Multifunctional Nanocomposite with Healing and Health Monitoring Capabilities

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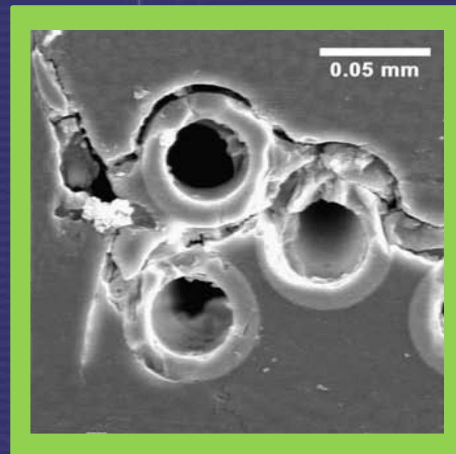
Applications in Space Exploration

- **Composites for Structural Materials**
  light weight → mass saving → cost effective
- **Applications**
  crew cabin primary & secondary structures
  heavy lift launch systems
  rovers
- **Concerns**
  damage tolerance → mass saving loss
- **In-Space Repair**
  enable safe, reliable long duration
  space exploration
  - additive manufacturing
  - self repairable systems

Self Healing Approaches

- **Variety of Repair Mechanism**
  - ❖ Irreversible Systems
  - ❖ Covalently Bonded Polymers
  - ❖ Non-Covalently Bonded Polymers
  - ❖ Ionomers
  - ❖ Hydrogen Bonded Polymers
  - ❖ Metal Ligand Coordination Polymers
  - ❖ Nanoparticle Diffusion
- **Irreversible Systems**
  - ❖ Encapsulation Techniques
  - ☺ Autonomous, quick, damage inspection
  - ☹ Single event, loading, complex machining
- **Reversible Systems**
  - ❖ Repolymerization Techniques
  - ☺ Multiple healing, independent of loading, allows complex shapes
  - ☹ Not autonomous, healing timeframe

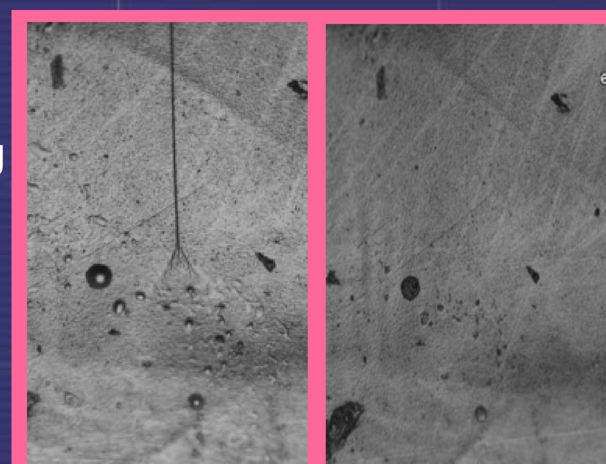


G.J. Williams, Composites: Part A, 2009

Hollow Fiber

Microencapsulation

B.J. Blaiszik, Polymer, 2009



Re-Polymerization

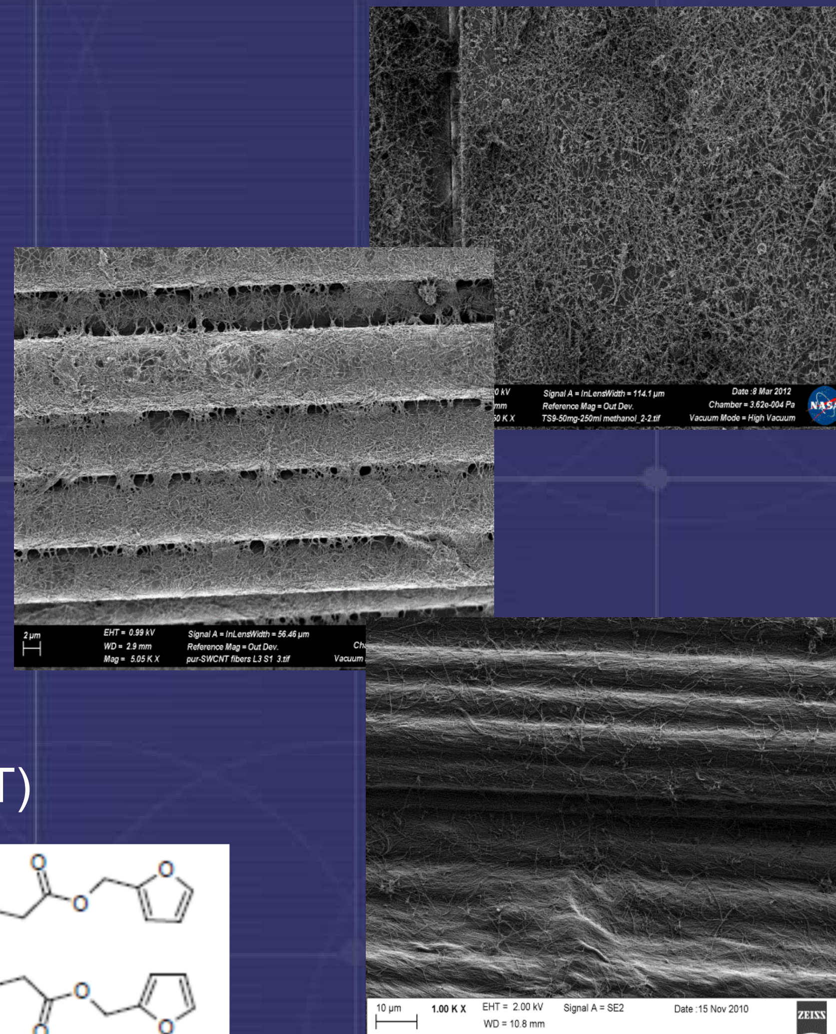
J.S. Park, Composites Sci. Technol. 2009

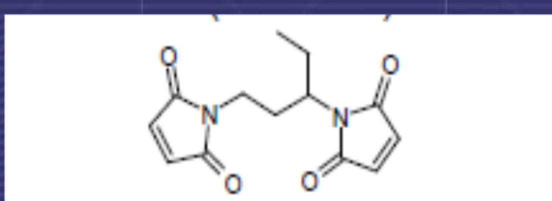
Multi-functional Nanocomposites

- **Reversible Polymerization Induced Healing**
  - photo-induced reversible crosslinking or thermal activation
  - increase lifetime performance
- **Thermally Activated Re-Polymerization**
  - reversible bond formation
  - retro- Diels Alder chemistry
- **Introduction of Multi-Functional Properties**
  - enhanced electrical conductivity
  - improved thermal management
  - radiation shielding/hardness
  - reduced gas permeation
- **Structural Health Monitoring**
  - damage detection
  - damage repair evaluation

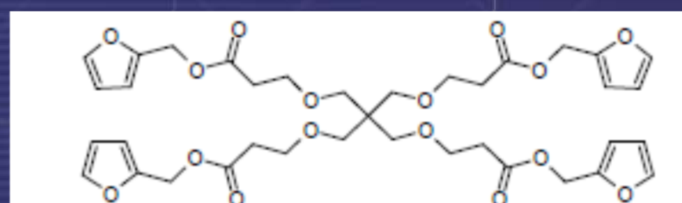
Composite Fabrication

- Carbon Fiber Coating
  - ❖ spraying dispersed CNTs
  - ❖ densification of spun MWCNTs
- Nanotube Chemical Modification
  - ❖ functionalization of SWCNTs & MWCNTs
  - ❖ furan & maleimide chemistries
- Composite Fabrication
  - ❖ $[0,60,-60]_{2s}$ fiber orientation
  - ❖ resin transfer molding/wet lay up
- Other Nano-additives
  - ❖ graphene, boron nitride nanotubes (BNNT)





2MEP (Bismaleimide)

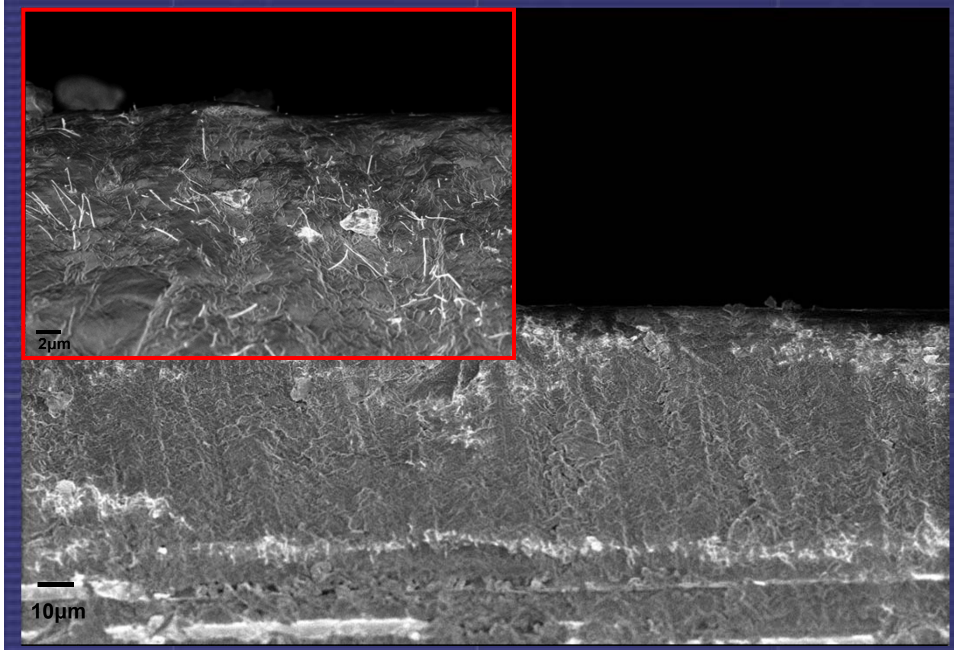


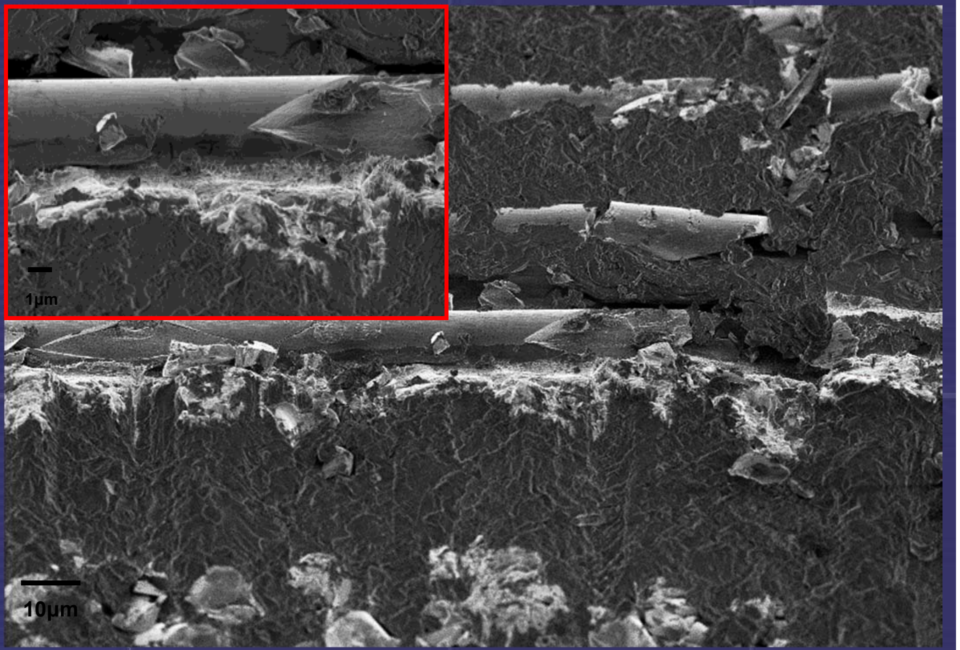
4F (Tetrafuran)

Composite Panels

Panel Number	Nano-Additive Inclusion
1	Control – carbon fiber only
2	Upper ply coated with spun MWCNT, lower 5 plies sprayed with MWCNTs
3	Spray coated fibers with Mitsui MWCNTs lot 061220-24
4	Spray coated fibers with Mitsui MWCNTs lot 061220-24
5	Spray coated fibers with Mitsui MWCNTs lot 05072001K28
6	Spray coated fibers purified laser SWCNTs
7	Unidirectional (0˚ orientation) spun MWCNTs on front side only
8	Unidirectional (0˚ orientation) spun MWCNTs on front side only
9	Bi-directional spun MWCNTs with dispersed purified HiPco SWCNTs
10	Bi-directional spun MWCNTs with dispersed purified PLV SWCNTs

Nanotube Residency

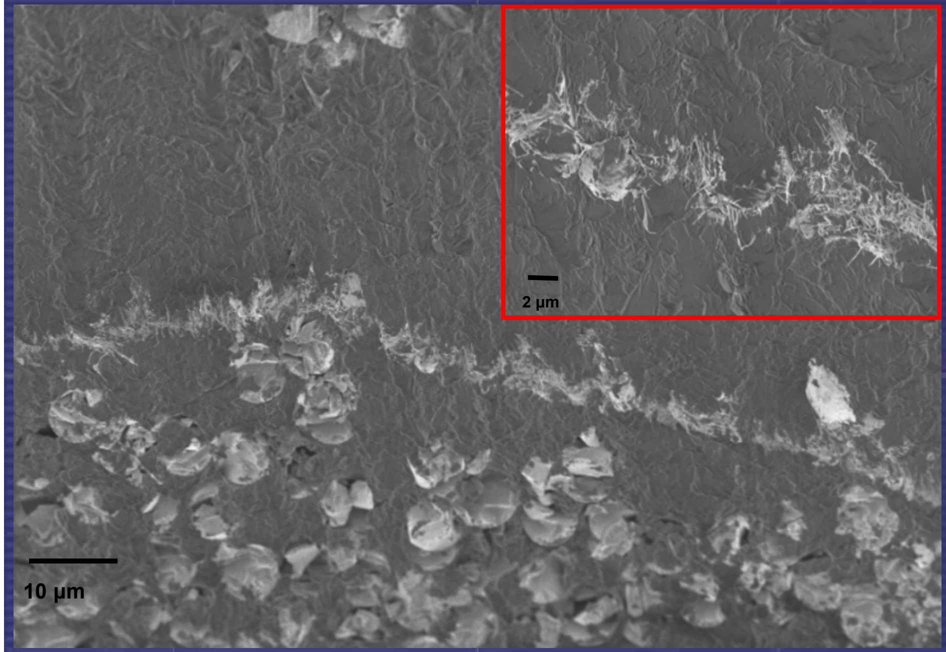


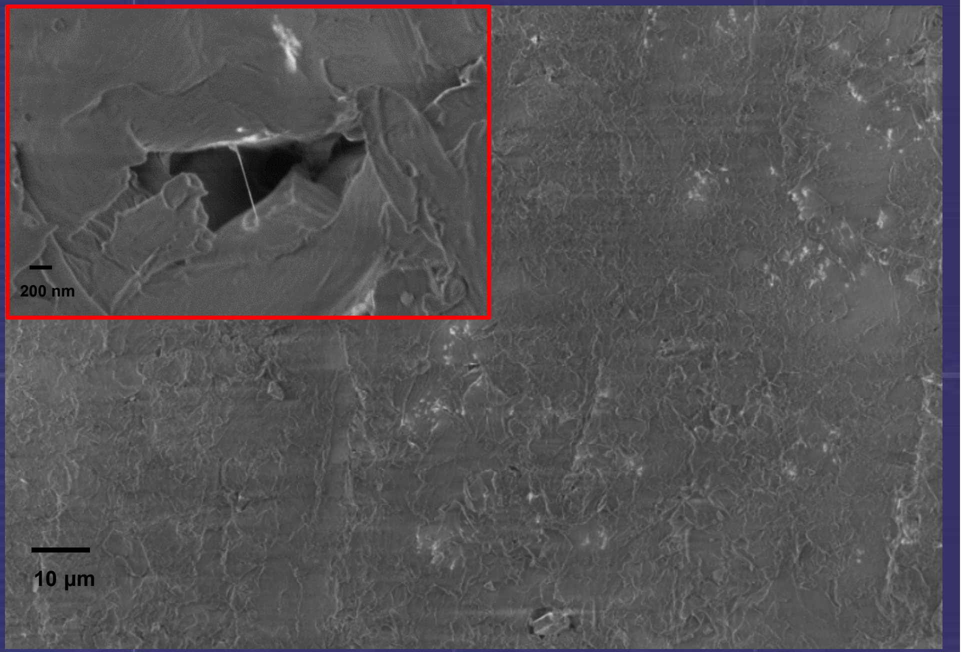


- MWCNTs show mixed behavior
- Some migrate into matrix, others remain in close proximity to fibers

- SWCNTs remain in close proximity to fibers

Nanotube Residency



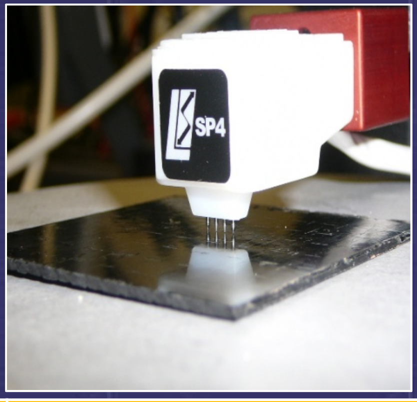


- s-MWCNTs stay highly intact and in close proximity to fiber

- SWCNTs directly dispersed in resin form small aggregates with matrix
- s-MWCNTs located near fibers

Electrical Properties

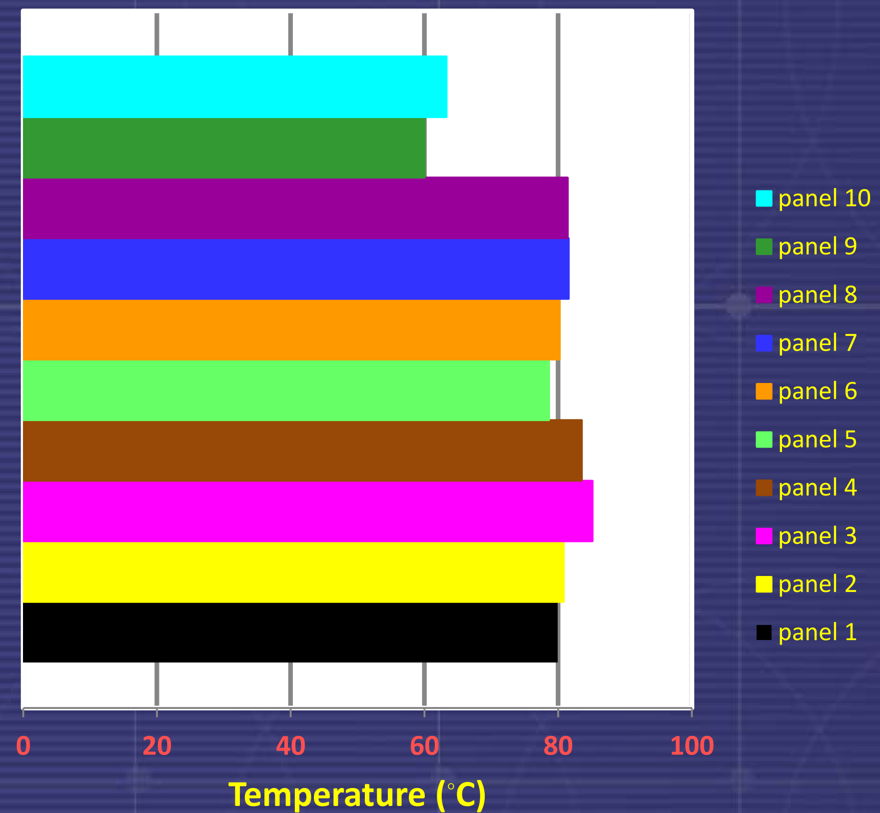
- Measured with 4-point probe in 2-point configuration
- Measured in 9 locations of each side of panel
- Lowest measurement reported
- Similar measurements were observed for through thickness measurements
- Greater loadings and better dispersion are expected to improve electrical conductivity
- Type specific CNTs would be most desirable



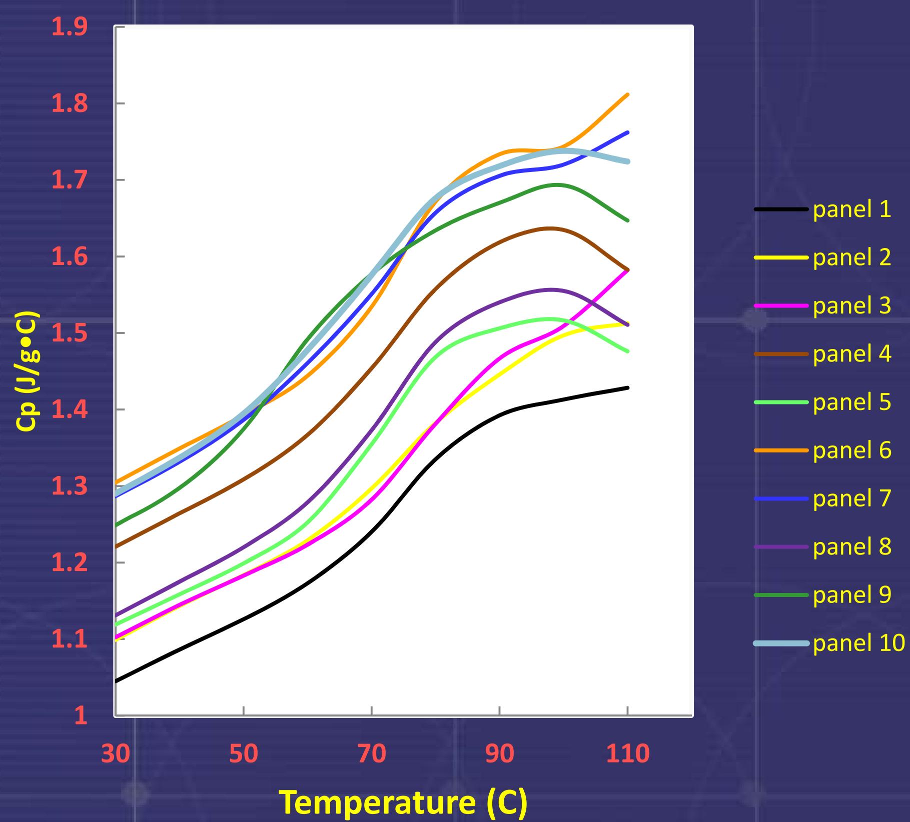
Panel	Surface Resistance (kΩ)
1	∞
2	∞
3	3.45
4	∞
5	3.00
6	∞
7	0.175
8	9.55
9	1.62
10	104.8

Thermal Properties

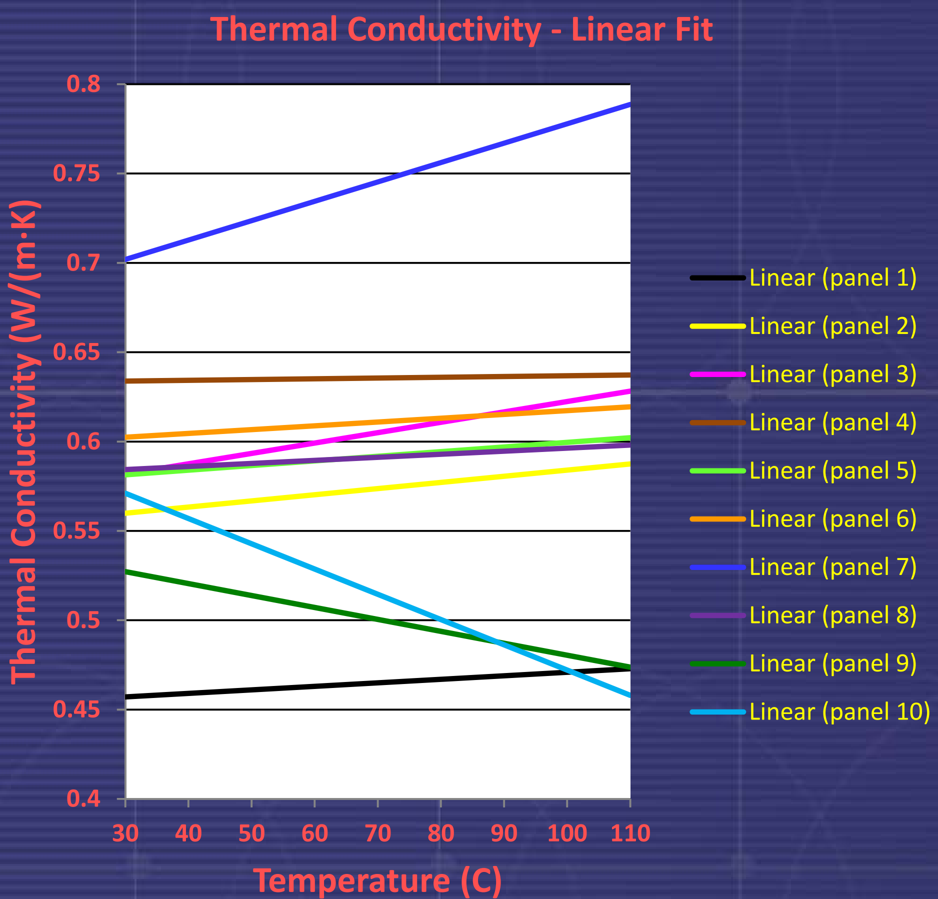
Glass Transition

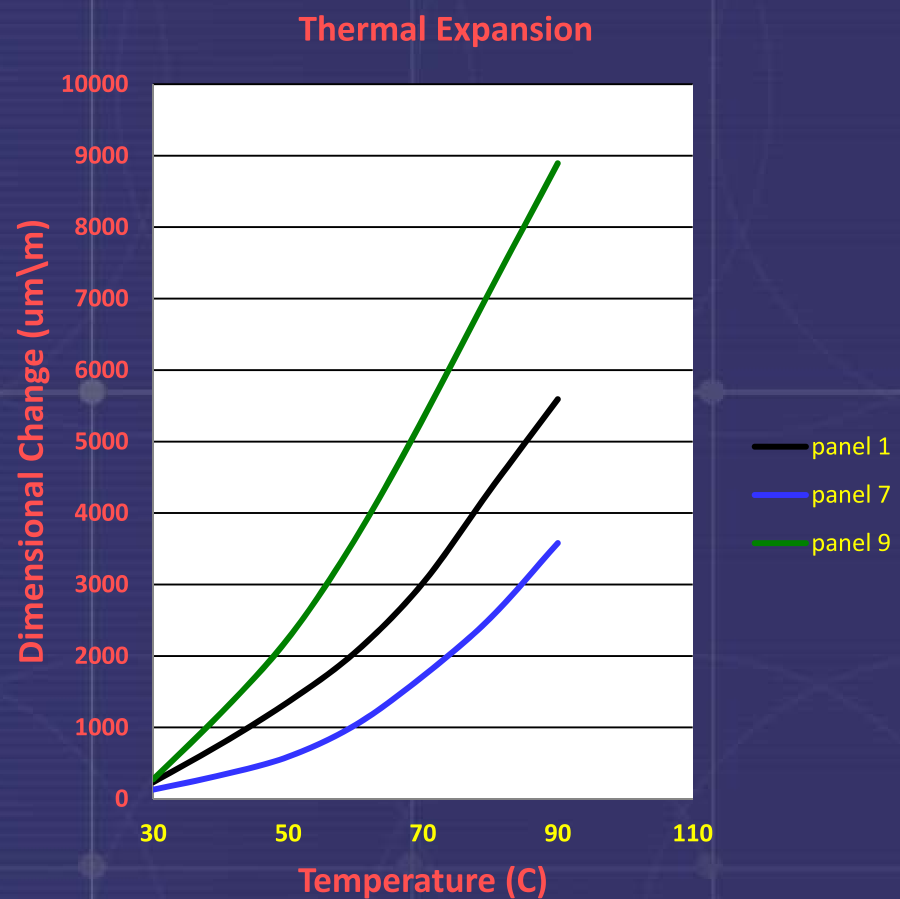


Heat Capacity



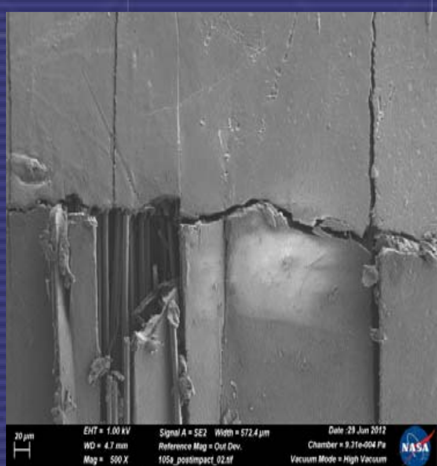
Thermal Conductivity

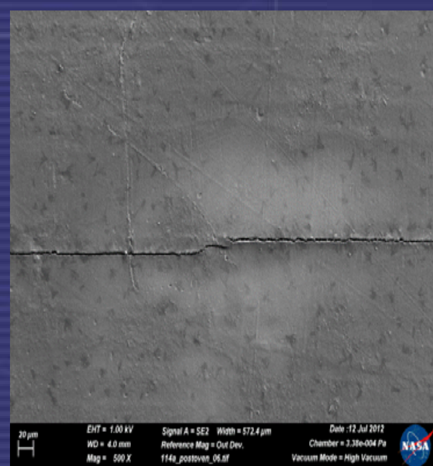


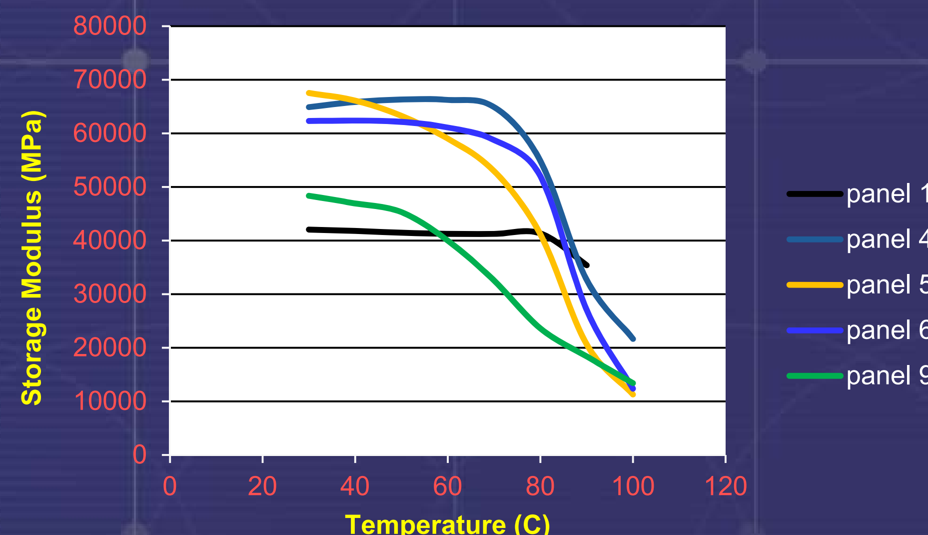


Mechanical Analysis

- Composite panels impacted with forces of x and y ft·lb
- Impacted surfaces inspected optical and electron microscopy
- Composites cut into smaller 10 x 50 mm specimens for DMA
- Addition of CNTs improves the mechanical properties of composite

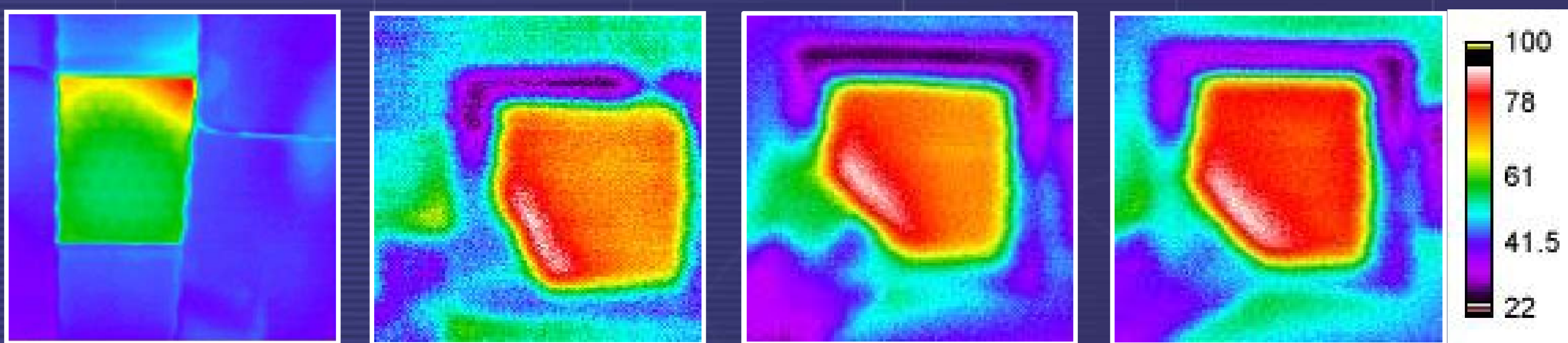






Microwave Heating

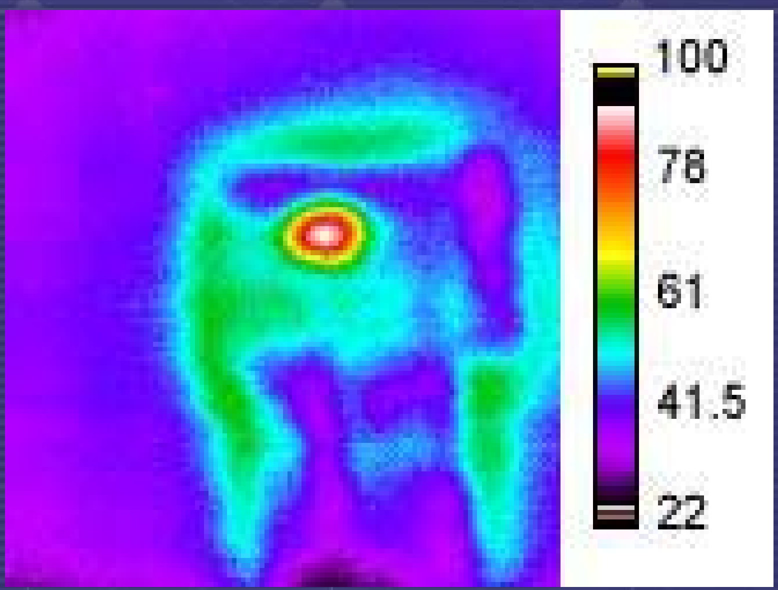
- Nanotubes well known to absorb microwave energy with high efficiency
- Intent is to use microwave absorption as means to supply thermal energy for repolymerization
- Additional improvement to thermal conductivity should also improve heating efficiency (power-time to reach desired temperature
- Composite panels exposed to 100W microwaves with in situ thermal imaging

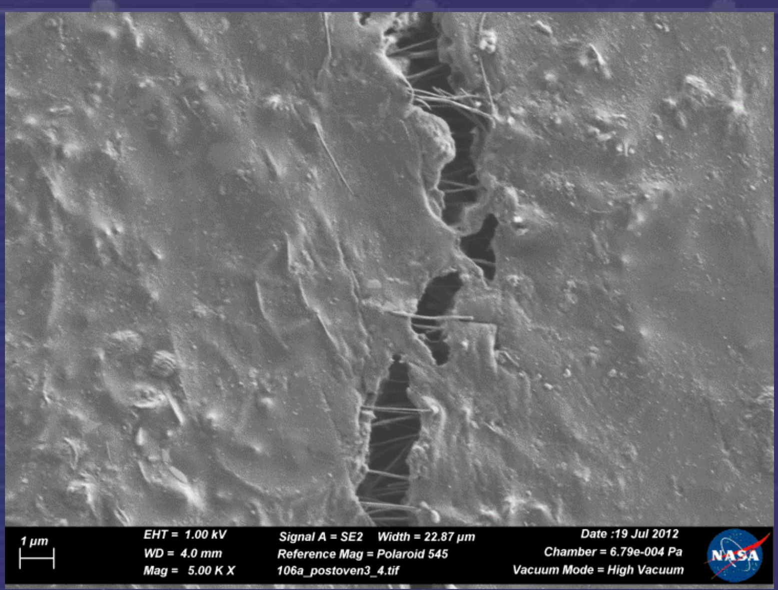


Control MWCNTs SWCNTs S-MWCNTs

Structural Health Monitoring

- Impacted panels show localized heating in area of impaction
- Localized hot spot due to exposed CNTs that bridge cracks
- Damage visible with greater resolution than flash thermography – possible tool for damage inspection
- Goal is to used localized heating for real time health monitoring





Conclusions

- Nanocomposites fabrciated using a variety of carbon nanotube materials
- Addition of CNTs introduces multi-functionality into composite increasing electrical and thermal conductivity while enhancing strength
- CNTs may have interactions with polymer matrix facilitating bond dissociation
- Microwave exposure of composite shows improved heating efficiency
- Microwave heating with in-situ thermal profiling can be used for damage inspection and possible health monitoring
- Better control of dispersion is expected to further improve properties

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