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Solid Phase Processing for Reduced Cost and Improved Efficiency Bipolar Plates

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Project ID# fc321

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PNNL is operated by Battelle for the U.S. Department of Energy

PNNL-SA-153031

Overview

- Schedule, Budget, Barriers, and Team

Timeline

Start date: October 2018

End date: March 2021*

Budget

DOE funding for FY19: $400K

Planned DOE funding for FY 20: $475K

Planned DOE funding for FY 21: $125K*

* Does not include any potential effects to project from COVID-19 stay-at-home orders

Barriers

A) Durability

B) Cost

C) Performance

Team / Collaboration

Prime: Pacific Northwest National Laboratory

Strategic Analysis Inc. — Industry collaborator

TreadStone Technologies, Inc. — Subcontractor and industry collaborator

Arconic (Innovation, engineered.) — Industry collaborator

Collaboration: Team

- Pacific Northwest National Laboratory: Prime
  - Process Trials, Forming Trials, and Characterization / Testing
  - Project Management
- TreadStone Technologies, Inc.: Subcontractor
  - Process Trials (DOTS Process)
  - Characterization Testing
  - Consulting
- Strategic Analysis: Collaborator
  - Assist with Concept Ranking
  - Assist with Cost Analysis
- Arconic
  - Assist with Concept Analsyis
  - Commercialization Input

PNNL provides advanced manufacturing and materials leadership

TreadStone provides corrosion barrier expertise and is a bipolar plates industry stakeholder

Relevance: Background Information

- Bipolar plates for PEM Fuel Cell performance
  - 30% of overall cost as of 2014[1]
  - 80% of the overall weight as of 2014[1]
- Multiple Material Choices
  - Carbon based
  - Metallic
  - Polymer composite
  - Each has advantages and disadvantages
- U.S. Department of Energy has established technical targets to address to improve Bipolar plate perform

[1] *R. Taherian, "Review of Composite and Metallic Bipolar Plates in Proton exchange Membrane Fuel Cell: Material, Fabrication, and Material Selection," Journal of Power Sources, Elsevier, Vol. 265, 2014, Pp. 370-390*

Relevance: Background Information

- Advantages and Disadvantages of Bipolar Plate Material Families

- Graphite Based
  - High corrosion resistance
  - Chemically stable
  - High thermal conductivity
  - Good availability
  - Poor mechanical strength
  - Poor structural durability
  - High weight
- Metallic Based
  - Metals typically have competing electric and corrosion properties
  - Need coatings, typically bi-metallic
  - High strength and structural durability
  - Thin sheet/foil limited availability
  - Can be high cost
  - Easy manufacturability
- Polymer-Composite Based
  - Low cost
  - Low weight
  - High corrosion resistance
  - Poorer electrical properties
  - Lower strength and structural durability
  - Poor manufacturability

Assuming an effective coating process can be developed, an aluminum substrate can address the most significant challenges prohibiting metallic bipolar plates from achieving DOE targets

Relevance: Objective and Impact

- Develop novel bipolar plate design and fabrication technique(s) that addresses barriers and develops processes towards meeting or exceeding 2020 technical targets[2]

Barriers	Project Impact
A. Durability	Improved durability of bipolar plates via reduced areal specific resistance and through plate electrical conductivity resulting in less thermal load which could be beneficial to durability of other components in the fuel cell
B. Cost	< 3 $/kW$_{net}$
C. Performance	- Plate weight ≤ 0.4kg/kW$_{net}$ - Plate H_2 permeation coefficient <1.3 x $10^{-14,f}$ @ 80°C, 3 atm 100% RH; - Corrosion, anode < 1 μA / cm^2 and no active peak; - Corrosion, cathode < 1 μA / cm^2; - Electrical conductivity > 100 S / cm; - Areal specific resistance < 0.01 ohm cm^2; Flexural strength > 25 Mpa - Forming elongation ≥ 40%. - Flexural Strength > 25 Mpa

Project objectives and impacts are directly in-line with HFCP Fuel Cell 2020 Technical Targets.

[2] *Fuel Cell Technologies Office Multi-Year Research, Development and Demonstration Plan, Section 3.4 Fuels, Pp. 22*

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Relevance: Impact-to-Date

Early project results are indicative that aluminum could be a viable material to improve performance and significantly reduce cost of bipolar plates

The reduction in material cost alone (assuming other costs similar) would nearly allow for the DOE cost target to be met

Approach: Unique Manufacturing Processes

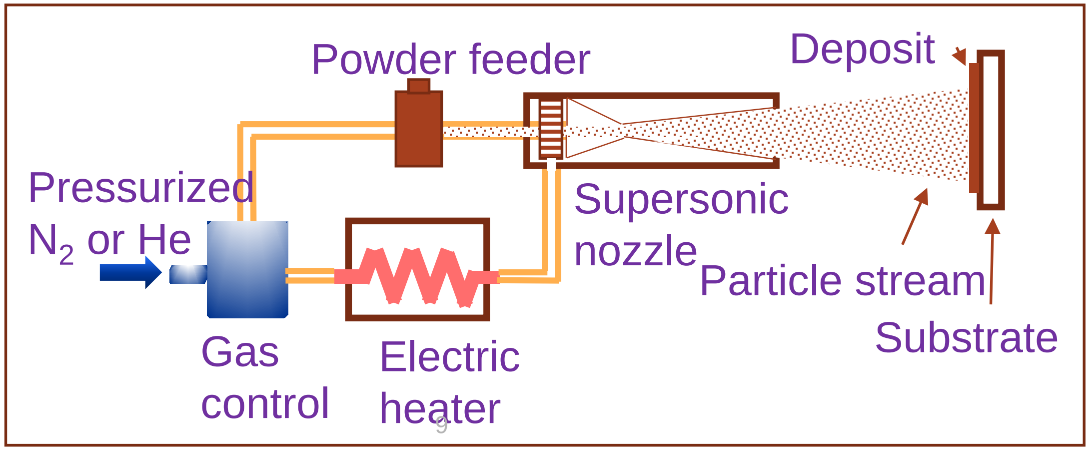
- Multi-Material Metallic
  - Can manage competing technical and cost properties
  - Base material + coating
- Aluminum base material with titanium coating
- Employ alternative manufacturing processes
  - Alternative coating processes are being investigated with prospective to provide fully dense Titanium coating on an aluminum substrate
  - Alternate forming methods are being investigated that potentially be used to reduce manufacturing cost

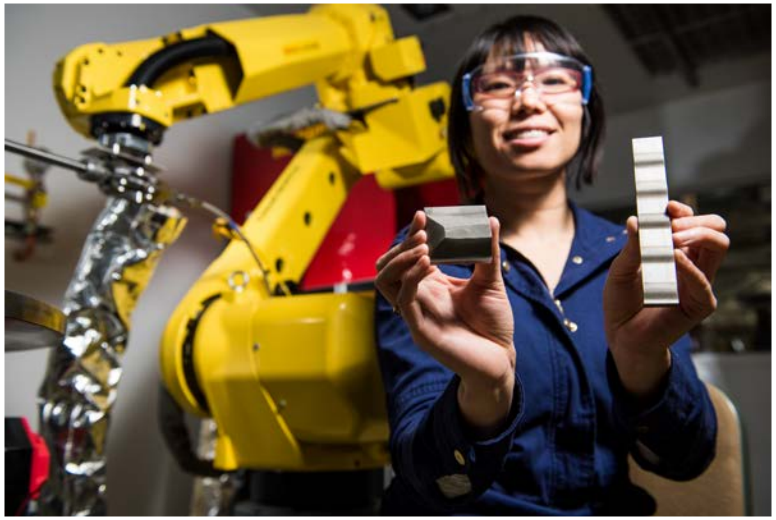
Use of unique manufacturing processes offer potential opportunity to allow an Aluminum substrate to be coated with a Titanium corrosion barrier

Approach: Cold Spray Coating Process

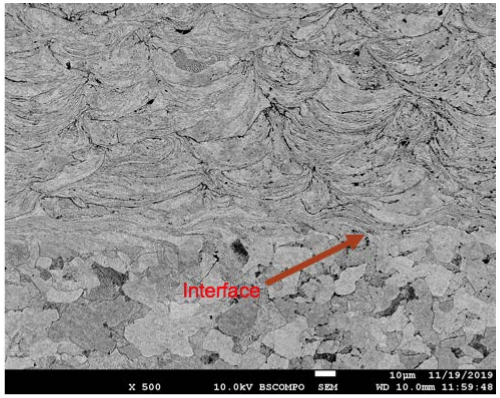
- Solid phase deposition process
- ~20-50µm particles are propelled at Mach 1-4 towards substrate
- Carrier gas: Nitrogen or Helium
- Impact energy causes extreme plastic deformation creates grain refinement and metallurgical bonds
- High density deposits
- Deposition rates up to 8kg/hour per nozzle
- No limit to deposit thickness
- Excellent corrosion barrier (no pinhole defects)
- Superior economics vs. traditional coating and additive manufacturing processes
- Readily automated

Cold Spray Process Schematic





Background: PNNL's high velocity cold spray system
Foreground: PNNL researcher with cold sprayed coupons.



Example Cold Spray Deposit

Aluminum 6061 substrate coated with commercially pure nickel using PNNL cold spray equipment

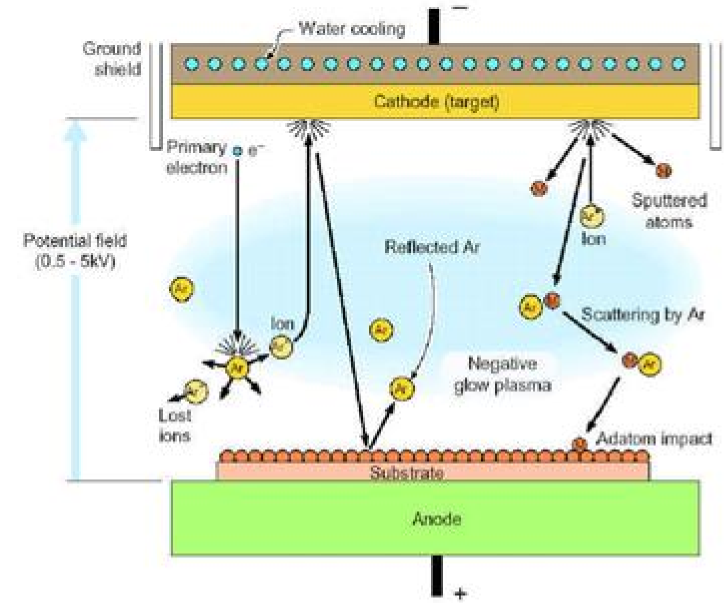
Approach: Diffusion Bonding Process

- Solid phase joining process
- Process parameters
  - Time
  - Temperature
  - Pressure
  - Non-Standard Atmosphere
    - ✓ Inert Gas
    - ✓ Vacuum
- Simple process
- Potential to fabricate multiple plates per run
- Potential for roll-to-roll process

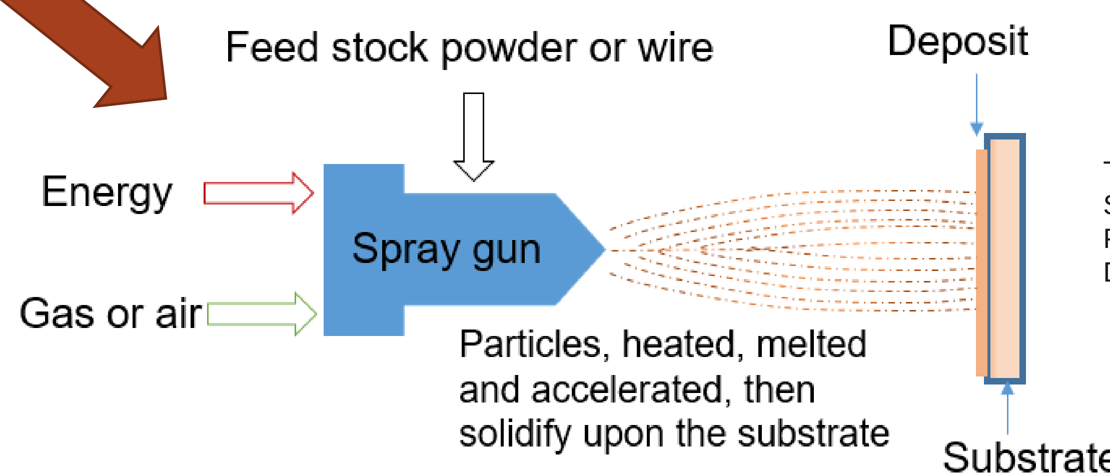
Image courtesy of the VPE, Inc.
http://www.vpei.com/diffusion-bonding/#process

Approach: DOTS™ Process

- Proprietary Treadstone Technologies, Inc. process
- Two step fusion based process
  - Step 1: Plasma Vapor Deposition (PVD)
    - ✓ Magnetron Sputtering
  - Step 2: Thermal Spray
    - ✓ Inert Atmosphere
    - ✓ Vacuum
- PVD of Titanium
- Thermal Spray of highly conductive particles
  - Gold
  - Platinum



Physical Vapor Deposition Diagram
Image Courtesy of Treadstone Technologies, Inc.



Thermal Spray Process Diagram

Approach: Major Task Breakdown

#	Name	Task Description	Status
1	1. Parametric Cost Analysis and Concept Scoring Tool	Create a tool to estimate quantify cost/value of bipolar plate fabrication concepts based on weighted factors to down-select concepts to be investigate	Complete
2	2. Process Development	Process development to be performed with flat sheet or foil for down-selected processes	In Progress
3	3. Process Characterization	Testing of coupons for various down-selected processes. Testing per 2020 DOE target requirements.	In Progress
4	4. Subscale Forming Study	Design and fabricate die for sub-scale formed coupons. Perform forming tests with coupons fabricated from down-selected processes.	In Progress
5	5. Subscale Materials Characterization	Testing of subscale formed coupons towards 2020 DOE Technical targets. Understand the process parameter relationships vs. the subscale forming study task. Down-select process for full scale forming study.	Not Started
6	6. Full Scale Forming Study	Design and fabricate die for sub-scale formed coupons (~300 cm^2) using down selected manufacturing process.	Not started
7	7. Full Scale Materials Characterization	Testing of full-scale formed coupons towards 2020 DOE Technical targets.	Not Started
8	8. Final Report and Publication	Provide final report to FCTO and submit two journal articles.	Not Started

Approach: Milestones

#	Milestone Description	End Date	Type
1	Selection of Fabrication Concepts: FCTO Project Manager Approval of the Tool and Selection of Fabrication Concepts	1/31/2018 (Completed)	Quarterly Progress Measure (Regular)
2	Diffusion Bonding of Titanium to Aluminum: 40% Elongation per ASTM E8 of Flat Plate	11/30/2019 (Completed)	Quarterly Progress Measure (Regular)
3	Completion of Sub-Scale Forming Study: Fabricated subscale plates are provided to the mechanical and environmental test lab at PNNL	2/31/2020* (In Progress)	Annual Milestone (Regular)
4	Technical Basis Established for Achieving Technical Targets for Bipolar plates: Forming elongation ≥ 32% per ASTM E8 (80% of the 2020 target) at temperatures and strain rates representative of the forming processes. Fabricated coupons will also demonstrate electrical conductivity > 100 S/cm	6/30/2020 (Completed)	Quarterly Progress Measure (Stretch)
5	Completion of Full Scale Forming Study: Fabricated full scale plates are provide to the mechanical and environmental test lab	10/30/2020*	Quarterly Progress Measure (Regular)
6	Bipolar Plates Targets Achieved: Test data and analysis reported showing all 2020 technical targets, except cost, are met.	12/31/2020*	Quarterly Progress Measure (Regular)
7	Business/Economic Analysis: Final Report Submitted to FCTO that includes analysis supporting compliance with the 2020 technical targets, including cost.	3/31/2021*	Annual Milestone (Regular)

* Does not include any potential effects to project from COVID-19

Approach: Project Flow Chart

- Aluminum Substrate, Titanium Coating
- 3 Coating Processes
  - Cold Spray
  - Diffusion Bonding
  - TreadStone DOTS Process
- Elevated Temperature Forming
  - Superplastic Forming
  - Quick Plastic Forming
  - Coating before, after, or during forming

Selected Concepts

- Perform Process Development
- Subscale Coupon Forming
- Testing to 2020 DOE Technical Targets

- Down-Select Manufacturing Process

- Process Optimization
- Full Scale Coupon Forming
- Testing to 2020 DOE Technical Targets

Accomplishments: Concept Down Select

- Strategic Analysis, Inc. developed tool
- Identify Concepts
  - Design
  - Manufacturing Processes
- Determine Criteria of Importance to Application
- Establish Weighting Factors for Criteria
- Create Rankings
- Determine Individual Scores
  - Relative to current baseline
- Determine Total Score

Note: user inputs are shown in **blue**

		Category 1				Categ			
		Concept 1A		Concept 1B		Concept 2A		Concep	
Selction Criteria	Criteria Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	W
Low Cost	30.0%	1.92	0.58	1.52	0.46	2.45	0.74	1.01	
Light weight	7.5%	3.20	0.24	3.20	0.24	1.00	0.08	3.20	
Low Plate H2 Permeation Coefficient	7.5%	1	0.075	1	0.075	1	0.075	1	
Corrosion resistance	15.0%	1	0.15	1	0.15	1	0.15		
Electrial Conductivity	10.0%	2	0.2	2	0.2	1	0.1		
Low Areal Specific Resistance	15.0%	2	0.3	2	0.3	1	0.15		
Flexural Strength	7.5%	1	0.075	1.5	0.1125	1	0.075		
Forming elongation	7.5%	2	0.15	2	0.15	2	0.15		
	Total Score	1.77		1.68		1.51			
1.00	Rank	5		6		9			

Tool created to rank concepts relative to HFCP Technical Targets and leveraged work previously performed by Strategic Analysis, Inc.

Accomplishments: Materials Selection

- Many potential alloys

Selection Criteria

- Criteria of Highest Importance
  - Electrical conductivity
  - Formability
  - Availability in thin sheet, foil, and powder form (titanium)
  - Cost (large quantity)
  - Corrosion (titanium)
- Criteria of Less Importance
  - Strength

Selected Materials

- 1100-O Aluminum
- Commercially Pure Titanium (Grade 2) Foil
- Commercial Pure Titanium (Grade 0) Powder

Accomplishments: Creation of Test Matrix / Plan

Improved upon defined DOE Technical targets by:

- Defining specification where none was specified
- Replacing plastic specific specs with relevant metallic specifications
- Defining test details where proprietary specifications are typically used
- Defining which tests must be performed on unformed material vs. formed material

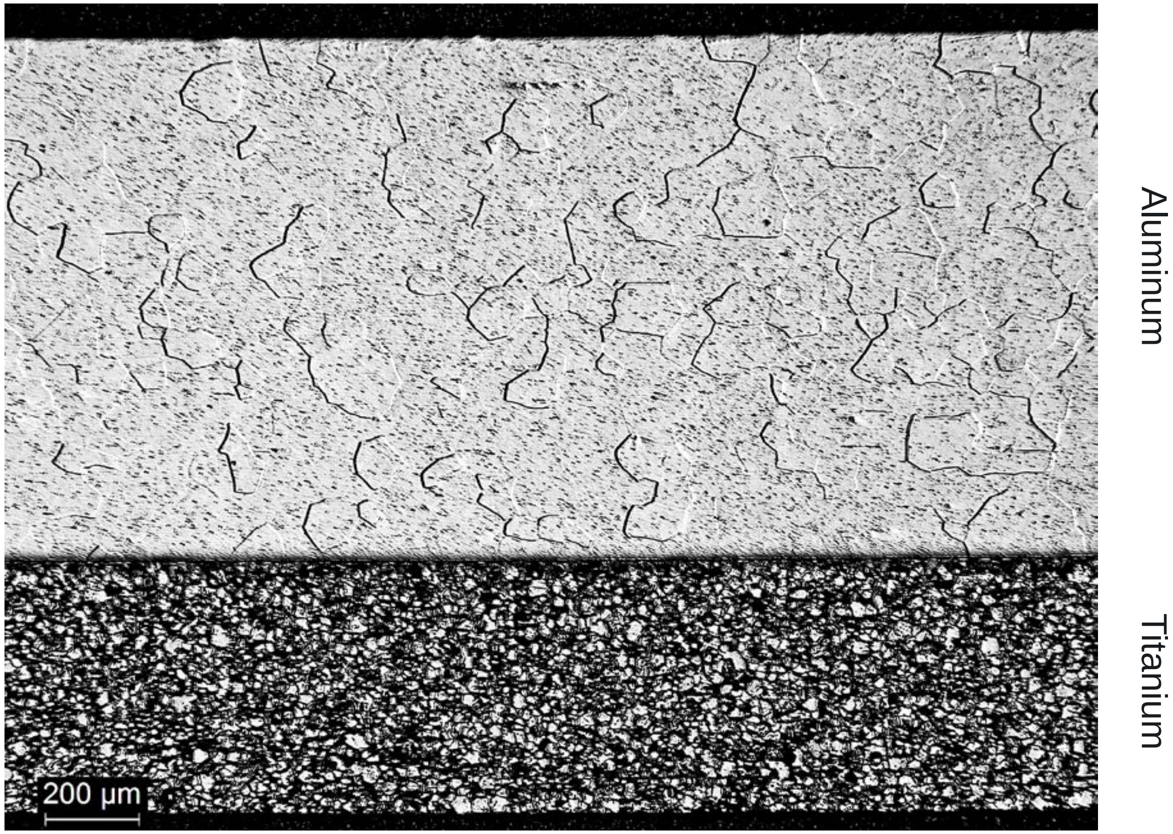
Test or Requirement	Target Metric	Maximum/ Minimum	Test Specification	Specification Notes	Applicability to Sub-Scale Couponm Full Scale or Both	Size of Test Coupon	Applicable to Formed Only, Unformed Part Only, or Both	Number of Coupons to Be Tested
Weight	0.4 kg/kW	Maximum	None	Not Full Size Part. Some assumptions will need to be made to transfer to full size fully functional bipolar plate.	Full Scale	Full scale coupon.	Formed Only	3 Parts
Hydrogen Permation Coefficient	1.3 x 10^-14	Maximum	D1434	Spec Applies to Plastics	Both	1" Disk	Unformed	Test 3 Coupons Cut from Flat Coupon
Anode Corrosion	1 uA / cm^2 w/o Active Peak	Maximum	FCTO Custom Procedure	Only making one half of BPP. Apply to Titanium side only.	Both	1" Disk	Both	Test 3 Coupons Cut from Flat Coupon
Cathode Corrosion	1 uA / cm^2	Maximum	FCTO Custom Procedure	Anode Corrision test applies, more stringent, and concept has same design for anode as cathode.	N/A. We are only making half.	N/A	N/A	N/A
Electrical Conductivity	100 S / cm	Minimum	None	Done per internal OEM Methods	Both	Both	Both	3 Separate Samples. Both formed and unformed.
Area Specific Resistance	.01 ohm cm^2	Maximum	None	Done per internal OEM Methods. Can get from same test as Electrical Conductiviy	Same as EC Test	Same as EC Test	Same as EC Test	Same as EC Test
Flexural Strength	25 Mpa	Minimum	ASTM D790	Spec applies to plastic, but don't see reason it can't be followed for metallic based component.	Both	With thicker material. 1 mm Al + .1 mm	Unformed	3 Coupons of Both Sub-Scale and Full-Scale Sheets
Forming Elongation	40%	Minimum	ASTM E2448	This elevated temperature specification. Elevated temperature forming is anctipated, so this spec chosen over ASTM E8	Process Development	Full size coupon on full-scale components, ASTM sub-scale coupon on sub-scale components	Unformed	Test one coupon at Room Temperature, then every 50 degrees C up to 500 C. Additional coupons (total of 3) will be tested at each temperature, if data indicates there may be variability.
Channel Repeatability	+/- 15 um	Maximum	None	Limited Testing On Sub Scale Size. Emphasis will be on full scale coupons.	Both		Formed	3 Parts, 3 Locations each.
Contact Resistance	20 mOhm/cm^2, 0 to 200 psi	Maximum	None	Perform before and after corrosion testing. Metric provided was provided by Treadstone	Both		Both	3 Parts, 3 Locations each.

Test Plan Detail

Worked with FCTO and industrial collaborators to develop test plan

Accomplishments: Initial Diffusion Bonding Trials

- Materials
  - 0.5 mm Titanium Grade 2
  - 1.0 mm 1100-0 Aluminum
  - 200 mm x 200 mm coupons fabricated
- Performed in a Vacuum
- Started thicker to avoid material handling challenges of foil

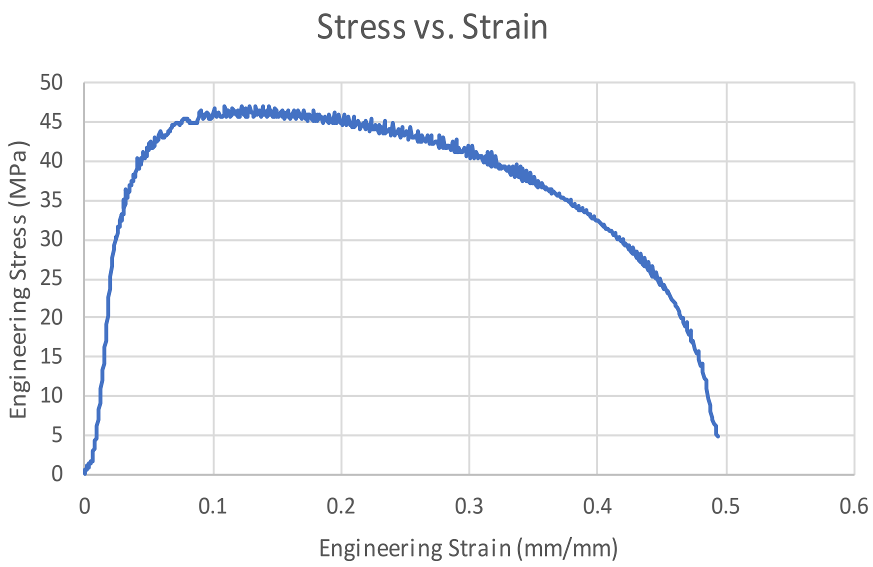


Cross-Section of Titanium to Aluminum Diffusion Bonded Material

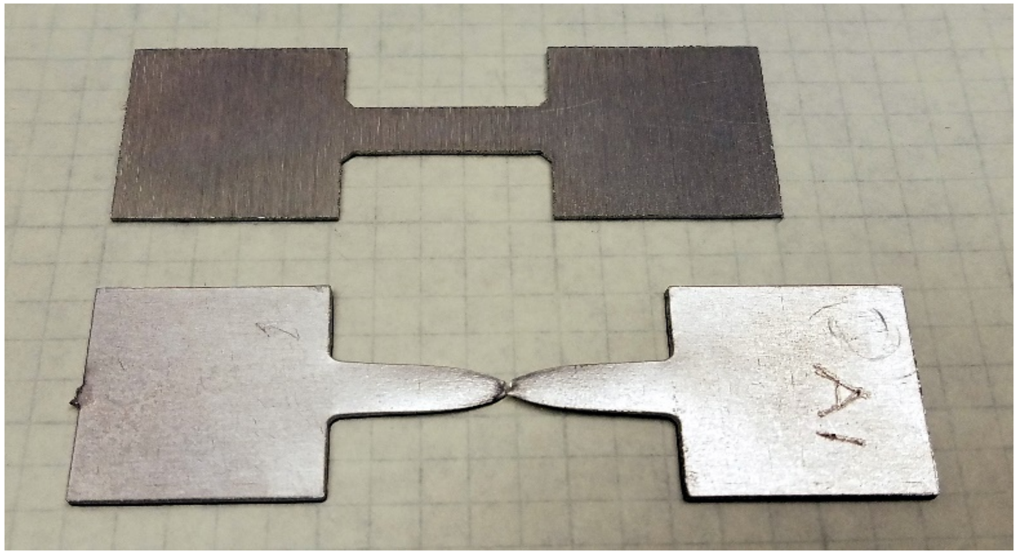
Diffusion Bonding of Titanium Grade 2 to 1100-O Aluminum Demonstrated to be Viable

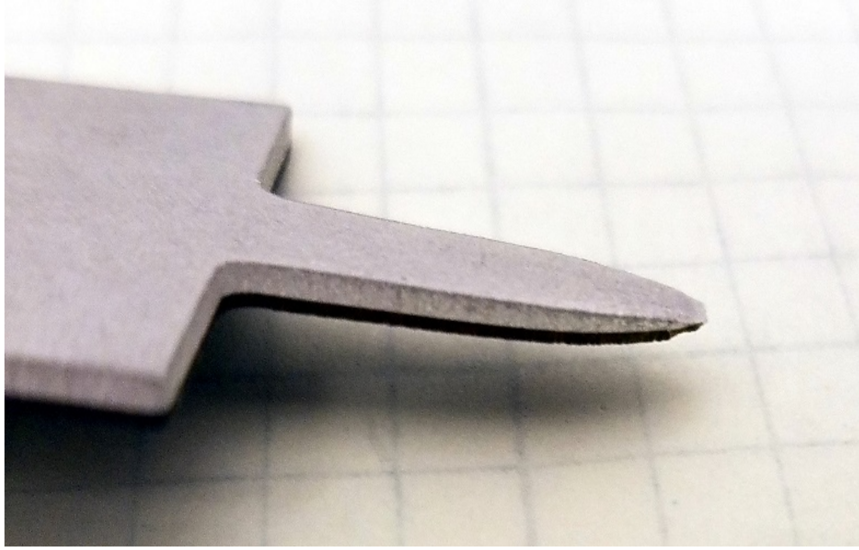
Accomplishments: Initial Diffusion Bonding Testing

- ASTM E2248 Tensile Testing
  - Elevated Temperature
- DOE Target: > 40% Elongation
- Results
  - DB at 450°C: 48%
  - Low cost alloys (non SPF)



DOE Elongation Target Met



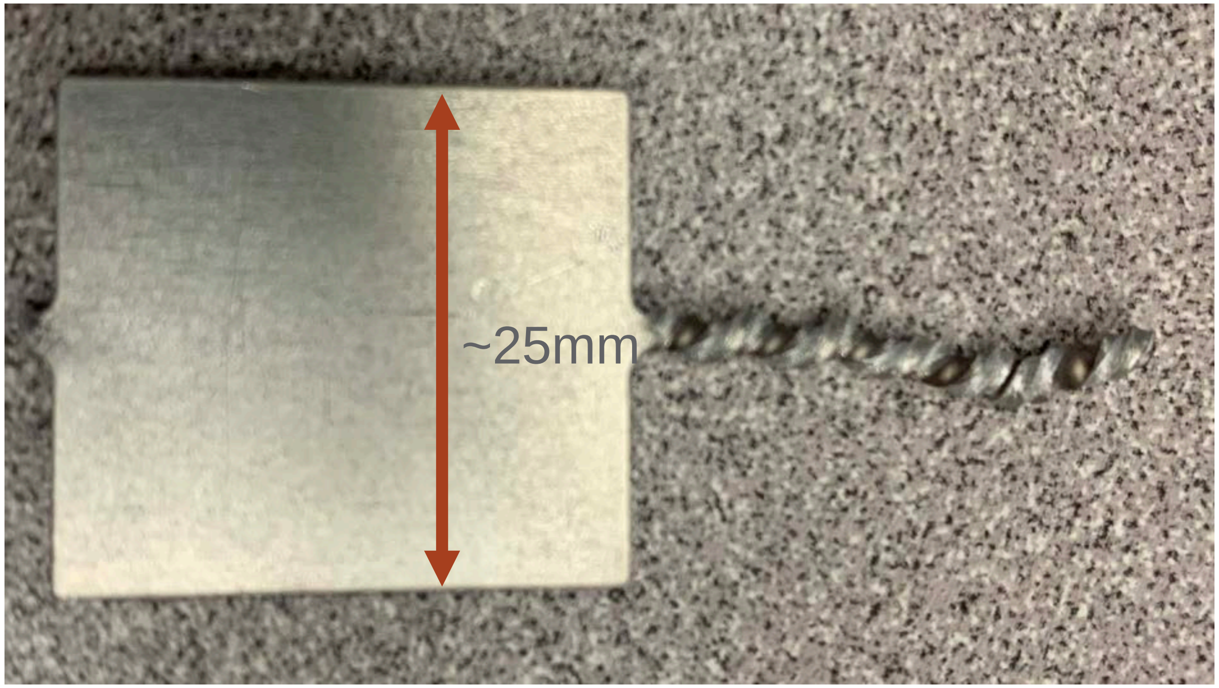


Diffusion Bonded Tensile Coupons Before and After Testing

Accomplishments: Initial Diffusion Bonding Testing

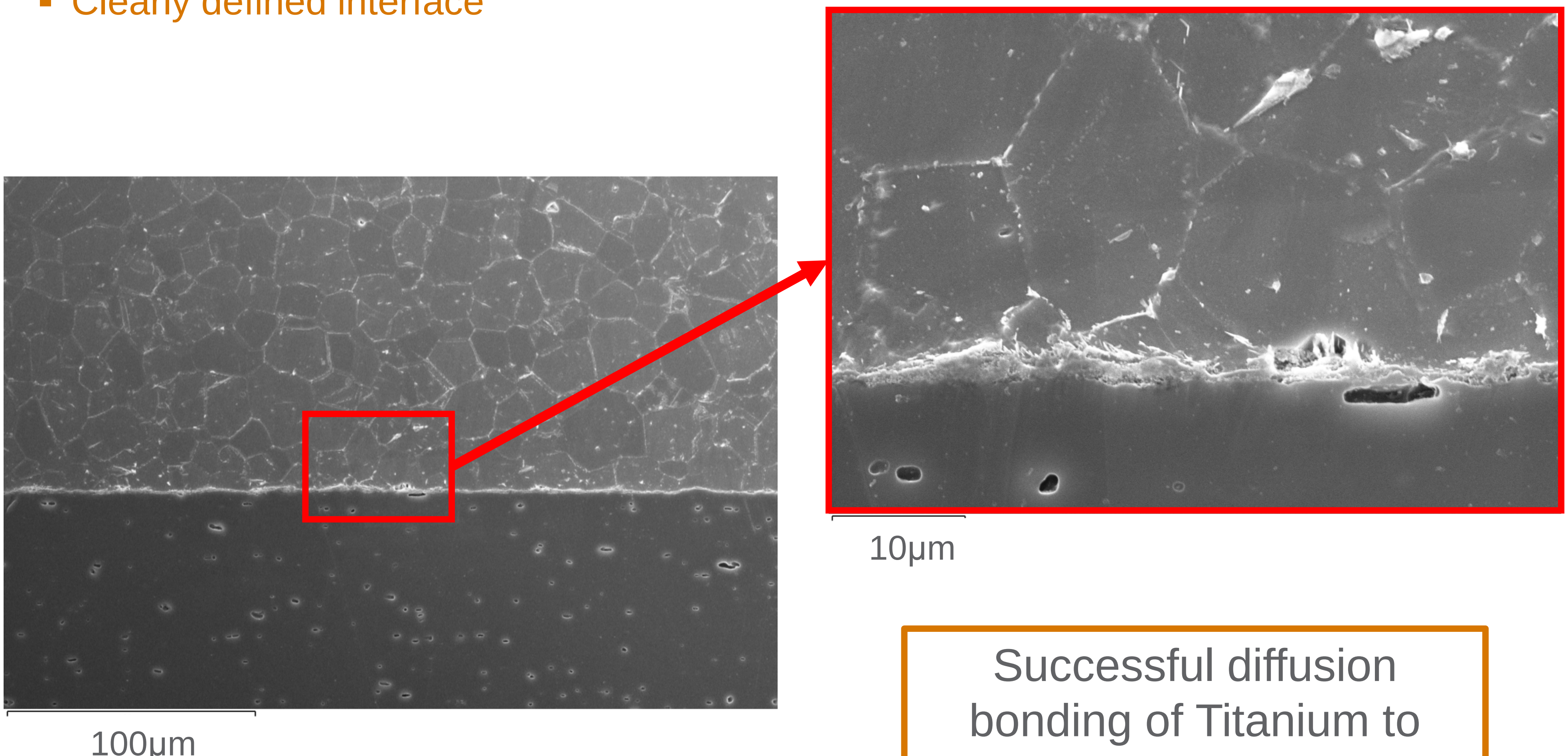
- Mechanical Testing: Twisting of Ribbon of Diffusion Bonded Material
  - No evidence of delamination even after extreme twisting

Indicates high probability of success with elevated temperatures forming



Accomplishments: Initial Diffusion Bonding Trials

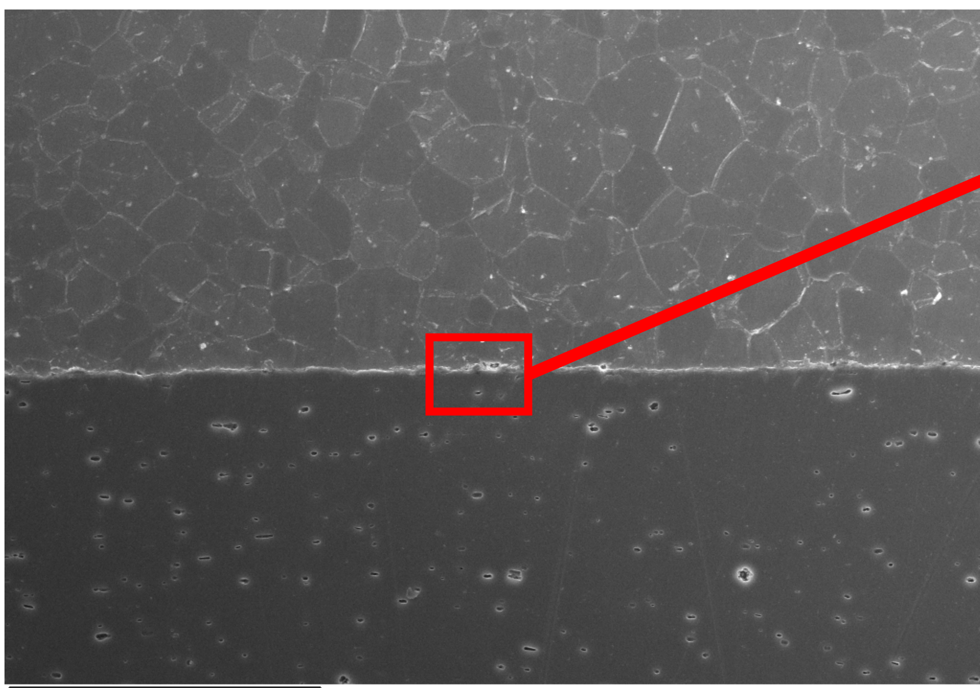
- SEM Analysis
  - Clearly defined interface



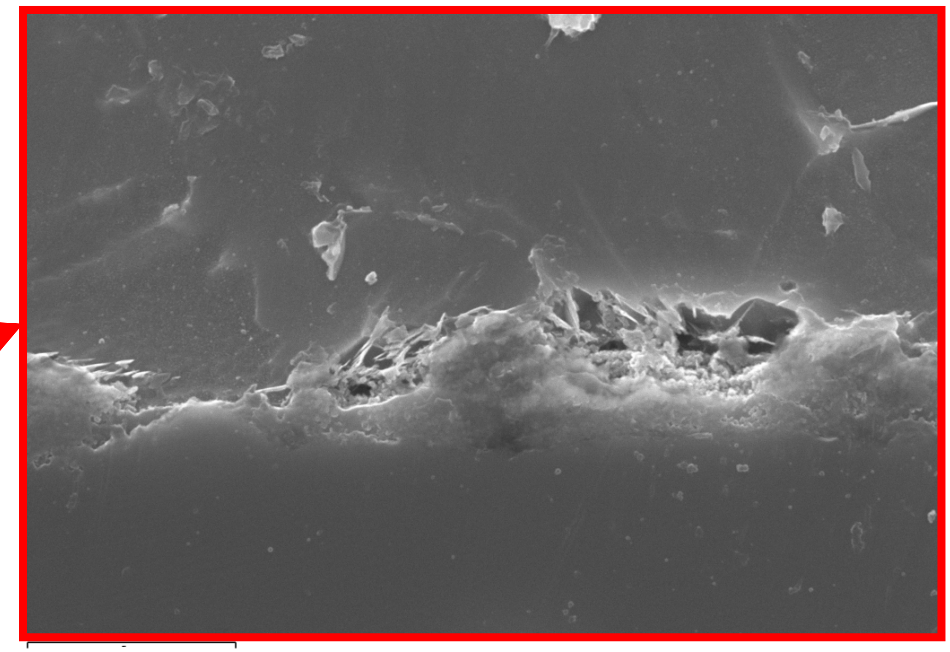
Successful diffusion bonding of Titanium to Aluminum evident

Accomplishments: Initial Diffusion Bonding Trials

- SEM Analysis
  - Potential evidence of minor voids in places



100 µm

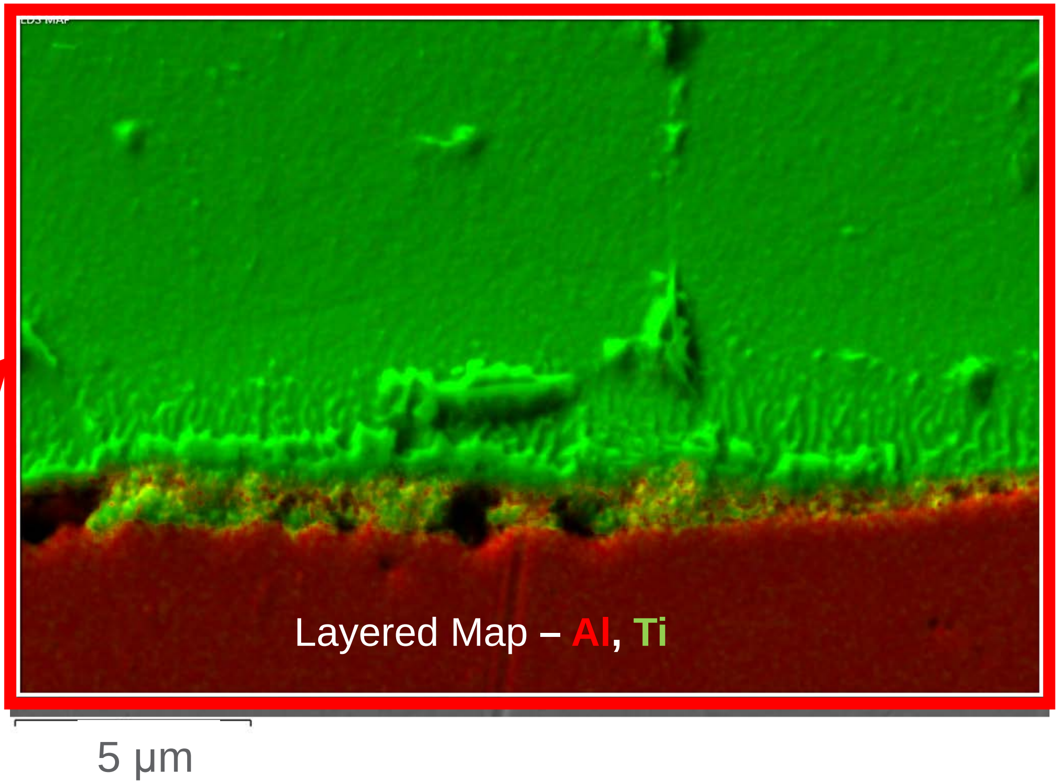


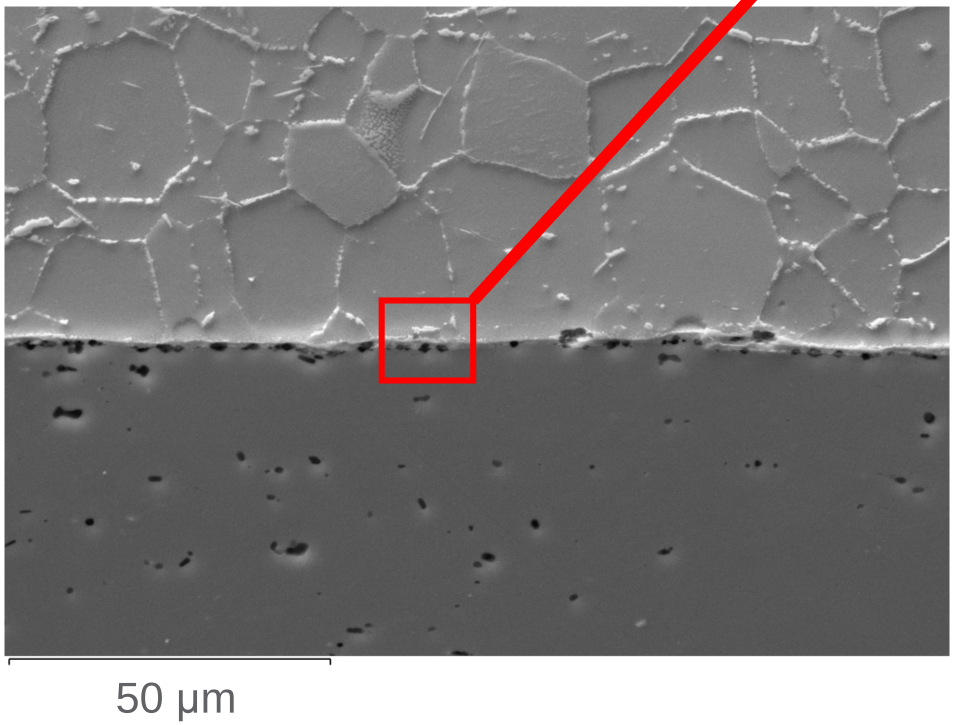
5 µm

Potential Indications Present but not Sufficient to Affect Tensile Testing

Accomplishments: Initial Diffusion Bonding Trials

- Elemental Analysis
  - Aluminum in Red
  - Titanium in Green
  - Minor evidence of intermetallic in places
  - ~1 µm in thickness

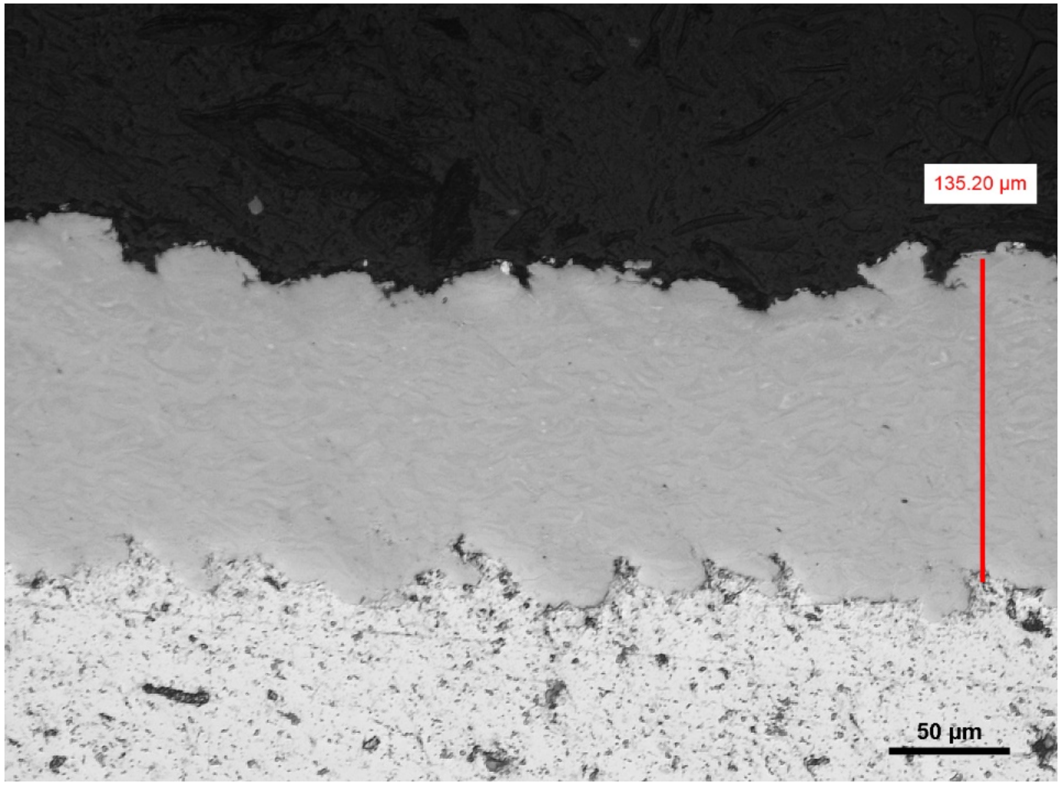




Potential Intermetallic Indications Present but not Sufficient to Affect Tensile Testing

Accomplishments: Initial Cold Spray Trials

- Titanium Grade 2 Powder to 1100-O Aluminum
  - 1 mm thickness
  - 0.25 mm thickness
- Carrier Gas
  - Helium
  - Nitrogen
- Deposit Density > 99% Achieved
- Highly Deformed Substrate
- Microscopy Indicates Acceptable Bonding

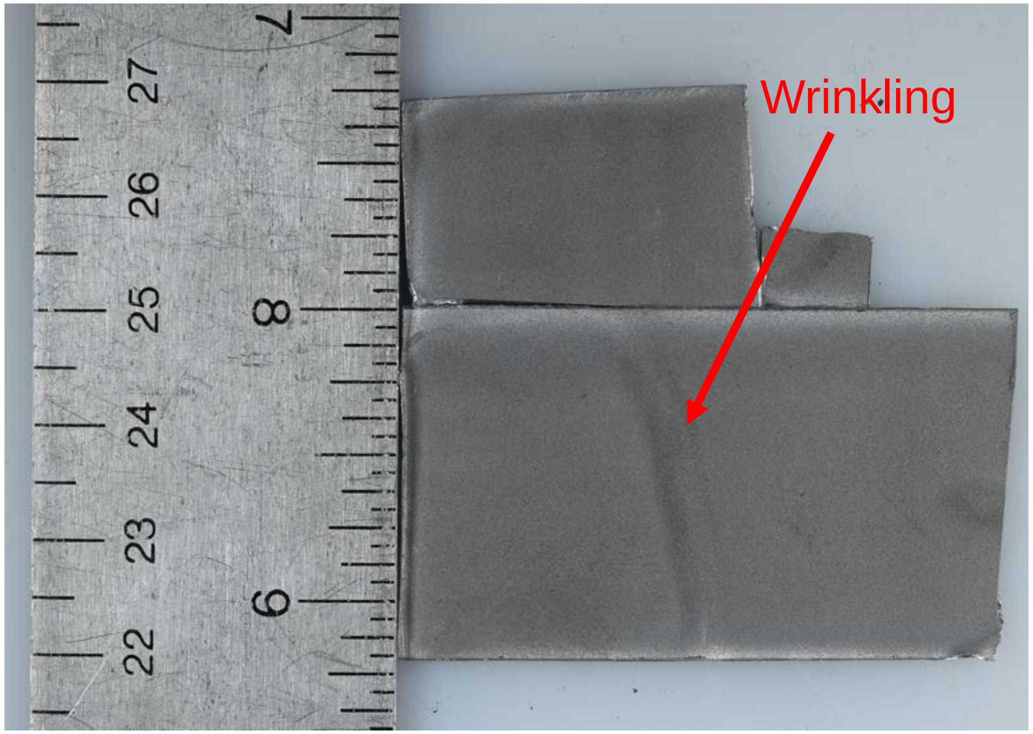


5 Pass Cold Spray Deposit of Ti Grade 2 to 1100-O

Cold Spray of Commercially Pure Titanium to Aluminum 1100-O is Viable

Accomplishments: Initial Cold Spray Trials

- Barriers observed
  - Clogging of cold spray nozzle
  - Deposit thickness achieved is greater than competitive coating processes
  - Wrinkling
    - ✓Not observed on 1.0 mm
    - ✓Observed on 0.25 mm Al

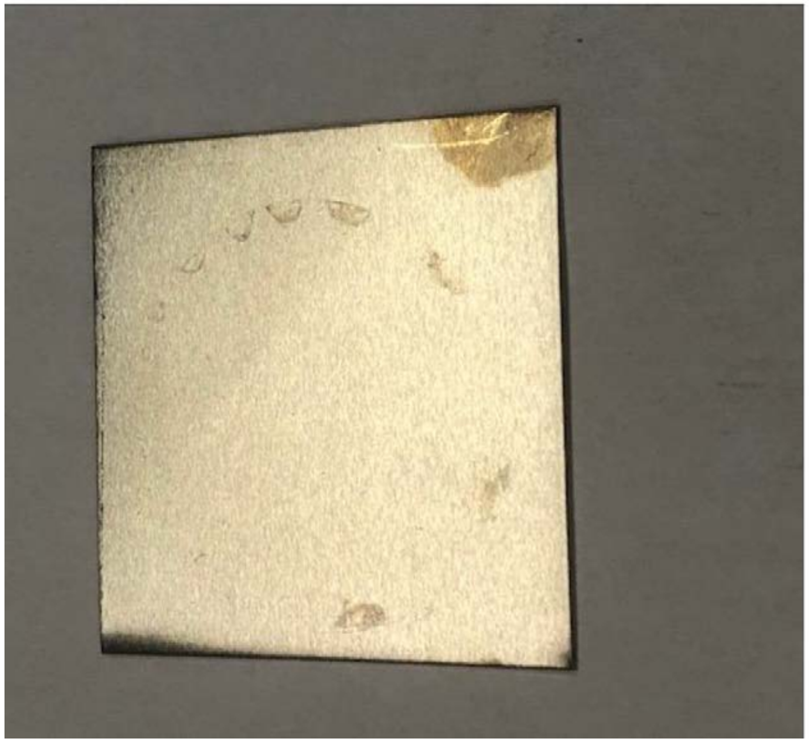


Titanium to Aluminum Cold Spray Coupon Surface

While barriers have been observed, solutions have been identified (see future work)

Accomplishments: DOTS™ Development

- Titanium to Aluminum DOTS process has not previously been developed
- Titanium Grade 2 to 1100-O Aluminum
- 2 Step Process
  - Titanium to Aluminum Physical Vapor Deposition
  - DOTS: Standard process
    - ✓ Thermal Spray
    - ✓ Platinum Tracer
- Initial Process Development in Progress
  - 5 micron thickness
  - Some pores observed
  - Microscopy in progress

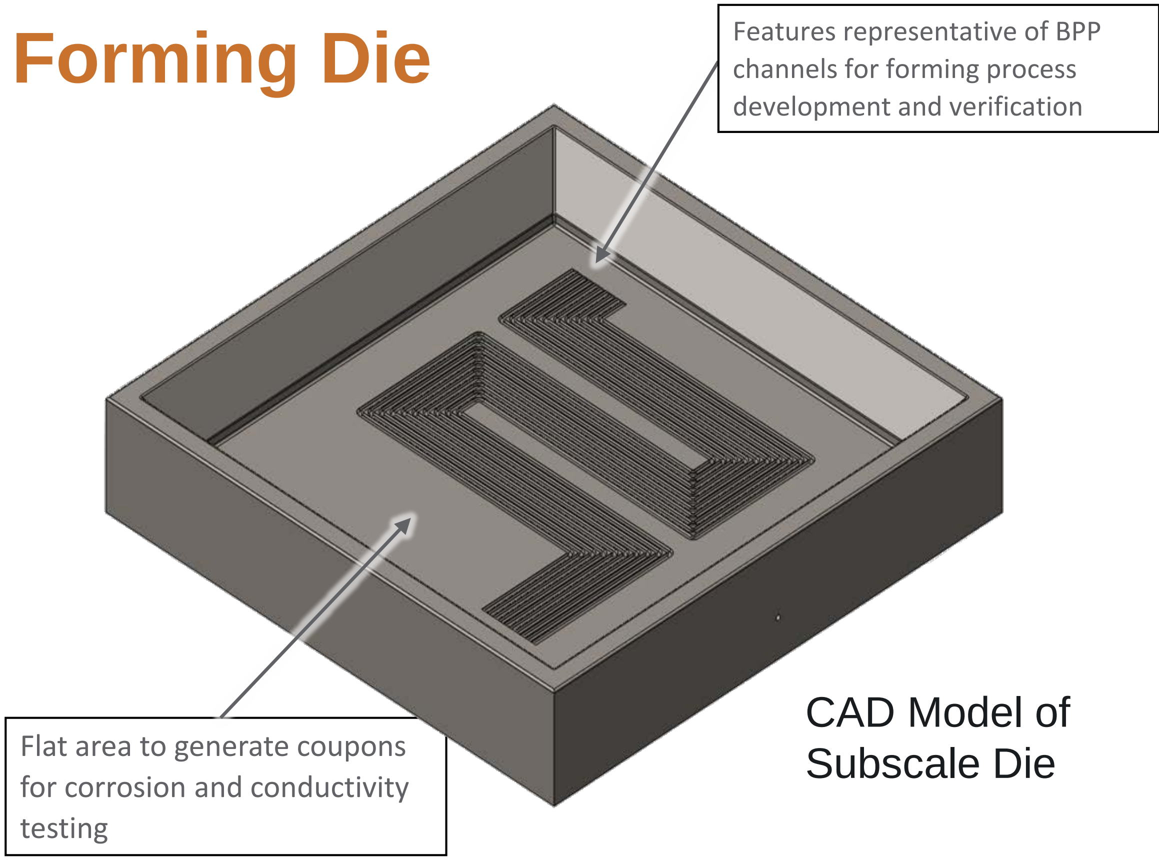


PVD of Titanium onto Aluminum in approximately 5 μm thickness

Initial DOTS Coating Process Trials of Titanium to Aluminum Complete

Progress: Subscale Forming Die

- Channel and Flat Area
  - Allows for forming trials and also DOE target testing for tests that require flat samples
  - Serpentine Channel Structure
- Design Complete
- Fabrication in Process



CAD Model of Subscale Die

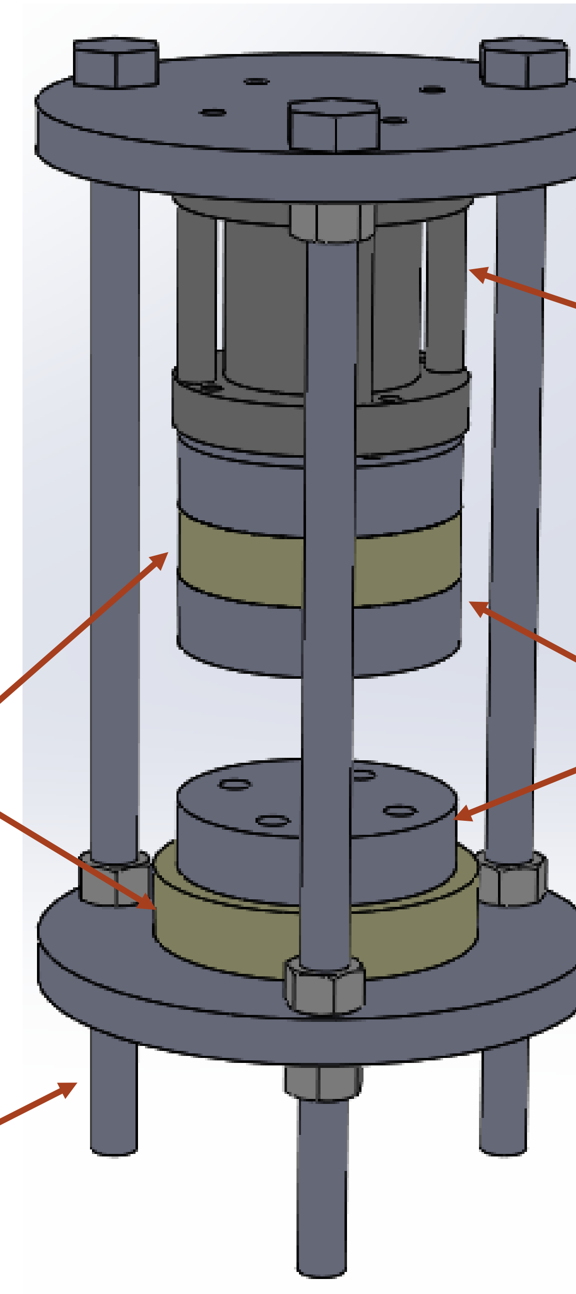
Machined Lower Lie

Lower Die Fabrication Complete, Upper Die Machining in Progress

Progress: Electric Testing Solution

- Contact Resistance Fixture
  - Frame
  - Pneumatic Cylinder
  - Coupon Mounts
- Test Conditions
  - 200 psi
  - 1” Disk
  - Coupon Sandwiched between carbon felt
    - ✓ AvCarb MGL 190
    - ✓ 190 µm thickness

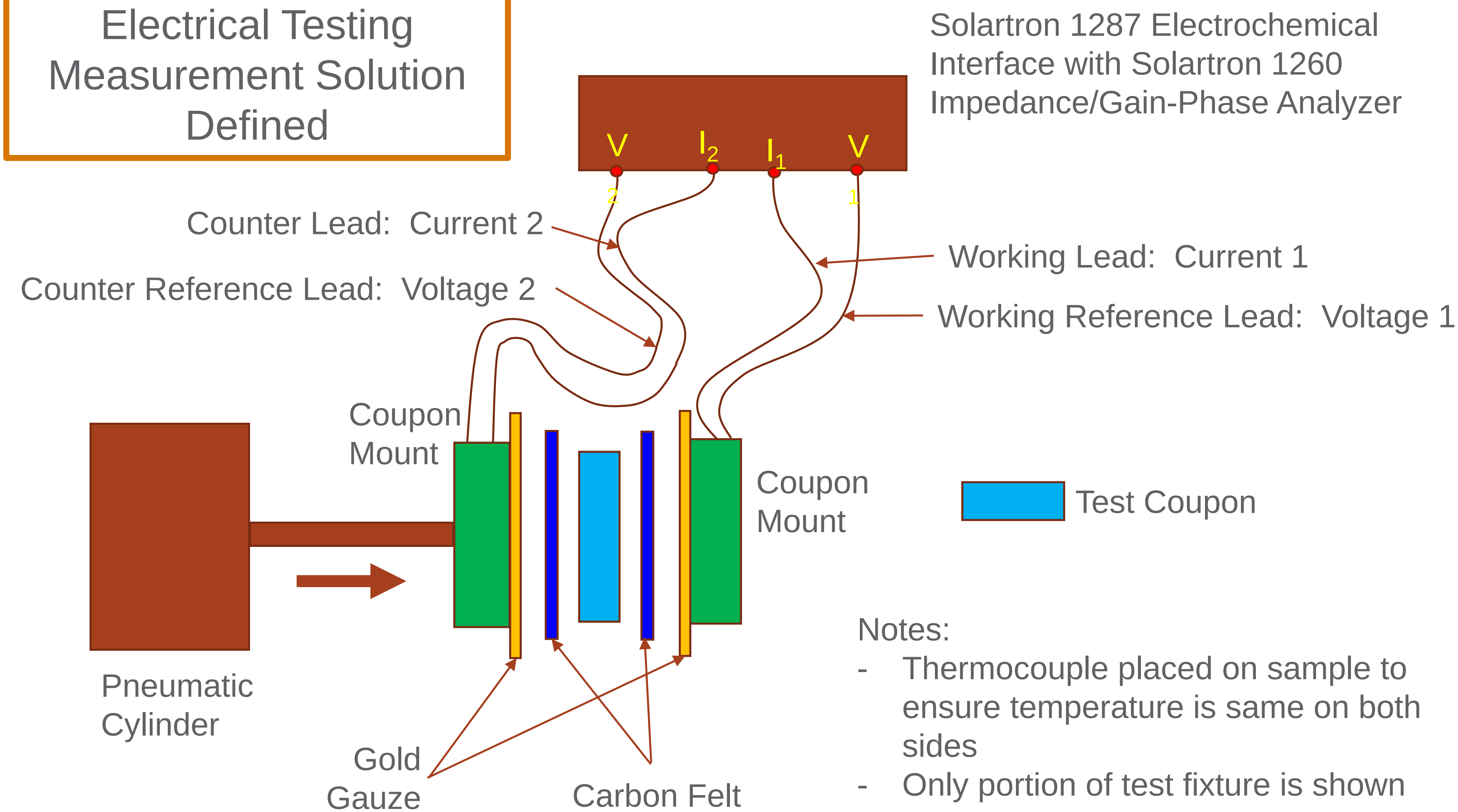
Electrical Testing Solution Defined and Being Setup



Progress: Electric Testing Solution

- Electrical Property Test Coupon Setup Detail

Electrical Testing Measurement Solution Defined



Notes:
- Thermocouple placed on sample to ensure temperature is same on both sides
- Only portion of test fixture is shown

Progress: Cost Model Development

- Detailed manufacturing cost model being developed
- Using same format as Strategic Analysis
- Impact of Aluminum, assuming equal manufacturing cost
  - Assuming equal weight as stainless steel
    - ✓ Saves ~$2 / kW assuming
      - $4.40/kg for Aluminum
      - $12.22/kg for SS304[4]
    - ✓ Equivalent weight Al is 3 x Thickness
  - Assuming aluminum is1.5 x thickness of stainless stainless steel
    - ✓ Saves ~$2.50 / kW

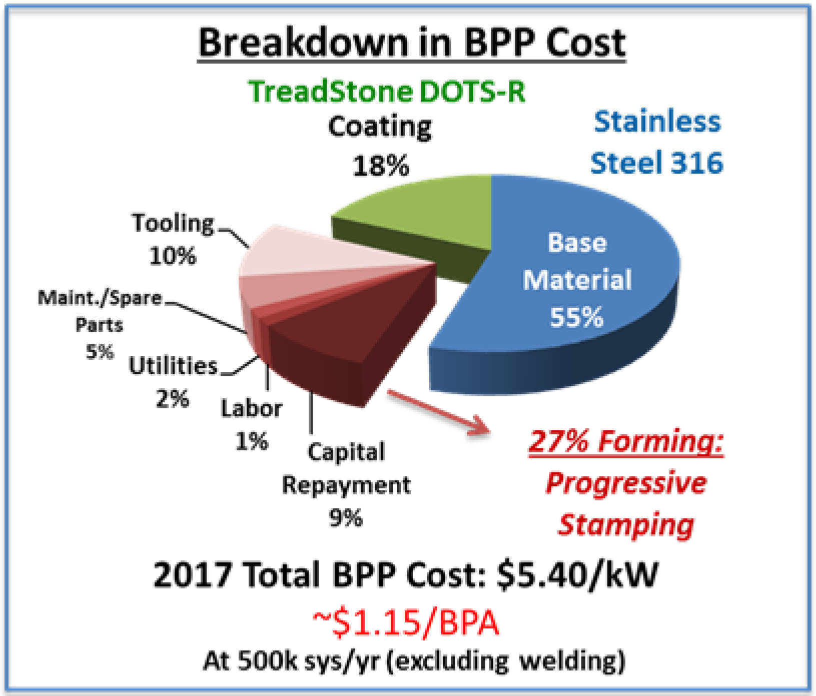


Image: Courtesy Strategic Analysis, Inc.[3]

Using aluminum, alone, has potential to allow for DOE cost target to be met!

[3] J.M; Huya-Kouadia et al, "Meeting Cost and Manufacturing Expectations for Automotive Fuel Cell Bipolar Plates, Strategic Analysis

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Progress: Cost Model Development

- Coating Process Cost for DOTS process has been estimated in high volume applications
- Coating Process Cost for Cold Spray has not been developed for high volume applications
  - Readily automated process
  - Model development in process
- Diffusion Bonding Process Cost for high volume applications has not been developed
  - Roll-to-Roll manufacturing process can be envisioned
  - Would likely require inert atmosphere (argon) vs. vacuum
  - Model development in process

Manufacturing cost models for diffusion bonding and cold spray for high volume application being developed

Proposed Future Work

- Next Steps: Cold Spray Process
  - Investigate Methods to Reduce Clogging
  - Forming tests
  - DOE Target Testing as appropriate
- Future Efforts: Cold Spray Process to Address Barriers Observed and Process Optimization
  - Reduce Thickness of Deposit
    - ✓ Finer Powder / Smaller Particle Size
    - ✓ Harder Aluminum Alloy
  - Testing of clogging reduction methods
  - Implement methods to reduce wrinkling on thin material
    - ✓ Vacuum fixturing/plates
  - Addition of Tracers
  - These activities are currently not anticipated to be part of this project due to down select process and funding level

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

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Proposed Future Work

- Next Steps Diffusion Bonding
  - Continue DOE target testing
  - Diffusion bonding of Titanium foil (0.025 mm) to Aluminum
  - Investigate diffusion bonding in Argon atmosphere
    - ✓ Will facilitate use of roll to roll manufacturing process

- Next Steps DOTS™ process
  - Complete coating analysis
  - Subscale Forming trials
  - DOE target testing

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

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Proposed Future Work

- Down-select manufacturing process for full scale coupon Fabrication
- Full scale coupon fabrication
  - Die design and fabrication
  - Forming Trials
  - DOE Target Testing
- Finalize cost modeling
- Reporting
  - Quarterly Reports
  - Final Report

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

Response's to Reviewers Comments

- Lack of details for technical approach
  - Limited information was provided because provisional patents were in processes
  - Relevant IP is now protected and technical details can be disclosed
  - This presentation provides detail
- Request for more precise manufacturing cost estimates
  - This is in progress and will be updated as development proceeds, as manufacturing process parameter information is needed finalize this task.
  - Cost data will be provided in final report
- Interact with OEM's
  - Planned and will continue.
  - Treadstone is part of the project and well established in the industry.
  - Interactions with various OEM's through Treadstone is planned

Technology Transfer Activities

- Provisional patents have been filed
- As this project is an early stage / low TRL level, other formal technology transfer activities are being performed, but in limited fashion. However, other groundwork activities are being performed towards eventual technology transfer, including
  - Collaboration with formal team partners
  - Working with industrial organizations for coating development and consulting
    - ✓ Treadstone Technologies, LLC (DOTS process)
    - ✓ Vacuum Process Engineering, Inc. (Diffusion Bonding)
    - ✓ VRC Systems (Cold Spray)
  - Consultation with OEM's through Treadstone Technologies and other routes

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Summary

- Initial process development and characterization towards three coating technologies for Titanium onto Aluminum has been completed or in progress
  - Diffusion Bonding
    - ✓ Initial process development trials completed
    - ✓ Some DOE target characterization testing has been completed
    - ✓ Process is viable
    - ✓ Characterization results to-date are promising
  - Cold Spray
    - ✓ Initial process development trials have been completed, with characterization in process
    - ✓ Results indicate process is viable,
    - ✓ Technical barriers exist that are straightforward to overcome but beyond the scope of this project
  - DOTS
    - ✓ Initial process development trials have been completed, with characterization in process
    - ✓ Characterization results are in process
- Detailed Cost Modeling Activities have been initiated
  - Initial results indicate the use of aluminum as the substrate material, alone, has the potential to allow DOE cost targets to be met, assuming all other costs are comparable.

Summary

Legend:
- IP = In Progress, N/A = Not Applicable, NS = Not Started
- Items in blue are data generated since last AMR

DOE Target	Metric	Diffusion Bonding Result	Cold Spray Result	DOTS Result
Cost	< $3/kW	IP	IP	IP
Weight	< 0.4 kg / kW	0.35[1]	0.35[1]	0.35[1]
Hydrogen Permeation Coeff.	< 1.3 x 10-14 @ 80°C, 3 atm 100% RH	N/A[2]	N/A[2]	N/A[2]
Corrosion, Anode	< 1µA / cm^2, no active peak	IP	IP	IP
Corrosion, Cathode	< 1µA / cm^2	N/A[3]	N/A[3]	N/A[3]
Electrical Conductivity	> 100 S / cm	>100[4]	NS	NS
Areal Specific Resistance	< 0.01 Ω cm^2	0[4]	NS	NS
Contact Resistance	20 mΩ/cm^2 @ 200 psi	IP	IP	IP
Forming Elongation	> 40%	48%	NS	NS
Flexural Strength	> 25 Mpa	NS	NS	NS

Notes:

1 - Assumes thicknesses of 0.5 mm and 0.025 mm for Al and Ti respectively. Assumes 1600 mW/cm^2 power density and 50% active area on 300 mm x 300 mm plate. Future optimization will likely allow for further reductions.

2 – Metallic based solutions will be 0 or infinity (if it cracks). Deemed not important per agreement with DOE sponsor

3 – Only making one half of bipolar and anode corrosion metric more strict. Data from anode corrosion will apply

4 – These data are not measurable given resolution of PNNL equipment and no reason to expect that they will not be achieved, given metallic based solution. Contact resistance more important per agreement with DOE Sponsor

Thank you