Solid-State Body-in-White Spot Joining of Al to AHSS at Prototype Scale

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LM104

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Overview

Timeline

- Project start date: Nov. 2014
- Project end date: Sept. 2017
- Percent complete: 50%

Barriers

- Barriers addressed

  F. Joining and assembly. High-volume, high-yield joining technologies for lightweight and dissimilar materials needs further improvement

Budget

- Total Project Budget: $3,187K
- Total Recipient Share: 53%
- Total Federal Share: 47%
- Total DOE Funds Spent: $782K

  * as of 3/31/2016

Partners

- Project participants

  Honda R&D Americas, Alcoa, Dow Chemical, L&L Products, Cosma Engineering, G-NAC, MegaStir Technologies, Brigham Young University, The Ohio State University

- Project lead

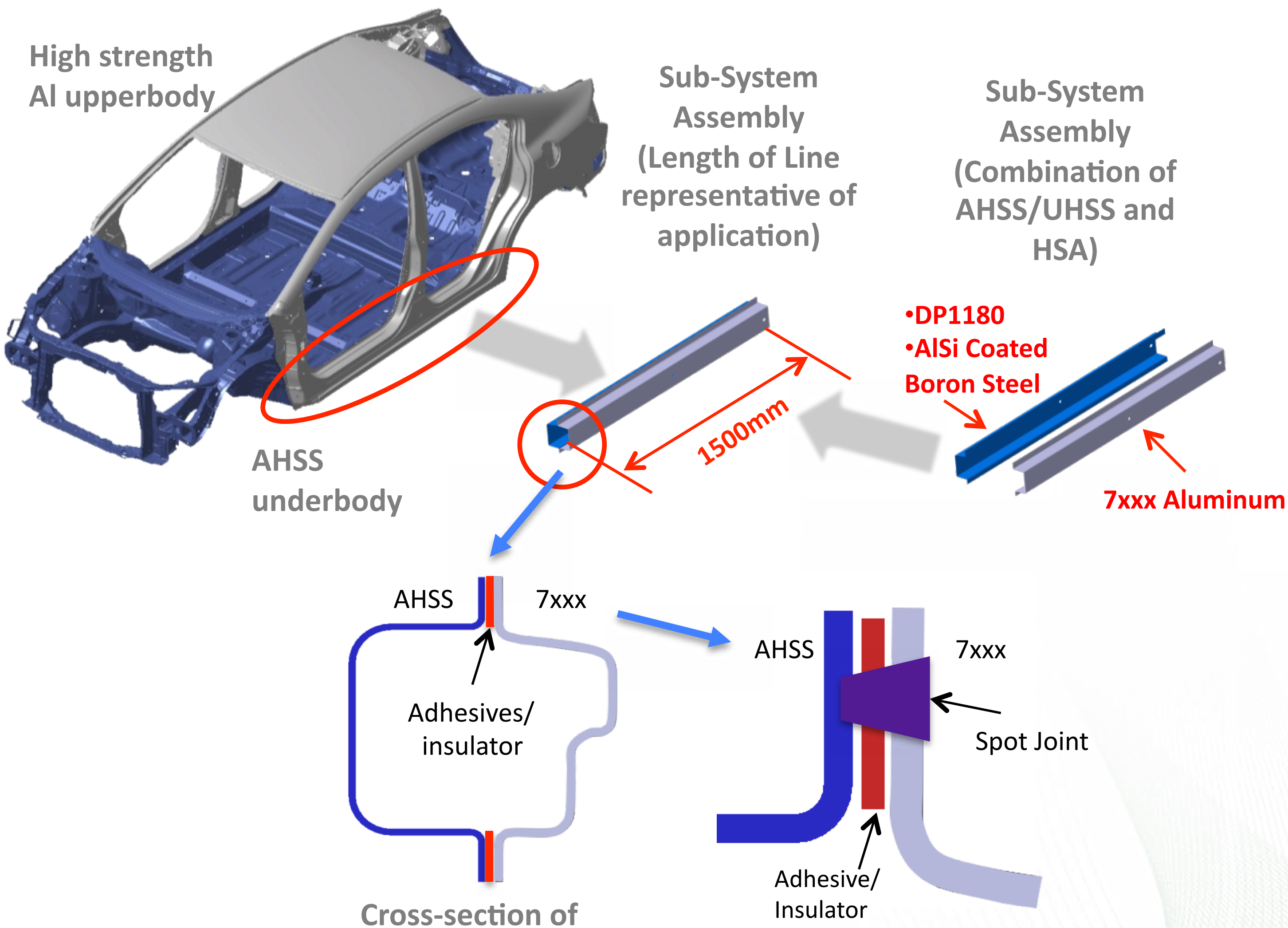
  Oak Ridge National Laboratory (ORNL)

Relevance – DE-FOA 793 AOI 3

- **Objectives**: Develop, mature, and validate near-production readiness of a solid-state *spot joining* technology to join prototype-scale auto body-in-white (BIW) sub-systems made of advanced high-strength steel (AHSS) and 7000/6000 series high-strength aluminum alloys, to meet the dissimilar metal joining challenges in high volume mass production.

- **Impact**: The project focuses on spot joint - the most common form of joints in BIW structures of high volume production vehicles. Thus, it enables the broadest insertion of lightweight materials in BIW, and has the highest potential as a joining technology to support the reduction of petroleum consumption, environmental impacts, and economic benefits in the transportation sector.

Relevance – Supporting Multi-Material Body Solution Concept



Cross-section of beam

Joint details

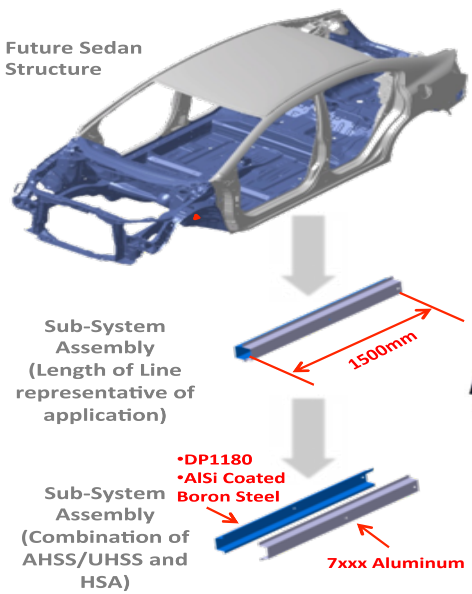
Milestones

Jan-15	Joint performance evaluation target plan. **Completed**
Apr-15	Baseline FBJ & FSSW process development. **Completed**
Dec-05	Baseline process model development and validation. **Completed**.
Feb-06	FBJ process control (option 1). **Completed**
Feb-16	FBJ joint bit design and material selection. **Completed**
May-16	FBJ process control option 2. **In progress**
Jun-06	Pass coupon level mechanical property target matrix and down-select the winning solid-state process. **Go/no-go decision**
Jun-16	System design for part level joining. **In progress**
Jun-16	Design and evaluation of automated bit feed system for FBJ. **In progress**
Jul-16	Coupon level corrosion test.
Aug-16	System for part level joining
Aug-16	System integration with automated bit feed system
Sep-16	Adhesive bonding modeling (coupon level)
Sep-16	Weld microstructure and property modeling (coupon level)

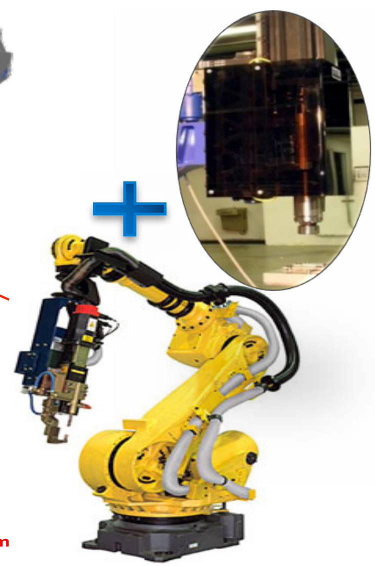
Approach/Strategy

- The proposed technology is based upon two emerging solid-state friction-heating based *spot joining* processes (FBJ and FSSW) with demonstrated success in coupon scale joining of dissimilar metals. Both processes will be refined. The winning process will be selected, further matured and integrated with an assembly-line welding robot for prototype scale BIW sub-system joining.
- An integrated weld process-structure-performance model will be employed to predict the joint performance at both coupon and sub-system levels to assist the process and sub-system design optimization.
- Prototype BIW parts will be assembled with the joining system to evaluate and validate the production readiness of the technology for BIW.

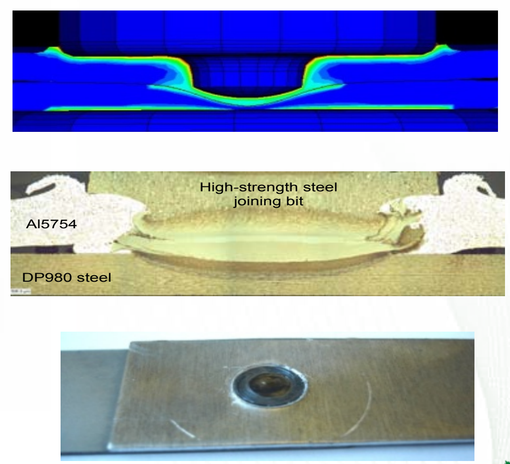
Production Relevant Prototype Scale Assembly



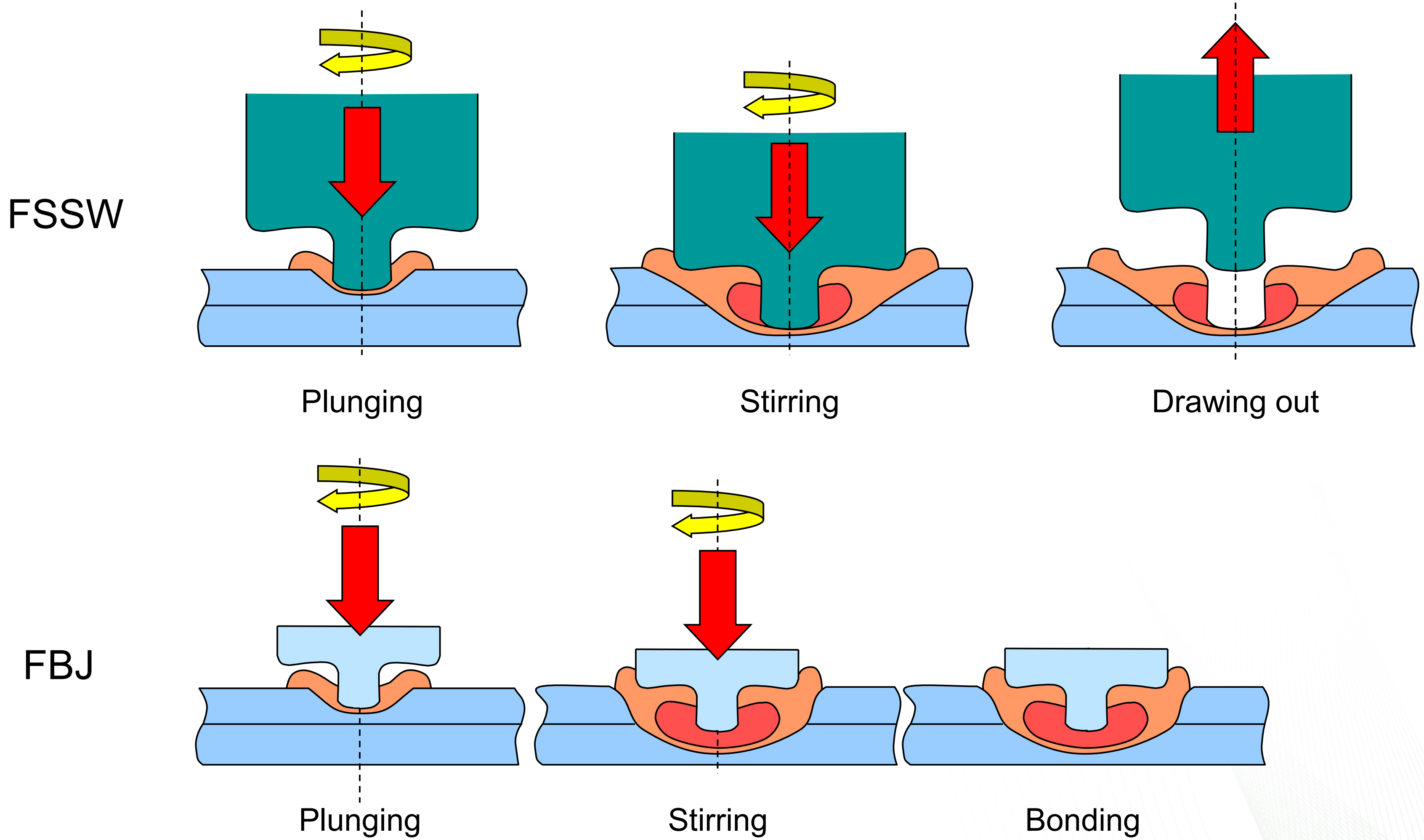
Robotic Spot Welding System



Strong Solid-State Metallurgical Bonding

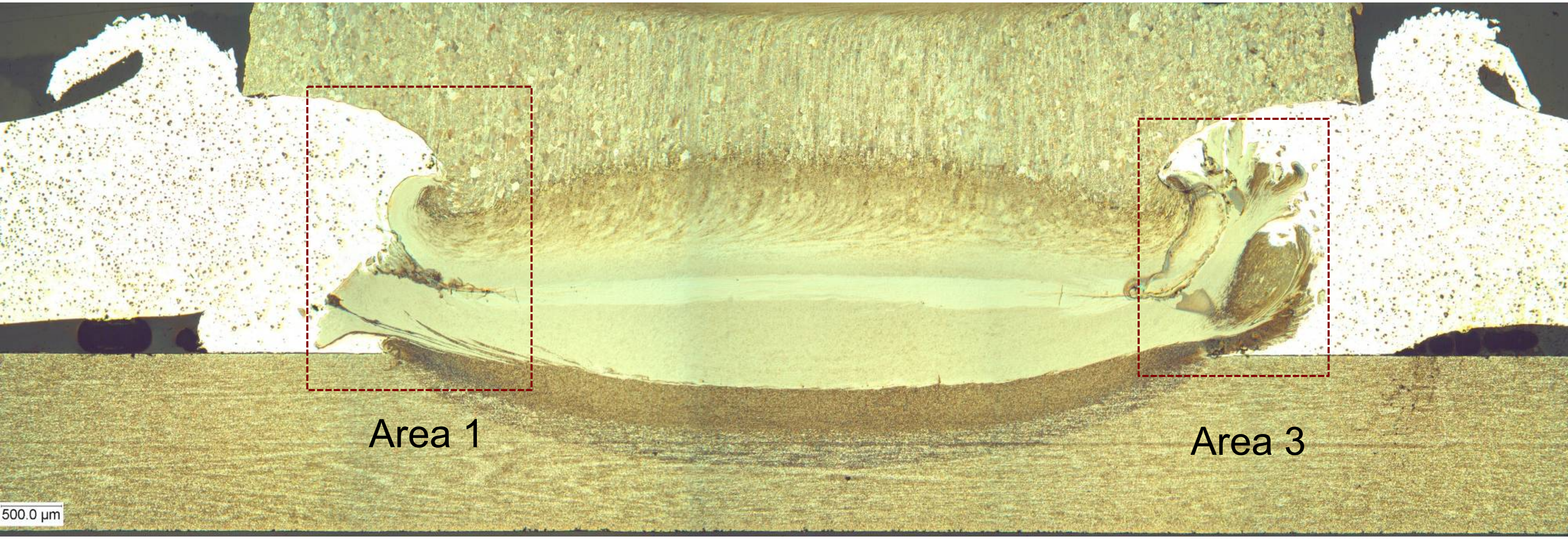


Based on Two Solid-State Joining Processes: Friction Bit Joining, Friction Stir Spot Welding



Example: FBJ between DP980/AA5754

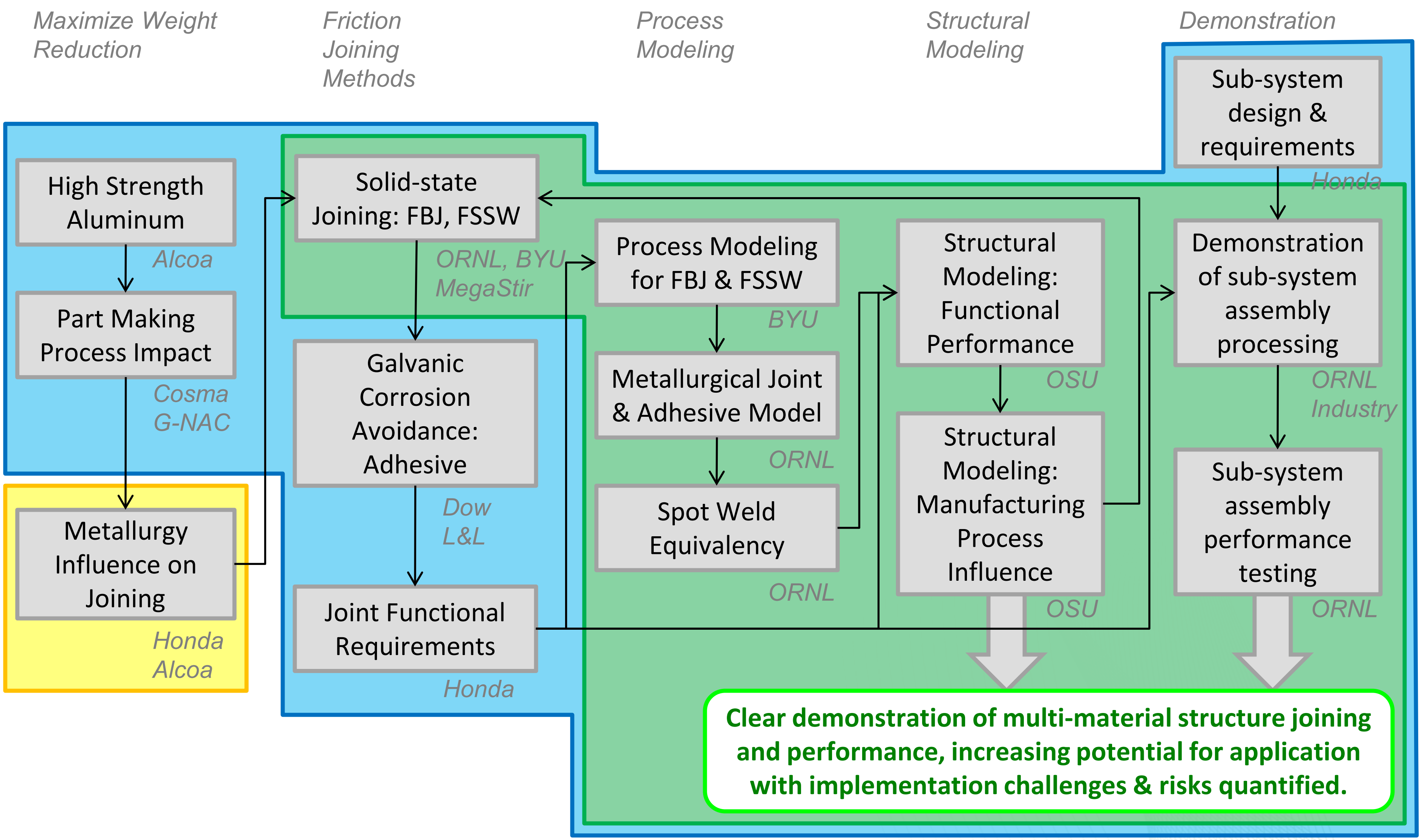
Metallurgical bonding



Process selection based on FOM Analysis

	FBJ	SPR	FSSW	Ultrasonic
Material Combination				
Steel to Al	yes	yes	coated steel	coated steel
Steel to Mg	yes	difficult	TBD	coated steel
Steel Grade	All AHSS	up to DP780	All AHSS	All AHSS
Stacks	2T, 3T	2T, 3T	2T	2T
Surface Requirement	no restriction	no restriction	Zn coating	Zn coating, some cleaning
Bonding Mechanism	Metallurgical + Mechnical	Mechanical	Brazing or Metallurgical	Brazing, or metallurgical
Lap shear strength (N)				
Steel to Al	6300 - 8100	5000 - 5500	2500 - 3500	~3000
Steel to Mg	~5400	cracking	N/A	4200
Z load (N)	~ 9000	20,000 or higher	TBD	~ 2000
Process Time (sec)	1.5 - 2	< 1	<4	1.2 - 2
Weld bonding	Feasible	yes	Difficult	TBD
Consumable Bit	Yes	Yes		
Cost	Comparable to SPR	low		
Nonconsumerable Tool			Yes	Yes
Cost			High	High
Machine cost	comparable	comparable	comparable	Potentially high
Machine automation	Feasible	Yes	demonstrated	Feasible

R&D Plan: Roles and Responsibilities



Key R&D Matrixes

- Process development and demonstration
  - Development and demonstration at a coupon-scale
  - Emphasis on demonstration with prototype-scale parts
  - Performance metrics at component level
- Joint characterization
  - Microstructure, joint defect, mechanical properties
  - Corrosion performance
- Model development and validation
  - Predict the post-weld microstructure based on process parameters and input microstructure
  - Predict quasi-static failure strength
    - Within 5% of experimental value at couple level
    - Within 10% of experimental value at the prototype scale
  - Predictive model to effectively control or mitigate component distortion and failure due to thermal expansion mismatch of Al and steel

Accomplishment

Identified coupon-level performance target metrics based on input from industry team members

	Steel Baseline	Steel-Al spot weld	Steel-Al Adhesive	Steel-Al Combined
Material Top	1500P	7xxx Al	7xxx Al	7xxx Al
Material Bottom	DP1180	DP1180	DP1180	DP1180
Tensile shear strength	>18kN	>5kN	>10kN	>15kN
Cross tension strength	>5kN	>1.5kN	>3kN	>4.5kN
CTS/TSS	0.28	0.3	0.3	0.3
Peel strength	>2kN	>1.5kN	Measure	Measure
Peel/TSS	0.12	0.3	Measure	Measure
TSS Fatigue @ 10^7 cycles	0.75kN	0.75kN	measure	0.75kN

Accomplishment

FBJ process development: successfully passes all joint strength target requirements

- Completed a number of iterative studies on joining bit geometry, material and heat treatment combinations, for joint strength, cost, and manufacturability
- Joining bit design finalized
- Joining bit material and heat treatment finalized
- Automated joining bit feed system under development and testing trials

Sample ID	TSS Peak load (kN)
2016-03-02-00	10.98
2016-03-02-01	10.56
2016-03-20-00	9.88
2016-03-20-01	8.96
Average	10.1
STDEV	0.88

TSS target: 5kN

T peel tests			
count	Sample #	Hardness RC	Peak Load N
1	2016-[redacted]-08	38	1656
2	2016-[redacted]-09	38	2087
3	2016-[redacted]-10	38	1624
4	2016-[redacted]-12	45	1675
5	2016-[redacted]-13	45	1675
6	2016-[redacted]-14	45	1711
7	2016-[redacted]-00	45	1900
8	2016-[redacted]-01	45	1713
9	2016-[redacted]-02	45	1794
10	2016-[redacted]-03	38	2053
11	2016-[redacted]-04	38	1740
12	2016-[redacted]-05	38	2004
13	2016-[redacted]-06	45	1921
14	2016-[redacted]-07	44	1182
15	2016-[redacted]-08	44	1814
16	2016-[redacted]-09	44	2136
17	2016-[redacted]-10	44	1914
		AVG	1799.94
		STD	226.762

T peel target: 1.5kN

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Accomplishment

FBJ is capable to meet coupon level strength targets for wide range of material combination and process conditions

Material combination		7xxx-1 /DP1180-GA	7xxx-1 /DP1180-GA	7xxx-2 /DP1180-GA	7xxx-2 /DP1180-GA	7xxx-2 /DP1180-GA	7xxx-2 /DP1180-GA	7xxx-1/ DP980	7xxx-1/ DP980	Strength Targets
Thickness (mm)		2.0/1.2	2.0/1.2	2.0/1.2	2.0/1.2	2.0/1.2	2.0/1.2	1.6/1.2	2.0/1.2	–
FBJ design/material		1	1	1	2	2	3	1	3	–
TSS (kN)	FBJ-A	10.0(P)	9.7(P)	8.3(P)	9.0(P)	9.9(P)	10.0(P)	10.3(P)	12.85(P)	>5kN
	FBJ-2	–	–	–	–	–	–	10.5(P)	12.9(P)	
CTS (kN)		1.91(P)	–	–	–	–	2.54(P)	2.77(P)	2.82(P)	>1.5kN
T-Peel (kN)		–	–	–	–	–	1.79(P)	–	1.63(P)	>1.5kN
TSS fatigue 20 Hz, R=0.1		Passed	–	–	–	–		–	Passed	10^7 @ 0.75kN

Accomplishment

FSSW alone is difficult to consistently achieve strength targets. When combined with adhesives, it is possible to achieve the strength targets of the project

- FSSW is attractive for process simplicity
  - No consumables
  - Tool life and cost can be challenging for Al-steel joining
- Results from open literature suggest the difficulties in achieving project joint strength target
- Process development focused on improving joint strength and long tool life
  - Process innovations to increase bonding area, control heat generation, and tool life
  - Weld bonding with adhesives offers potential to achieve strength targets

Tensile shear test results			
FSSW parameters	Target value, KN	Adhesive A	Adhesive B
1	15	Didn't pass	Passed
2	15	Passed	Passed

Accomplishment

Adhesives offers additional strength and galvanic corrosion avoidance

- Adhesives from two team members were systematically evaluated for joint strength and potential for galvanic corrosion avoidance

		Target	Adhesive A			Adhesive B		
Materials			7xxx-1/ DP1180GA	7xxx-1/ DP1180	7xxx-1/ DP980GA	7xxx-2/ DP1180GA	7xxx-1/ DP1180	7xxx-1/ DP980GA
Thickness (mm)		–	2.0/1.2	2.0/1.2	2.0/1.0	2.0/1.2	2.0/1.2	2.0/1.0
TSS (kN)	Adhesive bondline thickness: A	10	P	–	P	P	–	–
	Adhesive bondline thickness: B		–	P	P	–	P	P
	Adhesive bondline thickness: C		P	P	P	P	P	P
CTS (kN)		3	P	P	F	P	P	P
Peel (kN)		Measure	Measured	–	–	Measured	–	–
TSS fatigue (10^7) 0.75 kN, 13~20 Hz, R=0.1		Measure	-	All 3 samples passed	–	In test	–	–

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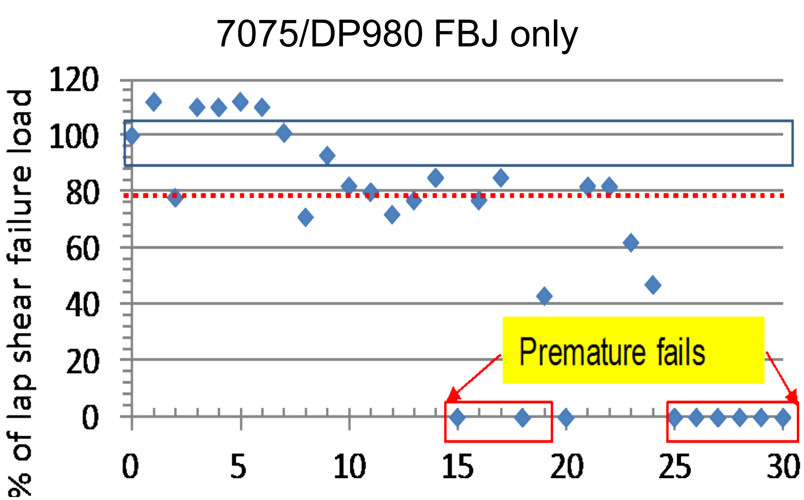
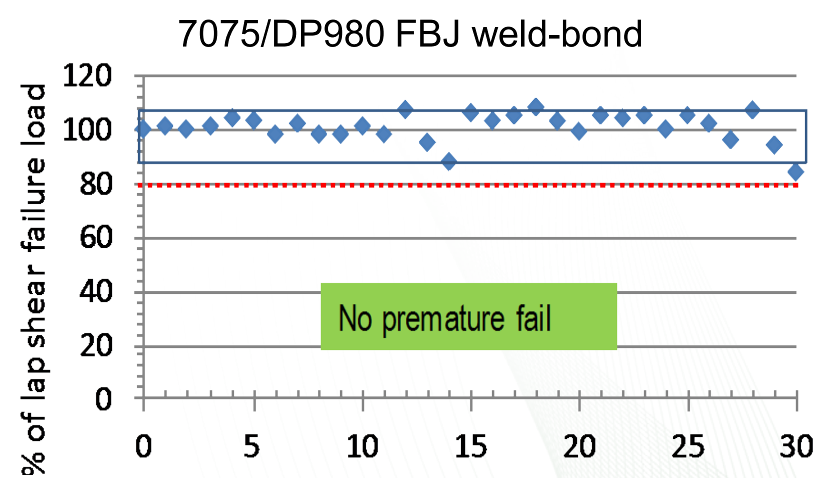
Accomplishment

Weld-bond, which combines spot weld and adhesives, further increases joint strength and provides effective corrosion avoidance

	FBJ	Adhesive A	Adhesive B	Weld-bonding (adhesive A)	Weld-bonding (adhesive B)
Lap shear	Pass	Pass	Pass	Didn't pass	Pass
Cross tension	Pass	Pass	Pass	Didn't pass	Pass
T-peel	Pass	Pass	Pass	To be tested	To be tested
Fatigue	More testing	1st sample passed	1st sample passed	To be tested	To be tested



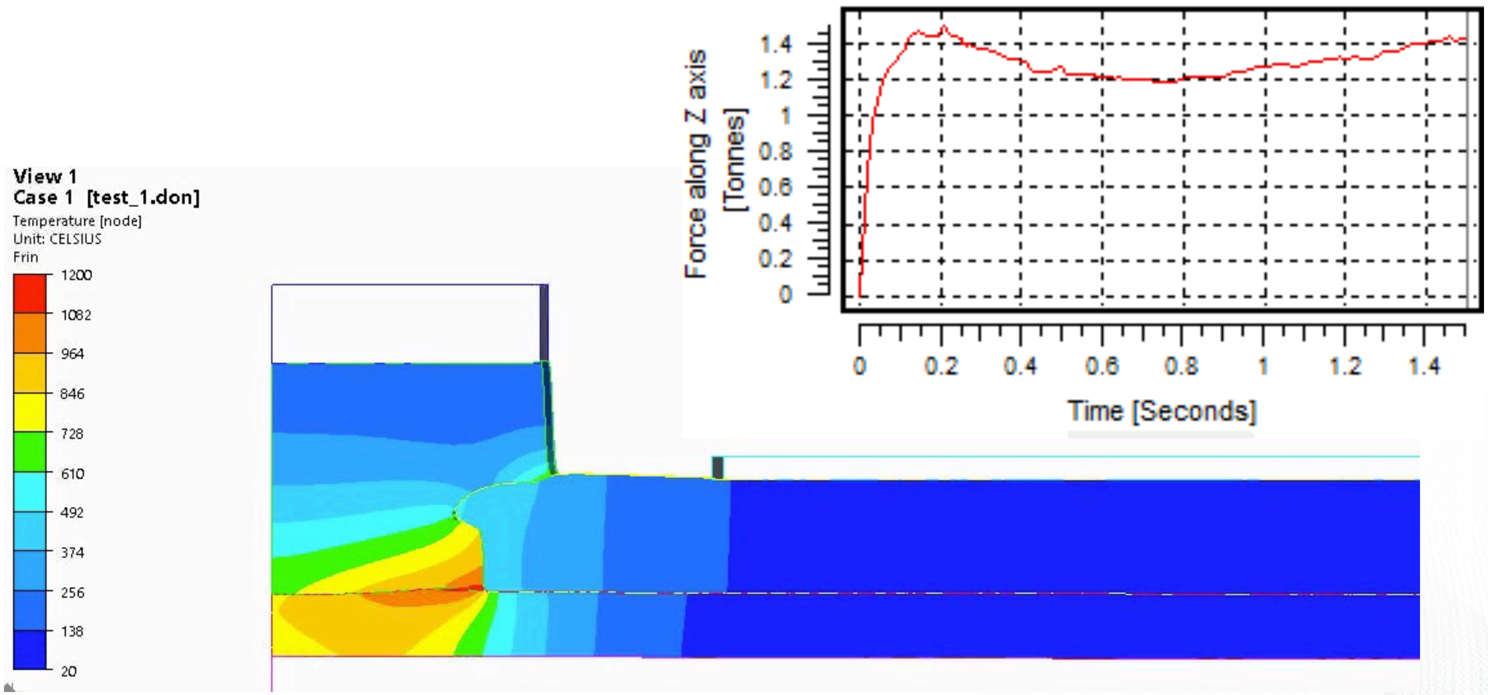


* Initial corrosion test results with DP980 steels

Accomplishment

Process model of FBJ has been developed that provides reasonable prediction of the process conditions and temperature distribution

- Output from the process model are being used to model the microstructure and properties of the joint, and thermal induced distortion during welding.

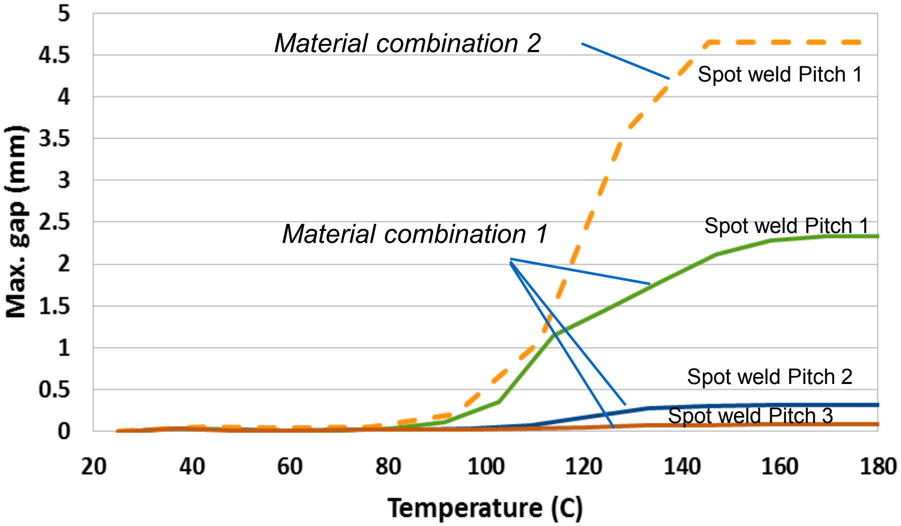


Accomplishment

Distortion modeling due to thermal expansion mismatch of bi-metal

- Coefficient of thermal expansion (CTE) for aluminum alloys is about twice that for steels; thus very high CTE mismatch.
- Recent paint baking experiment showed that part separation during paint baking could cause part dimensional changes and improper curing of adhesive .
- A thermal buckling modeling tool is being developed to understand and predict the thermally-induced buckling of spot-weld and adhesively bonded Al-steel component due to CTE mismatch during paint baking
- Measurement technique is being developed to experimentally determine the part dimensional changes during paint baking process, for model development and validation

Preliminary simulation results shows part separation during paint baking as function of pitch spacing and material strength



Responses to Previous Year Reviewers' Comments

- *This project has not been reviewed before*

Collaborations and Industry Participations

- Roles and Responsibility of Team Members
  - Honda: Define industry need and requirement (industry lead)
  - ORNL: FSSW and FBJ Process Development, Microstructure and property Modeling, Adhesive Modeling (project lead)
  - Alcoa: Alloy Development
  - BYU: FBJ Process Development, Process Modeling
  - Cosma: Forming Analysis, Technology Validation at Component Level
  - Dow: Adhesive Formulation
  - G-NAC: Forming Analysis, Technology Validation at Component Level
  - L&L: Adhesive Formulation
  - Mega-Stir: FBJ system
  - OSU: Performance Modeling

Remaining Challenges and Barriers

- Part distortion control due to thermal expansion mismatch of bi-metals
- Improve joint strength of FSSW

Propose Future Work

- FY16
  - Complete coupon scale process development. May 2016
  - Go/No-go: Pass performance target metrics for at least one spot-joining process. June 2016
  - Down-select the winning process for component level development. June 2016
  - Complete system integration including automated joining bit feeding system for FBJ for part joining. Aug 2016
  - Complete microstructure and property model development and adhesive bonding model development (coupon scale). Sept 2016
- FY17
  - Complete corrosion test. Oct 2016
  - Develop part distortion prediction model. Dec 2016
  - Complete hardware system integration for prototype scale trials. April, 2017
  - Complete integrated model for joint performance prediction and validation. Sept 2017
  - Complete project validation and verification by prototype scale testing and demonstration. Oct 2017

Project Summary

Relevance:	Address the critical need of dissimilar metal joining for effective use of multi-material auto-body structure for lightweighting while improving the performance and safety
Approach:	Combining solid-state spot welding and adhesive bonding to solve both joining and corrosion avoidance in use of advanced high-strength steel and 7xxx alloy for auto-body structures. Mature and validate near-production readiness of the integrated joining technology. Develop integrated weld process-property-performance model to assist the process development and multi-material structural optimization.
Technical Accomplishments:	• FBJ has successfully passed all coupon level performance targets that has been tested so far • Weld bonding further increases the joint strength and provides a potentially practical and effective means for corrosion avoidance. • FBJ process model has been developed • A thermal buckling modeling approach shows the potential to predict the part dimensional change of bi-metal parts.
Collaborations:	An exceptionally strong, strategically selected and vertically-integrated project team is well suited for both technology development and future technology commercialization.
Future Plan:	Follow the SOPO R&D plan; Other plans proprietary to industry participants that cannot be discussed in this forum.

Technical Back-up

Research Plan and Major Tasks

- Further develop and refine the solid-state joining process and identify process window/conditions to consistently meet the joint performance and joining cycle time requirement set forth by OEM;
- Combine adhesives with insulator properties to prevent galvanic corrosion between dissimilar metals and improve the structure performance of sub-systems;
- Design, engineer and build a near production ready solid-state spot joining system that can be integrated to an assembly-line welding robot;
- Integrate the solid-state spot joining process with an assembly-line welding robot for prototype scale BIW sub-system joining;
- Thoroughly characterize and evaluate the Al/steel joints against a set of process and performance criteria set forth by the OEM and industry team, at both coupon and sub-system scale;
- Refine and apply an integrated computational weld engineering (ICWE) modeling framework that is capable of accurately predicting the joint performance at both coupon and sub-system levels to assist the joining process development and sub-system design optimization;
- Develop an effective design and joining strategy to minimize the detrimental effects of thermal expansion mismatch between steels and aluminum alloys at sub-system component scale; and
- Demonstrate and validate the developed solid-state joining technology with prototypical BIW sub-systems.