Ultra-Conductive Carbon Metal Composite Wire for Electric Motors

DE-FE0032277

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U.S. Department of Energy

National Energy Technology Laboratory

Resource Sustainability Project Review Meeting

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Project Overview

Project Specifics

- DOE/NETL Cooperative Agreement No. DE-FE0032277
- DOE Project Manager: Dr. Brett Hakey
- Principal Investigator (PI): Yahya Al-Majali
- Participants: MetalKraft Technologies, Fisk Alloy, Hydro Precision Tubing North America, CONSOL Innovations, Clear Skies Consulting

Project Budget

- Federal: $1,000,000
- Non-Federal: $250,000

Project Duration

- July 26, 2023 – July 25, 2025

MetalKraft TECHNOLOGIES

FISK

CONSOL ENERGY
FUEL THE WORLD FOR A BETTER TOMORROW

Project Objectives

Overall: The objective of this project is to develop cost-effective Carbon-Metal Composites (CMCs) with enhanced bulk electrical properties for use in electric motors to increase American energy efficiency and reduce greenhouse emissions.

Budget Period 1 Objectives

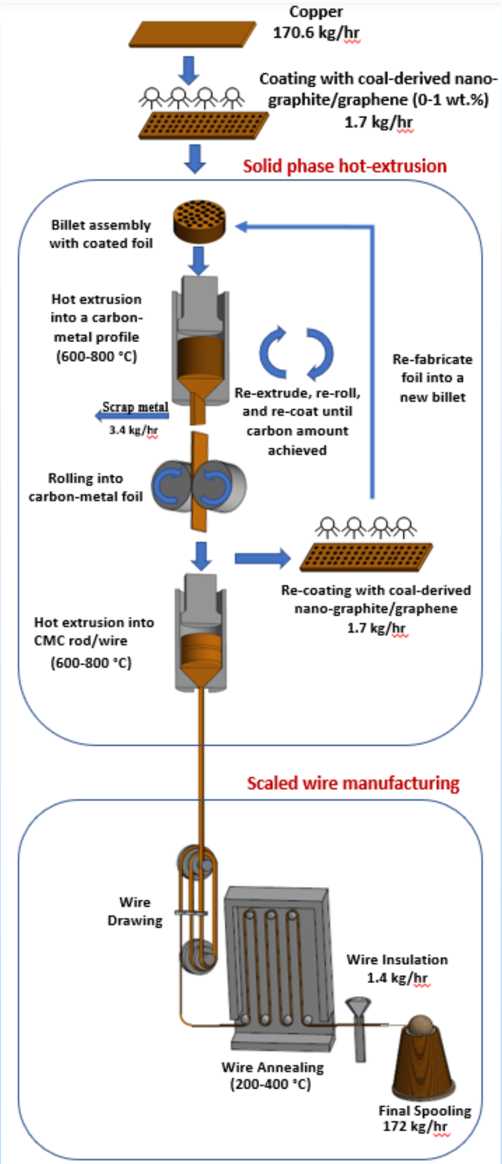
- Develop and refine CMC processing techniques to optimize coal-derived carbon content
- Characterize CMC wire properties and assess technical feasibility for electric motor applications
- Develop molecular dynamic and metal forming process simulations to predict properties and inform processing parameters

Budget Period 2 Objectives

- Conduct scaled CMC wire manufacturing to produce 12-22 AWG wire and quantify wire performance for electric motor applications
- Develop techno-economic and market analyses to assess the economic feasibility of the technology
- Identify additional commercial applications for the CMC materials

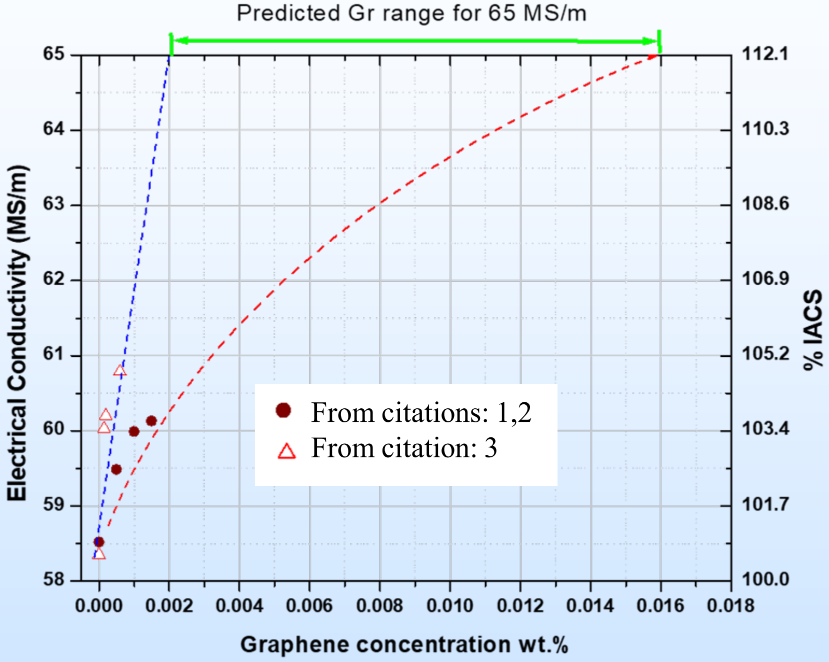
Technology Background

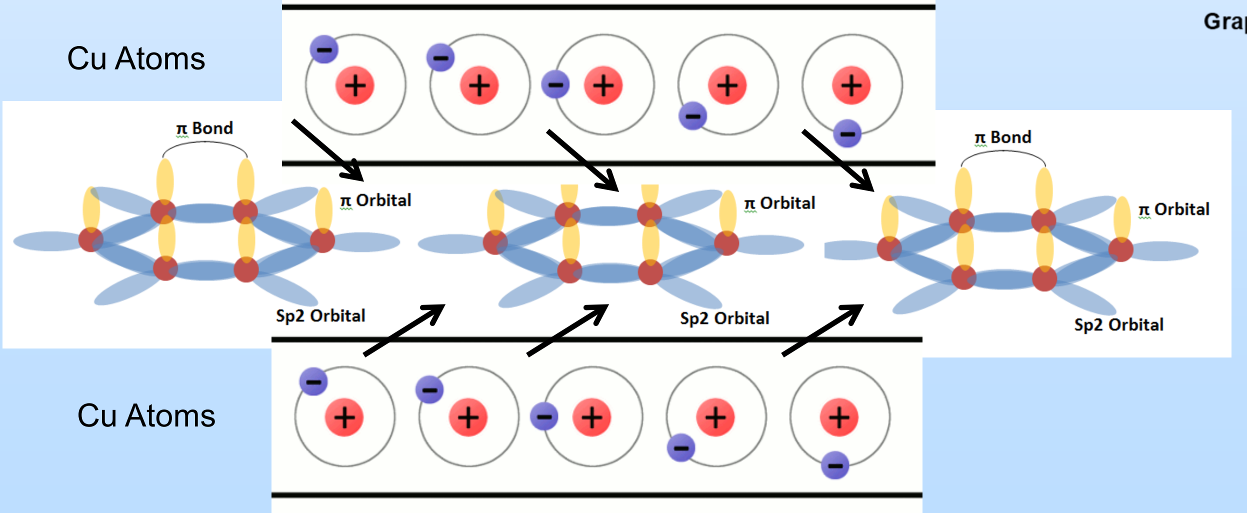
- Higher conductivity wires can enhance efficiency of electric motors and reduce weight, costs, and CO_2 emissions
- Higher electrical conductivity is achieved by incorporating coal-derived graphitic carbon into a metal matrix
- CMCs will be processed based on two unique techniques:
  - Solid phase hot-extrusion
  - Flash-melting thermo-mechanical processing
- CMC wire manufacturing techniques are based upon commercially mature and scalable metal-forming processes
- Primary conductor materials to be used are copper and aluminum
- Proposed techniques will further improve the bulk electrical performance of the CMC materials by
  - Achieving higher carbon content
  - Improving carbon distribution, alignment, and interfacial coherency
  - Exfoliating the coal-derived graphitic carbons
  - Retaining the carbon material's structure



Technology Background

- Solid phase hot-extrusion processing with CVD graphene (without iterative processing) demonstrated an increase to the bulk wire electrical conductivity at 103.65 %IACS (2.76 %IACS higher than the copper control sample)
- Improvements achieved with low graphene content (0.0015 wt.%)
- Extrapolation indicates graphene loading to 0.016 wt.% is needed to achieve 112 %IACS (65 MS/m)
- Proper and sufficient cohering of graphene to Cu/Al matrix atoms promotes electron flow preferentially along embedded coal-derived graphene additives





Technology Background

CMC Technical, Economic, and Environmental Advantages

- Utilization of inexpensive high-quality coal-derived nano-graphite and graphene
- Ability to achieve higher carbon content while overcoming processing/performance challenges
- Utilization of commercial manufacturing technologies to expedite commercialization
- Potential to achieve ≥10% electrical conductivity compared to conventional Cu and Al wire
- Annual energy savings of 36,000 GWh and elimination of 14 million tonnes of CO_2 emissions are projected if 20% of AC motors utilize ultra-conductive CMC wire in their windings

Technical Challenges

- Limited sources of coal-derived graphite and graphene
- Development of scaled carbon application methods

Technical Approach/Project Scope

Milestones

Task	Description	Planned Completion Date	Actual Completion Date	Verification Method
1.1	Updated PMP submitted	August 2, 2023	August 2, 2023	Submission of updated PMP to NETL FPM
1.0	Project Kick-Off meeting held	September 25, 2023	September 25, 2023	Presentation file
1.2	Technology Maturation Plan (TMP)	October 24, 2023	October 25, 2023	Report File
1.3	Diversity, Equity, Inclusion, and Accessibility Plan (DEIAP)	October 24, 2023	October 25, 2023	Updated Plan
2.2	Complete CMC processing and compositions assessment	April 25, 2023		Quarterly Report
2.3	CMC materials performance report	July 25, 2024		Quarterly Report
4.0	Complete pilot-scale wire manufacturing and assess performance	April 25, 2025		Quarterly Report
5.0	Techno-economic and Market Analyses	April 25, 2025		Quarterly Report

Technical Approach/Project Scope

Project Success Criteria

The success criteria for this project include the following:

- Develop 12-22 AWG CMC magnet wires with breakthrough improved electrical conductivity (≥110 % IACS for copper CMCs and 69% IACS for aluminum CMC) and assess performance in light of commercially available standard magnet wire used for electric motor windings,
- Demonstrate the ability to produce CMC wire utilizing pilot-scale wire drawing and annealing processes to AWG industry standards, and
- Demonstrate economic viability of CMC wire in comparison to current wire pricing by conducting detailed techno-economic and market analyses and targeting an acceptable premium price (within ~ 20%).

Technical Approach/Project Scope

Risks and Mitigation Strategies

Perceived Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Feedstock Availability	Low	Medium	Low	The project has commitments from industry to supply coal-derived graphitic carbons to support the development of the CMC materials. The project team plans to test a host of formulations to develop CMC materials with enhanced bulk electrical properties that can be drawn to a standardized wire gauge utilizing scaled wire drawing and annealing process.
CMC Processing	Low	Medium	Low	Processing should promote interfacial coherency between the carbon nano-filler and Cu or Al. It also should prevent porosity formation, nano-filler agglomeration, and nano-filler structure damage. The project team plans to process the CMC materials using two different processing techniques and establish a material-process-structure-property relationships. Proposed approaches are expected to overcome processing challenges and improve bulk electrical performance.
Drawability of CMC Materials	Low	Medium	Low	Drawing the CMC wire utilizing pilot-scale wire drawing and annealing processes is an important factor for commercial adoption of CMC wire technology. In budget period (BP) 2, a range of CMC formulations will be evaluated using pilot-scale wire drawing and annealing processes to demonstrate the drawability of CMC materials and compare to standard Cu and Al wires. The ductility and formability of CMC materials are expected to be dominated by the Cu or Al matrix. However, an additional annealing step might be needed to resolve wire drawing issues.
Market Acceptance	Medium	High	High	To generate market acceptance, the project team plans to conduct testing on the CMC wire produced using a scaled process and assess performance for electric motor application. The project team also plans to conduct market studies and identify additional applications for the CMC technology
Process Economics	Medium	Medium	Medium	To minimize CMC wire manufacturing costs, multi-variable techno-economic studies will be completed including but not limited to feedstock pricing, financing, product sales price, location, and capacity.

Progress and Current Status of Project

Cu and Al, wire and strip sample extrusion

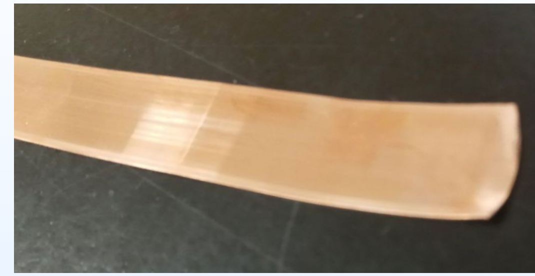
- Readily extrude small samples
- Accurate control of process parameters

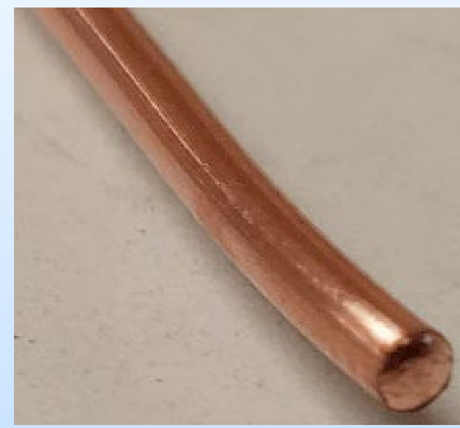
Development of precursor materials

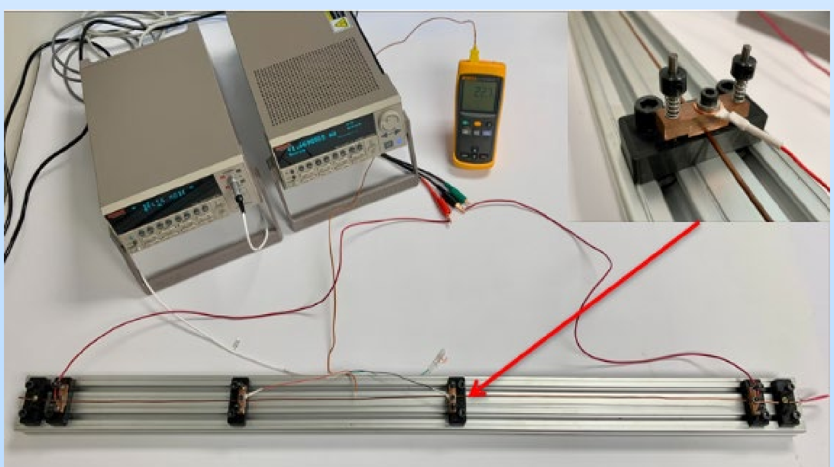
- Initial studies with powder
- Use of foils to produce CMC composites

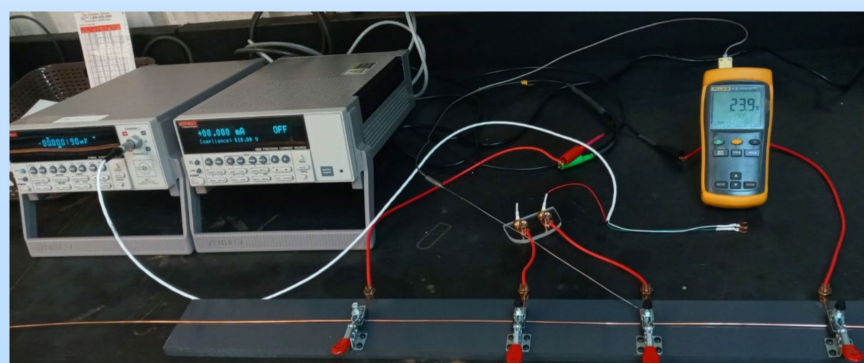
Wire and strip test capabilities

- Short length measurements
- Resolution of small gradients









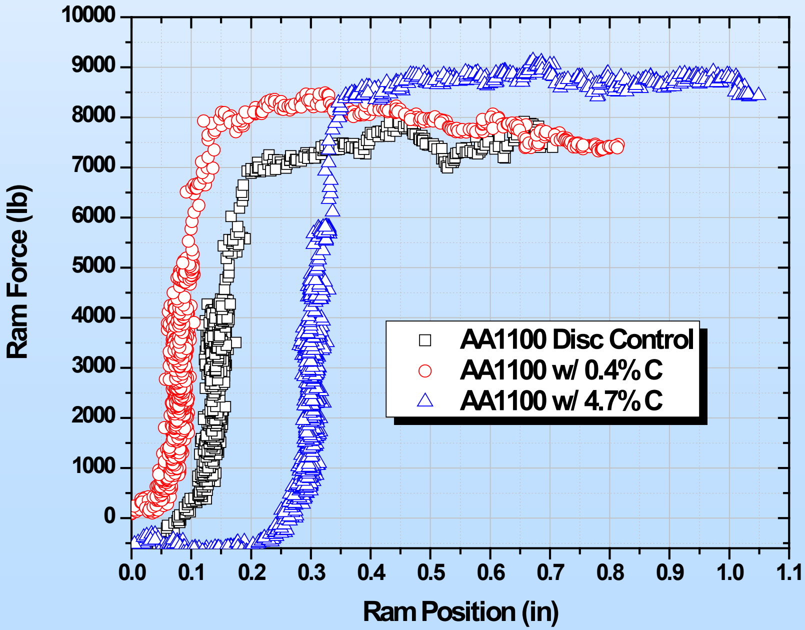
Progress and Current Status of Project

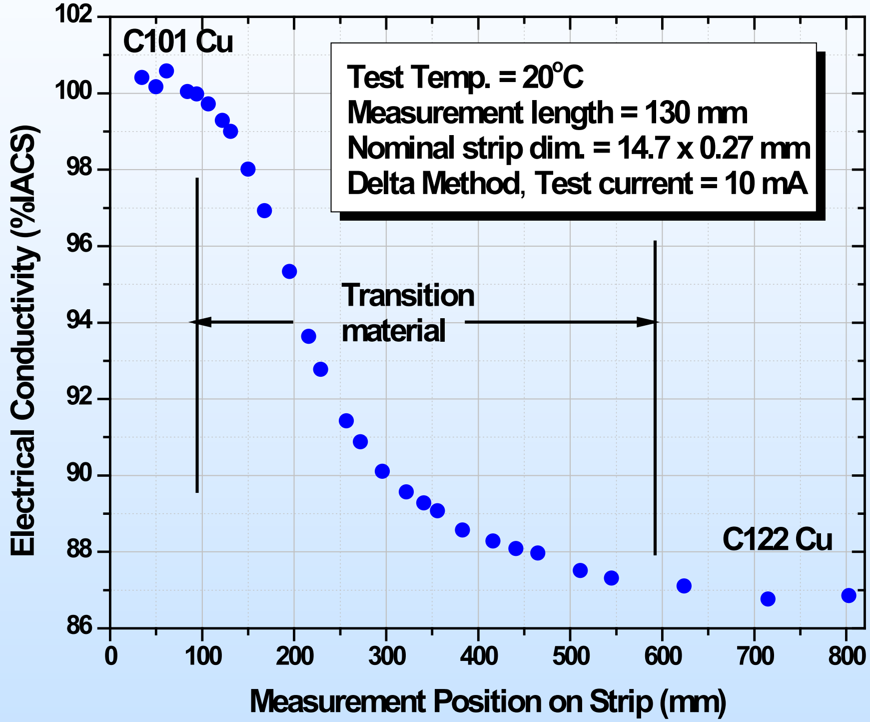
Characterization of extrusion gradients

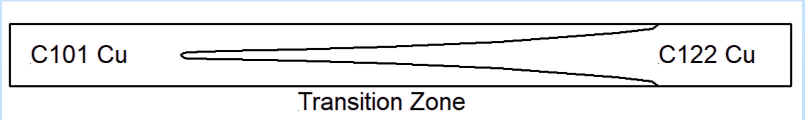
- Establish extrusion flow patterns
- Determine property consistency

Force data wrt to position

- Force increases with carbon content
- Hot extrusion develops composite structure







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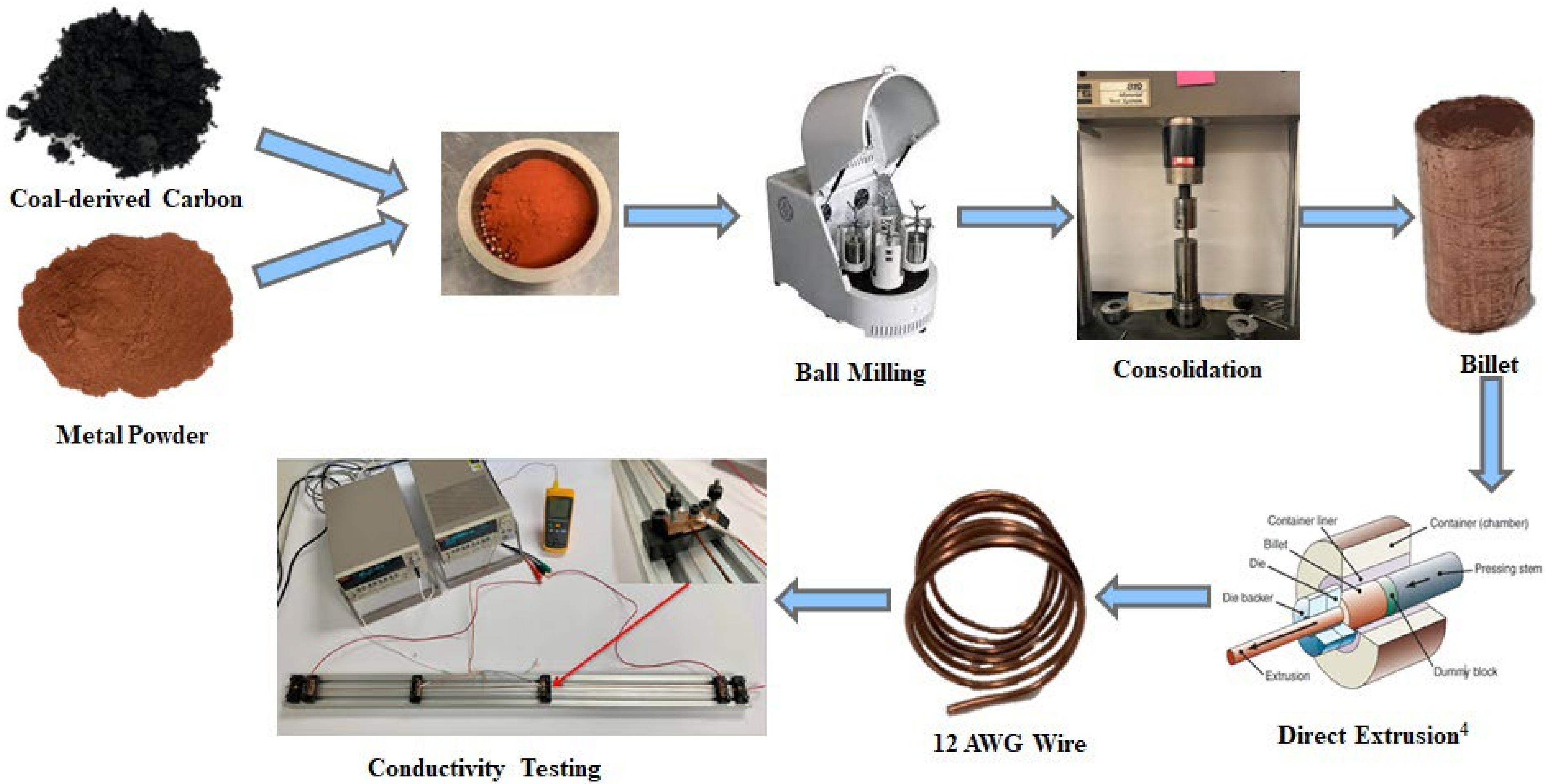

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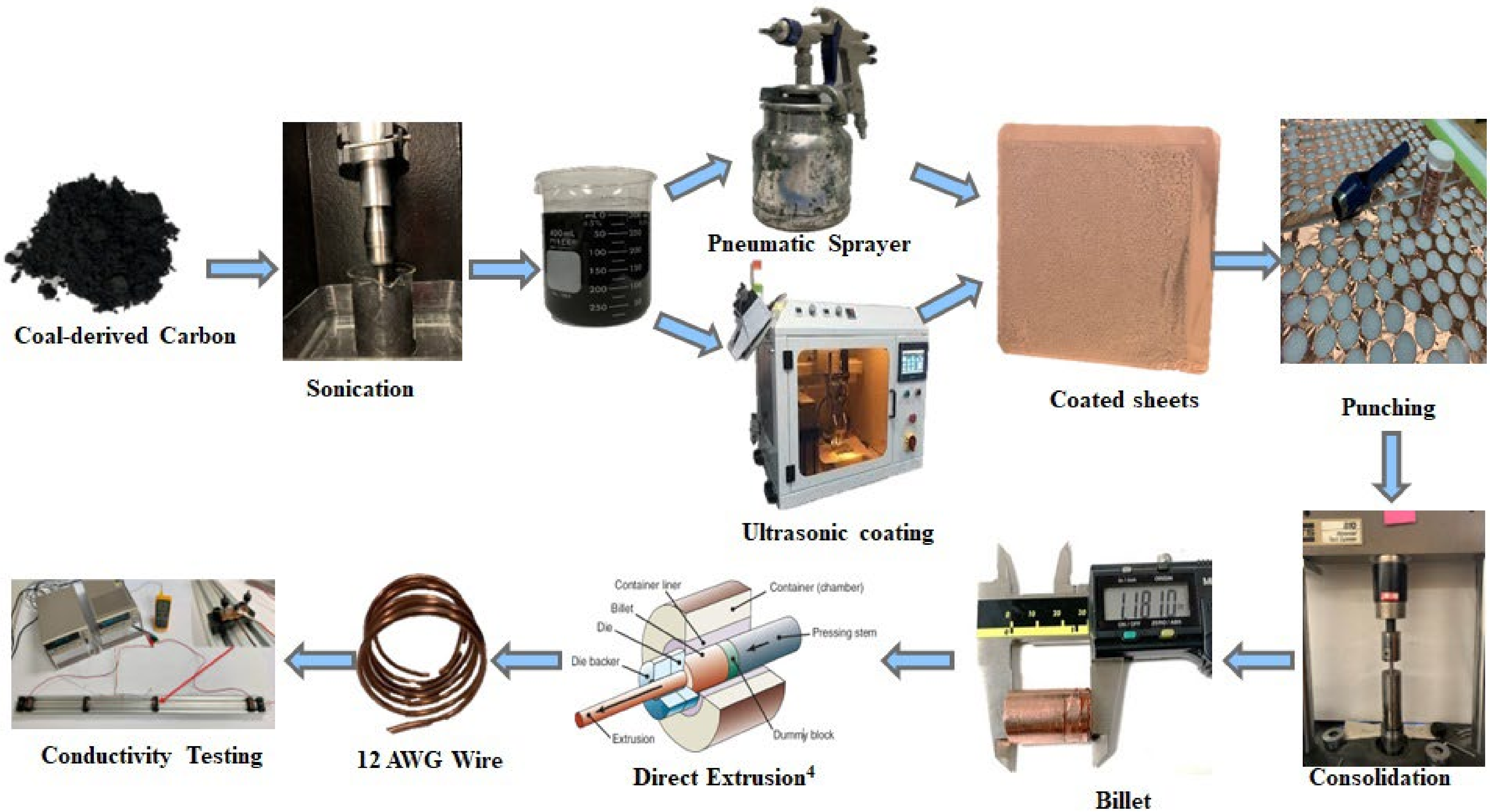

Progress and Current Status of Project

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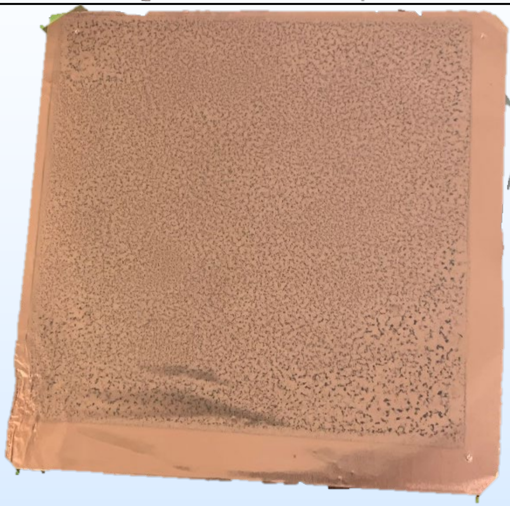
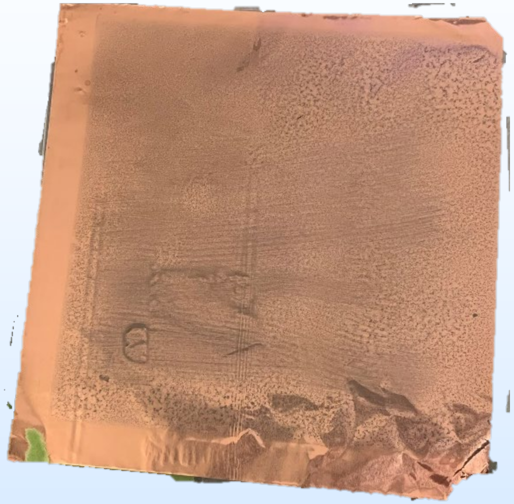


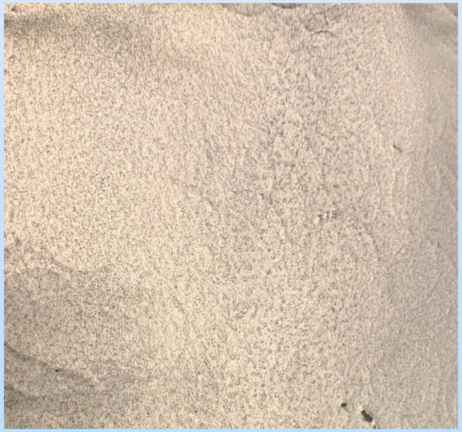
Coal-derived Graphite (CDG) coated on C110 at room temperature using ultrasonic coating (UC)



CDG coated on C110 at 30 °C using UC

Coal-derived Graphene coated on C110 at 40 °C using UC

CDG coated on AA1100 using pneumatic spraying

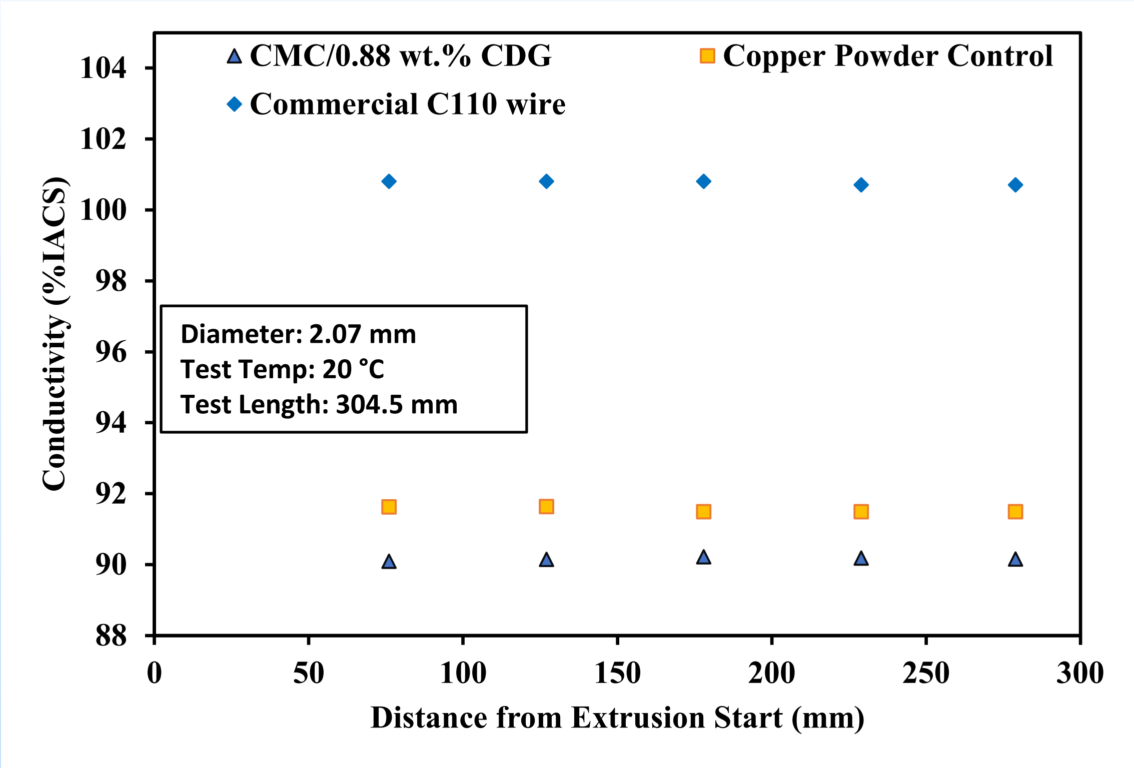


CDG coated on C110 using pneumatic spraying

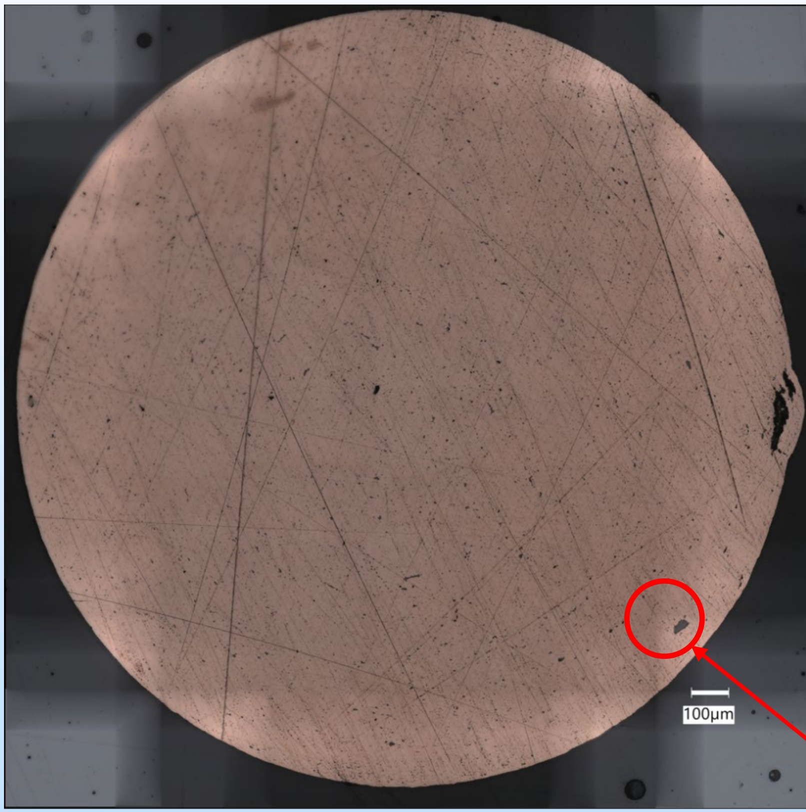
Progress and Current Status of Project

Powder CMC Results

CMC starts with blisters and some cracking

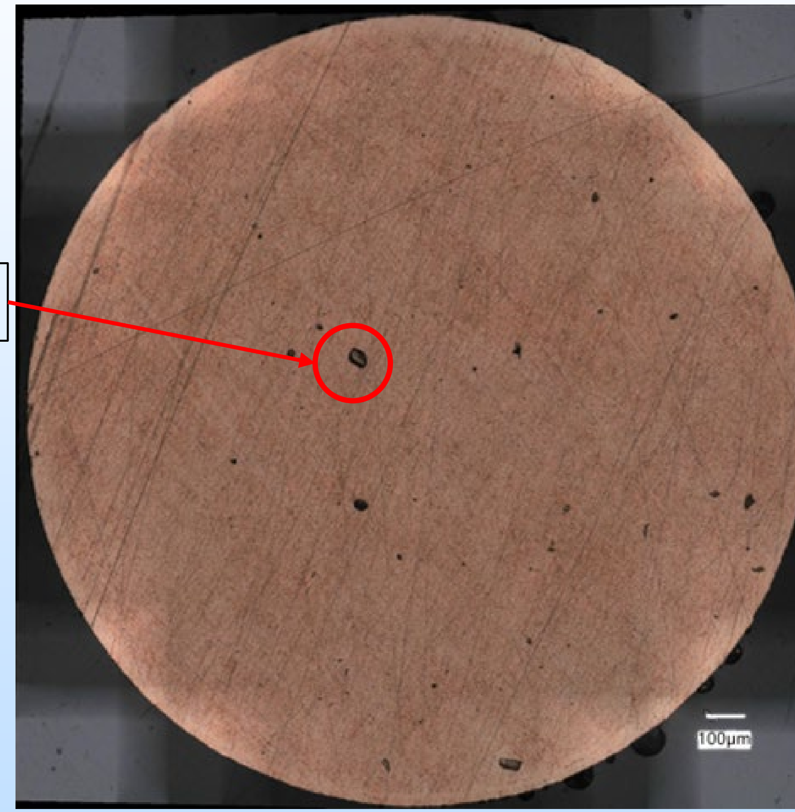


Progress and Current Status of Project



Cavity

Carbon



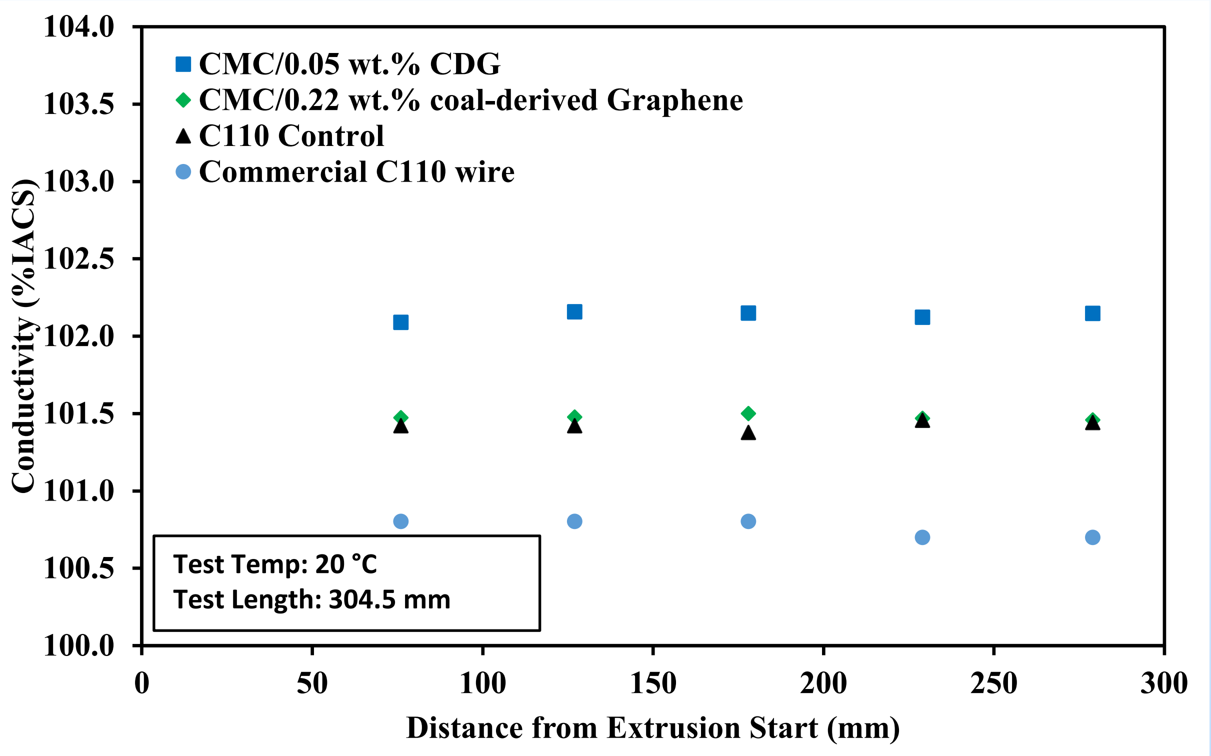
CMC (powder) with 0.9 wt.% Coal-derived Graphite

Copper (powder) control

Progress and Current Status of Project

Copper-based CMC (foil) Results

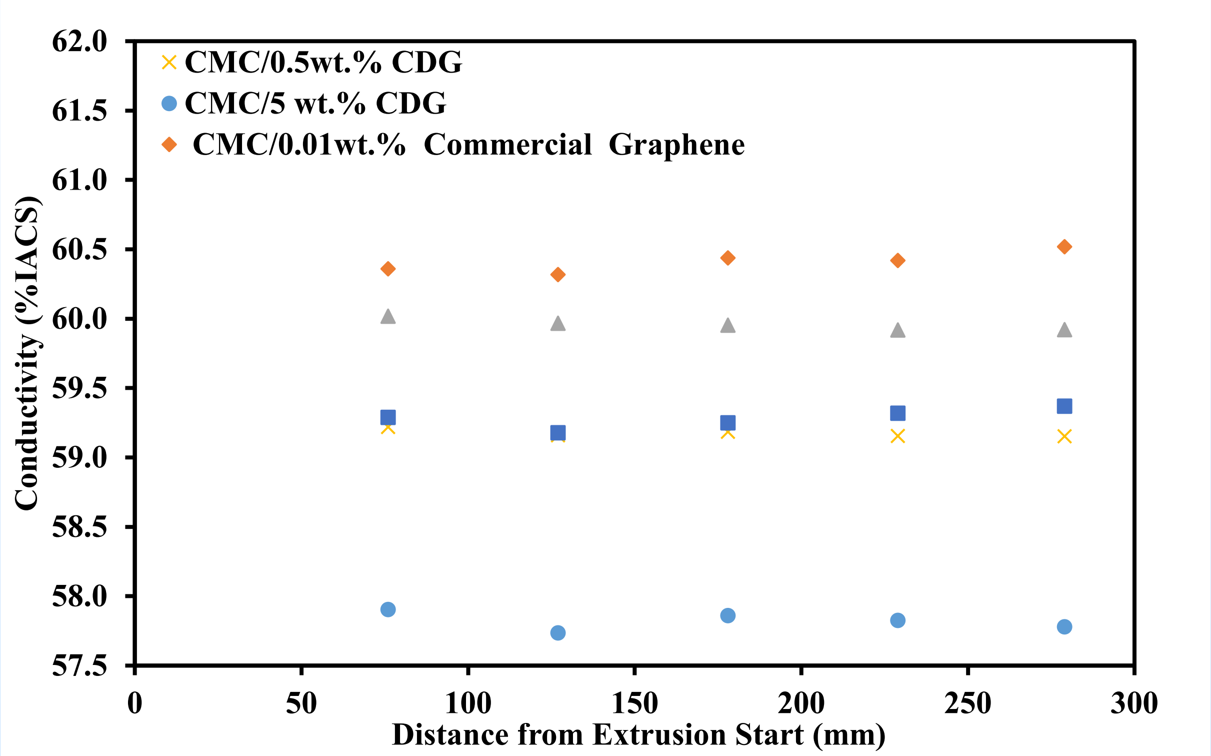
Matrix	Carbon Type	Wire Diameter (mm)	Application Method
Commercial Wire	N/A	2.01	N/A
C110 Foil	N/A	2.07	N/A
C110 Foil	Coal-derived Graphite (CDG)	2.07	Pneumatic Sprayer
C110 Foil	Coal-derived Graphene	2.07	Ultrasonic Sprayer



Progress and Current Status of Project

Aluminum-based CMC (foil) Results

Matrix	Carbon Type	Wire dimeter (mm)	Application Method
Commercial Wire	N/A	2.04	N/A
AA 1100	N/A	2.02	N/A
AA 1100	CDG	2.03	Pneumatic sprayer
AA 1100	CDG	2	Pneumatic sprayer
AA 1100	Commercial Graphene	2	Ultrasonic Sprayer



Plans for future testing/development/ commercialization

Current Project

- Further optimize CMC formulations and processing techniques
- Assess electrical/mechanical performance of CMC wires at room temp and elevated temperatures
- Evaluate effectiveness in high-voltage applications
- Develop detailed TEA and market analyses

Next Project

- Scale-up the technology (TRL 5/6)
- Test the wire in a real electric motor and quantify overall efficiency improvement
- Assess performance for additional commercial applications

Outreach and Workforce Development Efforts or Achievements

Training and Professional Development

- Graduate students: Trained two students on metal composite manufacturing, characterization techniques, and project reporting/presentations.
- Undergraduate students: Provided hands-on experience for two students and up to four students from different engineering disciplines will be trained this summer.

Summary Slide

- Developed unique high-resolution electrical conductivity testing methods
- Validated the hot-extrusion process with coated foils to produce better-performing wires compared to the powder-based process
- Achieved measurable improvements for CMC wire with coal-derived graphite and graphene
- Utilizing high-quality coal-derived graphene is expected to improve the performance compared to graphite significantly
- Availability of high-quality coal-derived graphene could be a challenge

Acknowledgements

DOE/NETL

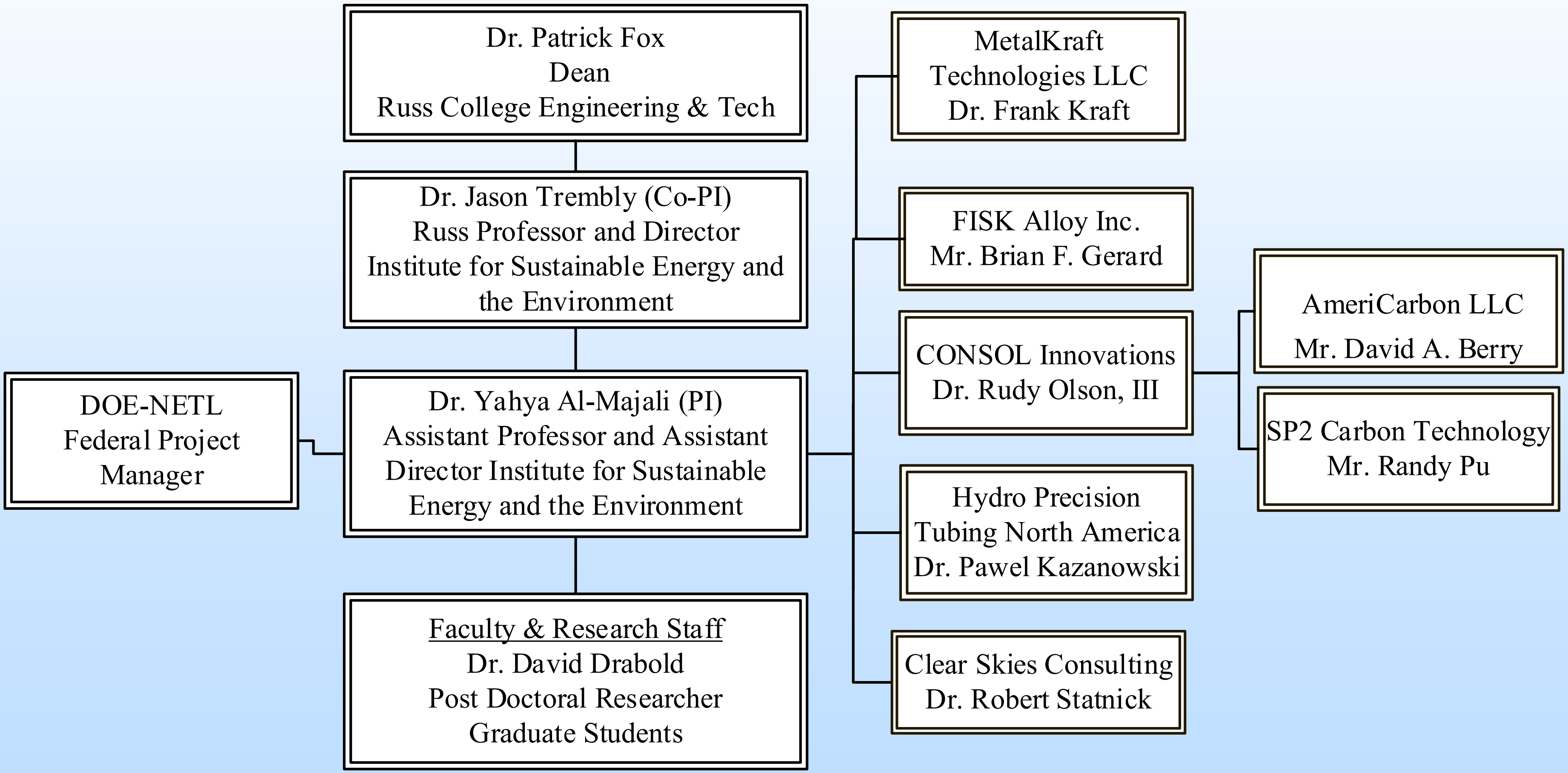
- Project Manager: Dr. Brett Hakey
- Technology Manager: Dr. Joseph Stoffa

Project Team

- OHIO: Matt Tucker, Obieda Altarawneh, Dr. Jason Trembly, Dr. David Drabold
- MetalKraft Technologies: Dr. Frank Kraft
- Fisk Alloy: Brian Gerard, Aiden Din
- Hydro Precision Tubing North America: Dr. Pawel Kazanowski
- CONSOL Innovations: Dr. Rudy Olson
- Clear Skies Consulting: Dr. Robert Statnick

Appendix

Organization Chart



Gantt Chart

Task	Responsible Organizations	BP1 Q1	BP1 Q2	BP1 Q3	BP1 Q4	BP2 Q5	BP2 Q6	BP2 Q7	BP2 Q8
Task 1.0 - Project Management and Planning	OHIO								
Sub-task 1.1 - Project Management Plan	OHIO								
Sub-task 1.2 - Technology Maturation Plan	OHIO								
Sub-task 1.3 - Diversity, Equity, Inclusion, and Accessibility Plan	OHIO								
Sub-task 1.4 - Summary of Environmental Justice Considerations	OHIO								
Sub-task 1.5 - Summary of Economic Revitalization and Job Creation Outcomes	OHIO								
Task 2.0 - Coal-Derived Carbon-metal Composites R&D									
Sub-task 2.1 - Coal-derived Graphitic Carbons and Metals Property Assessment	OHIO, MKT, CONSOL								
Sub-task 2.2 - Carbon Metal Composite Wire Manufacturing R&D	OHIO, MKT								
Sub-task 2.3 - Carbon Metal Composite Wire Performance	OHIO, MKT, FISK, PTNA								
Task 3.0 - Molecular Dynamic and Process Simulations									
Sub-task 3.1- Molecular Dynamic Simulation of Carbon Metal Composite	OHIO								
Sub-task 3.2- Processing Simulation of Carbon Metal Composite	OHIO, MKT								
Task 4.0 - Assessment of Scaled Wire Manufacturing	OHIO, MKT, FISK, PTNA								
Task 5.0 - Techno-economic Studies and Market Analyses	OHIO, FISK, CONSOL, CSC								
Milestone Log		AB	C	D	E			F	G

Ohio University (OHIO), MetalKraft Technologies (MKT), Fisk Alloy Inc. (FISK), Hydro Precision Tubing North America (PTNA) CONSOL Innovations (CONSOL), Clear Skies Consulting (CSC)

Milestones: A: Updated Project Management Plan; B: Project Kickoff Meeting; C: Preliminary Technology Maturation Plan; D:Complete CMC processing and compositions assessment; E: CMC materials performance report; F: Complete pilot-scale wire manufacturing and assess performance; G:Techno-economic and Market Analyses

References

(1) Smith, J. A. Electrical Performance of Copper-Graphene Nano-Alloys.
(2) Kappagantula, K. S.; Smith, J. A.; Nittala, A. K.; Kraft, F. F. Macro Copper-Graphene Composites with Enhanced Electrical Conductivity. Journal of Alloys and Compounds 2022, 894, 162477. https://doi.org/10.1016/j.jallcom.2021.162477.
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