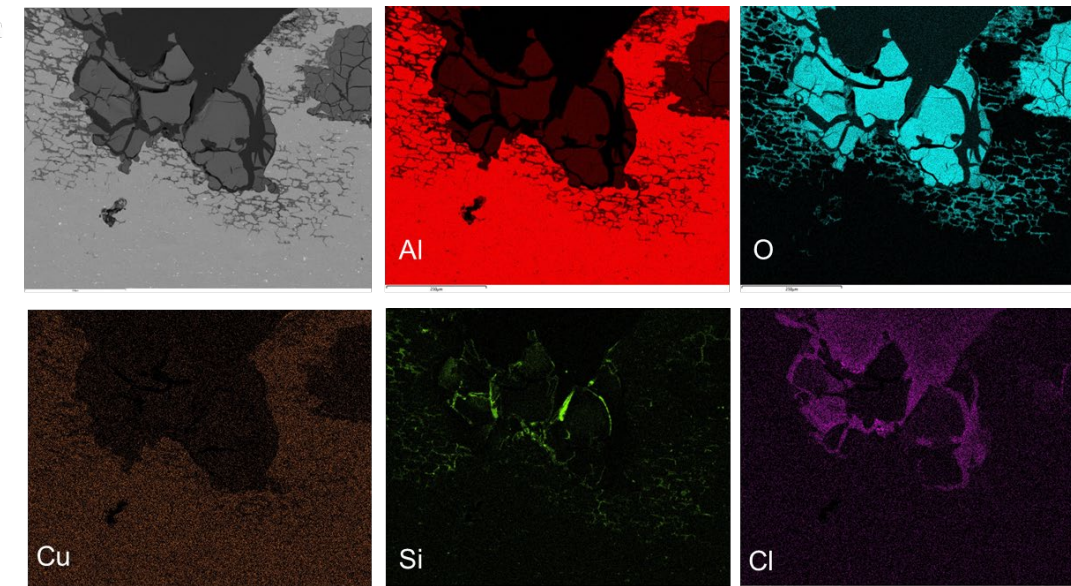
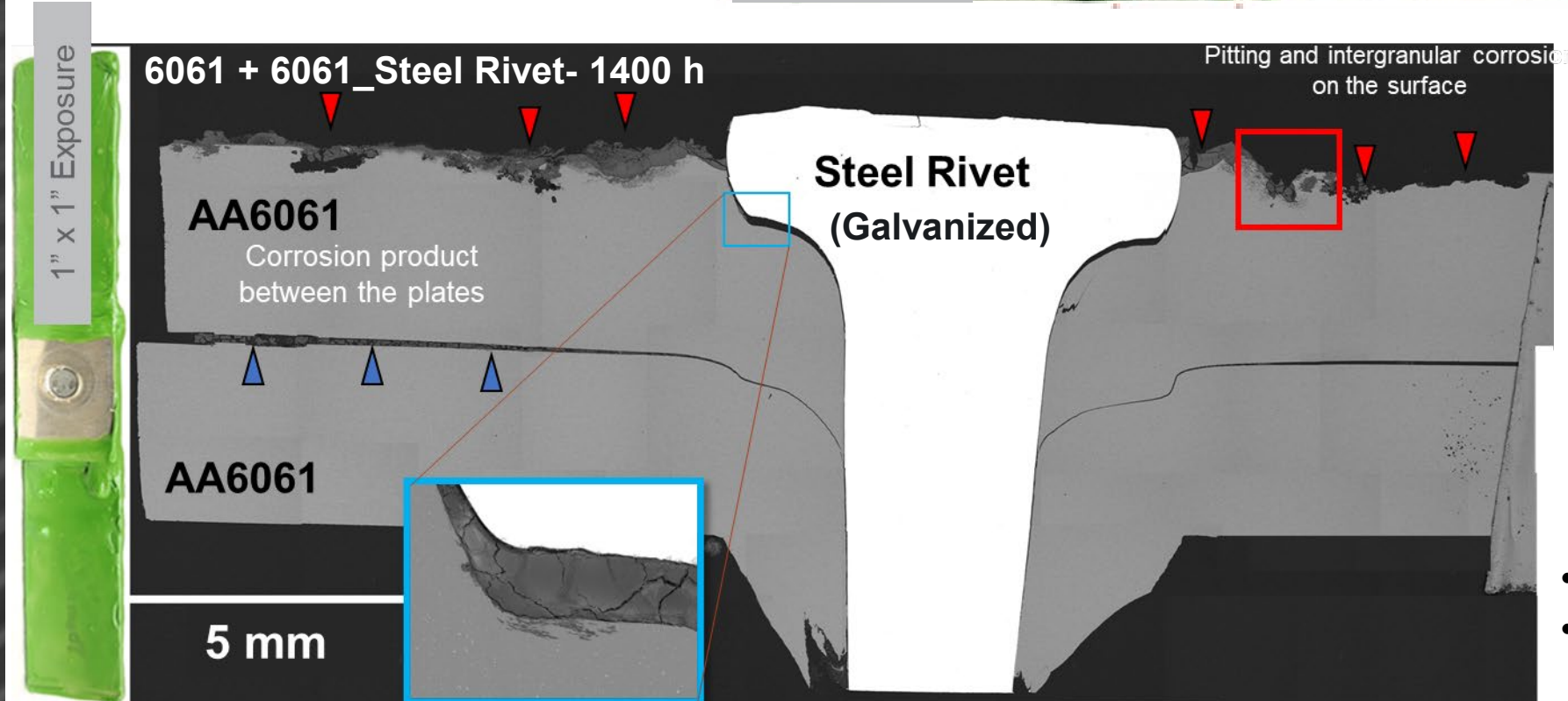
Design of Experimental Campaign to investigate corrosion in Multimaterial Joints- ASTM B117



Cathode: Galvanized steel rivet
Anode: AA6061 plates



Salt fog ASTM B117 tests performed until 1400h of continuous exposure.

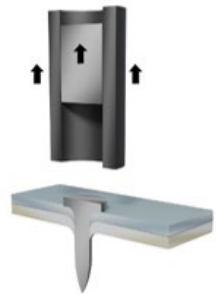


- Pitting corrosion observed on top plate
- Corrosion product between the plates- fluid has penetrated through the green paint that was protecting the sides.

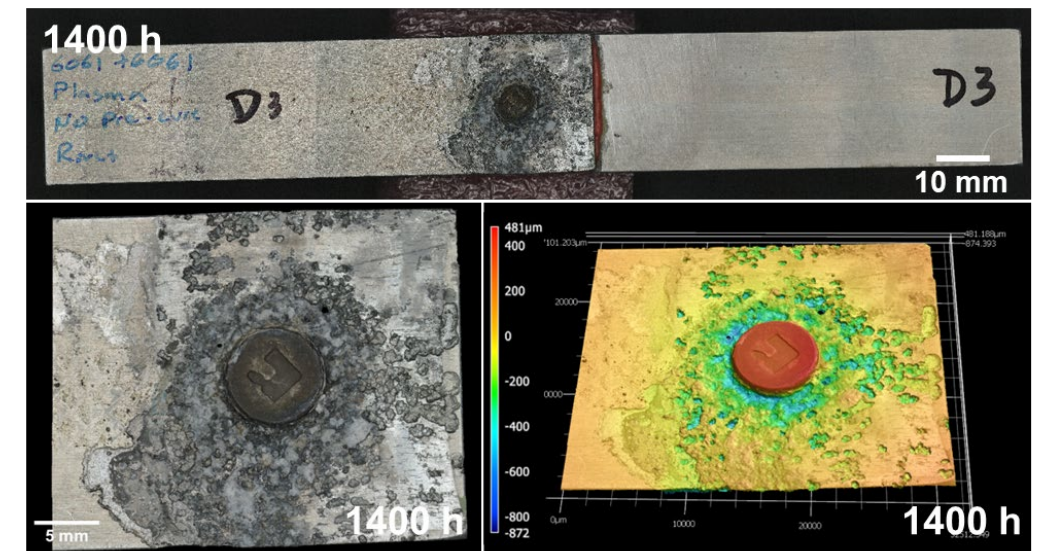
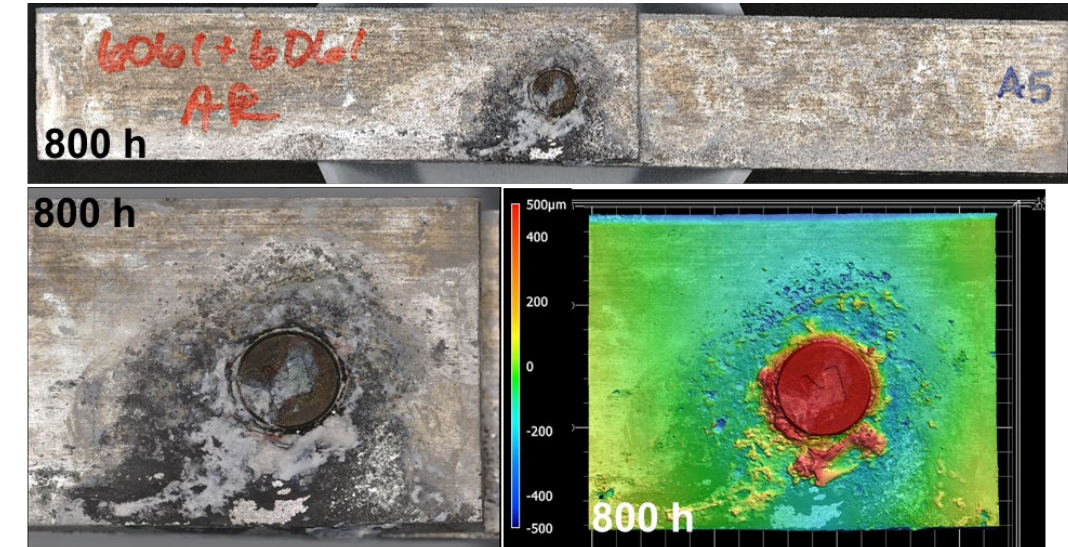
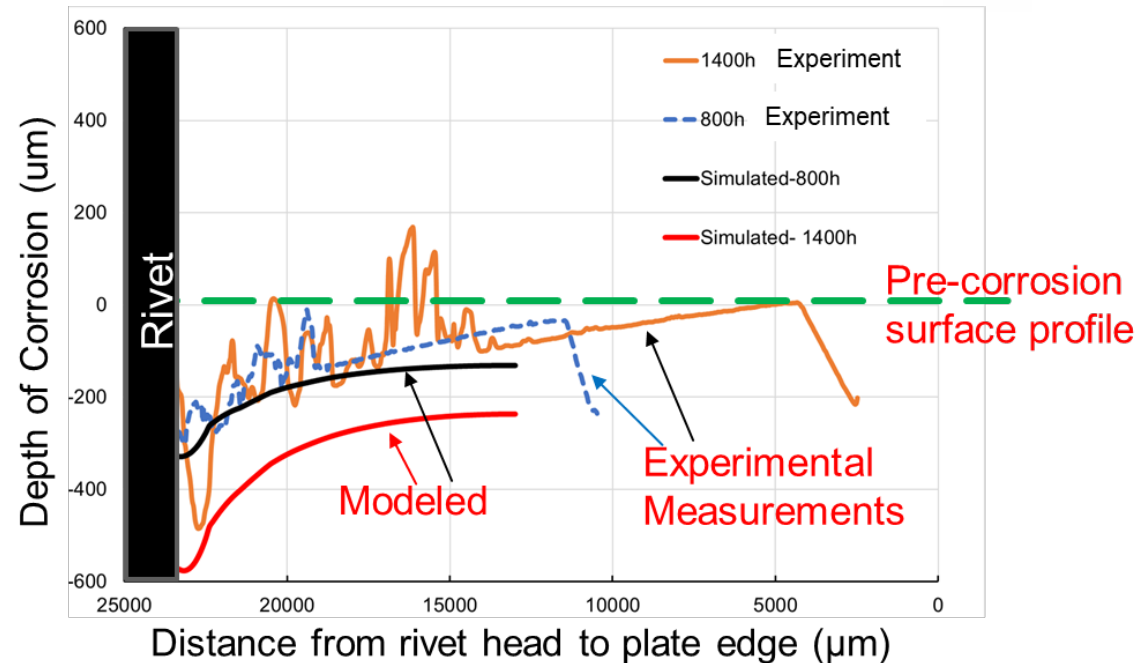
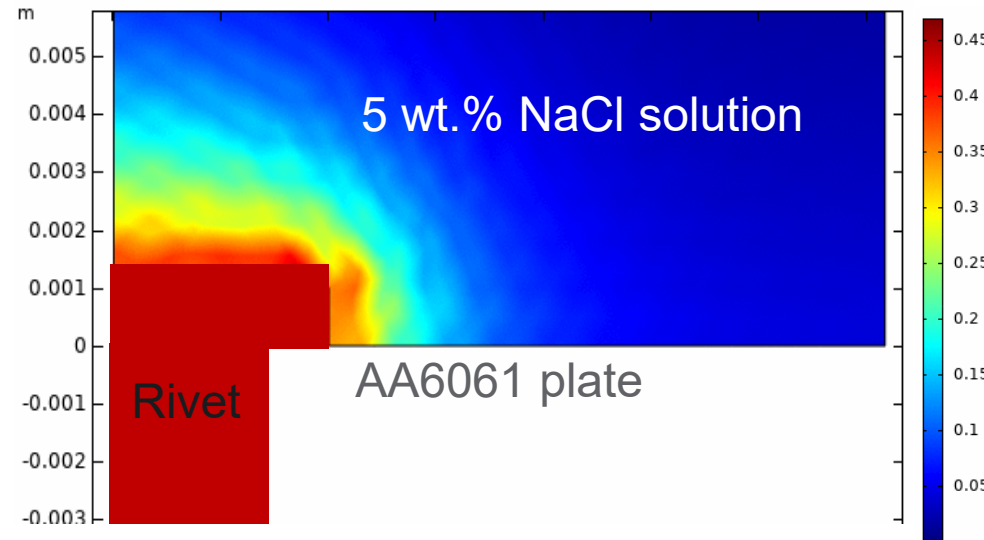
Comparing COMSOL Modeling and Experimental Measurements

Post-Corrosion Material Loss in AA6061 + AA6061 HiVe- Steel Rivet joints

COMSOL simulations to predict corrosion and reduce number of experiments (particularly long term).

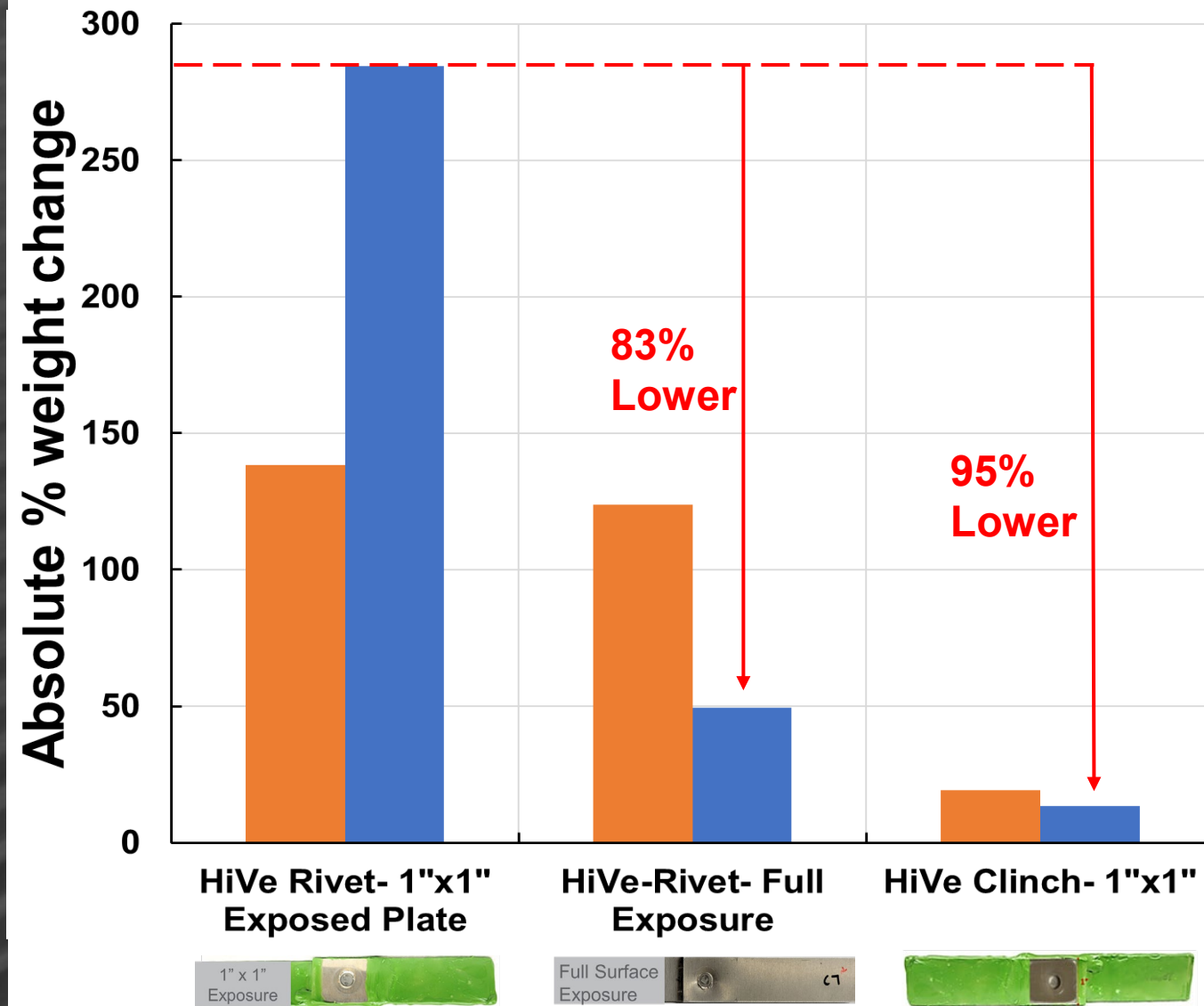


Salt Fog Corrosion Experiments in 5 wt.% NaCl solution- Full surface exposure 800h vs 1400h of immersion

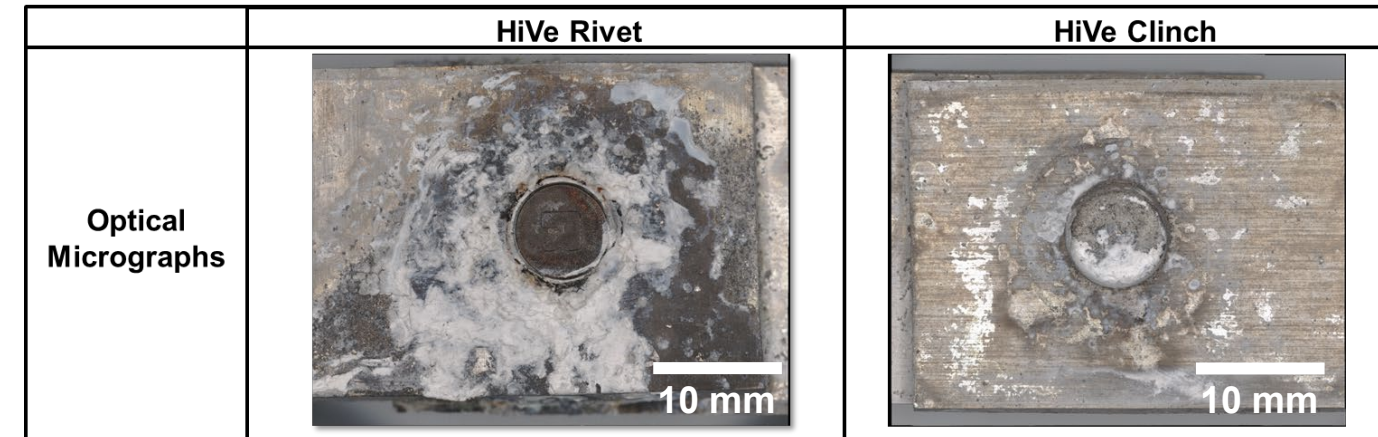


- Our COMSOL models can predict maximum depth due to galvanic pitting under salt fog corrosion well
- 5 Minutes of COMSOL modeling vs 1400 hours of Experimental Corrosion!!

Summary: Demonstrated Significant Decrease in Corrosion Rate



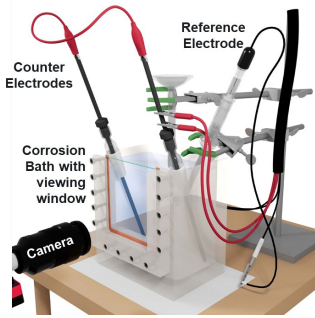
After 1400h of ASTM B117 corrosion exposure



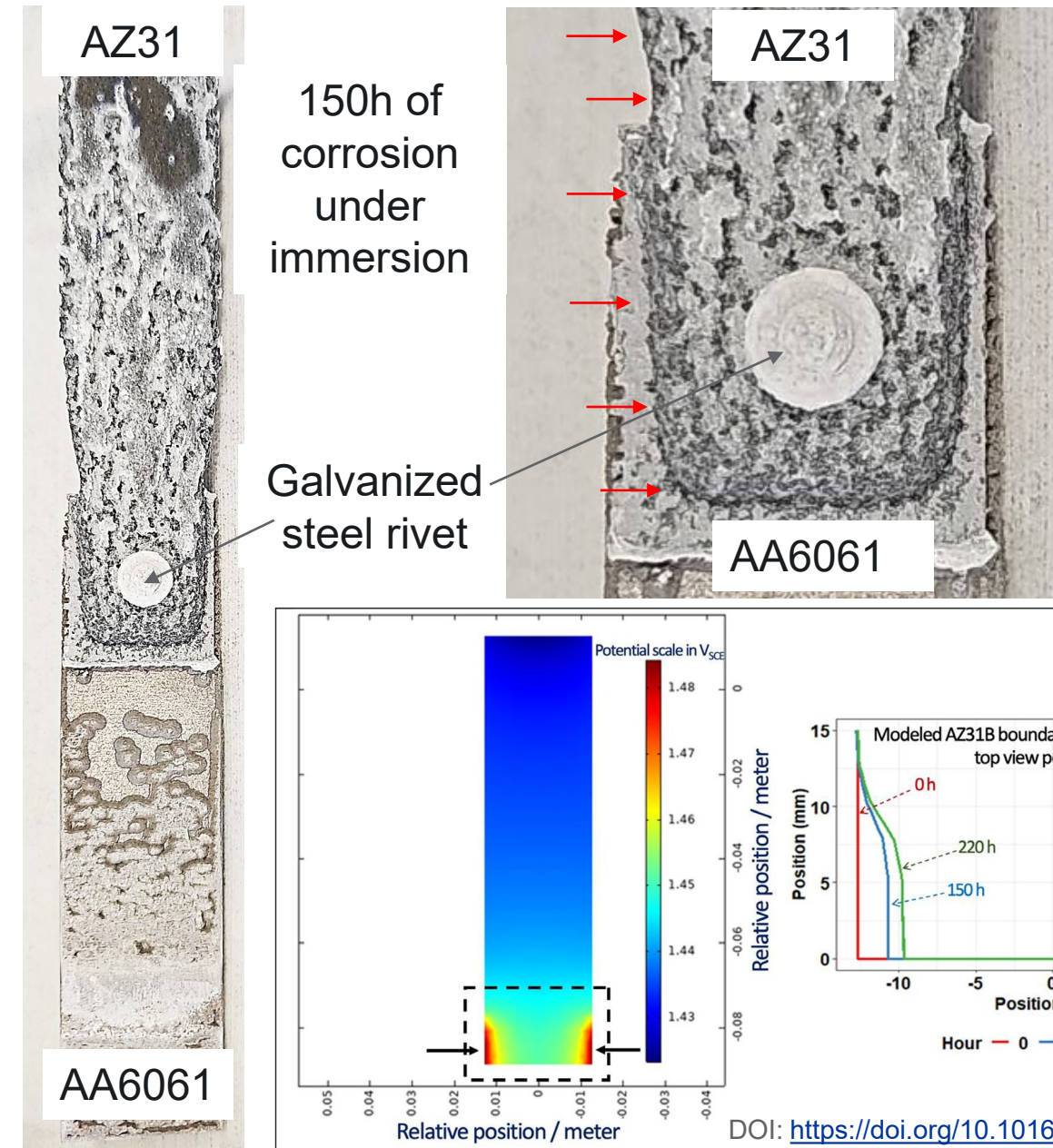
800
1400

- Multivariate Analysis and Experiments quantitatively confirm that area ratio of exposure drastically affects multimaterial joint response.
- HiVe Clinch Configuration shows substantially lower corrosion induced weight change.

Current Efforts: Corrosion Investigation and Mitigation in HiVe Riveted Al-Mg Joints

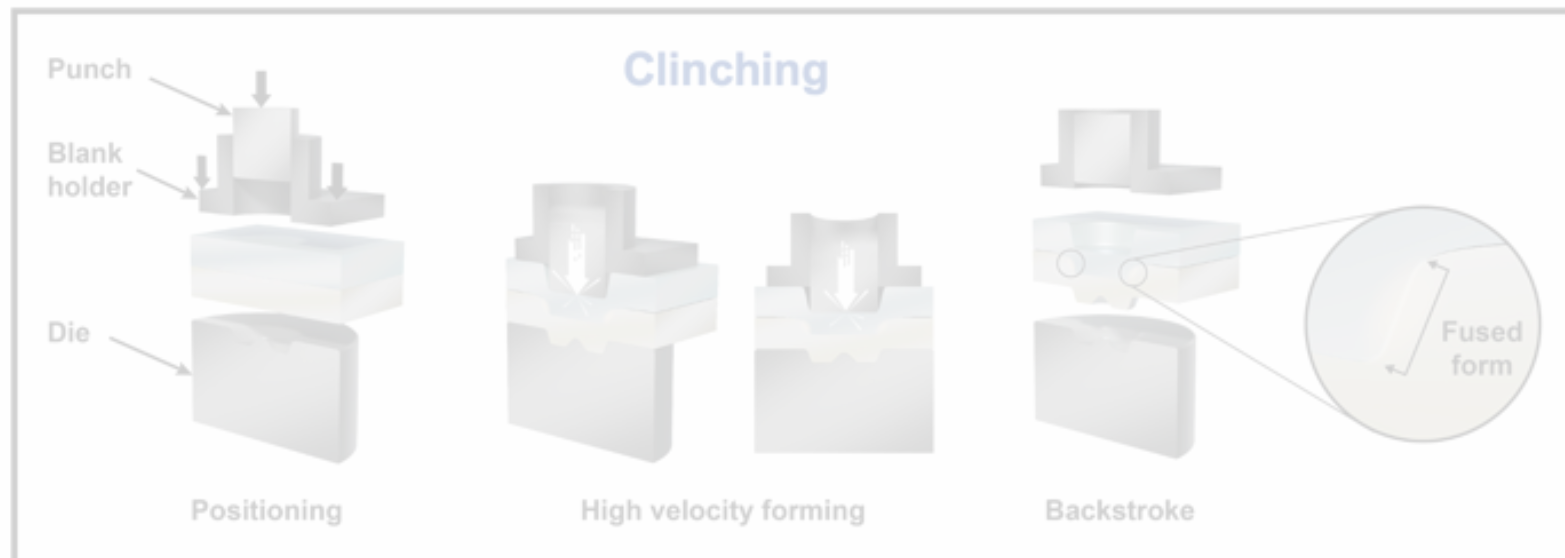
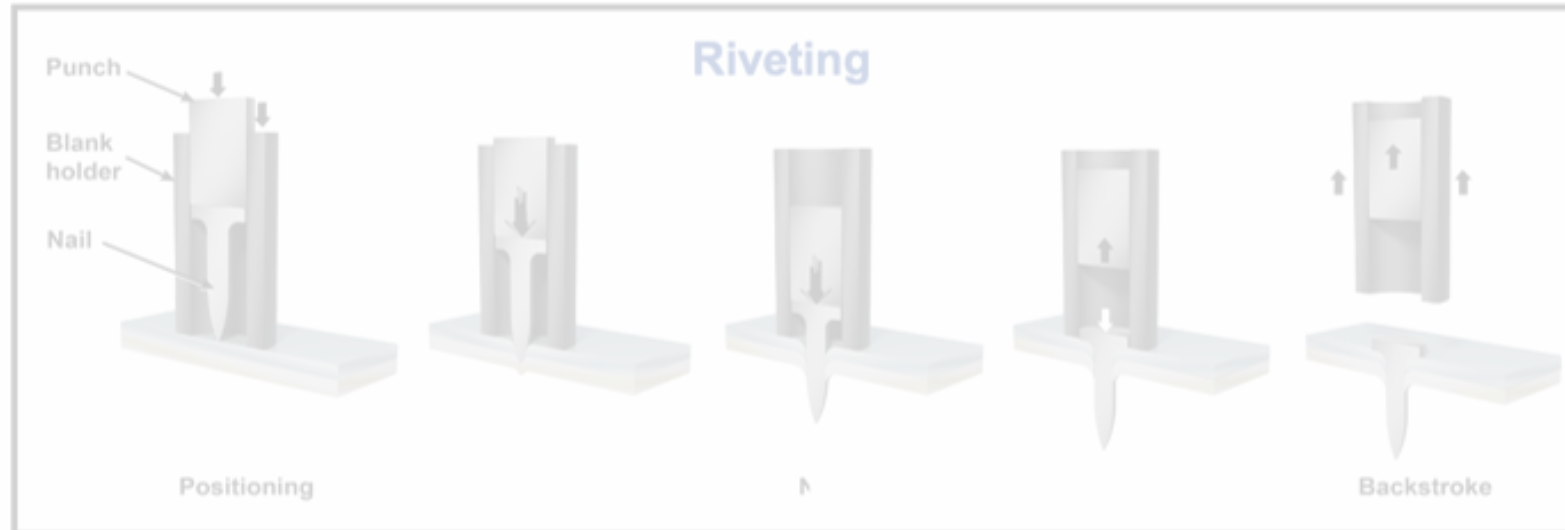


- Corrosion was performed in 3.5 wt.% NaCl solution
- Corrosion Duration shown here – 2 hours

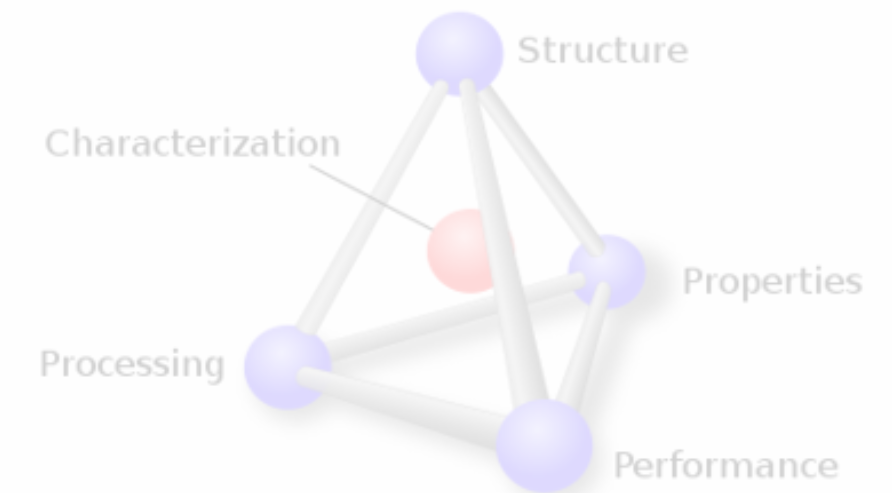
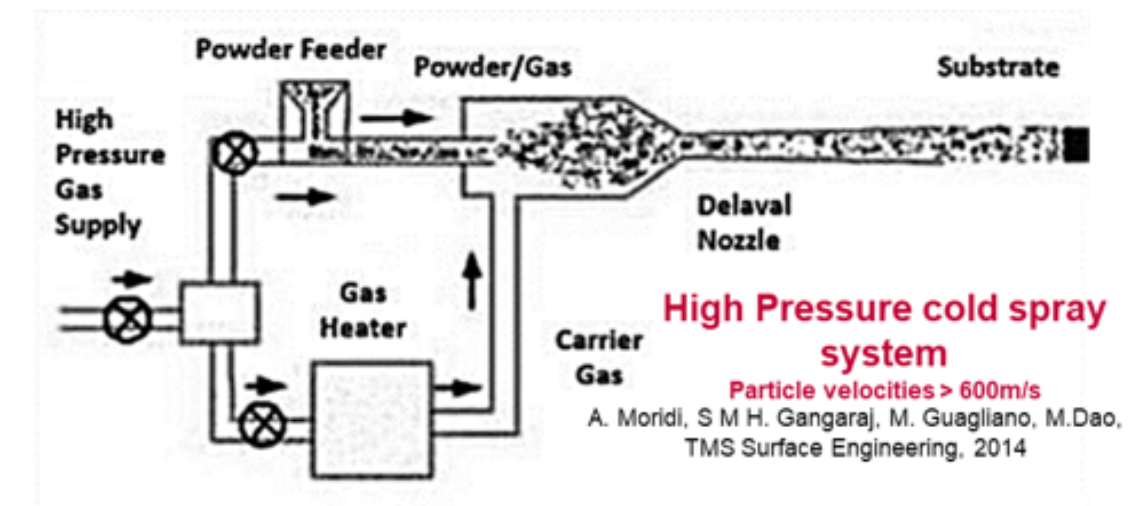


Focus Areas of Dissimilar Materials Joining and Surface Processing for Corrosion Mitigation

Materials Joining and Corrosion



Enhancing Surface Properties



Structure-Processing-Performance Improvement

Approach to Corrosion Modeling and Experimentation

Length Scale (m)

1

1E-2

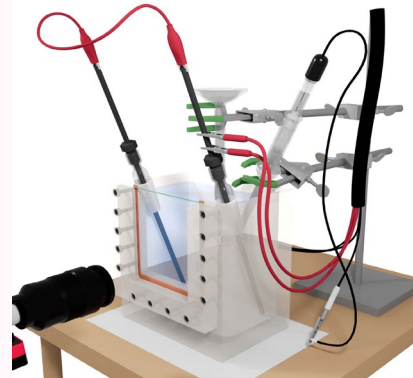
1E-4

1E-6

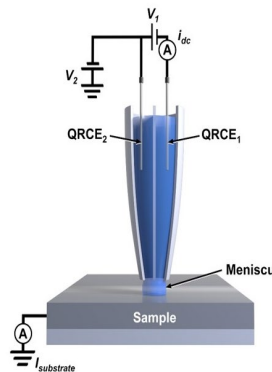
1E-8

Corrosion

Salt Fog and immersion corrosion



In situ
Multimodal Bulk
Corrosion
System



Scanning
Electrochemical Cell
Microscopy (SECCM)

V. Prabhakaran, *J. Phys. Chem. C* 2022,
126, 30, 12519–12526

Scanning Kelvin
Probe Force
Microscopy (SKPFM)



Imaging

OM



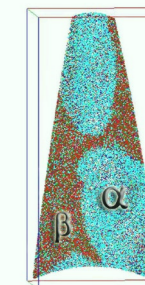
XCT



SEM +
EBSD+
PFIB+EDS



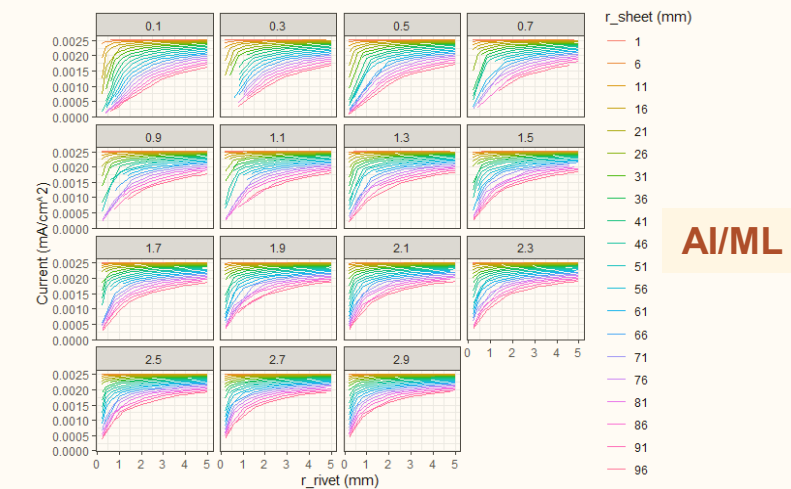
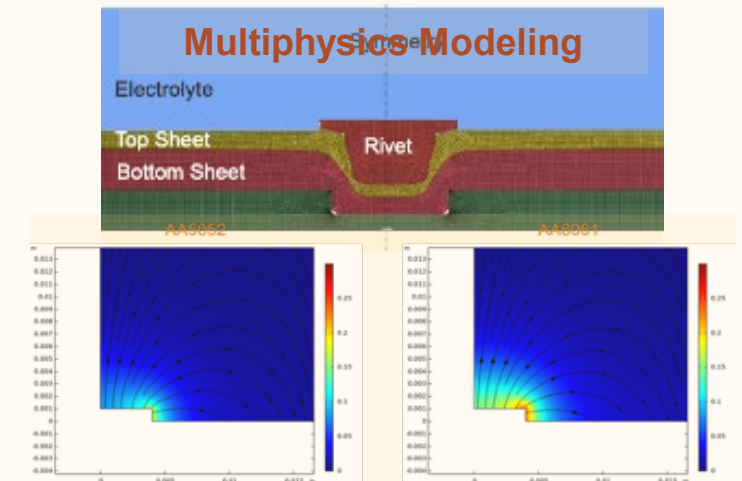
APT and TEM



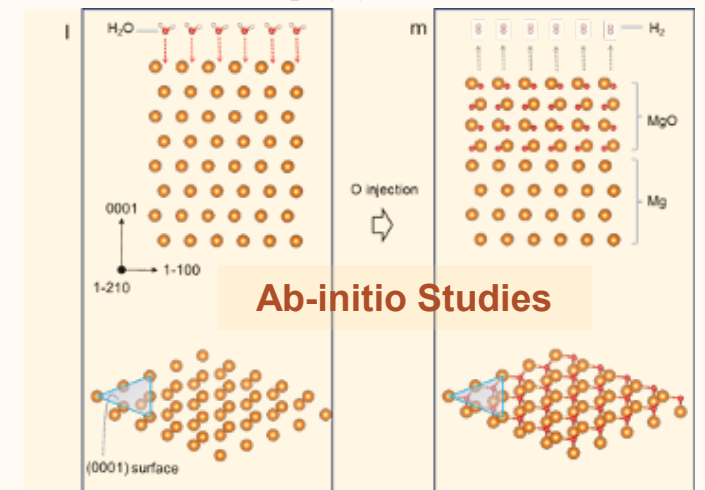
A. Devaraj, *Nature*
Communications, 2016

Modeling

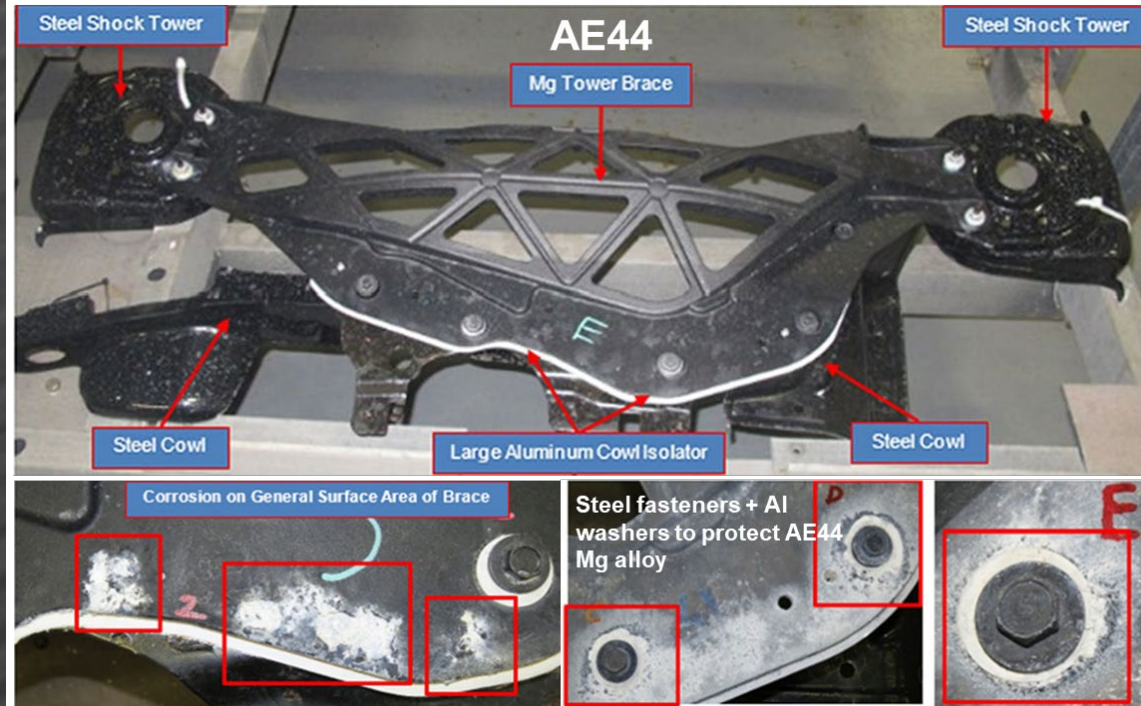
Multiphysics Modeling



Ab-initio Studies

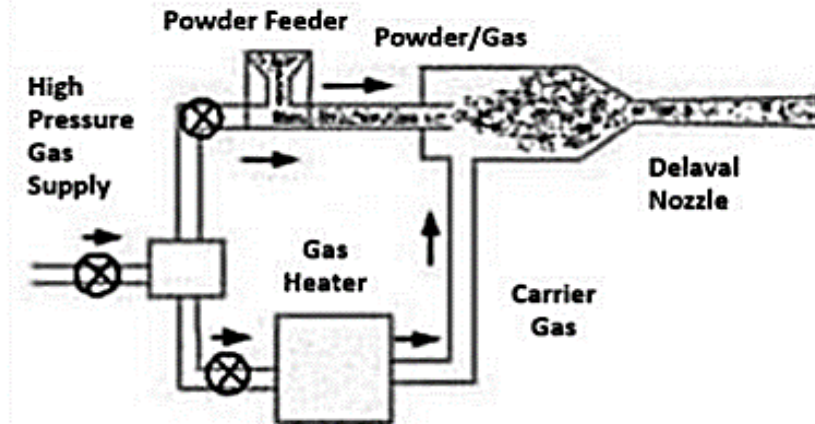


Enhancing Surface Properties and Circumventing Challenges with Complex Oxides

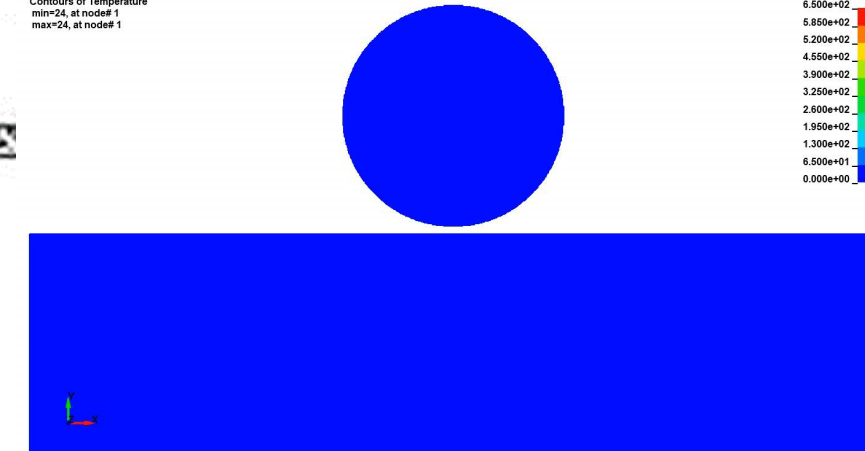


K. Lazarz, J. Cahill, TJ Ciccone, K. Redlin, S. Simko, Corrosion Performance of a Mg tower brace, SAE technical papers, 2021

High Pressure cold spray system Particle velocities > 600m/s



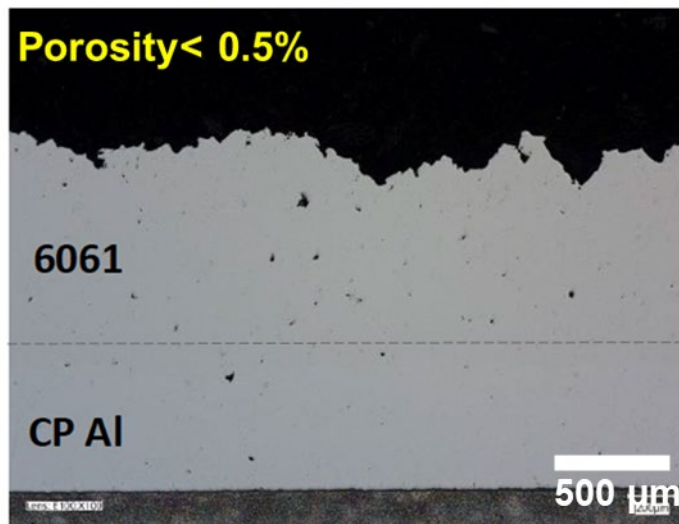
AZ91-1100-600ms-D26um
Time = 0
Contours of Temperature
min=24, at node# 1
max=24, at node# 1



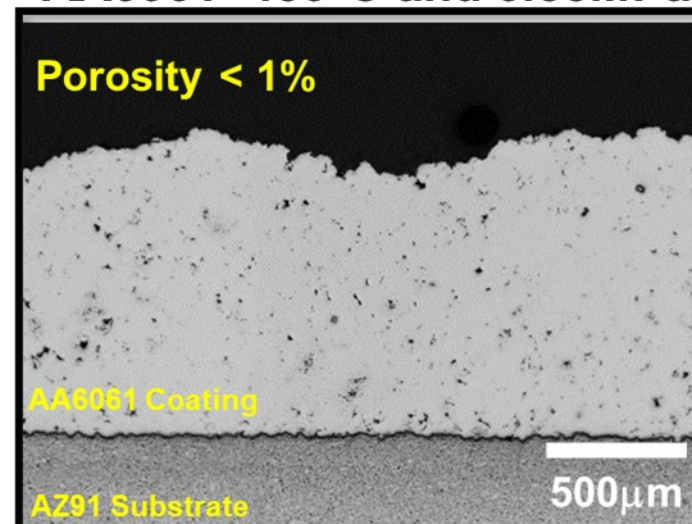
- Solid phase coating deposition.
- High deposition rate.
- Metallurgical bond
- Scalable into vehicle production lines.

Successfully
developed and
Optimized
Cold spray
coatings

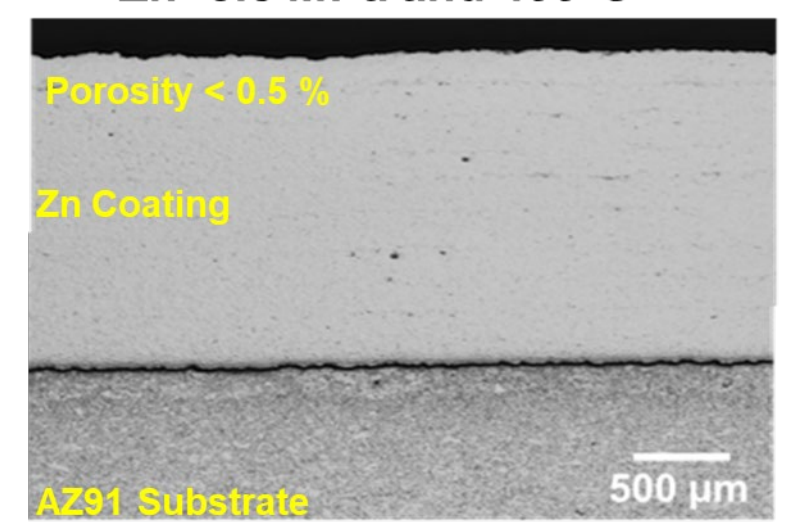
CP Al (375°C)/6061 (425°C)



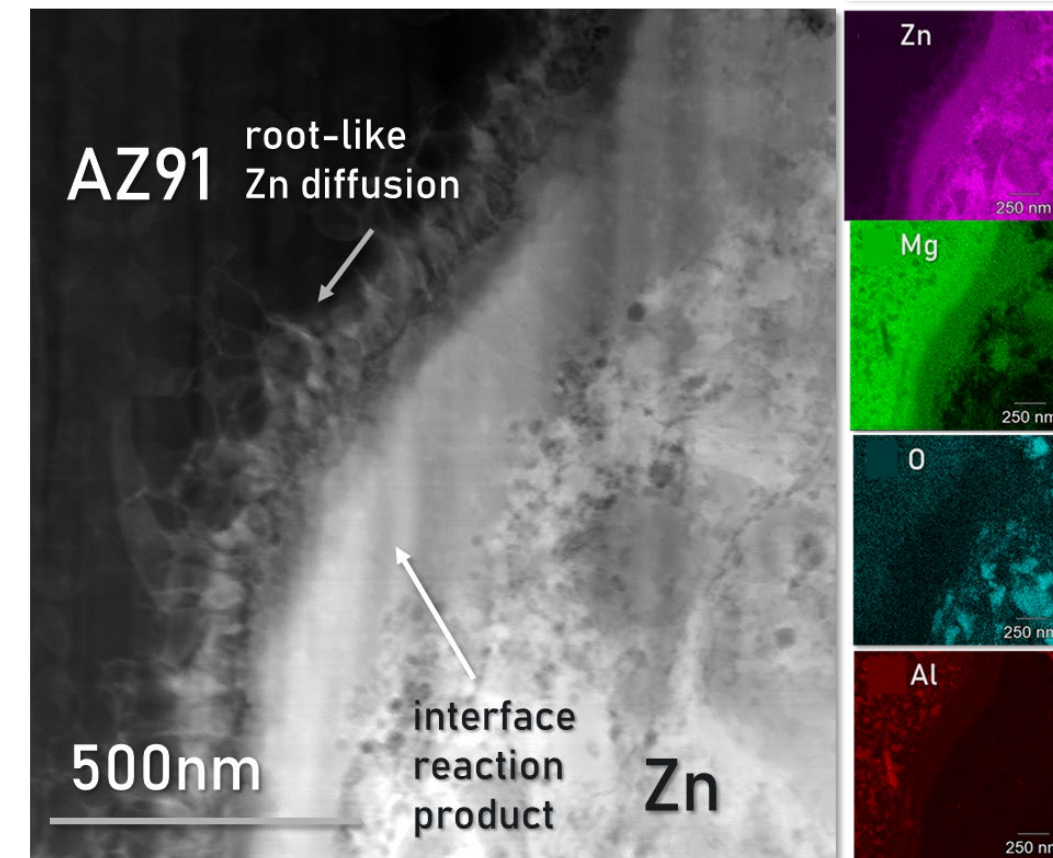
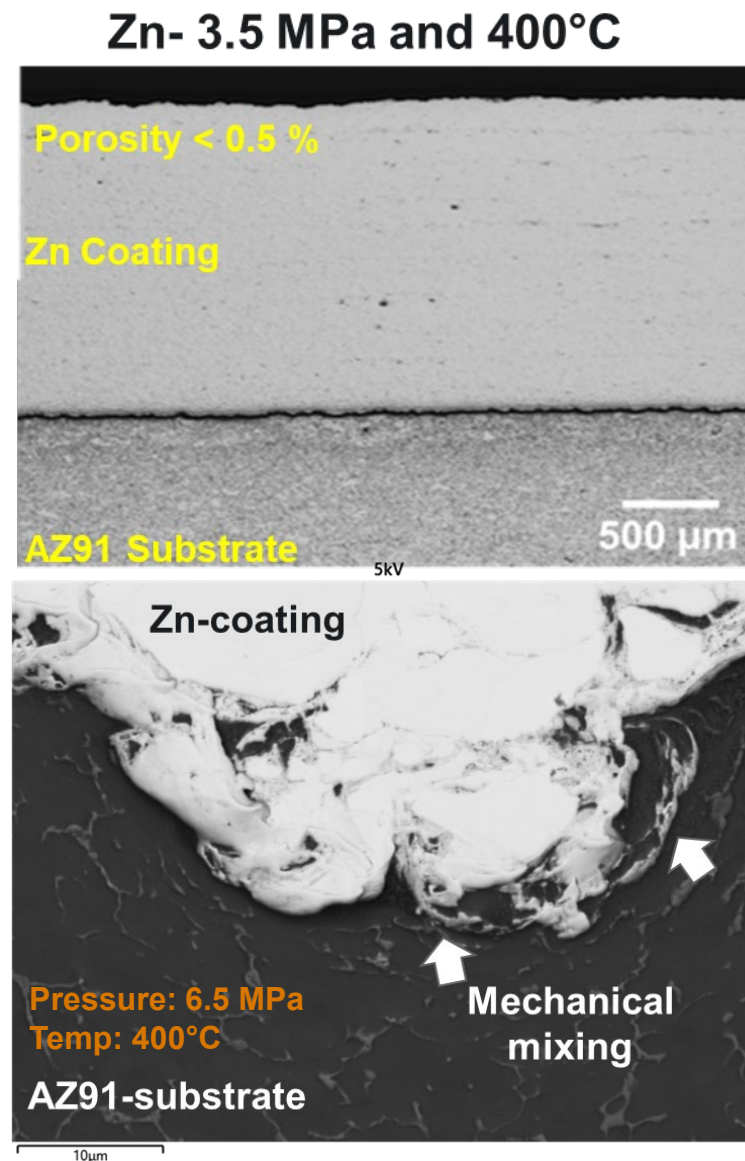
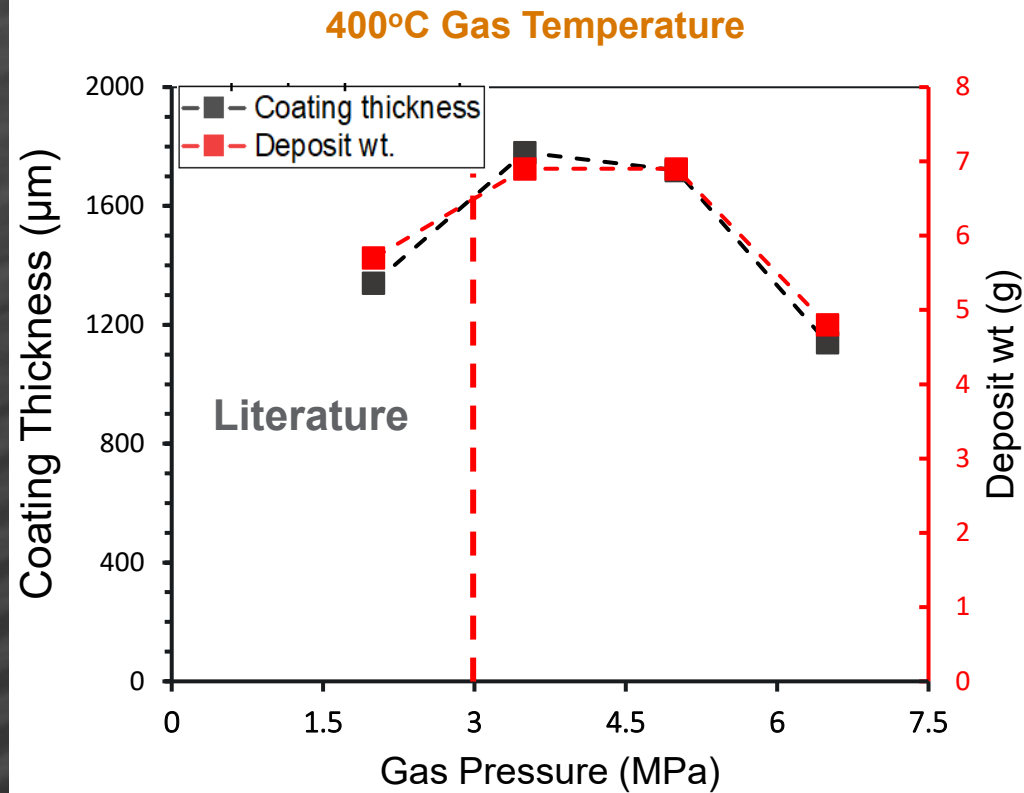
AA6061- 450°C and 6.55MPa



Zn- 3.5 MPa and 400°C



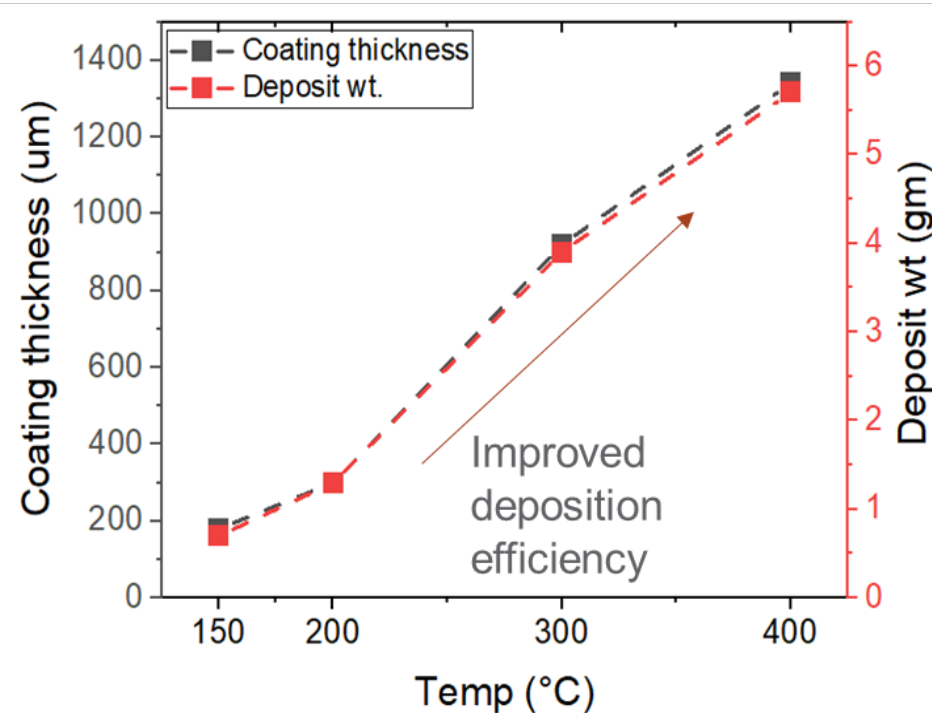
Zn coating – Nature of Deposition



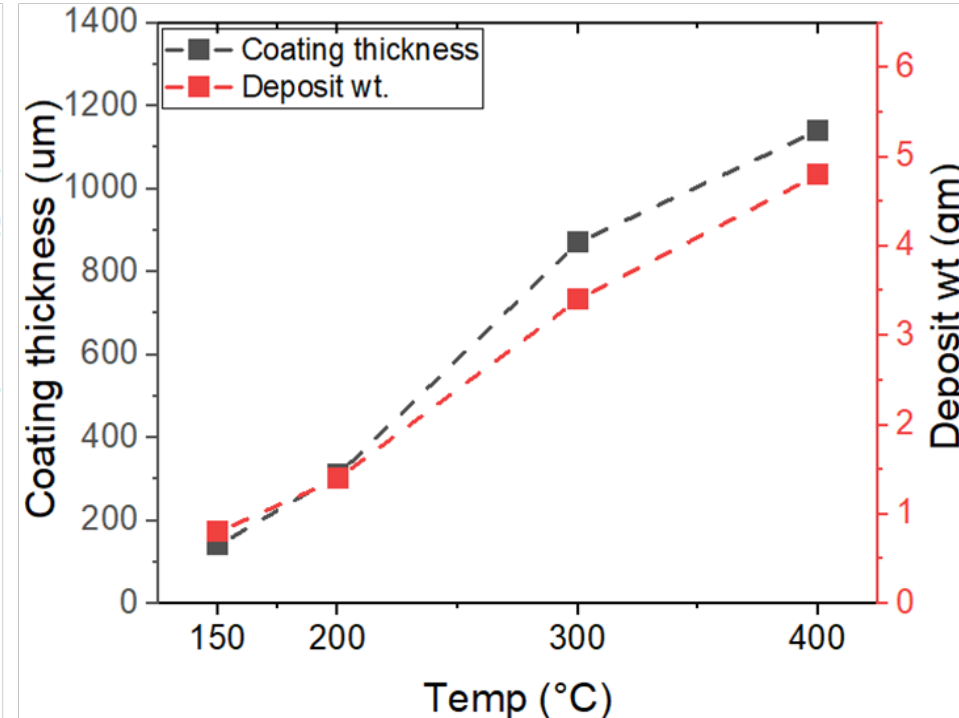
- Optimization is key to developing coatings with low porosity (less than 0.5%) and high deposition efficiency.
- Development of a metallurgical bond is key to enhancing adhesion strength in CS coatings.

Zn coating – Nature of Deposition

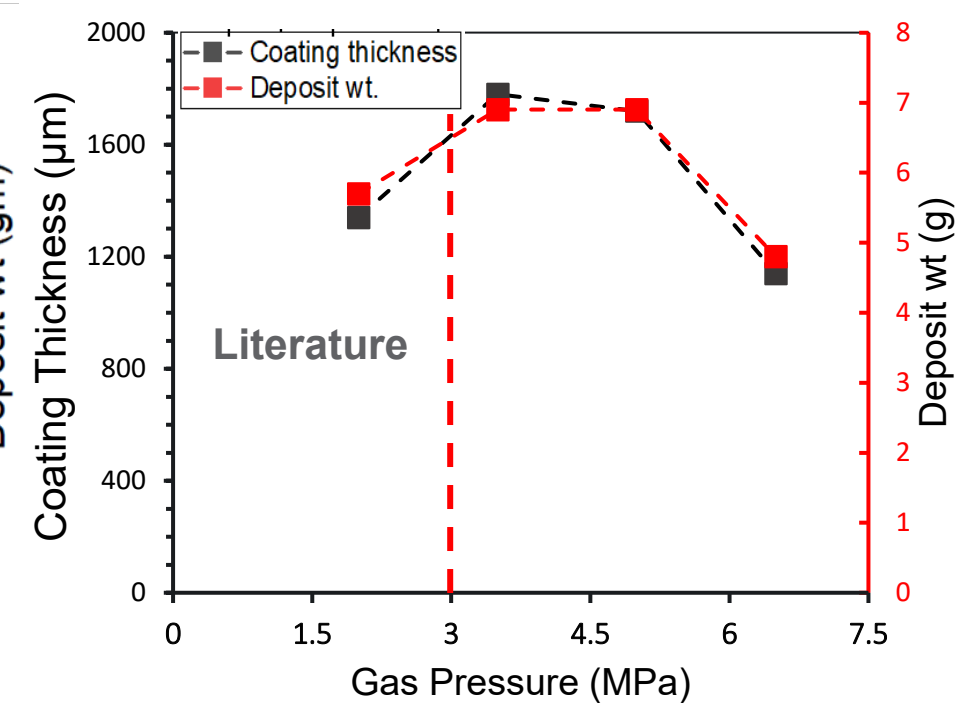
2 MPa/290 psi



6.5 MPa/943 psi



400°C Gas Temperature



- Increasing gas temperature improves deposition of coatings on to the substrate.
- Deposition is seen to peak at gas pressure values over what has been documented in the literature

Zn coating – Microstructure and Performance

	Deposit weight(g)			
	2 MPa (290 psi)	3.5 MPa (508 psi)	5 MPa (725 psi)	6.5 MPa (943 psi)
150°C	0.69	0.96	0.92	1.06
200°C	0.98	1.26	1.55	1.67
300°C	3.77	4.72	4.97	4.46
400°C	6.95	7.96	6.51	7.35

	Deposit Thickness (mm)			
	2 MPa (290 psi)	3.5 MPa (508 psi)	5 MPa (725 psi)	6.5 MPa (943 psi)
150°C	0.1	0.23	0.275	0.22
200°C	0.2	0.3	0.35	0.4
300°C	0.84	1.14	1.125	0.94
400°C	1.66	1.89	1.55	1.74

	Porosity (Area %)			
	2 MPa (290 psi)	3.5 MPa (508 psi)	5 MPa (725 psi)	6.5 MPa (943 psi)
150°C	1.06	0.97	1.12	1.31
200°C	0.7	1.06	0.98	0.92
300°C	0.6	0.43	0.48	0.37
400°C	0.61	0.29	0.56	0.77

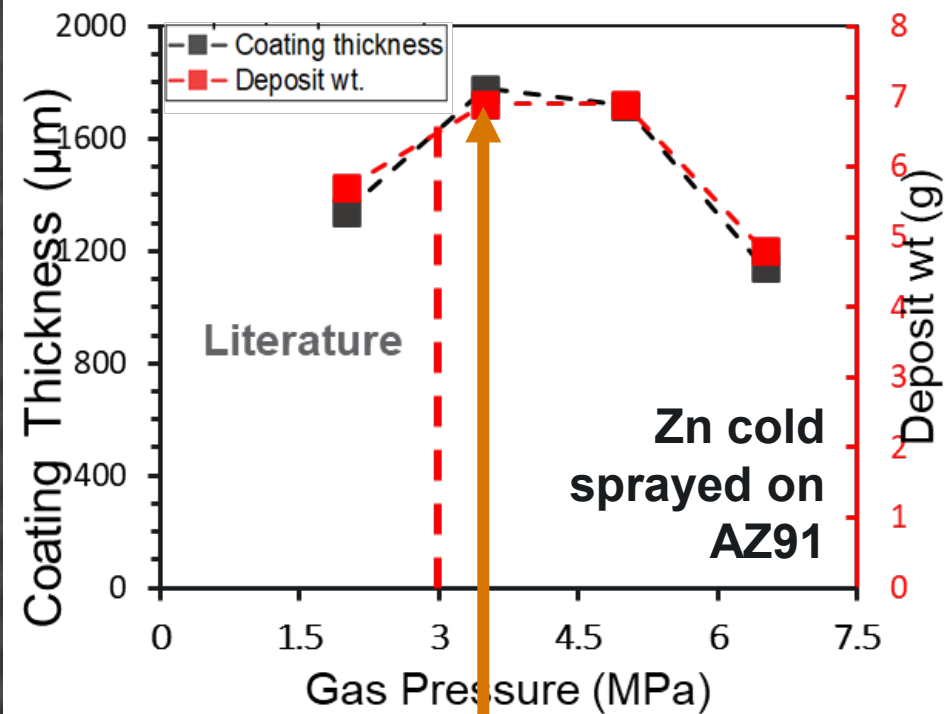
	Adhesion strength (ASTM D4541)			
	2 MPa (290 psi)	3.5 MPa (508 psi)	5 MPa (725 psi)	6.5 MPa (943 psi)
150°C	34.57	24.91	27.38	
200°C	33.18	33.15	31.57	25.22
300°C	26.27	32.26	33.9	29.16
400°C	29.16	34.54	33.49	30.78

A range of parameters show consistently better deposition, lower porosity and better performance

Correlating Smooth Particle Hydrodynamics Modeling and Single Particle Impact Tests for Optimizing Deposition

Macroscale Zn Cold spray coating deposition

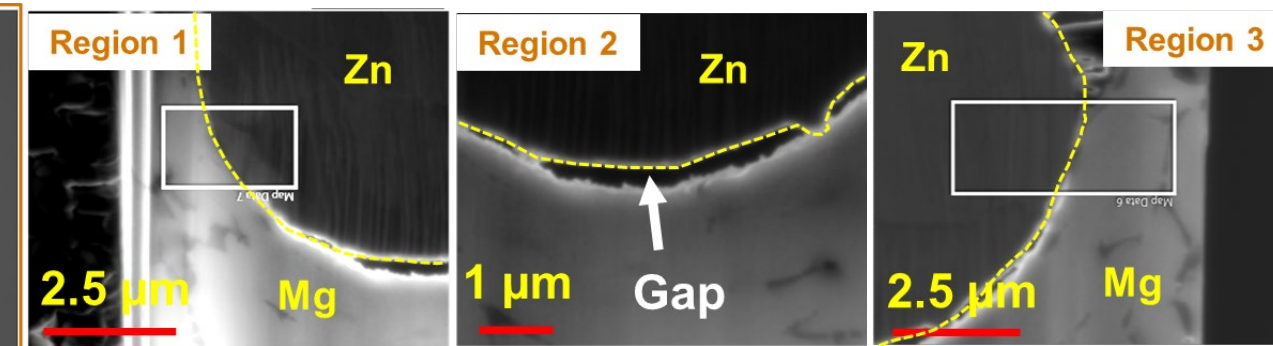
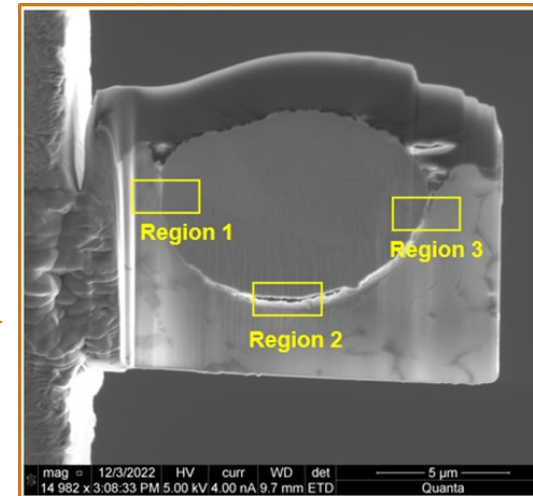
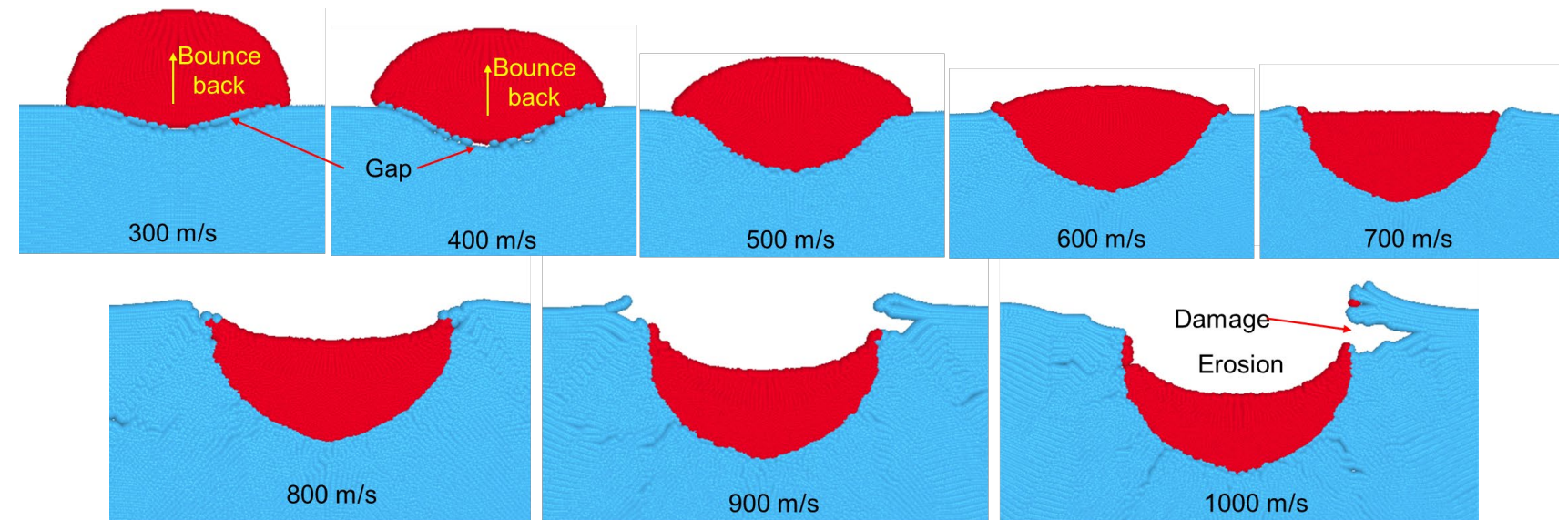
400°C Gas Temperature



Optimum
Deposition
Parameters

3.5 MPa pressure,
400°C gas temperature,
90° spray angle

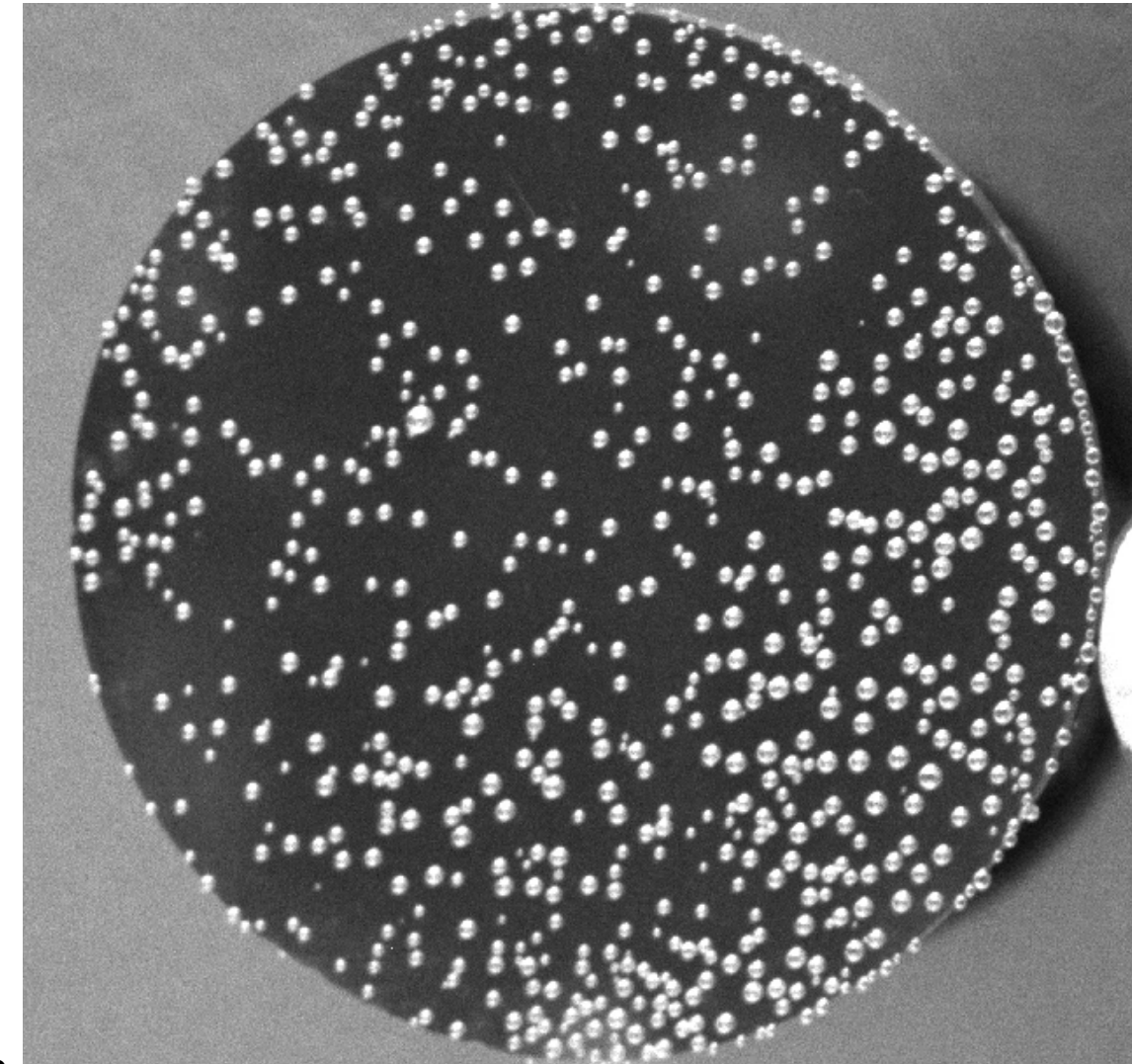
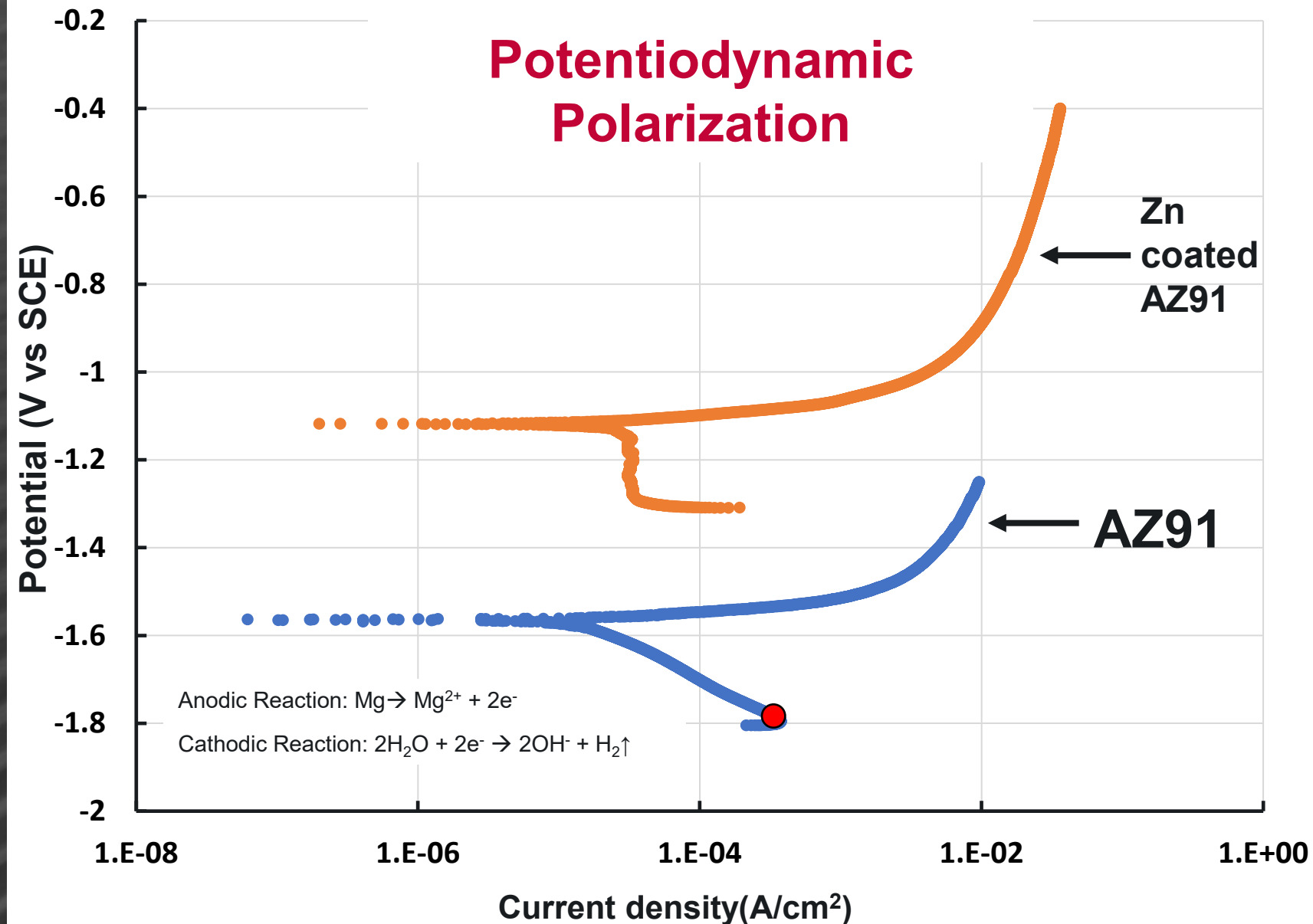
Microscale Coating Deposition



SPH is effective in improving our understanding of optimal range for deposition and the mechanisms that govern them.

Corrosion performance- Coated vs Uncoated AZ91

AZ91- Polished to 1 μ m finish
0.6 wt.% NaCl solution

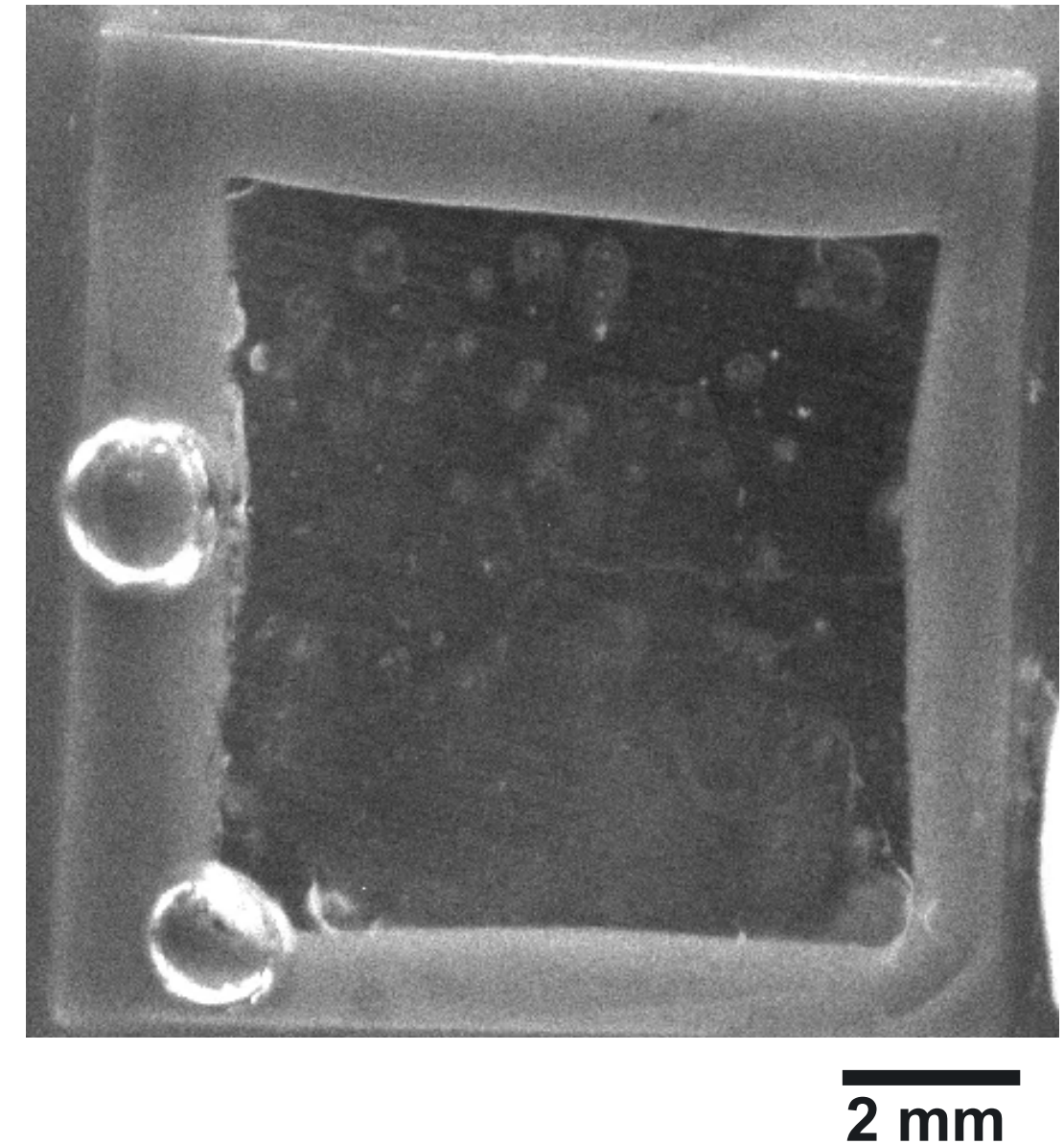
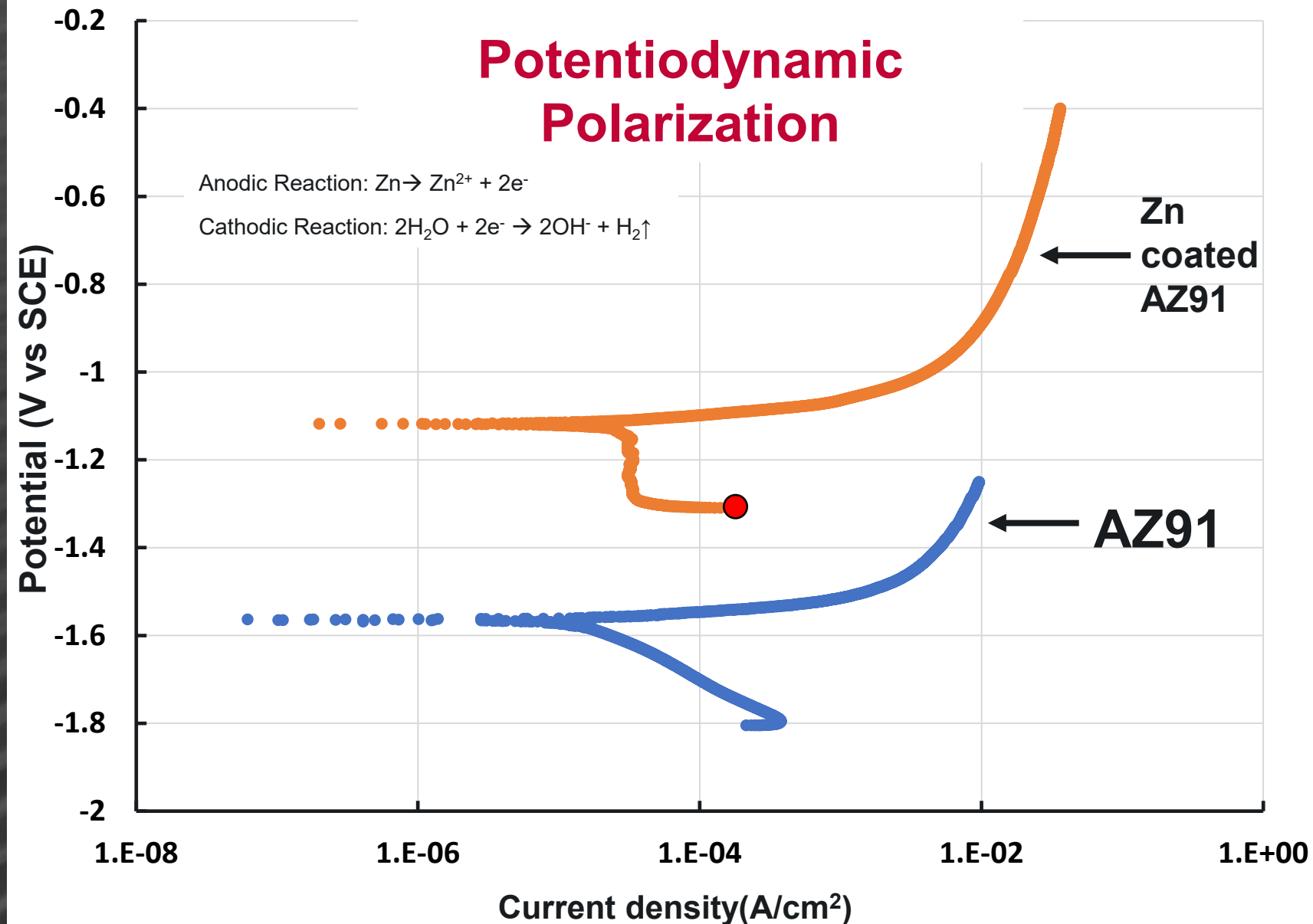


5 mm

Corrosion in AZ91 is characterized by pitting and Hydrogen evolution

Corrosion performance- Coated vs Uncoated AZ91

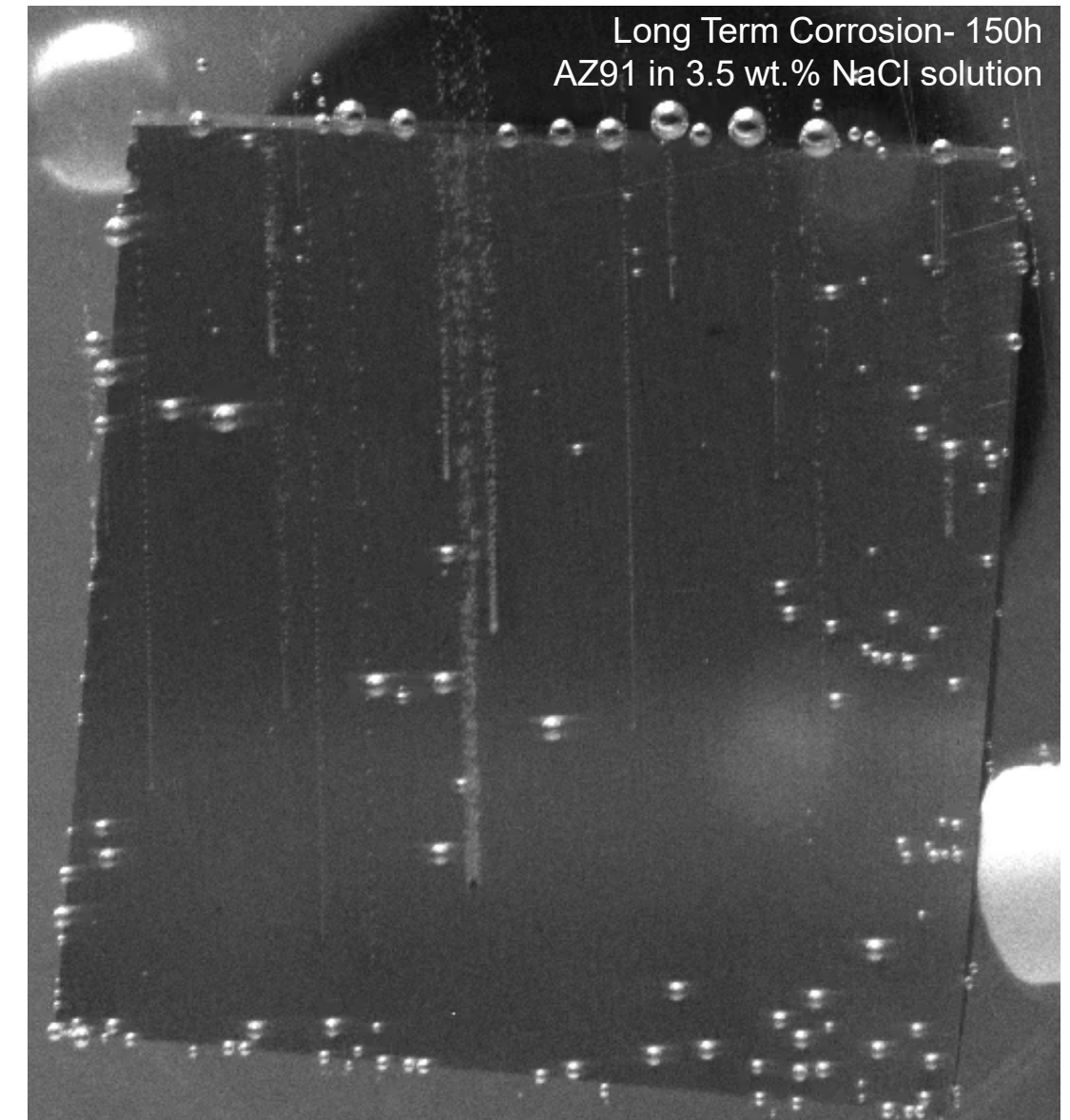
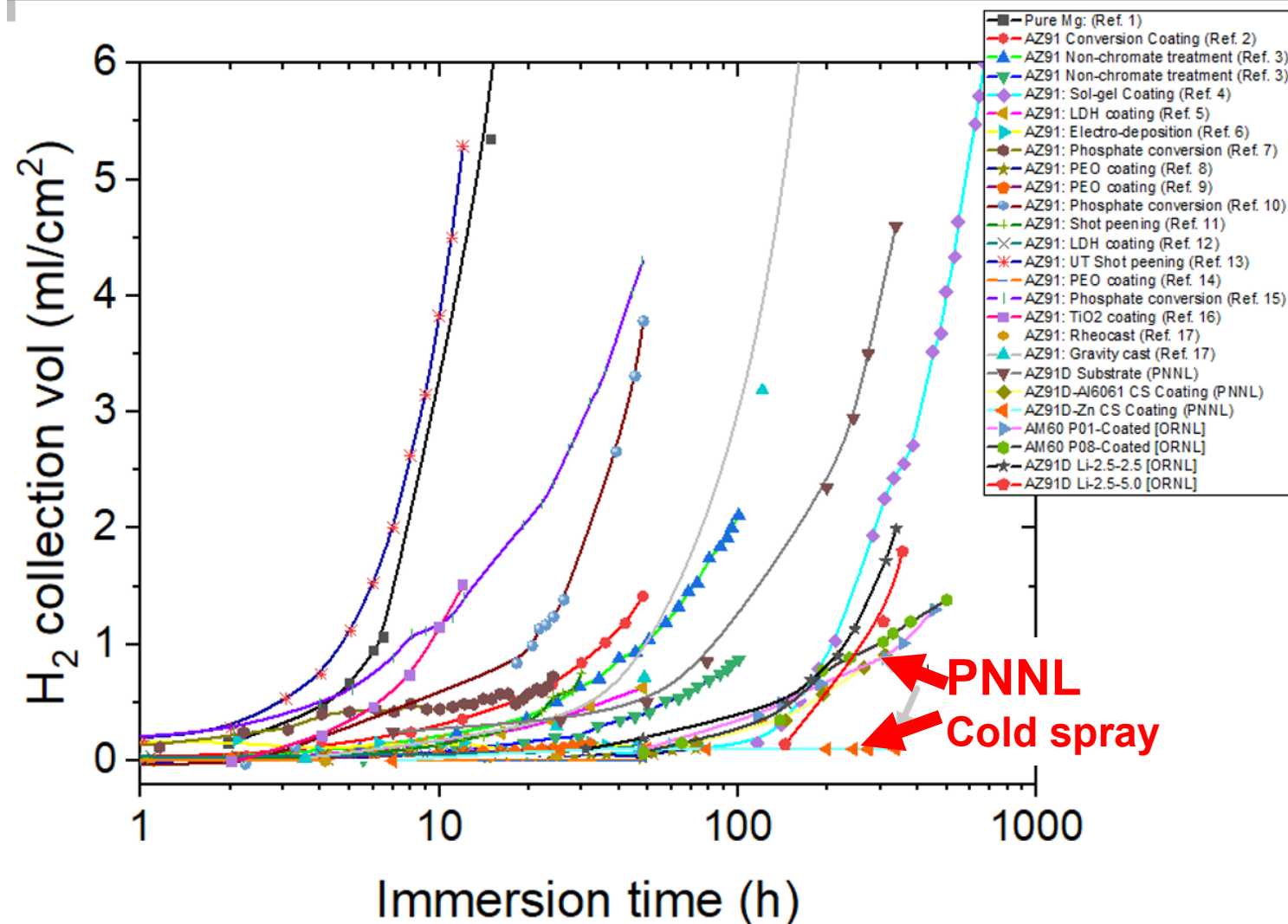
Zn coated AZ91-Polished to 1 μ m finish
0.6 wt.% NaCl solution



The corrosion potential of Zn coated AZ91 is more noble (~500mV) to the corrosion potential of uncoated AZ91.

Improved Corrosion Performance of AA6061 coatings

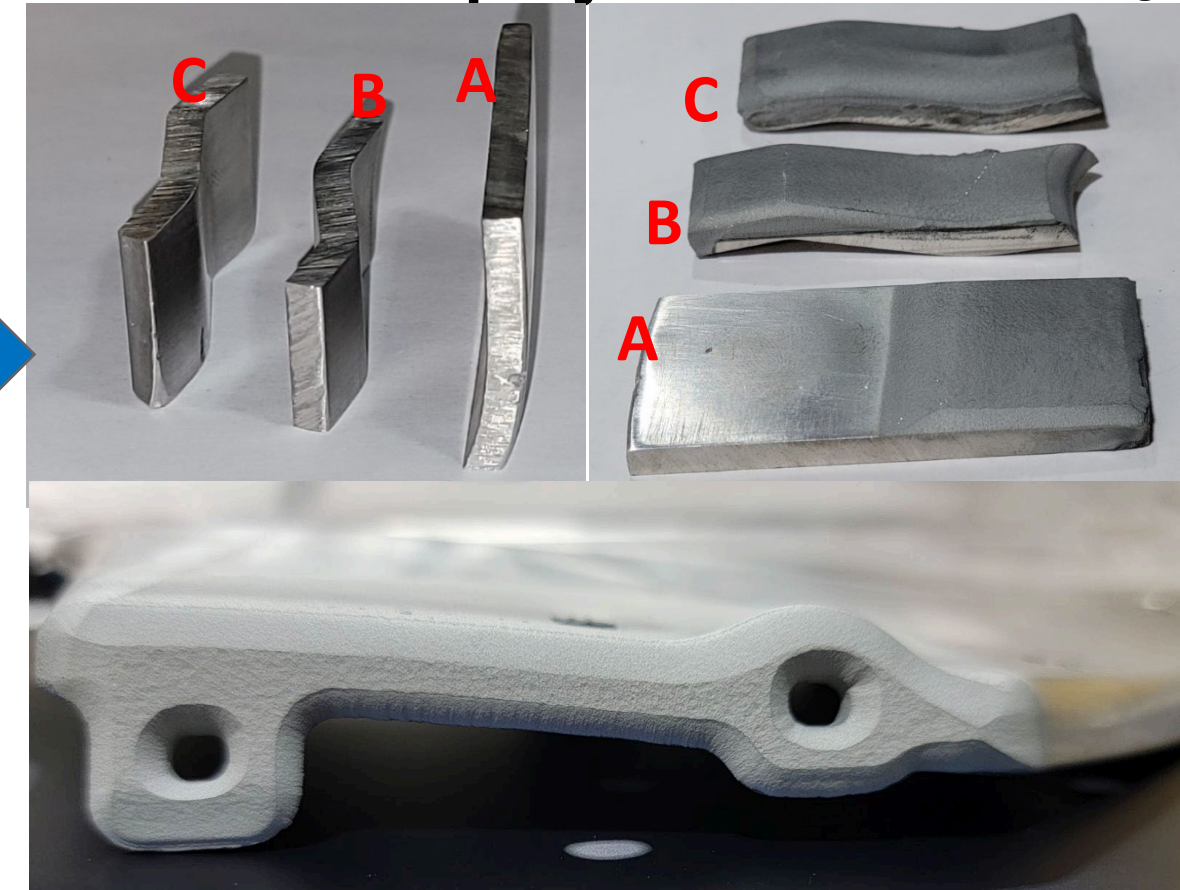
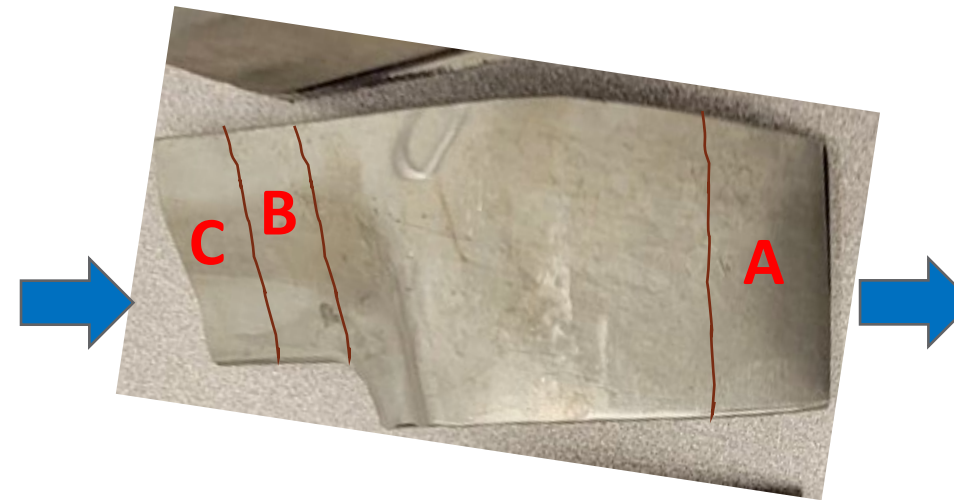
Long-term Corrosion: Hydrogen Collection



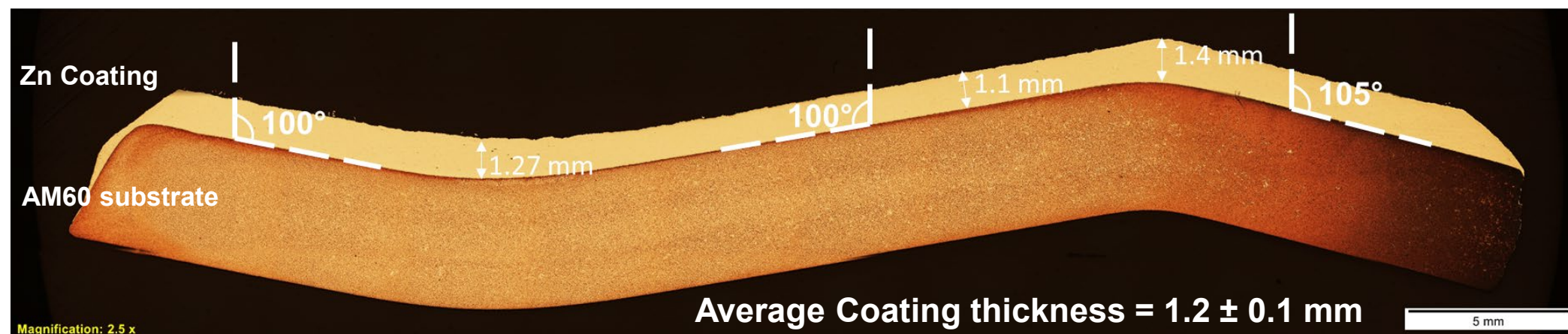
Volume of hydrogen released from uncoated AZ91 is 4500% greater than coated AZ91

Zinc Cold Spray Coating on a Curved AM60 Automotive Component

Before Cold spray After Cold spray

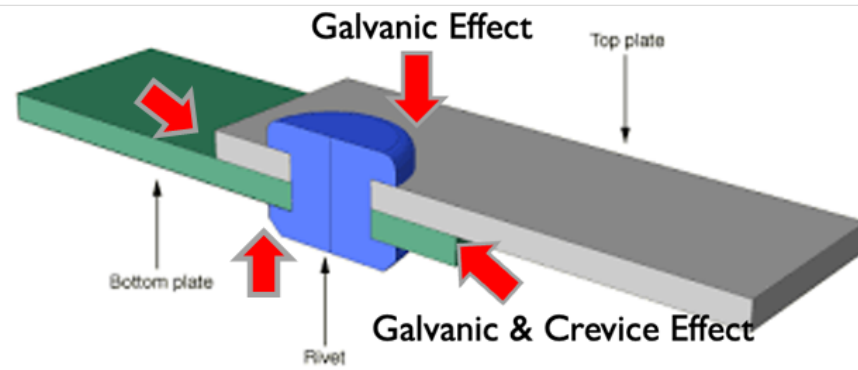


- Curved samples were cut from a larger AM60 automotive part.
- Samples were polished to 600grit finish on the surface to be coated.
- Coating was performed using a straight nozzle path.



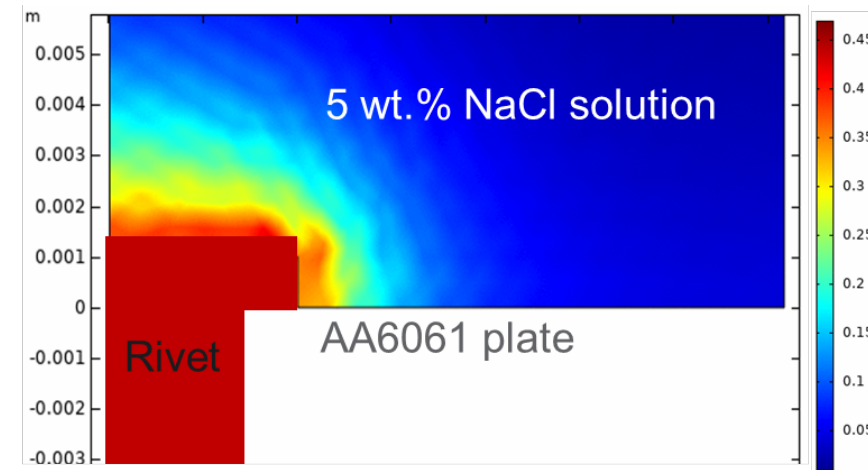
Summary

COMSOL Modeling

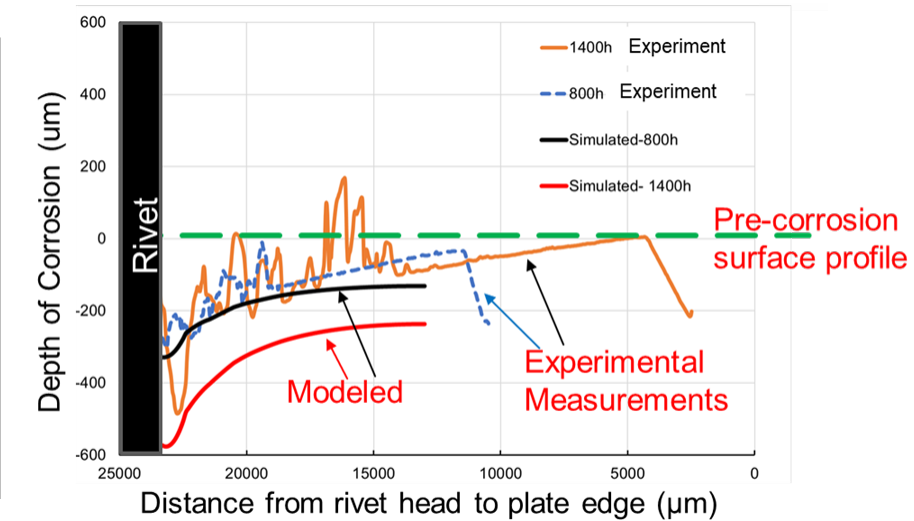


+

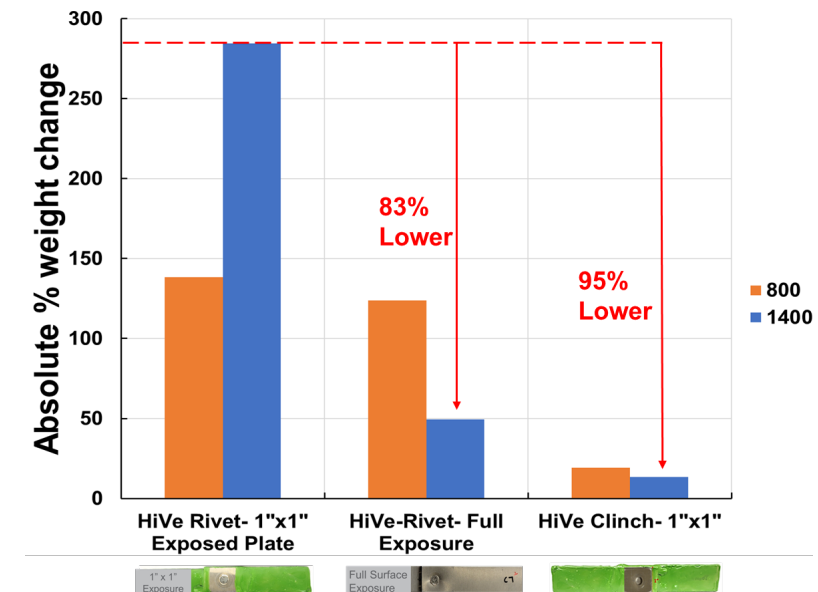
Macroscopic Experiments



Long Term Corrosion Modeling



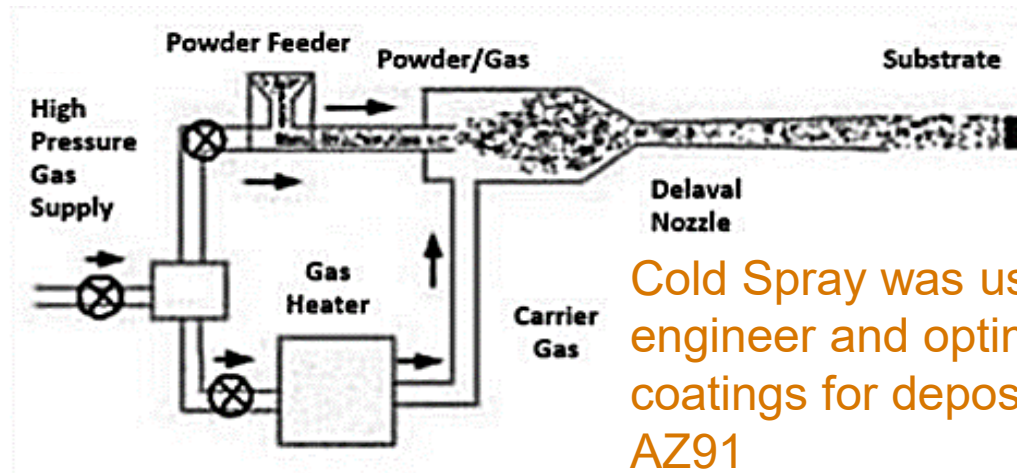
Modeling – Simulation Correlation



Decrease Corrosion Rate in joints

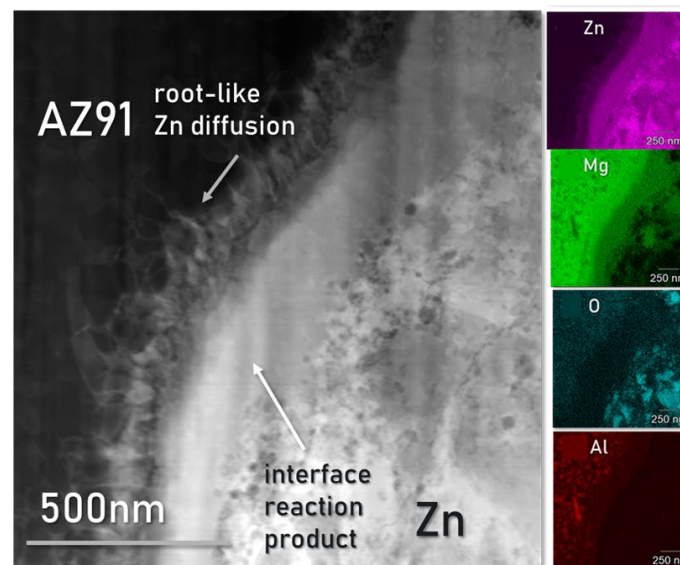
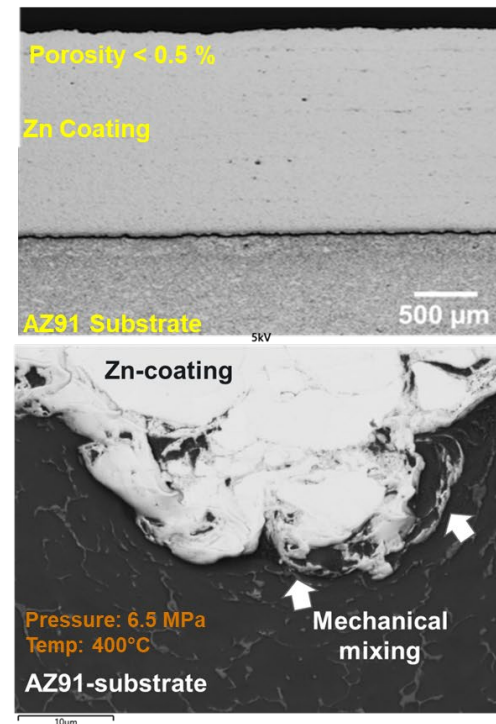
Summary

High Pressure cold spray system Particle velocities > 600m/s



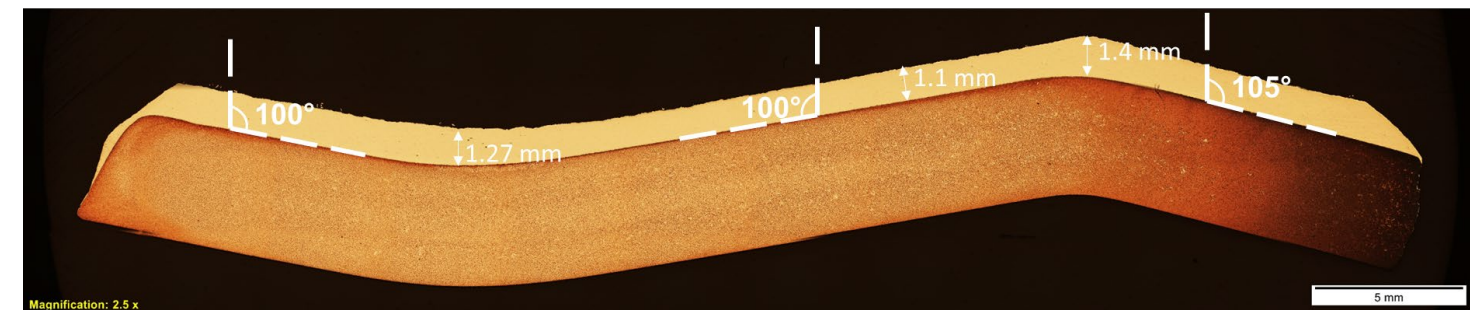
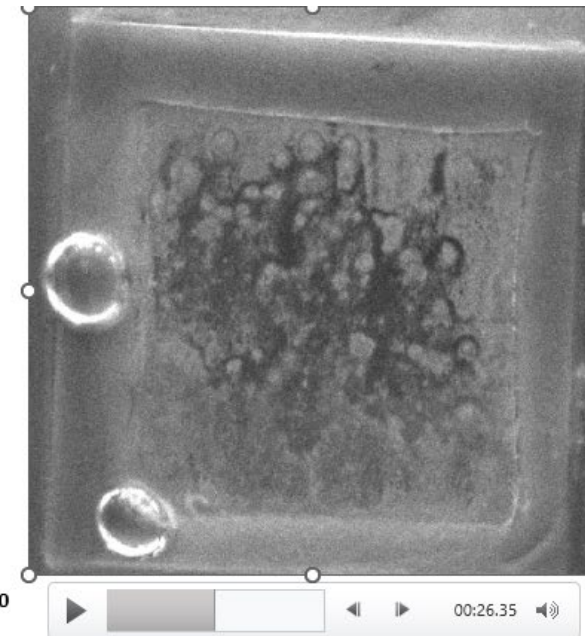
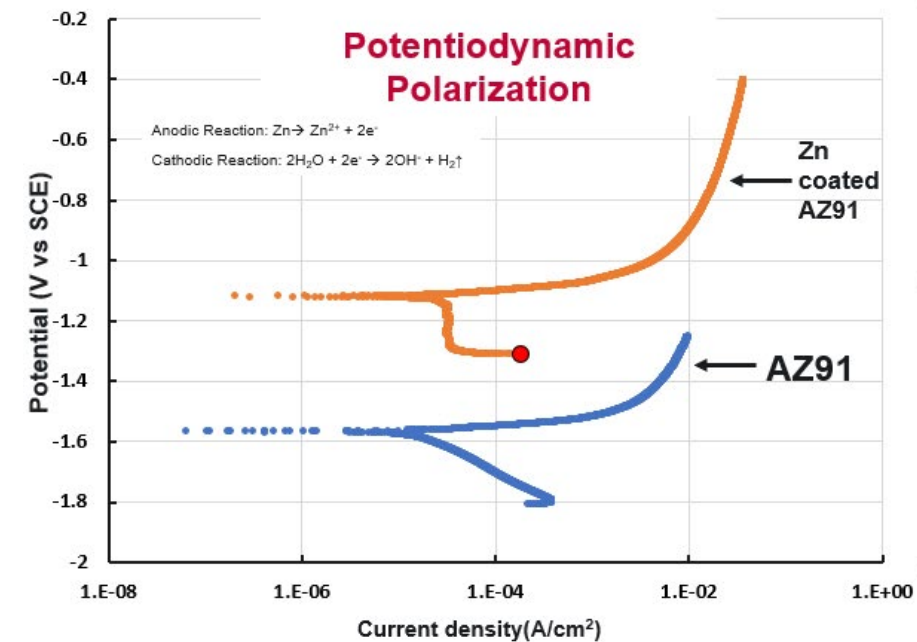
Cold Spray was used to engineer and optimize Zn coatings for deposition on AZ91

Zn- 3.5 MPa and 400°C



Coatings demonstrated low porosity, good deposition and metallurgical bonding

Coatings demonstrated excellent corrosion performance compared to AZ91



Zn coatings can be viable for surface protection of Auto Parts

Thank you