Phase Field Modeling of Corrosion for Next-Generation Aluminum-Magnesium Vehicle Joints

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Overview

Timeline:

- Project start date: Oct 2018
- Project end date: Dec 2021
- Percent complete: 10%

Budget:

- Total project funding
  - DOE Share $1.5M
  - Cost share: $400k
- Funding for FY 2018-19
  - DOE Share: $499k
  - Cost share: $130k

Barriers & Technical Targets:

- Multi-Material Systems Enablers
  - High-Volume Joining (Fusion)
  - Predictive Modeling
- Magnesium
  - Galvanic Corrosion Protection

Partners:

- WPI – Project Lead
- Magna Services of America – challenge problem relevance
- Pacific Northwest National Laboratory – welding, modeling
- Oak Ridge National Laboratory – characterization

Relevance

- **Objective:** Develop and validate a phase field model of corrosion and mechanical failure in aluminum-magnesium alloy joints
  - Predict strength of corroded joints within 10% of measured performance
- **Challenge Problem:** FCA-Magna ultra-light door welds
  - 6022 Al outer, ZEK100 Mg inner
  - Model based on friction stir welded (FSW) hem welds 6022 Al–ZEK100 Mg
  - Validate model using FSW beam welds: 7xxx Al beam–ZEK100 Mg inner
- **Bigger picture goal:** <u>Remove a key barrier to Al-Mg structures</u>
  - Magnesium: stiffness/weight, strength/weight
  - Aluminum: paintability, energy dissipation, corrosion resistance
  - Corrosion/mech model → robust welds → performance needs at low cost
- **Weight reduction potential:**
  - Doors: Al 40% mass reduction, Al-Mg 50% vs. steel baseline
  - Other closures are similar
  - Roof, bumper: similar weight – plus safety and performance benefits
- **Energy savings benefit:**
  - Ultra-light closures → marginal vehicles meet small engine weight targets

Challenge Problem: Ultra-Light Door

Aluminum door: 40% lighter than steel baseline

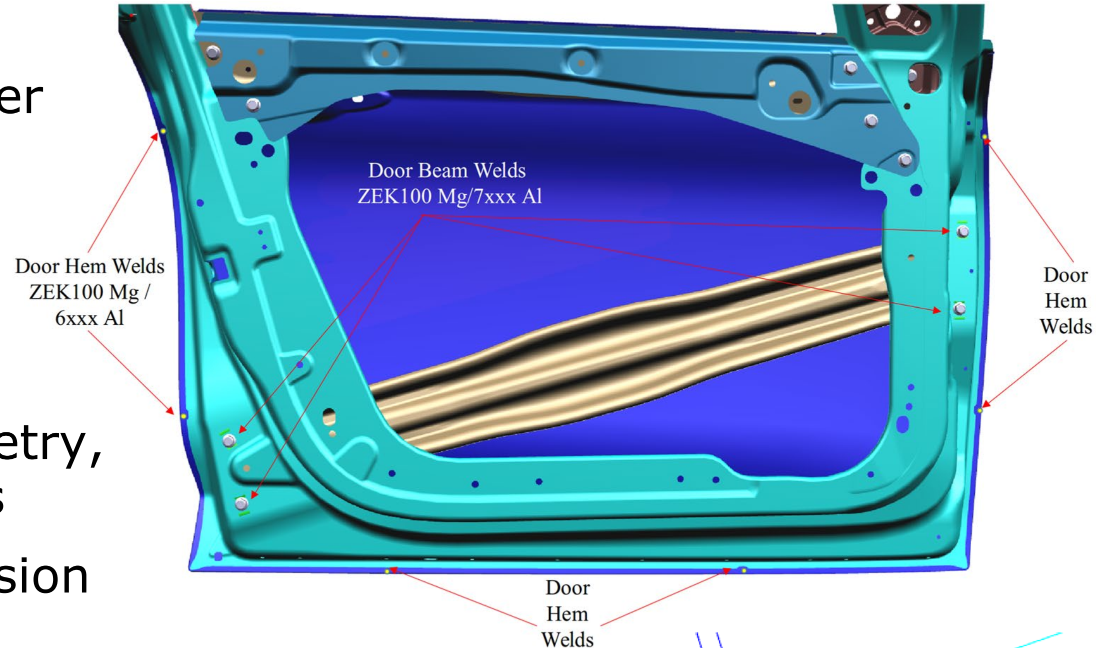
<u>Al-Mg door: 50% lighter</u>

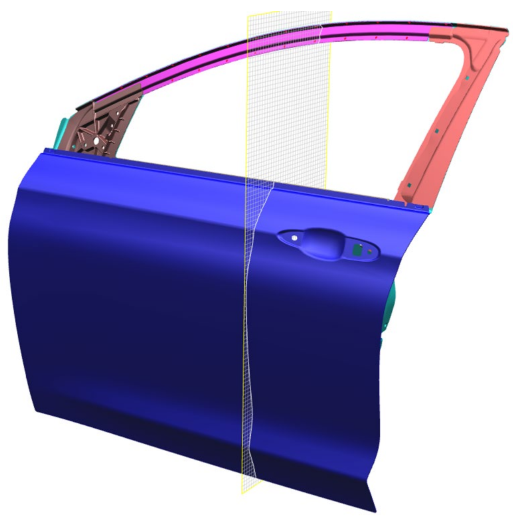
Can FSW joints meet corrosion/strength needs?

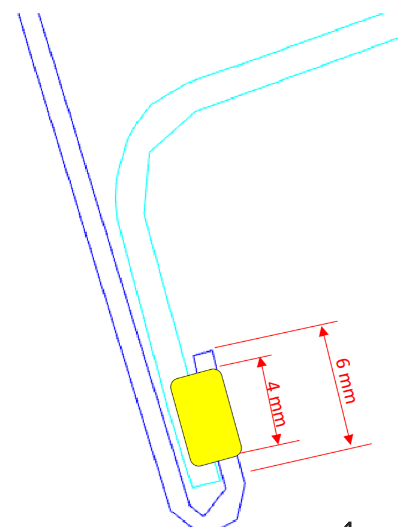
Start with hem weld geometry, alloys, corrosion conditions

- Use/model cyclic corrosion test (CCT) protocols
- Understand corrosion initiation
- No coating – simpler model, worst-case

Validate with beam weld geometry, alloys

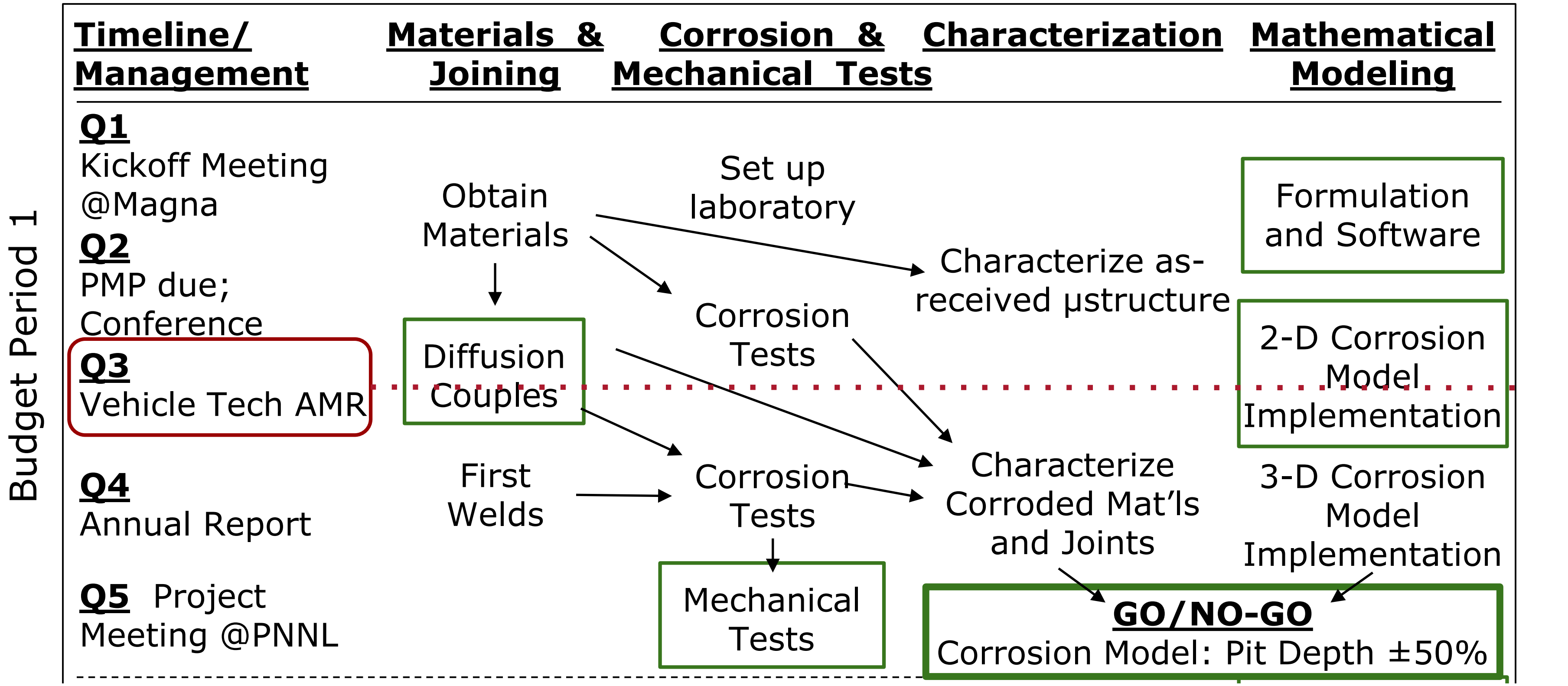




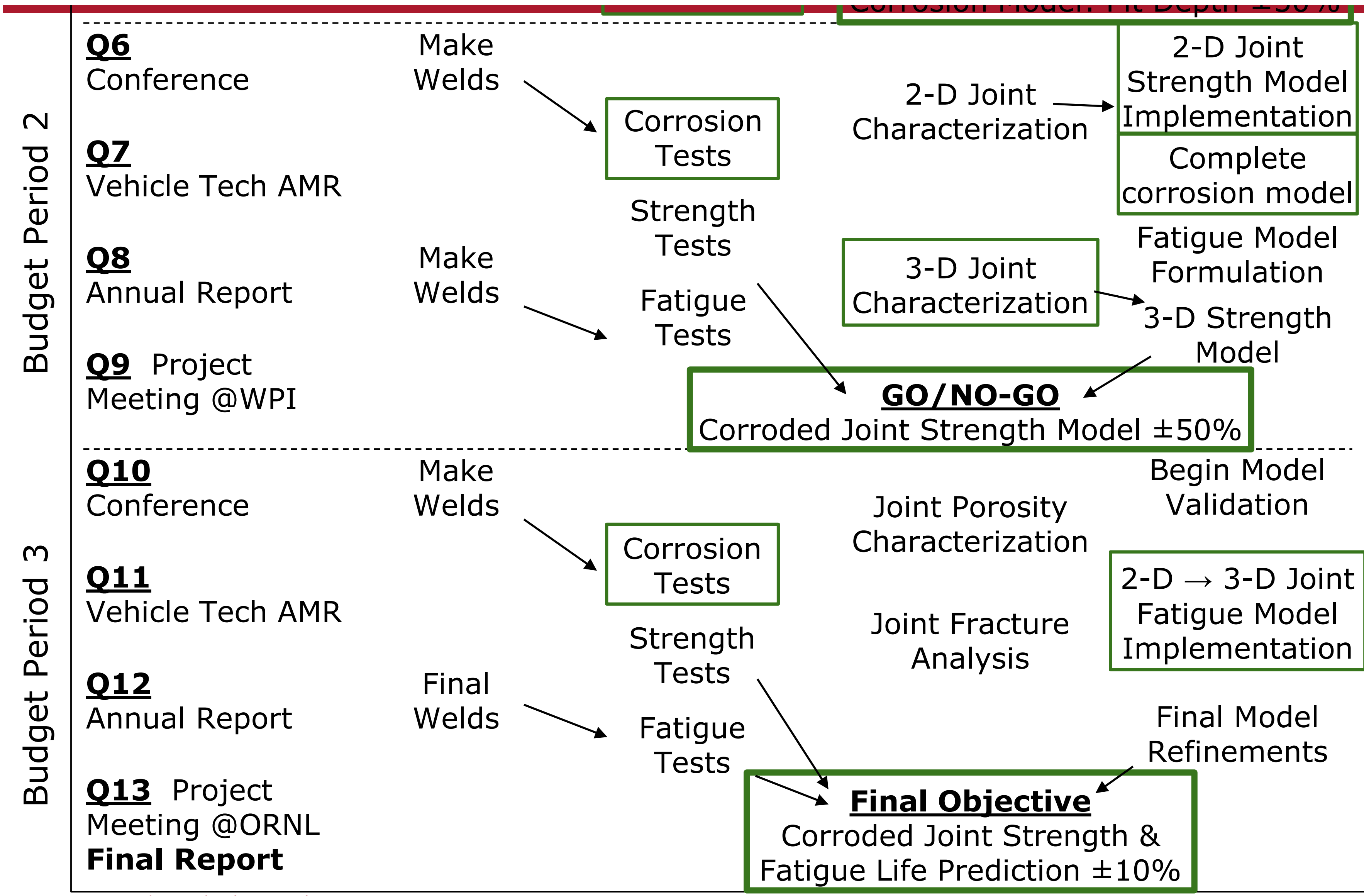


Milestones

Tasks, activities, material/information flow; milestones in green boxes



Milestones (cont’d)



Approach

Validated modeling: corrosion ↔ mechanical failure in Mg-Al FSW

- Close coupling with experiments
- Develop understanding → confidence in deployment
- Use findings to improve corrosion/failure performance of welds
- Assume weak (one-way) coupling corrosion → mechanical failure

Multi-scale model: can't model 10 μm grains in 3-5 mm weld in detail

- Microstructure as initial condition – this is not a process model
- Detailed models of clusters of ~100 grains in FSW joint
- Reduced order models of overall joint

Work closely with PRISMS Center on scalable weakly-coupled phase field → crystal plasticity model

- Build on existing PRISMS-PF pitting/galvanic corrosion model
- Improve phase field solvers → high-throughput 3-D modeling

Work with Magna on options for technology transfer to industry

Phase Field Modeling

Based on chemical free energy

Diffuse interface accurately models interface curvature

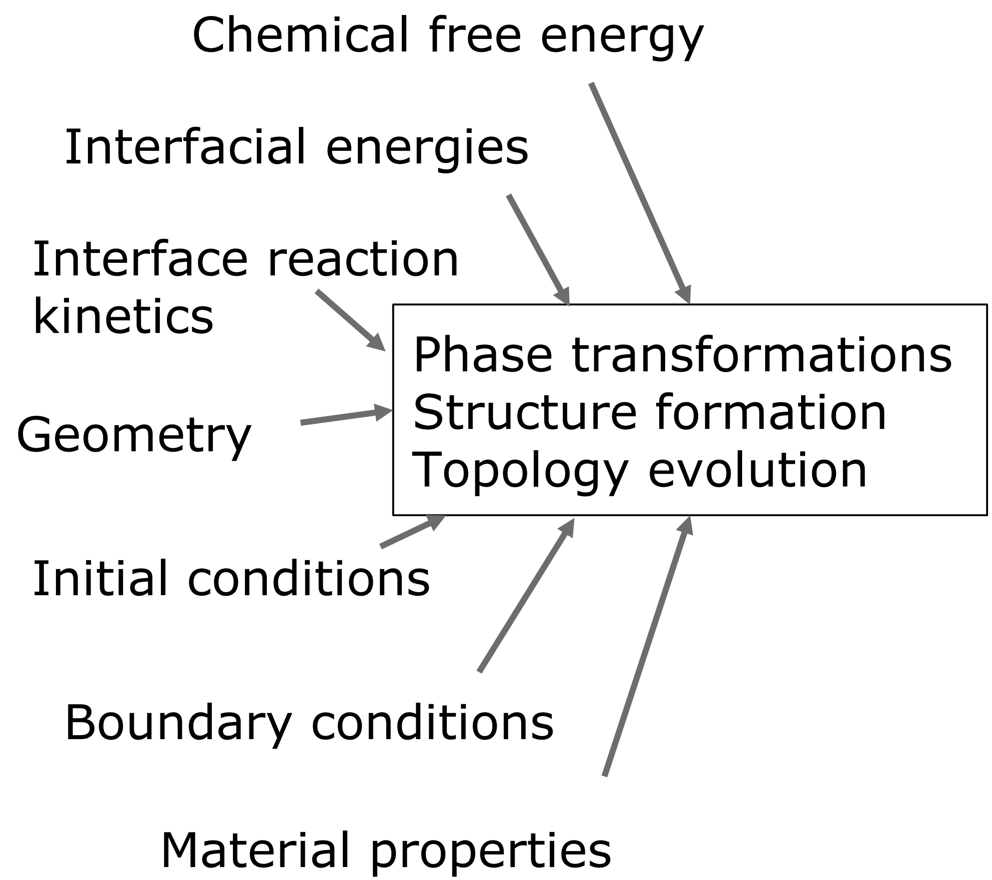
Solve one equation system everywhere

No explicit interface tracking

Interface topology changes handled implicitly

BUT computationally expensive!

- Nonlinear electrochem kinetics

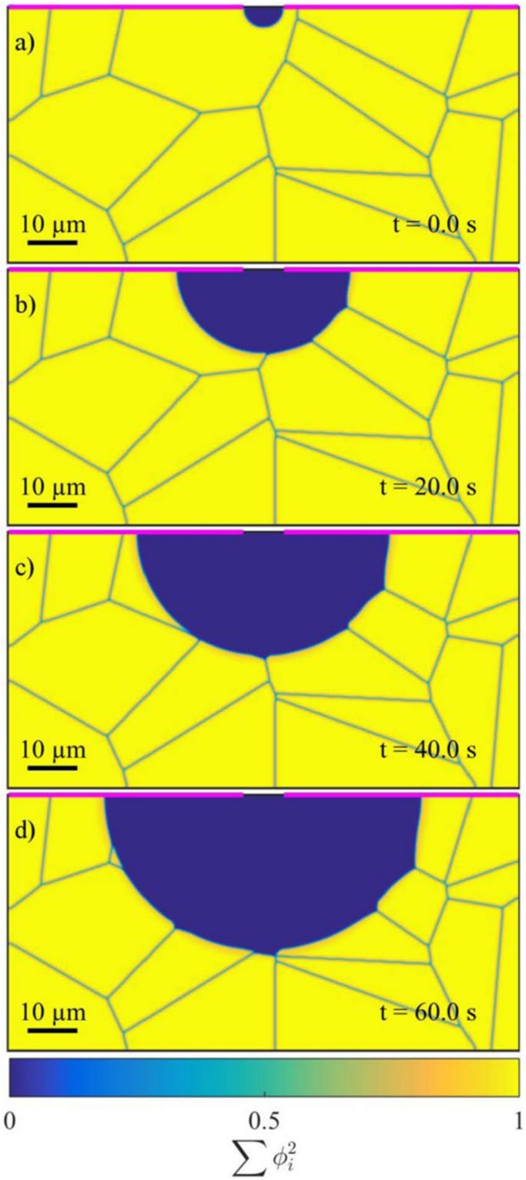


Phase Field Corrosion Modeling

PRISMS Group, U Michigan

- Galvanically driven pit development
- Metal and aqueous phases
- Electrical potential
- Full Bulter-Volmer electro-chemical interface kinetics
- Polycrystalline metal using separate field variables for each grain
- Includes grain boundary motion

Chadwick, Stewart, Enrique, Du, Thornton, *J. Electrochem. Soc.* 165(10) C633 (2018), DOI: [10.1149/2.0701810jes](10.1149/2.0701810jes)



Technical Accomplishments and Progress

- Obtained materials and developed bonding protocol for Mg-Al sheet diffusion bonding experiments
- Began developing Mg-Al sheet friction stir welding protocol, tooling selection
- Ordered cyclic corrosion testing equipment, anticipate installation by AMR meeting
- Began characterizing baseline Mg and Al sheet materials
- Started corrosion phase field model development in collaboration with U Michigan PRISMS Center

Response to Previous Year Reviewers' Comments

Not reviewed last year – not applicable

Collaboration and Coordination with Other Institutions

Prime: WPI Materials Science and Engineering

- Project coordination, mathematical modeling, corrosion testing
- Also WPI Math Department, Academic & Research Computing

Subcontractor: Magna Services of America

- Challenge problem relevance, material provider

Subcontractor: Pacific Northwest National Laboratory

- Mg-Al FSW development and coupon fabrication
- Model development consulting

Subcontractor: Oak Ridge National Laboratory

- Advanced characterization: electron microscopy with element and orientation mapping, ion etching → 3-D microstructure; transmission electron microscopy; neutron scattering

University of Michigan PRISMS Center

- PRISMS-PF and PRISMS Plasticity open source software
- Electrochemistry formulation, solvers

Remaining Challenges and Barriers

Assumption of weak/one-way corrosion → mechanics coupling

FSW specific to this challenge problem

- Must go through hard material (6022 Al) into softer (ZEK100 Mg)

Three-dimensional nature of corrosion → mechanical failure

- Requires a computation-intensive model

Proposed Future Research

Test corrosion → mechanics coupling assumption

Develop FSW method for joining 6022 Al into ZEK100 Mg

- Opportunity to tune parameters to minimize intermetallic phase formation

Subject as-received, diffusion-bonded and FSW joints to cyclic corrosion, mechanical failure

- Characterize corroded-failed joints and interpret results

Develop corrosion and mechanics detailed and coarse-grained models

- Capture macrogalvanic corrosion between sections, microgalvanic corrosion between various phases
- Computationally intensive 3-D models

Any proposed future work is subject to change based on funding levels

Summary

New project with goal of addressing a key barrier to Mg-Al structures

- Build OEM confidence in understanding multi-material corrosion and mechanical failure

Mg-Al welded structures can enable weight savings beyond aluminum alone

This model of corrosion and mechanical deformation aims to advance ICME with broader vehicle technology impact