Effect of Electron Beam Irradiation on the Tensile Properties of Carbon Nanotube Sheets and Yarns

Tiffany Williams[1], Sandi Miller[1], James Baker[2], Linda McCorkle[3], Michael Meador[1]

[1]NASA Glenn Research Center
Cleveland, OH

[2]NASA Postdoctoral Program
Cleveland, OH

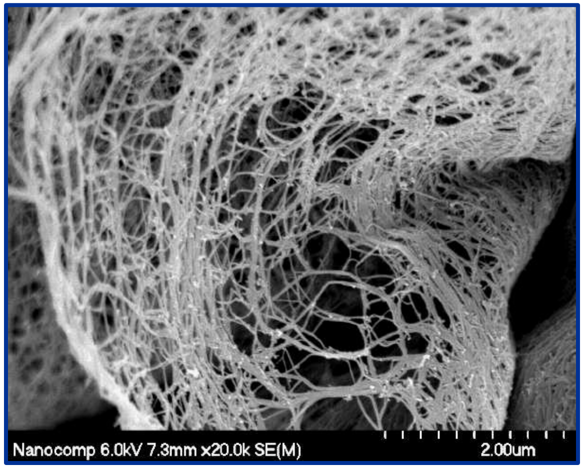
[3]Ohio Aerospace Institute (OAI)
Cleveland, OH

Presentation outline

- Background and Motivation
- Experimental
- Results and Discussion
- Conclusions

Background and Motivation

- Lightweight materials and structures
  - Reduced vehicle mass
  - Incorporation of nanostructured reinforcement could decrease aircraft and spacecraft weight by one-third
- Strength of carbon nanotubes (CNTs)
  - 1 TPa E' and 100 GPa tensile strength (SWNTs via arc discharge)
- Properties much lower in commonly used nanomanufacturing methods
- Weakness attributed to entanglements, slippage of CNTs, van der Waals forces



SEM image of Nanocomp CNT sheet

Goal is to investigate various routes to introduce covalent crosslinks in CNTs via e-beam irradiation for increased tensile strength

Crosslinking of CNTs

- **Common irradiation methods[1-4]**
  - Microwave irradiation
  - Electron beam energy
- Electron beam irradiation usually carried out using TEM
- Covalent crosslinking in CNTs is believed to take place at sites where vacancy defect edges face each other
- E-beam irradiation introduced defects (loose or dangling bonds) that can lead to crosslinking

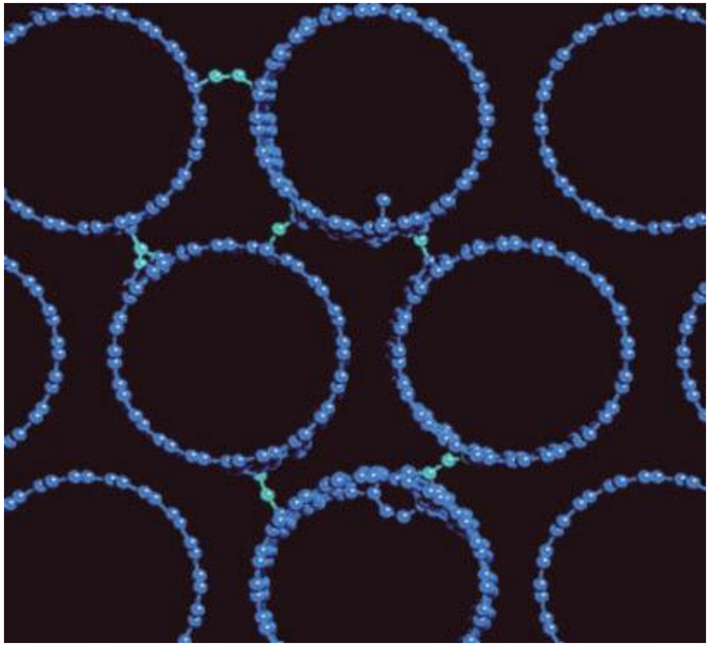


Image taken from Thess, A., *et. al,* Crystalline Ropes of Metallic Carbon Nanotubes, *Science* **273**, 483-487 (1996) and Ajayan, P. Banhart, Nanotubes Strong Bundles, *Nature Materials* **3**, 135-136 (2004)

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[4]Duchamp, M., Meunier, R., Smajda, R., Mionic, M., Magrez, A., Seo, J.W., Forro', L., Song, B., Toma'nek, D., Reinforcing multiwall carbon nanotubes by electron beam irradiation, Journal of Applied Physics 108, 2010, 084314-1—084314-6

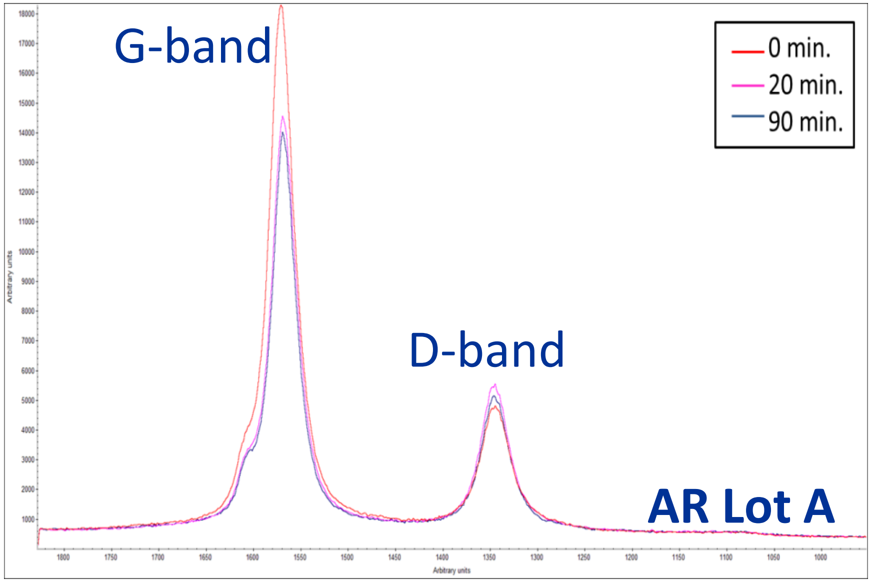
Electron beam irradiation setup

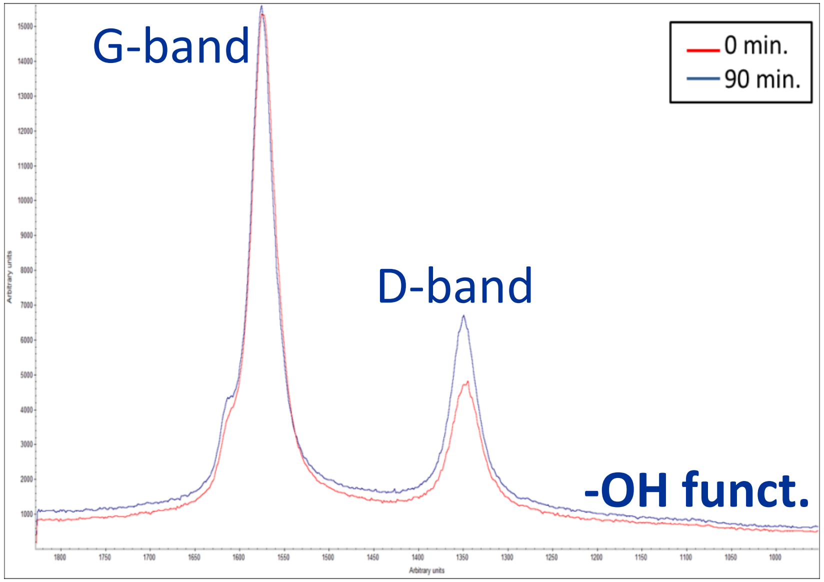
- **Materials**
  - **CNT sheets (Nanocomp)**
    - As received
    - Functionalized
    - Stretched
  - **CNT yarns (General Nano and Nanocomp)**
  - **Northeast Ohio (NEO) Beam Facility (Middlefield, OH)**
- **Energy of electrons:** 2 MeV
- **Beam current:** 36 mA
- **Irradiation time:** 20-90 min. (fluence 4.8 x 10^{16} –2.2 x 10^{17} e/cm^2)
- **Irradiated in air**

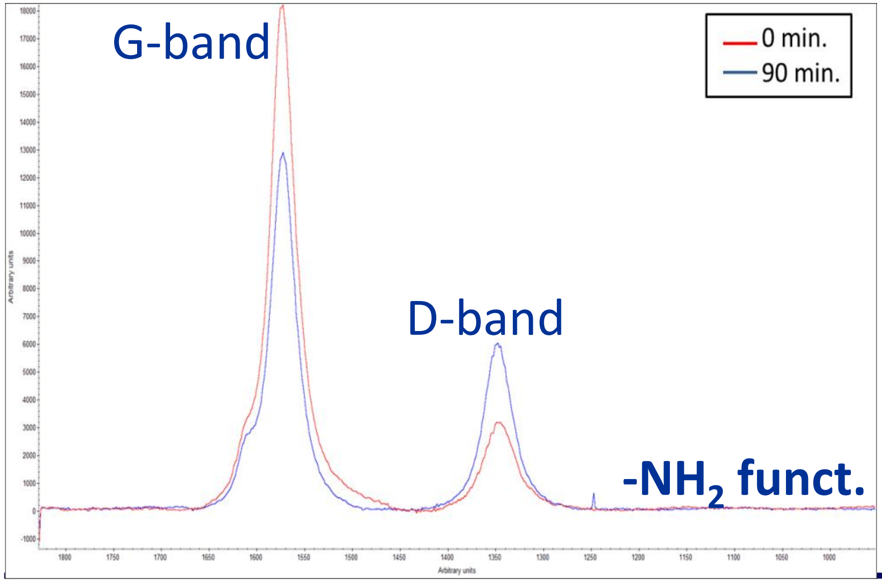
Sample stage (water cooled)

CNT samples

Effect of irradiation on the structure of CNT sheets

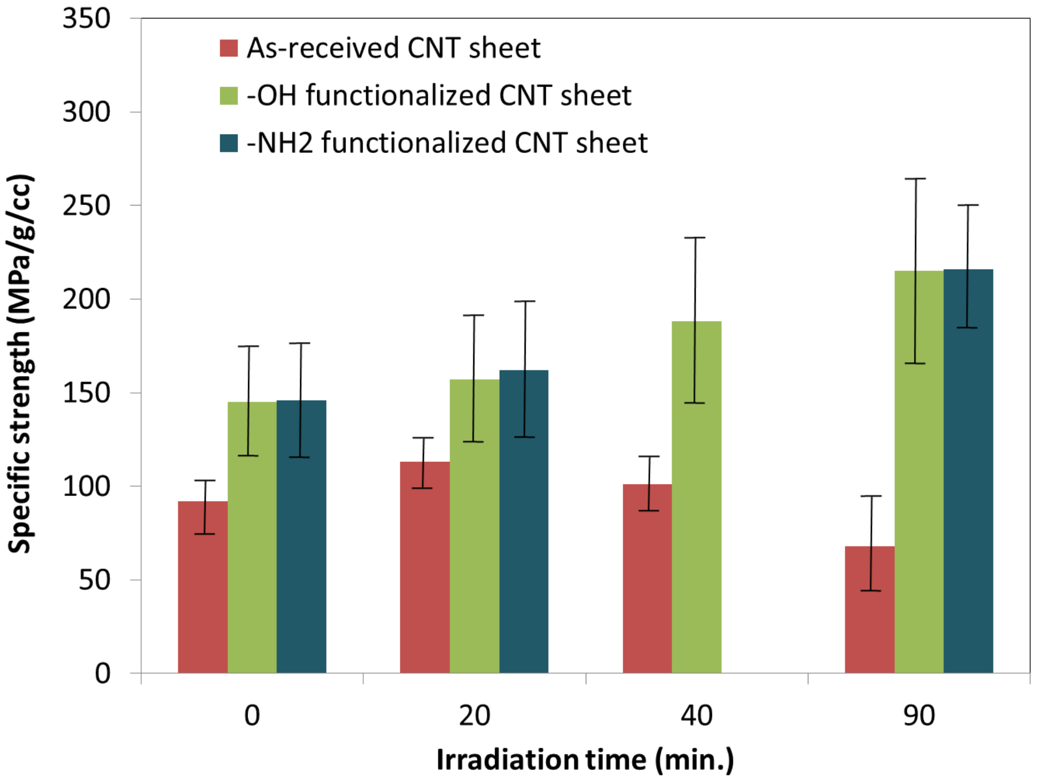






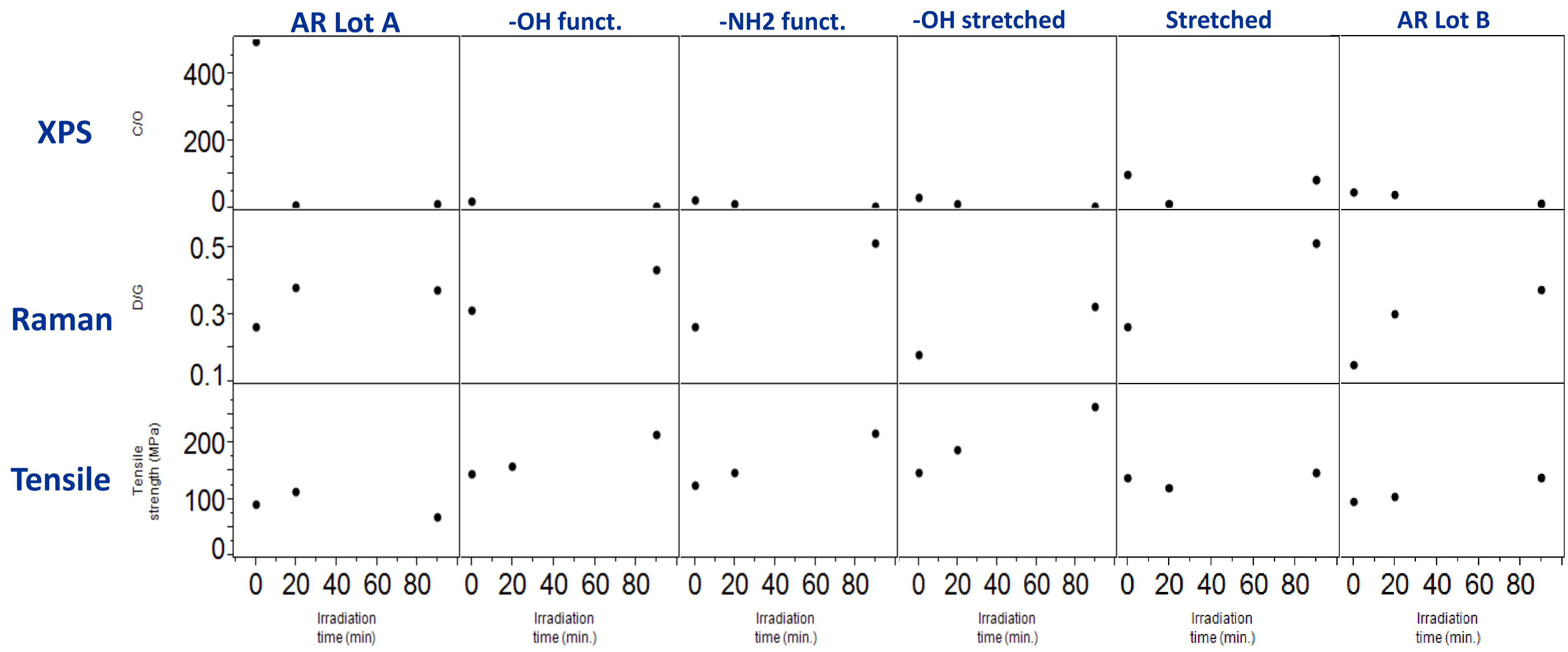
D/G ratio increased in functionalized CNT sheets as the irradiation time/dosage increased

Functionalization and irradiation effects on tensile properties of CNT sheets



- As-received sheets showed minimal change in tensile strength with increasing e-beam irradiation dosage
- Higher tensile strength observed in -OH and -NH_2 functionalized irradiated sheets
- Irradiation increased tensile strength by approx. 57%
- Over 200% increase in tensile strength in functionalized, irradiated sheets compared to unfunctionalized, irradiated CNT sheets

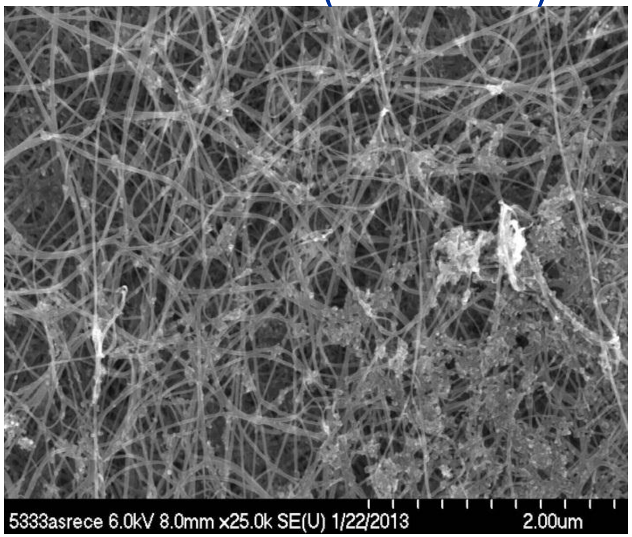
Structure-to-property relationship comparison of irradiated CNT sheets



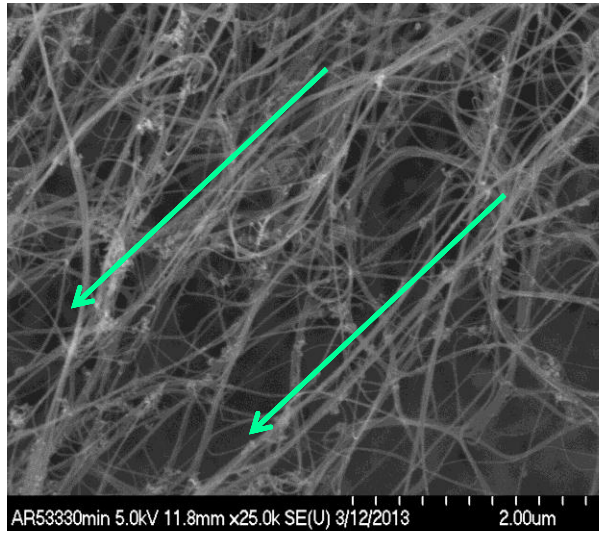
D/G ratio and tensile strength increase with increasing irradiation dosage/time
C/O ratio generally decreased with increasing irradiation dosage/time

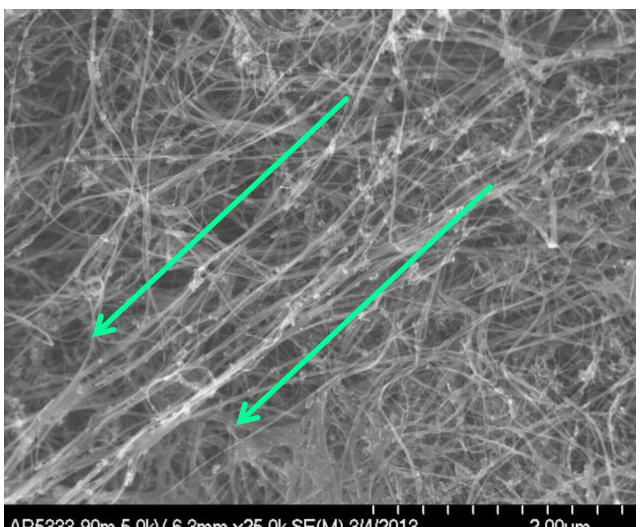
Surface of irradiated CNT sheets (before and after tensile failure)

As-received (not tested)



As-received tensile tested

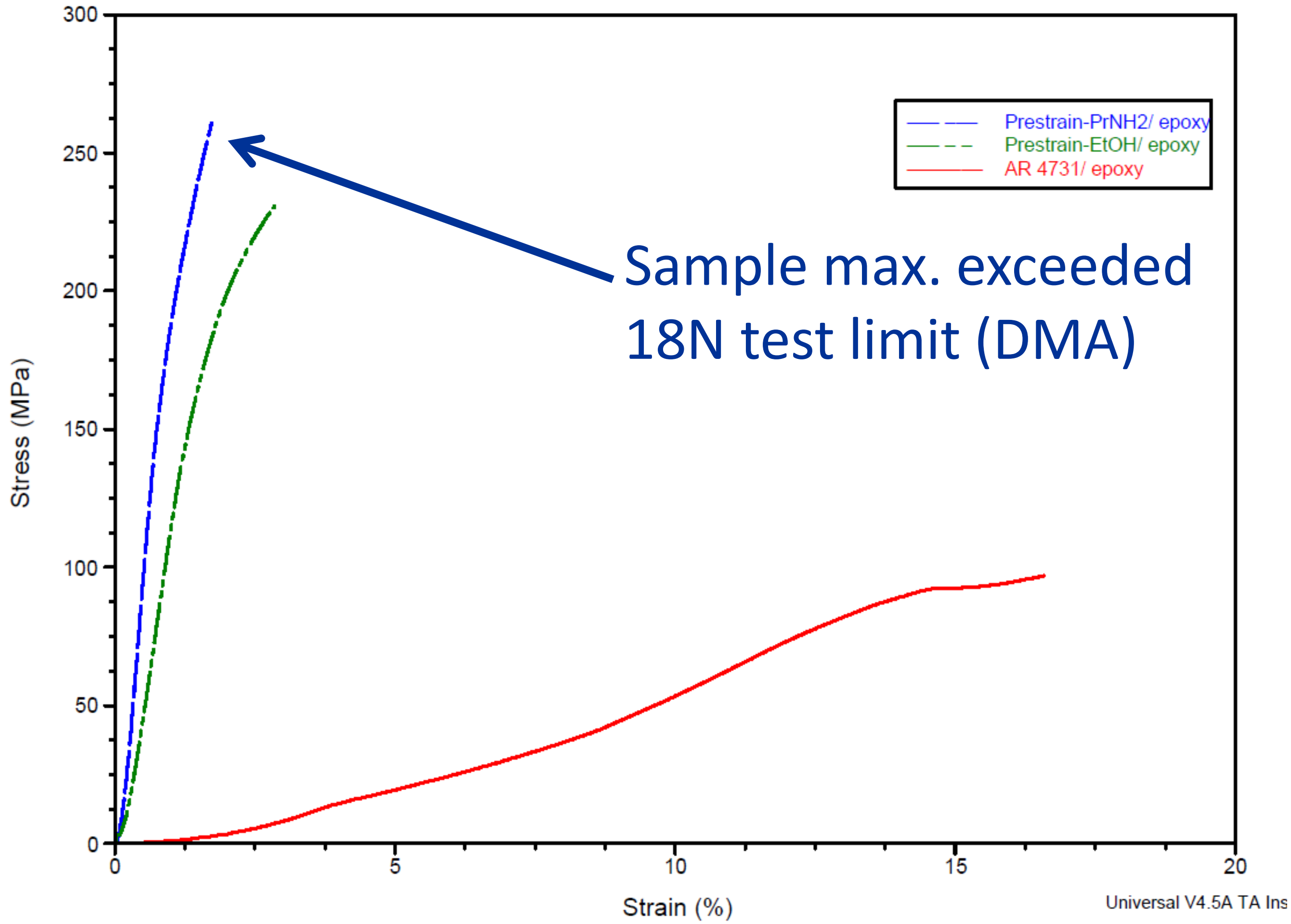




90 min irradiated tensile tested

- Random orientation prior to tensile testing
- Sheets could be strained up to 25% in as-received sheets. Lower strain in irradiated sheets
- No visible changes in failure or orientation when irradiating up to 90 min

Effect of functionalization on tensile properties of resin infused composites (DMA)

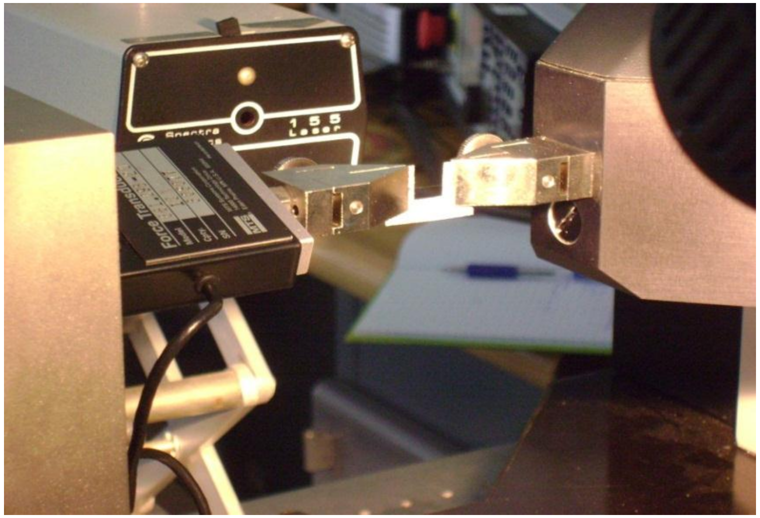


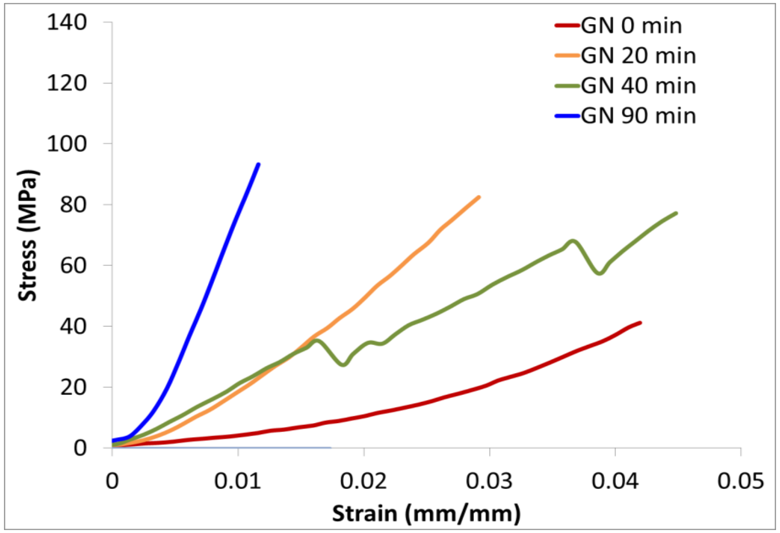
At least 160% improvement in tensile stress

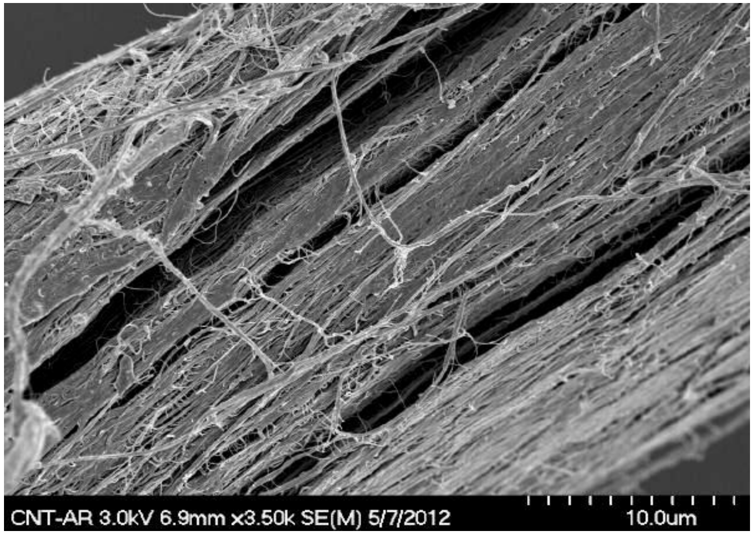
Lot B CNT sheets

Effect of irradiation on the tensile properties of CNT yarns (General Nano)

- Mounted on paper brackets
- Tested using Tytron Microtester
- 25 N load cell
- 7-10 specimens/ sample
- Strain rate: 7.5 mm/min

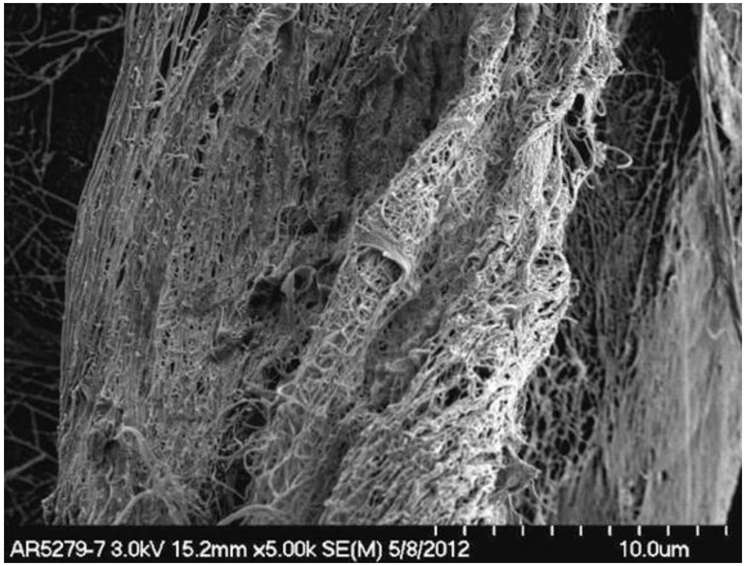


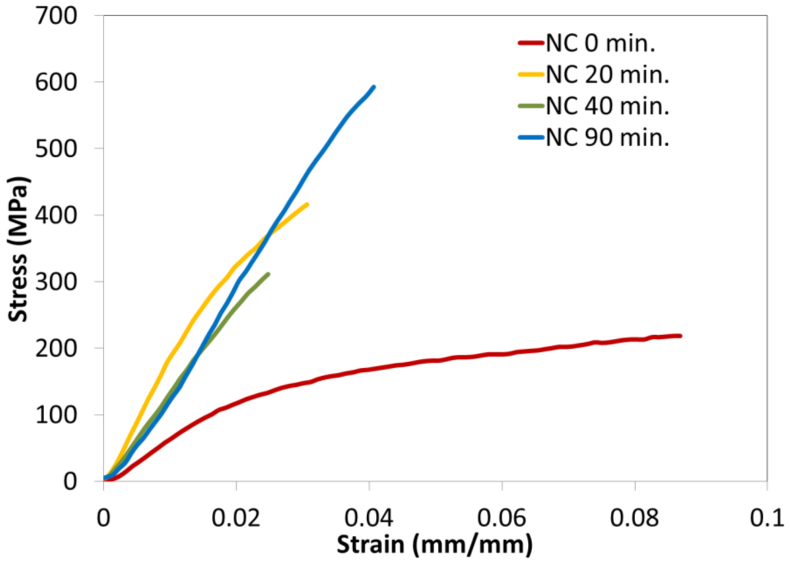




Effect of irradiation on the tensile properties of CNT yarns (Nanocomp)

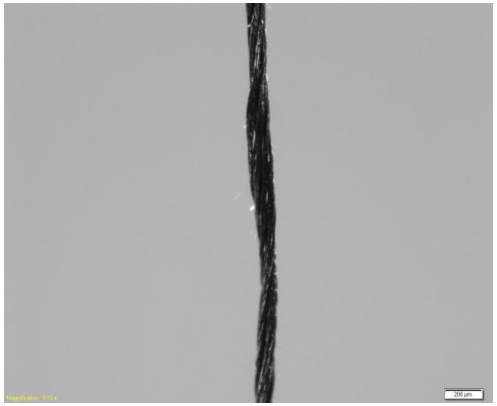
- Tensile stress increased with longer irradiation times
- Strain % decreased as irradiation time increased
- Tighter CNT packing in wires was believed to help with crosslinking in unfunctionalized CNT wires

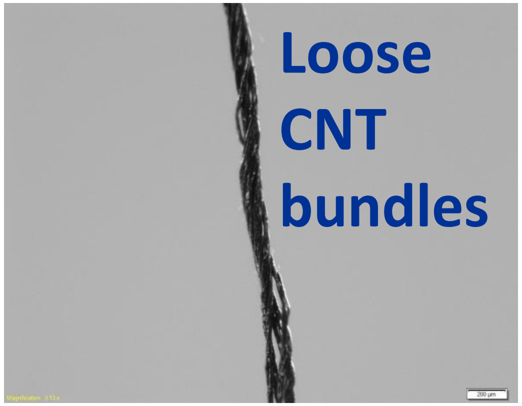


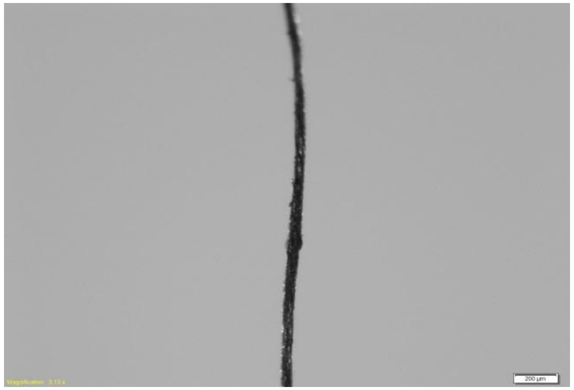


Tensile properties of irradiated CNT yarns

General Nano			
	Time (min.)	Tensile stress (MPa)	Stress (N/tex)
	0	54.4 ± 20.1	0.21 ± 0.05
	20	67.9 ± 24.6	0.28 ± 0.1
	40	56.1 ± 33.9	0.20 ± 0.1
	90	90.9 ± 53.0	0.16 ± 0.08
Nanocomp			
	0	202.0 ± 28.2	0.39 ± 0.04
	20	394.5 ± 56.5	0.69 ± 0.06
	40	319.9 ± 148.1	0.6 ± 0.1
	90	587.7 ± 300.1	0.97 ± 0.1

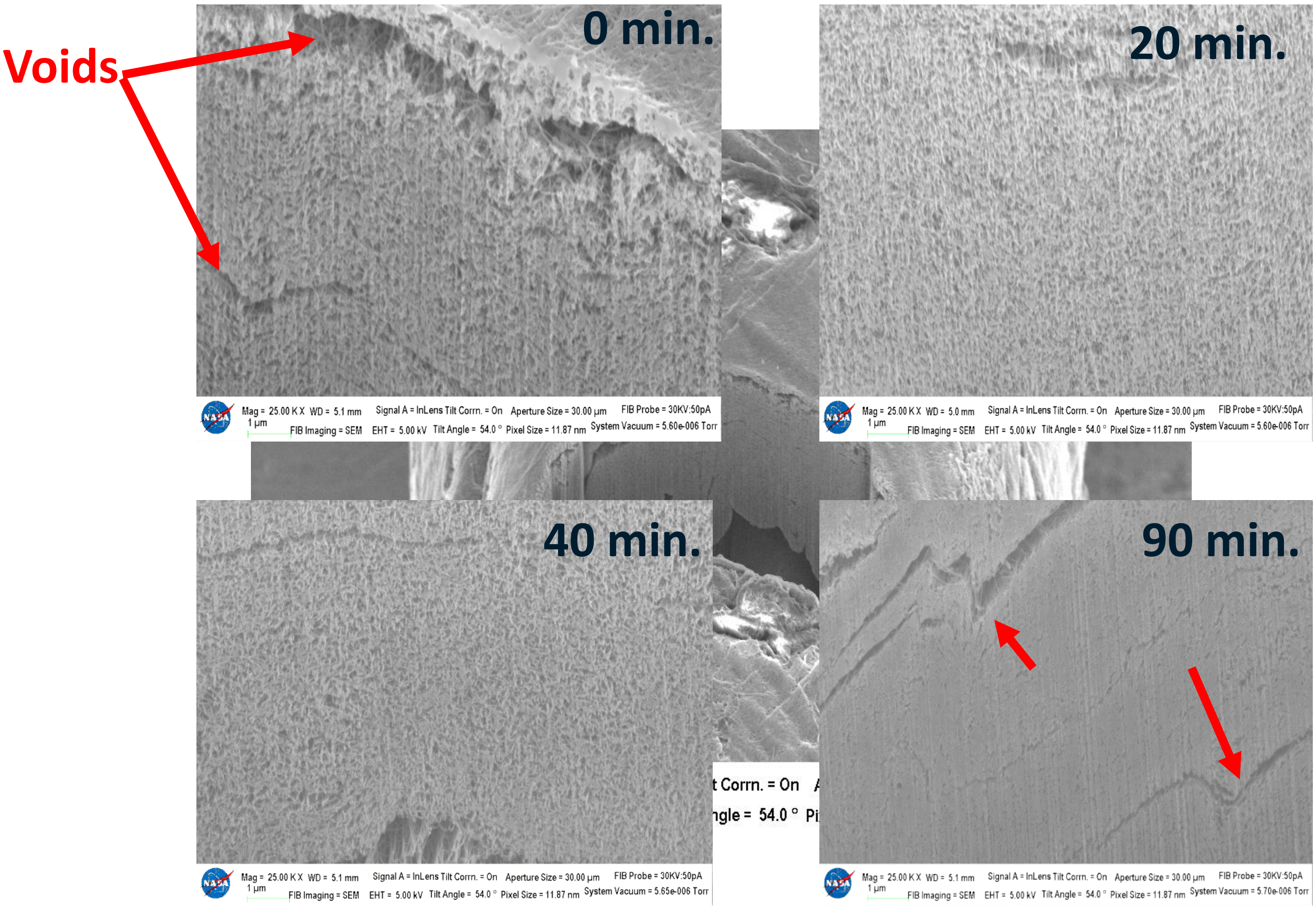






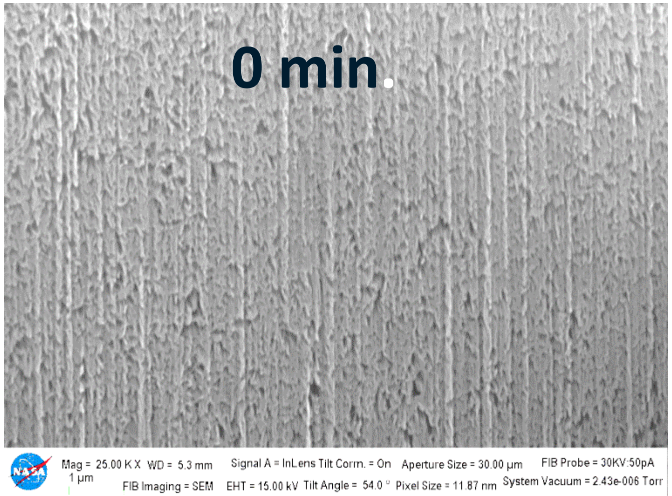
Large variation in diameter measurements

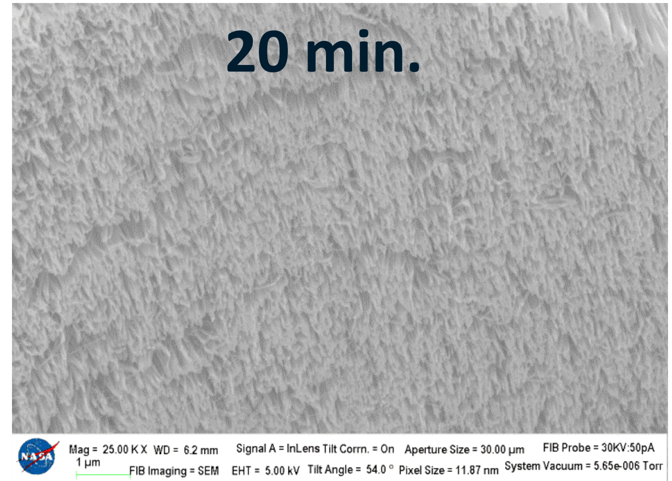
Irradiation effects on CNT yarns (Nanocomp)

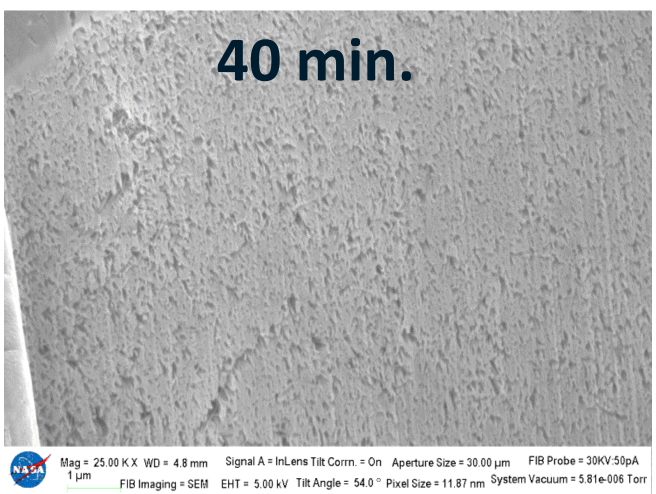


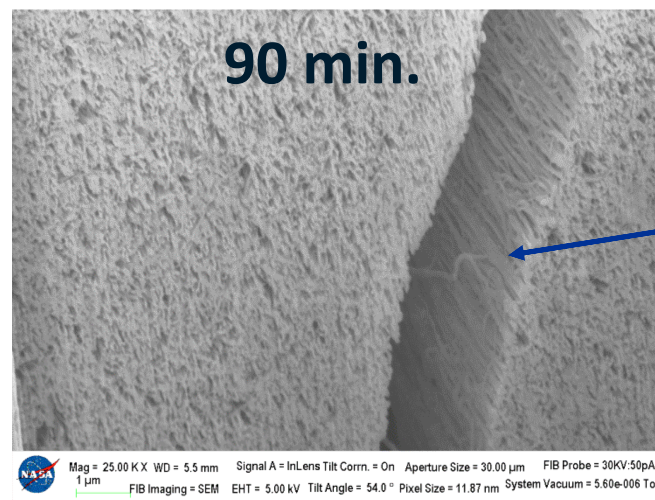
Tighter CNT packing as irradiation time increases

Irradiation effects on CNT yarns (General Nano)









Voids

Conclusions

- Irradiating for 90 minutes led to at least a 47% increase in tensile strength for untreated CNT sheets
- Significant increase in tensile strength observed in resin infused composites containing functionalized CNT sheets compared to unfunctionalized CNT sheets
- FIB microscopy revealed CNTs in wires became denser with increasing irradiation dosage

Acknowledgements

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