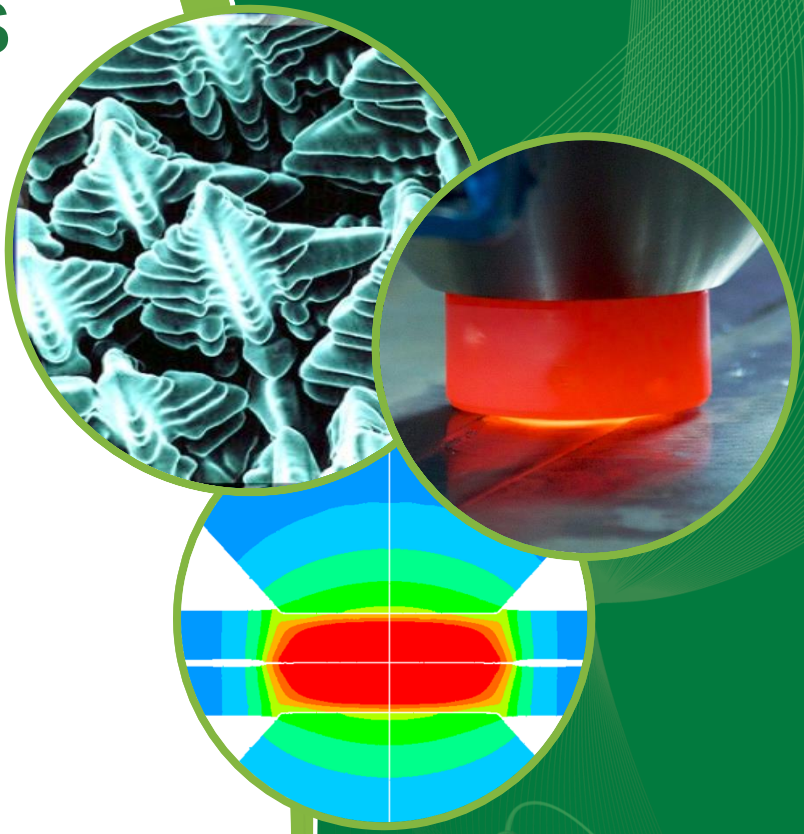
Solid-State Body-in-White Spot Joining of Al to AHSS at Prototype Scale



PI: Zhili Feng

Oak Ridge National Laboratory
Honda R&D Americas, Arconic, Dow Chemical, L&L,
Cosma Engineering, G-NAC
MegaStir Technologies
Brigham Young University, Ohio State University

June 12, 2019 **Project ID: mat155**

ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE
National Laboratory

Overview

Timeline

- Project start date: Nov. 2014
- Project end date: Dec. 2019
- Percent complete: 70%

Barriers

- Barriers addressed

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

** 2017 U.S. DRIVE MTT Roadmap Report, Section 4*

Budget

- Total Project Budget: $3,187K
  - DOE Share: $1,500K
  - Recipient Share: $1,687K
- Funding for FY18: $500K
- Funding for FY19: $0K

Partners

- Project participants

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

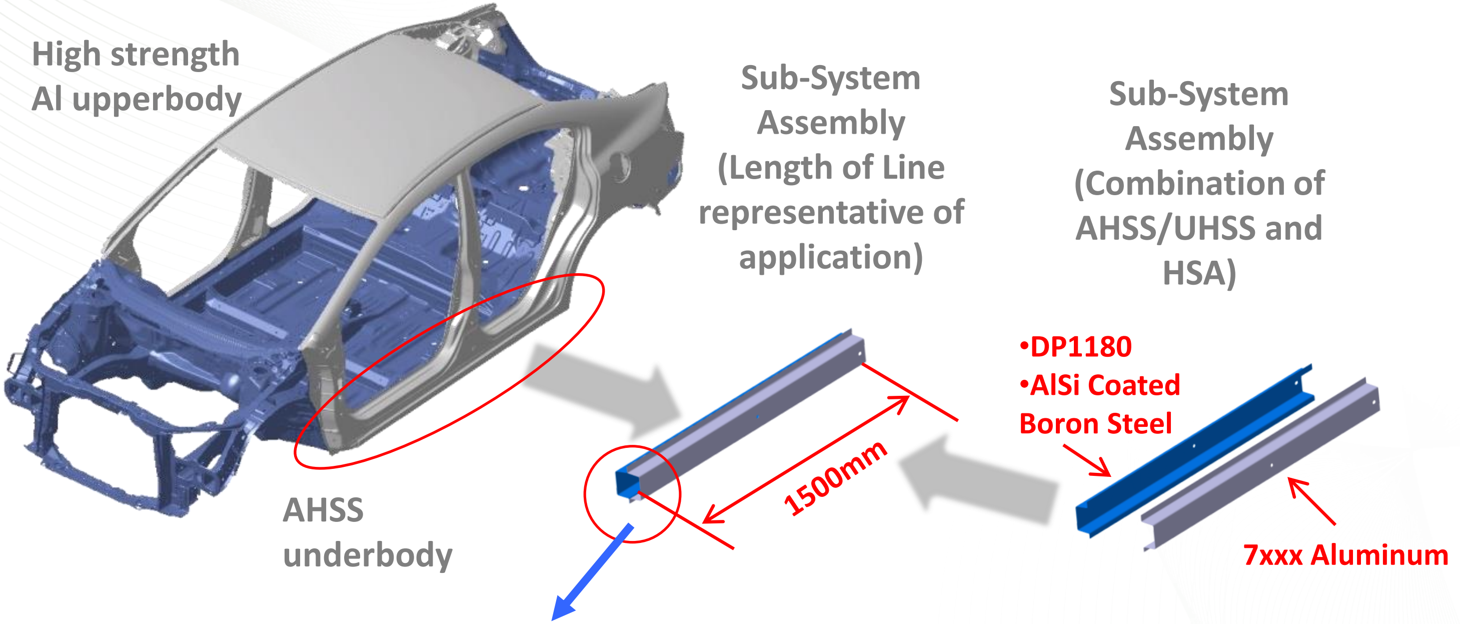
  Oak Ridge National Laboratory (ORNL)

Relevance

- **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.

Project Goal: Multi-Material Joining at Component Level



Sub-System Assembly (Length of Line representative of application)

Sub-System Assembly (Combination of AHSS/UHSS and HSA)

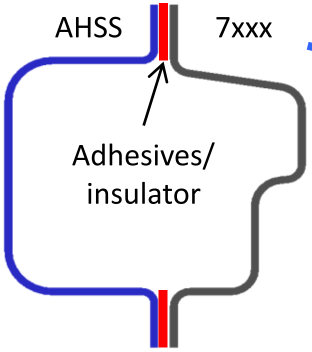
- DP1180
- AlSi Coated Boron Steel

7xxx Aluminum

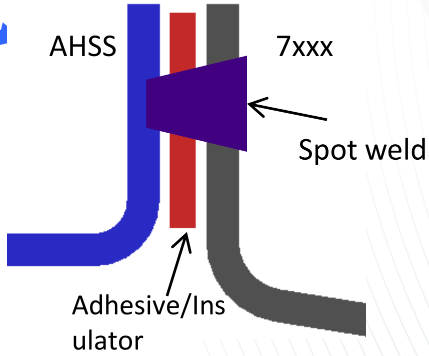
Future Sedan Structure

AHSS

HSA



Cross-section of beam



Joint details

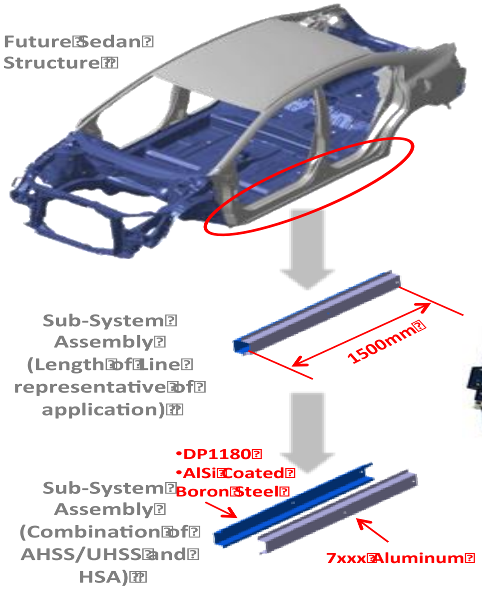
Key Milestones

Jan-15	**Define joint performance evaluation target. Completed**
Apr-15	Baseline FBJ & FSSW process development. **Completed**
Dec-15	Baseline process model development and validation. **Completed**
Jun-16	**Pass coupon level mechanical property target matrix. Go/no-go decision Passed**
Feb-17	**Coupon level corrosion test. Passed**
April-17	**Multi-weld development. Completed**
June-17	**Transition to Component Level Development – Down-Selection of Spot Joining Processes. Go/no-go decision Passed**
June-17	**Distortion model due to part thermal expansion mismatch. Completed**
April -19	System design for component level joining **Completed**
Sept-17	Weld microstructure model **Completed**
July-19	System for component joining In progress
Aug-19	**Sub-component level joining and demonstration**
Dec-19	**Sub-component testing and reporting**

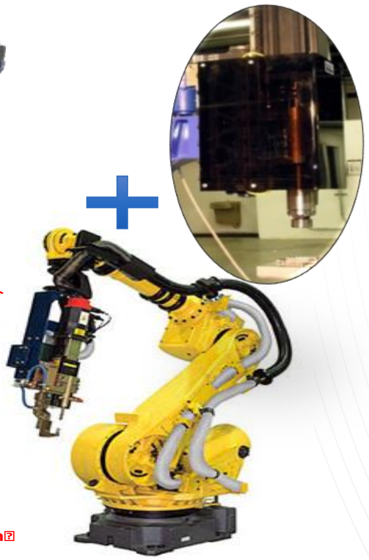
Approach/Strategy

- 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.

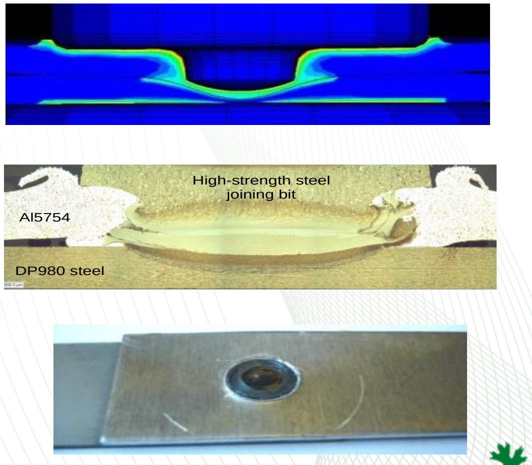
Production Relevant Prototype Scale Assembly



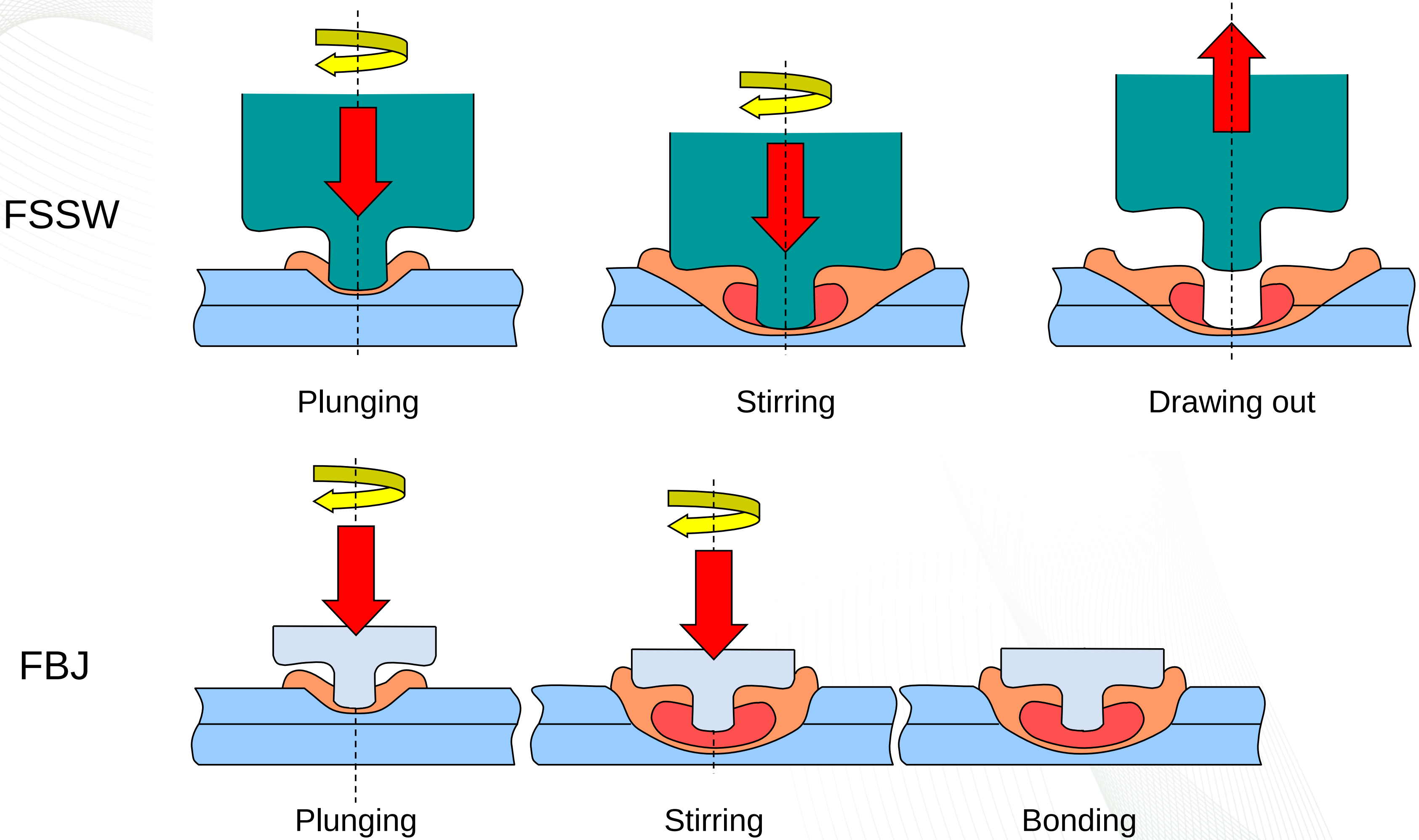
Robotic Spot Welding System



Strong Solid-State Metallurgical Bonding

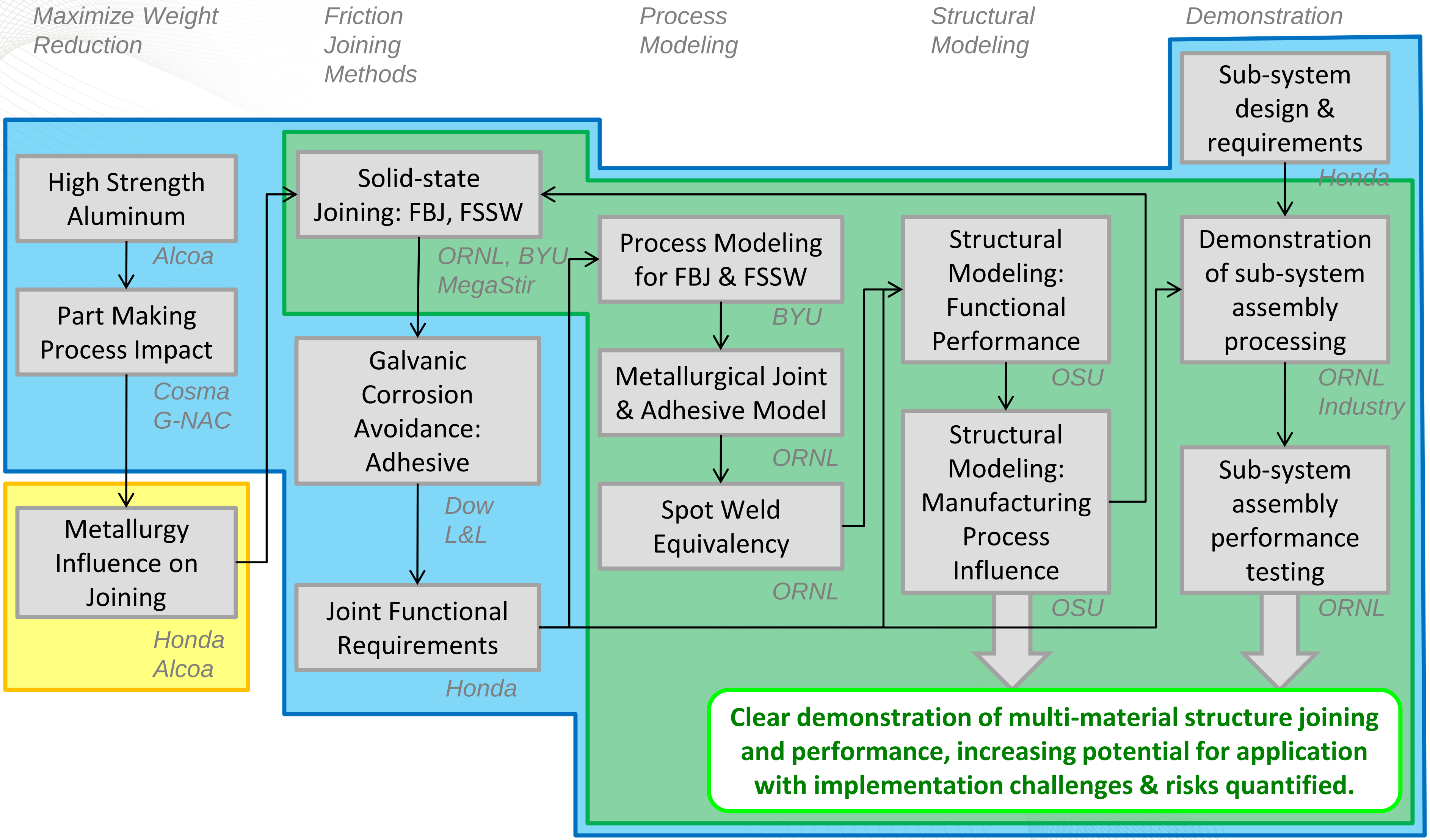


Based on Two Solid-State Joining Processes: Friction Bit Joining, Friction Stir Spot Welding



FBJ was finally down-selected for Phase 3 after joint performance review

R&D Plan: Roles and Responsibilities



Maximize Weight Reduction

High Strength Aluminum
Alcoa

Part Making Process Impact
Cosma
G-NAC

Metallurgy Influence on Joining
Honda
Alcoa

Friction Joining Methods

Solid-state Joining: FBJ, FSSW
ORNL, BYU
MegaStir

Galvanic Corrosion Avoidance: Adhesive
Dow
L&L

Joint Functional Requirements
Honda

Process Modeling

Process Modeling for FBJ & FSSW
BYU

Metallurgical Joint & Adhesive Model
ORNL

Spot Weld Equivalency
ORNL

Structural Modeling

Structural Modeling: Functional Performance
OSU

Structural Modeling: Manufacturing Process Influence
OSU

Demonstration

Sub-system design & requirements
Honda

Demonstration of sub-system assembly processing
ORNL
Industry

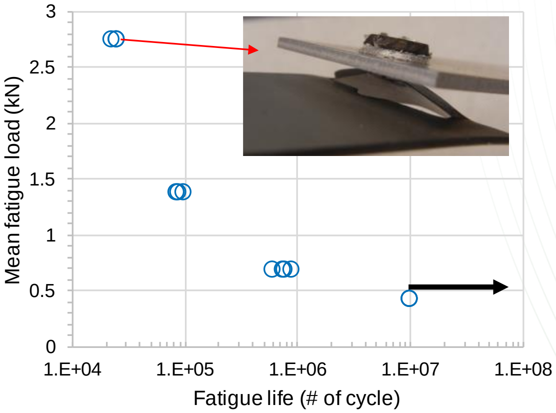
Sub-system assembly performance testing
ORNL

Clear demonstration of multi-material structure joining and performance, increasing potential for application with implementation challenges & risks quantified.

Accomplishment: Friction Bit Joining

Passed first go/no-go decision point with FBJ: meet coupon level strength targets for wide range of material combination and process conditions in FY16

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-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	2.0/1.2	1.6/1.2	2.0/1.2	–
FBJ design/material		1	1	1	2	2	3	4	1	3	–
TSS (kN)	FBJ-A	10.0(P)	9.7(P)	8.3(P)	9.0(P)	9.9(P)	12.2(P)	13.0(P)	10.3(P)	12.85(P)	>5kN
	FBJ-2	–	–	–	–	–	–		10.5(P)	12.9(P)	
CTS (kN)		1.91(P)	–	–	–	–	2.54(P)	4.33(P)	2.77(P)	2.82(P)	>1.5kN
T-Peel (kN)		–	–	–	–	–	2.17(P)	2.15(P)	–	1.63(P)	>1.5kN
TSS fatigue (10^7) @ 0.75kN 20 Hz, R=0.1		Passed	–	–	–	–	Passed	–	–	Passed	0.75kN



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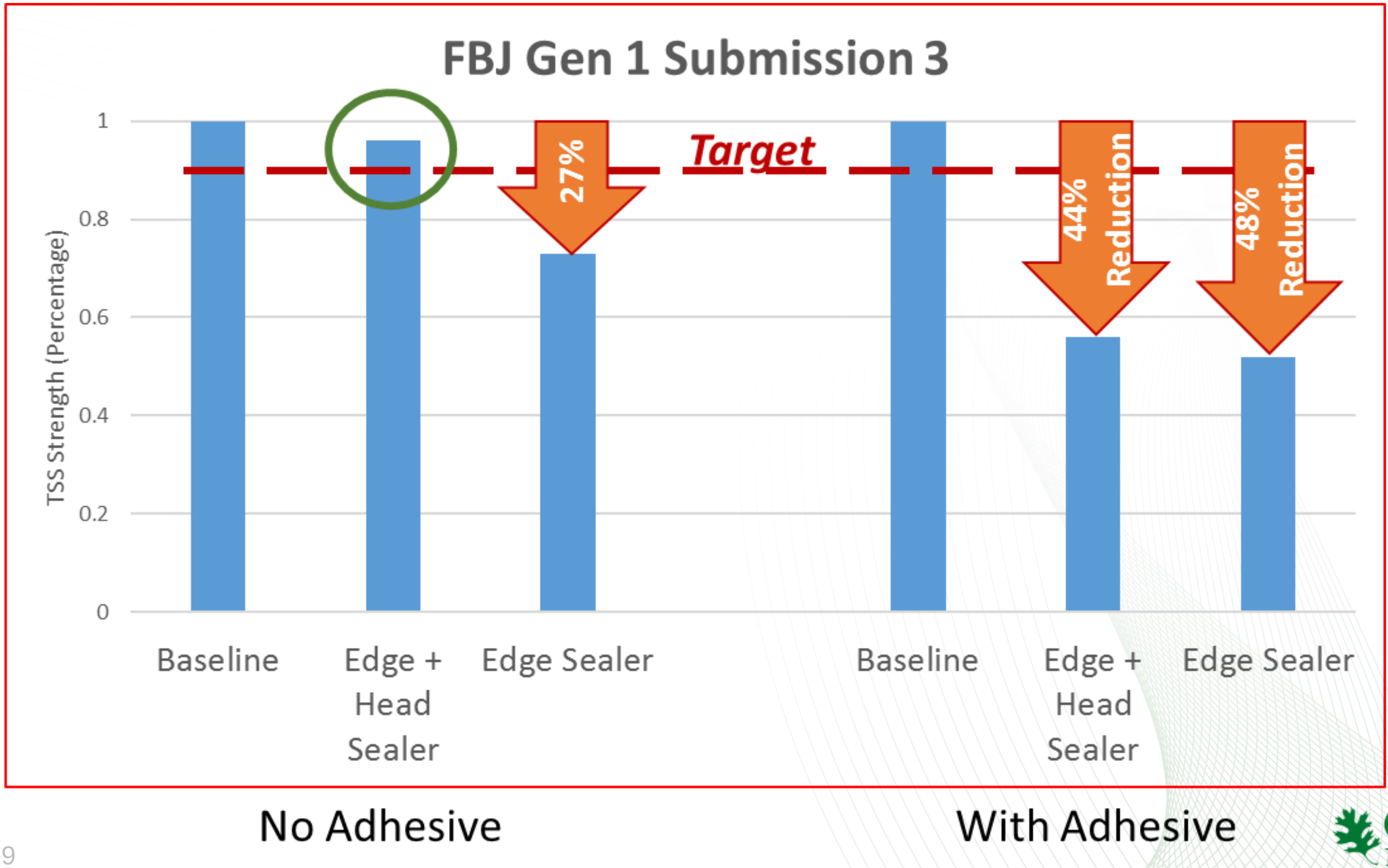
Accomplishment: Cyclic Corrosion Test

Target: Post CCT strength within 90% of original pre-CCT strength

- New coupon style tailored to support sealer systems improved assessment activity.
- Significant galvanic corrosion present with exposed fastener head.
- Without adhesive, tight joint fit helped to avoid crevice corrosion (above target).
- With adhesive, inconsistent joint fit & sealer covered degraded adhesion continuity.
- Technique improvements for prepared corrosion coupons will allow for validation of joint durability.



Accomplishment: Cyclic Corrosion Test

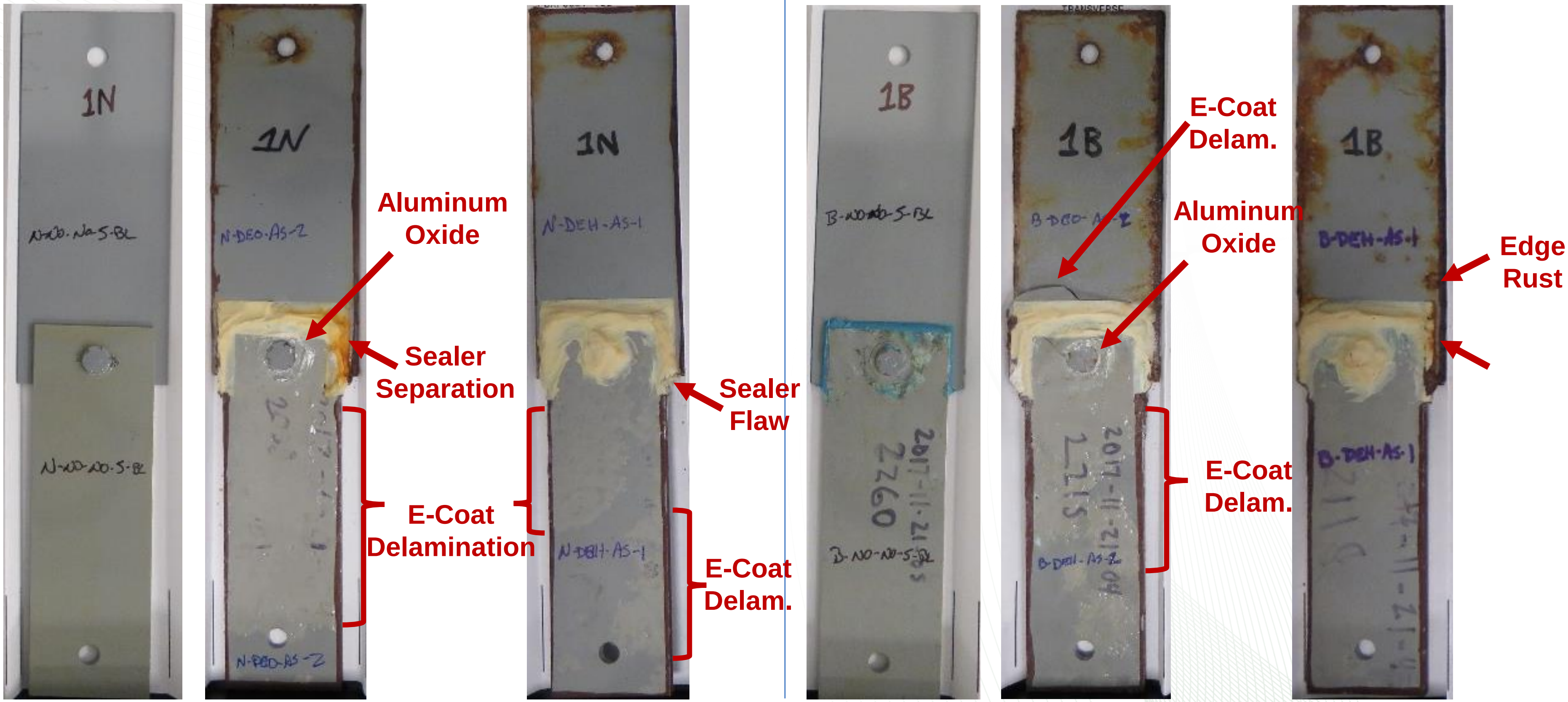
Post CCT inspection of multi-material coupons showed various levels of corrosion:
E-coat delamination, edge rust, aluminum oxide, gapping between sealer to substrate.

No Adhesive

Baseline | **Covered Edge** | **Covered Edge & Head**

With Adhesive

Baseline | **Covered Edge** | **Covered Edge & Head**

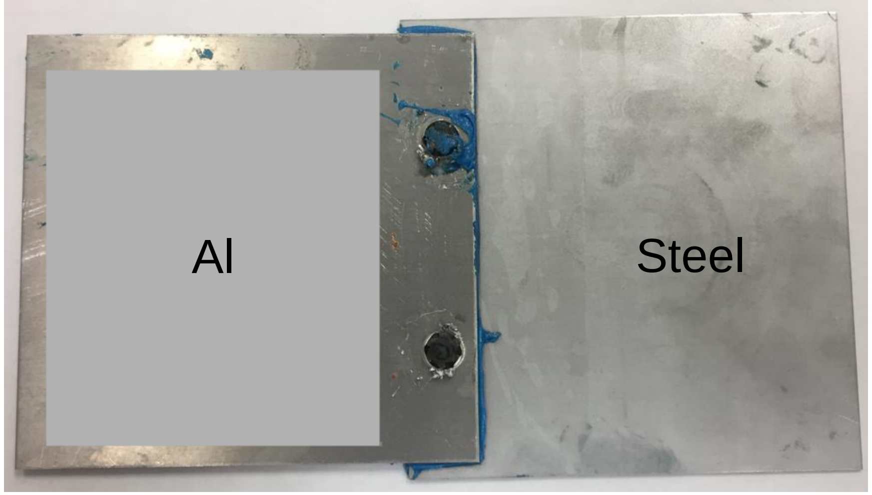


Methodology improvements for sample preparation are still possible as coupons attempt to recreate production intent processes using sealer materials for isolation.

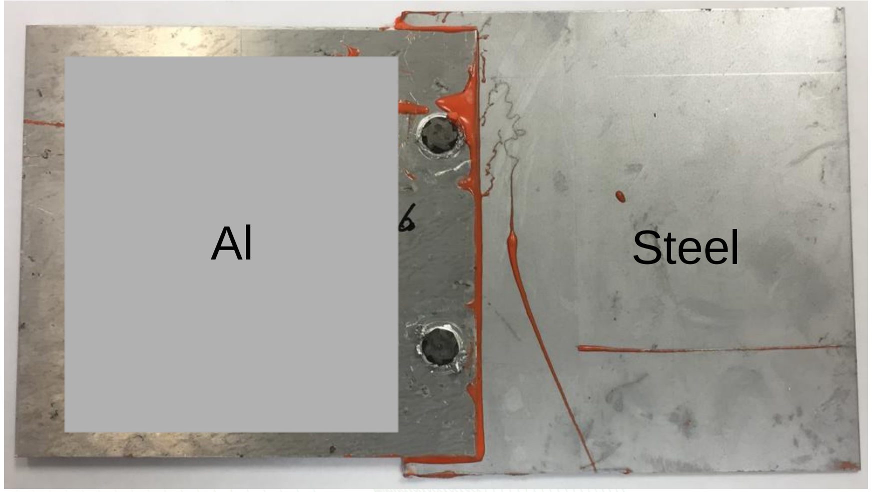
Accomplishment: Weldbonding of scale-up coupons

- Weldbonding (FBJ with adhesive) was developed on scale-up coupons prior to joining of sub-component parts.
- Lap shear tensile testing was performed, but joint strength with each adhesive is not disclosed to public based on IPMP agreement.
- Down-selection of adhesive for Phase 3 was made after review process.

Weldbonding (adhesive A)



Weldbonding (adhesive B)

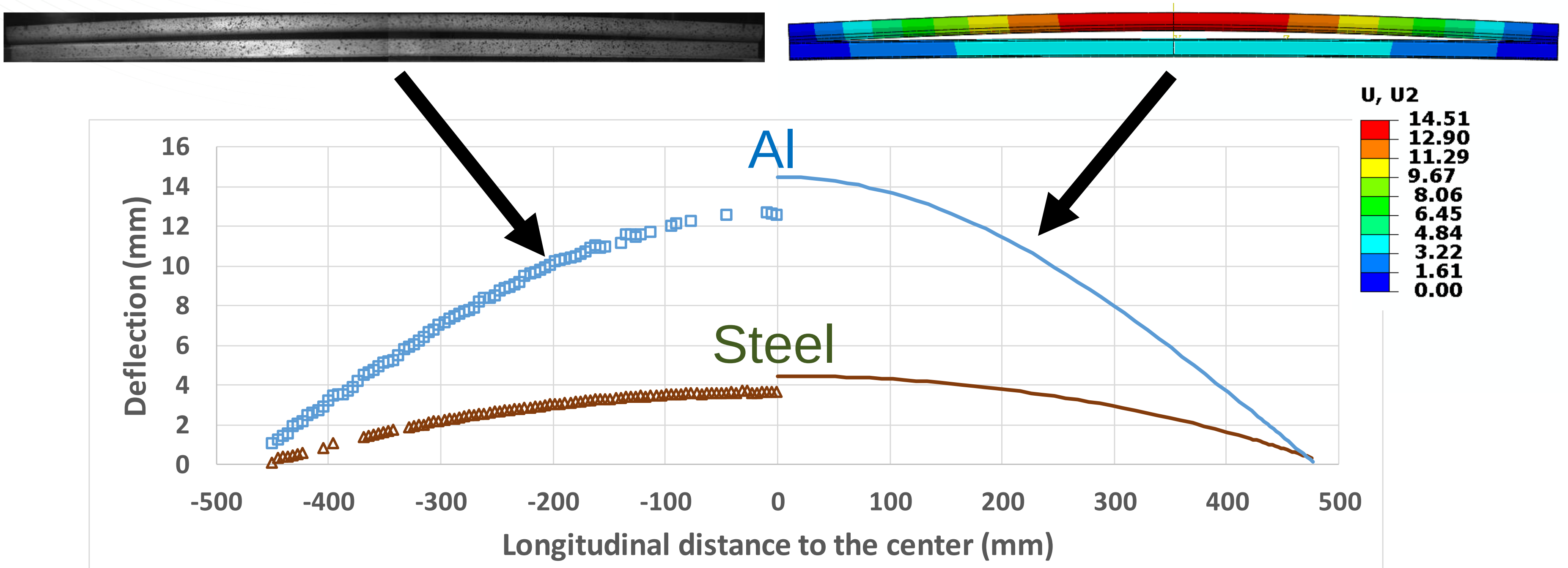


Accomplishment: Thermal expansion mismatch effect in joining dissimilar materials

In-situ distortion measurement by Digital Image Correlation (DIC) technique is being developed to experimentally determine the part dimensional change during paint baking process, to support and guide numerical modeling development and validation

DIC measurement

Numerical distortion model

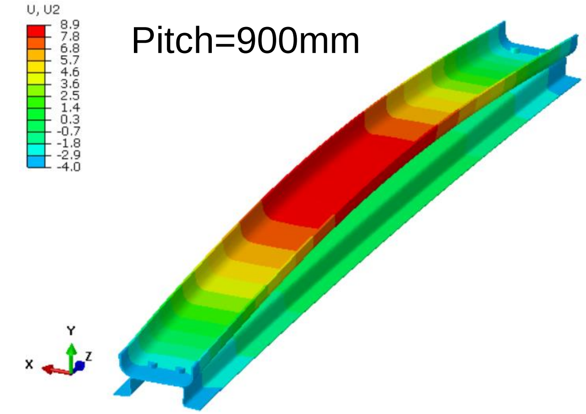


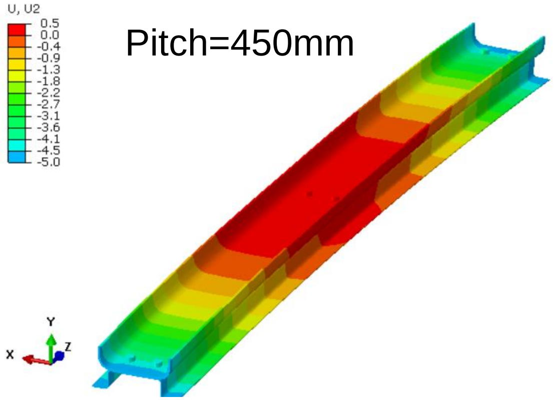
Panel Length	Flange Height	Al Alloy	Initial Gap at center (mm)	Gap (mm) at 197°C	Residual Gap (mm), DIC	Residual Gap (mm), Caliper	Panel ID
Full	½	6111	0.6	9.09	2.36	-	F-H-6111-1

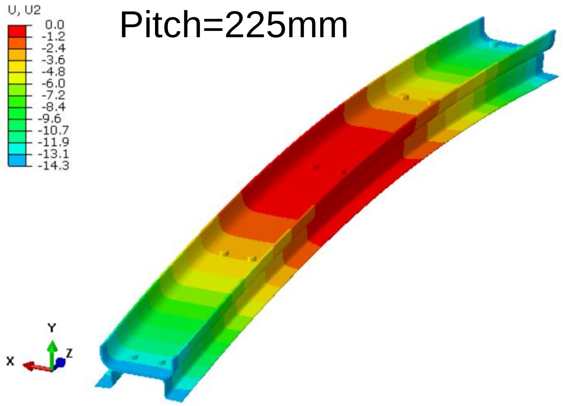
Accomplishment: Managing thermal distortion effect with different weld pitches

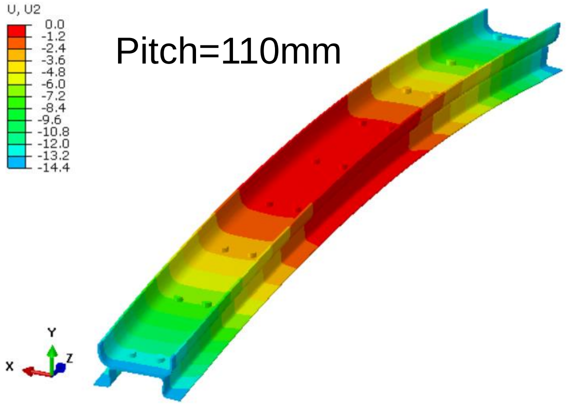
To quantify the maximum gap and residual gap between Al/steel component under different pitches and explore options to minimize thermally-induced distortion of Al-steel sub-assembly due to CTE mismatch

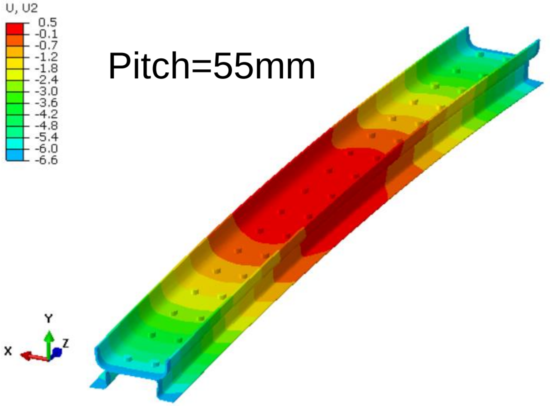
- Reducing pitch distance significantly reduces thermal distortion. Overall thermal distortion ranges from 5mm~14mm.
- Pitch distance also influences local stresses in the joint region.


Pitch=900mm


Pitch=450mm

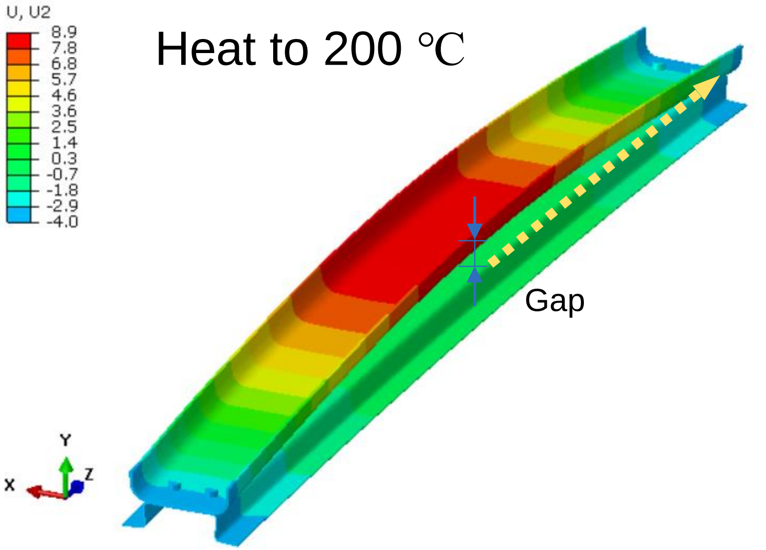

Pitch=225mm


Pitch=110mm

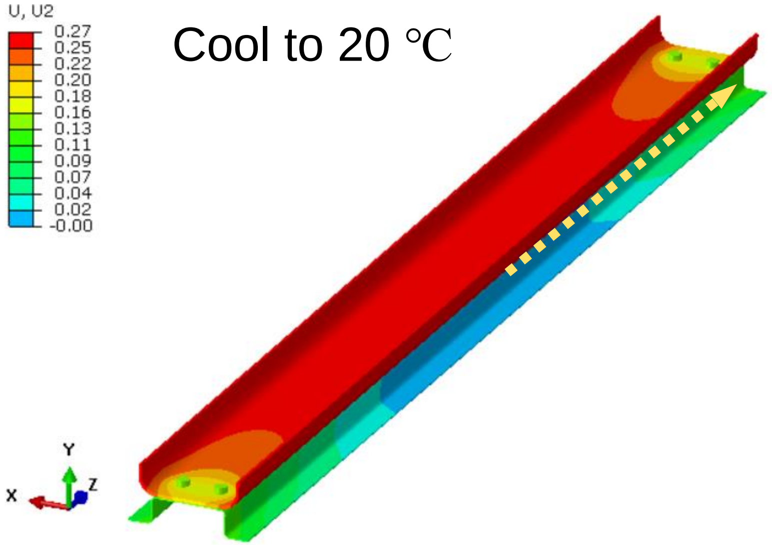

Pitch=55mm

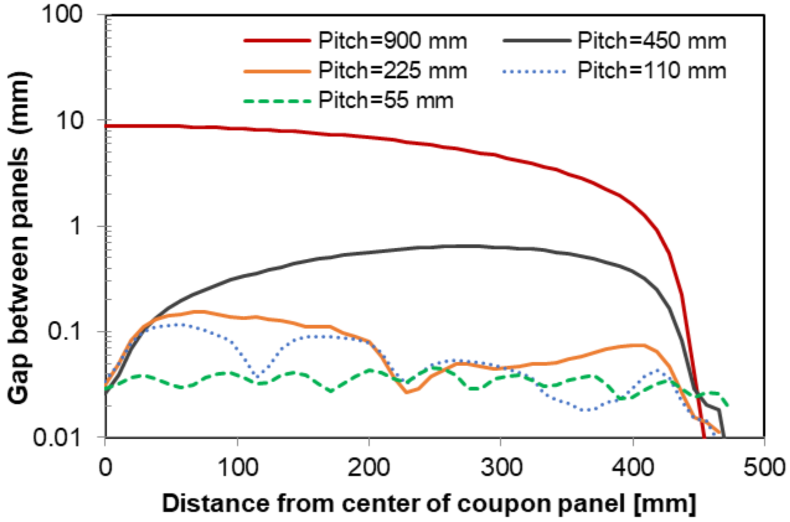
Accomplishment: Managing thermal distortion effect with different weld pitches

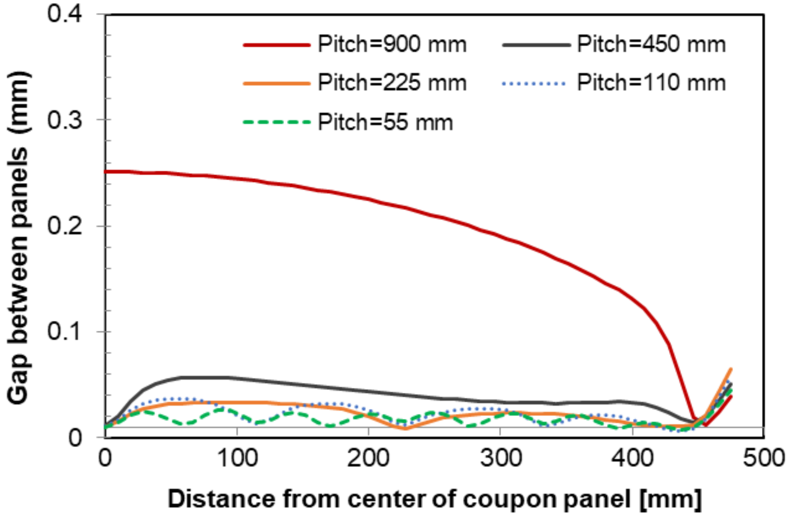
Heat to 200 ℃



Cool to 20 ℃



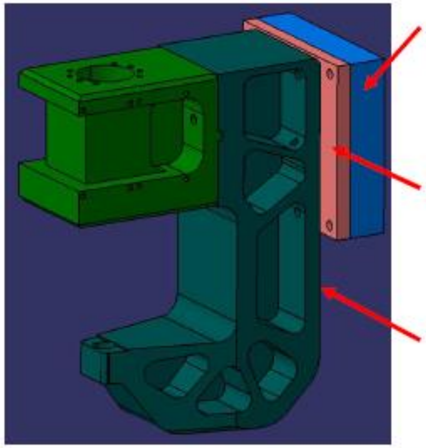




The case pitch-55 has very small gap (<30μm) during heating and cooling

Accomplishment: Refinement of FBJ C-frame design

MJD C-FRAME OPTIMIZATION MACHINING FRIENDLY



Plate, 2" Aluminum

Plate, ¾" Steel
Mass : 6.3Kg

C-Frame, Steel
Mass : 53.9Kg

FRAME, PROP-3
MASS : 60.2Kgs
(-10Kgs)

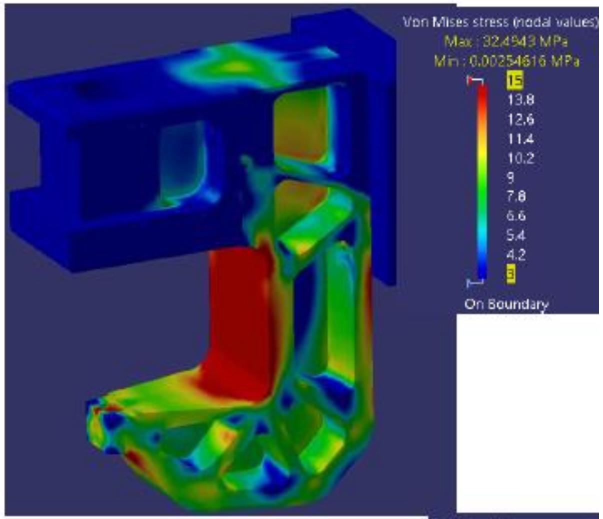
14.25%

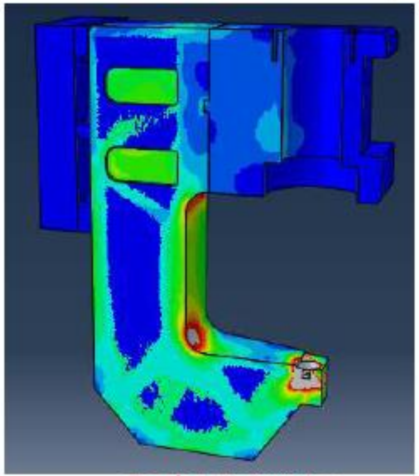
OUTPUT:
0.125 mm
Displacement

After Machining Group consultation, base profile was simplified to a more basic rectangle (added adaptor plate, in addition to representative robot mounting plate) and 3rd round optimization showed rib locations (interpreted based on tool size and pocket depth criteria)

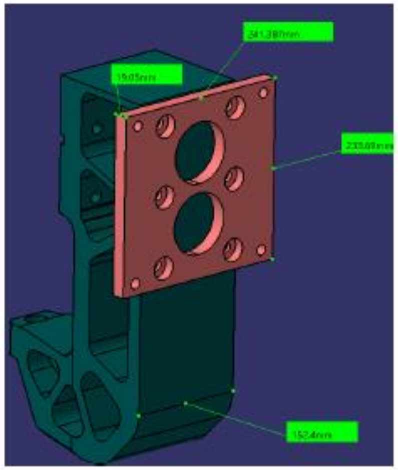
→ 10kg weight reduction of C-Frame + Plate combination.

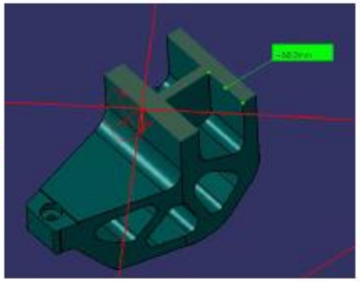
→ Next step: Bearing Block

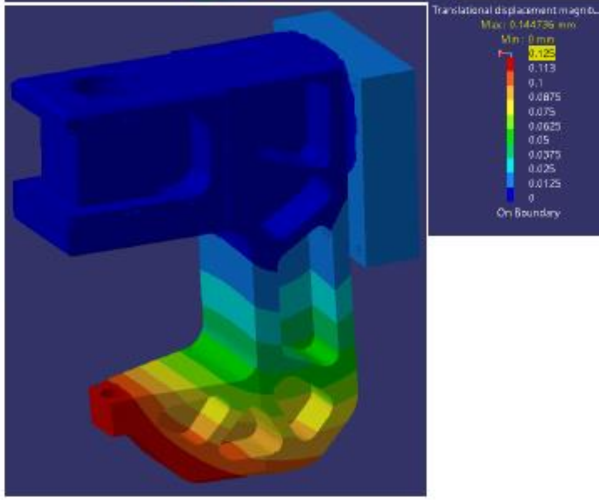




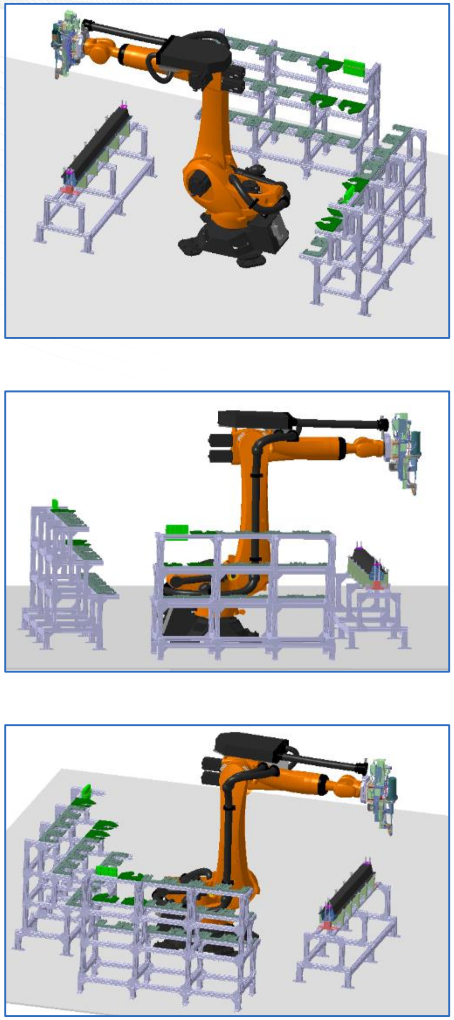
Topology Optimization Results

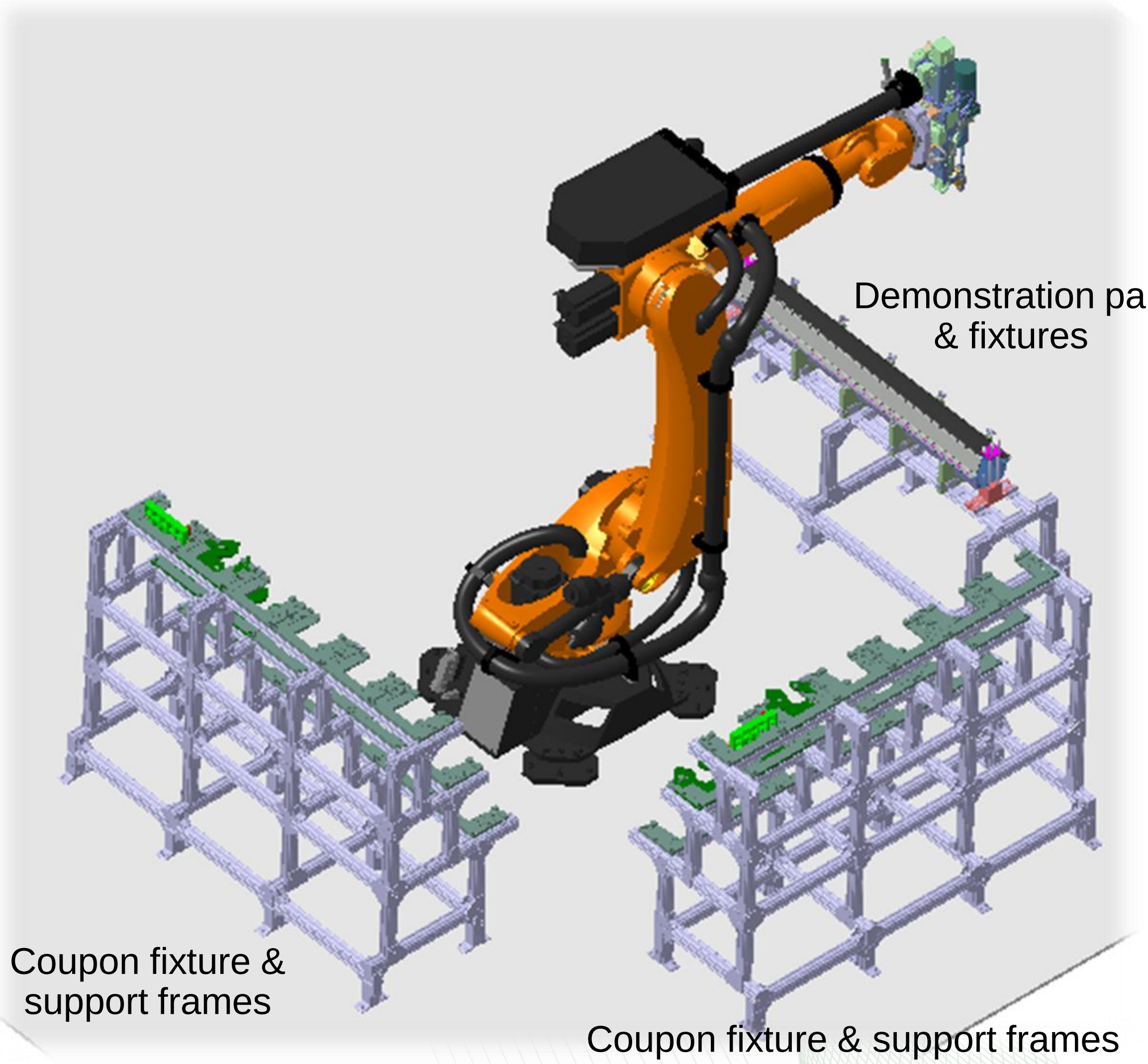






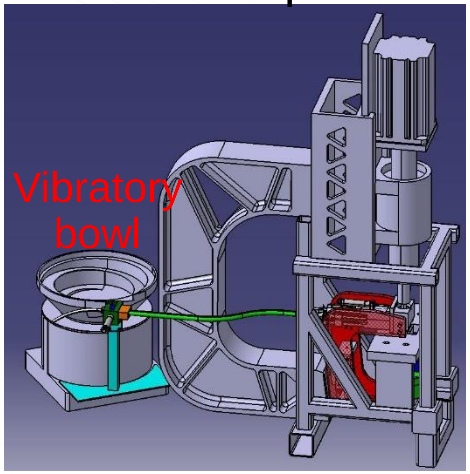
Accomplishment: Weld cell fixture design for Phase 3

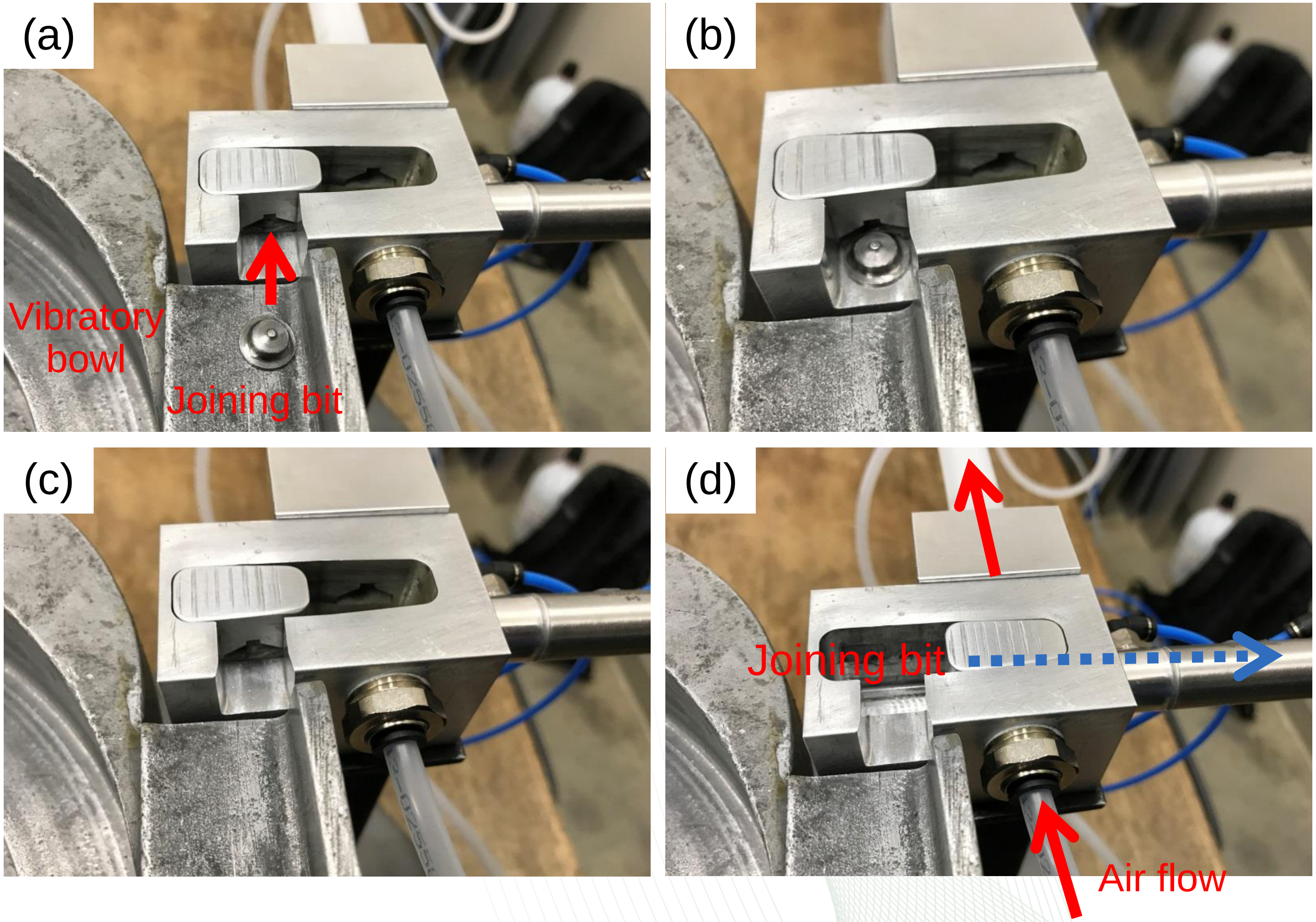




Accomplishment: Automated joining bit feed system

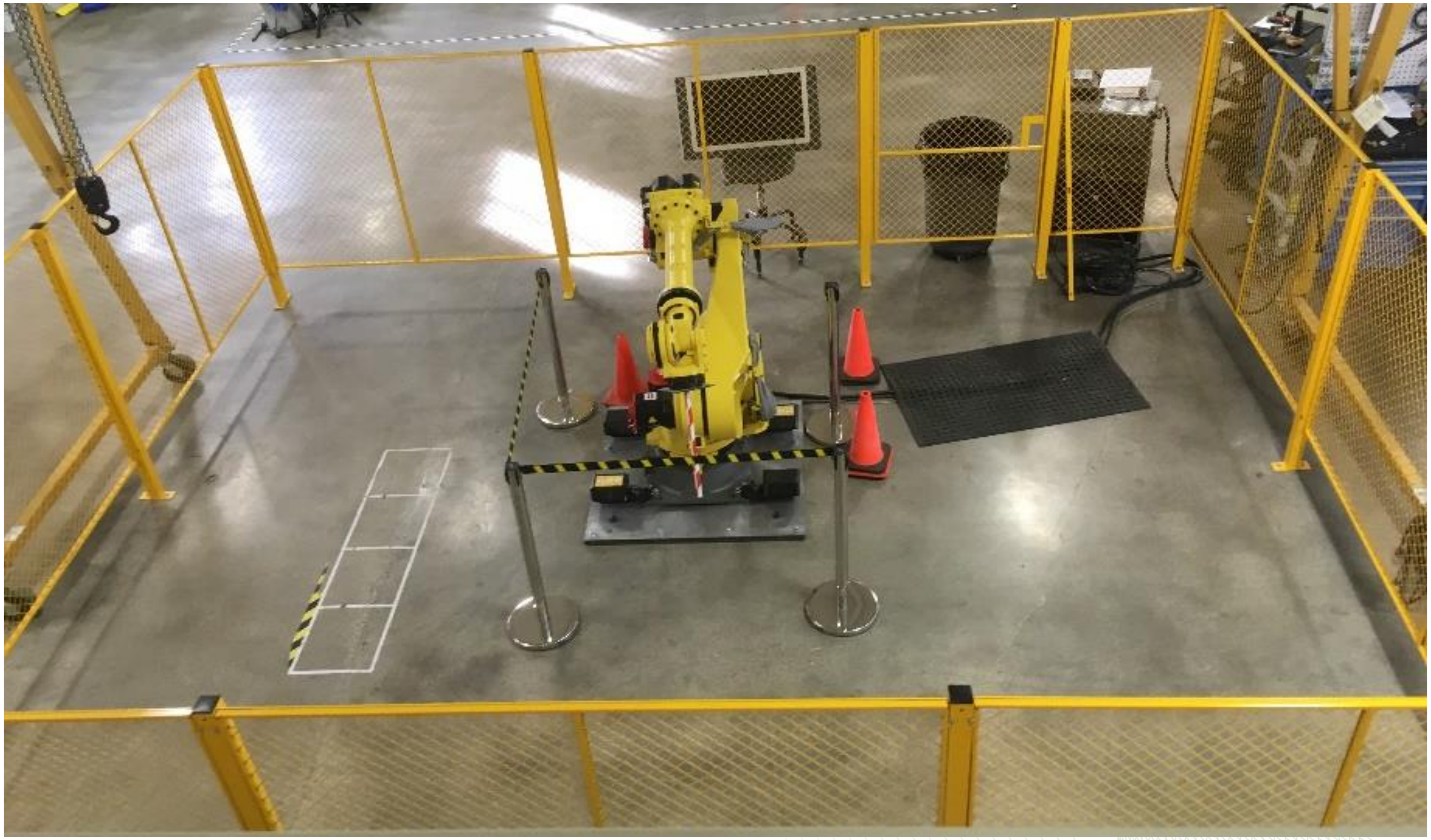
Concept





Accomplishment: installed robot at weld cell

Coupon fixtures, supporting frames, demonstration part and fixtures were shipped to the industrial partner facility and will be integrated with robot at weld cell.



Responses to Previous Year Reviewers' Comments

- ***The chemistry of adhesive used should be presented. An understanding of temperature at the joint interface on adhesive degradability?***

  There are two adhesive team members (Dow and L&L). Per CRADA requirement, the chemistry of adhesives are proprietary at this stage. The effects of temperature from spot joining on adhesives have been examine. They are rather localized within ~1mm from the bonded region, as revealed in FBJ process model and observation of broken samples. They have minimal effects on the joint strength and corrosion resistance from coupon level test.

- ***Predictive capability of microstructure model, and how this effort will integrate into the process***.

  The microstructure model is under development. It is based on phase transformation theories high strength steels and Al alloys, therefore applicable to the AHSS and Al alloys commonly used in auto BIW. The model is informed by experiments. The basic input of the model are chemistry, microstructure of base metal, and welding thermal cycles. The predictability of microstructure model will depend on the predictability of welding process model. In this regards, the process model, microstructure model, and performance model are integrated in this project.

Collaborations and Industry Participations

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

Remaining Challenges and Barriers

- Managing part distortion due to thermal expansion mismatch of dissimilar material at the component level.

- Ensuring adequate corrosion resistance performance at the component level

Proposed Future Work

- FY19
  - System design for component level joining. April 2019
  - System for component joining. June 2019
  - Sub-component level joining and demonstration. August 2019
  - Sub-component testing and reporting. November 2019

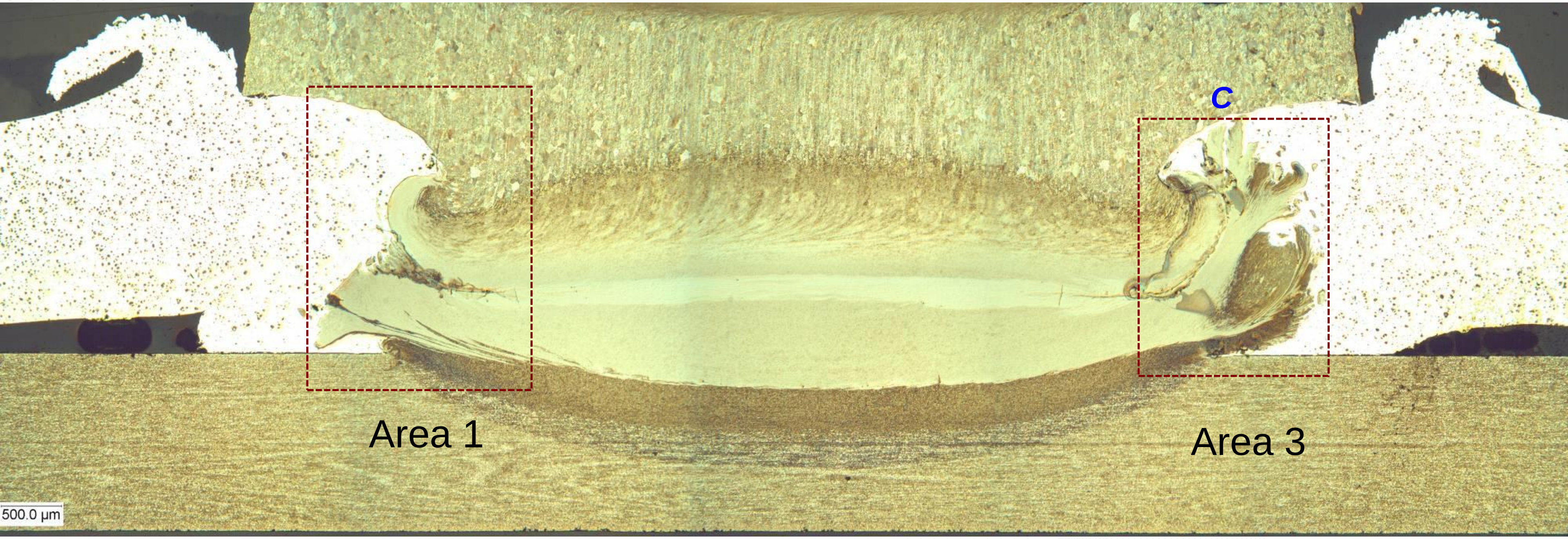
Any proposed future work is subject to change based on funding levels

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: refined joining bit design. passed multi-weld development gate. Applied for scale-up coupons with and without adhesive. Down-selected for Phase 3 • Adhesives: applied for scale-up coupons. Down-selection was made for Phase 3 • Corrosion performance of FBJ and weldbonded coupons was evaluated. Passed OEM criteria. Remedies to further improve corrosion performance are suggested. • Integrated system scale up for component level joining: refined joining bit feed systems for FBJ. Refined FBJ C-frame design • Modeling: numerical model for thermal distortion was improved and validated with experiment results. • Demonstration part joining: designed weld cell. All coupon fixtures, demonstration parts and fixtures were prepared and shipped to the industry partner.
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

Technical Back-up

DP980/AA5754 Weld Cross-Section


Metallurgical bonding

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
  - Predictive model to effectively control or mitigate component distortion and failure due to thermal expansion mismatch of Al and steel

Research Plan and Major Tasks

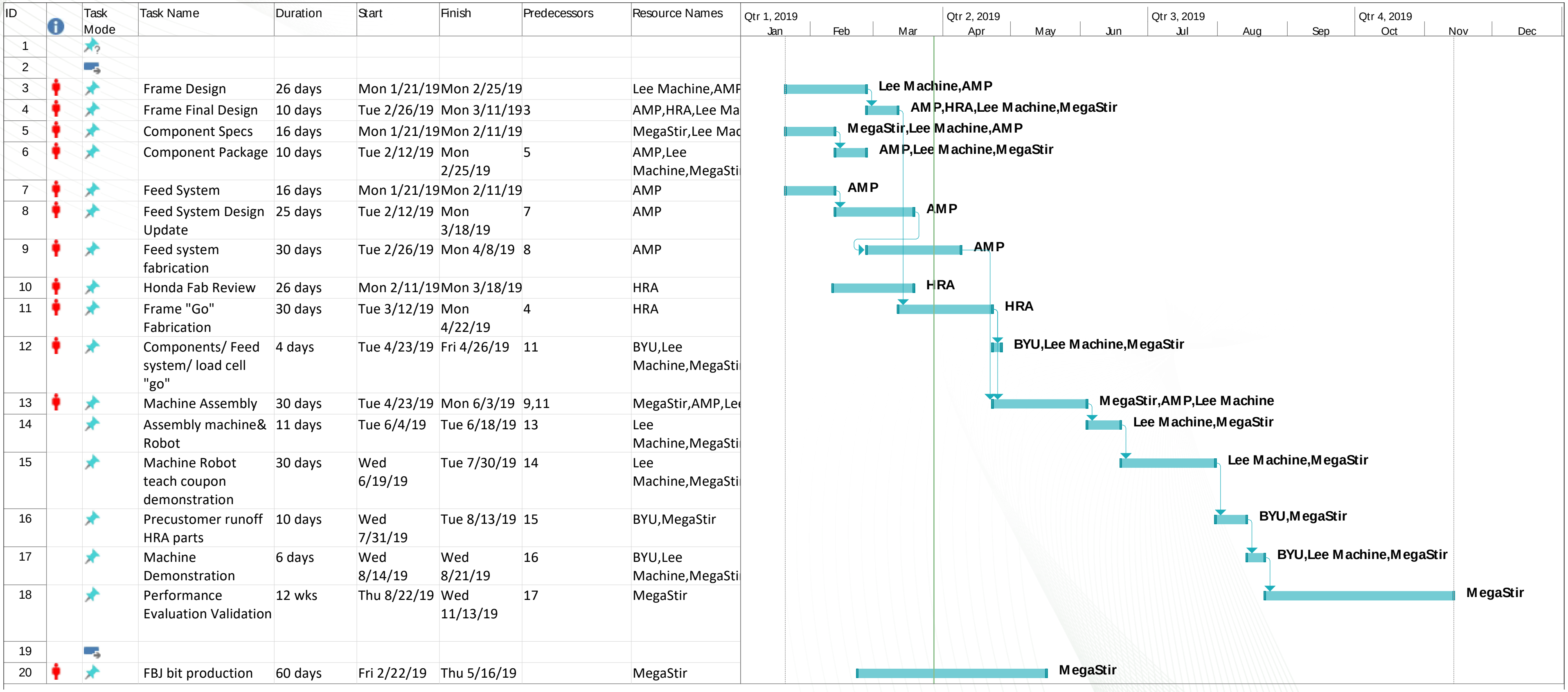
- Further develop and refine the solid-state joining process and identify process window/conditions to consistently meet the joint performance and joining cycle time requirement set forth by OEM;
- Combine adhesives with insulator properties to prevent galvanic corrosion between dissimilar metals and 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.

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

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



ID		Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1								
2								
3			Frame Design	26 days	Mon 1/21/19	Mon 2/25/19		Lee Machine,AMP
4			Frame Final Design	10 days	Tue 2/26/19	Mon 3/11/19	3	AMP,HRA,Lee Ma
5			Component Specs	16 days	Mon 1/21/19	Mon 2/11/19		MegaStir,Lee Mac
6			Component Package	10 days	Tue 2/12/19	Mon 2/25/19	5	AMP,Lee Machine,MegaSti
7			Feed System	16 days	Mon 1/21/19	Mon 2/11/19		AMP
8			Feed System Design Update	25 days	Tue 2/12/19	Mon 3/18/19	7	AMP
9			Feed system fabrication	30 days	Tue 2/26/19	Mon 4/8/19	8	AMP
10			Honda Fab Review	26 days	Mon 2/11/19	Mon 3/18/19		HRA
11			Frame "Go" Fabrication	30 days	Tue 3/12/19	Mon 4/22/19	4	HRA
12			Components/ Feed system/ load cell "go"	4 days	Tue 4/23/19	Fri 4/26/19	11	BYU,Lee Machine,MegaSti
13			Machine Assembly	30 days	Tue 4/23/19	Mon 6/3/19	9,11	MegaStir,AMP,Le
14			Assembly machine& Robot	11 days	Tue 6/4/19	Tue 6/18/19	13	Lee Machine,MegaSti
15			Machine Robot teach coupon demonstration	30 days	Wed 6/19/19	Tue 7/30/19	14	Lee Machine,MegaSti
16			Precustomer runoff HRA parts	10 days	Wed 7/31/19	Tue 8/13/19	15	BYU,MegaStir
17			Machine Demonstration	6 days	Wed 8/14/19	Wed 8/21/19	16	BYU,Lee Machine,MegaSti
18			Performance Evaluation Validation	12 wks	Thu 8/22/19	Wed 11/13/19	17	MegaStir
19								
20			FBJ bit production	60 days	Fri 2/22/19	Thu 5/16/19		MegaStir