Project ID: MAT165_grant_2020

Direct-Extruded High-Conductivity Copper for Electric Machines

(Agreement ID 69145)

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General Motors Research and Development Laboratory

2020 DOE Vehicle Technologies Program

Annual Merit Review and Peer Evaluation Meeting

June 1, 2020

Virtual Meeting



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Overview

Timeline

- Start date: Sept 2017
- Project end date: Dec 2020
- Percent complete: 98%

Budget

- Total project funding: $1.15M
  - DOE: $600,000
  - Industrial cost share: $550,000
- Future Funds Anticipated: $ 0

Barriers

- Need Increased Efficiency – bring power density to 33 kW/L for a 100 kW peak system by 2025*
- "Reduction in the volume of the components is necessary to enable electric traction drive systems to fit within the increasingly smaller spaces available on the vehicle. Motor volume reduction is limited by the flux density capacities of materials used in current electric steels and electrical conductivity limitations of copper windings"[1]
- Need higher conductivity electrical conductors

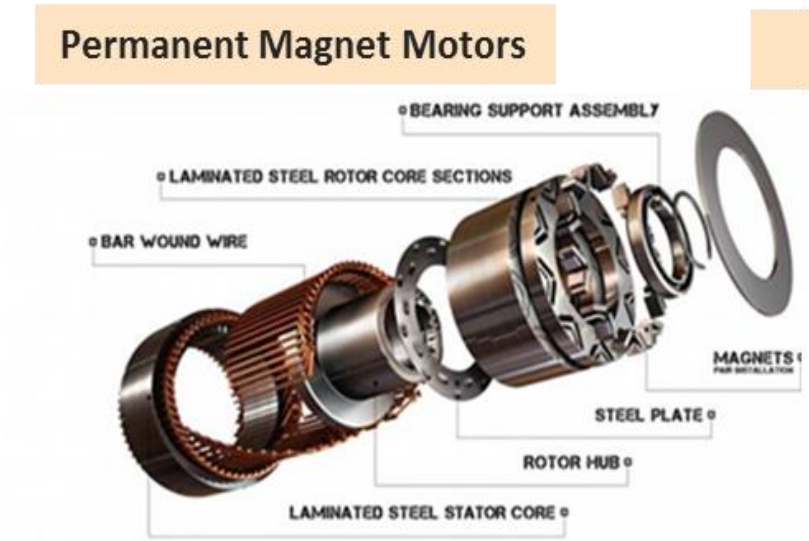
Partners

- CRADA with General Motors Research and Development
- Project lead: PNNL

* Electrification - 2018 Annual Progress Report Vehicle Technologies Office – EDT Program Goal
[1]U.S. DRIVE Electrical and Electronics Technical Team Roadmap October 2017
https://www.energy.gov/eere/vehicles/us-drive-partnership-plan-roadmaps-and-accomplishments

Relevance

Impact of increasing conductivity







The efficiency, weight, power density, and therefore the cost of an electric machine could be improved if the primary conductors could be made with much higher conductivity than standard electric copper

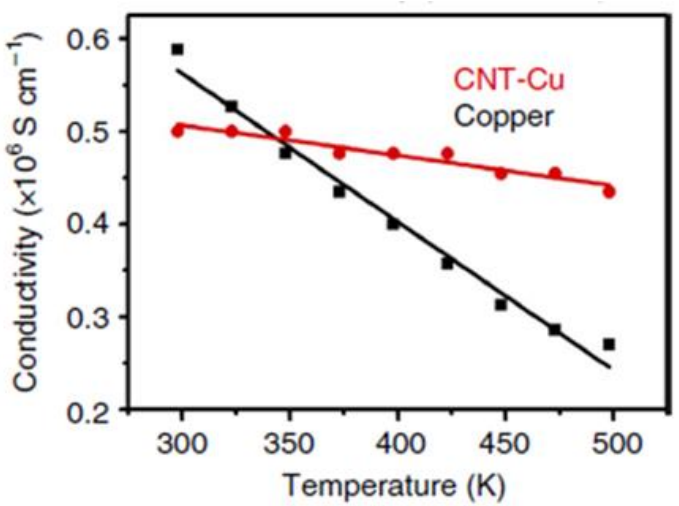
Relevance

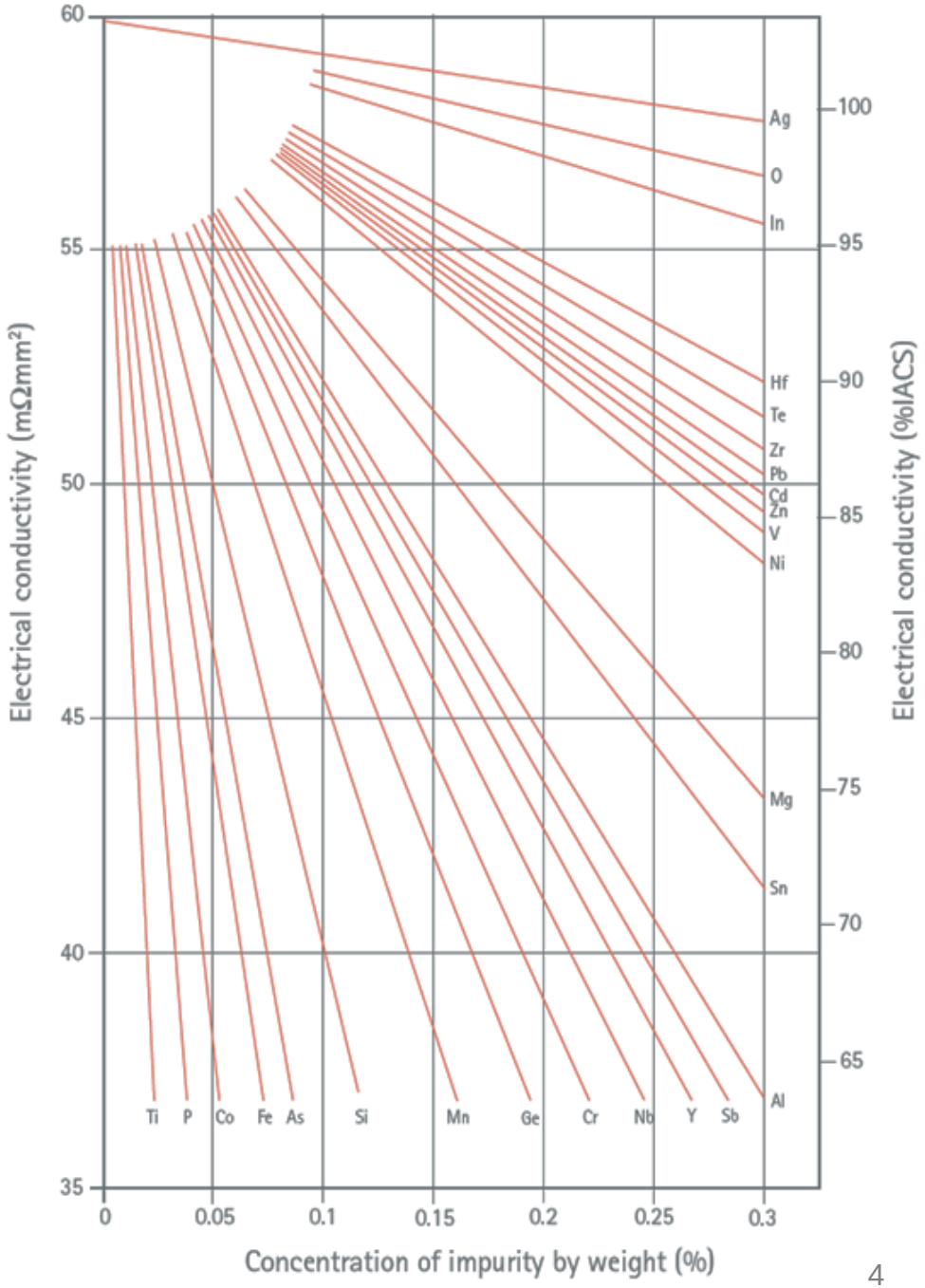
Challenge of increasing conductivity

Pure copper is already <u>very</u> conductive

- As temperature increases in electric motors, electrical conductivity of the pure cupper components goes down, reducing motor efficiency
- Anything added to Cu makes conductivity worse

…with the possible exception of Carbon





Relevance

Copper - Carbon Composites

- Fully dense Cu-C Composites have been made that show conductivity better than pure copper at elevated temperatures
- Carbon is immiscible with copper, this work is to evaluate process to make the composite and..
- Validate if adding carbon increases conductivity

Forms of Carbon

- Graphite
- Reduced Graphene Oxide
- Graphene
- Single and Double Wall Carbon Nanotube
  - metallic or covalent

Possible manufacturing Process

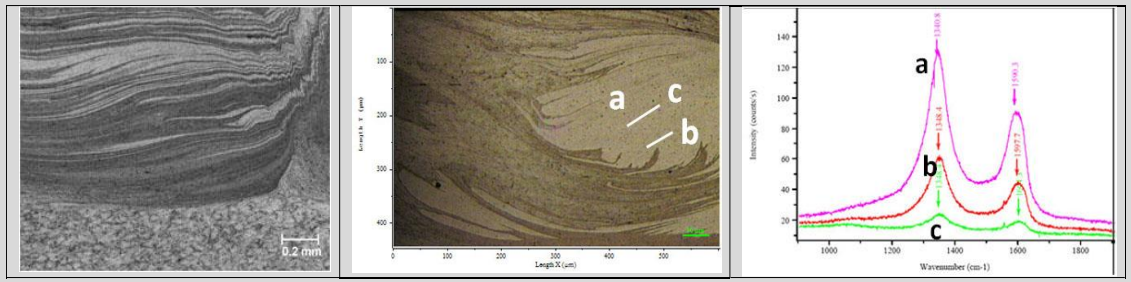
- Layered Structures (PVD-CVD- other thin film methods)
- Super saturated solutions from ball milling or Magnetron Sputtering
- Bulk Composites from melt solidification Processes
- Covetic processing (melt solidification in a magnetic field)
- Hot Extrusion

To date, few bulk methods have been successful at demonstrating increased conductivity

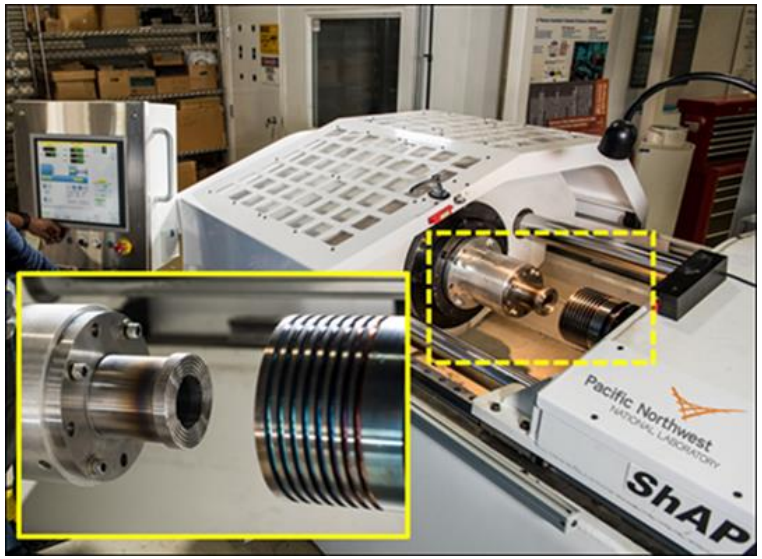
Approach

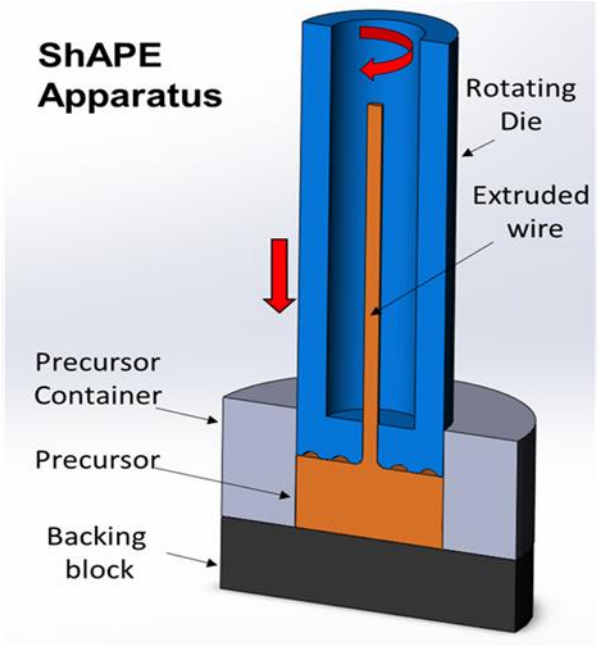
Need a new bulk manufacturing process to form the Copper-Carbon Composites

- Observed super-saturated and non-equilibrium mixtures and alloys can be made using severe plastic deformation
- Developed techniques at PNNL to combine this severe plastic deformation process with an extrusion process to make it scalable



Shear Assisted Processing and Extrusion (ShAPE)





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Solid Phase PROCESSING

Approach

Objectives

- Develop and demonstrate a high conductivity copper-based material composed of a copper-carbon composite
- The copper composite will be fabricated using the ShAPE process
- Show that ShAPE can shear, mix to a high level of homogeneity, and extrude wire and bar that is a combination of copper and various forms of carbon (including graphene and graphite)
- Measure, to a high level of accuracy, the conductivity improvements and all aspects of mechanical and thermal properties relevant to an electric motor application



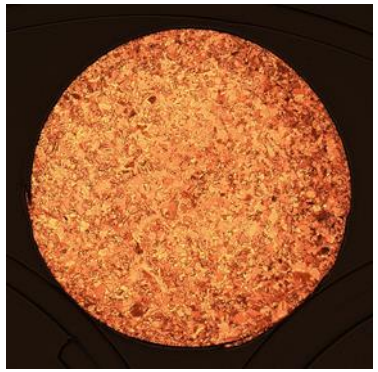
At the conclusion of the project, feed this data into motor FEA models using various motor designs to make predictions on total motor efficiency gains

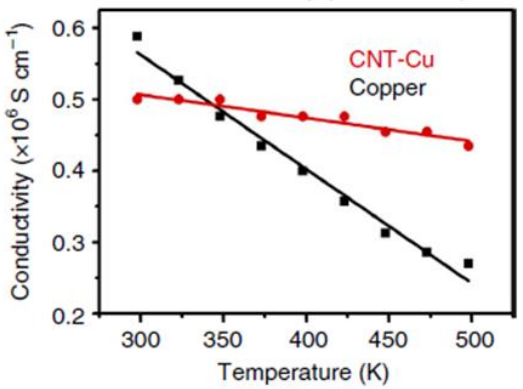
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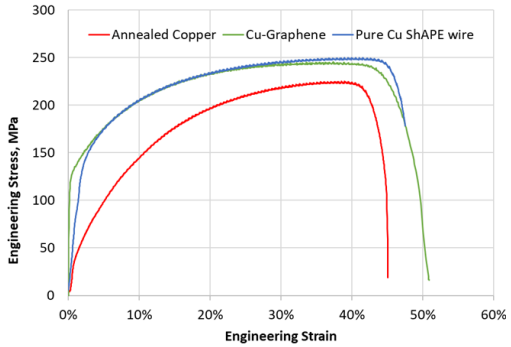
Approach
Task structure

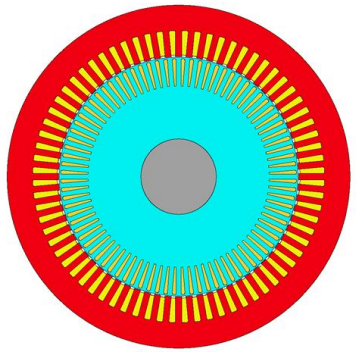
Solid Phase PROCESSING

- Task 1: Make a good composite
  - Methods to mix carbon (graphite and graphene) into copper
  - Die fabrication and testing
  - Extrusion Trials
  - Detailed microstructural characterization
- GATE - Electrical resistivity at temperature
- Task 2: Make the correct shape extrusion
  - Wires and Rods
- Task 3: Join wire/rod (welding / brazing)
- Task 4: Demonstrate mechanical properties appropriate for roll forming
- ~~Task 5: Rotor assembly by FSW and testing~~
- Task 5: Motor FEA analysis and modeling on example induction motor designs







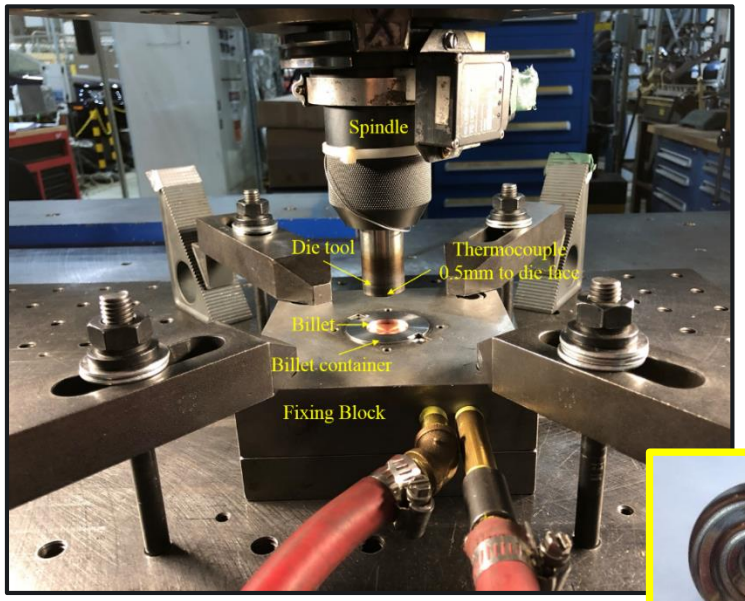


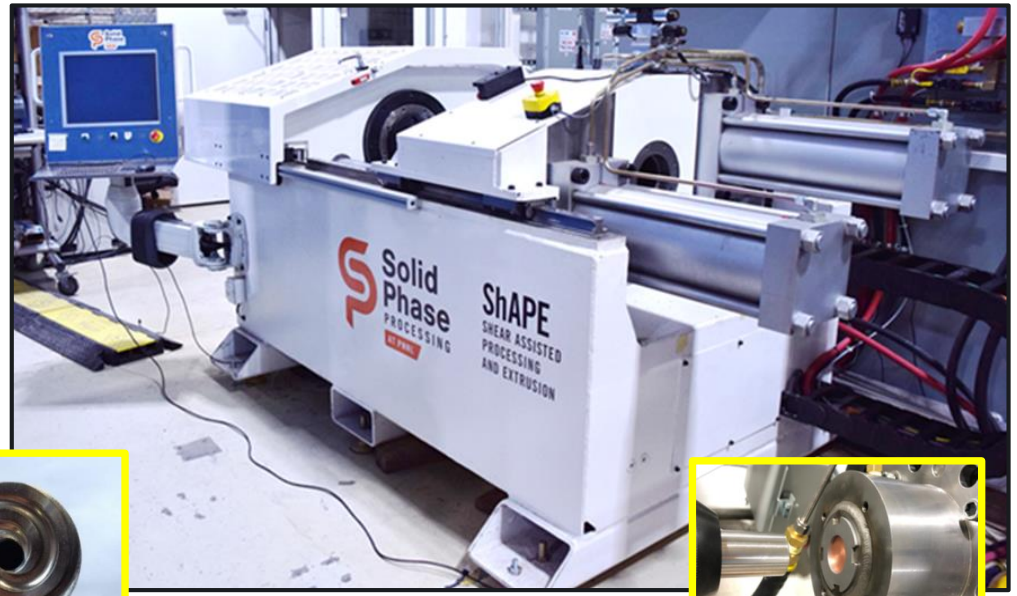
Milestones

Milestone 1	Micrographs showing composite cross section free of defects in the composite	Completed
Milestone 2	At least one of the copper carbon composites must show electrical performance (elevated temperature conductivity) significantly higher than current pure copper materials.	Completed
Milestone 3	Batch to batch electrical conductivity does not show significant variability	Completed
Milestone 4	Copper composite weld joint on rod material with joint strength at least 80% of base material and small to insignificant electrical losses across joint	Completed
Milestone 5	Sufficient ductility to produce a rolled product in the form of a square bar wire or a shorting bar	Completed
Milestone 6a	~~Full-sized rotor assembly for GM high power induction motor and electrical performance testing~~	Deferred to Milestone 6b
Milestone 6b	Induction Motor CAD/FEA analysis to model Efficiency gain	Completed
Final	T2M, Tech Transfer	In progress

Technical Accomplishments

Process Development

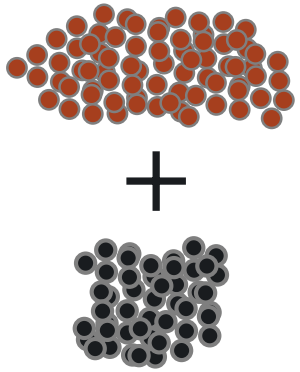




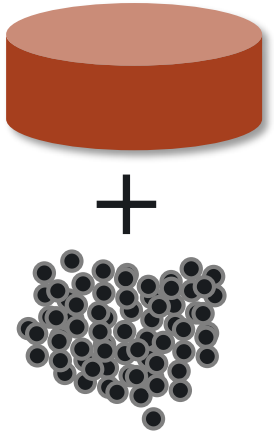




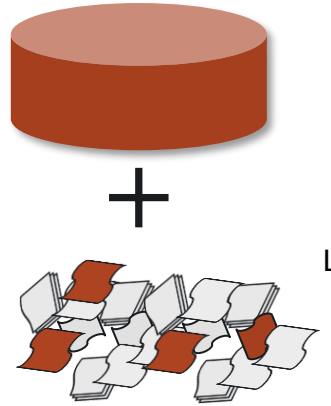
Precursor materials:



Copper powder (<45um, 99.7% purity) Blend with 1%-15wt% Graphite powder (<45um, >99.9%)



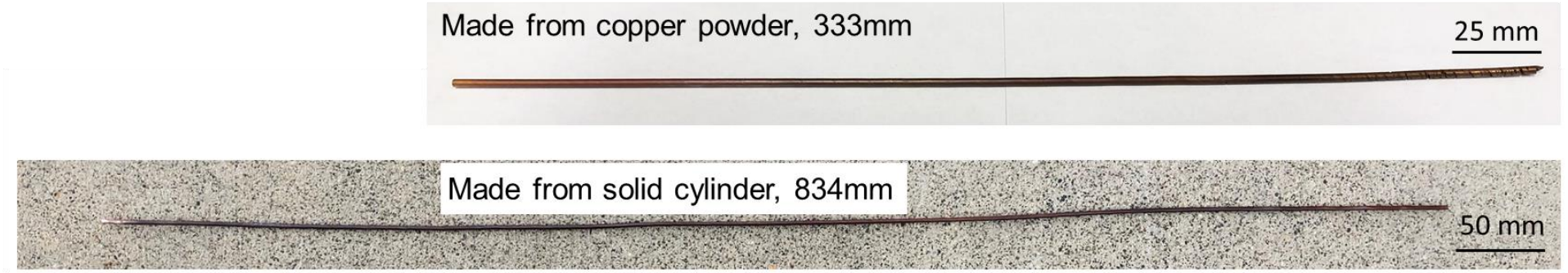
Solid Copper cylinder (C10100, <99.99% purity) Drill and filled with Graphite, Reduced graphene oxide, and Graphene oxide powder (<45um, >99.9%)

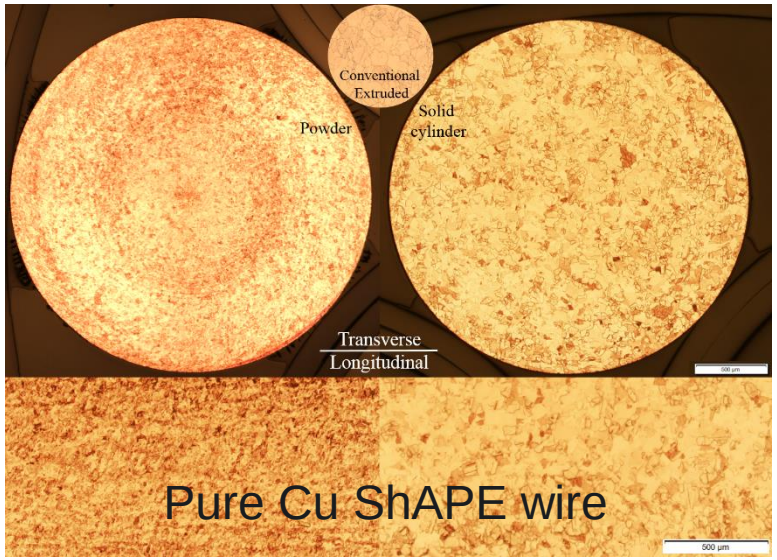


Solid Copper cylinder (C10100, <99.99% purity) Loaded with Monolayer Graphene on Cu foil

Technical Accomplishments

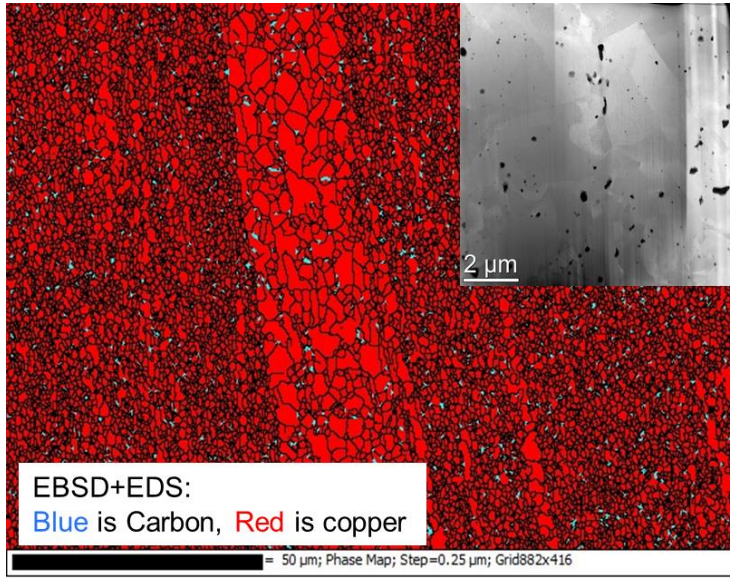
Process Development



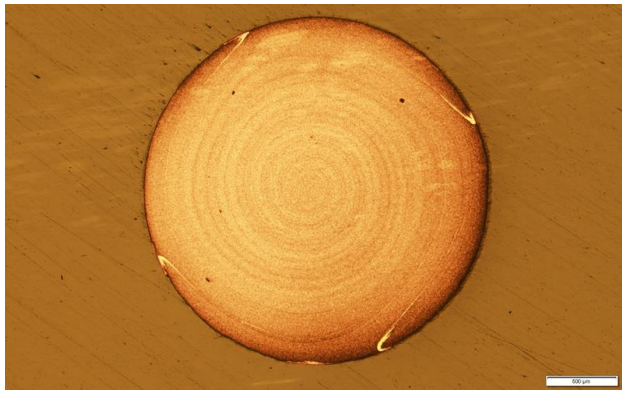


Fully dense wires can be made from all precursors, both powder and billet. Wire extruded even direct from powder is as dense as the billet precursors.

Carbon (Graphite, RGO,etc.) is evenly dispersed in the copper by ShAPE

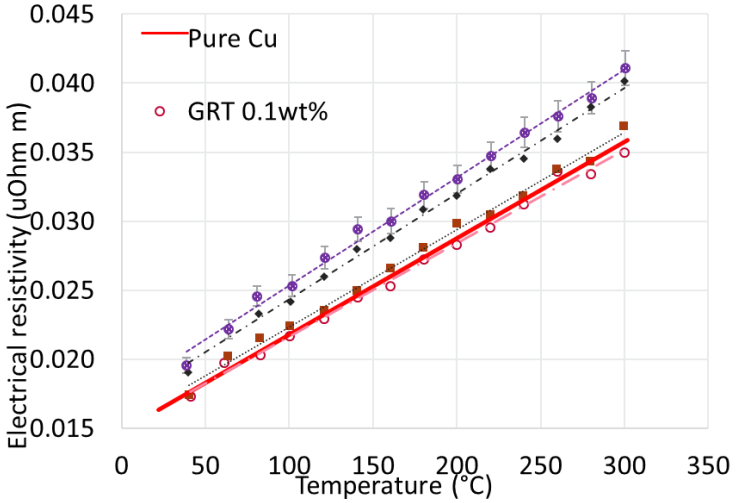


Even for high Carbon loading (15 wt% graphite) the carbon is well dispersed, without agglomeration



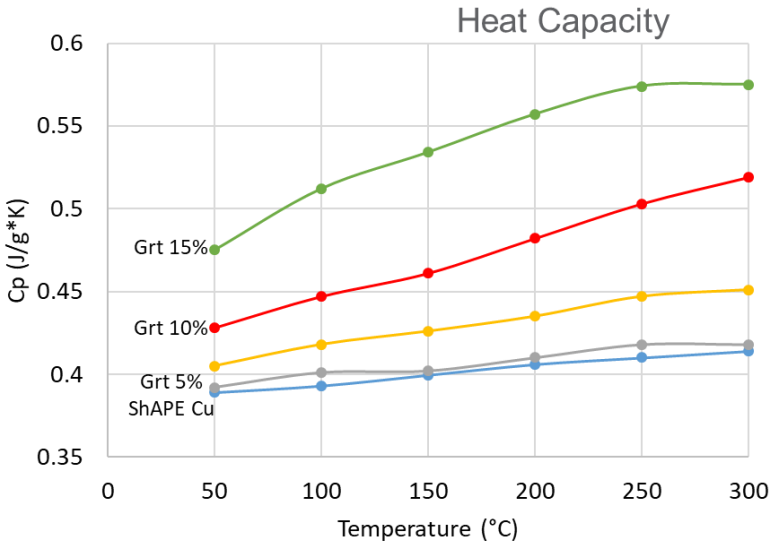
Technical Accomplishments

Copper-Graphite vs Copper Graphene

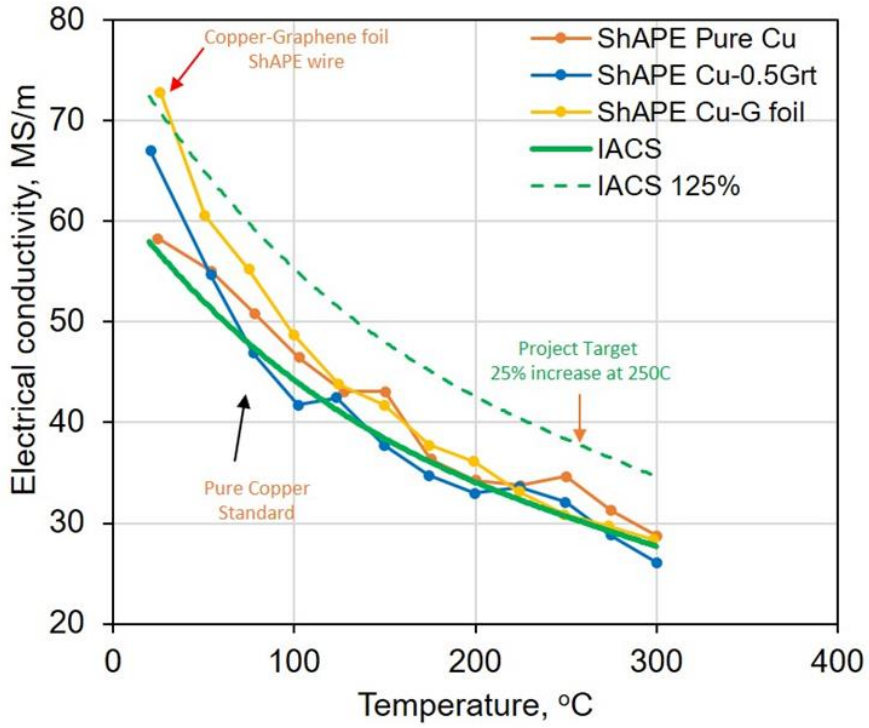


Adding graphite into copper makes conductivity worse

- The electrical resistivity increases with increased graphite content.



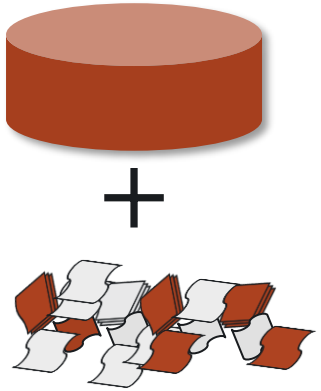
Adding graphite into copper can significantly increase the heat capacity

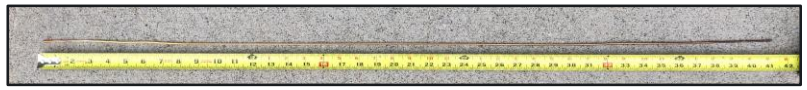


However, graphene is another story

Technical Accomplishments

Cu-Monolayer graphene



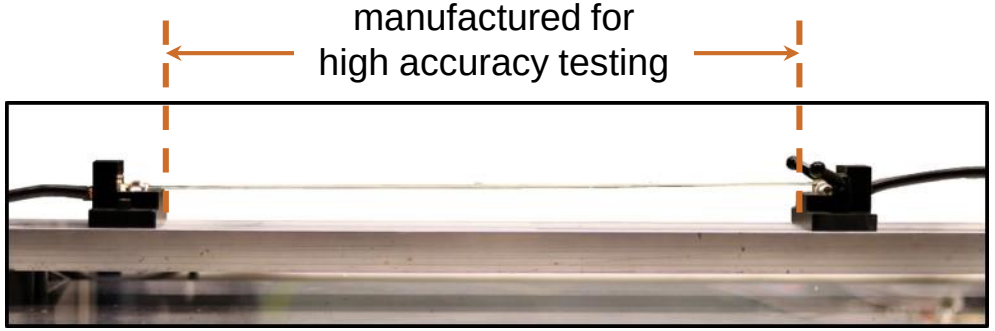


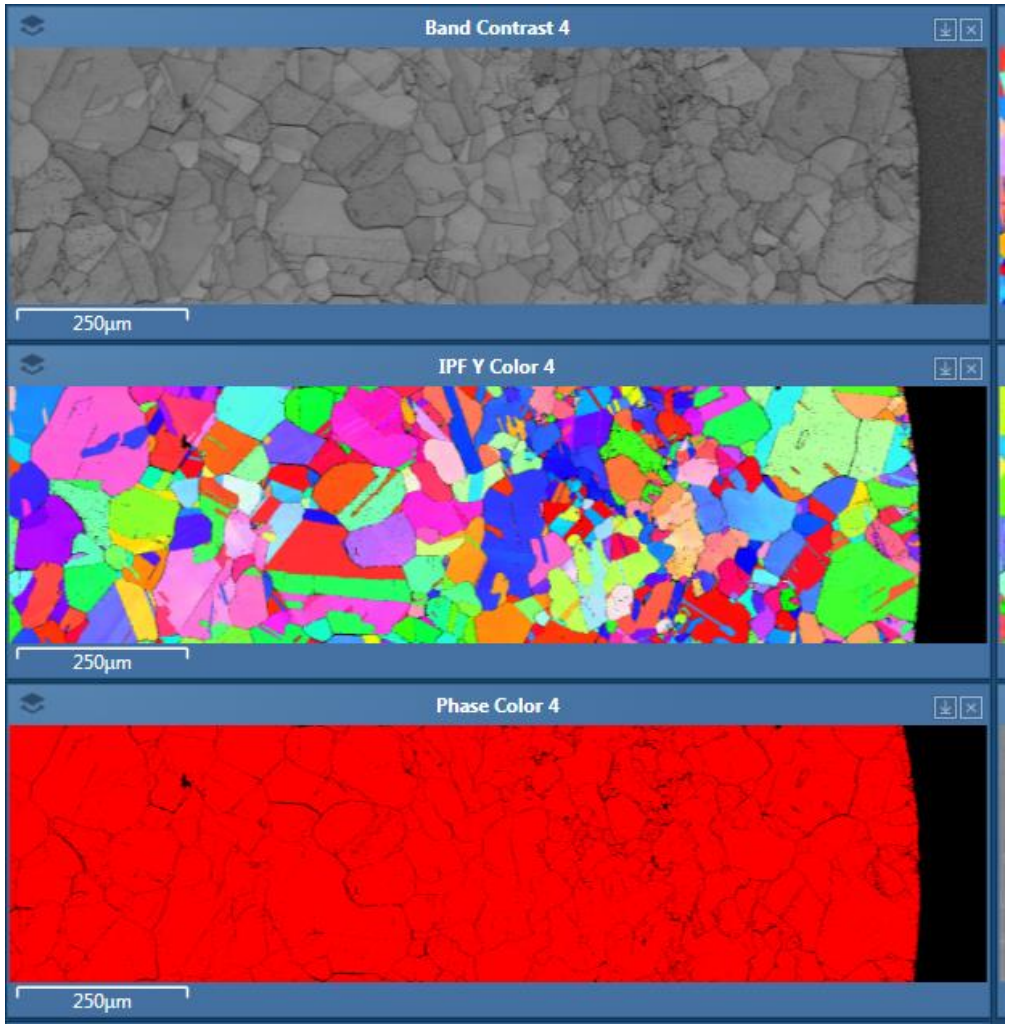
Solid Copper cylinder (C10100, <99.99% purity) Loaded with Monolayer Graphene on Cu foil

Graphene precursor materials combined with Cu were extruded into wires by ShAPE and measured for their conductivity properties.

Graphene content ranged from 0 – 6 ppm.

0.5-m-long wires manufactured for high accuracy testing





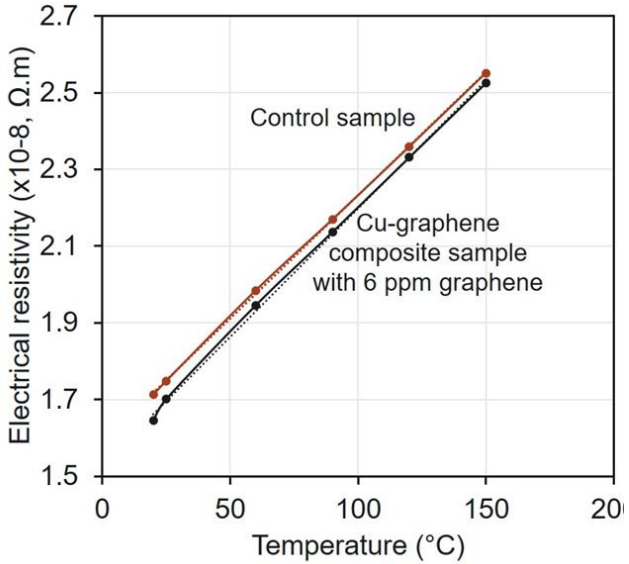
Technical Accomplishments

Best results to date…

Property	Control sample	1.5 ppm	6 ppm
Electrical conductivity at 20°C (%IACS)*	100.75 ± 0.002	103.57 ± 0.001 (2.9% ↑)	104.84 ± 0.003 (4.1% ↑)
Electrical conductivity at 60°C (%IACS)**	86.95 ± 0.0146	88.43 ± 0.0296 (1.7% ↑)	88.69 ± 0.0193 (2.0% ↑)
Electrical conductivity at 90°C (%IACS)**	79.57 ± 0.0146	80.23 ± 0.0296 (0.8% ↑)	80.67 ± 0.0193 (1.4% ↑)
Temperature co-efficient of resistance (/°C)	0.0037	0.004[a]	0.004[a]

- Very low levels of graphene produce large changes in conductivity
- Increasing graphene level leading to increasing advantage
- At elevated temperature the Cu-C shows improved conductivity over pure copper. (Important for elevated temperature operation in electric drives for EVs)

*Measured using Delta method
**Measured using Joule heating method
[a]Indicates property may be not measured as accurately owing to surface features

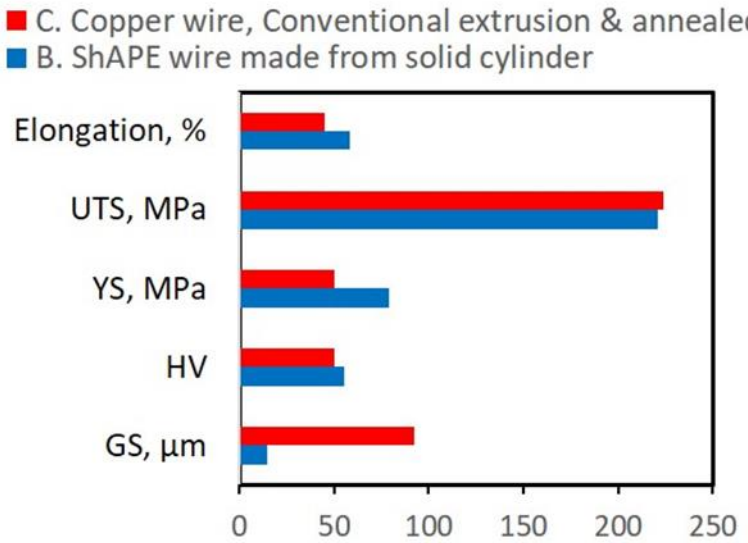


Electrical conductivity of copper + graphene composite samples with 6 ppm graphene content as a function of temperature. Testing performed by Ohio University.

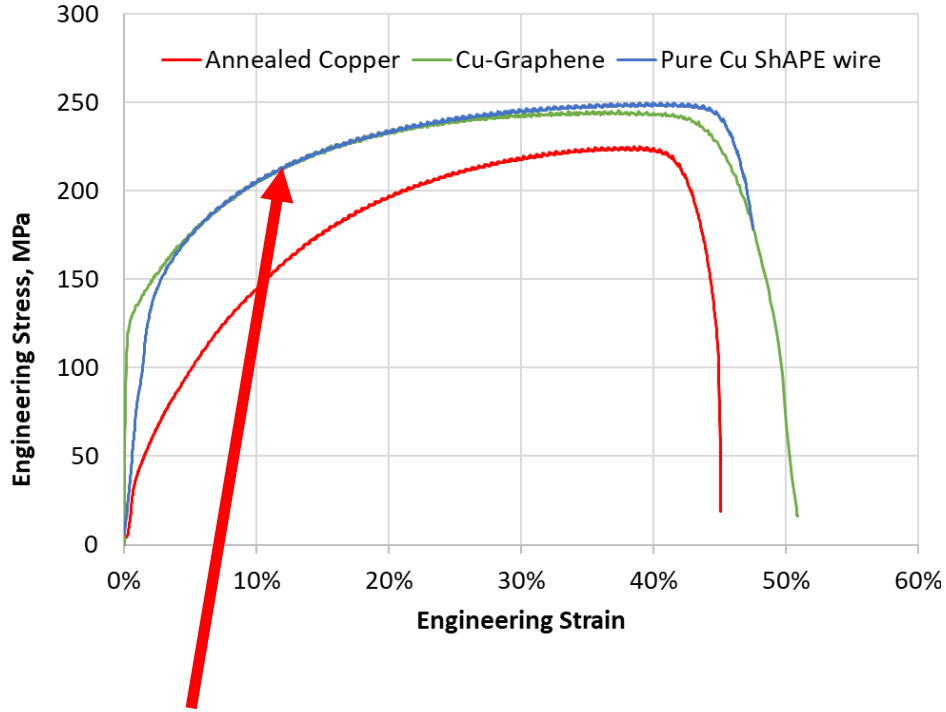
Task 4 Mechanical Properties

- Meter-long defect free wires have been made; longer wires are possible
- Mechanical properties are very similar to pure copper





240 MPa UTS, 45% elongation



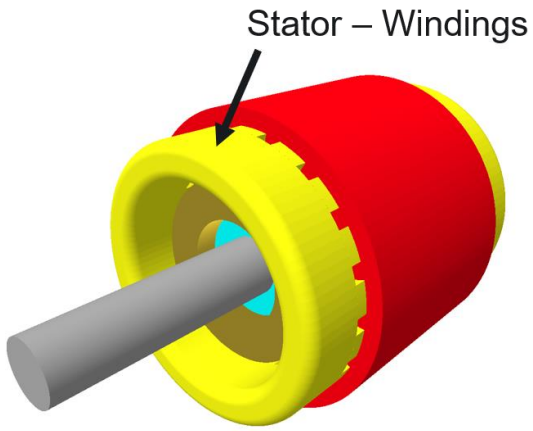
- The ShAPE-processed pure copper and the ShAPE processed copper-graphene composite have the same properties, because the graphene is at the ppm level
- Ductility for post processing (rolling) is better for ShAPE wire than conventionally processed pure copper wire

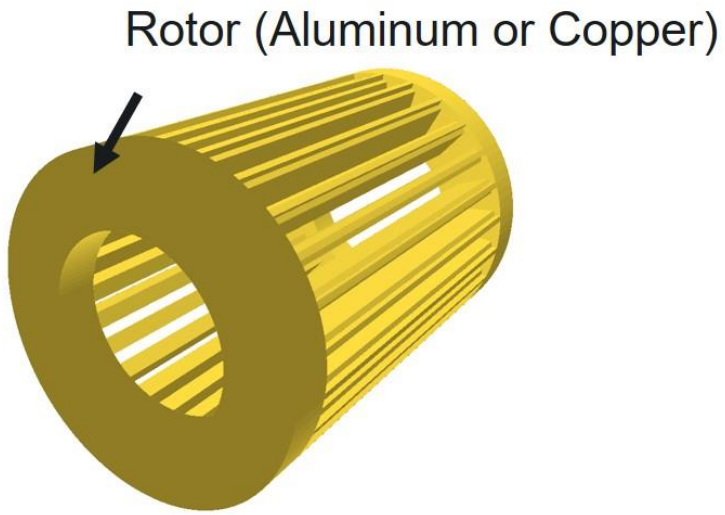
Task 5 Induction Motor-CAD Simulation Motor FEA Analysis

Modeling potential efficiency gain when using higher conductivity materials –

Why could higher conductivity make a difference?

- Losses in the stator and squirrel cage
  - Friction and windage losses (constant regardless of the motor load)
  - Load losses
  - Stator winding losses (I^2R losses)
  - Rotor losses - (I^2R losses)
  - Additional load losses – stray load losses
- Although the I^2R are some of the most important in motor efficiency we haven't had the ability to really change these since copper is as good as it gets
- A material with higher conductivity (and potentially higher current carrying capacity as well) may be an opportunity for a step change in motor efficiency



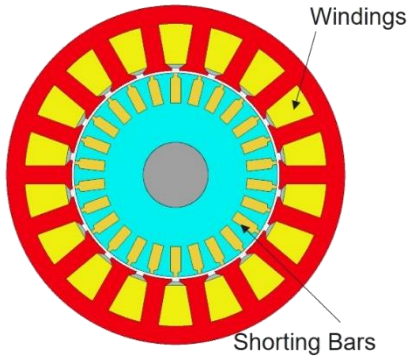


Technical Accomplishments and Progress:

Motor FEA Analysis

Conductivity at 20°C (MS/m)	Conductivity at 20°C (%IACS)	Temperature Coefficient of Resistance [%/°C]	Efficiency [%]	Improvement [%]
58.4	100.7	0.0037	76.3	--
60.8	104.8	0.0040	76.8	0.66
60.8	104.8	0.0036	77.3	1.3
63.8	110	0.0037	78.1	2.4
87	150	0.0033	82.7	8.4

- 0.66% improvement in efficiency in this simulation (using our results for conductivity and TCR)
- 1.3% efficiency improvement (using “smooth wire” post-processing lowers the TCR to .0036)
- We have not yet tested higher graphene loading than 6 ppm
- The bottom two rows are results if we can reach 110% IACS and the theoretical limit of 150% IACS
- Nothing suggests that we have hit the limit of efficiency improvement possible



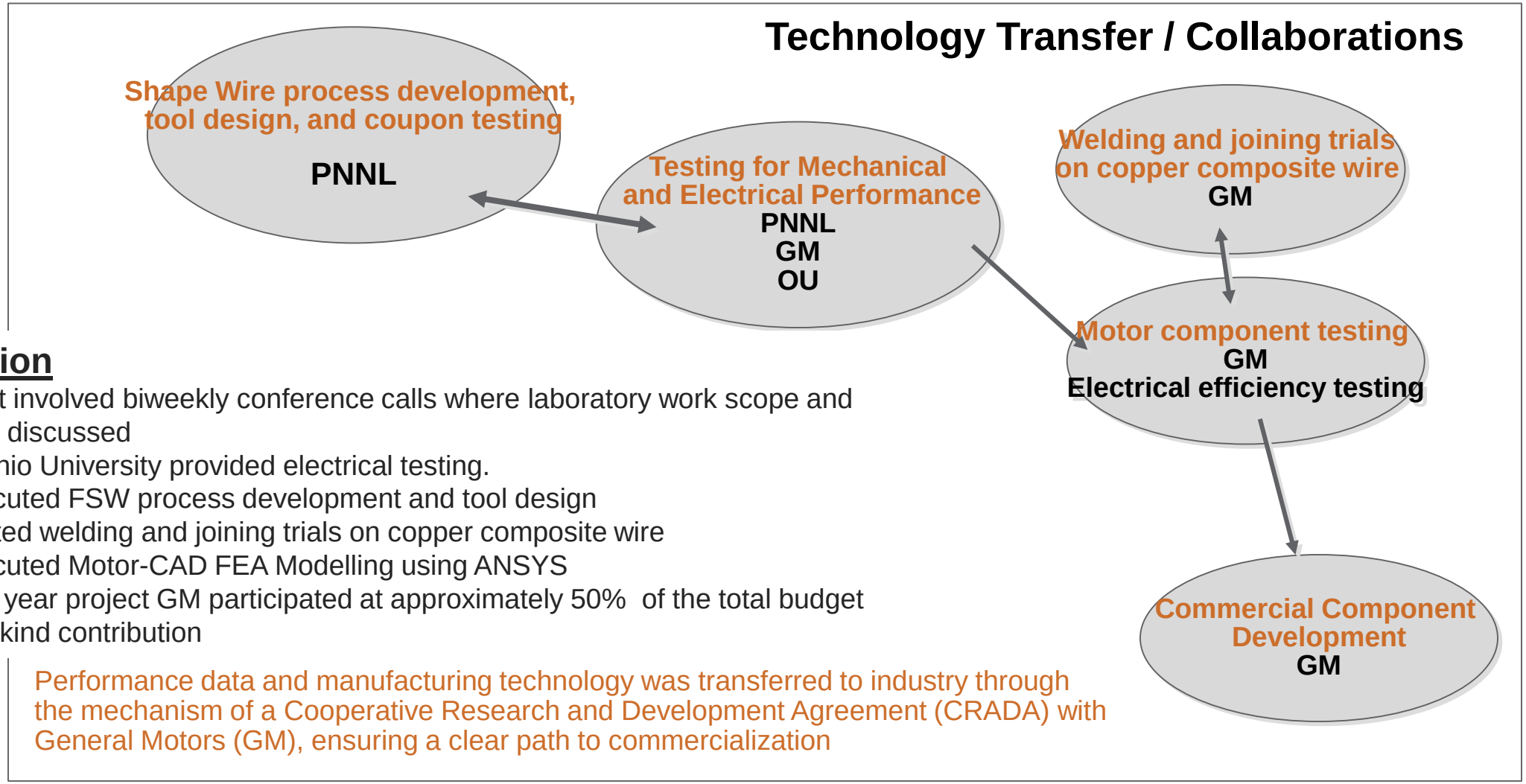
Model Assumptions

- Induction Motor
- 4 poles, 50Hz, 18 slots, 26 bars induction machine
- 100 turns per coil with two winding layers
- 430 V RMS, 3kW power motor
- Ansys Motor-CAD simulation

Responses to Previous Year's Reviewers' Comments

- Technical Accomplishments and Progress - The reviewer said this project has overcome a key barrier in finding a method of measuring conductivity, but the real "proof of the pudding" will come once components are made and tested—and it is too early to determine how that phase will go. Similarly, the **issues of mechanical properties and production cost will emerge as core to the feasibility of commercial adoption of the technology**—and it is too early to comment with any certainty on those issues. In short, the next evaluation of this project should yield some very important information.
  - *We have tried to address one issue of cost by restricting the experimental investigations to very low levels of graphene (ppm levels). Ultimately these low levels combined with a continuous method of fabrication through perhaps a roll to roll type process could lower precursor material cost. Like semiconductor materials in the last 30 years, the cost of graphene will likely scale down with the volume demand. In addition we have produced mechanical property data that shows the composite behaves very similarly to pure copper suggesting that no additional efforts will be needed for this material to drop into all the wire and shorting bar fabrication processes used today. Certainly the manufacturing process will need to move away from a batch type process for the cost to efficiency gain calculation to turn favorable.*
- Resources - This reviewer said that there do not appear to be any difficulties on the resource side of this project at-present, but the **work on durability and manufacturability may require additional resources** once those issues come into focus.
  - *We are at the end of the project and have demonstrated something that has not been seen in a material with this level of scale-up potential, and that is a material with a higher conductivity than copper, yet in other ways acts like copper. The next steps include increased Graphene content to see how close we can approach the theoretical percolation limit somewhere near 150% IACS. The second major future effort needs to be around manufacturing process scale up and moving to a continuous process. These will require additional resources.*

Collaboration and Coordination with Other Institutions

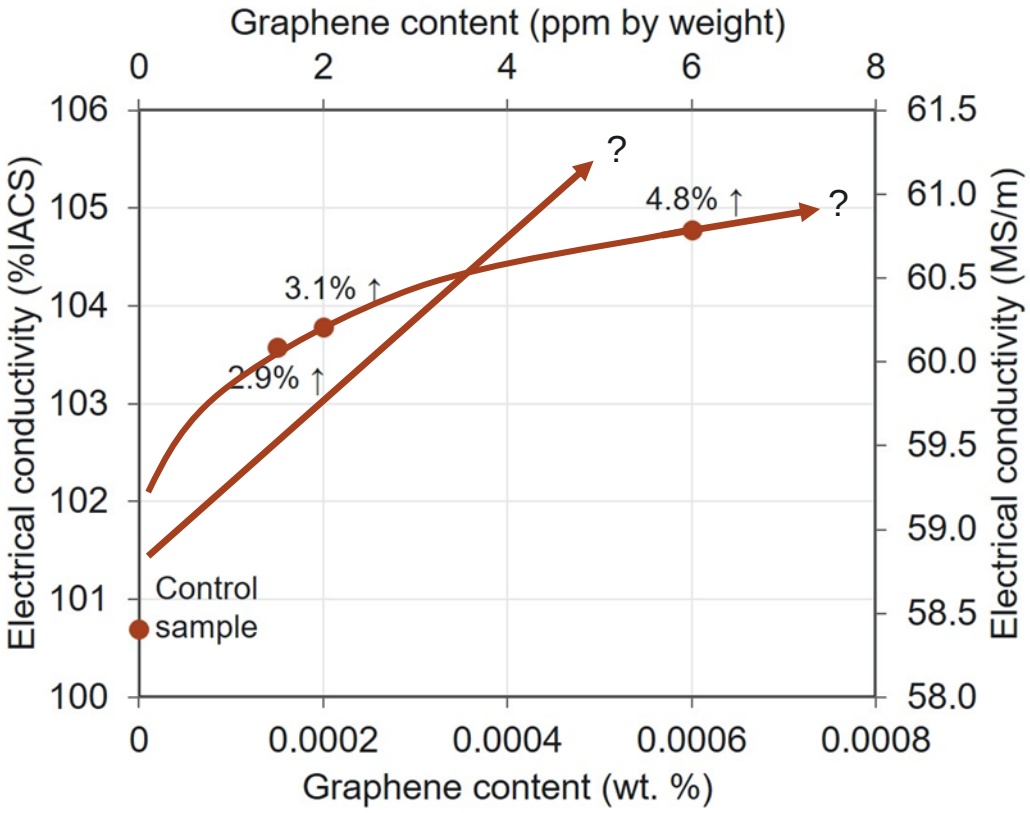


Collaboration

- The project involved biweekly conference calls where laboratory work scope and tasks were discussed
- GM and Ohio University provided electrical testing.
- PNNL executed FSW process development and tool design
- GM executed welding and joining trials on copper composite wire
- PNNL executed Motor-CAD FEA Modelling using ANSYS
- Over the 3 year project GM participated at approximately 50% of the total budget through in-kind contribution

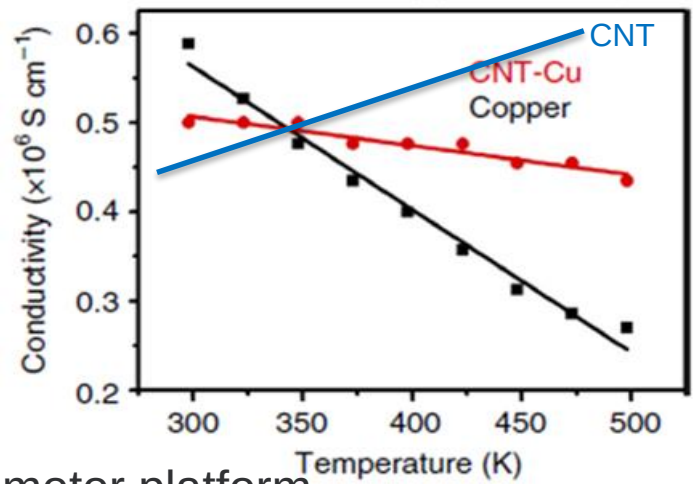
Performance data and manufacturing technology was transferred to industry through the mechanism of a Cooperative Research and Development Agreement (CRADA) with General Motors (GM), ensuring a clear path to commercialization

Remaining Challenges and Barriers



Electrical conductivity of copper + graphene composite samples as a function of graphene content measured at 20 °C. Testing performed by Ohio University.

- Can higher Graphene loading result in higher conductivity?
- TCR should go other way. As graphene content goes up we see the effect of decreasing TCR



- Scale up in a relevant motor platform –
  - This project has primarily addressed the question of whether or not it is possible to make a higher conductivity conductor with potential to scale to relevant products (wire and bar).
  - The obvious next challenge is to verify its performance and efficiency improvement potential in a real motor.
- This will require an effort closely integrated with a motor developer, motor end user, and supported by wire and graphene suppliers

Summary

Accomplishments

- We have used Shear-Assisted Extrusion and Processing (ShAPE) to fabricate Copper-carbon composite wires and rods up to 1 meter in length, with full density and homogenous microstructure.
- We have demonstrated that these wires have similar mechanical properties to pure copper implying they will drop into applications requiring conventional fabrication (drawing, rolling and joining).

Technical highlights

- We have demonstrated a verifiable increase in conductivity as high as 4.1% over the ICAS pure copper standard with only 6 ppm graphene, and seen trends that indicate the potential for improvements to over 110% IACS
- We have completed preliminary motor efficiency modelling that suggests our current copper composite materials can produce 1 to 2 percent efficiency increase in an induction motor with trends indicating higher efficiencies are possible at higher graphene loading

Impact toward VTO Objectives

- Leverages a new manufacturing process involving high shear and plastic deformation to make high conductivity wire.
- Provides a disruptive way which automotive traction drives can be constructed, sized or powered.
- The high conductivity wire for stator winding could spill over into permanent magnet motor space where there are also strong incentives to improve motor performance.

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Technical Backup Slides



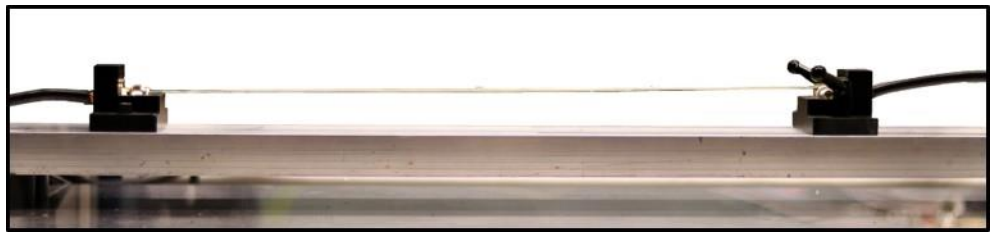
Conductivity in MS/m instead of %IACS

Property	Control sample	1.5 ppm	6 ppm
Electrical conductivity at 20°C (MS/m)	58.44 ± 0.0012	60.07 ± 0.0006 (**2.9%** ↑)	60.81 ± 0.0017 (**4.1%** ↑)
Electrical conductivity at 60°C (MS/m)	50.43 ± 0.0085	51.29 ± 0.0172 (**1.7%** ↑)	51.44 ± 0.0112 (**2.0%** ↑)
Electrical conductivity at 90°C (MS/m)	46.15 ± 0.0085	46.53 ± 0.0172 (**0.8%** ↑)	46.79 ± 0.0112 (**1.4%** ↑)
Temperature co-efficient of resistance (/°C)	0.0037	0.004	0.004

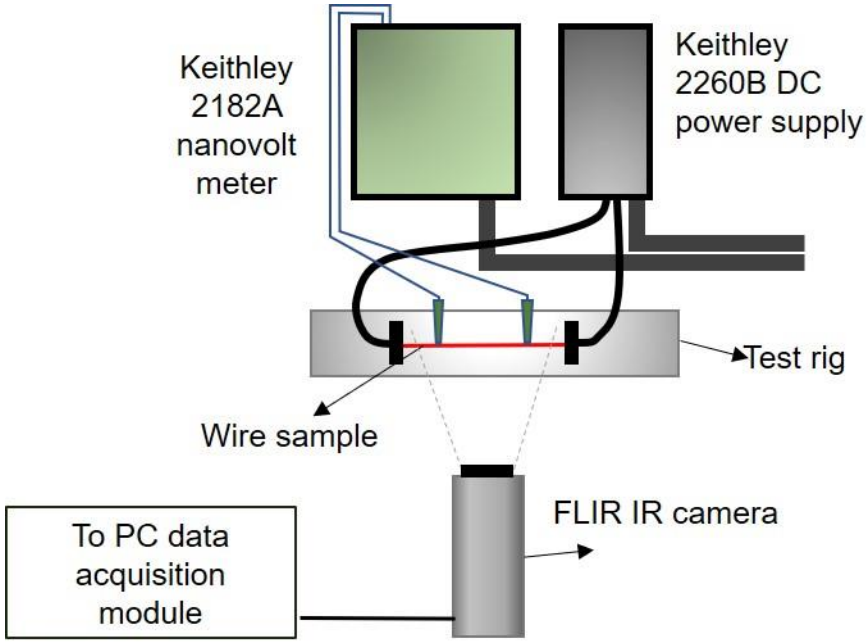
*Measured using Delta method
**Measured using Joule heating method
[a]Indicates property may be not measured as accurately owing to surface features

Technical Accomplishments and Progress:
Electrical Property Measurement Performed at Ohio University

Conductivity measurements done by Keerti Kappagantula and her students at Ohio University gave us much higher fidelity conductivity measurements







Custom designed electrical performance measurement set-up using non-contact infrared thermometry, nano-voltmeter and high-current power supply. Electrical conductivity and current density at elevated temperatures are measured using this set-up.

Electrical Performance of UC-Copper with Graphene

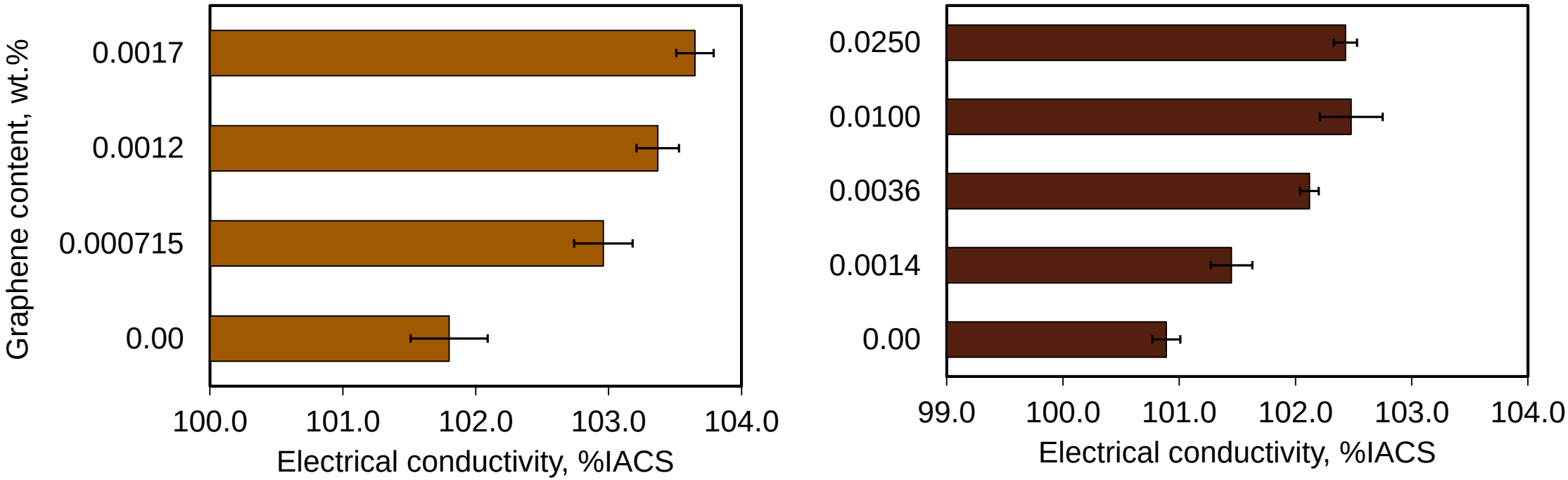


Fig. 1. Electrical conductivity of UC copper alloy manufactured with low defect density graphene (left); and high defect density graphene (right). Note: 100% IACS = 58.001 MS/m.

Property	Cu*	UC Cu	Change
Electrical conductivity at 20°C (MS/m)	58.5	60.3	↑3.1%
Electrical conductivity at 60°C (MS/m)	46.5	48.2	↑3.7%
Current density at 60°C (A/mm^2)	14.8	15.7	↑6.1%
Current density at 150°C (A/mm^2)-projected			↑12.6%