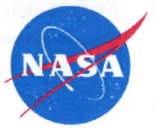
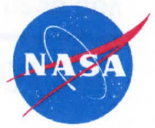


Magic Molecules: Material Innovations for Lightweight, Adaptive, and Multifunctional Structures

Dr. Ajay Misra
NASA Glenn Research Center
Cleveland, OH 44135

Presented at the CAFÉ Electric Aircraft Symposium VI, Santa Rosa, CA, April 27-28, 2012

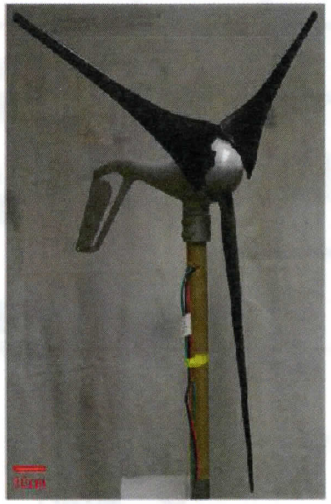


Material Innovations

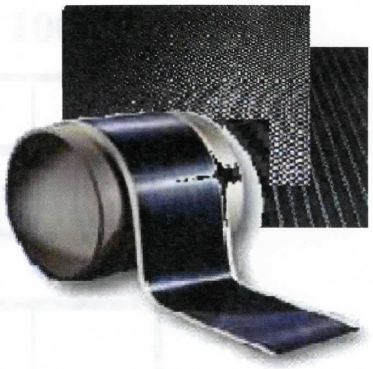
- Composites reinforced with nanotubes, nanofibers for improving structural properties
- Nanotube reinforced composites for enhancement of functional properties (e.g., thermal and electrical conductivity, damping)
- Adaptive structures based on smart materials, including shape memory materials and superelastic materials
- Self healing materials
- Thin, flexible, and mechanically strong aerogels
- Multifunctional structures incorporating a wide range of materials

Carbon Nanotubes – Where Are We Today ?

CNT Reinforced Polymer in LockHeed Martin's Lighting II Aircraft Wingtip Fairing (Non-load bearing structure)



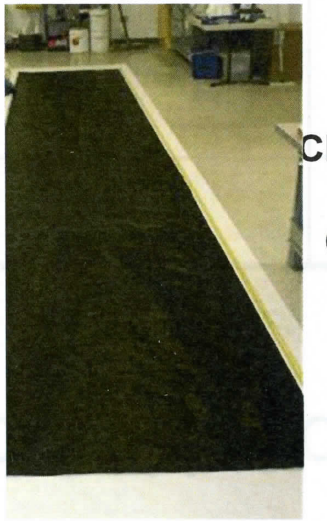
Wind Turbine Blade with CNT (CWRU)



CNT Sheets, Fabric and Wire (*Nanocomp, General Nano, FSU*)

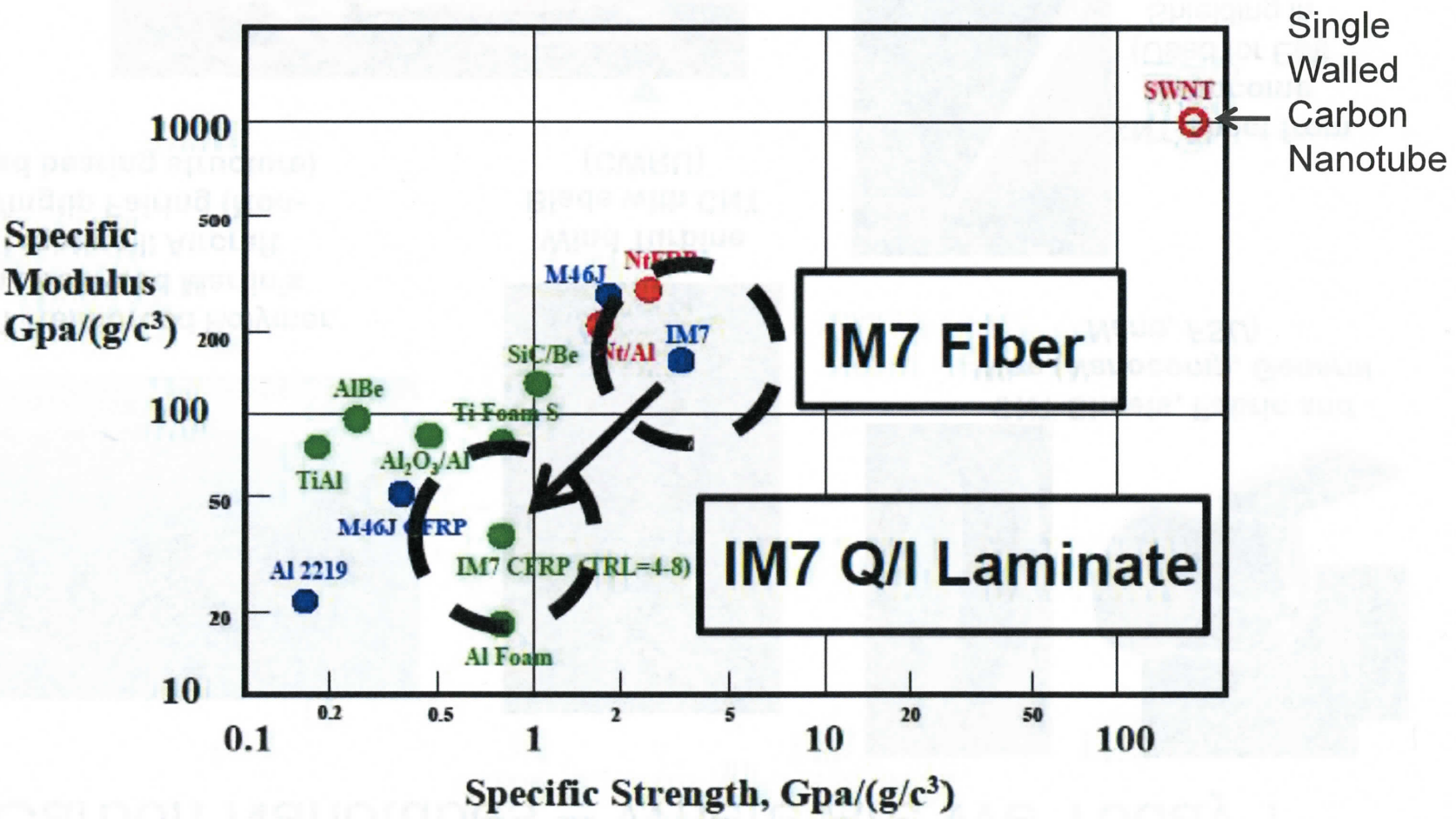
Lightweight Cables

Nanocomp, Inc.



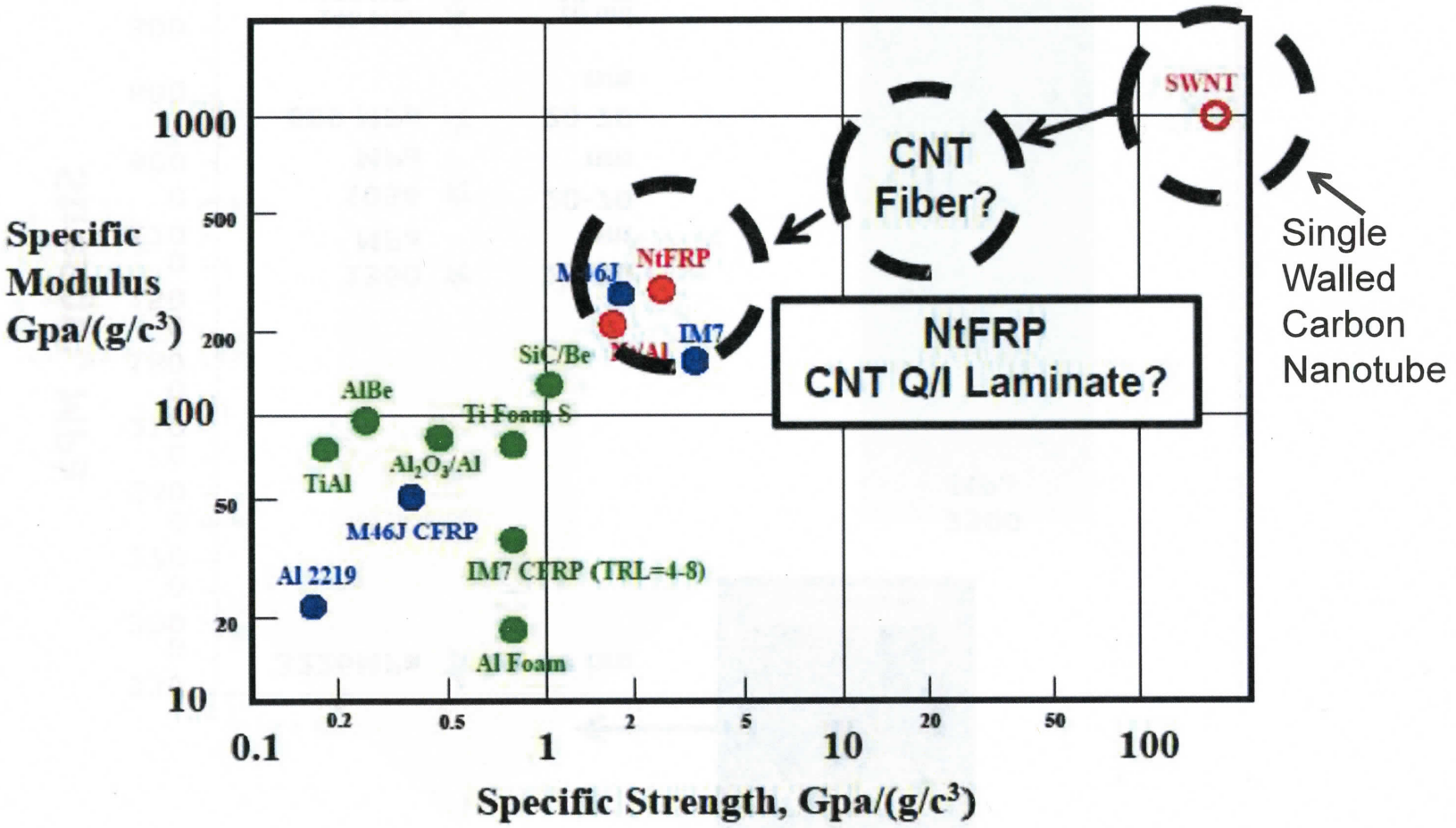
CNT Sheet from Nanocomp (Used for EMI Shielding in NASA's Juno Spacecraft)

Superior Strength of Carbon Nanotube



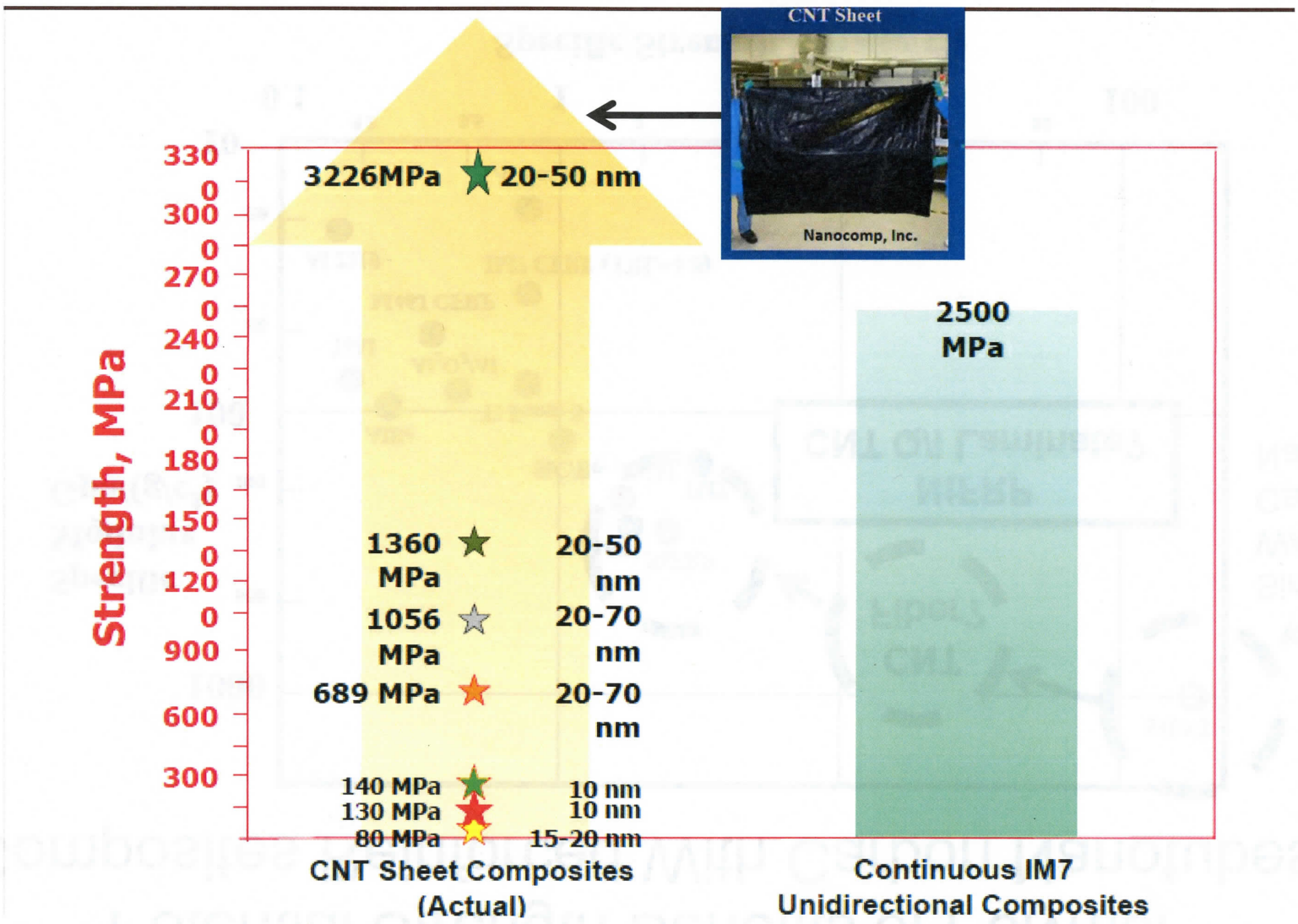
Harris, Shuart, Gray, NASA TM 211664, 2002

Potential Strength Benefits of Polymer Composites Reinforced With Carbon Nanotubes



Harris, Shuart, Gray, NASA TM 211664, 2002

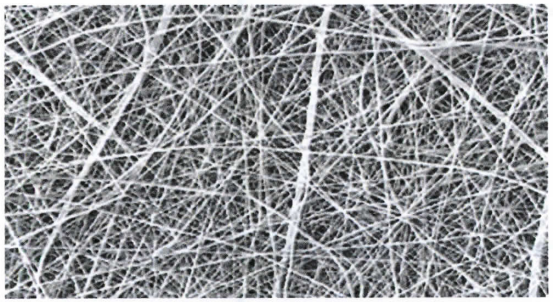
CNT Sheet Composite Vs IM7 Composite

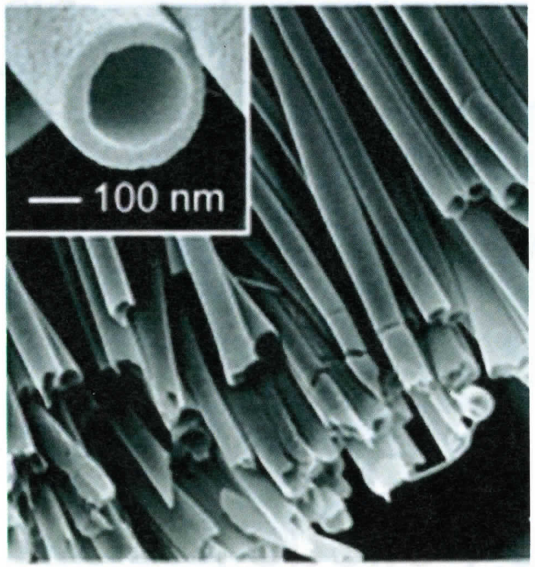


Cheng, Wang, Zhang, and Liang, "Functionalized Carbon Nanotube Sheet/Bismaleimide Nanocomposites: Mechanical and Electrical Performance Beyond Carbon-Fiber Composites," *Small*, 6(6), 763-763 (2010).

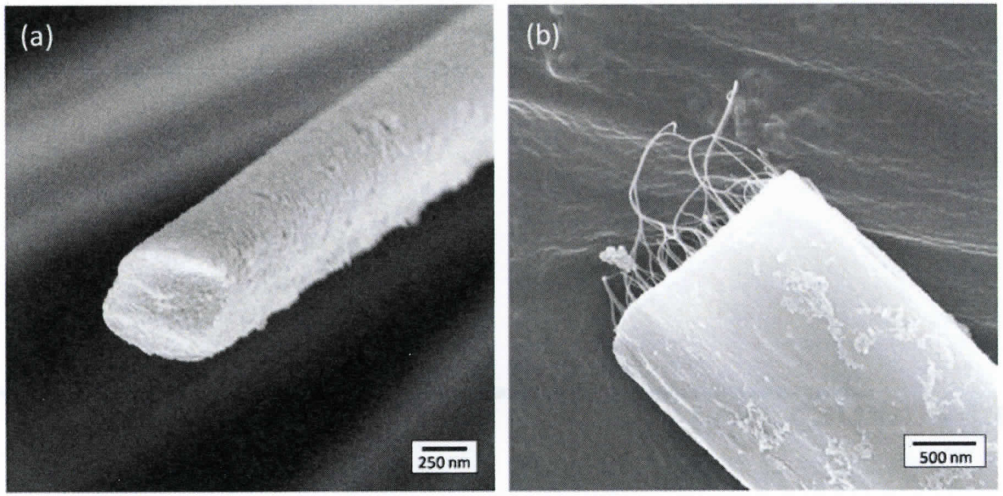
Fibers Incorporating Nanotubes

Polymer – CNT Nanocomposite Fiber By Electrospinning



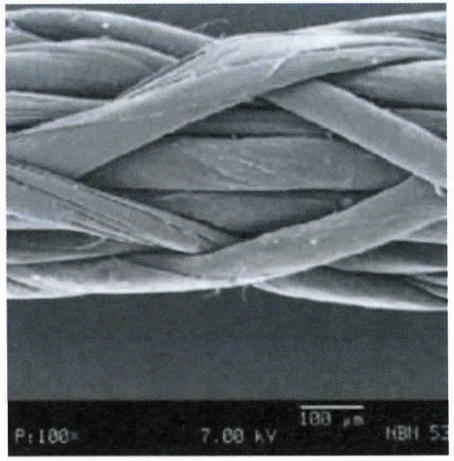


TISSUE ENGINEERING
Volume 12, Number 5, 2006

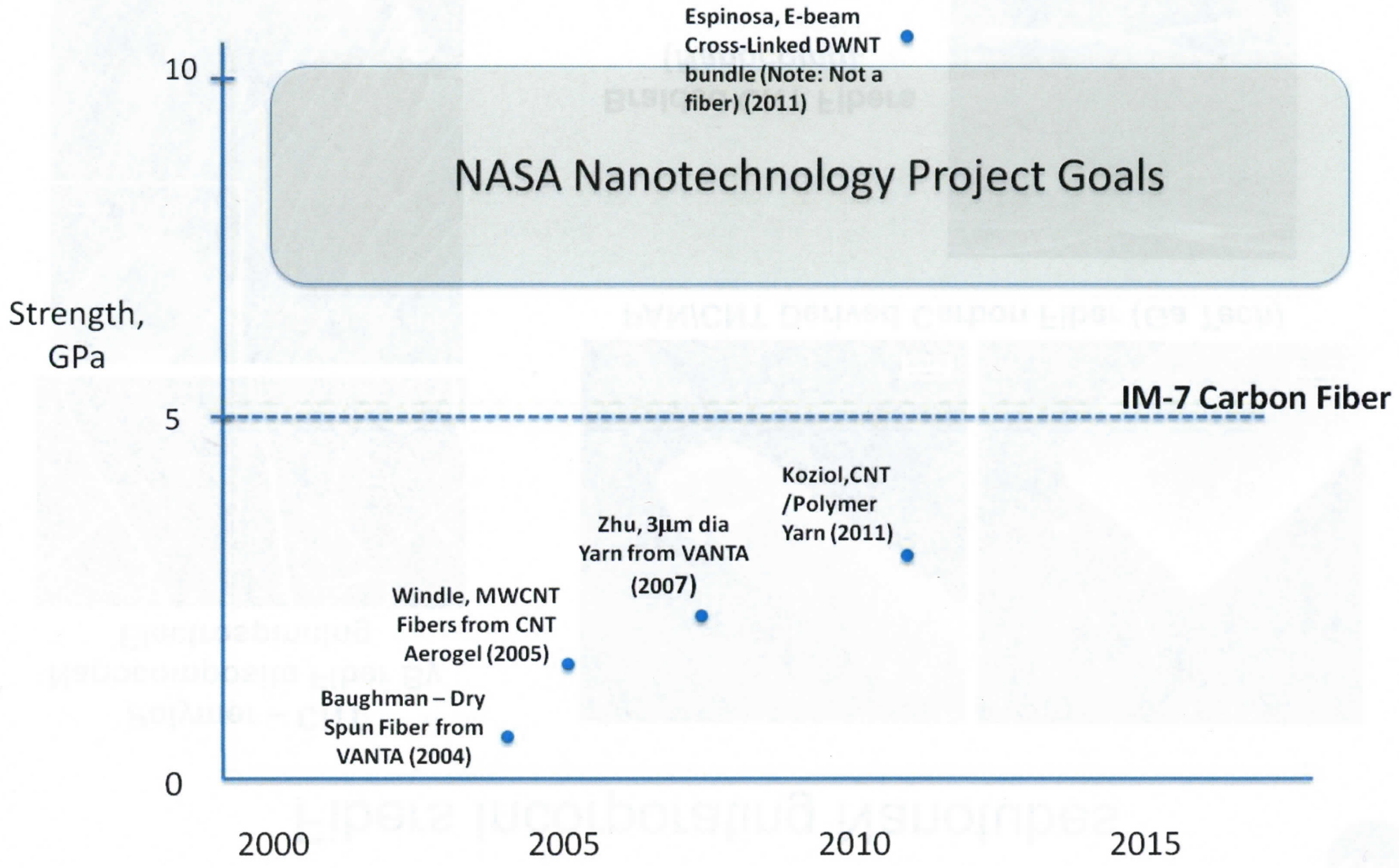


PAN/CNT Derived Carbon Fiber (*Ga Tech*)

Braided CNT Fibers (*Nanocomp*)

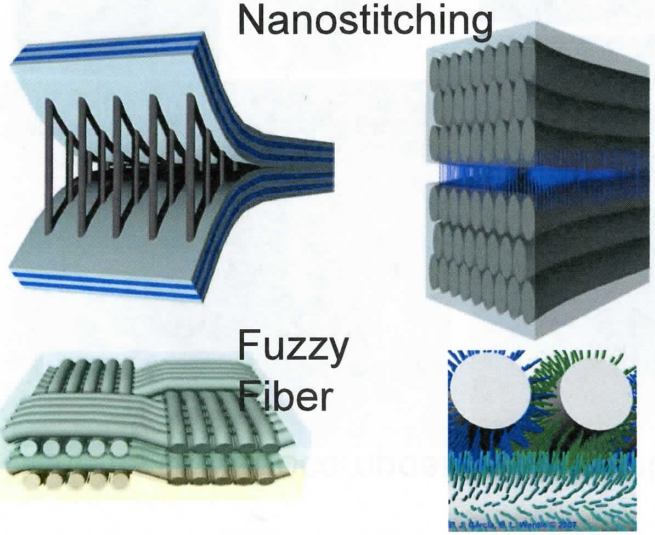


Tensile Strength of CNT- Based Fibers



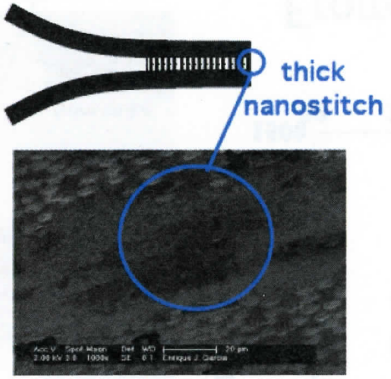
Enhancement of Composite Mechanical Properties by Incorporation of Nanotubes

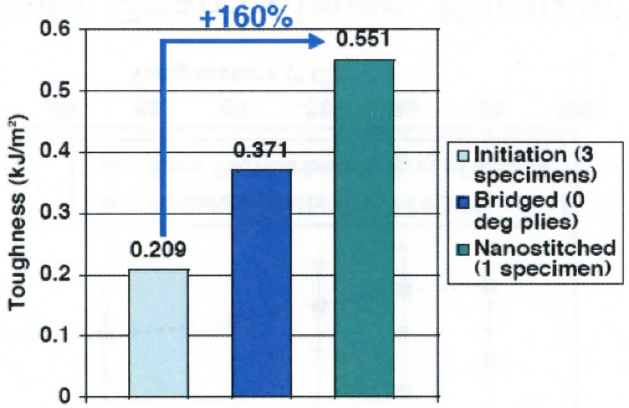
Nanostitching

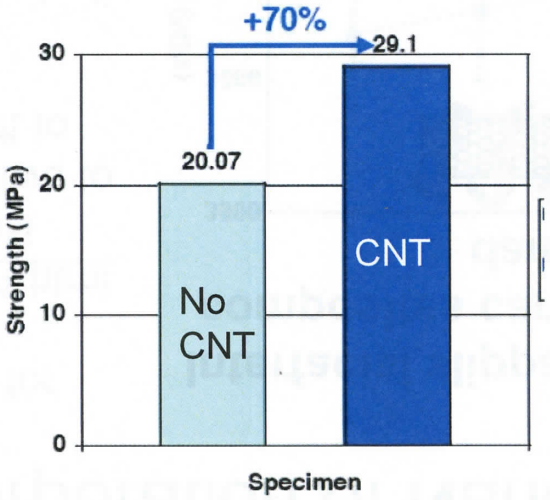


Fuzzy Fiber

MIT – Wardle et al.







Increase in Interlaminar Toughness Through Incorporation of Aligned Carbon Nanotubes

Nanotubes used to enhance properties of continuous fiber reinforced polymer composites

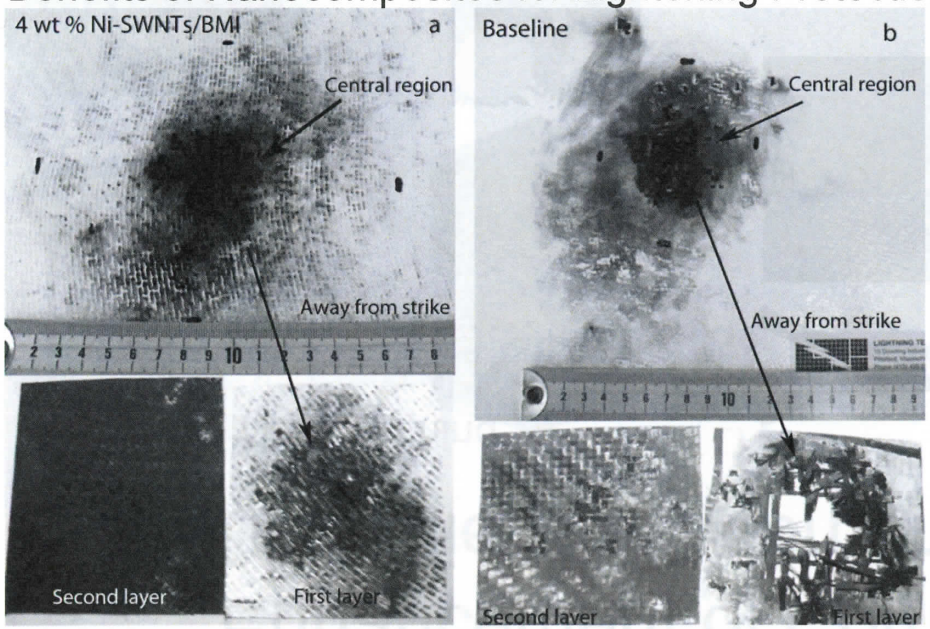
Airbus – Nanocomposites for Future Airbus Airplanes

Enhancement of Composite Functional Properties By Incorporation of Nanotubes

TUESDAY, APRIL 03, 2012

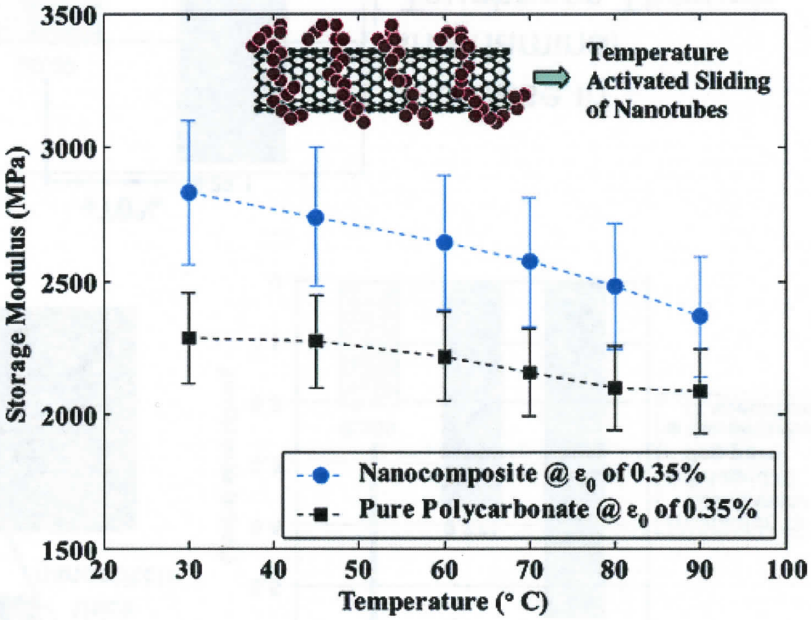
US Patent 8146861 - Lightning protection for aircraft using CNT material
http://www.freepatentsonline.com/8146861.html
This patent from Airbus Deutschland GmbH teaches a carbon nanotube based alternative to aluminum or copper-mesh skins for aircraft to protect from lightning strikes.

Benefits of Nanocomposites for Lightening Protection



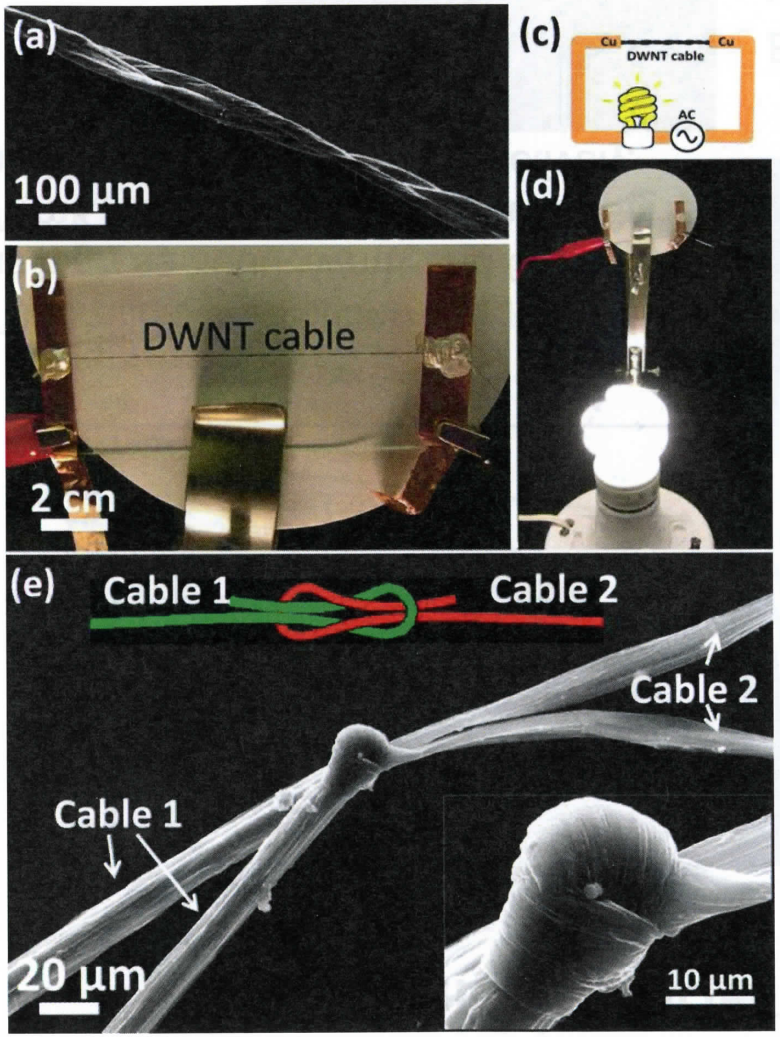
Rice Univ: *Adv. Funct. Mater.* ***2011, 21, 2527–2533***

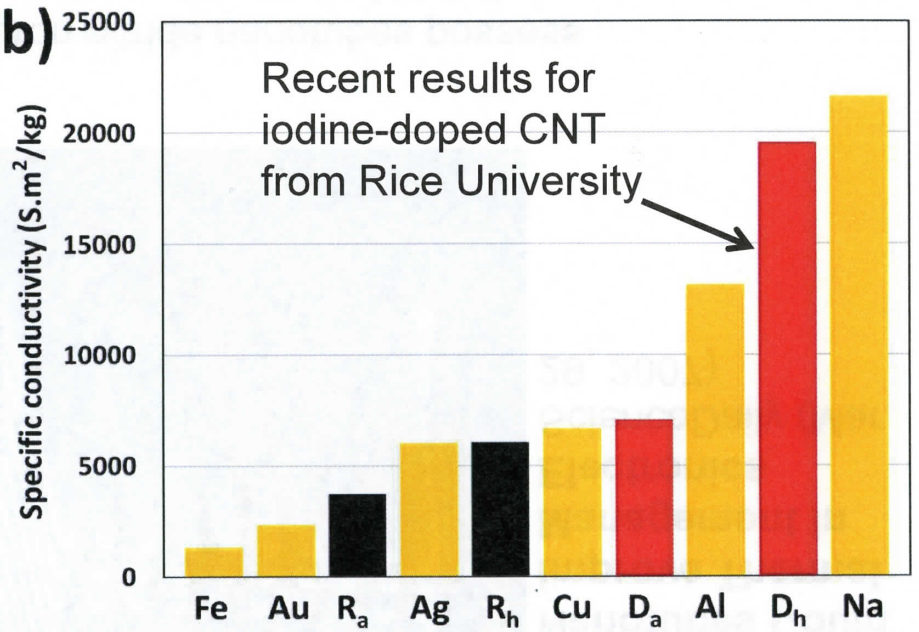
Interfacial slippage/sliding in CNT composites can enable vibration damping



From Suhr, Zhang,Ajayan, Karatkar *Nano. Lett.* **2006**, *6 (2)*, 219-23

Nanotube Cables Hit a Milestone: As Good as Copper

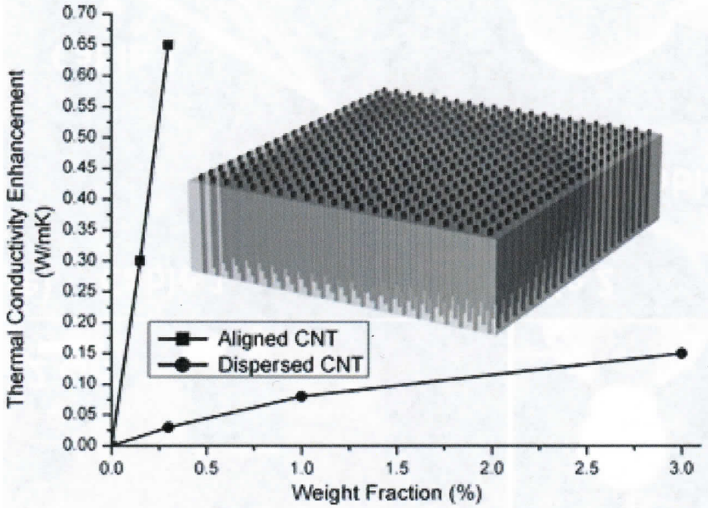




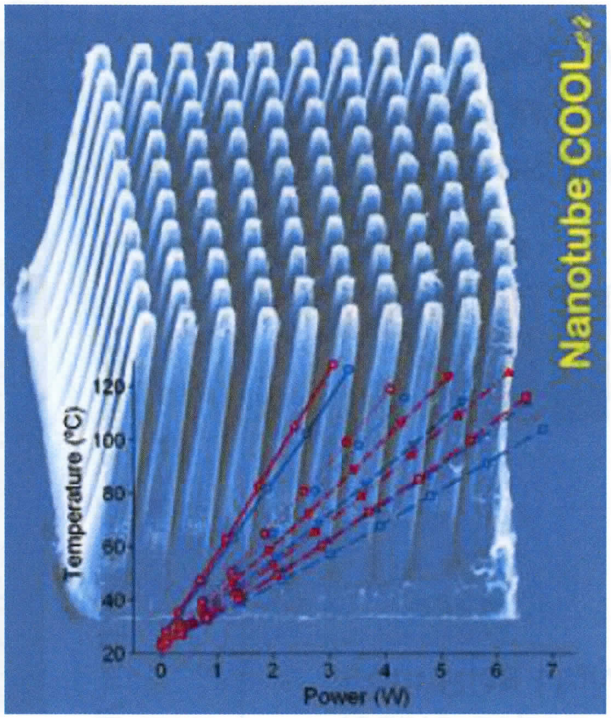
Carbon nanotubes with same electrical conductivity as Cu developed by researchers at Rice University

Potential for lightweight electrical wirings, multifunctional conductive structures, and high power density electric motors

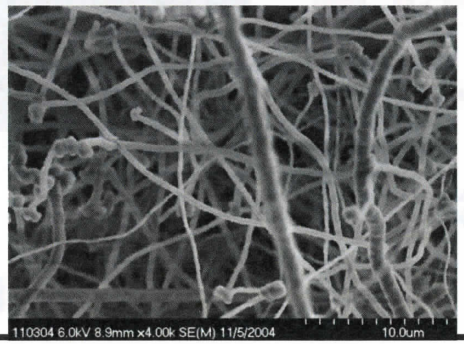
Thermal Management Using Nanotubes



Theoretical predictions suggest values as high as 3000 W/mK and 6600 W/mK] for individual multiwalled CNTs and single-wall CNTs, respectively.

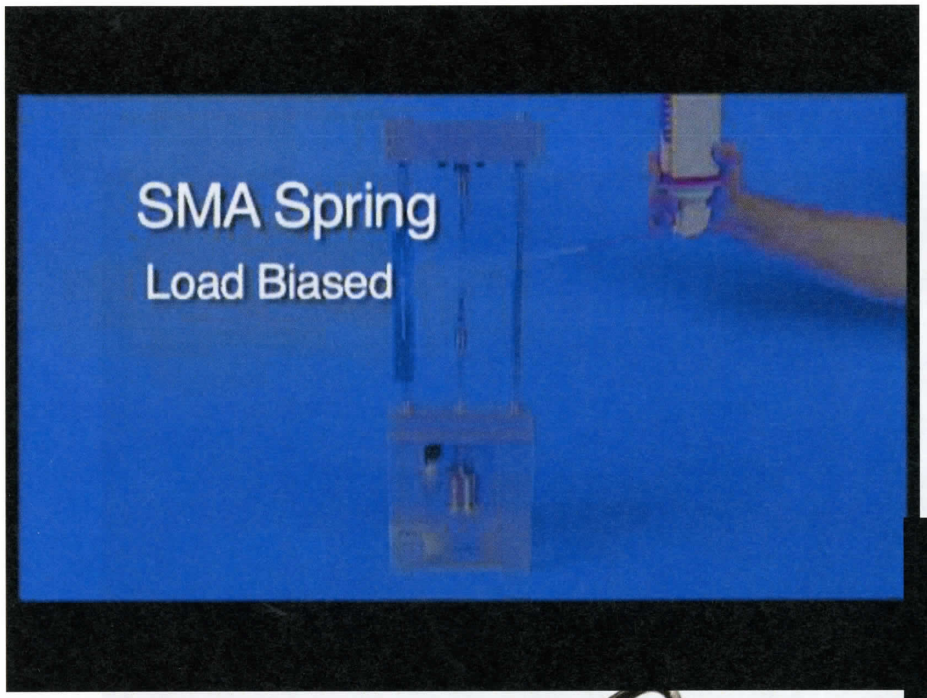


Cool Findings -- Nanotubes Could Improve Thermal Management In Electronics
ScienceDaily (Mar. 29, 2007)

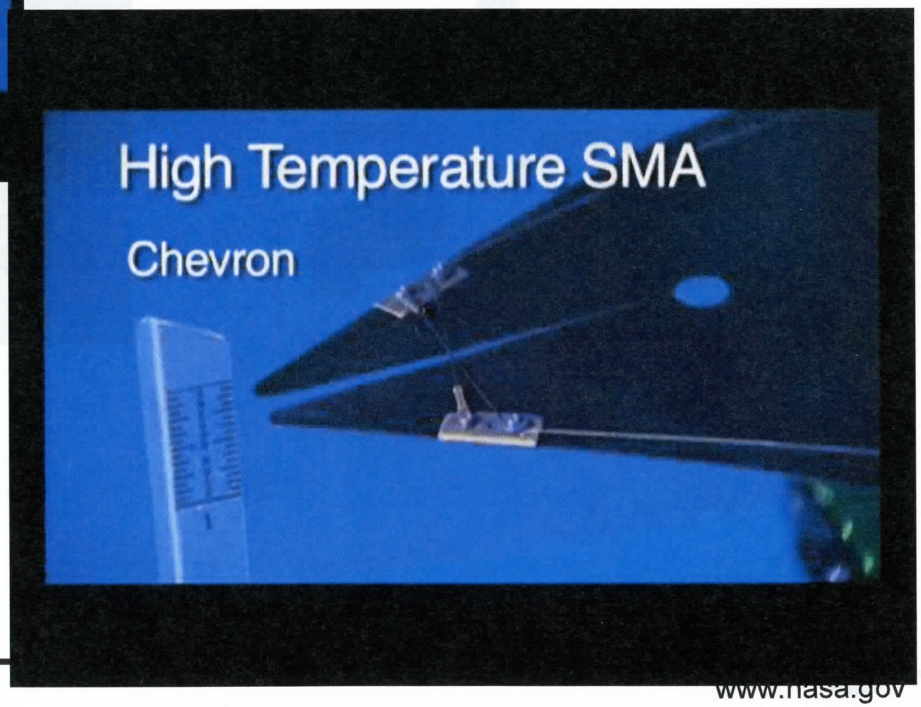


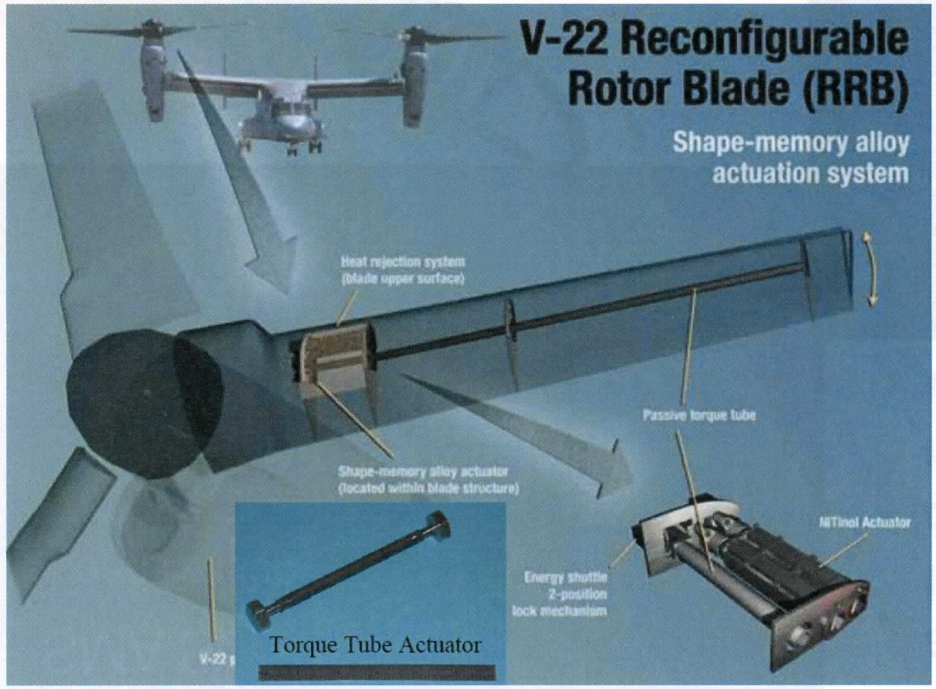
Boron nitride nanotubes possess unique combination of high thermal conductivity and electrical insulation characteristics

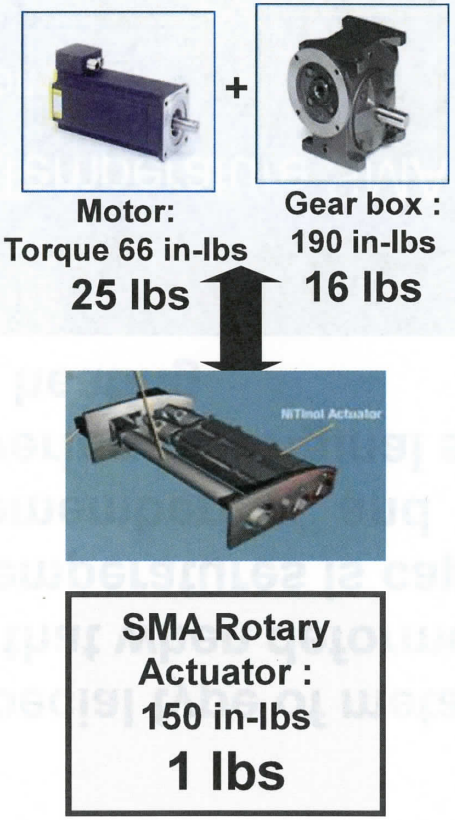
Actuation Based on Shape Memory Alloys



- **A special type of metallic alloy that when deformed at low temperatures is capable of "remembering" and recovering its original shape upon heating**




V-22 Reconfigurable Rotor Blade (RRB)
Shape-memory alloy actuation system
Heat rejection system (blade upper surface)
Passive torque tube
Shape-memory alloy actuator (located within blade structure)
NiTinol Actuator
Energy shuttle 2-position lock mechanism
Torque Tube Actuator

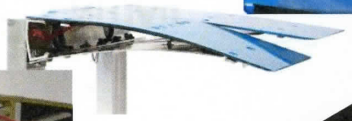

+
Motor:
Torque 66 in-lbs
25 lbs
Gear box :
190 in-lbs
16 lbs
NiTinol Actuator
SMA Rotary Actuator :
150 in-lbs
1 lbs

SMA-enabled adaptive technology

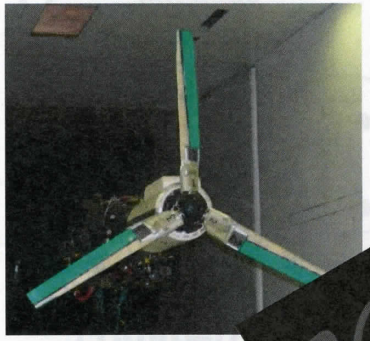
Wing Tip

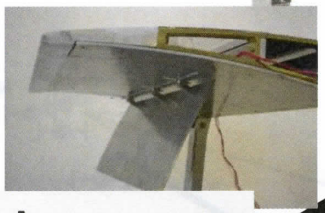
Future Applications?

Variable Camber LE/TE



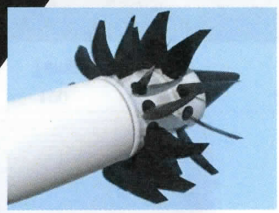
Reconfigurable Rotor Blade



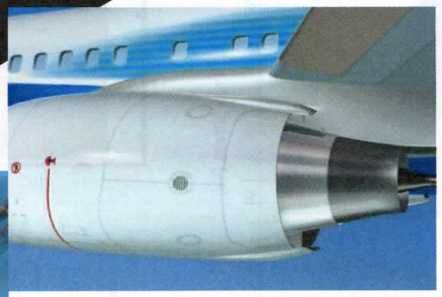


Aerogurney

2006 2010 2016



Variable Turbine

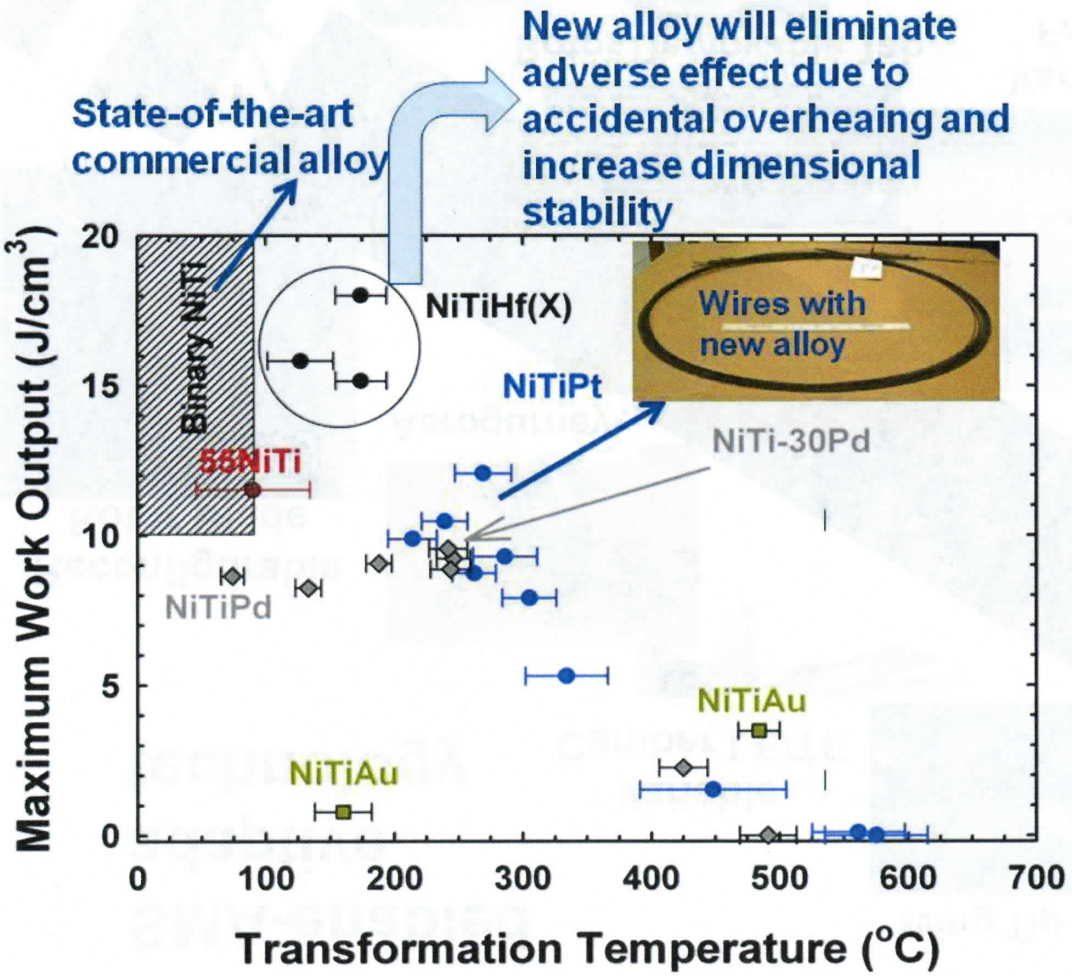


Variable Area Fan Nozzle

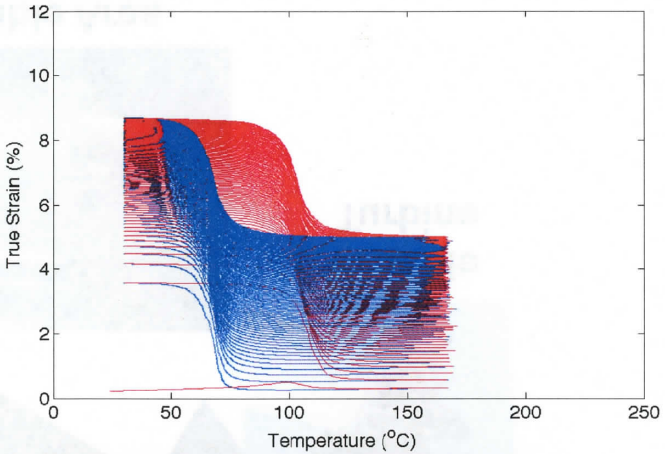
Rotor Deployable Tab

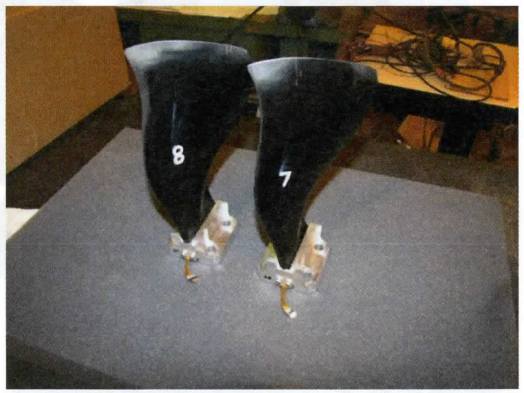
Variable Geometry Chevron

Current NASA Research on Shape Memory Alloy



Modeling to Predict Performance and Enable 3-D Actuation

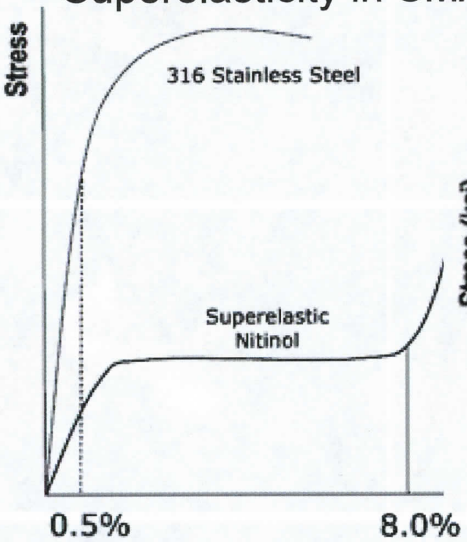


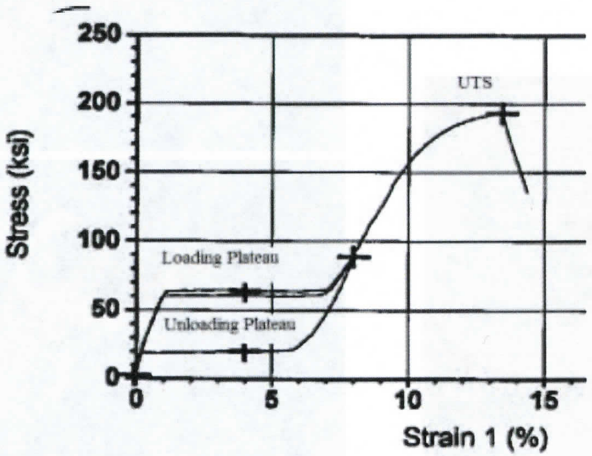


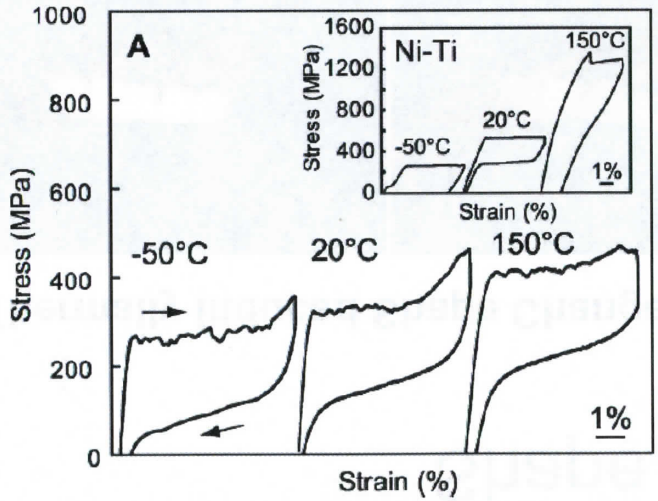
Shape Change for Rotating Fan Blade

Superelastic Materials

Superelasticity in SMA class of Materials



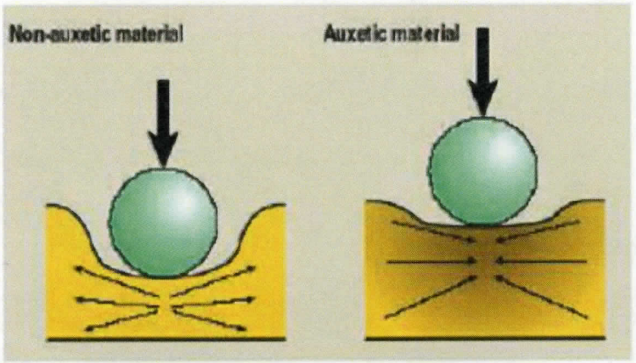


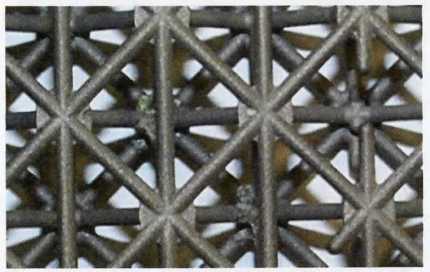


T Omori et al. Science 2011;333:68-71

New Fe-Mn-Al-Ni Superelastic Material

Application to Lattice and Auxetic Structures

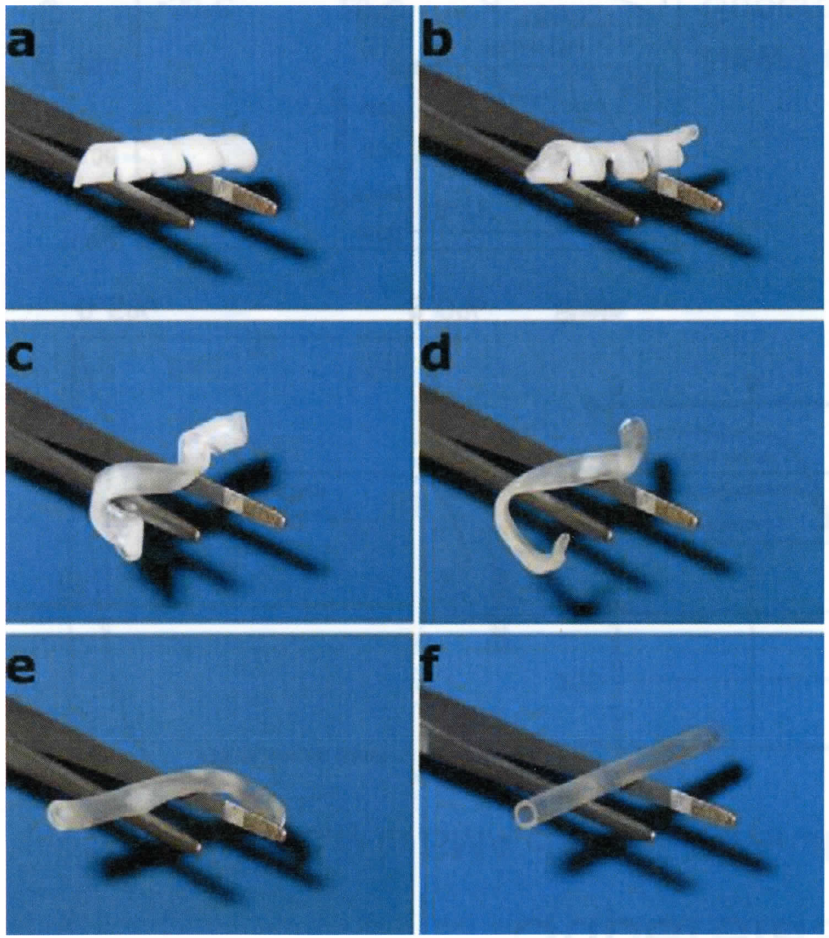




Expands capabilities into three dimensional actuation, new flap and winglet designs, variable geometry inlets and nozzles, as well as highly-impact resistant structures. Takes advantage of superelastic nature of SMAs

Shape Memory Polymers

Thermally Induced Shape Change

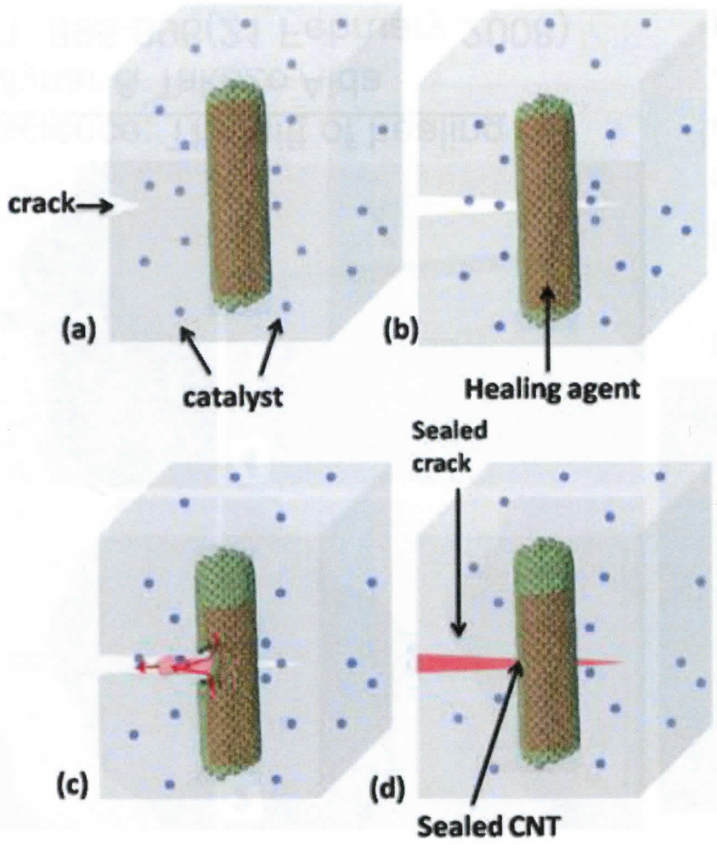


Langer, R., and Tirrell, D. A., *Nature (2004)*

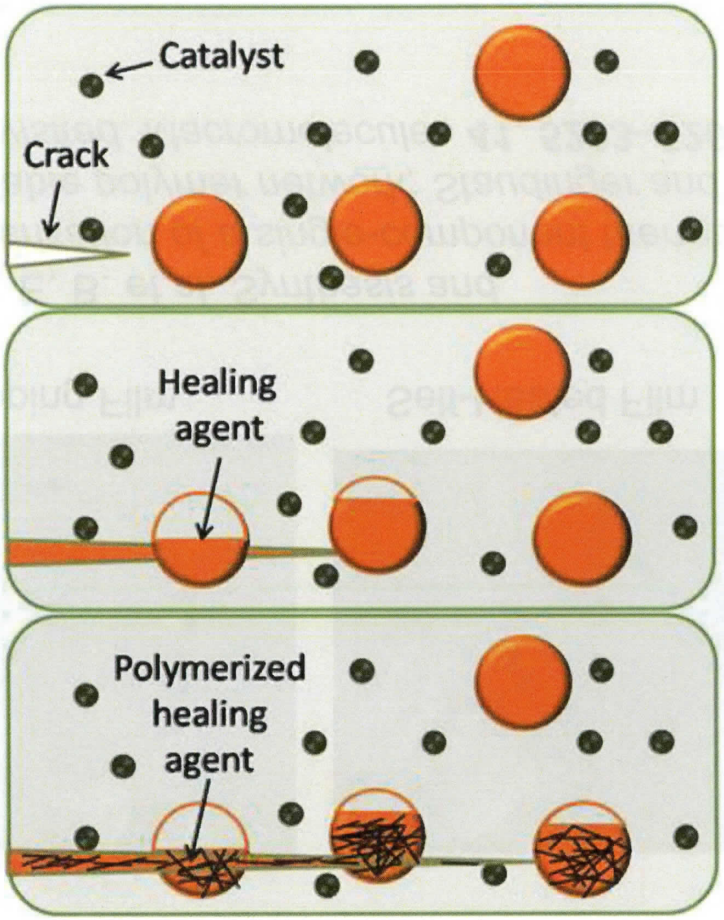
Magnetically Induced Shape Change

Mohr, R., *et al., Proc. Natl. Acad. Sci. USA (2006)* ***103, 3540***

Self Healing Composites

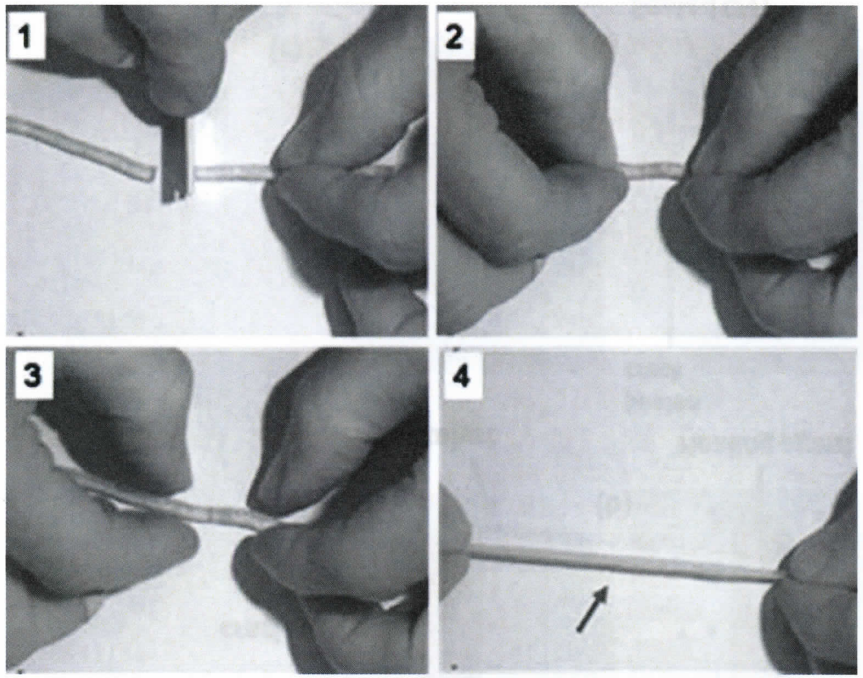


G. Lanzara, Y. Yoon, H. Liu, S. Peng and W. I. Lee, Nanotechnology, 2009, 20, 335704

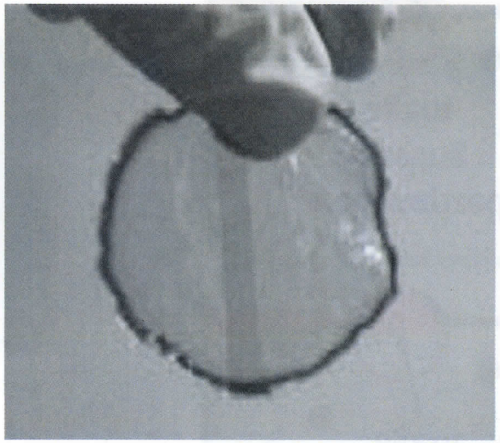


S. R. White, N. R. Sottos, P. H. Geubelle, J. S. Moore, M. R. Kessler, S. R. Sriram, E. N. Brown and S. Viswanathan,
Nature, 2001, 409, 794–797

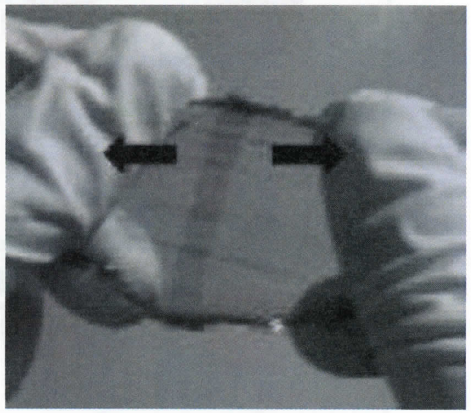
Self Healing Polymers



Materials science: The gift of healing
Justin L. Mynar & Takuzo Aida
Nature 451, 895-896(21 February 2008)



Overlapping Film

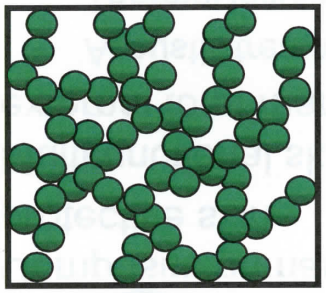


Self-Healed Film

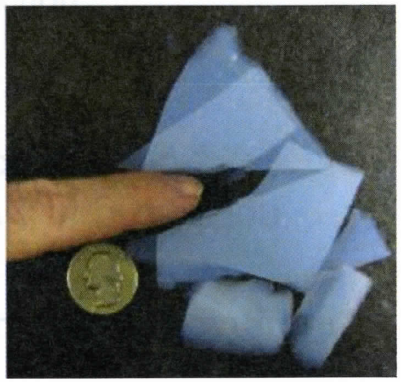
Murphy, E. B. *et al. Synthesis and characterization of a single-component thermally remendable polymer network; Staudinger and Stille revisited. Macromolecules* ***41, 5203–5209 (2008***

***Possi*ble through engineering of the dynamic bond within the polymer**

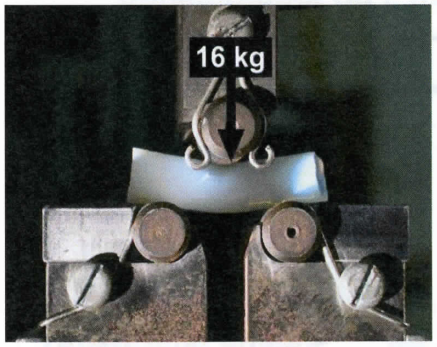
Mechanically Strong Aerogels



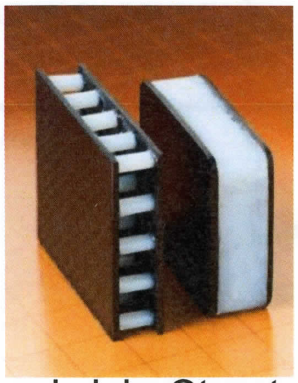
Highly porous solid,
10-40 nm pore size



…but are extremely fragile and moisture sensitive

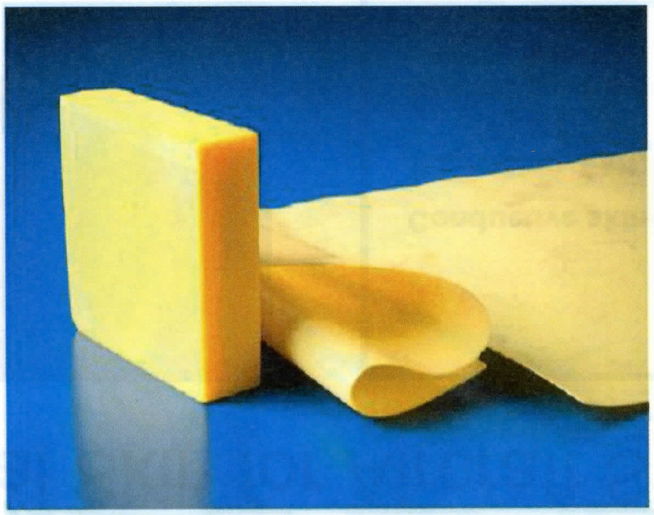


NASA developed strong silica aerogel

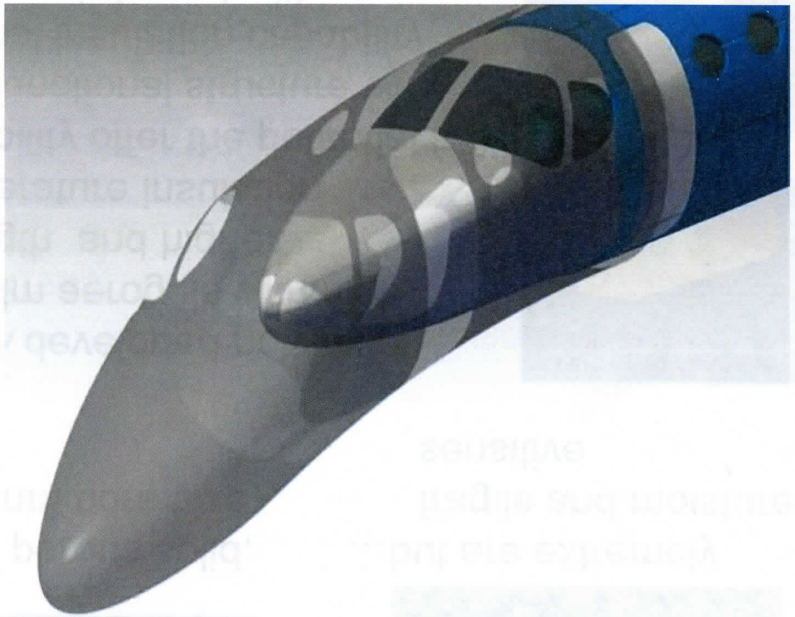


Sandwich Structure Incorporating Aerogels

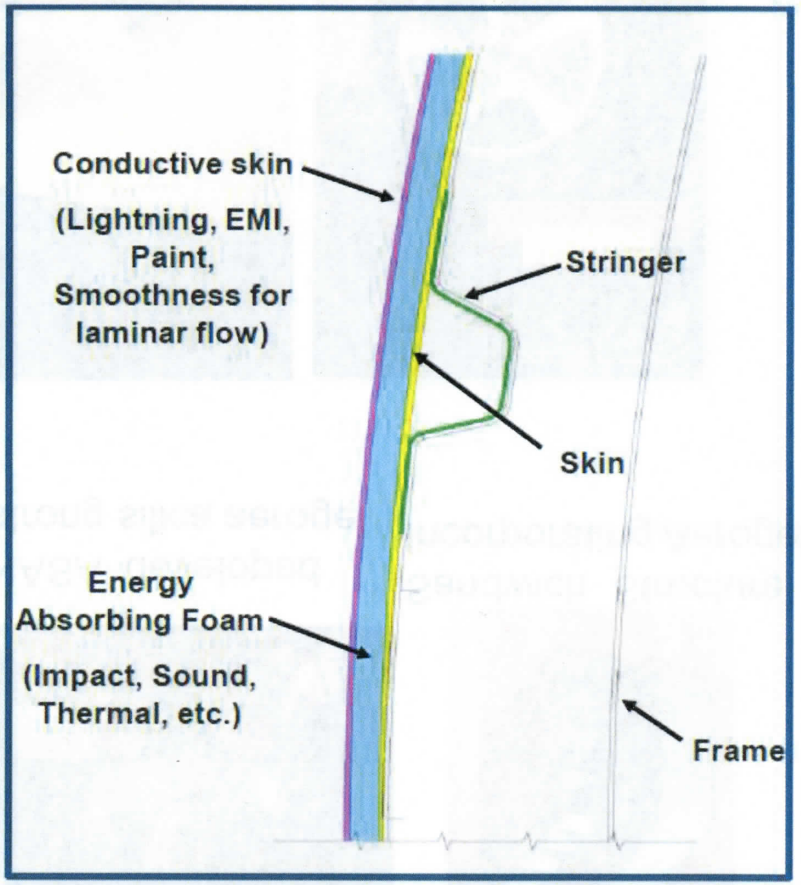
NASA developed polyimide thin film aerogels with high strength and higher temperature insulation capability offer the potential for multifunctional structure with thermal insulation capability - can be reinforced with nanotubes and nanofibers to further improve strength



Multifunctional Skin for Aircraft Structure



- Composite primary structure with external protective skin
- Multifunctional skin provides protection external to primary structure
  - Acoustic treatment
  - Thermal insulation
  - Lightening strike protection
  - Smoothness to facilitate laminar flow
  - Impact detection/indication
  - Ice protection



Schematic of STAR-C² concept (under development on Cessna NRA contract)

Smoothing, Thermal, Absorbing, Reflective, Conductive, Cosmetic (STAR – C²) Concept Being Funded by NASA

Concluding Remarks

- Reinforcement of composites with nanotubes and nanofiber offer the potential for significant improvement in strength, but replacement of carbon fibers with nanotubes or nanofibers in polymer composites is still a long term goal
- Near-term application of nanotubes or nanofibers in continuous carbon fiber reinforced composites
  - Increasing interlaminar strength and fracture toughness
  - Increasing thermal and electrical conductivity
  - Improving damping resistance
- Lightweight adaptive structures can be achieved by use of smart materials
- Basic research on self healing materials offers future potential
- Thin, flexible, mechanically strong aerogels offer promise for structural applications
- Multifunctional structures will require combination of new materials and advanced structural concepts