Copper-Carbon Nanotube Composite Fiber for Lightweight Electrical Conductors in Aircraft Propulsion

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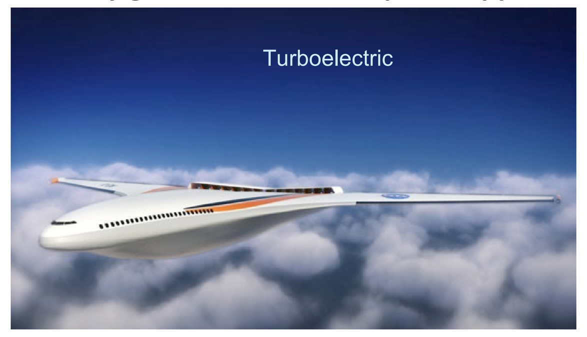
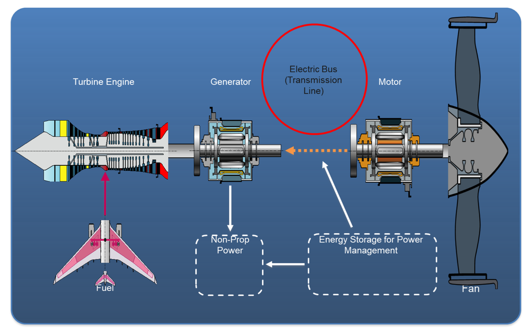
Abstract

Replacement of traditional propulsion systems with Electrified Aircraft Propulsion (EAP) is needed to overcome issues with emissions due to fossil fuels, and noise levels in commercial transport aircrafts. Current generation EAP`s have a huge amount of copper for power distribution, which limits the performance due to great heat losses and high weight. To enhance the efficiency of motors, generators, and other electrical systems in EAP`s, we are exploring copper-carbon nanotube (Cu-CNT) composite fibers as electrical conductors for power distribution. Carbon nanotube (CNT) fibers were spun from CNT arrays grown in a chemical vapor deposition (CVD) process. The fibers were then decorated with palladium before coating them with copper. The combination of electroless deposition of palladium and double electrodeposition of copper proved to play a key role to avoid copper dendrite growth thus contributing to the higher electrical conductivity of the composite fibers. With properties such as high tensile strength, good electrical conductivity, light weight, and scalability in production, Cu-CNT composite fibers are a very good alternative to pure copper wires in EAP`s.





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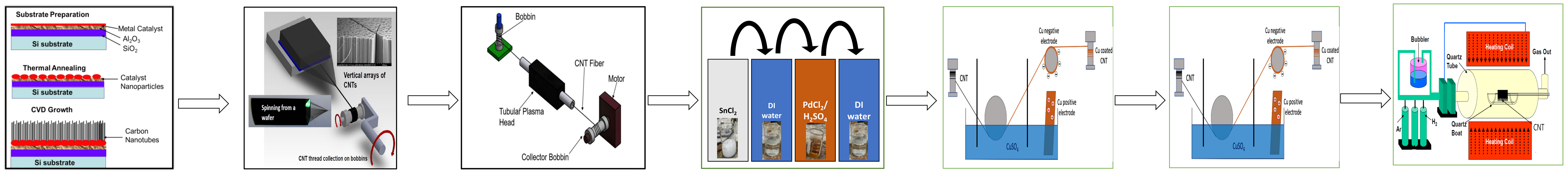
Synthesis of Copper – CNT Composite Fibers



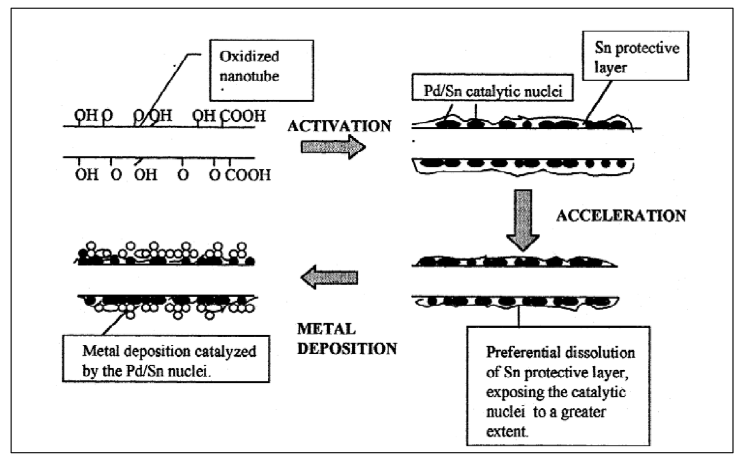
CNT growth on a Si substrate | CNT Fibers Spinning | Plasma Functionalization | Electroless Palladium Pre-Treatment | First Copper Electrodeposition 0.25 m/min | Second Copper Electrodeposition 0.1 m/min | Annealing

1. Carbon Nanotube (CNT) arrays are synthesized on a patterned Si substrate using water assisted CVD in Easy Tube^{TM} furnace ET3000.
2. CNT arrays synthesized are spun into CNT threads/fibers via a complex twist and pull motion and are collected on aluminum bobbins.
   - CNT fiber diameter was controlled by altering the spinning (pull + twist) speed control. The faster the speed, the smaller the diameter.
3. The CNT fibers are treated with atmospheric pressure oxygen plasma causing the fiber functionalization which improves wettability of CNTs towards copper during the electrodeposition.
   - Tubular plasma head and Sufix Atomflo 400 system are used with plasma power of 100W, and flow rate of the plasma gases He and O_2 of 15L/min and 0.3L/min respectively.
4. The plasma functionalized CNT fibers are decorated with palladium:
   - The fibers are immersed into $SnCl_2$ solution for 10 sec followed by rinsing off the excess $SnCl_2$ with DI water before immersing in $PdCl_2/H_2SO_4$ solution, rinsed again with DI water to remove the unreacted $PdCl_2$.
5. Copper was deposited on palladium decorated CNT (Pd-CNT) fibers using a two-step electrodeposition.
   a. First deposition uses $CuSO_4$ with applied voltage of 7V and pulling speed of 0.25m/min. With short exposure time, copper grains with globular morphology are formed on the CNT surface.
   b. Second deposition uses $CuSO_4$ with deposition voltage of 7V and pulling speed of 0.1m/min. With longer exposure time, the globular copper grains forming an uniform copper layer on the fiber surface.
6. The Pd-CNT double Cu coated (Pd-2Cu-CNT) fibers are in oven to remove excess water and to prevent oxidation of copper before annealing:
   - The Pd-2Cu-CNT is annealed in 95%:5% Ar:H_2 environment at 400°C for one hour.

Objectives

- Create lightweight Cu – CNT composite fiber with good mechanical strength and high electrical conductivity.
  - Optimize copper deposition procedure to obtain dendrite free-uniform copper coating on the CNT fiber.
  - Improve the adhesion between the copper coating and CNT fiber surface.
  - Increase diffusion of copper metal into the core of the fiber.
- Develop a scalable Pd decoration on the CNT fibers followed by Cu electro-deposition.

Key Chemistry



Electroless Palladium Deposition**

$Sn^{2+} \rightarrow Sn^{4+} + 2e^-$

$Pd^{2+} + 2^- \rightarrow Pd$

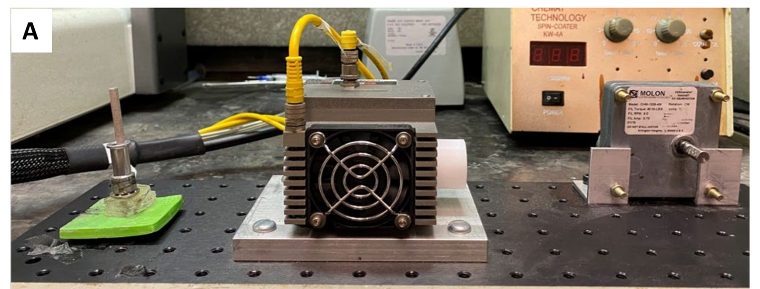
Electro Copper Deposition

$Cu^{2+} + 2^\circ \rightarrow Cu$

*L.M.Lang etal,"Decoration of activated carbon-nanotubes with nickel and copper" (*Carbon 38 (2000) 363–372*)
**McConnell, *et al.* "Hydrogen Sensors Based on Flexible Carbon Nanotube-Palladium Composite Sheets Integrated with Ripstop Fabric" ACS Omega (2020) 5, 487-497

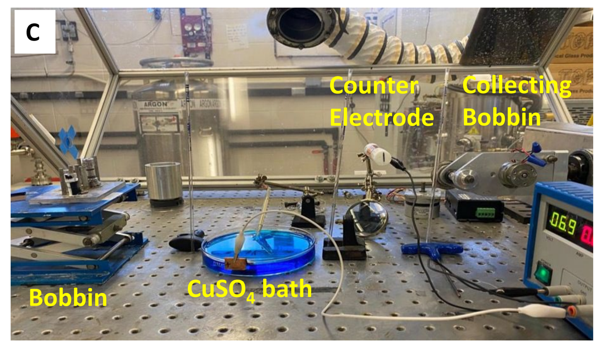
Experimental Facilities

A. Set up for continuous plasma functionalization
B. Set up for palladium electroless deposition
C. Set up for copper electro-deposition



Bobbin | Turbular Plasma Head | Collecting Bobbin

$SnCl_2$ | DI Water | PdCl



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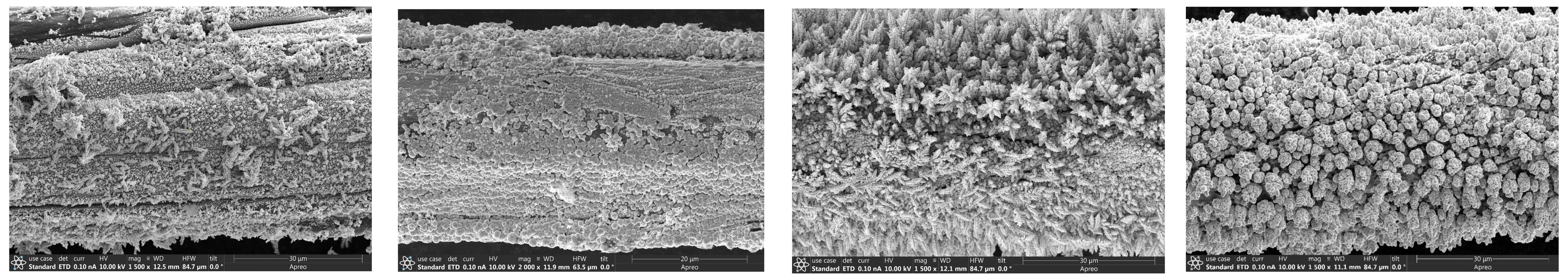
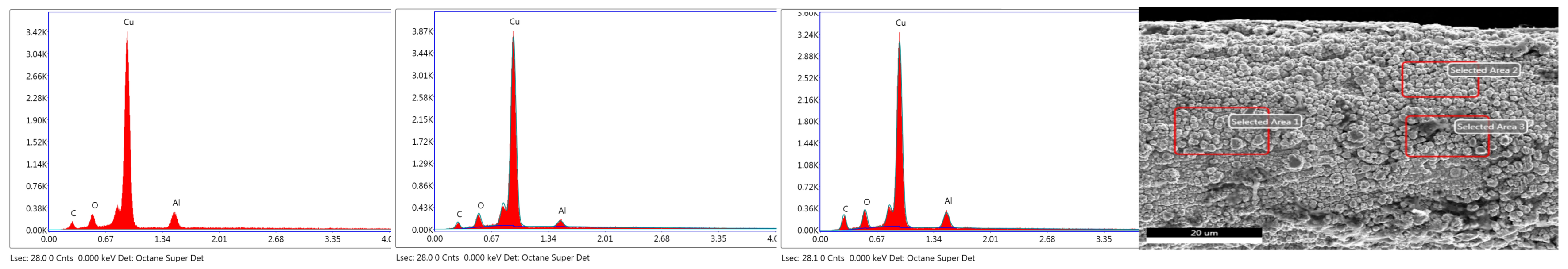
Results

Scanning Electron Microscopy (SEM)



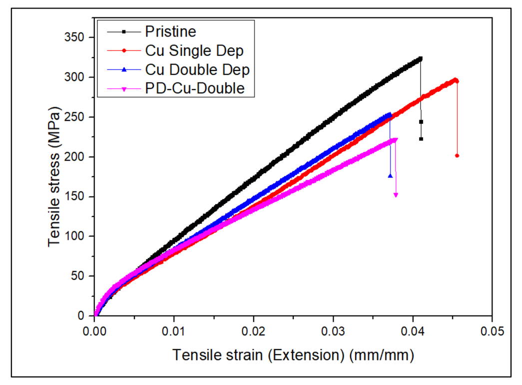
Non-Pd single Cu deposition | Pd pre-treated Cu deposition | Non-Pd double Cu deposition | Pd pre-treated double Cu deposition

Energy Dispersive Spectroscopy (EDS)



EDS of selected area 1 | EDS of selected area 2 | EDS of selected area 3 | Pd-double Cu deposition after annealing

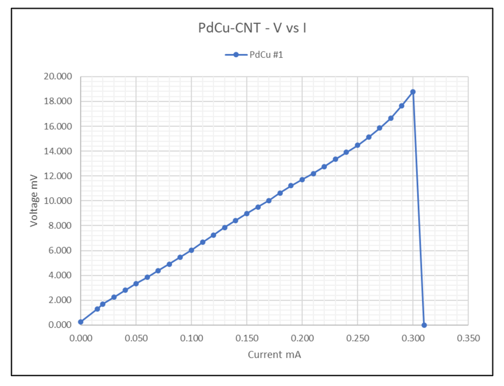
Mechanical Strength (Tensile Test)



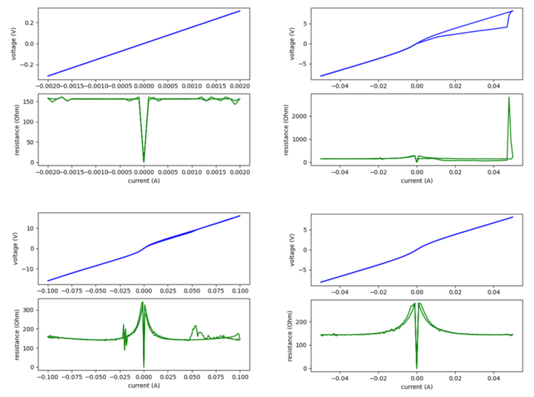
Four Probe Resistivity Measurement

Specimen Name	Equation	Resistance Ω	Resistivity Ω m
CNT fiber	y = 48.891x + 13.813	37.75	4.3 x 10^{-5}
Cu-CNT_Single Dep.	y = 37.229x + 5.6751	33.55	1.2 x 10^{-5}
Cu-CNT_Double Dep.	y = 14.747x - 14.947	14.75	1.04 x 10^{-5}
Pd-Cu-CNT_Double Dep.	y = 8.6366x - 6.7835	8.64	3.79 x 10^{-6}

Ampacity Measurement (Pd-Cu CNT)

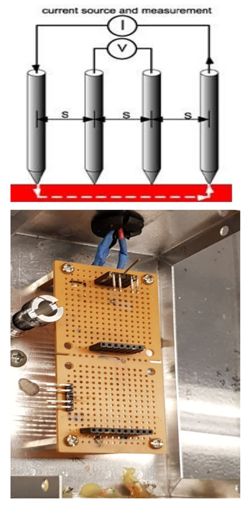


Sample ID	Max. Calc. Current Density (A/cm²)
Cu-CNT #1	1.42*10^4
Cu-CNT #3	7.31*10^3
Pd-Cu-CNT #1	2.39*10^4
Ag-Cu wire ref.	2.57*10^4
CNT-Cu composite†	6.00*10^8
Pure Copper†	~1*10^6

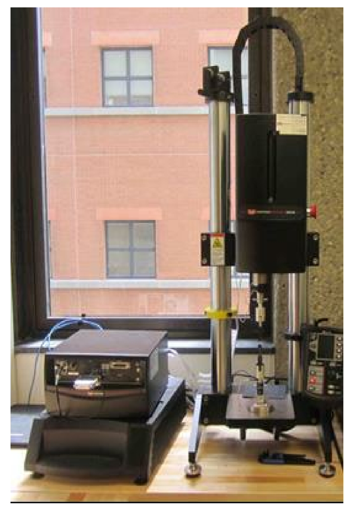


Characterization and Testing System

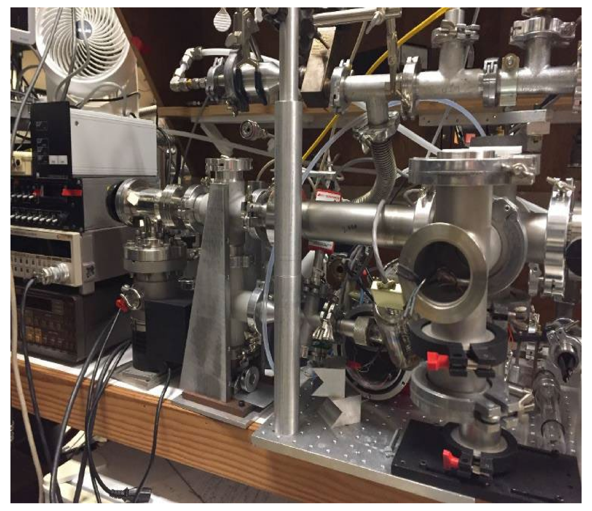
Environmental SEM for morphology study



Four-Probe resistivity measurement



Tensile strength testing system



32-pin connector Turbo-Pumped vacuum system with nano-voltmeter and current source

Conclusion

- Palladium decoration of CNT fibers followed by copper double deposition process is simple and scalable to industrial scale.
- Palladium pre-treated was advantageous: Uniform distribution of Sn/Pd nuclei normalizes the current density during electrodeposition of Cu on the CNT fiber resulting in homogenous Cu coating on the CNT surface and preventing dendrite growth.
- Copper double deposition produces Cu globules on the fiber surface before the actual copper layer forming, which increases the amount of copper coating on CNT surface and makes the copper layer more uniform.
- Palladium decoration of CNT fibers followed by Cu double deposition process showed promising potential resulting in high tensile strength of about 225MPa, low resistivity of 3.79e-6 Ωm, and high current density of 2.39*10^4 A/cm².

Future Work

- Optimize the setups for ampacity measurements.
- Explore new setups/ procedures to deposit copper during the manufacturing step of the CNT fiber formation.
- Further testing to build a database for statistical analysis.

Acknowledgement

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