NANOMETAL-INTERCONNECTED CARBON CONDUCTORS FOR ADVANCED ELECTRIC MACHINES

DE-EE0007862

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

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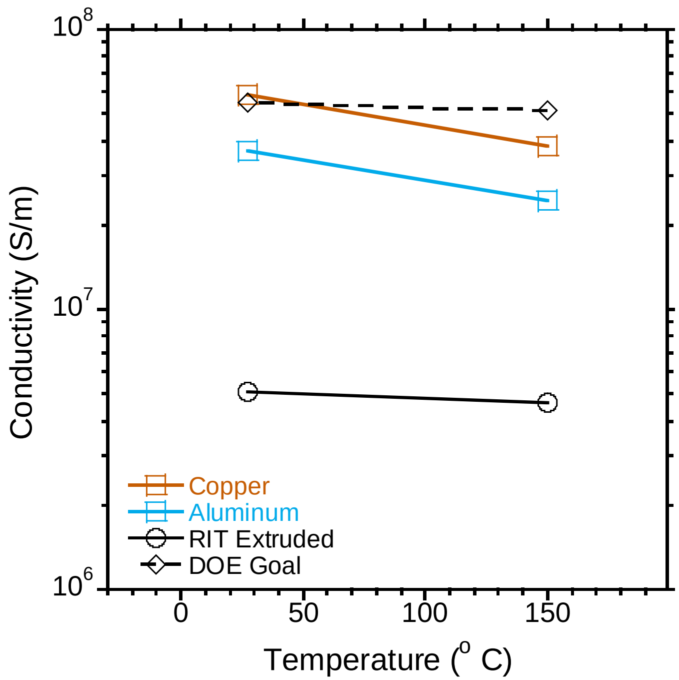
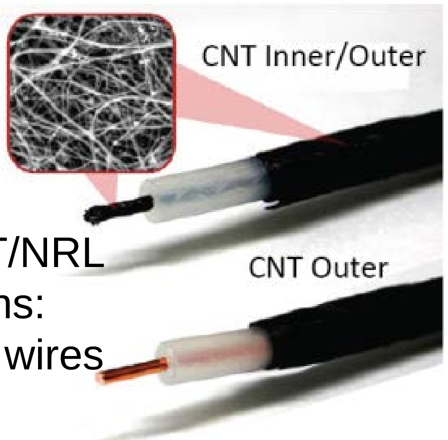
Project Objective

- What are we trying to do?
  - Fabricate Nanometal-Interconnected Carbon Conductors (NICCs) – [carbon nanotubes, CNTs] - with a:
  - 33% reduction in I^2R losses @ 150°C.
  - 50% weight reduction @ 28 AWG size.
- What is the problem?
  - I^2R losses and excess mass amount to inefficiencies in electrical transport and energy conversion (kinetic <-> electrical).
  - System heating exacerbates the problem due to the positive thermal coefficient of resistance (TCR) of most metals used in electrical conduction.
  - Carbon conductors are ~10x lower conductivity than Cu/Al, but have improved TCR and density – How do we get the best of both?
- Why is this difficult?
  - Metal – CNT junctions often not Ohmic, nor strongly coupled mechanically.
  - How to minimize metal integration while maximizing its ability to bridge CNTs?
  - How to integrate metal while maintaining optimal CNT transport and geometric alignment.

Temperature Dependence of Electrical Conductivity



Previous RIT/NRL Collaborations: CNT coaxial wires



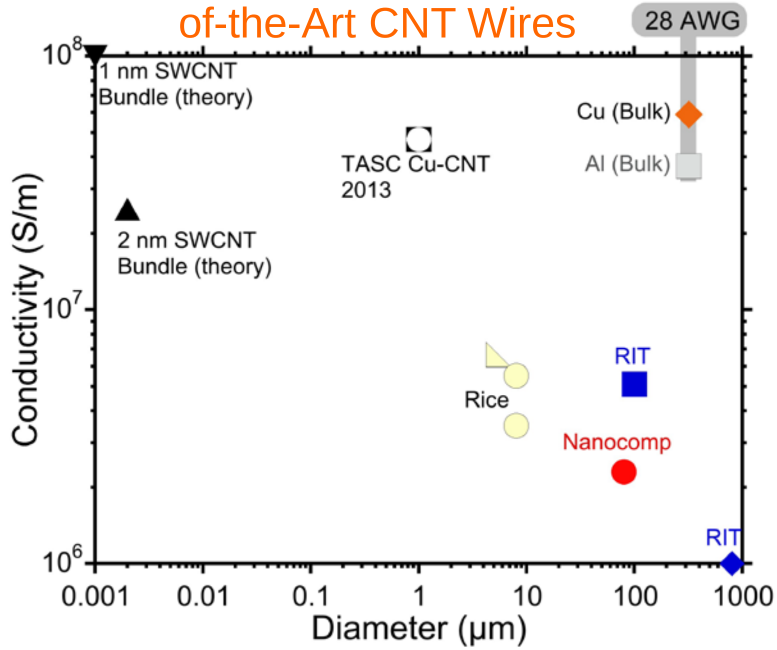
Technical Innovation

- How is it done today?
  - Extrusion – produces highly aligned, pure CNT wires from liquid-crystal dispersion in chlorosulfonic acid
  - Chemical Vapor Deposition – High throughput method for pulling wires from a continuous CNT feed-stock
- What are the limits of current practice?
  - Extrusion
    - Requires ultra-pure feedstock (Less scalable)
    - Time intensive
    - Requires aggressive solvent
  - Chemical Vapor Deposition (CVD)
    - Less control over CNT morphology
    - Less control of directionality of tubes
    - Impurities present in wires
  - Both: Product limited by process constraints.

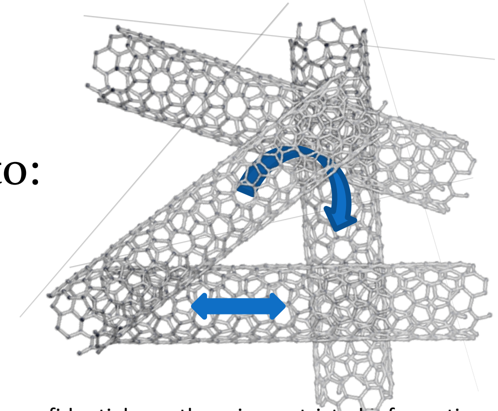
OPPORTUNITY: Leverage existing processes and develop post-production modifications to:

- Improve alignment
- Scale size of high-conductivity wires
- Improve intra- and inter-CNT transport

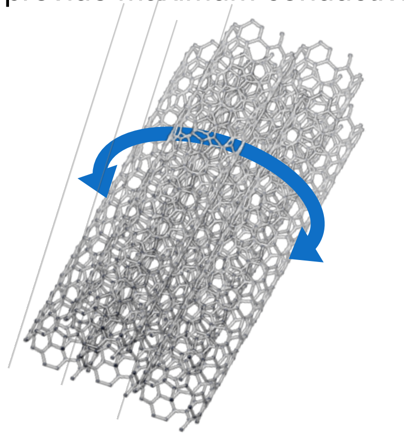
Conductivity and Size of Recent State-of-the-Art CNT Wires



Methods are required to improve the conductivity within and between individual CNTs



CNTs must be bundled into dense, well-aligned aggregates to provide maximum conductivity



Technical Innovation

- What's new in our approach, and why it will be successful:

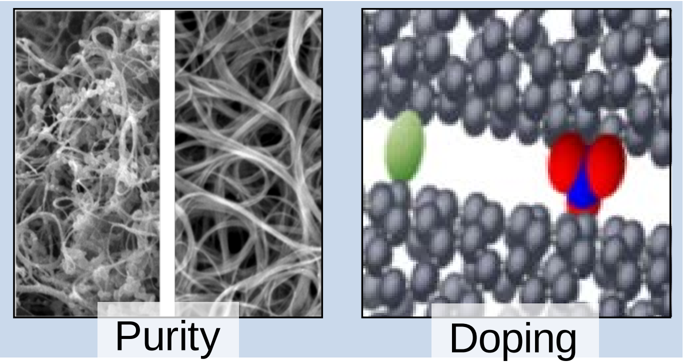
NICCs - Nanometal Interconnected Carbon Conductors

1. Alignment

- Inherent Alignment (Extrusion)
- Chemical Stretching(Post Process)
- Solvent densification (Post Process)

2. Intra-CNT Transport

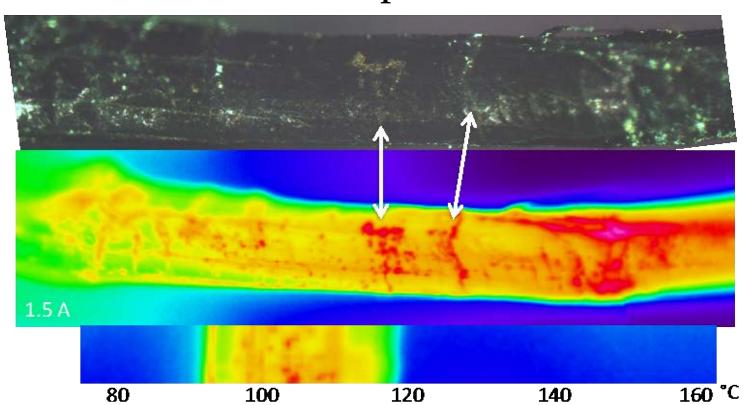
- Improving Purity
- Chemical Doping

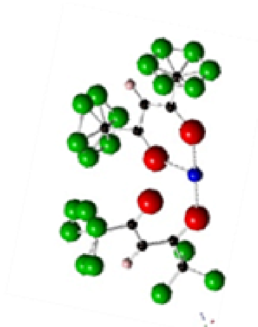


3. Inter-CNT Transport

- Vapor Phase – Novel Atomic Layer Deposition (ALD) Technique
- Liquid phase nanometal electrodeposition and graphene additives

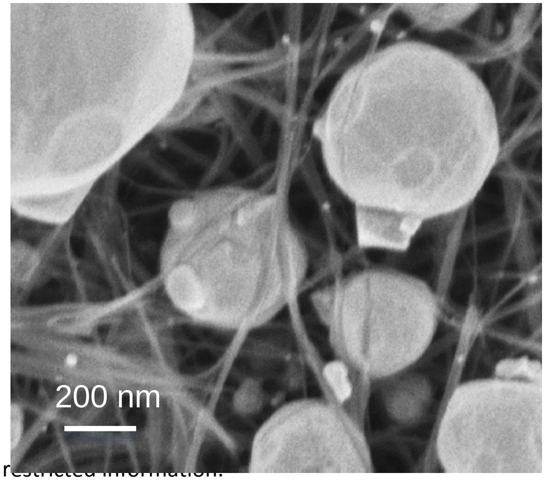
Joule Heating, Hotspot-Driven Metal Deposition





Sublimate: 90°C
Decompose: 160°C

SEM image of copper electrodeposition



Technical Approach

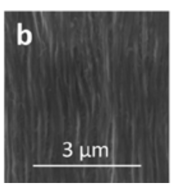
- What is the technical approach for the project:
  - Combine RIT and NRL fundamental knowledge of wire modification and evaluation with Nanocomp Technologies and MN Wire and Cable knowledge of scalable wire production and finishing.

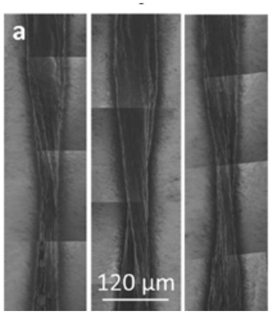
CNT Production

Roving spool

Using commercially scaled CVD process to enhance production roving prior to spinning

Extruded Wires





Using high purity CNTs through a chemical extrusion process

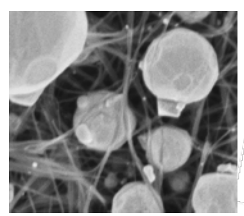
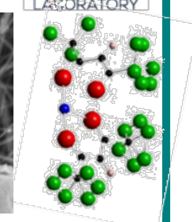
Processing

Chemical Doping and Graphene Modification

Increase susceptibility to deposition and improve conduction pathways

Electrodeposition and Vapor-phase deposition

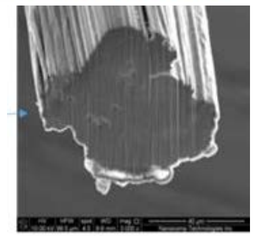
U.S.NAVAL RESEARCH LABORATORY

Improve conduction between CNTs at resistive junctions

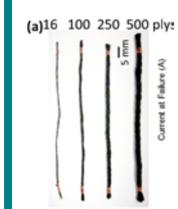
Finishing

Densification & Stretching

Eliminate void space and improve bundle alignment

Braiding, Coating and Termination





Passivation and preparation for use

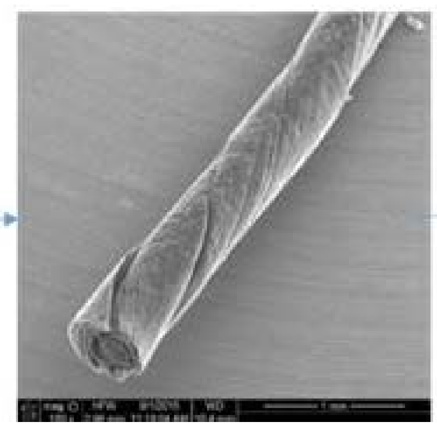
CNT Materials → NICCs → Advanced Wires

Technical Approach

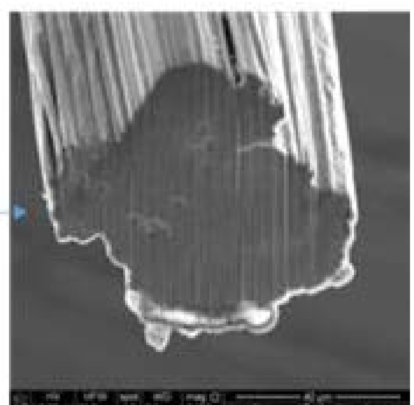
- End-of line treatments of Roving for improved NICCs
  - Enhance porosity
  - Modify surface chemistry / wettability
- Chemical stretching
- RIT/NRL – Designing NCTI compatible NICCs processing
- Integration with Minnesota Wire and Cable for braiding, coating, and termination.

Roving

Spun Yarn



Stretch Yarn



Transition (beyond DOE assistance)

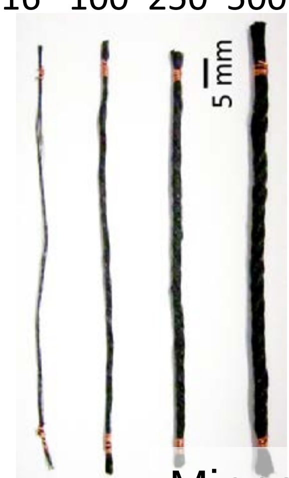
- Who Cares?
  - All producers and consumers of electricity benefit from
    - Improve efficiency
    - Lower weight
    - Lower electricity costs
  - End users: Industry, non-industry, transportation (electric vehicle)

- Advantages of NICCs:
  - Energy savings through improved conductivity: Motors, generators, all forms of electricity distribution.
  - Weight reduction for aerospace applications – additional fuel savings
  - Simplification of heat-dissipation systems (Data Centers)
  - Improved Reliability:
    - Extreme flexure tolerance
    - Chemical stability (non-corrosive)

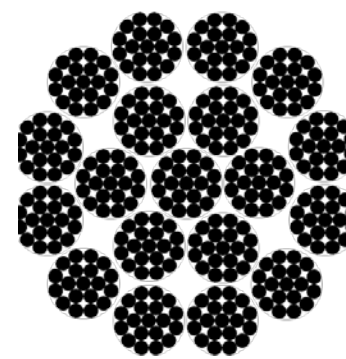
Transition (beyond DOE assistance)

- 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 for wire braiding, coating, and termination.
- What is the technology sustainment model?
  - Seek early adoption by DoD (Navy/Air Force) & Aerospace industry
    - Efficiency outweighs higher costs
    - Leverage NRL / ONR connections
  - Electric vehicle / rotating machinery gradual adoption as costs reduces and technologies mature:
    - Uniformity of wires meet specifications
    - Production yield meets demand.

16 100 250 500



Braided CNT Wires



Nanocomp Technologies, Inc.

Minnesota Wire

Measure of Success

- If you're successful, what difference will it make? What impact will success have? How will it be measured?
  - Impact: NICCS replace copper/aluminum, lower energy consumption.
  - Measured electrical conductivity of NICCs at 150°C > 30 MS/m (success) >60 MS/m (goal).
  - Measured weight of 28 AWG NICCs is 50% of copper equivalent.

- What is the potential energy impact? Economic impact?
  - Potential of 1% energy savings of total US electricity consumption (http://www.totalenergycompany.com/pdf/Motor_Efficiency_DOE1999.pdf).

Table 1: ***Potential energy savings opportunity from deployment of three identified enabling technologies in U.S. industrial motor systems.***[5]

Topic Areas	**Technical Target**	**Performance Metrics**	**Potential Energy Savings in GWhr/Yr & % of Total US electricity**		
			Industrial	**Non-Industrial**	**Total**
High performance conductors	>33% reduction in stator I^2R losses	Electrical conductivity at 150°C > 59.52 MS/m	2,861 & 0.09	22,772 & 0.87	25,633 & 0.96

~1% Savings of Total US Electricity

Project Management & Budget

3 Year Project

Year 1 Task – Conduct fundamental research on carbon nanotube (CNT) rovings and extruded wire materials through CVD process modifications, chemical treatments, and electroplating to properly incorporate nanoscale materials and enhance network transport.

Year 1 Key Milestone– Develop CNT wires with enhanced electrical conductivity of 7 MS/m in ~10 cm length samples at room temperature.

Year 2 Task – Modifying CNT surface chemistry to develop solution phase and vapor phase deposition technologies to increase the mass loading of dopants or metals in a CNT wire, and optimize the synergy between roving production, chemical and electrochemical modification, and vapor phase deposition to enhance conductivity.

Year 2 Key Milestone– Develop CNT wires with enhanced electrical conductivity of 10 MS/m in >10cm length samples at 150°C.

Year 3 Task – Enhance conductivity of CNT wires and fabrication studies through modified deposition and reactor conditions which can lead to braiding 28 AWG structures and application of insulation for stability at an operating temperature of 150°C.

Year 3 Key Milestone– Achieve electrical conductivity of ~15-30 MS/m at 150°C which is a 33% improvement in conductivity and a 50% reduction in density compared to equivalent copper wire in meter length testing.

Total Project Budget	
DOE Investment	$1,000,000
Cost Share	$163,130
Project Total	$1,163,130

Results and Accomplishments

- RIT and NRL are now under contract; NCTI subcontract nearly complete (unofficial kick-off: May 16th, 2017)
- NCTI – Materials Delivered to RIT/NRL (>200 m roving & 20 m 10 tex wire)
- RIT – Initiated work on Electrodeposition; Roving material characterization; Extrusions
- NRL – Procurement of Joule Heating ALD system parts / supplies complete, waiting for delivery; Initiated Roving material characterization (Joule heating & thermal imaging)