NANOMETAL-INTERCONNECTED CARBON CONDUCTORS (NICCs) FOR ADVANCED ELECTRIC MACHINES

DE-EE0007863

Rochester Institute of Technology, US Naval Research Labs, Nanocomp Technologies, MN Wire and Cable

April 1, 2017 – March 31, 2020

Dr. Brian J. Landi, Rochester Institute of Technology (PI)

U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
July 17-19, 2018

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- RIT Award Issued April 2017
- NCTI Subcontract July 2017
- NRL directly funded by DOE
- Project Complete March 2020
- Project ~40% Complete

Barriers

Research needed to overcome CNT transport in bulk conductors by nanoscale alignment, chemical doping, and selective metallic interconnection; which achieves superior electrical performance over metals in a 28 AWG wire for electric machine applications.

Project Budget

Budget Period	FY 17 Costs	FY 18 Costs (through Quarter 2)	Total Costs (through FY 18 Quarter 2)	Total Planned Funding (FY20 End Date)
DOE Investment	$157,036	$176,015	$333,052	$1,000,000
Cost Share	$13,032	$57,877	$70,909	$163,130
Project Total	$170,068	$233,892	$403,961	$1,163,130

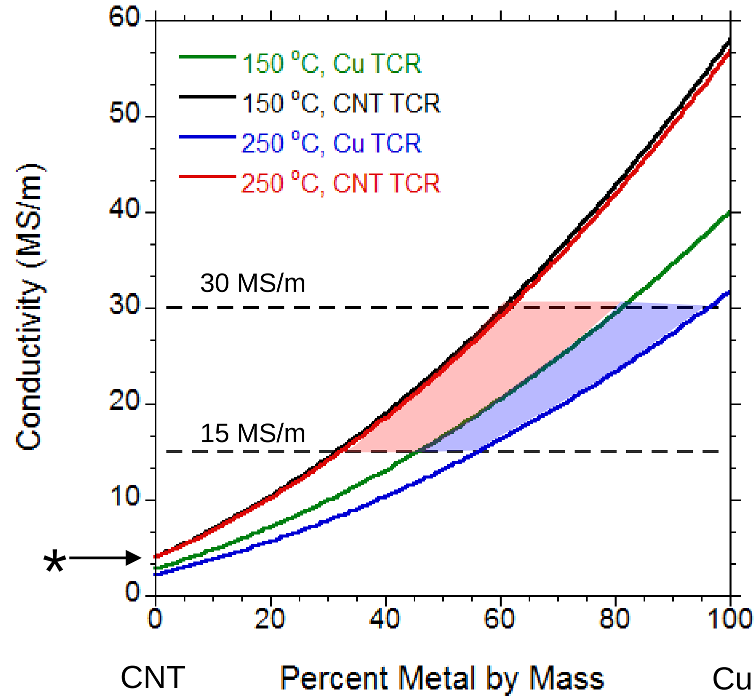
Partners

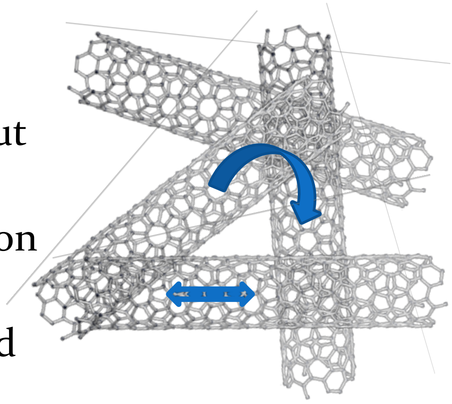
- U.S. Naval Research Laboratory (NRL): Dr. Cory Cress – CNT modification and evaluation
- Nanocomp Technologies Incorporated (NCTI): Mr. Eitan Zeira, Dr. Mark Schauer – Scalability and wire production
- Minnesota Wire (MW): Mr. Tom Kukowski – Scalability and wire finishing

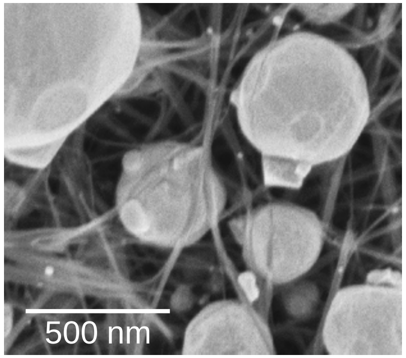
Project Objective

- What is the problem?
  - I^2R losses and excess mass leads to inefficiencies in wire electrical transport and energy conversion.
  - Potential of 1% energy savings of total US electricity consumption (source: DOE).
  - System heating to 150-250 °C exacerbates the problem due to the positive temperature coefficient of resistance (TCR) of most metals used in electrical conduction.
- What are we trying to do?
  - Bulk carbon conductors are ~10x lower conductivity than Cu/Al, but have improved TCR and density.
  - Goal: Fabricate Nanometal-Interconnected Carbon Conductors (NICCs) using carbon nanotubes (CNTs) with 28 AWG wire conductivity between 15 – 30 MS/m at 150 °C.
- Why is this difficult?
  - Individual CNT ~2 times better conductor than Cu, but bulk CNT limited by CNT:CNT junction resistance.
  - Metal integration to bridge CNTs affected by deposition technique and CNT surface "wettability".
  - Metal – CNT junctions may not be ohmic, nor coupled mechanically, and need to maintain optimal CNT transport and geometric alignment.

Temperature and Electrical Conductivity







*Bucossi, A. et al. *ACS Appl. Mater. Interfaces*, **2015**, 7, 27299–27305

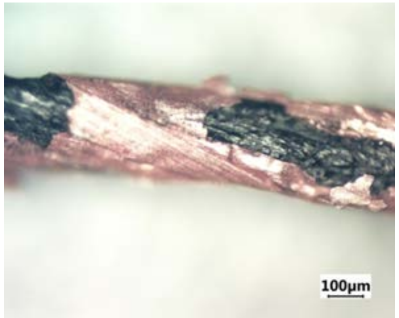
Technical Innovation

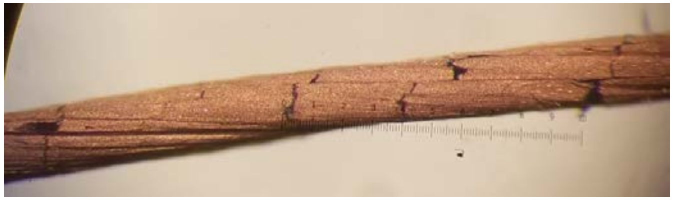
- How is it done today?
  - Physical Vapor Deposition – Provides a surface coating or shell for conductive composites.
  - Electroplating – Enables fabrication of metal-CNT composites via organic and aqueous based solvents.
- What are the limits of current practice?
  - Surface coatings suffer from non-uniform deposition.
  - Bilayer conductor in which metal overcoat provides majority of the electrical work; benefits are unclear.
  - High mass loadings required to achieve competitive conductivities.
  - At the nanoscale there exists poor connectivity between traditional conductor metals and CNTs, and delamination at elevated temperatures.

OPPORTUNITY: Leverage existing processes and develop post-production modifications to achieve:

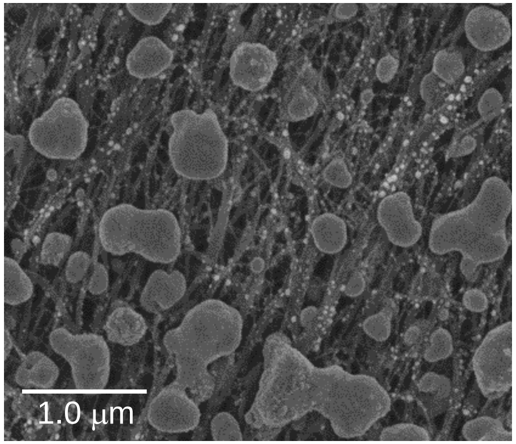
- Effective utilization of metal will decrease conductor mass (e.g. particle size, mass, location, etc.).
- Nanoscale integration of metals via network penetration and "bridging" between CNTs.
- Improved deposition and transport through wetting metals.
- Develop relationship for CNT-metal hybrids and the TCR.

Electroplating & Physical Vapor Deposition





Network Integration and Effective Utilization of Metal

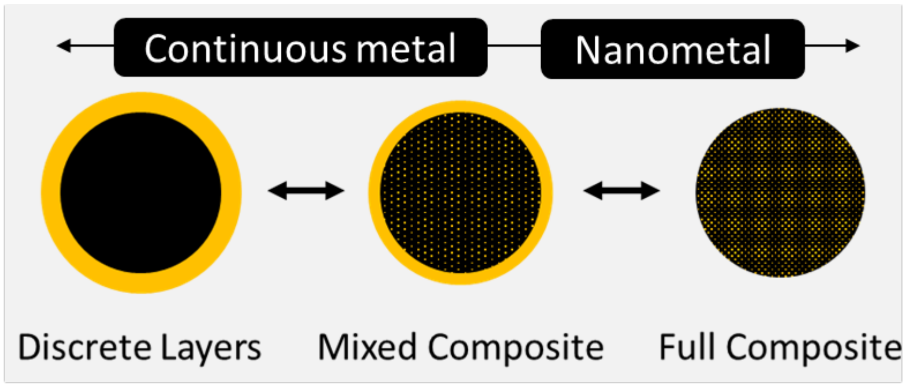


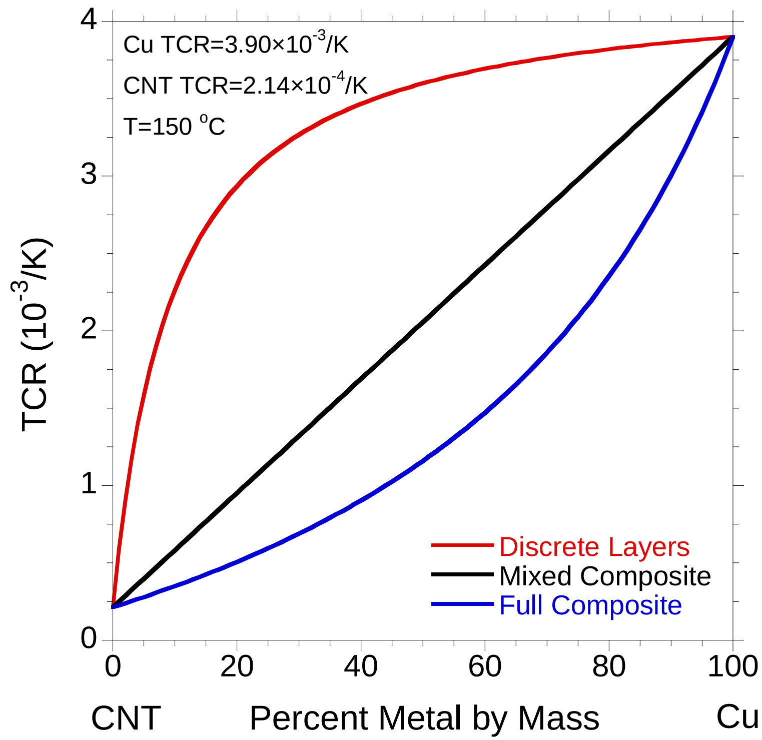
Technical Innovation

NICCs - Nanometal Interconnected Carbon Conductors

1. Efficient Utilization of Metal

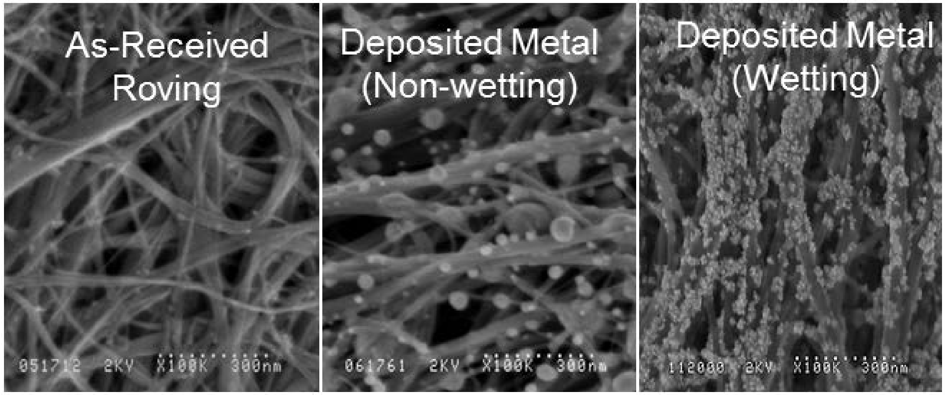
- Bridging the resistive CNT junctions with metals helps to reveal the inherent high conductivity of the CNTs while requiring low amounts of metal.
- Moving towards a fully integrated nanometal composite enables efficient metal utilization.





2. Surface Functionalization

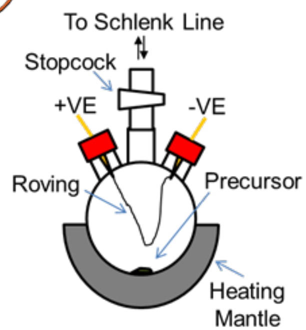
- Proper metal adhesion promotes interaction between components, enhancing their hybrid effects. CVD can provide nanometal seeds for electrodeposition and interconnects.
- Provides electrical contact while suppressing delamination at elevated temperatures.

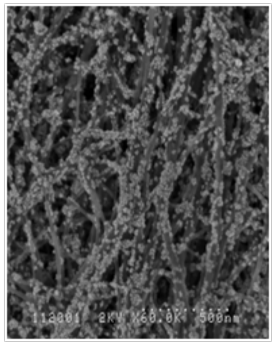


Technical Approach

Technical approach for the project: Combine RIT and NRL knowledge of CNT wire modification with Nanocomp Technologies and MN Wire and Cable knowledge of scalable wire production and finishing.

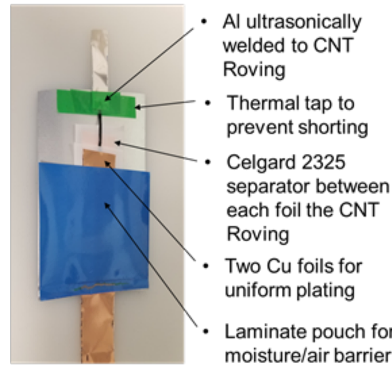
CVD

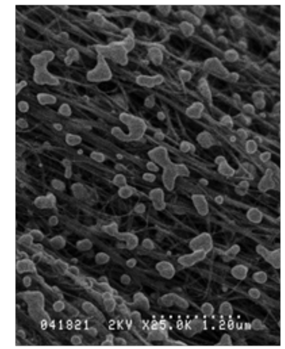




Vapor-phase deposition used to selectively deposit metal precursors at junction sites through Joule heating.

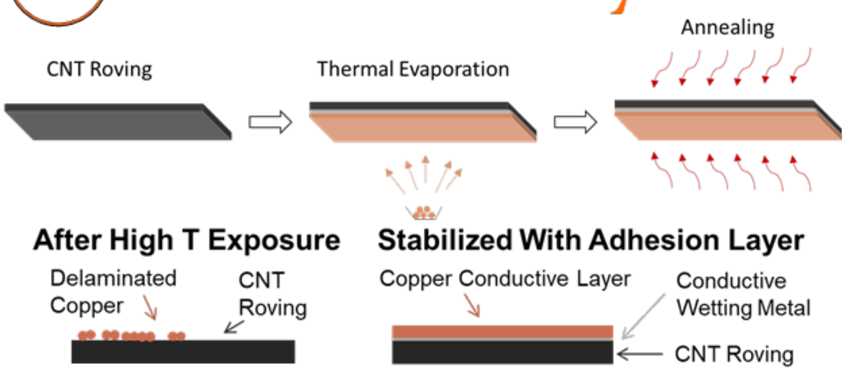
Electroplating





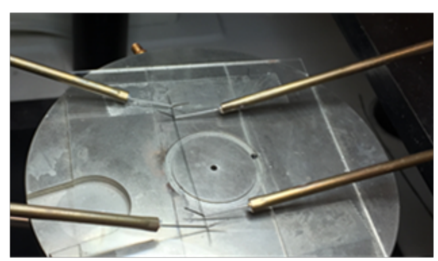
Enhanced conduction achieved via network bridging by electroplating in organic and aqueous solvents.

Interfacial Analysis



Temperature stability of metal overcoats analyzed via SEM.

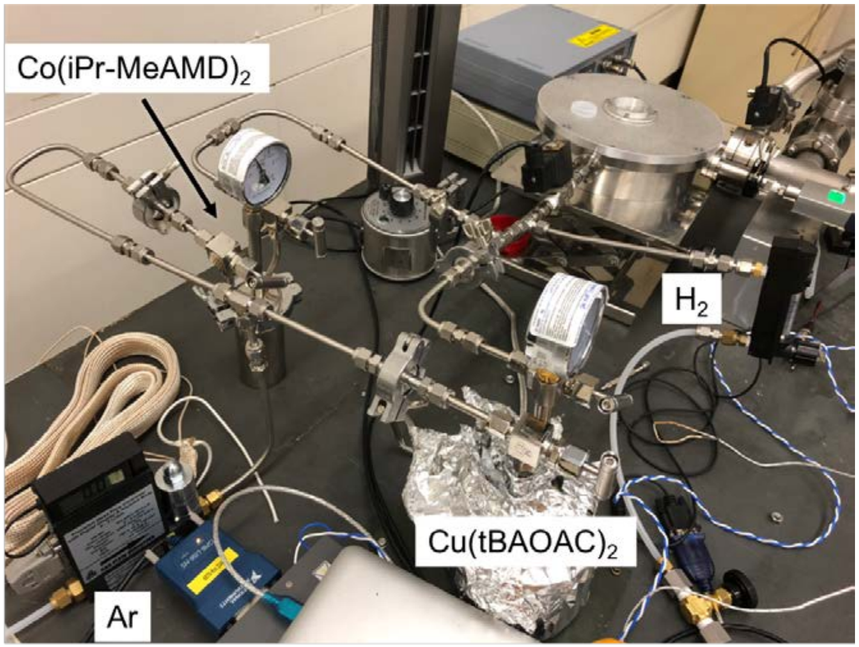
Characterization

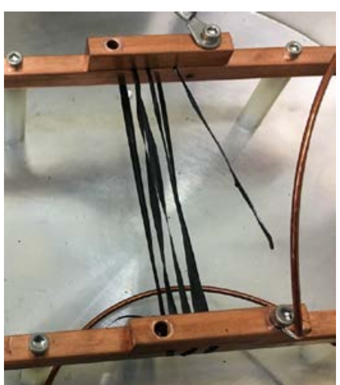


Electrical and temperature-dependent properties of NICCs materials evaluated via resistance per length and TCR.

Technical Approach

NRL facilities produce coated CNT materials using a pilot scale vapor-phase deposition technique which can support spooling.

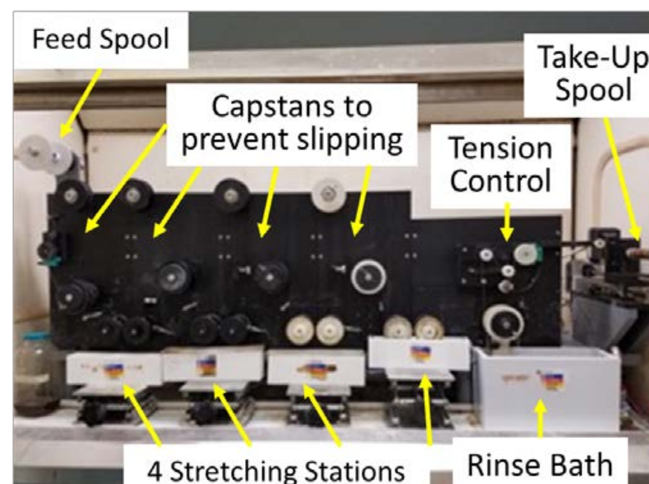




U.S. NAVAL RESEARCH LABORATORY

Industrial scale manufacturing of bulk CNT materials achieved through CVD synthesis.

Electrochemical stretching and post-processing to promote CNT alignment and doping.



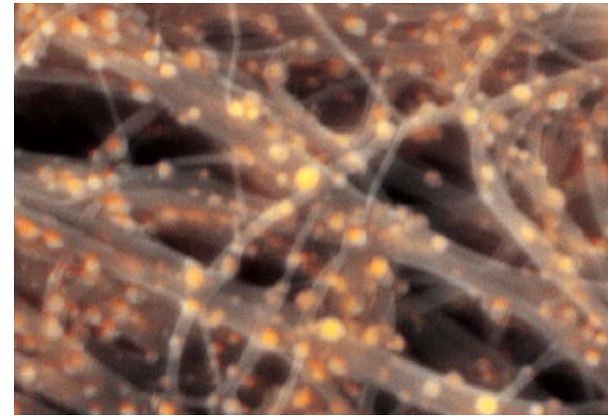
Results and Accomplishments

Accomplishments since 2017:

- CVD process optimized for seeding CNT materials with metal adhesion particles.
- Thermal evaporation used to analyze interfacial behavior of metals on CNTs after exposure to high temperatures.
- Conductivity of 11.6 MS/m achieved on a finished 10 cm ribbon conductor via CVD deposition and electroplating at room temperature. Measured TCR of 2.6 10^{-3}/K is lower than predicted for high Cu mass loadings.
- Large-scale vapor-phase deposition capabilities developed at NRL and similar CVD results have been obtained.
- High tex roving materials (i.e. 35 tex ~28 AWG diameter) with comparable performance manufactured at NCTI.

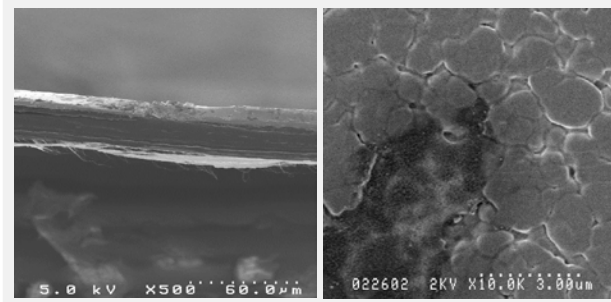
Work to be completed:

- Modify mass loading of metals for efficient utilization with CVD and electroplating.
- Measure the TCR for varying amounts of metal to update modeling and understanding of transport limitations.
- Optimize CVD and electroplating conditions for an extruded and/or treated roving single strand conductor with ~10 cm length and conductivity of 10 MS/m at 150°C.
- Transition CVD deposition onto new 35 tex CNT roving.

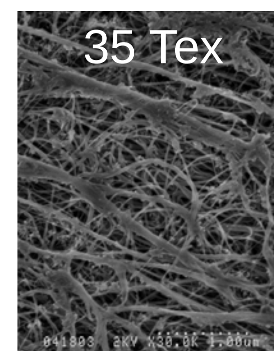


Cu particles in image are false colored

Cu/CNT Ribbon Conductor



nanocomp TECHNOLOGIES, INC.



Transition (beyond DOE assistance)

- What is the commercialization approach?
  - Leveraging highest production continuous CNT CVD growth and spooling capabilities in the US. – Plans to produce 40 metric tons yearly.
  - Program includes RIT & NRL tasks to design and implement post processing methods at NCTI (year 3).
  - Partnered with Minnesota Wire (year 3) for wire braiding, coating, and termination.
- What is the transition to the commercial marketplace?
  - Seek early adoption by DoD (Navy/Air Force) & Aerospace industry.
    - Energy savings through improved conductivity: Motors, generators, all forms of electricity distribution.
    - Weight reduction for aerospace and vehicle applications – additional fuel savings.
    - Simplification of heat-dissipation systems (e.g. data centers).
  - Electric vehicle/rotating machinery gradual adoption as costs reduces and technologies mature:
    - Uniformity of wires meet specifications.
    - Production yield meets demand.

Scalable nanometal CVD approach can be integrated with CNT post processing to directly impact manufacturing.

Questions?