Collision Welding of Dissimilar Materials by Vaporizing Foil Actuator: A Breakthrough Technology for Dissimilar Materials Joining

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Project ID # LM086

Overview

Timeline

- Start date - October 2013
- End date – September 2015
- Percent complete – 75%

Barriers & Targets

- Barriers addressed
  - Joining and assembly of dissimilar materials to create lightweight structures for civil and military vehicles

Budget

- Total project funding
  - DOE share: $568,499

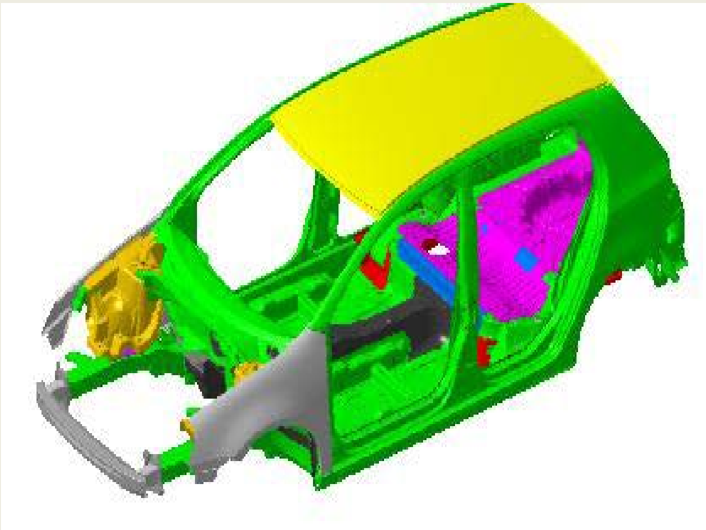
Partners

- Honda: Materials selection and procurement, industrial adaptation
- Alcoa: Materials procurement
- EWI: Industrial adaptation
- Johnson Control Inc.: Materials selection and procurement, industrial adaptation

Relevance

Objectives

- To utilize Vaporizing Foil Actuator Welding (VFAW) to create welds between pairs of three alloy systems which are relevant to land vehicles: magnesium, aluminum and steel.
- The objective of the current phase (technical feasibility) is to conduct screening tests on 15 different material combinations and downselect 5 pairs for building prototype samples.

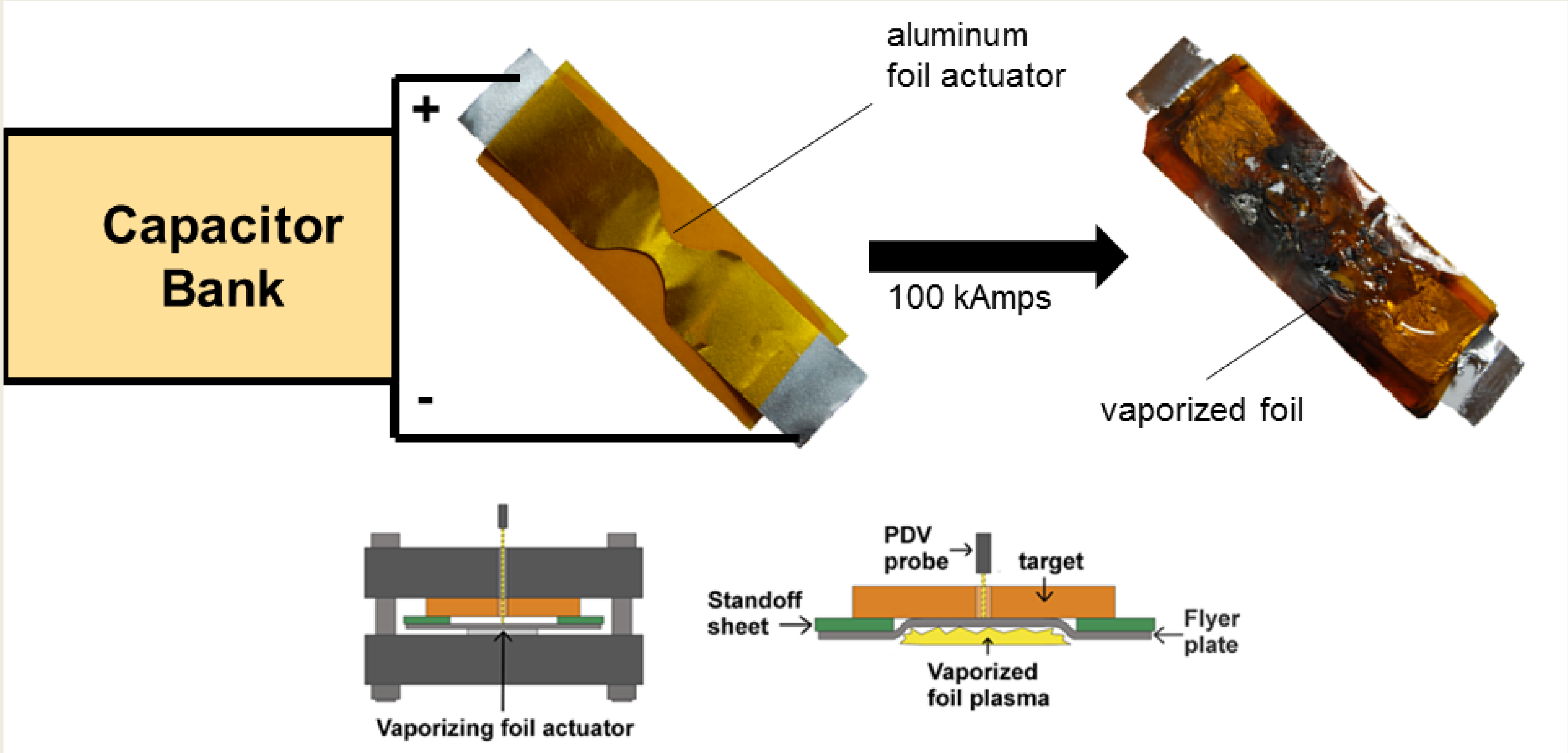


Uniqueness and Impacts

- This method develops collision welding to laboratory and industrial scale.
- While this project can help overcome fundamental barriers in the development and use of multi-material structures.
- The 2nd phase of the project also aims to develop corrosion mitigation strategies for such structures.

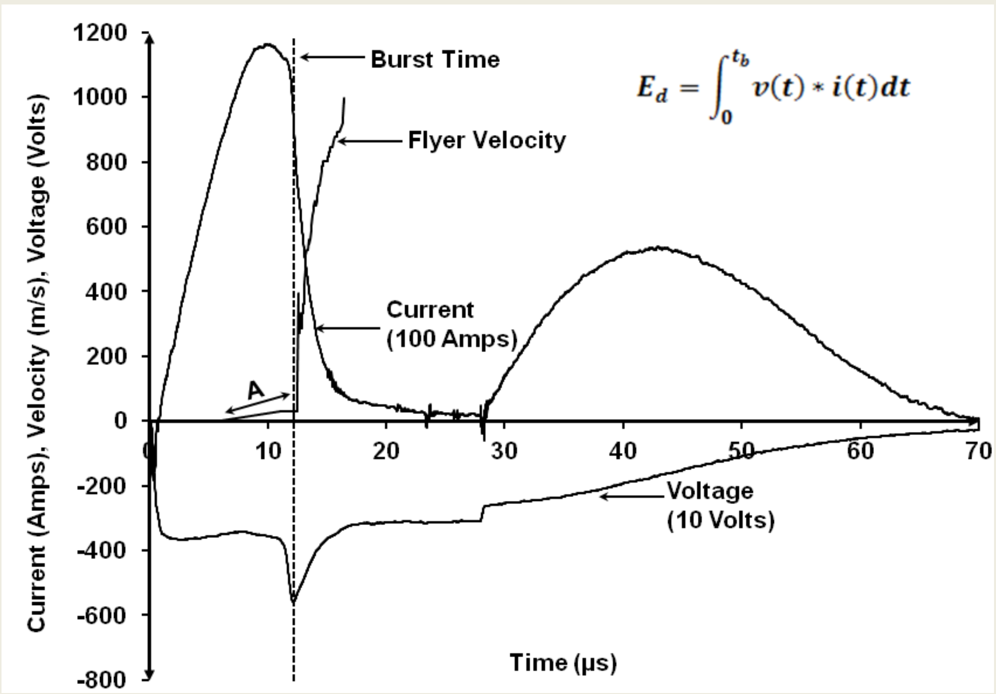
Approach: Basic Method of VFAW **NOT MPW** (Magnetic Pulse Welding)

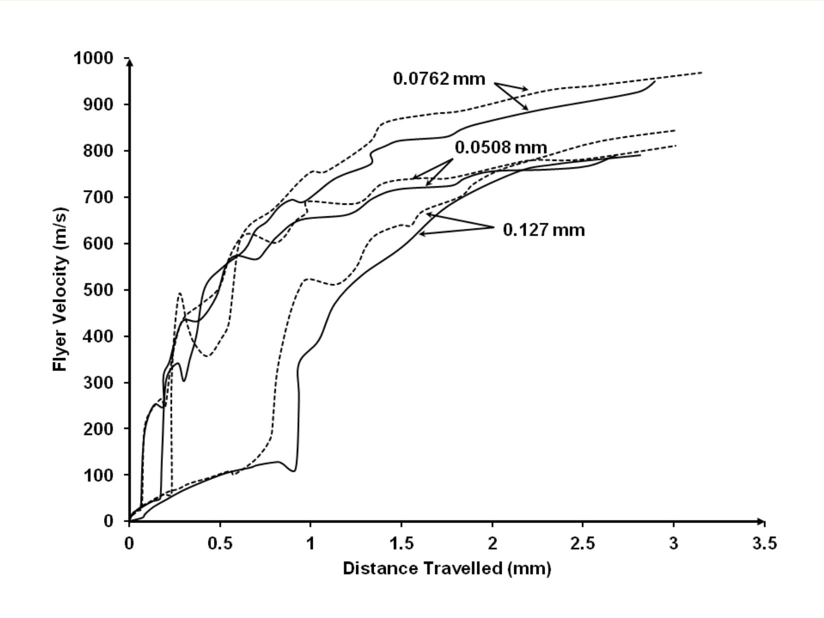
Energy is deposited at a very high rate to a thin conductor, far beyond its sublimation energy; inertia and magnetic constraint hold the foil together momentarily. The superheated conductor vaporizes discontinuously, producing a pressure pulse.

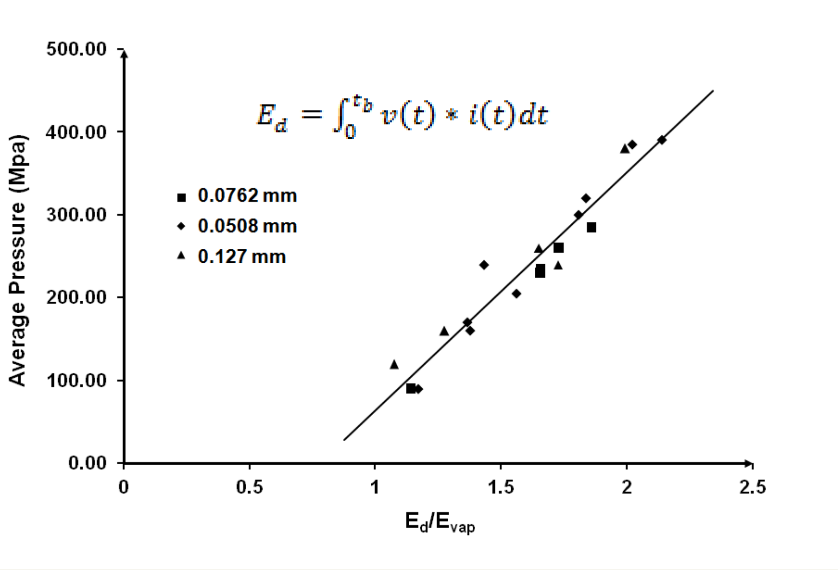


Vivek, A., Hansen, S. R., Liu, B. C., & Daehn, G. S. (2013). Vaporizing foil actuator: A tool for collision welding. *Journal of Materials Processing Technology*, *213*(12), 2304-2311

Approach: Process Detail



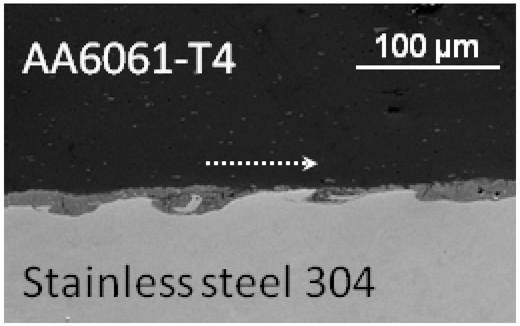




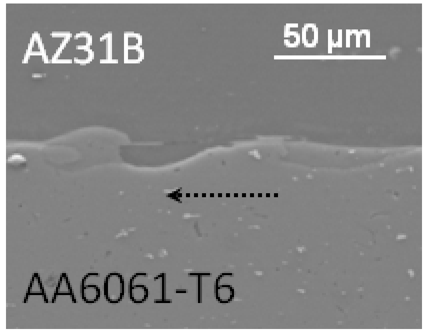
Current, voltage and velocity measurement

Vivek, A., Hansen, S. R., & Daehn, G. S. (2014). High strain rate metalworking with vaporizing foil actuator: Control of flyer velocity by varying input energy and foil thickness. *Review of Scientific Instruments*, *85*(7), 075101

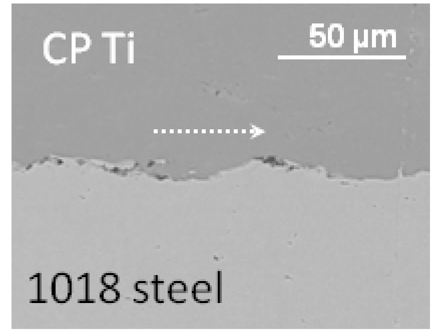
Approach: Dissimilar Welds



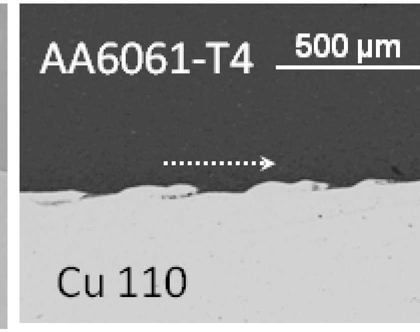
16 N/mm



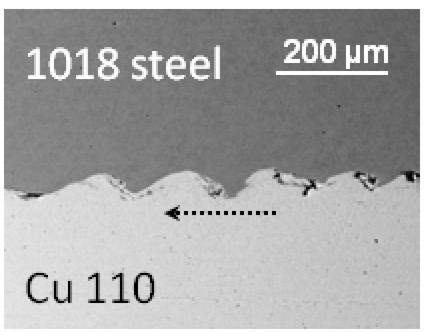
3 N/mm



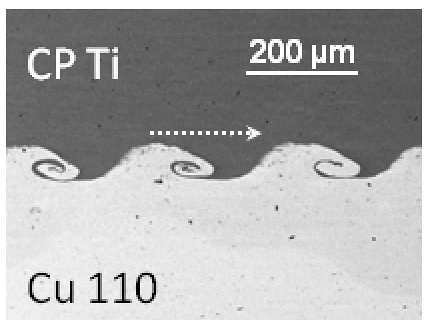
8 N/mm



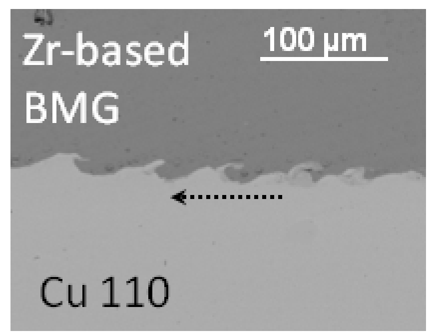
Failed in aluminum



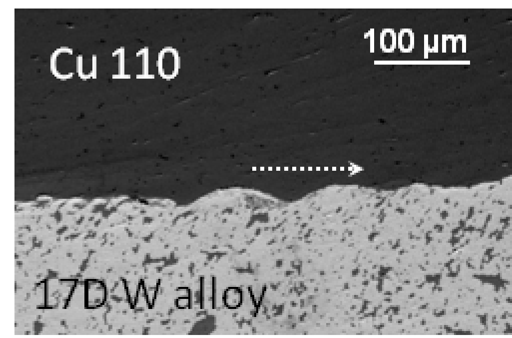
Failed in copper



Failed in copper



Failed in copper



Failed in copper

Vivek, A., Taber, G. A., Johnson, J. R., & Daehn, G. S. (2015). Vaporizing Foil Actuator: a Tool for Creating High-Pressure Impulses for Metalworking. In *60 Excellent Inventions in Metal Forming* (pp. 77-82). Springer Berlin Heidelberg.

Approach: Project

<u>Year 1: Selection of materials and systems</u>

•Goals: Industrially useful strong and corrosion resistant desired couples

•Honda, EWI, and Johnson Control Inc. assist in selection of 1mm thick sheet alloys and corrosion strategies.

•Pairs to be joined:

Al-Fe, Fe-Mg, Mg-Al and Fe-I-Al, Mg-I-Fe

•When corrosion potentials <~0.25 V different, intermediate layer may be needed.
3-layer bonding is feasible based on preliminary work.

<u>Year 2: System joint testing and characterization</u>

•Microscopy: optical microscopy, SEM, EDS

•Mechanical testing: lap shear, peel

•Corrosion testing: B-117 (with and without e-coating)

•Characterization of corrosion-tested samples: mechanical testing and microscopy

<u>Scale up and commercial viability</u>

•Strategic partnerships with OEM, Tier 1, 2 suppliers, and equipment integrators

•Ongoing interactions with Honda, JCI, EWI. Will keep work guided to utility

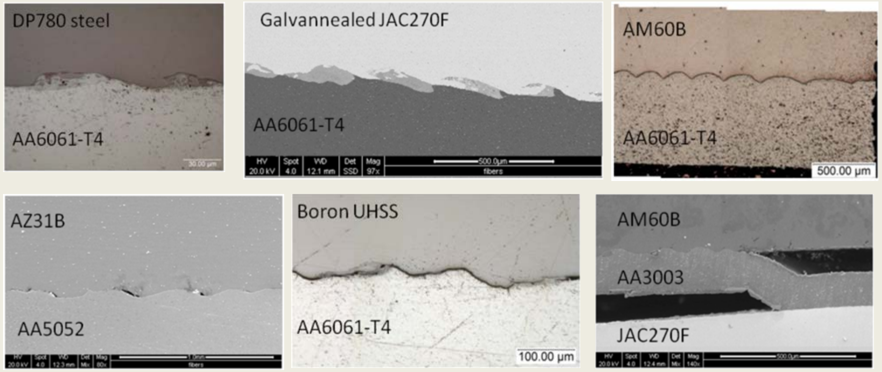
•Small efforts in: determining limits of vaporizing foil method with respect to geometries possible and length and area of foil that can be vaporized and developing a design methodology.

Milestones

Period	Task	Status
Year 1	Selection of 15 material combinations	Completed
	Screening test of the 15 material combinations	Completed
	Down selection to 5 material combinations	Completed
	Microscopy/microstructural analysis	Completed, but further work will continue
Year 2	Mechanical testing	In progress
	Corrosion testing	In progress
	Microscopy of corrosion-tested samples	Upcoming
	Mechanical testing of corrosion-tested samples • Retain 80% strength	Upcoming
	Developing techniques and fixtures for industry readiness	In progress

Technical Accomplishments and Progress

- Screening test of 17 metal combinations has been completed by VFAW
- 6 metal combinations have been selected for further investigation in the second year:
  - DP780/AA6061-T4
  - JAC270F/6061-T4
  - AM60B/AA6061-T4
  - AZ31B/AA5052
  - Boron steel (1.5 GPa)/AA6061T4
  - AM60B/AA3003/JAC270F (uncoated)

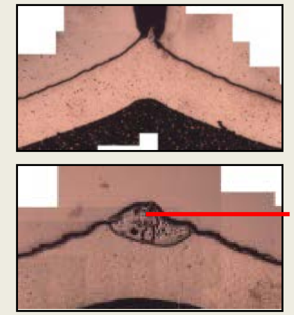


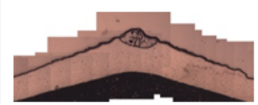
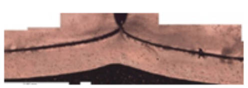
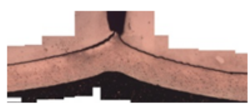
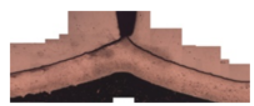
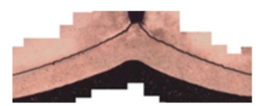
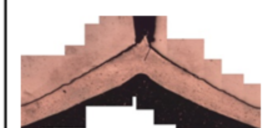
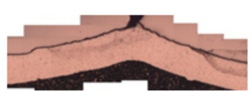
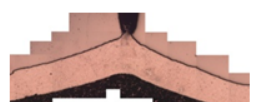
- Vacuum and through slots were successfully implemented to improve HSLA/Al welding in the grooved-target configuration
- *Pivot in screening method: flat lap welding*
- Optical microscopy and SEM for analyzing the microstructure of joint
- Mechanical testing: peel and lap-shear testing done for many combinations
- SEM and EDS imaging of fracture surfaces to diagnose the nature of fracture
- Salt-spray corrosion testing of coated and un-coated samples
- Industry readiness: improving appearance of weldment; automation

Technical Progress: Improved HSLA/Al welding

1. Vacuum – eliminates air rebound

2. Through slots – eliminate jet trapping



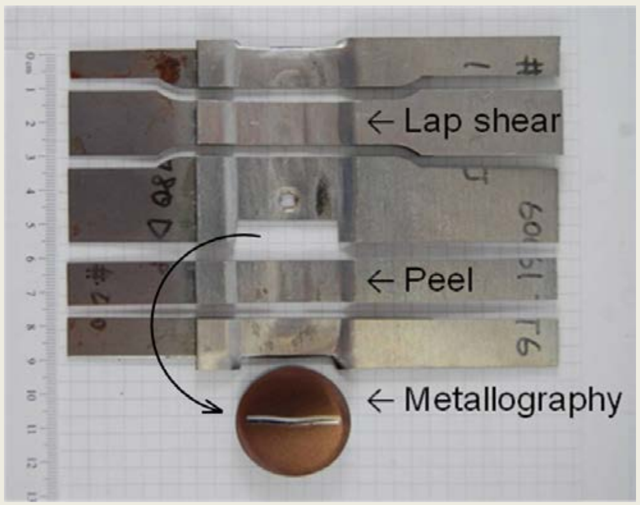
	8°	12°	16°	20°	24°	28°
#5 No vacuum	Peeled open	Peeled open	Peeled open	Peeled open		Peeled open
#6 No slots	Peeled open	Peeled open	Peeled open		Peeled open	Peeled open
#7 Best case						
#8 Lower energy	Peeled open					

Top material: HSLA a656 Bottom material: AA5052 5 mm

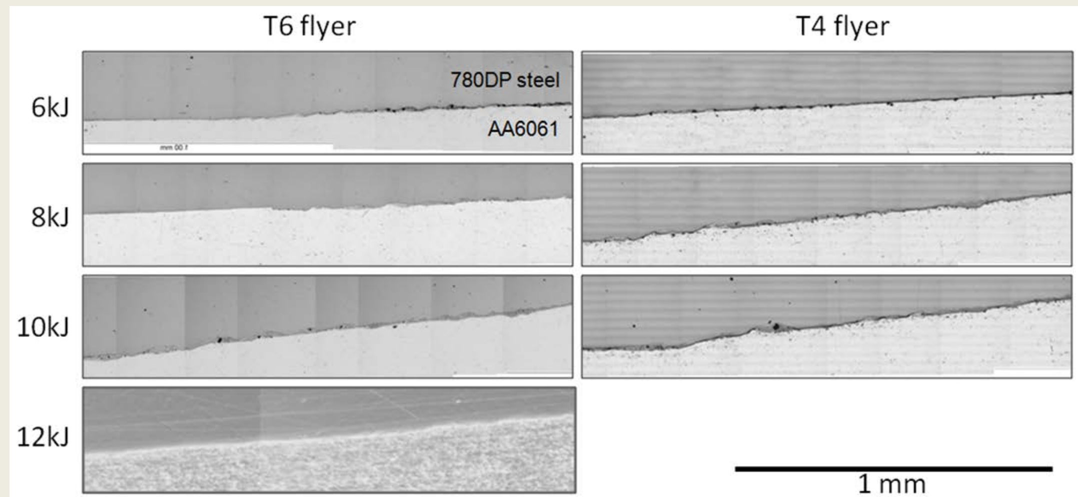
- Combination of vacuum, through slots, and higher energy yielded best result

Technical Progress: 780DP steel/AA6061

- 780DP steel/AA6061-T4 and -T6 – with Johnson Controls Inc.
  - 3 input energies (6, 8, and 10kJ) and 2 flyer tempers (T4 and T6).
  - 3 repeats at each condition. One extra sample at 12kJ, with T6 flyer.



EDM sectioning

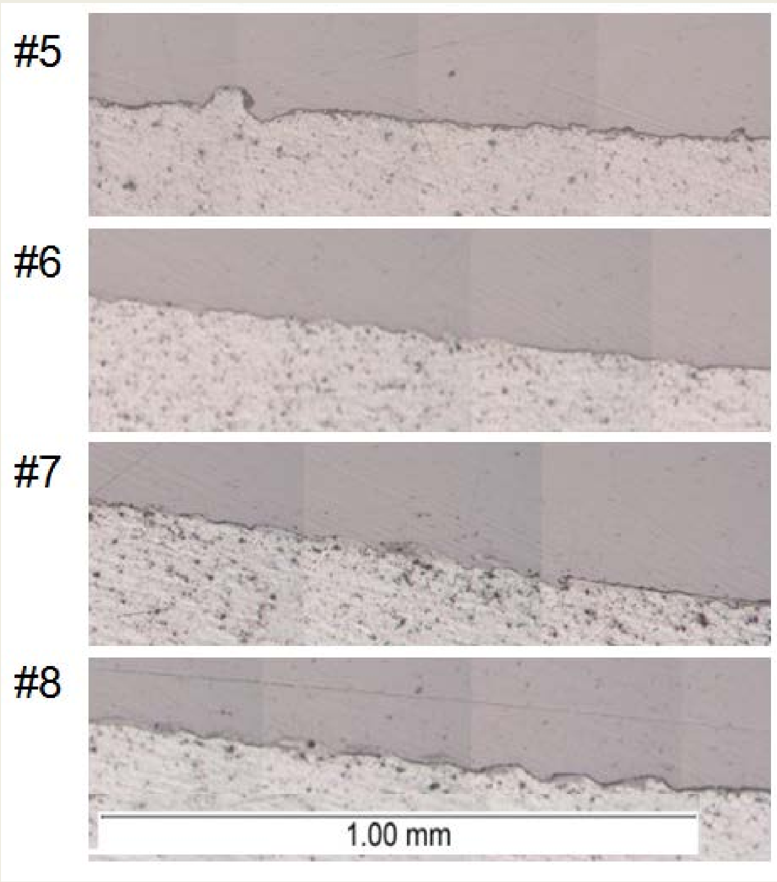


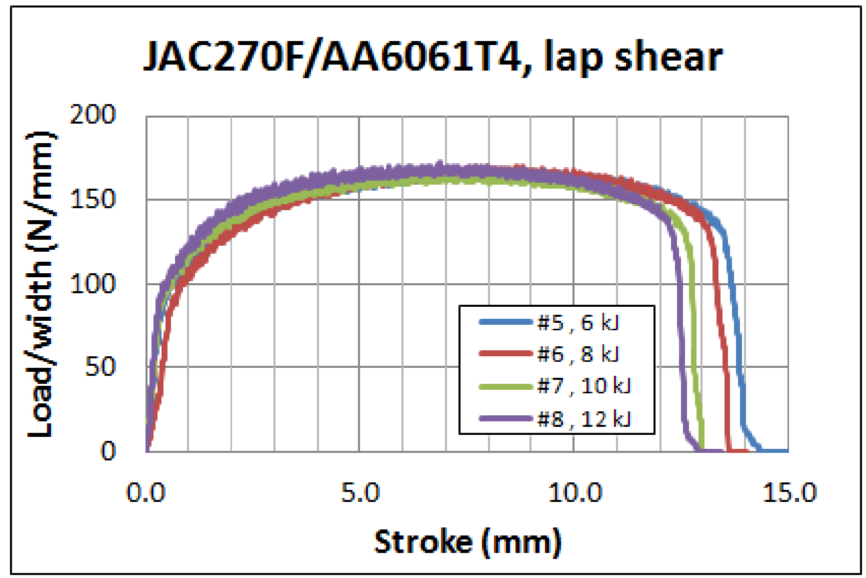
Cross sections of weld interfaces

  - All interfaces had some IMCs, but most also have IMCs-free regions.
  - In both peel and lap-shear testing, <u>most T4 welds failed outside the weld</u>, while most T6 welds failed along the weld interface.
  - Peel strength > 31 N/mm (T4); Lap Shear Strength > 307 N/mm (T6)

Technical Progress: JAC270F/AA6061-T4

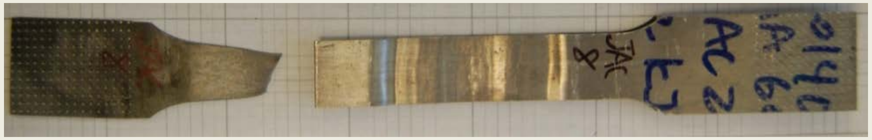
- Galvannealed steel JAC270F, with Zn coating ground off





Sample	Peak shear load (N/mm)	Site of failure
#5, 6 kJ	169.39	Fe
#6, 8 kJ	169.86	Fe
#7, 10 kJ	167.34	Fe
#8, 12 kJ	172.31	Fe

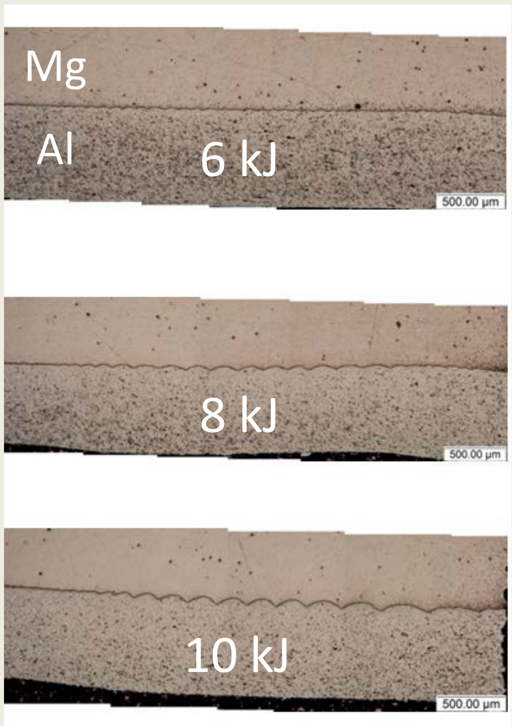
In lap-shear, failure consistently occurred in the steel:



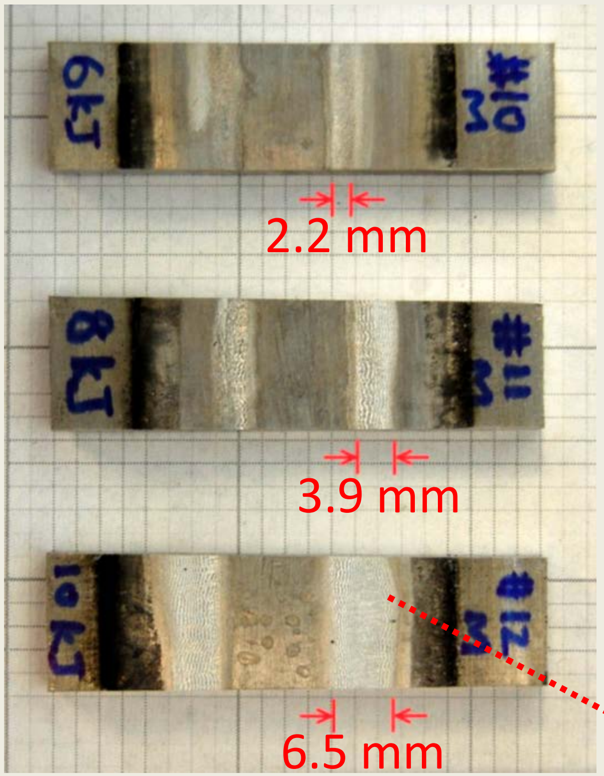
Technical Progress: AM60B/AA6061T4

- AM60B (0.12"/3.05 mm)/AA6061T4 (0.032"/0.81 mm)

Cross section



Peeled surface



Average peel strength

11.93 N/mm

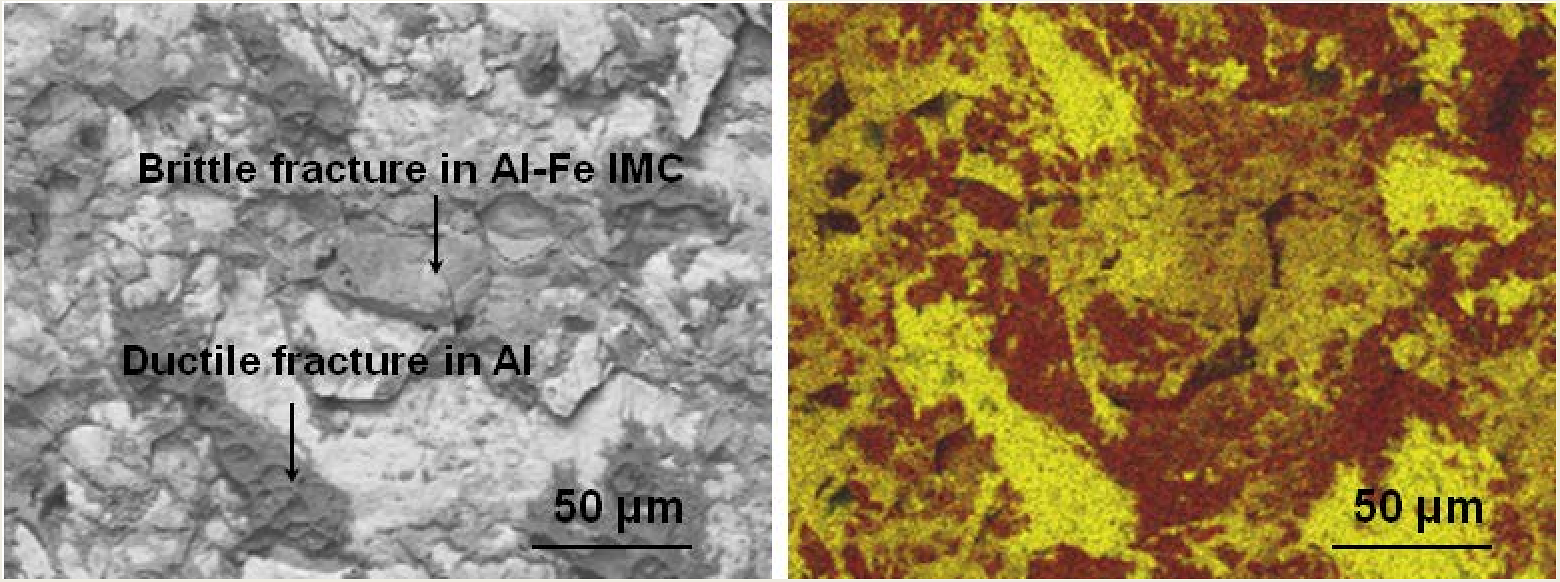
28.41 N/mm

31.44 N/mm

- In this case, higher input energy yielded "wavier", larger, and stronger bonds

Technical Progress: Studying Fracture Surfaces

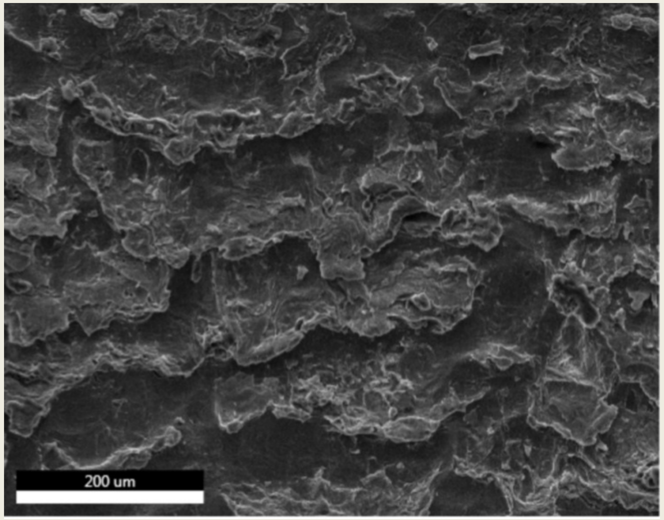
- 780DP steel/AA6061 SEM image (left) and EDS map (right)

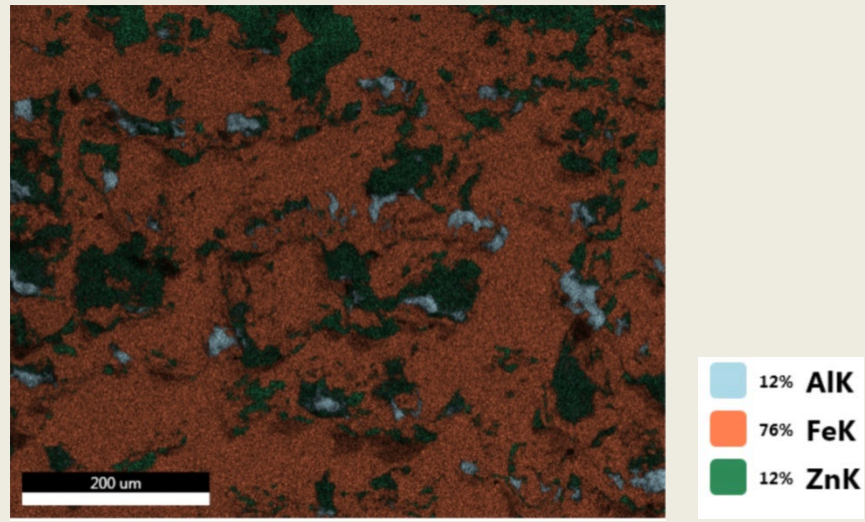


Even for the samples that seemed to through the interface in a brittle fashion during mechanical test, there are regions where good bonding occurred and mechanical failure was ductile in nature

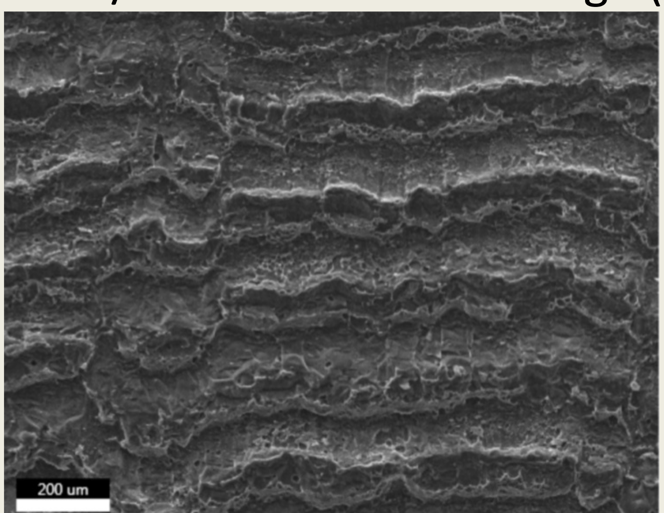
Technical Progress: Studying Fracture Surfaces

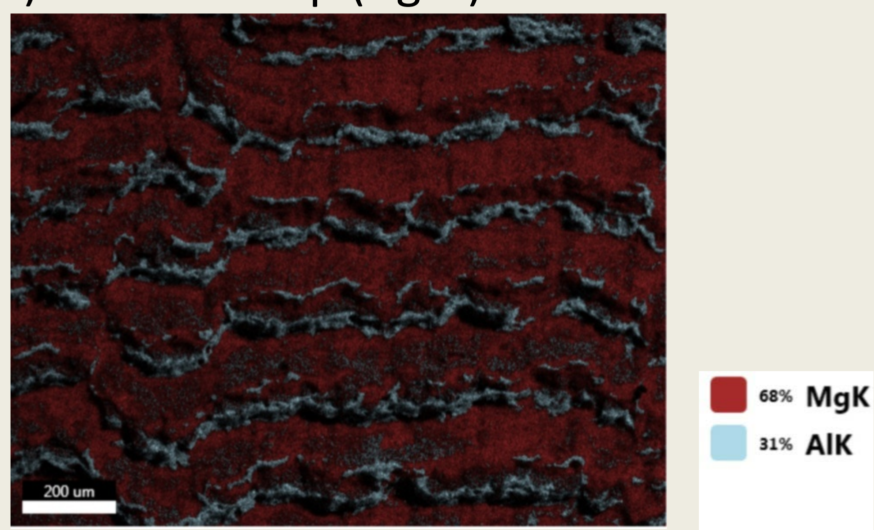
- JAC270F/AA6061-T4: SEM image (left) and EDS map (right)





- AM60B/AA6061-T4: SEM image (left) and EDS map (right)





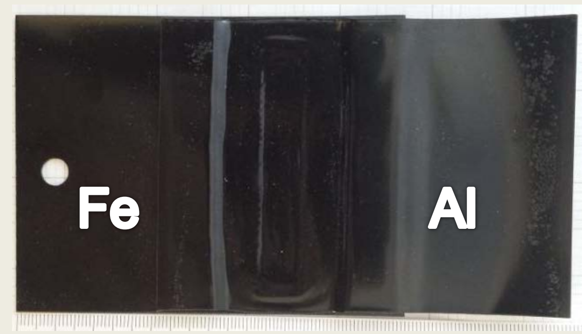
Technical Progress: Corrosion testing

- 780DP/AA6061T4: uncoated vs. coated, in B117 salt-spray (35° C, 5% NaCl)
  - Preliminary results after 24 hours in the chamber:

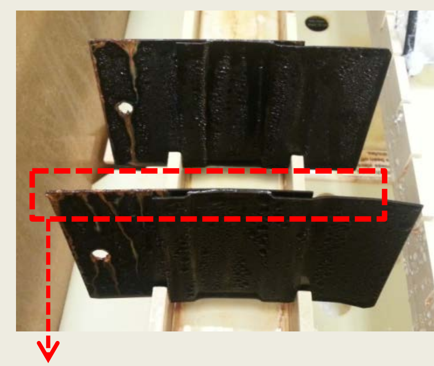
← Uncoated

vs.

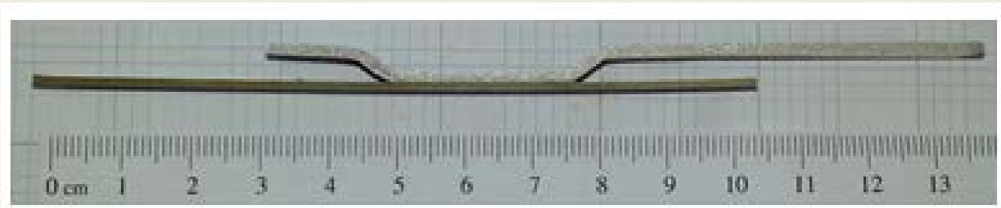
Coated →



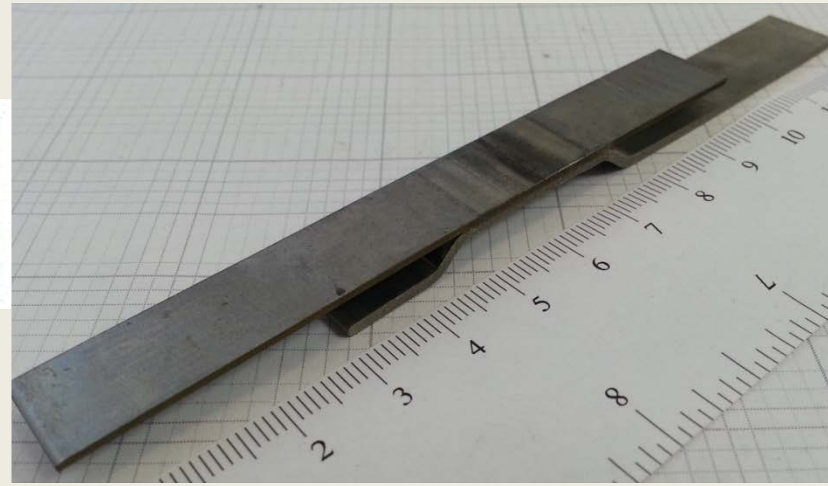
  - Fe suffered general corrosion.
  - The coated samples were returned for longer corrosion testing.
  - Fe suffered general corrosion at the edges (coating defects).
  - No corrosion on Fe near Al, perhaps due to galvanic protection.
  - Some white corrosion products (?) found near Al.
  - Further microscopy work and mechanical testing will follow.



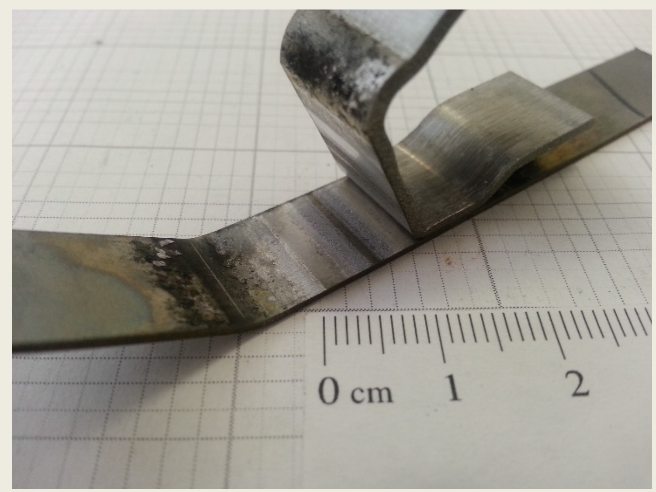
Technical Progress: Thickness Limit?



2mm thick Al6061-T4 welded to DP780 steel



5000 N

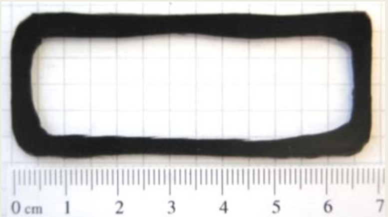


25 N/mm

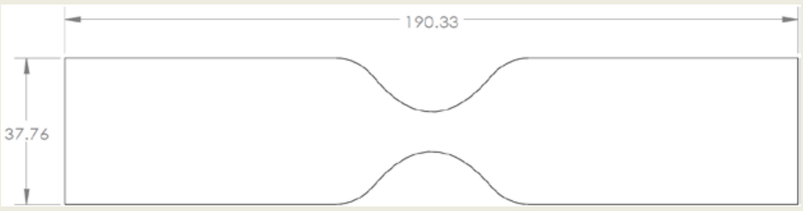
Technical Progress: Pushing for industry readiness

- Flush welds by "vanishing" standoffs

vs.



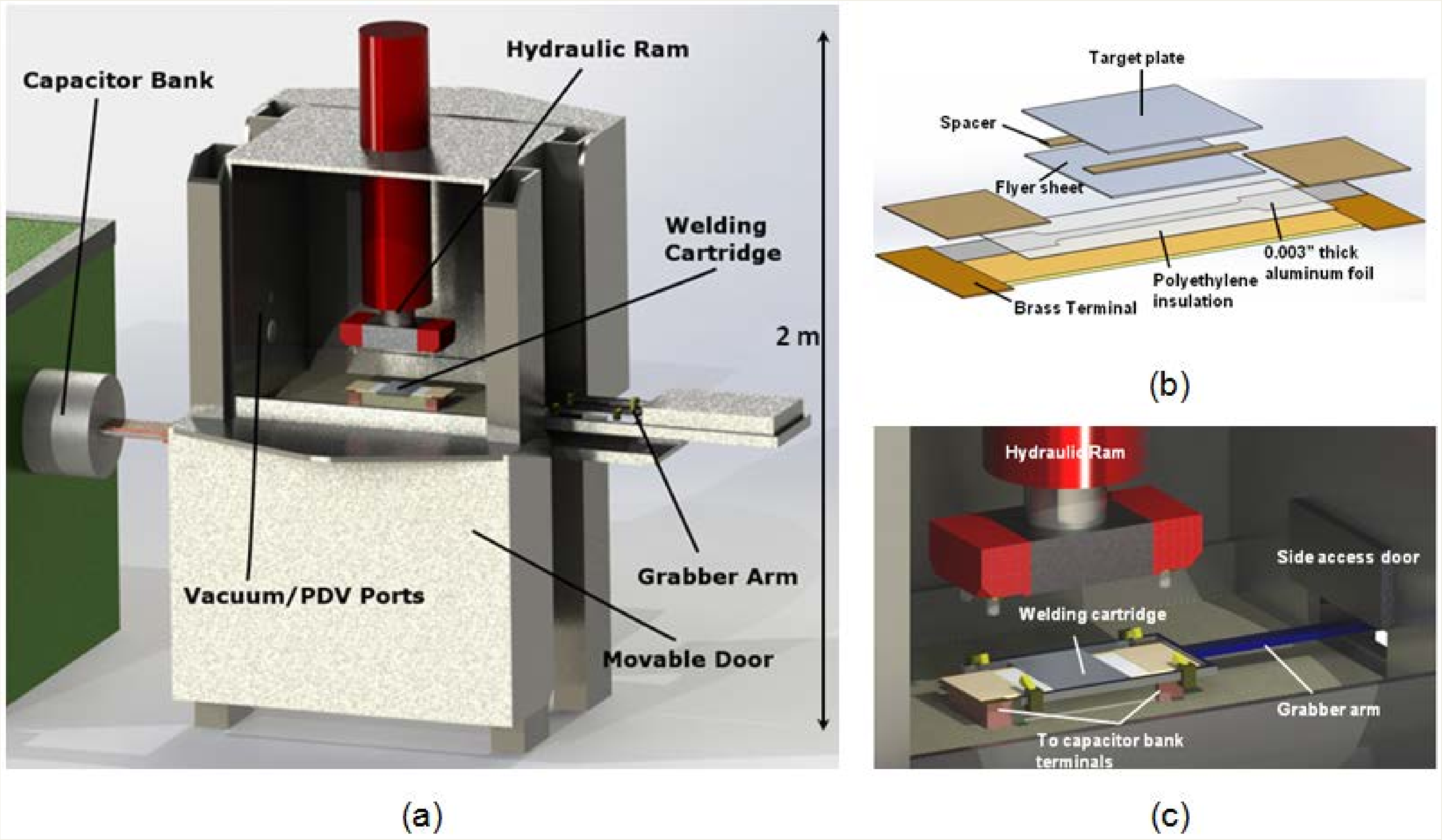
- Spot welds by special foil actuator and standoff



- "Lighter" capacitor bank: welding at < 1.5 kJ
  - Compare with 6kJ~12kJ previously—4X to 8X more energy efficient
  - More effective foil burst due to faster current rise time
  - Smaller/lighter equipment

Technical Progress: Pushing for industry readiness

- Design for automation



Answers to Reviewers' Comments

Comment	Response
"Investigation was broad and objective"	The first year of the project involved screening of 15 material combinations. In the second year, we will focus on 5 of the combinations and perform deeper investigation with microscopy, mechanical testing, corrosion testing, etc.
"The project is not a breakthrough; similar technologies have been developed more than 10 years ago."	VFAW is different MPW. MPW, limited by the actuator's longevity, energy input, driving pressure, and cycle frequency and the conductivity of the flyer.
"This technology may have limitations in the size and shape of parts that can be joined effectively"	VFAW was developed for a flat-on-flat welding configuration, but we are demonstrating broad applicability, such as to spot welds and seam welds.

Collaboration and Coordination with Other Institutions

Honda America: Eric Boettcher, Duane Detweiler (Honda R&D, Advanced Design Research), Pete Edwards (Honda Engineering)

Role: Guidance with material selection and procurement. Will also help with e-coating of welded samples

Alcoa: Mario Greco (Alcoa)

Role: Guidance with material selection and procurement.

Ohio State University, Fontana Corrosion Center: Prof. Rudy Buchheit

Role: Will help with corrosion testing of coated and uncoated welds

Johnson Control Inc.: Dan Sakinnen, Mark Harris

Role: Provide materials, A2LA-accredited lab facilities, and guidance on commercialization pathway.

Technical Summary/Future Work

- Vaporizing foil actuator welding (VFAW) offers a possible tool for welding dissimilar metals together
- 6 material combinations have been downselected.
- In order to fully understand failure mechanisms, deeper investigations involving microscopy, mechanical testing, and corrosion testing are underway
- New supplemental techniques are being developed to improve welding.
  - Vacuum, through slots, etc.
- We continue to push for industry readiness.
  - Techniques are being developed to perform welding in industrially relevant geometries and to improve the appearance of the weldment.
  - Thicker aluminum sheets (2mm) are being welded to steel.
  - New equipment is being developed for automation.
  - Using a faster capacitor bank, welding was achieved using 4X to 8X less energy.