Multifunctional Carbon Nanotube Yarns and Transparent Sheets: Fabrication, Properties, and Applications

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CTFT Research in Advanced Materials (Collaborators)

Carbon Nanotubes

- Solid-state processing: yarns & sheets (NanoTech Institute)
- Melt spun composite fibres (Monash University)
- Gel spun fibres (University of Wollongong)

Nanoparticles (clays)

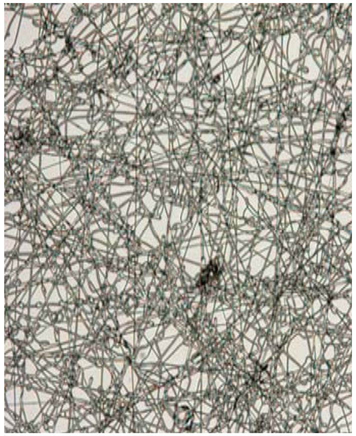
- Flammability (Deakin University)

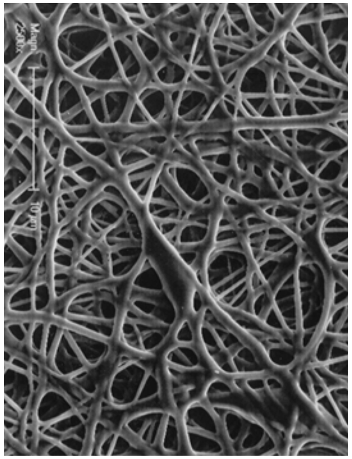
Conducting Polymers

- Electronic textiles (University of Wollongong)

Smart Textiles

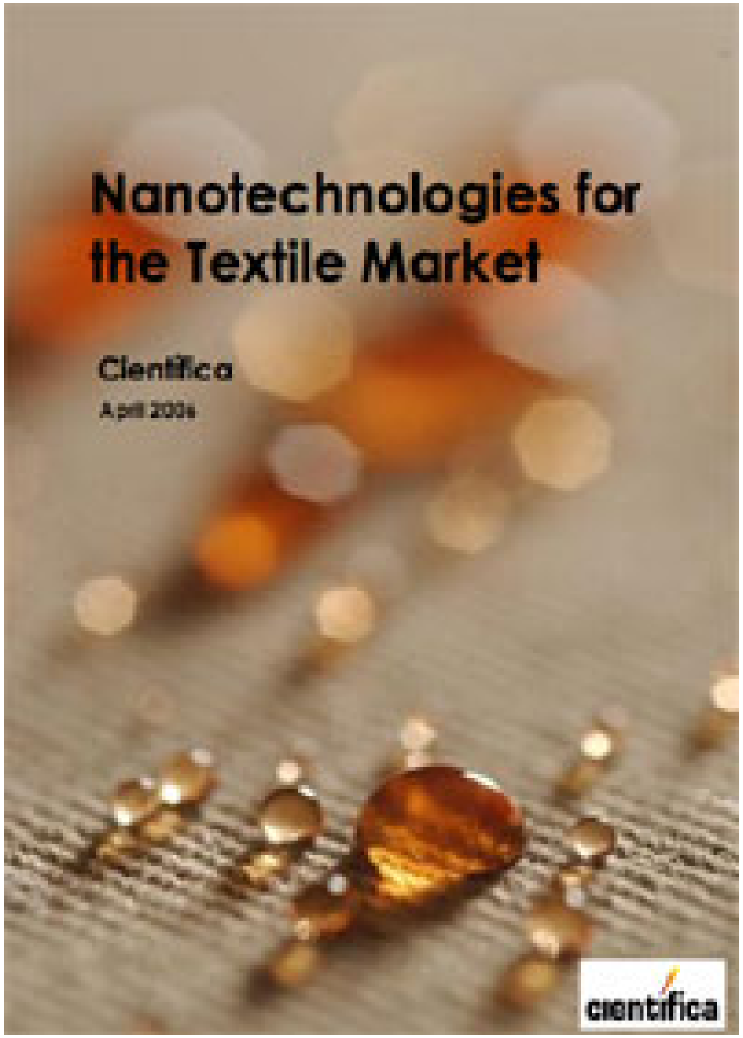
- Flexible electronics, sensors, and batteries (CMHT, CTIP, CET)
- Next-generation medical textiles (University of Wollongong)
- Electrospinning for medical applications





CTFT Electrospun membranes

Forecasts for Nanotechnologies in Textiles



'More than 60% of the U.S. population ages 15 to 50 will carry or wear a wireless computing and communications device at least six hours a day by 2007'

Gartner

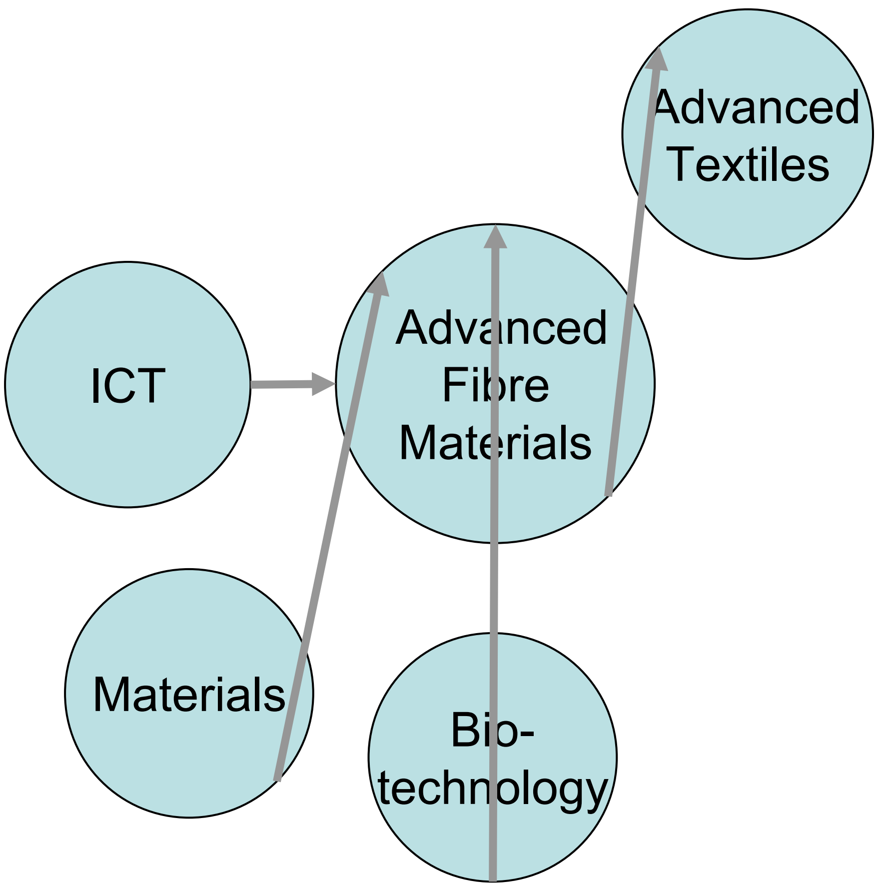
"By 2012, the potential market for interactive textiles may be worth $US 7 billion".

Venture Development Corporation

"The market for textiles making use of nanotechnologies will reach US $13.6 billion by 2007, and expand to US $115 billion by 2012"

Cientifica, April '06

Technological Convergence



Advanced Textiles with Engineered Fibre Structures and Fully Integrated Functionality:

Mechanical properties

- Strength, stiffness

Communications

Computing

Sensing

- Biological, chemical, physical, electronic

Responsiveness to:

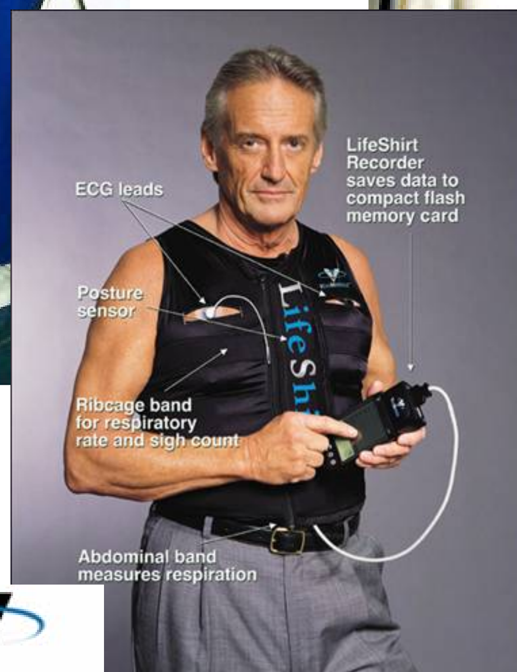
- Health
- Injury
- Attack
- Damage

Regulation of:

- Heat and Humidity
- Colour
- Thermal/optical signature

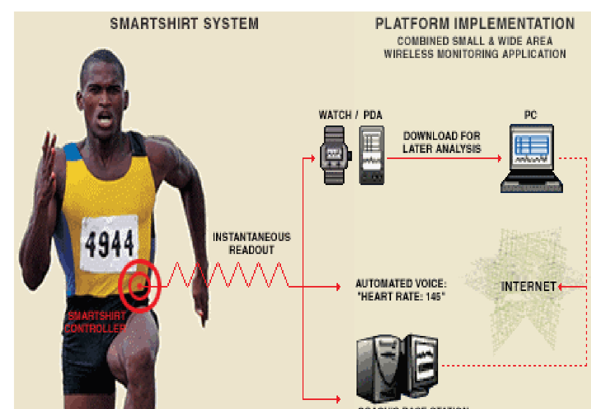
Advanced Textiles: Wearable Computing & Physiological Monitoring

Hospitals without walls



VivoMetrics®
Continuous Ambulatory Monitoring

Sensatex™
SENSATEX



Advanced Textiles: 21C Combat Apparel

Full garment integration of:

Physiological status monitoring

Power/data-bus/sensor system

- Communication, navigation, range finding, and night vision

Casualty care

Multi-functional exterior

- Nuclear/Biological/Chemical protection
- Signature management (visible and IR)

Harvesting of energy and water

Passive/active thermal management

Ultra lightweight ballistic protection

Some Examples of Nanotechnology in Textiles

Nanofibres

- Electrospun nylon, polyester, polypropylene
  - Hygroscopic multifilament PA (Toray)

Nanofilms on Fibres

- Hygroscopic PE
- Luminescent PE
  - PE/PA nanofilms

Nanoparticles

- Clays
  - Dyeability (PP), flammability , UV blocking, mechanical
- Metal Oxides
  - Antimicrobial, UV blocking, antistatic (PA), electrical conductivity
- Silver
  - Antimicrobial

Finishing

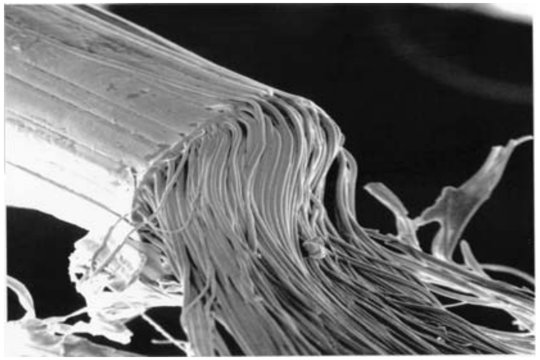
- UV resistance
- Stain & water repellency
- Stain resistance
- Wrinkle resistance
- Water & oil repellency
- Self-cleaning (NanoSphere™ Schoeller)

Smart Textiles

- Flexible electronics, textile batteries

Emerging Developments

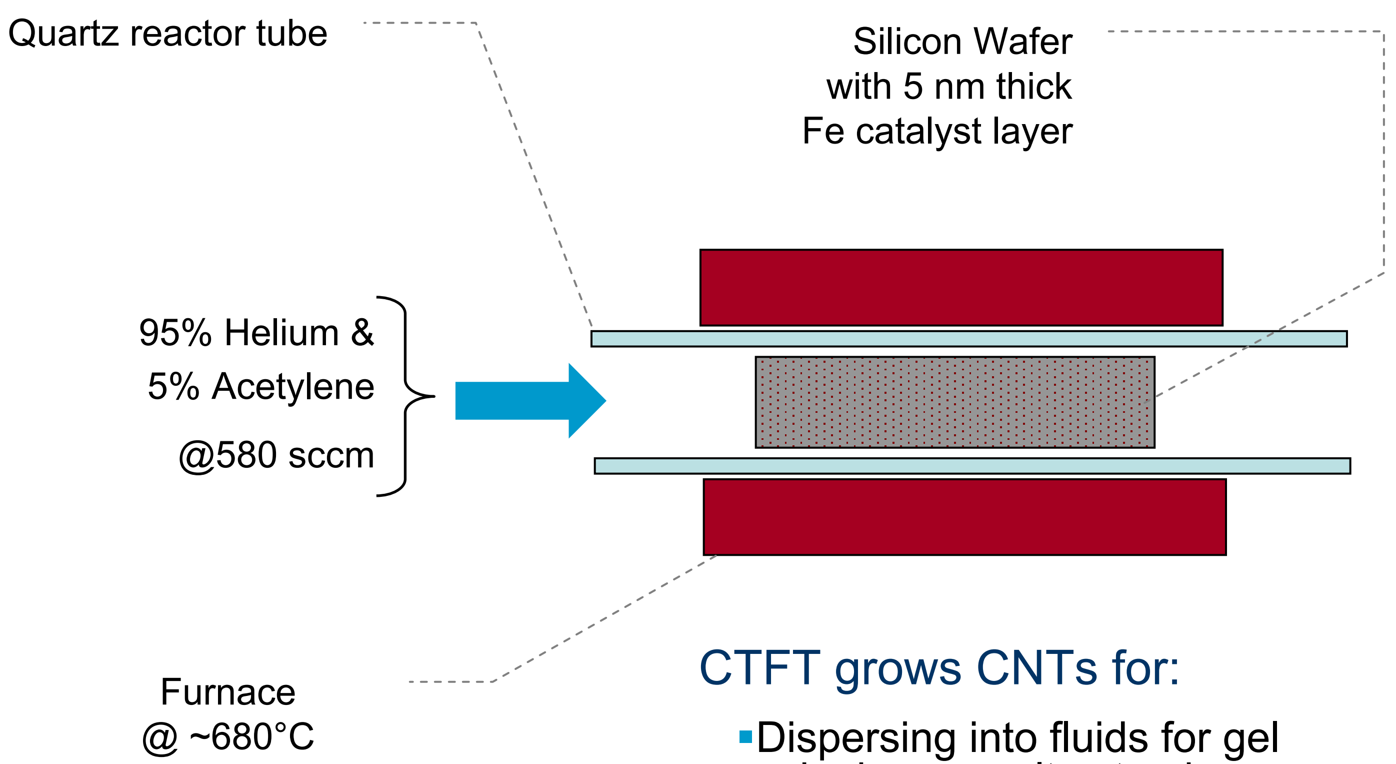
- Tissue and cell scaffolds for neural & bone cell regeneration
- OLEDs



PP nanofibres:
600 Islands-in-a-Sea
Bico Fibre.

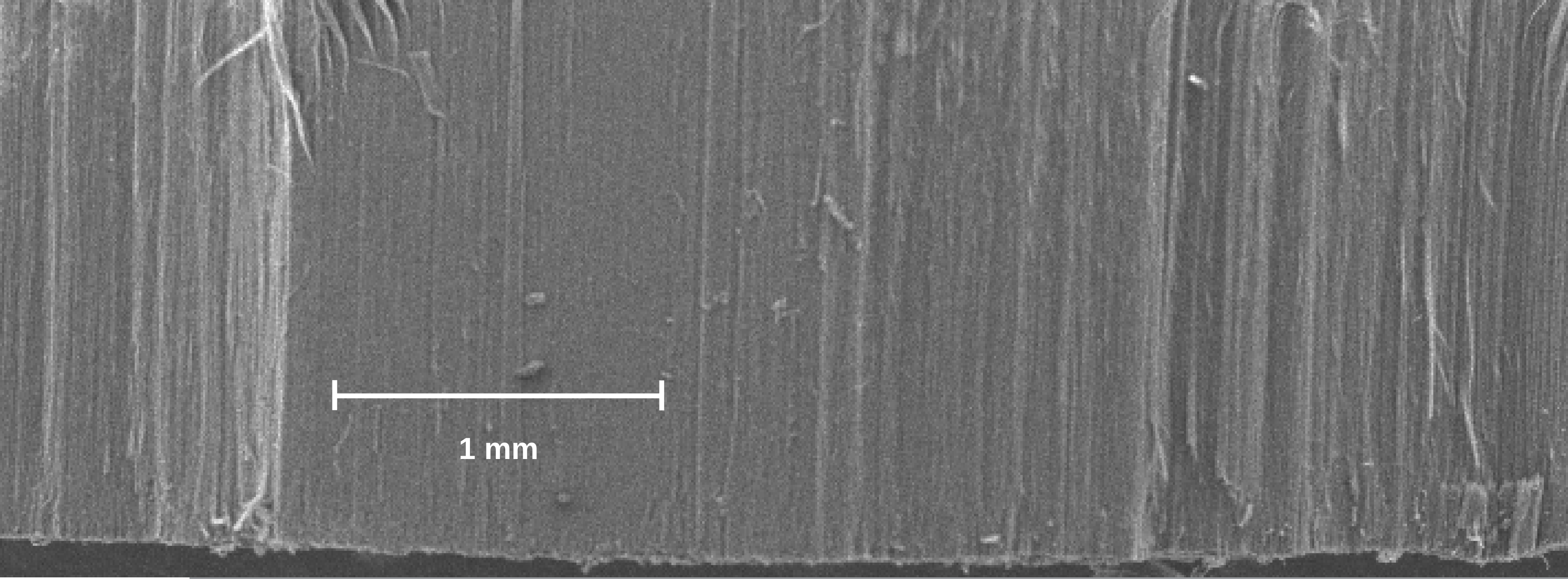
Hills Inc

Synthesis of CNT Forests at CTFT



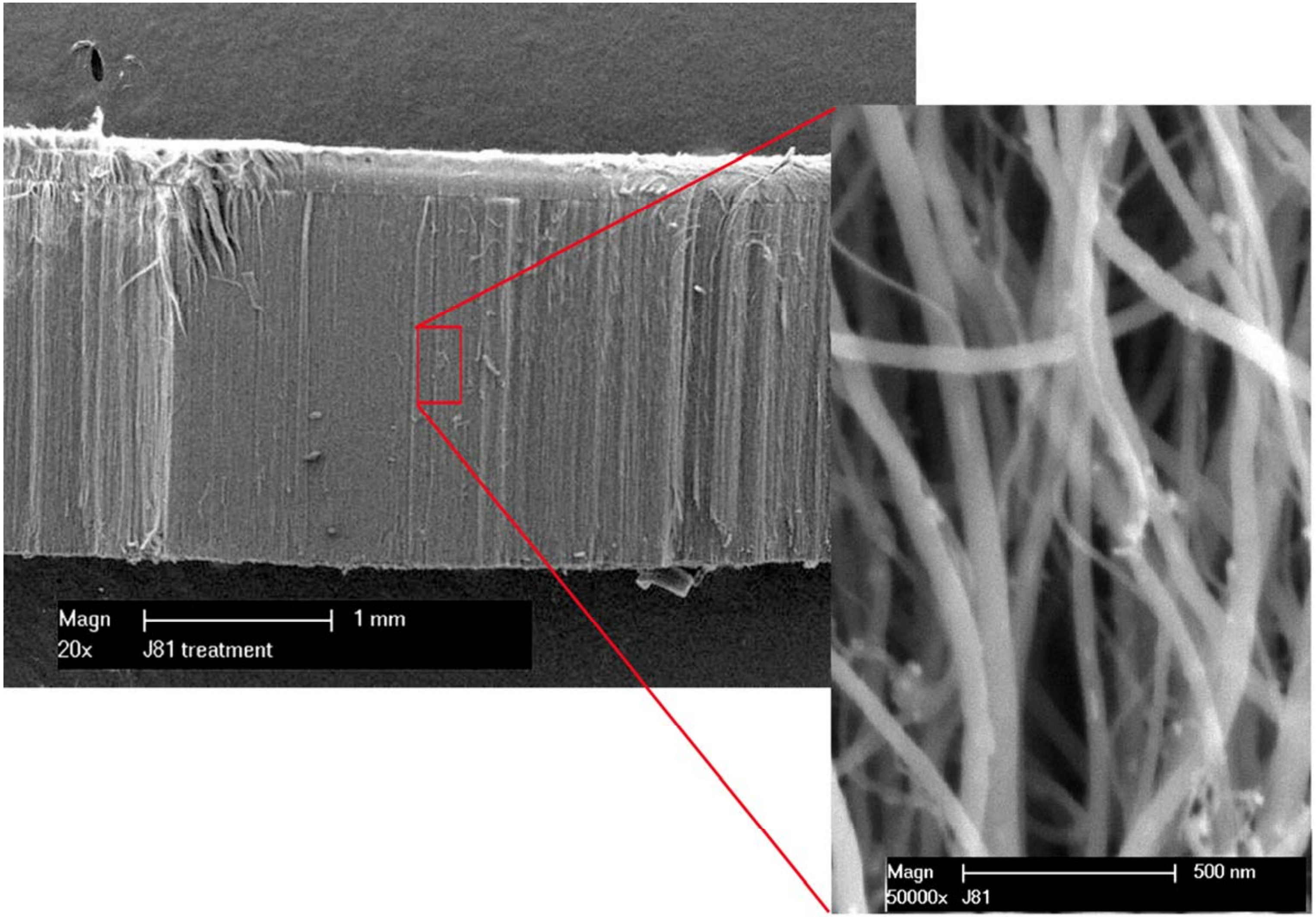
CTFT grows CNTs for:

- Dispersing into fluids for gel spinning or melt extrusion
- Solid-state processing, i.e., for spinning yarn and drawing webs

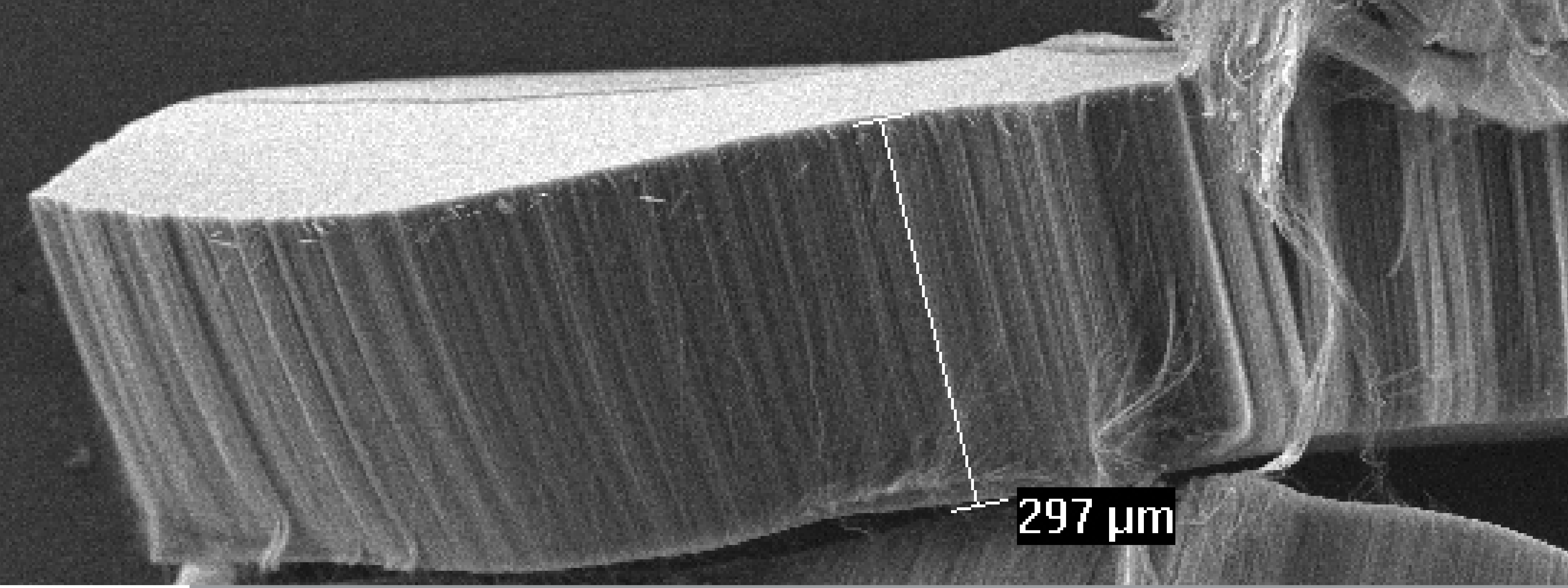


CTFT Research into CNTs for Composites

Long CNT Forests … for Composite Fibres



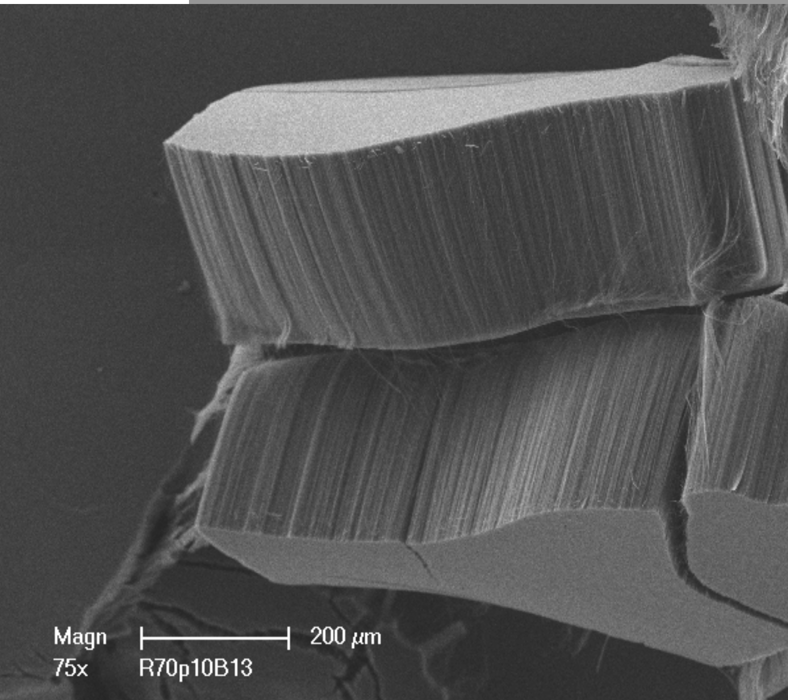
CNTs in Polymers … Composite Fibres

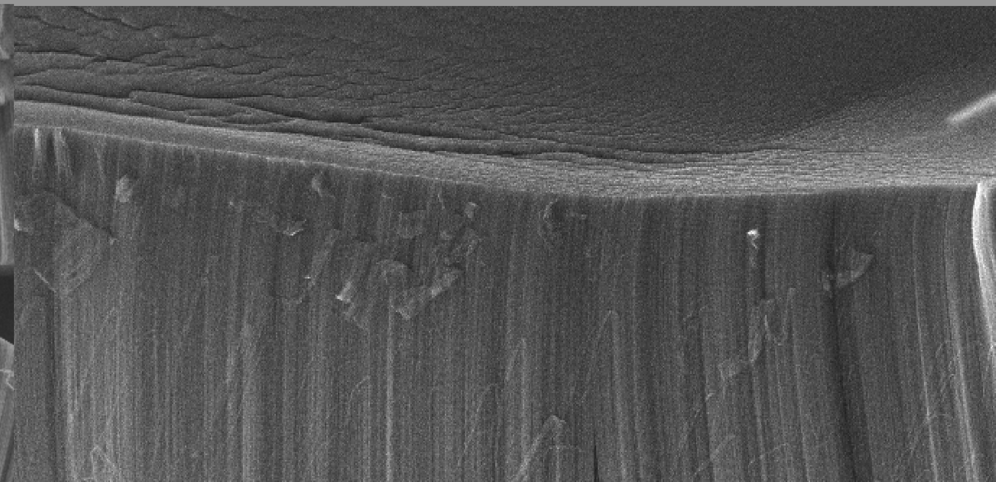


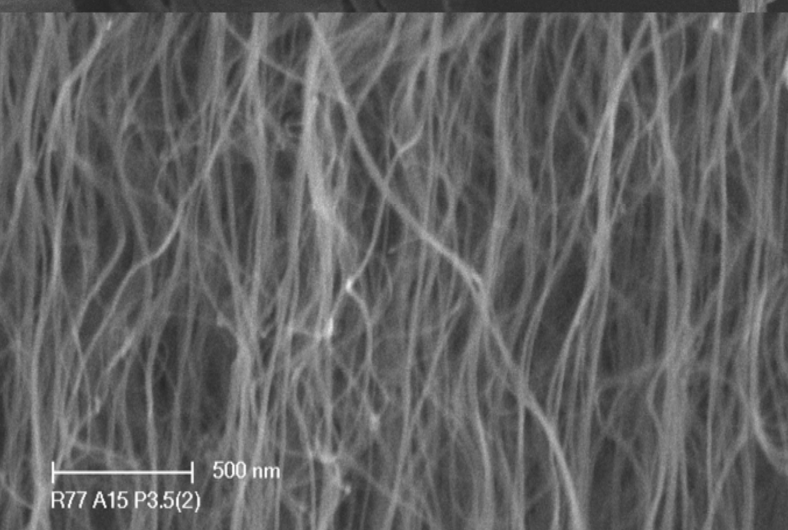
CSIRO

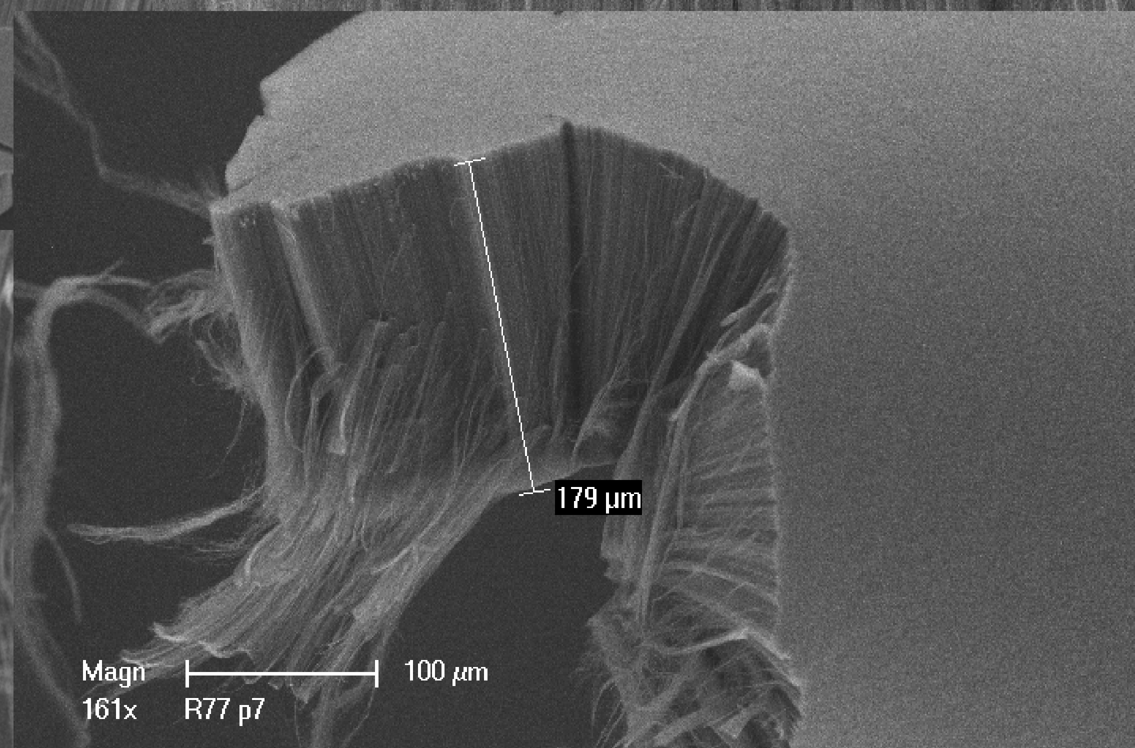
CTFT Research into Production of Drawable CNT Forests

Drawable CNT Forests Produced at CTFT









Conditions for Forest Drawability

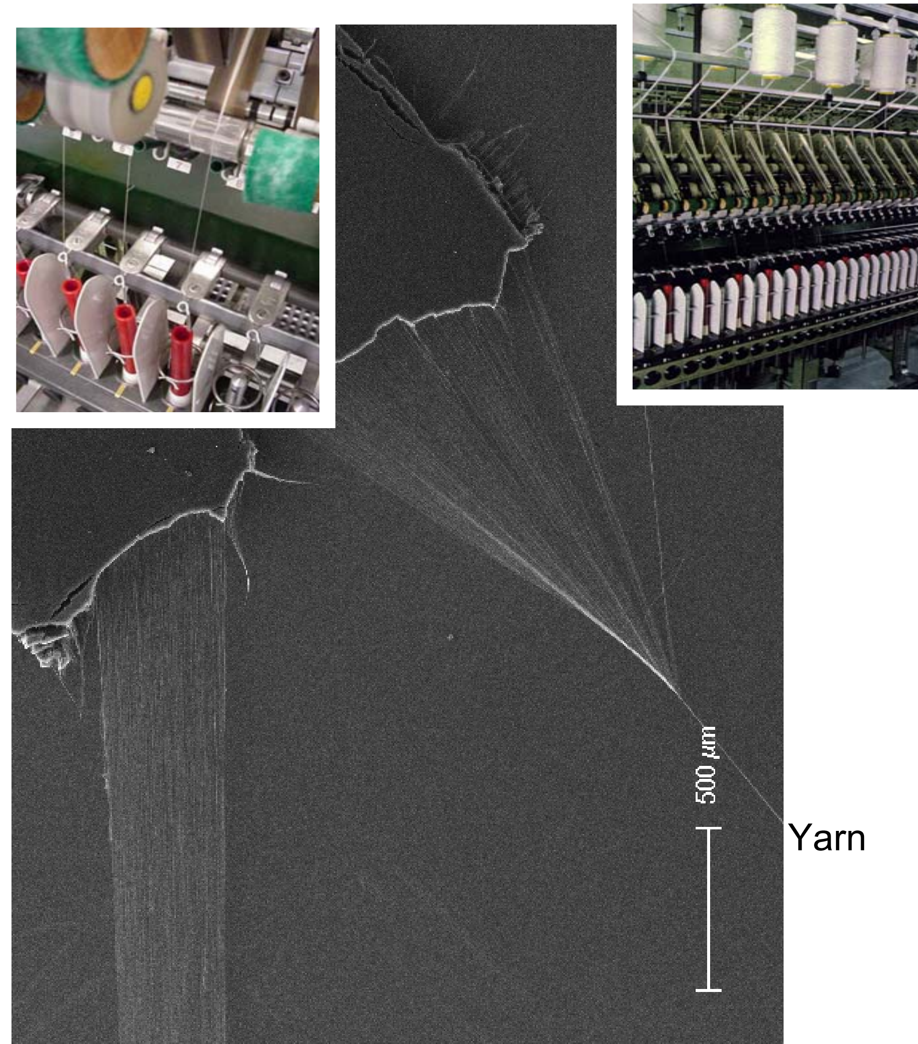
Primary

- Lengths >80 µm and preferably >150 µm.
- Diameters of around (10 to15) nm.
- Areal densities in the forest of at least ~1×10^{10} cm^{-2} and preferably ~(9 to 20)$\times 10^{10}$ cm^{-2} .
- Have a suitable level of bonding and entanglement

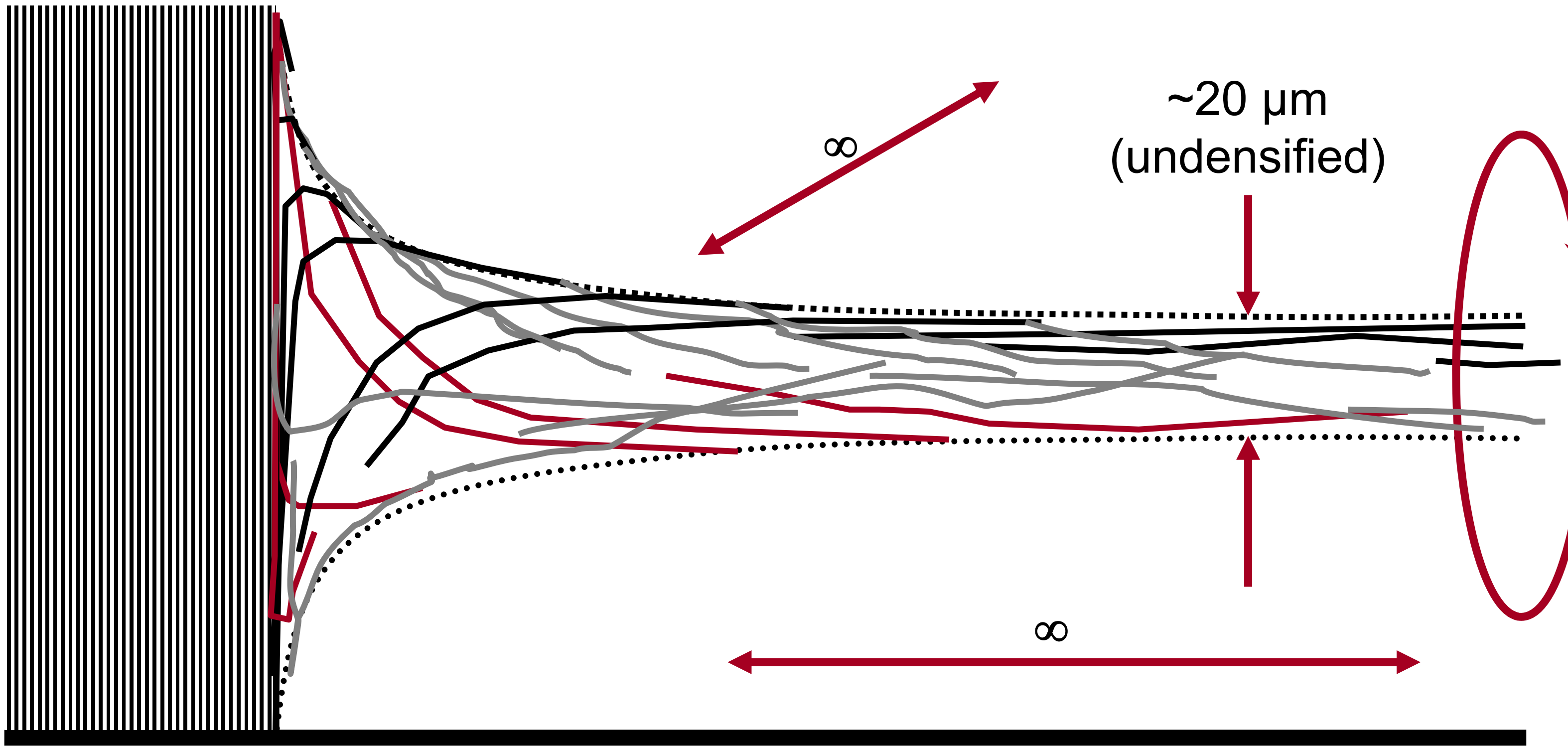
Secondary (under study)

- Substrates
- Catalyst thickness
- CVD conditions
  - Flows, HC proportions, temperature profiles

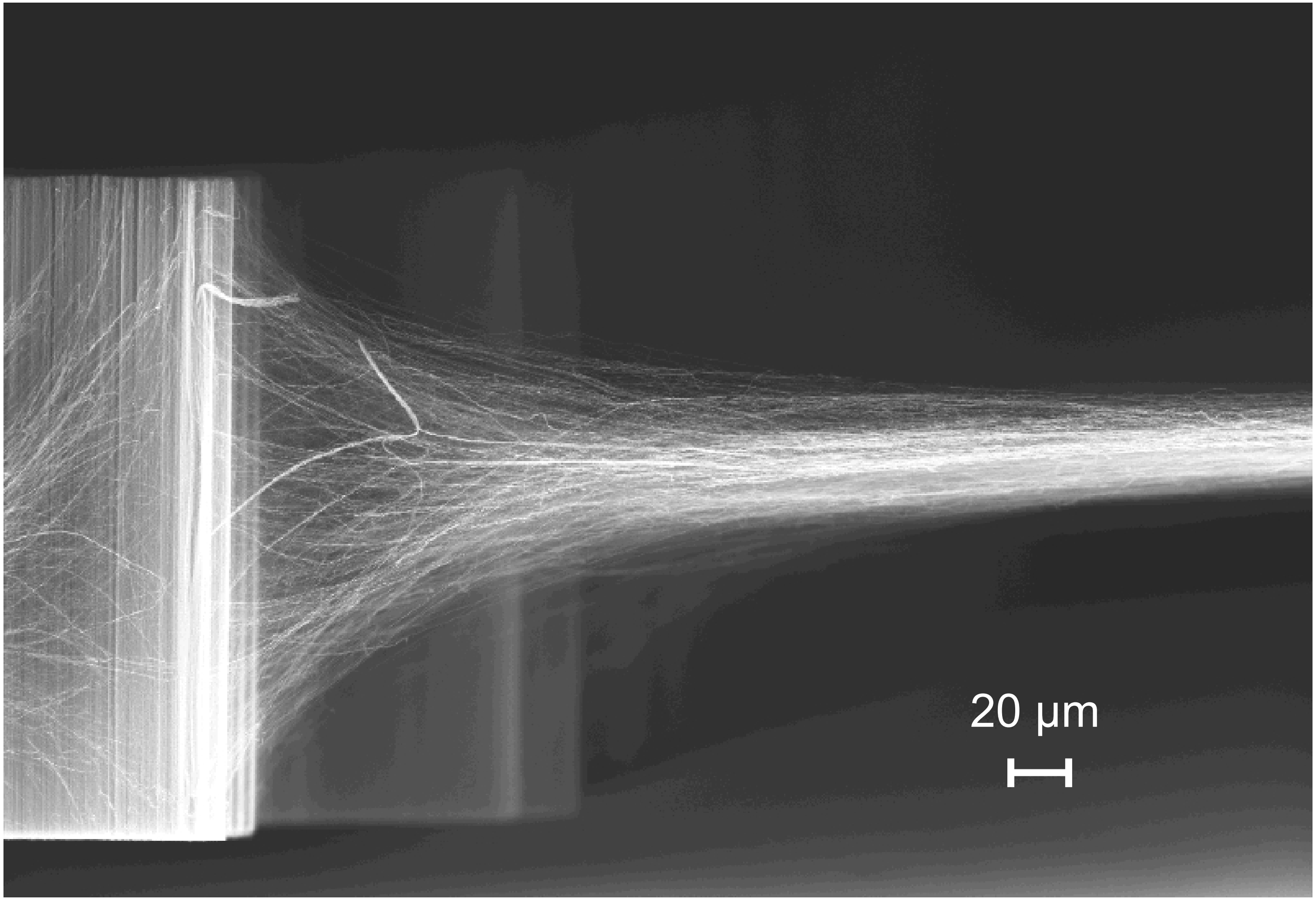
Growing drawable forests requires careful control of all aspects of the process



Schematic of Web Formation



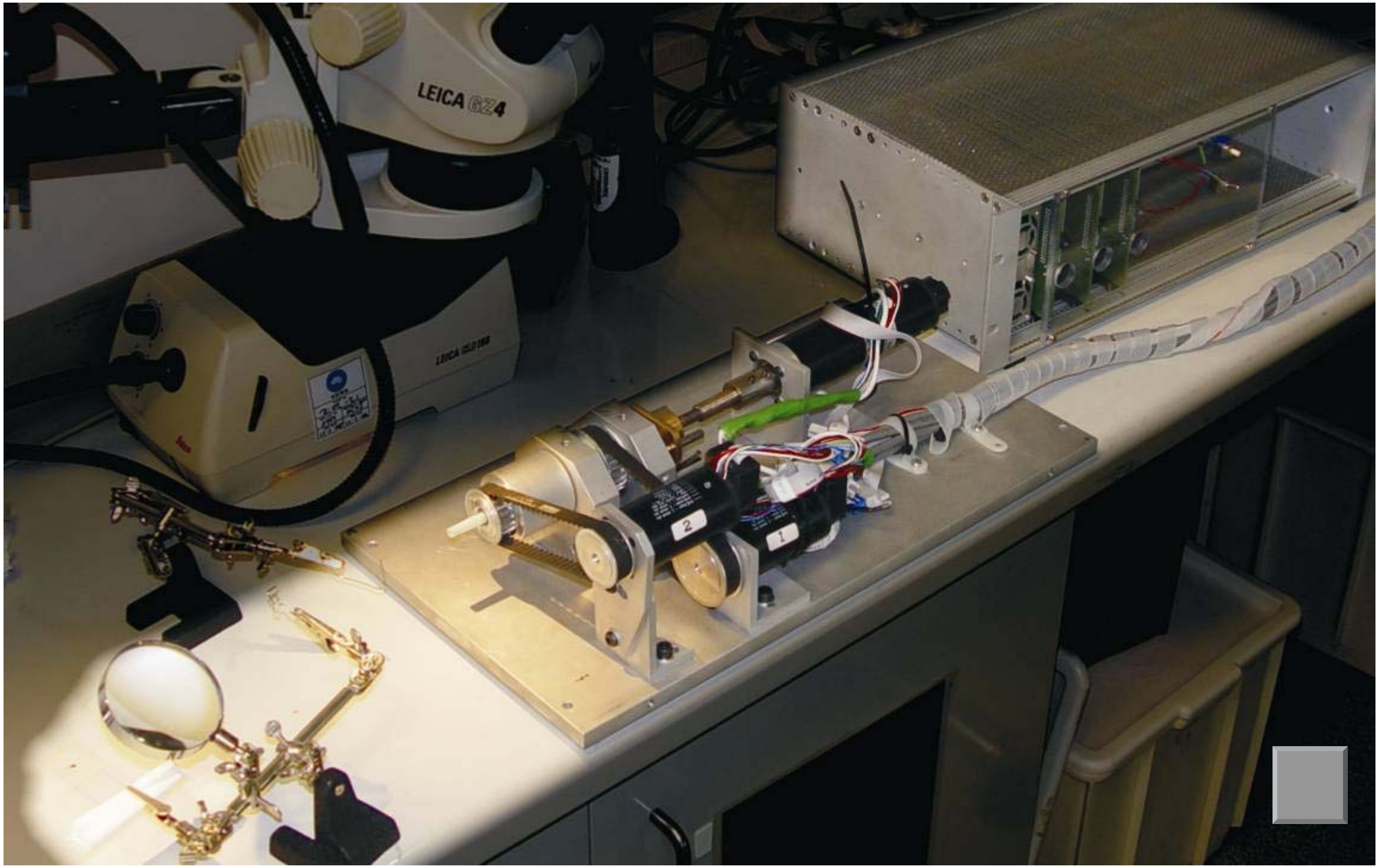
SEM of Solid-State Process of Nanoweb Formation



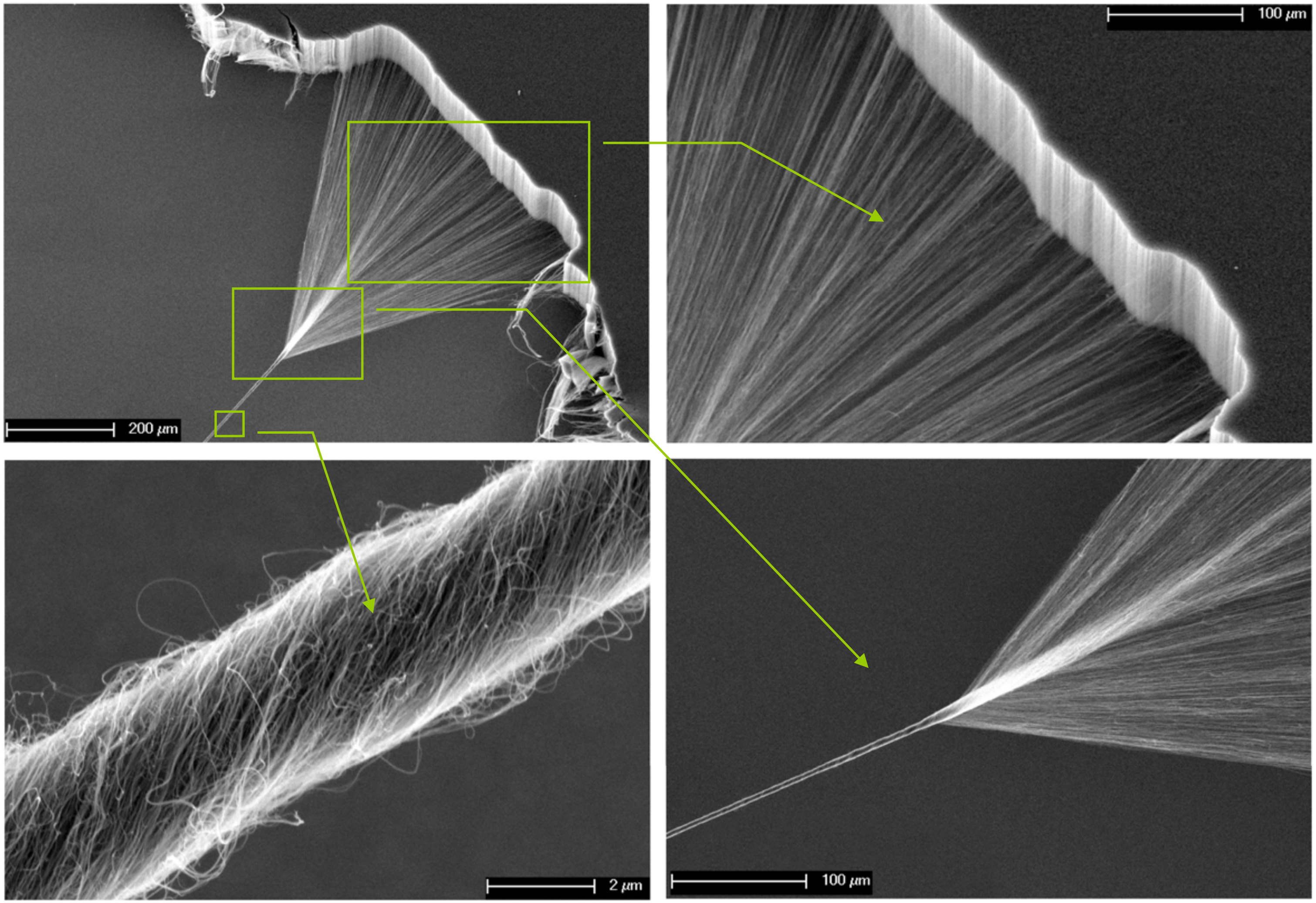
Spinning CNTs into Yarns

Multifunctional Carbon Nanotube Yarns by Downsizing an Ancient Technology, M. Zhang, K. R. Atkinson, & R. H. Baughman, *Science*, **306**, 1358, 2004.

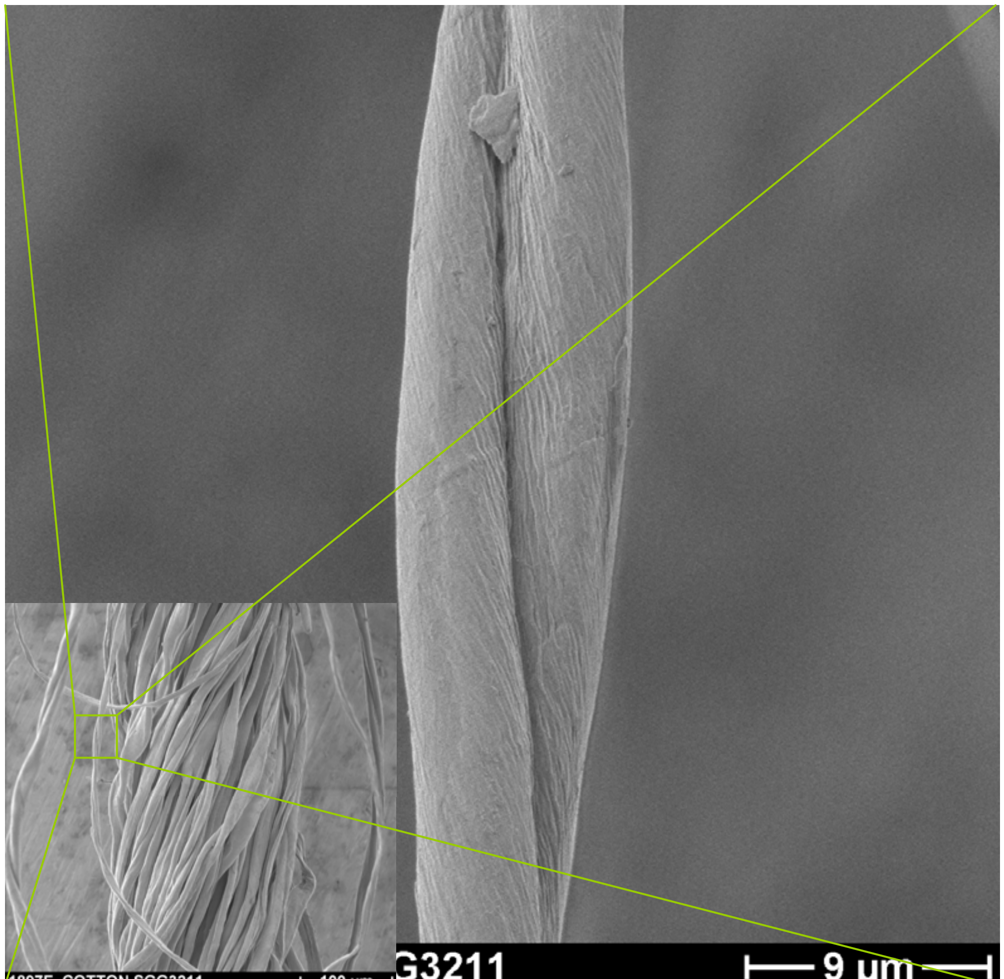
CSIRO CNT Spinning Machine

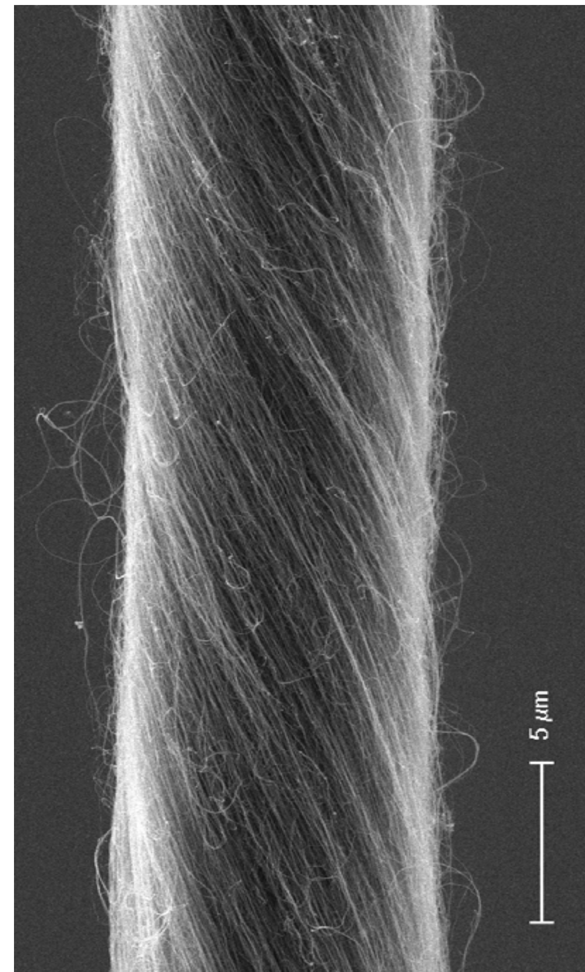


Spinning CNT Yarns



SEMs of Cotton and CNT Yarn (not at same scale)





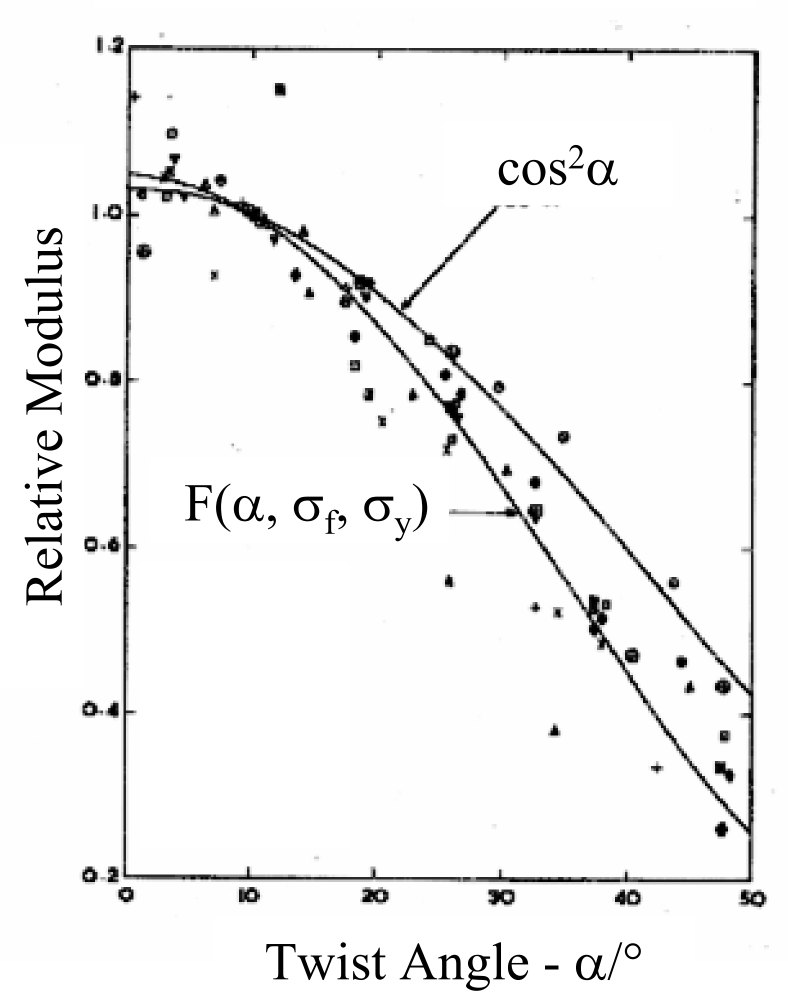
Role of Twist in a Continuous Filament Yarn

Tenacity of a continuous filament yarn decreases with twist:

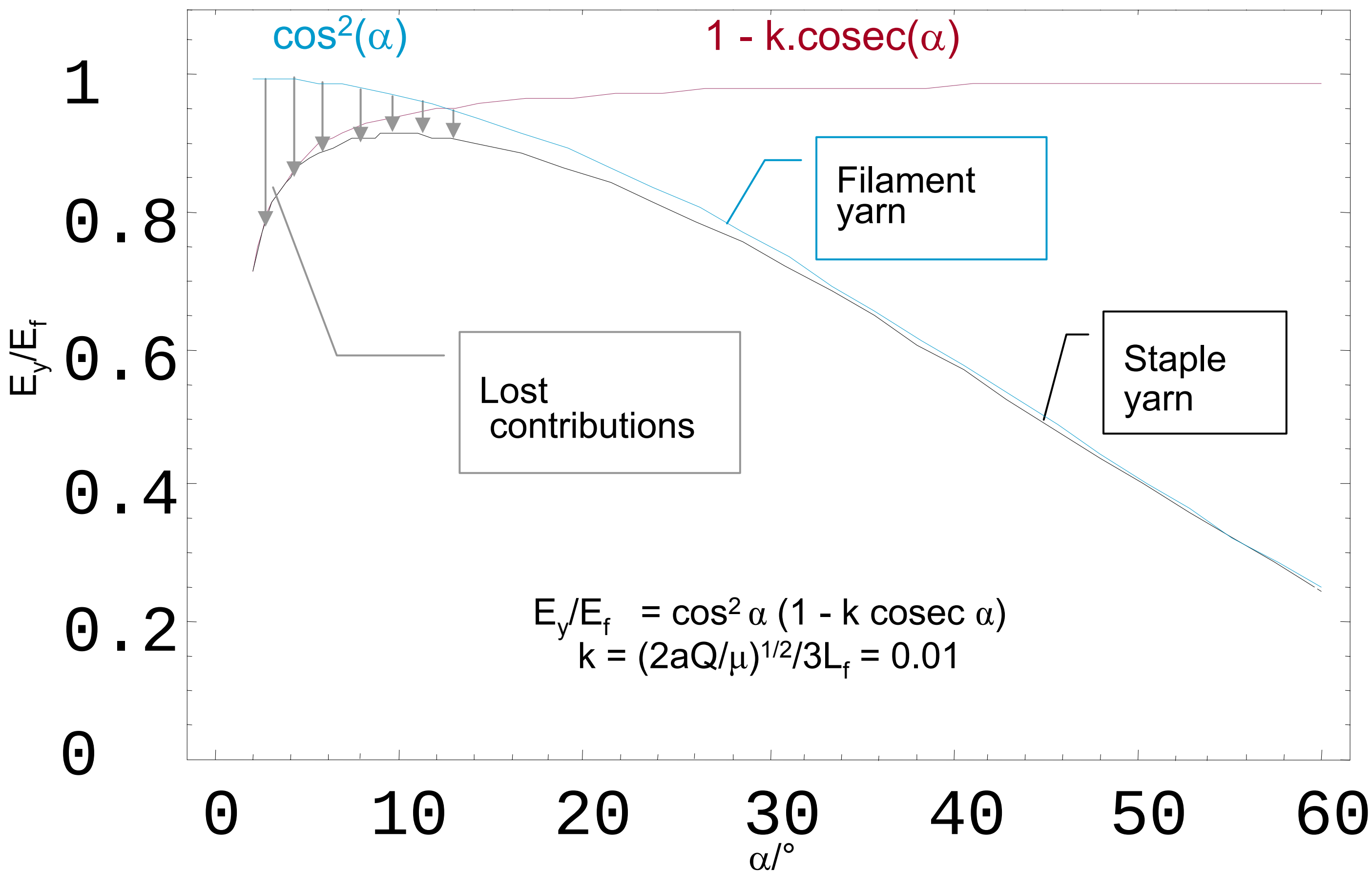
$$E_y = E_f \cos^2\alpha$$

Ref: Structural Mechanics of Fibres, Yarns, & Fabrics, Backer, Hearle, & Grosberg.

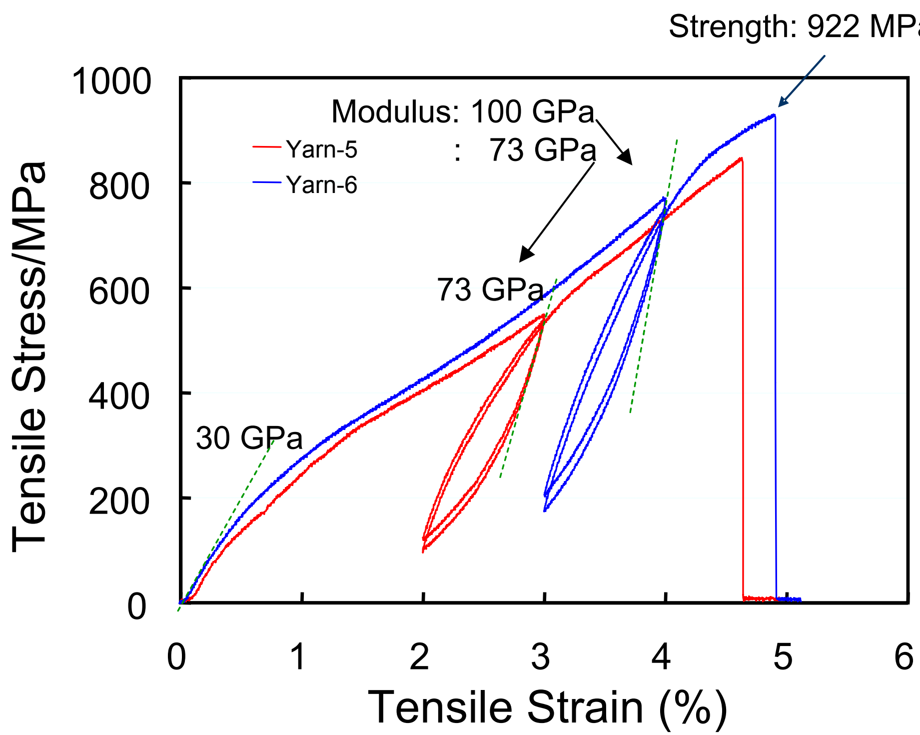
Continuous Filament Yarns



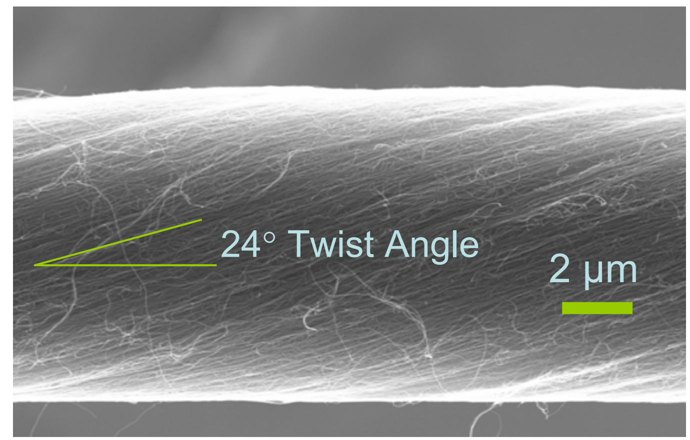
Role of Twist in a Staple Fibre Yarn



Latest Results I: Tenacity
NanoTech Institute UTD



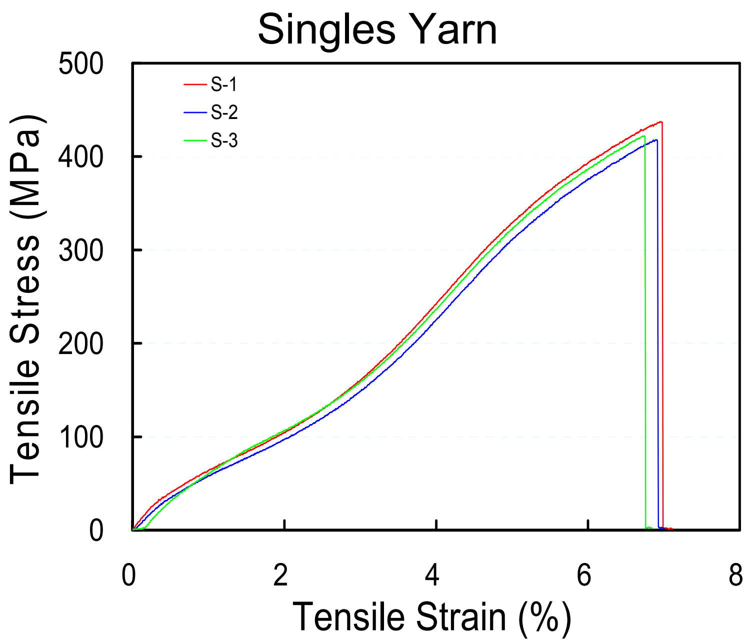
Yarn performance improved by decreasing twist angle

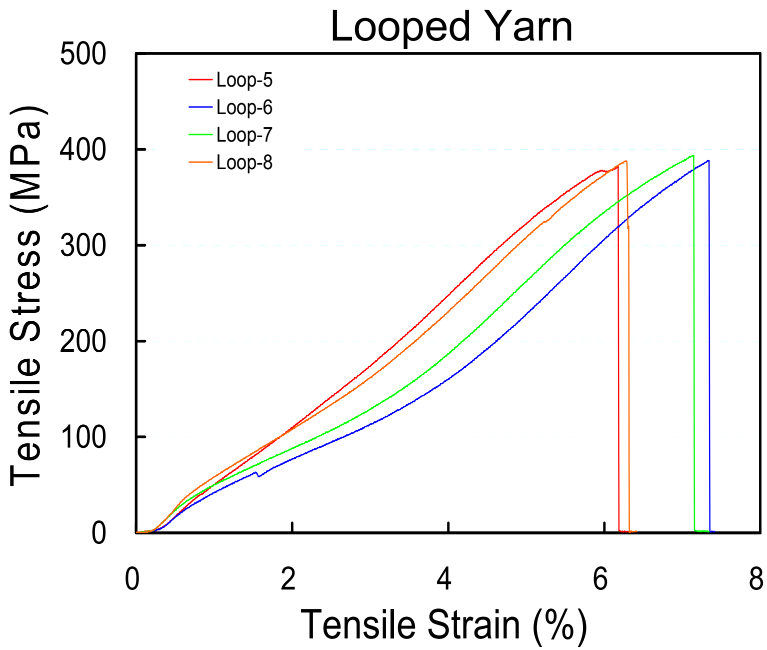


- Previous Best Results: Strength - 0.6 GPa; Modulus - 30 GPa; Toughness - 14 J/g for MWNT yarn with a 45° angle of twist.
- Present Results: Strength - 0.92 GPa; Modulus - 100 GPa; Toughness - 22 J/g for 24° angle of twist.
- Graphite fibre is less tough (12 J/g), breaks at knots, and has higher density (1.8 g/cm^3 vs. 1.27 g/cm^3 for the CNT yarn).

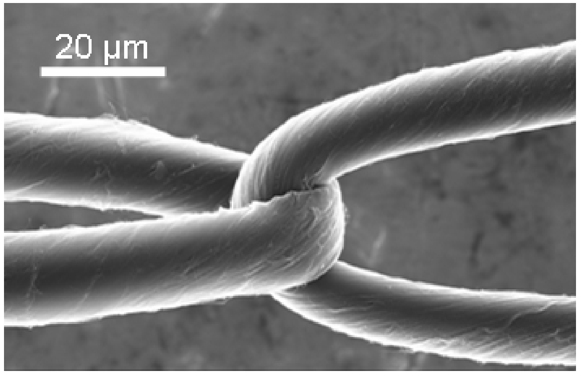
Latest Results II: Loop Strength Of Nanotube Yarns

NanoTech Institute, UTD





- Loops of CNT yarns have strengths 1.86 times that of the singles, i.e., the tenacity of the loop is 93% that of the singles.



Selected Properties of CNT Yarns

Data for CNT Yarns

Electrical Conductivity (S/cm):

- Singles yarn ~300

Density/(g/cm^3):

- Singles yarn ~1.27

Modulus/GPa: (Singles 24° twist)

- ~100

Strength/GPa: (Singles 24° twist)

- ~0.92

Toughness/(J/g):

- Singles Yarn ~14
- Twofold Yarn ~20

No creep:

- >20 h at 6% strain (~50% breaking strain)

Knots do not degrade tensile strength:

Retain flexibility/strength :

- after heating in air at ~450°C
- when immersed in liquid N_2

Comments and comparisons

Electrical Conductivity/(S/cm):

- Graphite CF: ~167 – 3333

Density/(g/cm3):

- Graphite CF ~1.8

Modulus/GPa:

- Graphite CF ~300

Strength/GPa:

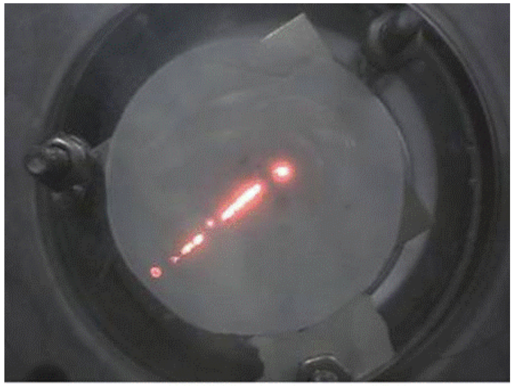
- Graphite CF ~3

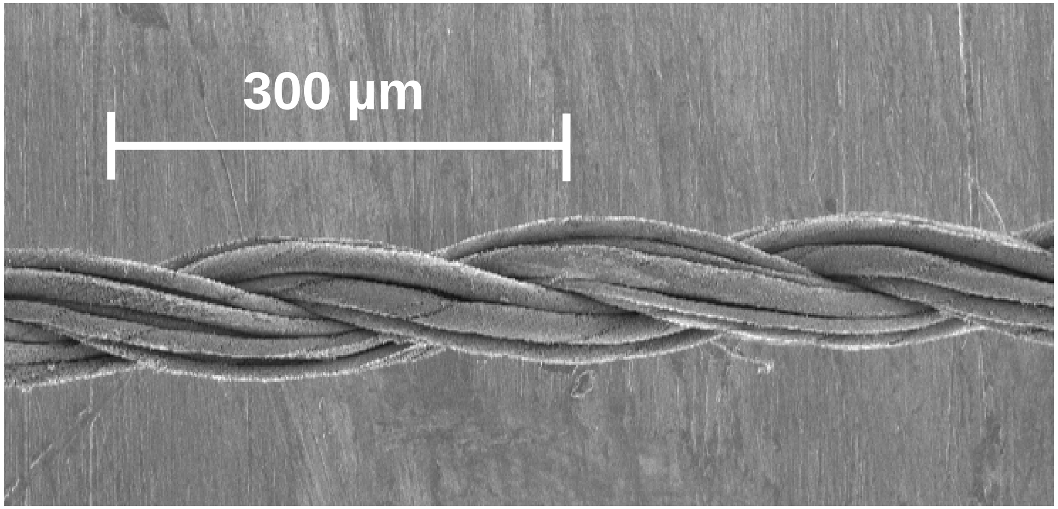
Toughness/(J/g)

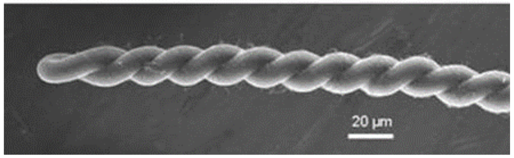
- Graphite CF ~12
- Solution-spun SWNT/PVA yarns ~600

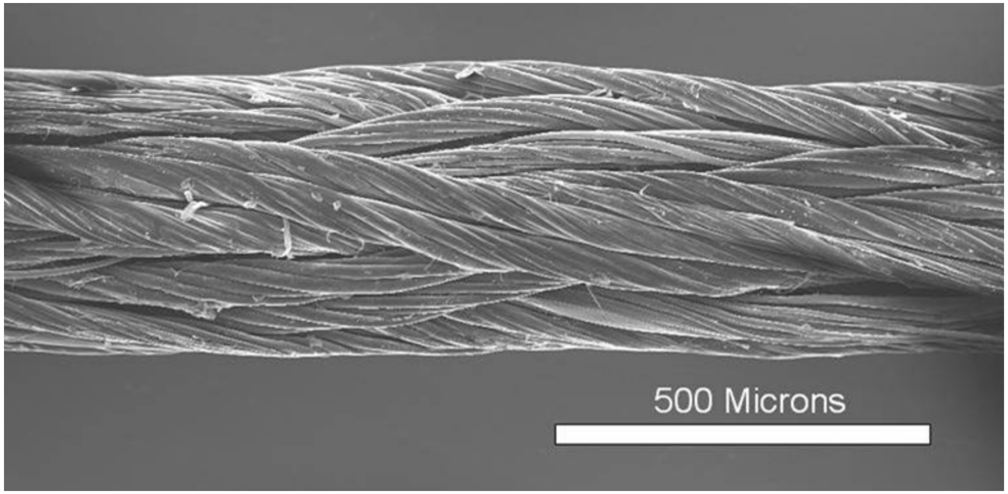
Knots degrade tensile strengths of most textile fibres

Possible CNT Yarn Applications: Light Emission

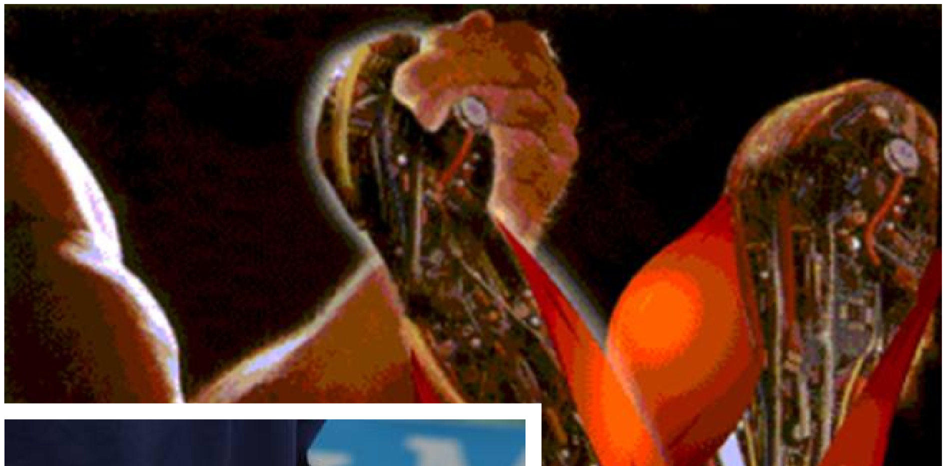


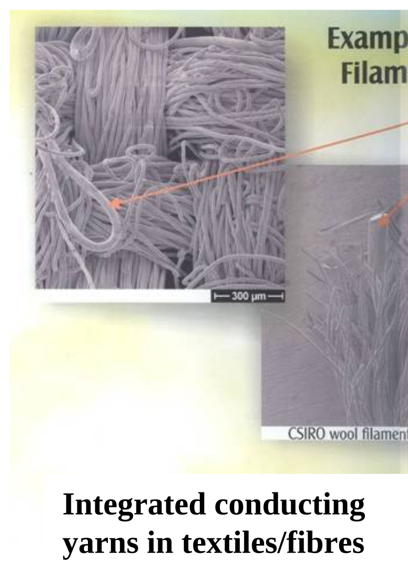




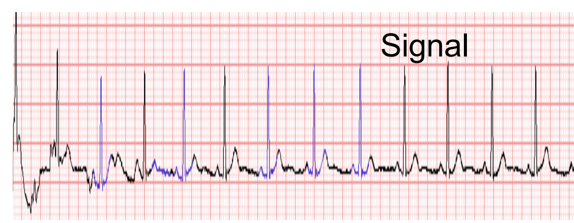


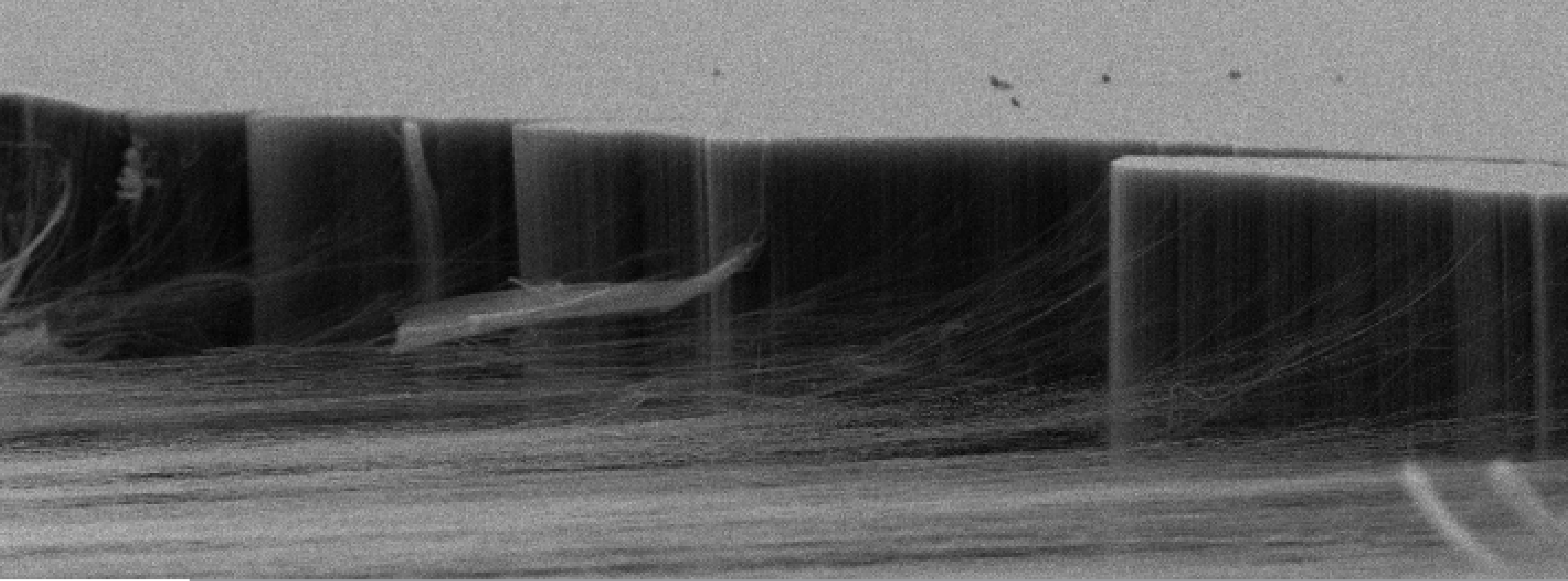
Possible CNT Yarn Applications: Sensors and Actuators





Integrated conducting yarns in textiles/fibres

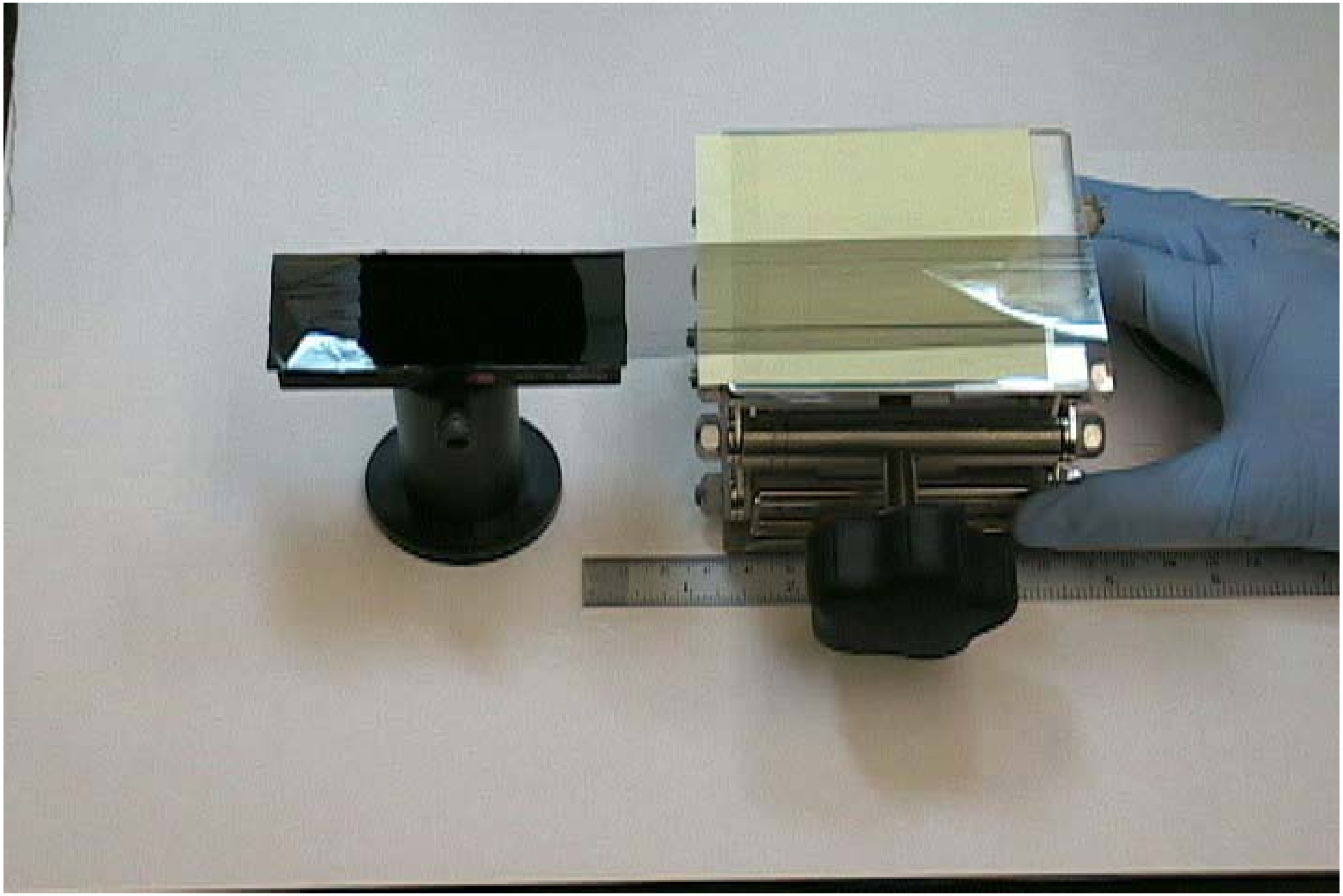




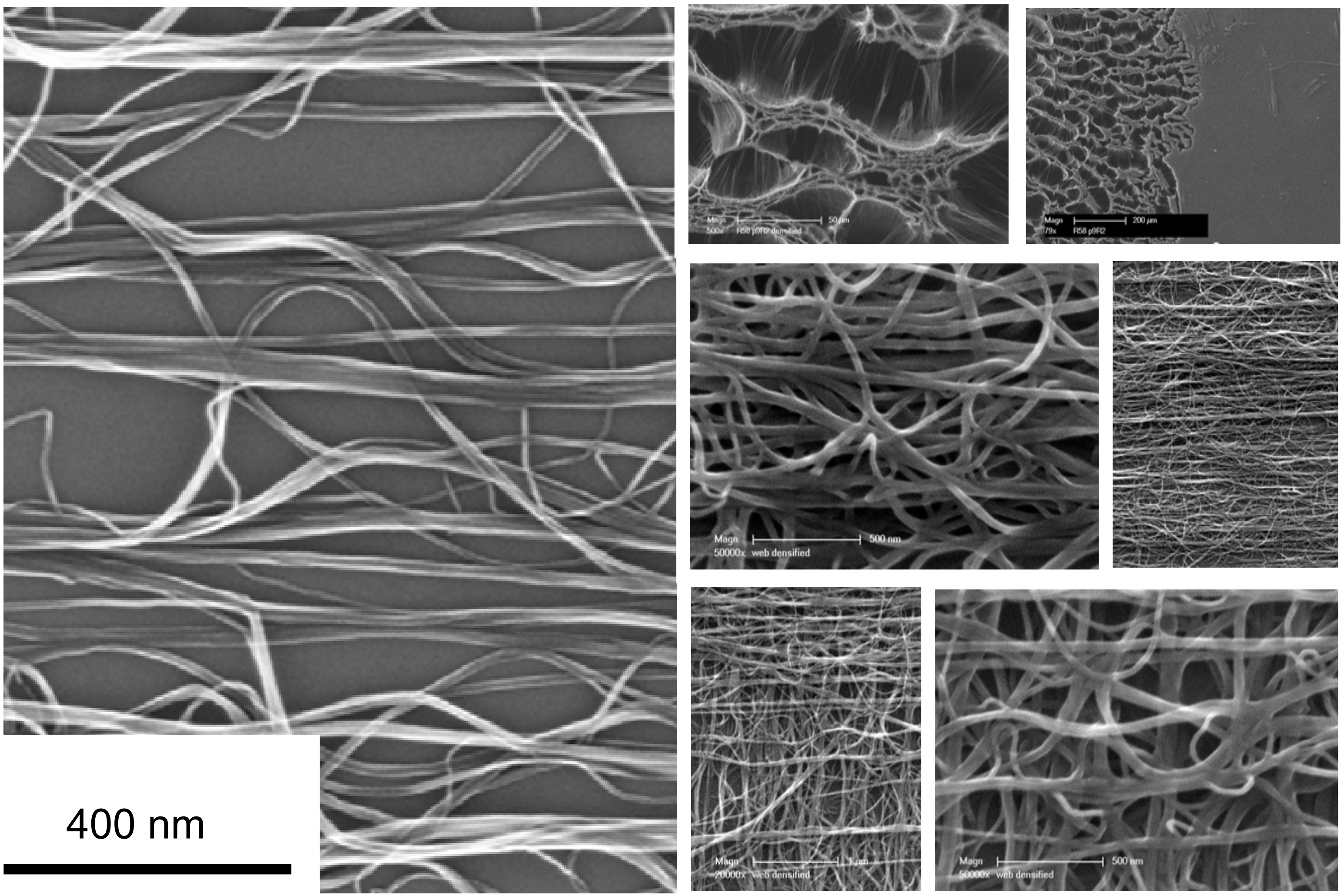
Nanowebs: Production and Properties

Strong, Transparent, Multifunctional, Carbon Nanotube Sheets, Mei Zhang, Shaoli Fang, Anvar A. Zakhidov, Sergey B. Lee, Ali E. Aliev, Christopher D. Williams, Ken R. Atkinson, Ray H. Baughman, *Science*, **309**, 1215, 2005.

NanoTech Institute Video of Hand Drawing



Fibrillar Structure of Densified Nanowebs



Selected Properties of Transparent CNT Webs

Data for Webs

Areal Density/(mg/m^2):

- As-produced ~27

Volumetric density/(kg/m^3):

- As-produced ~1.5

Gravimetric strengths/(MPa/(g/cm^3))*:

- As-produced - 120 and 144
- Densified: 465
- Densified, biaxially oriented: 175

Surface Resistivity/Ω:

- As-produced and densified ~750

Work Function/eV:

- Densified ~5.2

* Tensile tests on sheets performed in the direction of CNT alignment, ie, the draw direction

Comments and Comparisons

Extremely light:

- Aerogel, density of air ~ 1 kg/m^3

Gravimetric Strength/(MPa/(g/cm^3)):

- Mylar® & Kapton® ~160
- Ultra high strength steel sheet ~125
- Aluminium alloy ~250

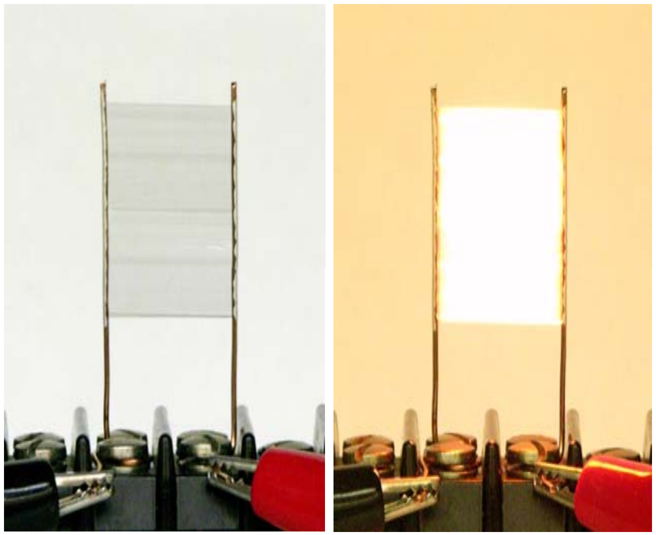
Surface Resistivity:

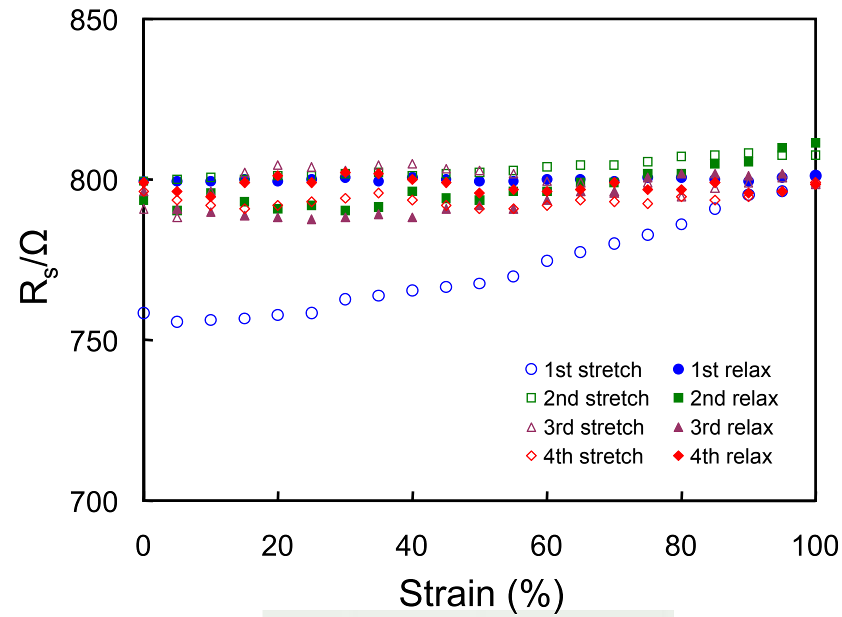
- Unaffected by ~360-fold densification
- Conductivity anisotropy ~50-70 before densification and 10-20 after.

Work Function/eV:

- Slightly higher than ITO (~4.5)

Applications of NanoWebs:
Polarised Light Emission, Appliqués, Actuators



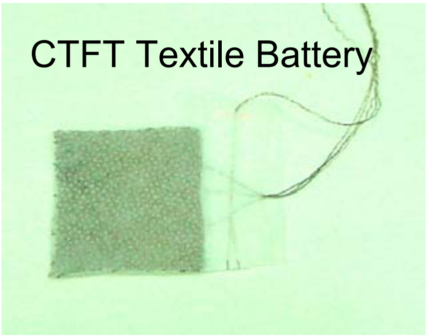


Summary

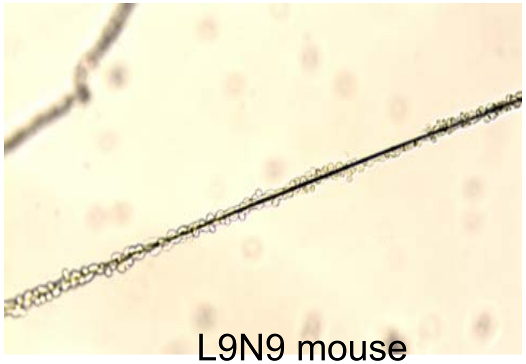
CTFT R&D is in the context of Smart Textiles

Future Directions:

- Scale-up production
- Improve quality of the yarn and web
  - Industrialise the technology
  - Develop properties further
- Applications
  - Refine existing technologies
  - Develop new technologies
    - Flexible electronics
    - Sensors - chemical, mechanical, biological
    - Mechanical - strength, impact resistance
    - Electrodes – OLEDs, flexible batteries, supercapacitors


CTFT Textile Battery


Commercial product


L9N9 mouse fibroblast cells growing on a MWNT yarn

Team from CTFT & CAH

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CSIRO

Thank You

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