Presentation Submission Information:

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- Presentation Title: Hybrid Low Copper Busbars
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- Organization(s): Pacific Northwest National Laboratory

Pacific Northwest NATIONAL LABORATORY

U.S. DEPARTMENT of ENERGY

EATON

Hybrid Low Copper Busbars

Md. Reza-E-Rabby

Pacific Northwest National Laboratory

DOE OE TRAC Peer Review 2026

Information Release # PNNL-SA-226939

U.S. DEPARTMENT of ENERGY



Project Overview

Project Description: Develop a copper-aluminum hybrid busbar with current-carrying capacity comparable to that of a copper-only busbar

Period of Performance: 10/01/2025 to 09/30/2028 (3 years)

Award Amount: $750,000

Prime Awardee: Pacific Northwest National Laboratory

Partners: Eaton Corporation

Technology Area: Advanced Conductors, Busbars, and Dielectric Materials

Alignment/Supports strategic pathway: Optimize the grid by reducing demand for critical materials, lowering costs, and providing high-performance busbars.

Problem Statements

- Copper busbars are extensively used in electric power grids due to their unmatched electrical performance (higher conductivity)
- Copper is classified as a critical material by DOE recently
  - Increased pressure on the copper supply and cost
- Partial replacement with aluminum reduces supply-chain criticality



Copper intensive busbars with bolted connections [1]

Challenges for Hybrid Copper-Aluminum Busbar

- Copper-clad aluminum busbar or hybrid copper-aluminum busbar is a commercially available product
- Manufacturing challenges
  - High process complexity
  - Limited scalability
  - Undesired intermetallic at the contact
  - Short-circuit reliability issue



Copper cladding aluminum core for busbars [2]

NEED: Scalable manufacturing of hybrid copper-aluminum busbars producing good interfaces with optimal electrical performance

Project Objective

Develop a copper-aluminum hybrid busbar with a current-carrying capacity comparable to that of a copper-only busbar using advanced manufacturing approaches.

FRICTION STIR WELDING (FSW)



Precise process control and optimal interface development

SHEAR ASSISTED PROCESSING & EXTRUSION (ShAPE)



Novel co-extrusion technique using friction extrusion

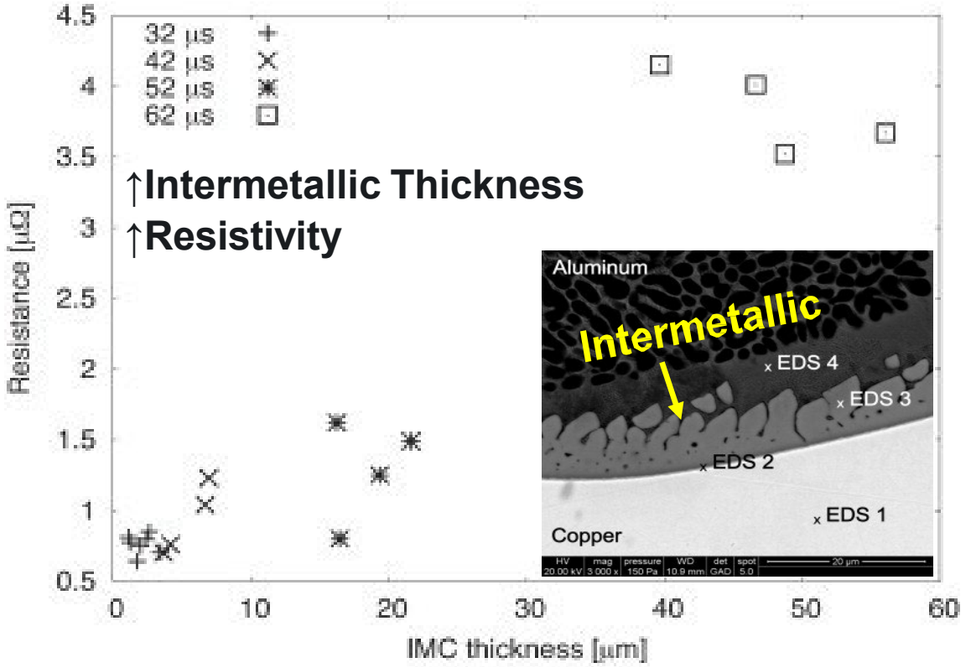
Current State of Copper-Aluminum Hybrid Busbar Development

Diffusion Bonding
Friction Stir Welding
Ultrasonic Welding
Rolled Bonding

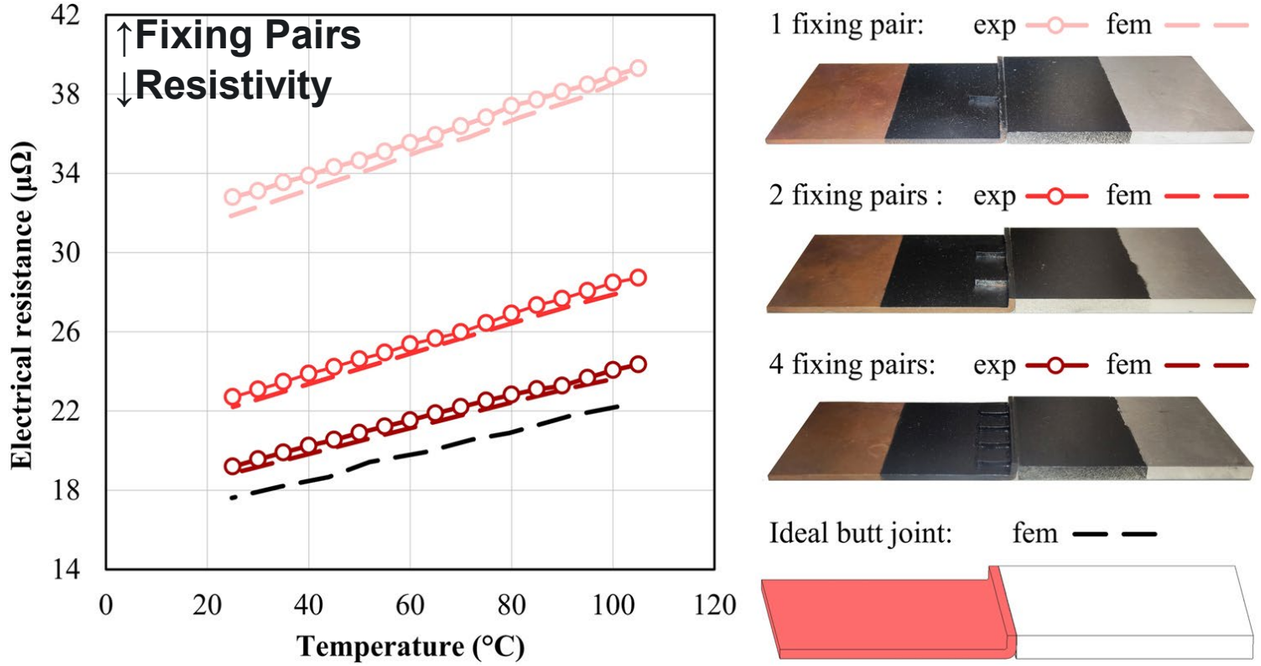
Compared to the fusion-based process

Avoid bulk melting
Reduce thermal distortion
Improve mechanical integrity

No dramatic improvement in electrical performance, while balancing between bonding and intermetallics



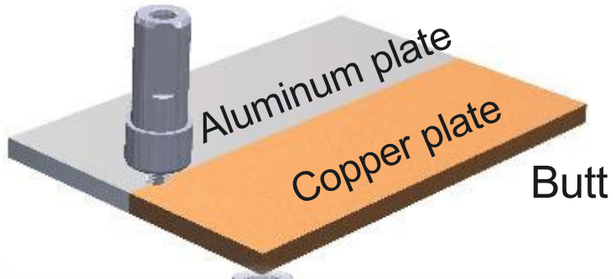
Electrical resistance as a function of intermetallic thickness of copper-aluminum joint [3]



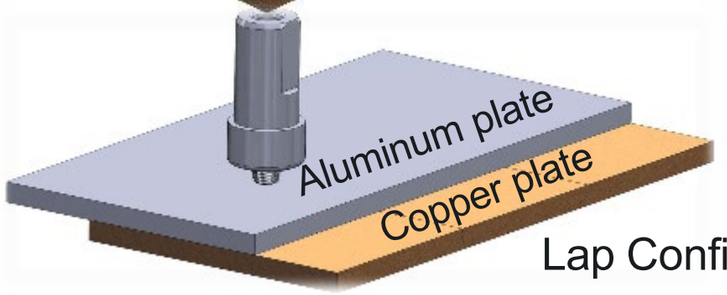
Electrical resistance as a function of temperature of copper-aluminum mechanical joint (fixing pair interlock) [4]

Technical Approach – Development of Hybrid Copper-Aluminum Busbars with Optimal Interfaces

Friction stir welding (FSW) of copper and aluminum plates

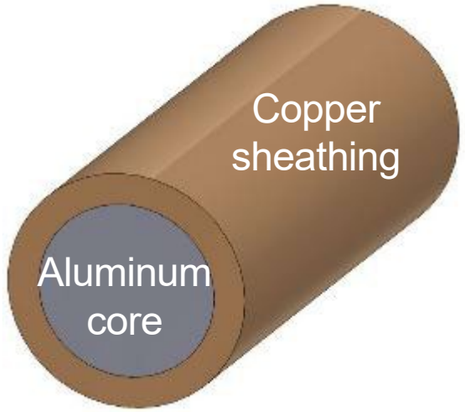


Butt Configuration

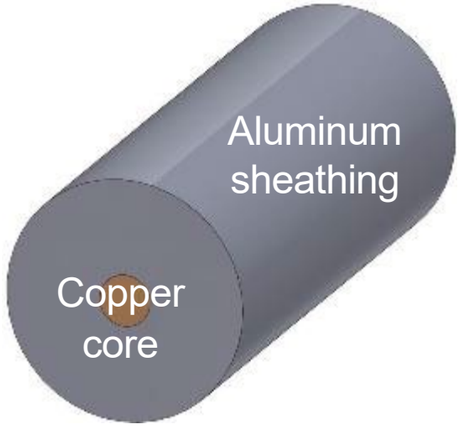


Lap Configuration

Friction co-extrusion (FCE) of copper and aluminum rods



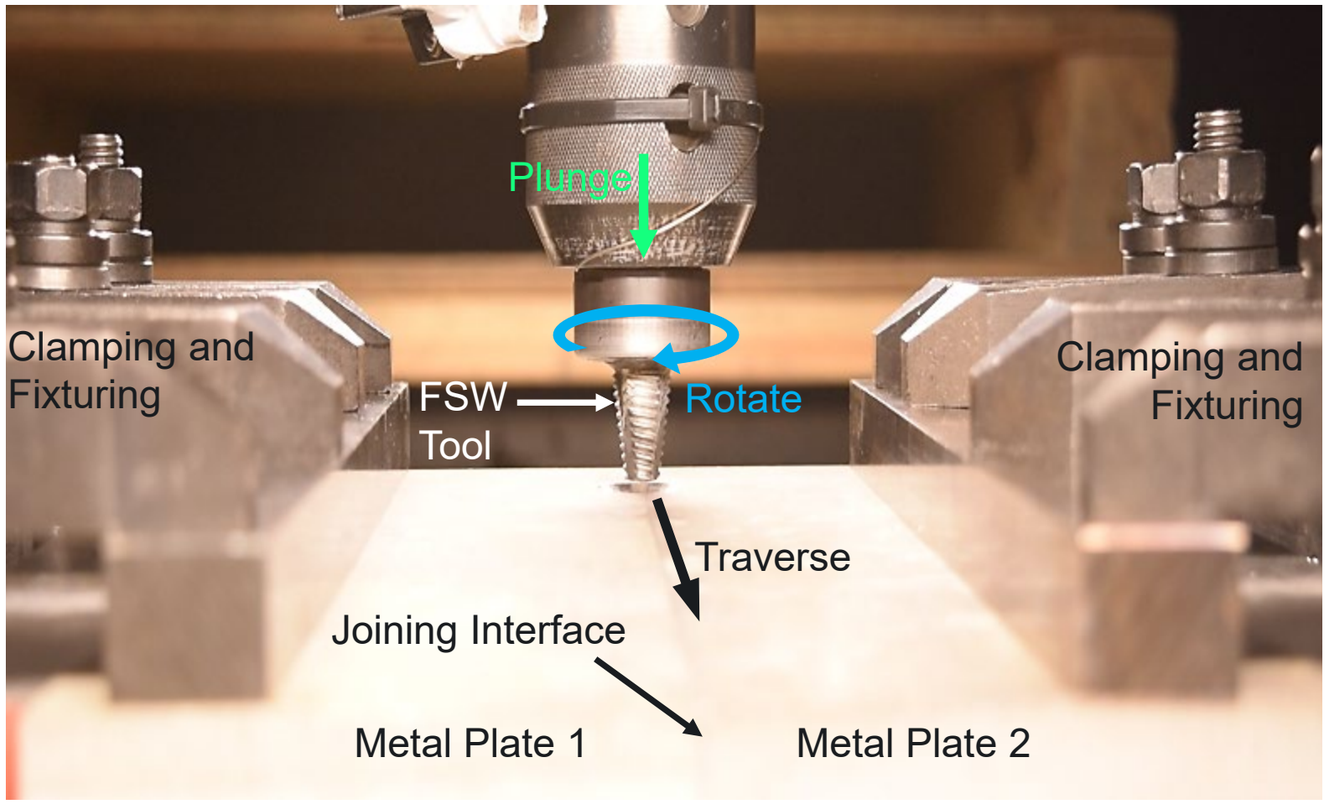
Configuration 1



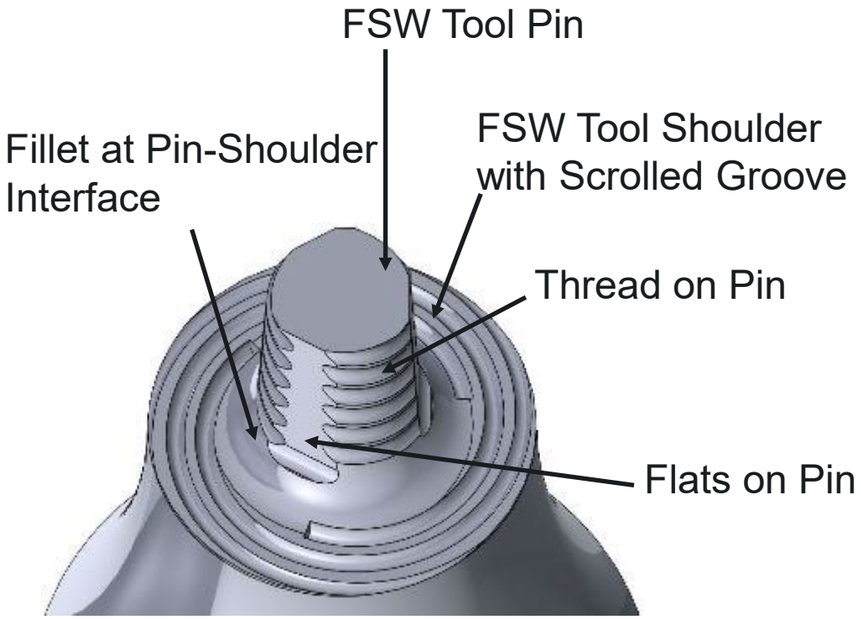
Configuration 2

- Manufacturing process is controlled to operate below the melting temperature of aluminum
- Optimal interfacial chemistry and minimal loss of electrical & mechanical performance

An Introduction to Friction Stir Welding (FSW) Process and Tooling



Friction stir welding (FSW) process with tooling, joining plates, fixturing and other important considerations

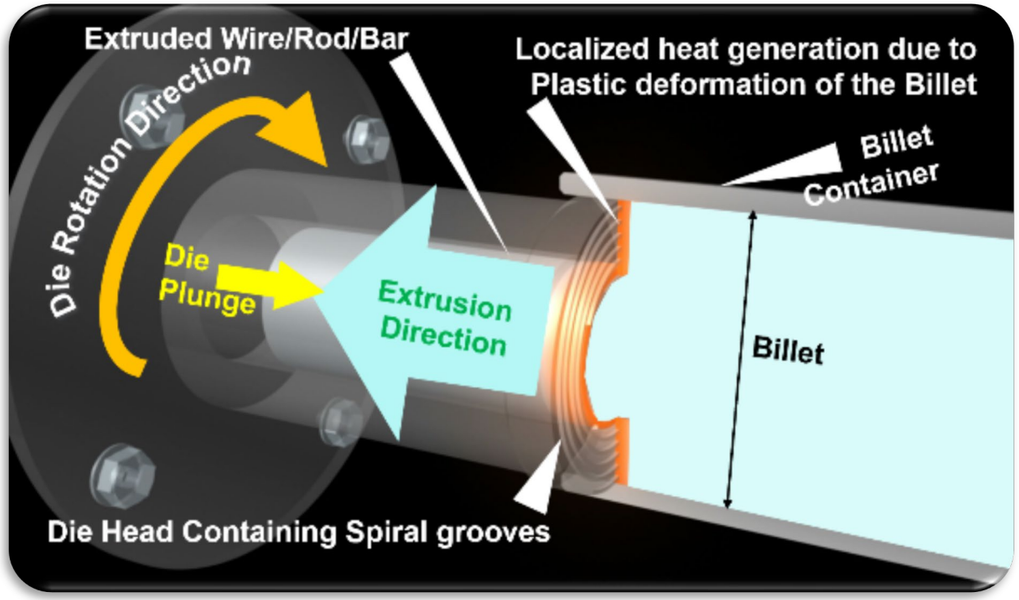


Friction stir welding (FSW) tool schematic showing critical features required for achieving an optimal joint

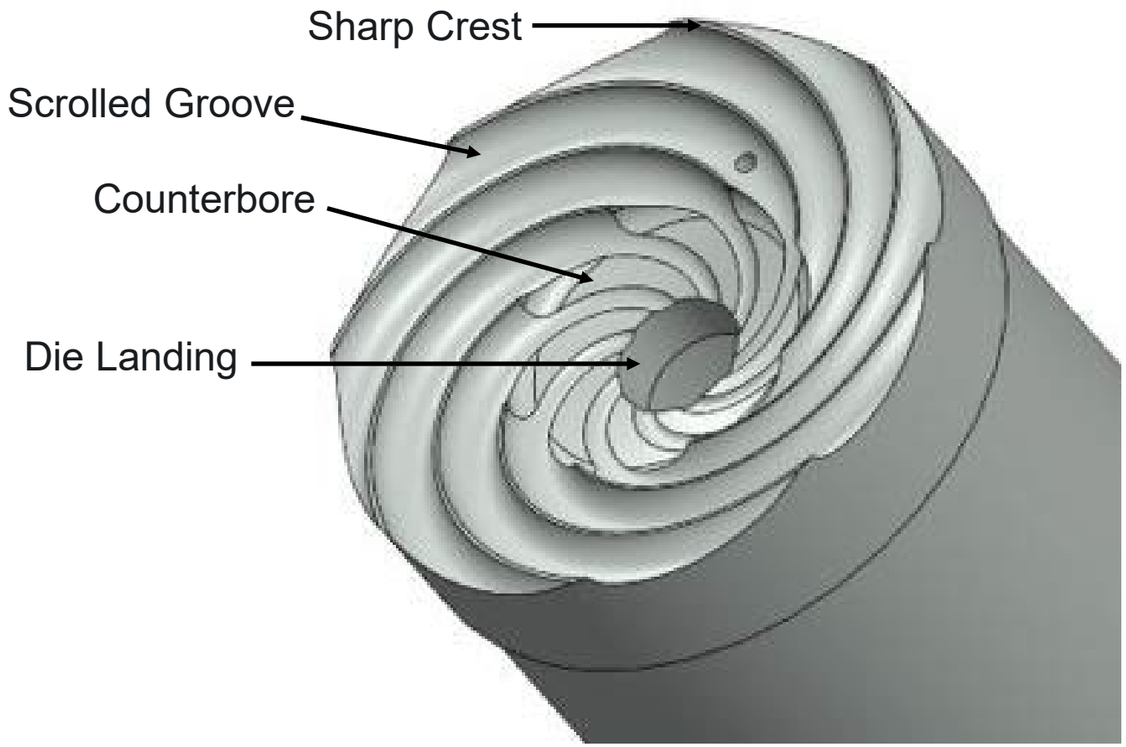
An Introduction to Friction Co-Extrusion (FCE) Process on ShAPE Platform and Tooling



First-generation ShAPE machine



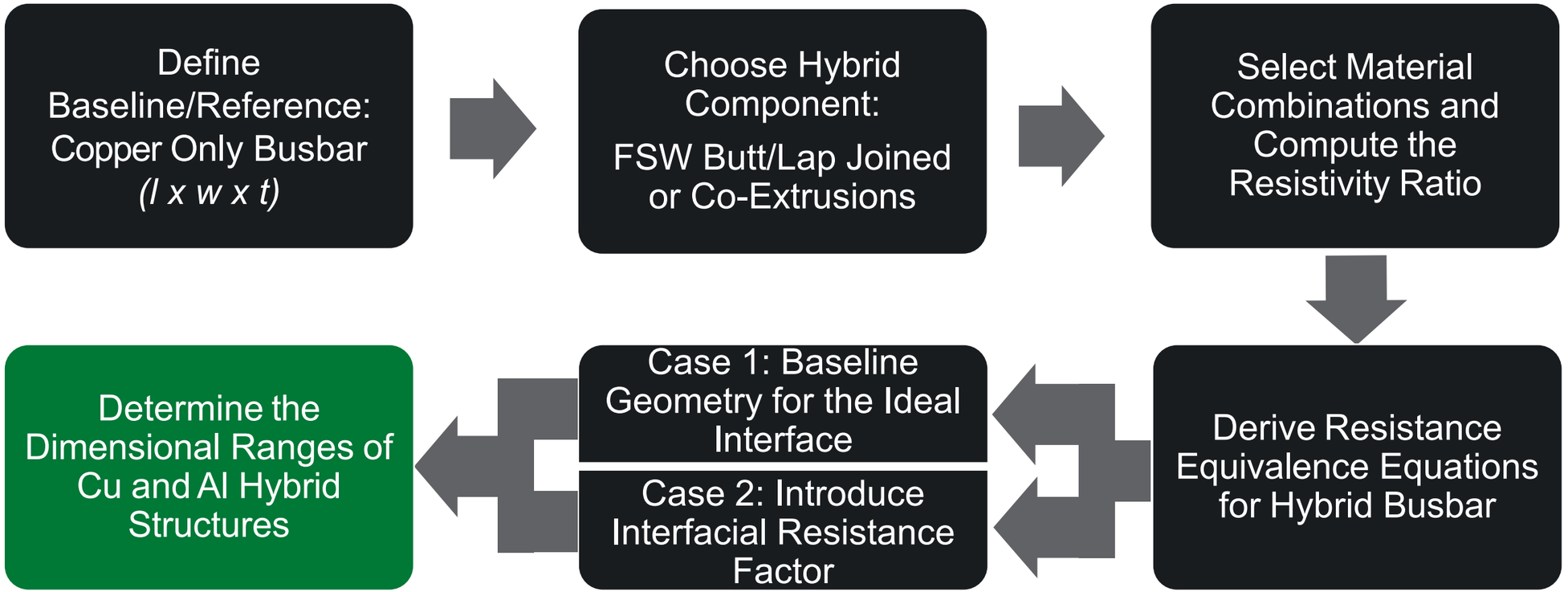
Schematic of the friction extrusion process and tooling



Friction co-extrusion (FCE) tool schematic showing critical features required for achieving optimal coextrusion of copper and aluminum

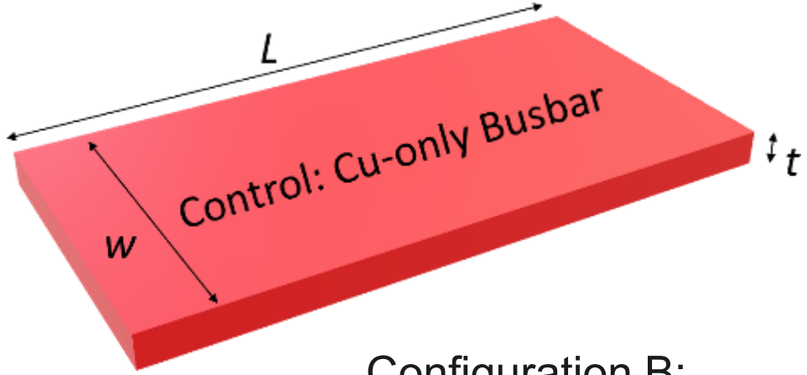
Technical Approach to Hybrid Copper-Aluminum Busbar Coupon Design

- Goal: select hybrid architectures and material pairs to replace majority of copper in a busbar with aluminum
- Develop resistance-equivalent designs for interfaces with varying quality

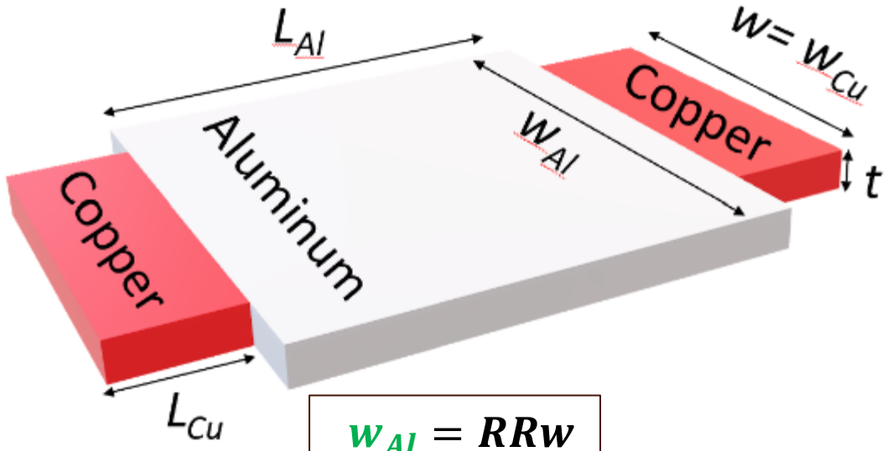


Copper-Aluminum Hybrid Coupon Design Configurations

Cu-only busbar Baseline (*L x w x t*)

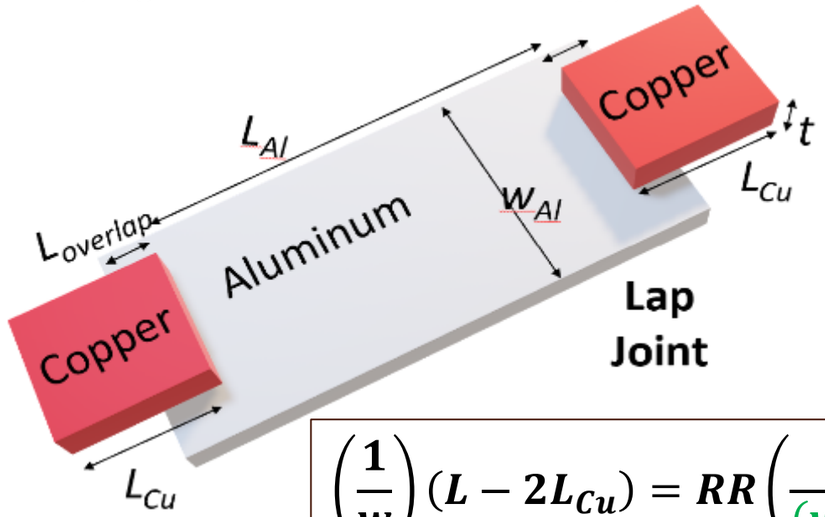


Configuration A:
Constant length (L) and thickness (t), varying aluminum width in the butt joint



$$w_{Al} = RRw$$

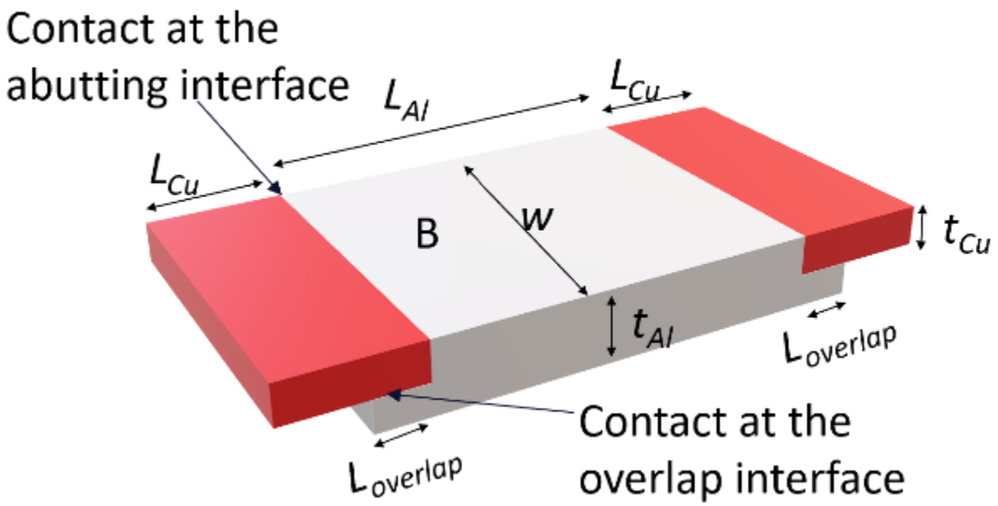
Configuration B:
Constant length (L) and thickness (t), varying aluminum width in lap joint



$$\left(\frac{1}{w}\right)(L - 2L_{Cu}) = RR\left(\frac{2L_o}{(w_{Al} + RRw)} + \frac{L_{Al}}{w_{Al}}\right)$$

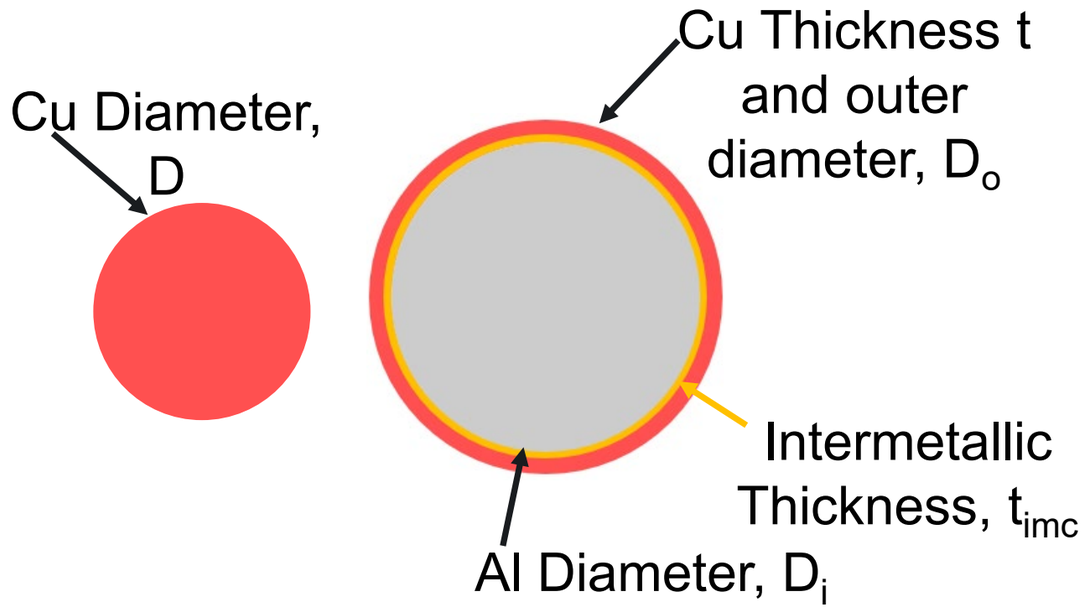
Copper-Aluminum Hybrid Coupon Design Configurations

Configuration C:
Constant length (L) and width (w), varying Al thickness at lap and/or butt joint



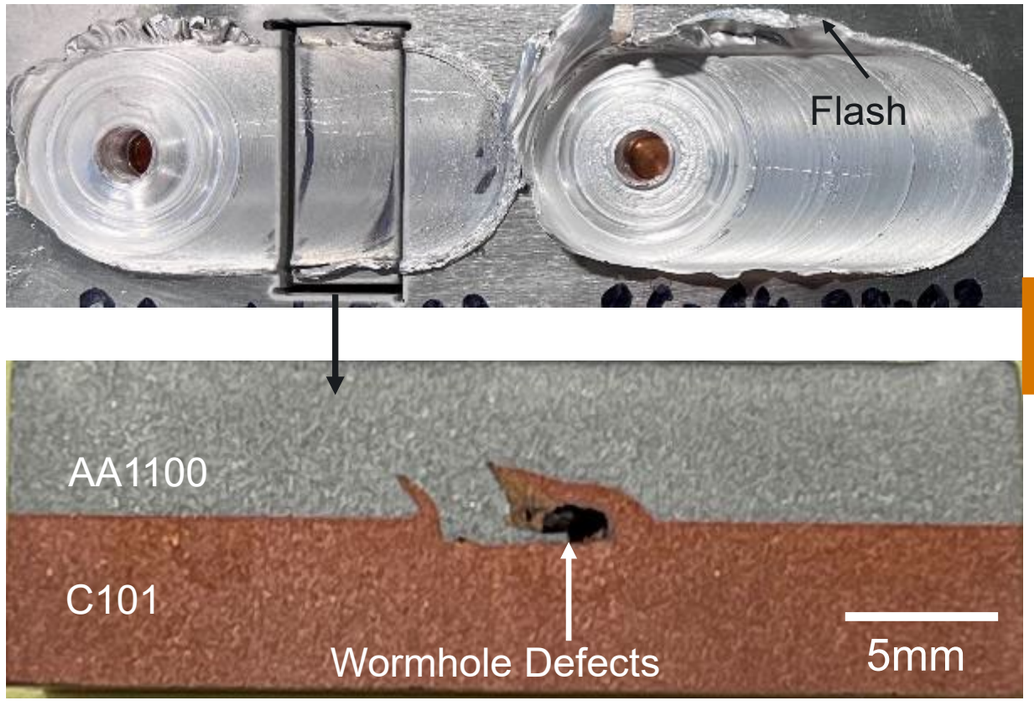
$$\left(\frac{1}{t}\right)(L - 2L_{Cu}) = RR\left(\frac{2L_o}{(t_{Al} + t(RR - 1))} + \frac{L_{Al}}{t_{Al}}\right)$$

Configuration D:
Aluminum Core and Copper-Clad Co-extrusion Rod (Round Bars)



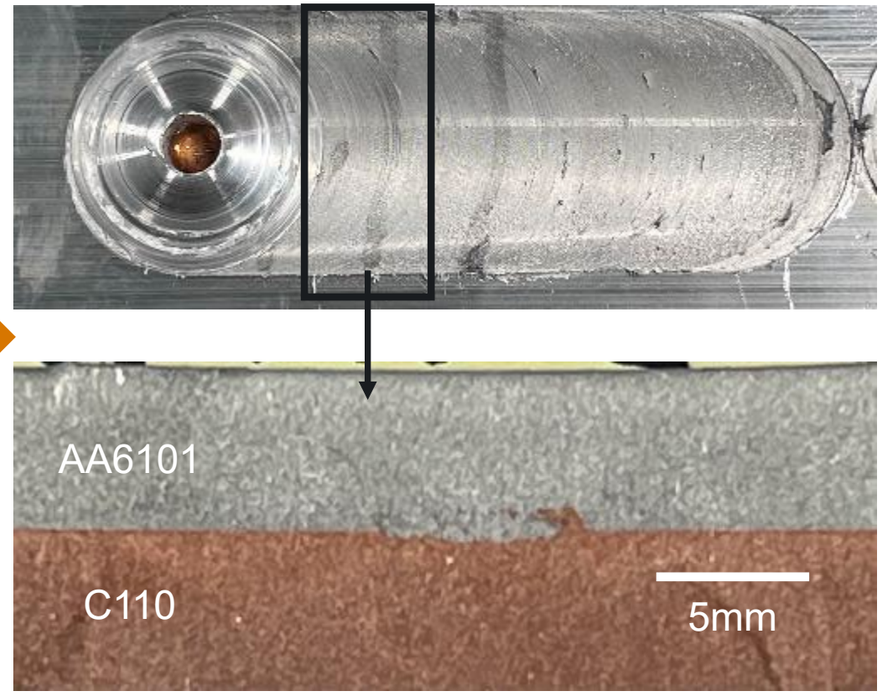
$$D^2 = \frac{D_i^2}{RR} + 2tD_i + t^2 + \frac{4t_{imc}D_i + 2t_{imc}^2}{x\,(RR + 1)}$$

Development of Hybrid Copper-Aluminum Busbar Coupons via Friction Stir Welding



Higher temperature (550 °C)
Lower welding force (14 kN)

Friction stir welded AA1100 (aluminum)-C101 (copper) plates with defects

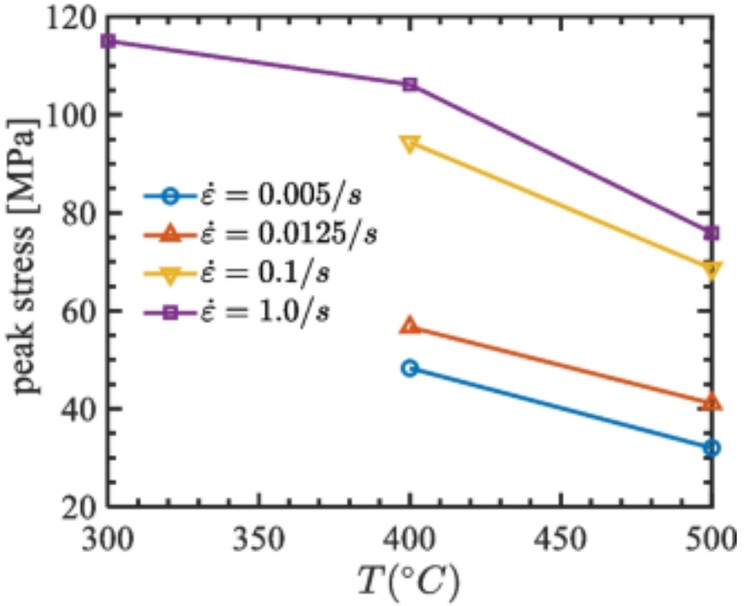


Lower temperature (535 °C)
Higher welding force (24 kN)

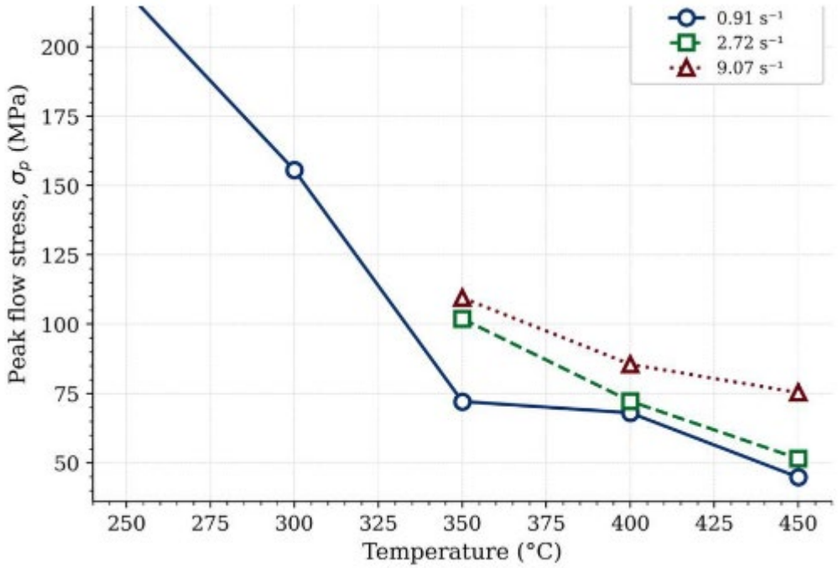
Friction stir welded AA6101 (aluminum)-C110 (copper) plates without defects

Lower process temperatures, higher forces and a harder aluminum alloy required for defect free joints

Flow Stress and Friction Stir Weldability Comparison of AA1100 vs AA6101



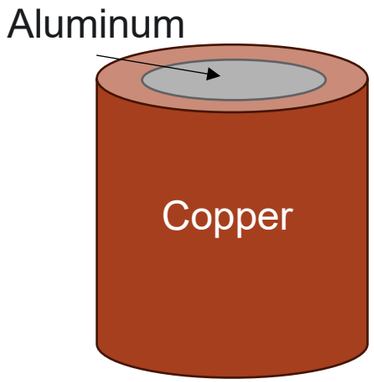
AA1100 peak flow stress as a function of temperature [5]



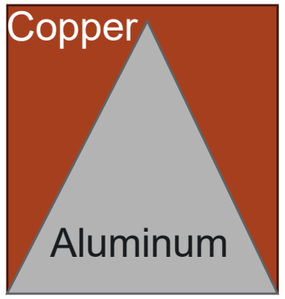
AA6061 peak flow stress as a function of temperature [6]

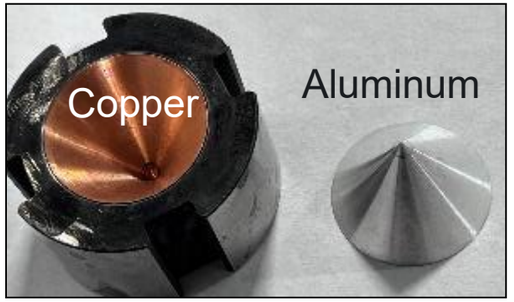
- Higher flow stress leads to more stable material flow during joining with AA6101
- Helps resist over-softening and excessive expulsion under the shoulder/pin
- Comparison of AA6101-copper FSW to AA1100-copper FSW: AA1100-copper exhibits a narrower process window and lower robustness, resulting in excessive flash and internal wormhole defects

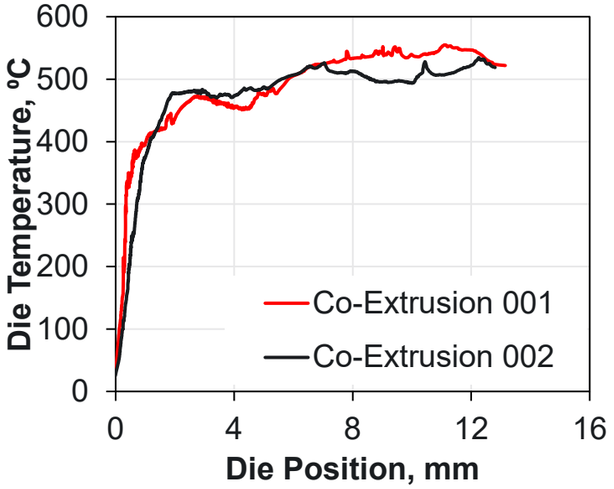
Development of Friction Co-Extruded Copper-Aluminum Hybrid Busbar Coupons

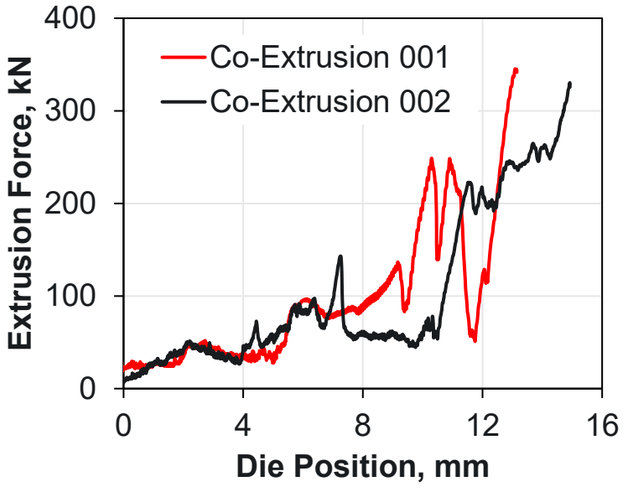




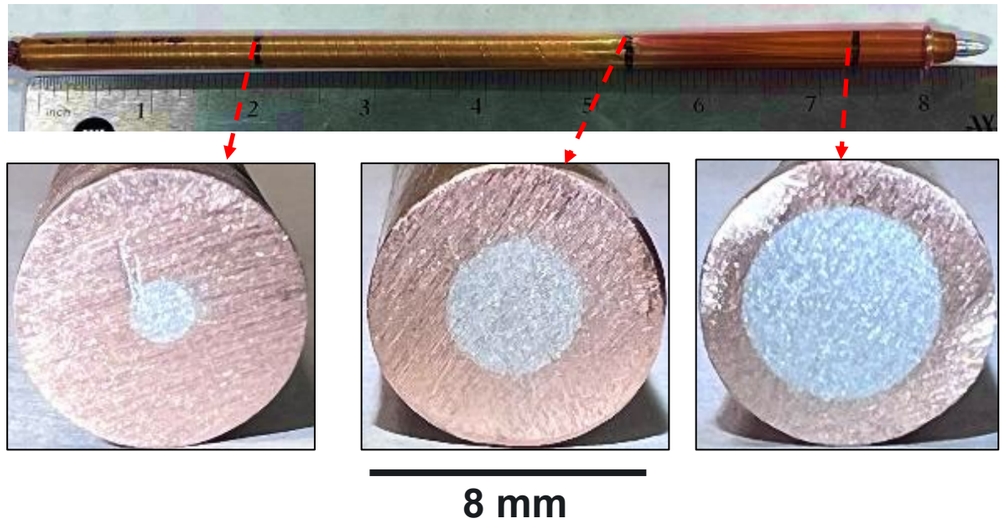








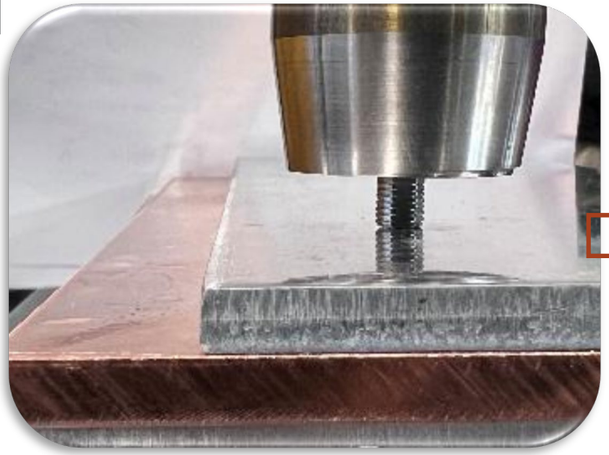
Material-flow mismatch: copper clogs the die landing in tool, only aluminum emerges

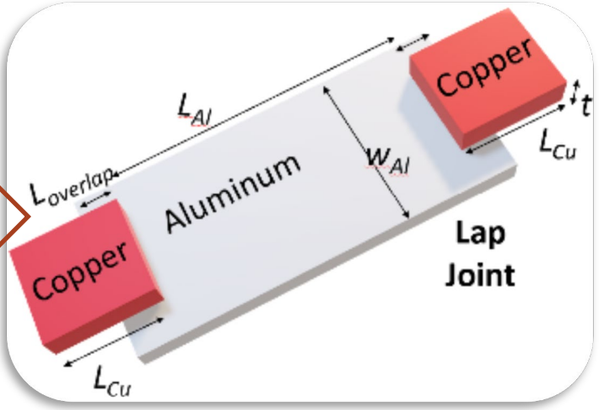


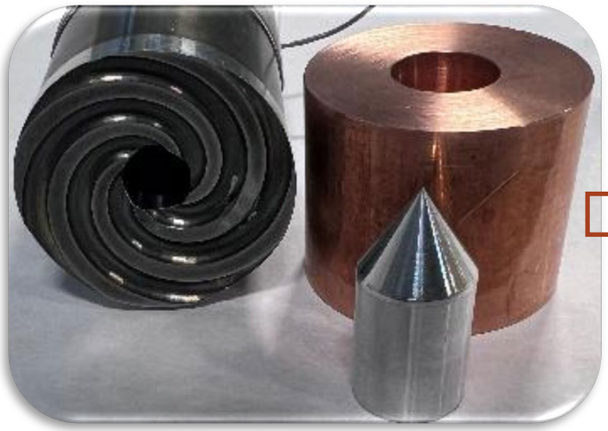
Modified feedstock design enables better co-flow of copper and aluminum during extrusion

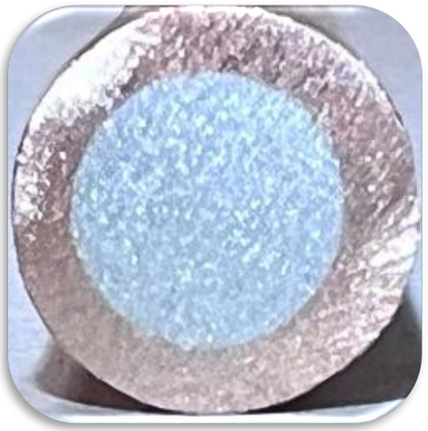
Conclusion & Impact

- Successfully designed and developed custom friction stir welding and friction co-extrusion tooling for hybrid copper-aluminum busbar coupon manufacturing
- Developed coupon-scale hybrid busbar designs
- Developed friction stir welding and friction co-extrusion process envelopes resulting in optimal copper-aluminum hybrid busbars with minimal porosity at interfaces









Future Direction and Next Steps: FY27 Plan

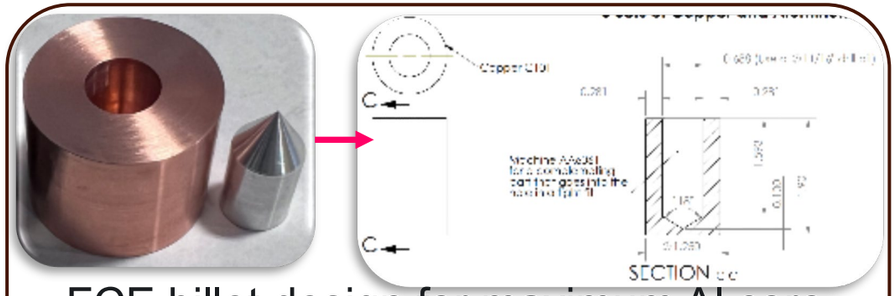
Process development and microstructural characterization:

- Quantify tooling and process effects
- Identify alloy effects and intermetallic formation
- Microstructural characterization to identify process defects and failure mechanisms

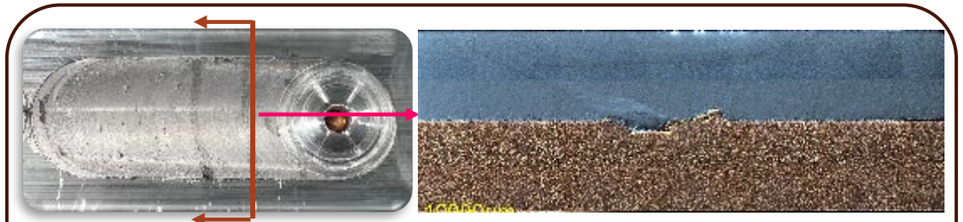
Link process to performance:

Correlate process parameters and microstructure with electrical performance

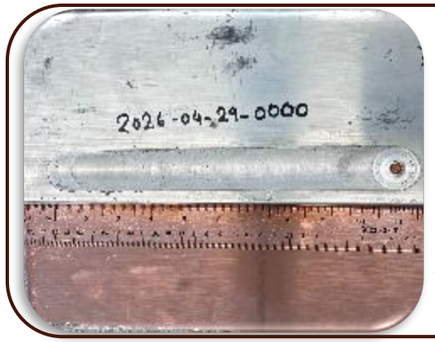
Building on the foundation of the first 2 years, FY28 will focus on prototype busbar manufacturing in collaboration with Eaton



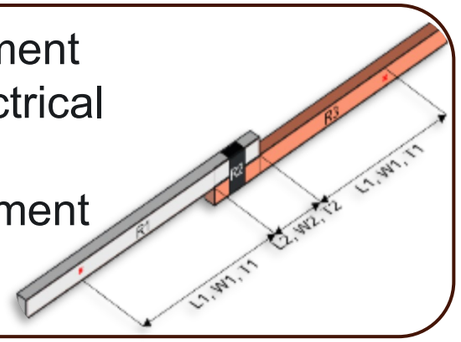
FCE billet design for maximum Al core diameter and process stability



Optimize FSW for defect-free, high-performance welds



Development of an electrical property measurement system



Acknowledgements

- This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE).
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- Pacific Northwest National Laboratory (PNNL) Leadership
  - Kevin Schneider: Sub-sector Manager
  - Keerti Kappagantula: Grid Materials Program Lead
  - PNNL Project Team:


Areesa Trevino


Hrishikesh Das


Aditya Nittala


Shivakant Shukla

  - PNNL 3410 Met Lab: Michael Blazon, Nate Brown
  - PNNL 350 Machine Shop

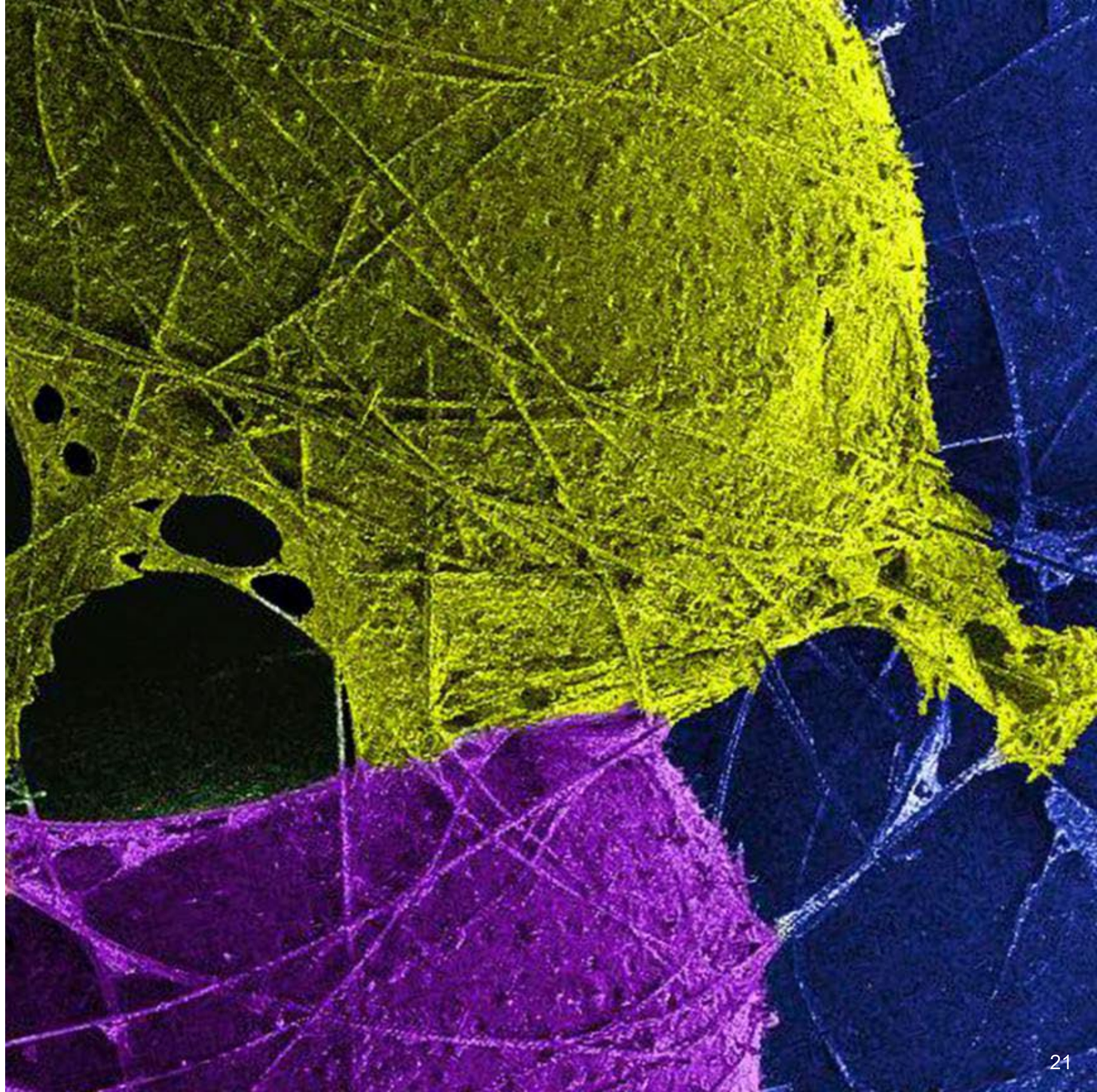
References

1. Tuling Metal https://www.tulingmetal.com/copper-clad-aluminum-busbar/
2. Ambro Metals https://www.ambrometals.com/copper/product-bare-copper-busbar/
3. Solchenbach, T. et al. Journal of Manufacturing Processes, (16) 2014, 183-189
4. Pragana et al. CIRP J. of Manufacturing Science and Technology, 205–213, 2023
5. Lan Li et al., Int. J. of Advanced Manufacturing Technology, 1201-1216, 2024.
6. Elalem, A. N. et al. Preprints 2026, https://doi.org/10.20944/preprints202607.0240.v1

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Thank you



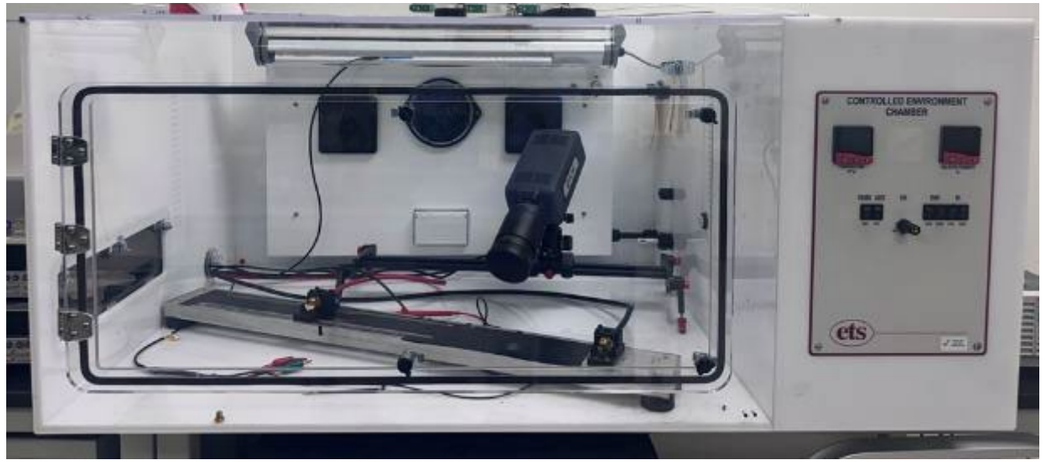
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Back up Slides

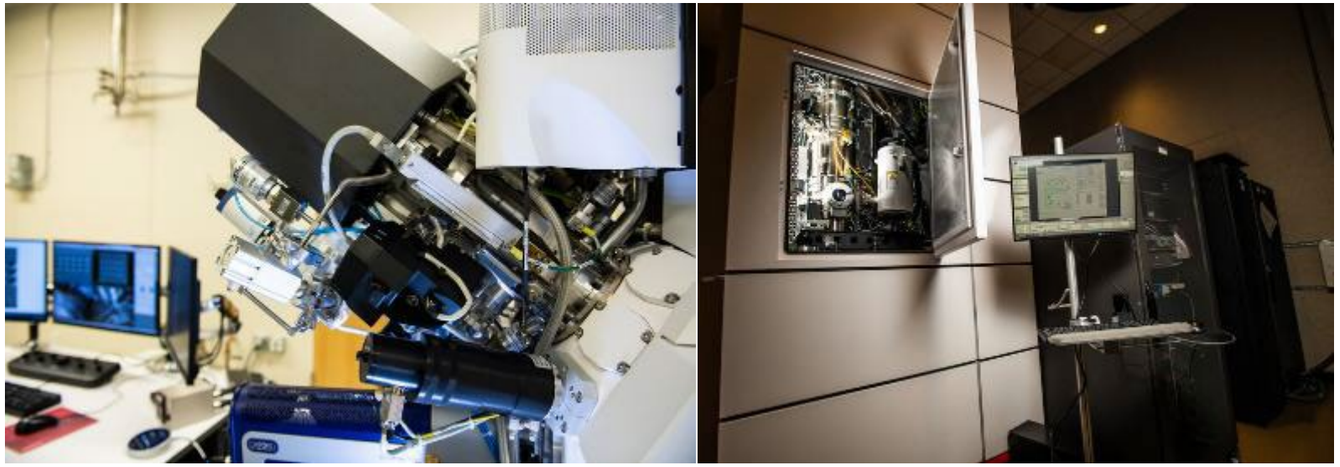
Teams and Resources

Pacific Northwest National Laboratory

- Smart Advanced Manufacturing (SAM) Lab: FSW and ShAPE Machines
- Environmental Molecular Sciences Laboratory (EMSL): A User Facility



High Accuracy, High Precision Electrical Property Measurement System @ PNNL



Scanning and Transmission Electron Microscopes @ EMSL User Facilities

EATON: Industry Advisor

Hybrid Copper-Aluminum Busbar: 3-Year Development Roadmap

- FSW and ShAPE Process Envelope
  - Tooling Design, Manufacturing, and Procurement (*Year 1*)
  - Hybrid Copper-Aluminum Coupon Design (*Year 1*)
  - Coupon-scale Manufacturing Envelope Development (*Year 2*)
    - Performance evaluation of coupon-scale busbar *(Year 2)*
- Prototype Busbar Development (*Year 3*)
  - Prototype Busbar Design and Manufacturing
  - Performance evaluation of prototype busbar
  - Cost analysis and industrial adoption of busbar

Hybrid Copper-Aluminum Busbar: 3-Year Development Roadmap



Period of Performance: FY26 to FY28

FY26 Q1	FY26 Q2	FY26 Q3	FY26 Q4	FY27 Q1	FY27 Q2	FY27 Q3	FY27 Q4	FY28 Q1	FY28 Q2	FY28 Q3	FY28 Q4

FSW and ShAPE Process Envelope

Hybrid Busbar Prototype Development

Tooling Design and Procurement

M1: Tool Design Complete

M3: Tool Procurement Complete

M7: Finalize Busbar Design

M8: Prototype Busbar Manufacturing

M10: Cost Analysis and Industry Adoption

Busbar Coupon Design

Coupon-Scale Manufacturing Envelope

Go/No-Go: Minimum Porosity Demonstration (Copper-Aluminum: FSW Plate/Co-extruded Bar)

M9: Prototype Busbar Deliver to EATON

M2: Busbar Coupon Design Complete

M4: Tooling Effect

M5: Process Effect

M6: Alloy Effect

Go/No-Go: Electrical performance equivalent to copper-only coupons demonstrated

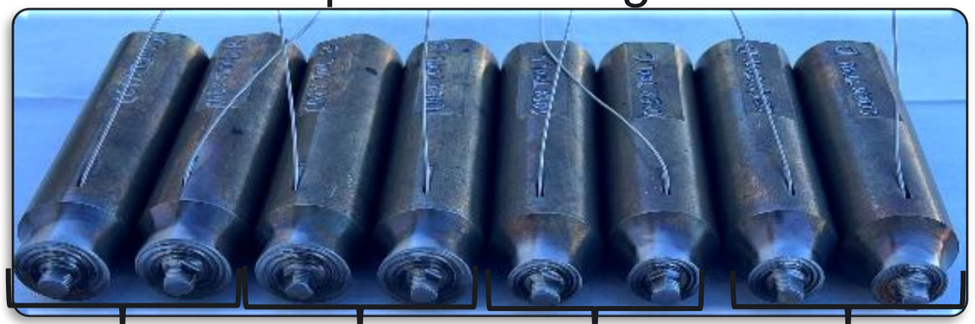
'**M(1-10)**' refers to Milestones 1-10

FSW and FCE Tool Design, Manufacturing and Procurement

Pacific Northwest NATIONAL LABORATORY

FSW Tools

Butt/Lap Joint Configurations

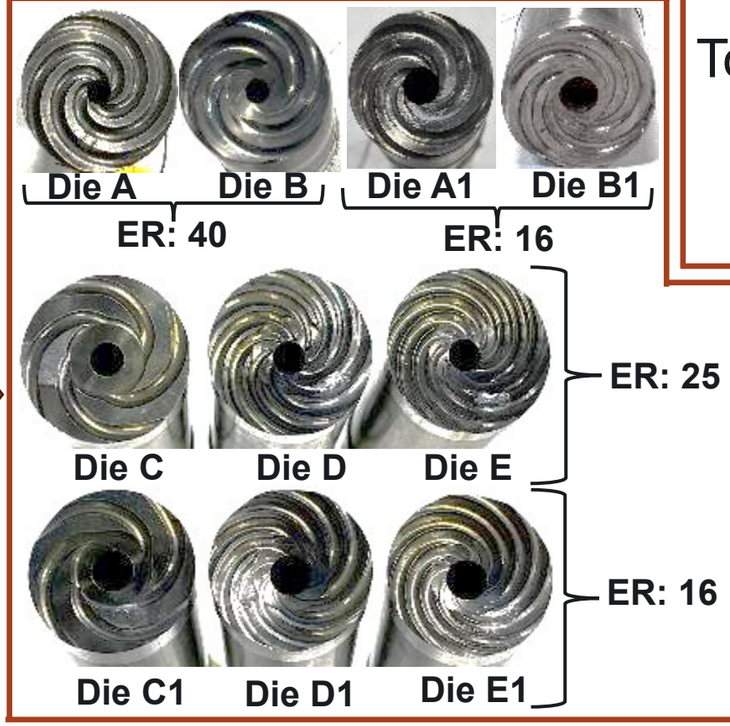


Lap Joint Configurations



Tool shoulder: 20-30 mm, with pin length 6-9.5 mm
Same outer diameter for all dies
Extrusion ratio (ER) 40; range 5- 8 mm

FCE Dies



Co-extrusion die feature variations:

- Flat face die (C)
- Conical face die (A, B, D, and E)
- Four scrolls (A, B, and C)
- Eight scrolls (D and E)
- Counterbore (B, C, D, and E)

Current Year's Milestones

List of Milestones and Go/No Go Decision Point for FY26

Milestone Descriptions	FWP Task/ Subtask Number(s)	Date	Status
Milestone M1: Tool design - FSW and ShAPE tooling CAD drawings completed	2.1	12/31/2025	Completed
Milestone M2: Coupon design - Dimensions of aluminum and copper plates, rods and tubes to be used in hybrid coupons	2.2	03/31/2026	Completed
Milestone M3: Tool procurement - FSW and ShAPE tooling procured from external vendors.	2.1	06/30/2026	Completed
G/NG1: Coupon preliminary demonstration - Hybrid copper-aluminum coupons with minimal porosity at the interfaces manufactured by either FSW or ShAPE	2.3	09/30/2026	On-track

Next Year's Milestones

List of Milestones and Go/No Go Decision Point for FY27

Milestone Descriptions	FWP Task/ Subtask Number(s)	Date	Status
G/NG1: Coupon preliminary demonstration - Hybrid copper-aluminum coupons with minimal porosity at the interfaces manufactured by either FSW or ShAPE	2.3	9/30/2026	On-track
M4: Property plots showing the effect of tooling designs on the electrical performance of hybrid copper-aluminum coupons.	2.3	12/31/2026	On-track
M5: Property plots showing the effect of process parameters on electrical and mechanical performance of the hybrid copper-aluminum coupons.	2.3	03/31/2027	On-track
M6: Property plots showing the effect of process parameters on electrical and mechanical performance of the hybrid copper-aluminum coupons.	2.3	06/30/2027	On-track

FSW Process Development: Short Stitch Weld to Full Length Weld

Based on the surface appearance and cross-sectional evaluation of the short stitch welds, a full-length weld is developed for detailed sample characterizations

Short Stitch Weld



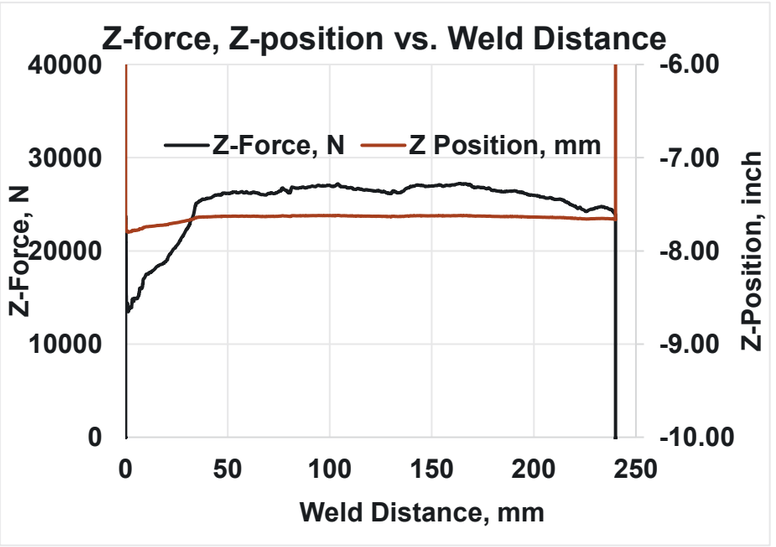
Weld Surface of a 60 mm long Weld

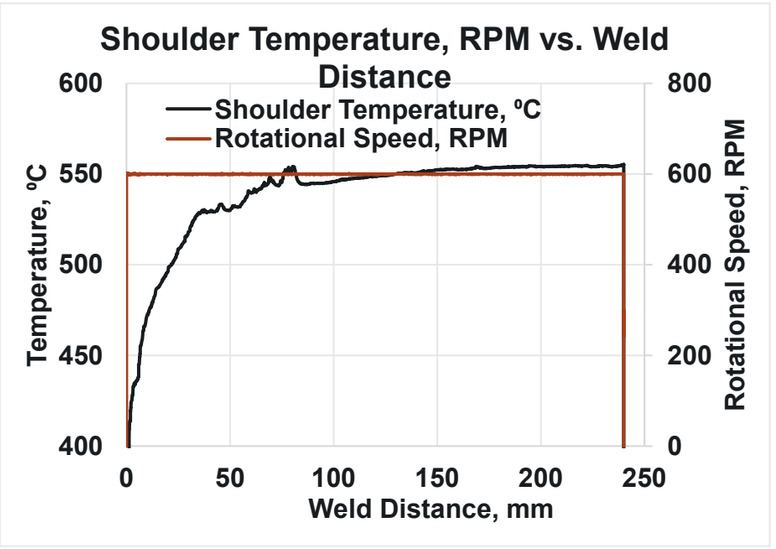


Weld Cross Section as waterjet cut

Develop a full-length (>250 mm long) Weld

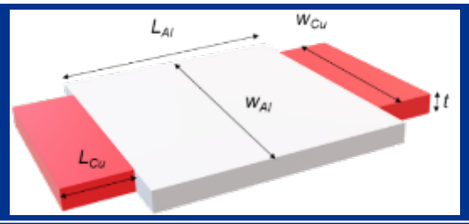
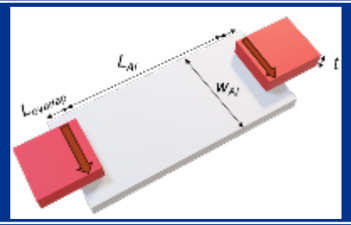
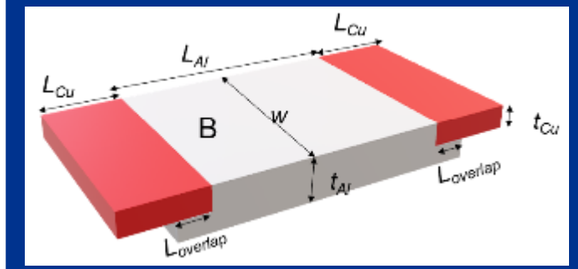




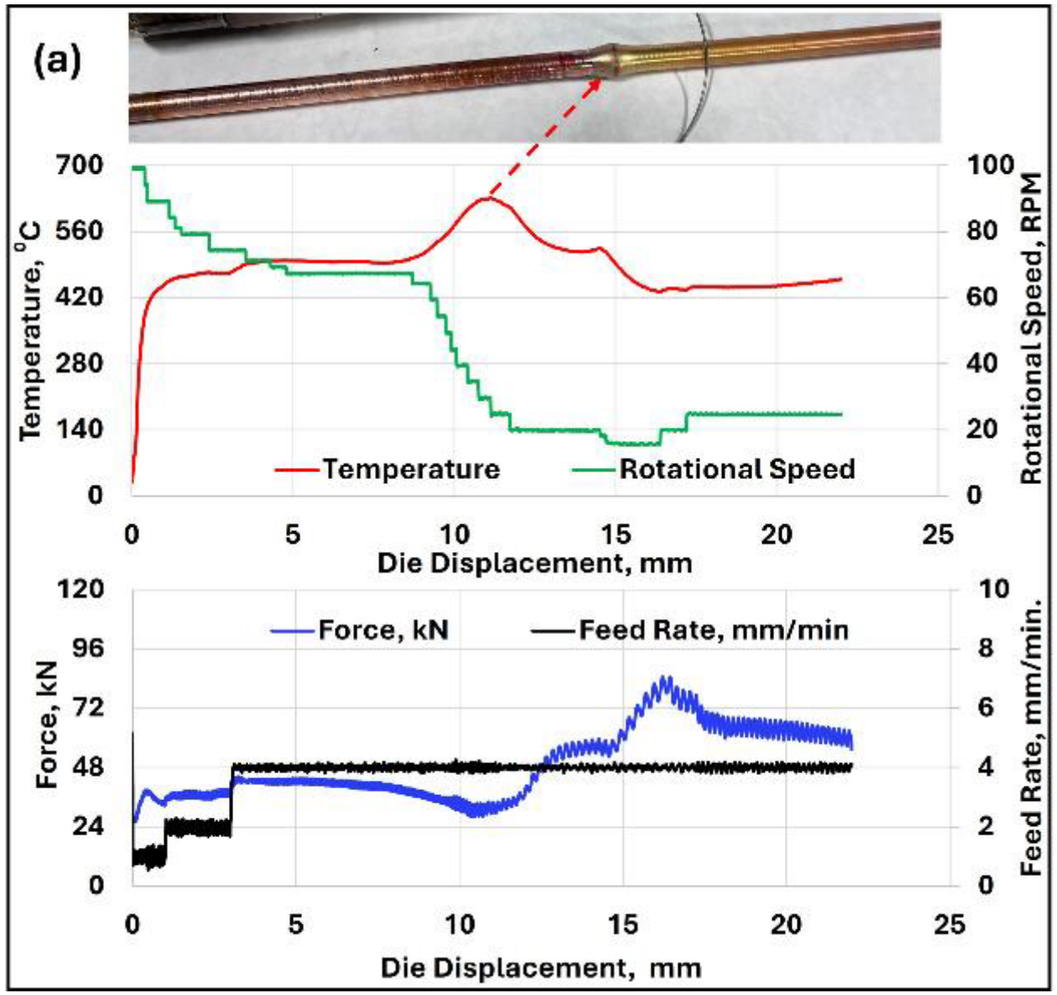


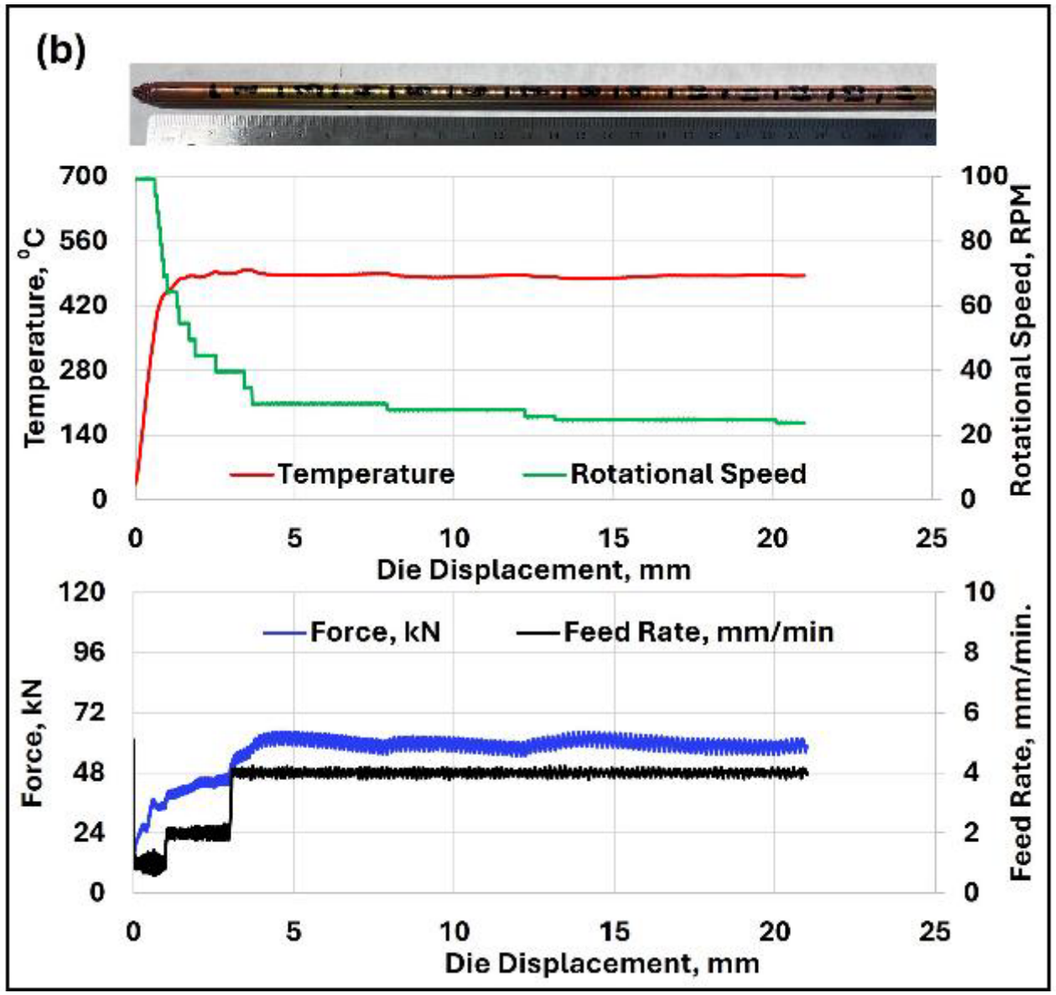
Summary Output from the Busbar Coupon Design

Numerically solving for Cu and Al dimensions from the constitutive equation

Configurations ▲Ideal interface, no defect, no IMCs ▪With interfacial resistance due to intermetallic or defect formation	Materials (Cu-Al)	Resistivity Ratio, RR	Hybrid Coupon (Cu+Al+Cu)					
			Cu Segments (2x)			Al Segment		
			L_{Cu}	t_{Cu}	w_{Cu}	L_{Al}	t_{Al}	w_{Al}
			mm	mm	mm	mm	mm	mm
 A	C101-AA1100	1.69	50	6.35	**10**	300	6.35	16.9▲ 21.6▪
	C101-AA6101	1.81	50	6.35	**10**	300	6.35	18.1▲ 23.5▪
 B	C101-AA1100	1.69	75	6.35	**10**	250	6.35	15.4▲ 15.9▪
	C101-AA1100	1.69	75	6.35	**10**	300	6.35	16.6▲ 17.1▪
 C	C101-AA1100	1.69	75	3.96▲ 4.80▪	10	250	**6.35**	10
	C101-AA6101	1.81	75	3.71▲ 4.48▪	10	250	**6.35**	10
	C101-AA6101	1.81	75	6.35	10	250	11.5▲ 11.3▪	10

Development of Friction Extruded Copper Aluminum Hybrid Busbar Coupons



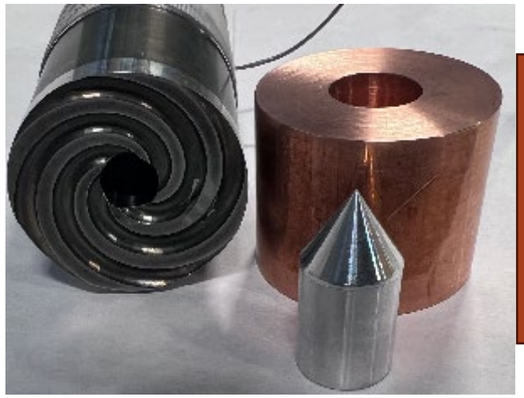


Precise temperature control key for optimal material flow

FE Process Development Initial Co-extrusion Trials

Approach 3: Introduce the conical shape of Al to gradually increase the volume fraction of Al in the transition region

Die and Feedstock Billet



Cu-Clad/Al-Core Co-extruded Rod

Start of Extrusion

End of Extrusion

