International Institute for Multifunctional Materials for Energy Conversion IIMEC

TEXAS A&M UNIVERSITY

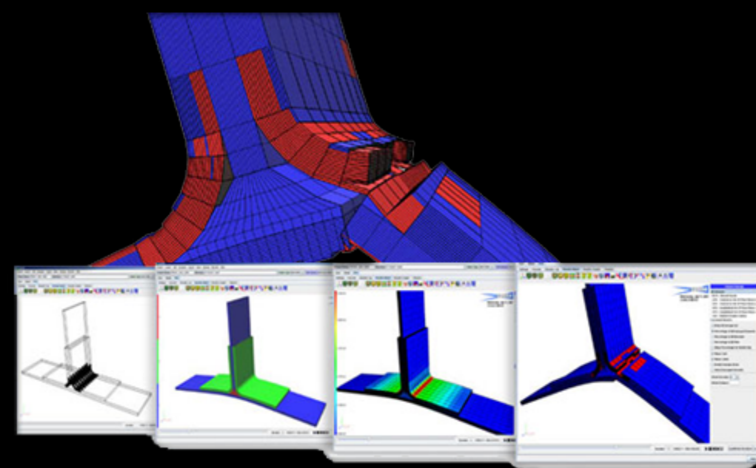
AEROSPACE ENGINEERING

Multifunctional Composites

Theocharis Baxevanis

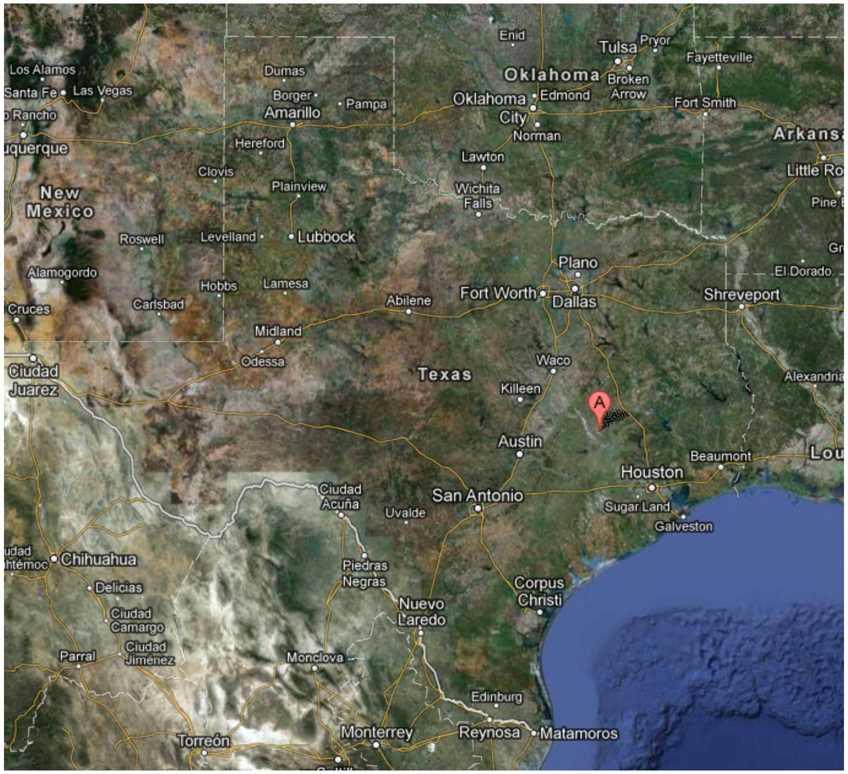
2012 SUMMER SCHOOL IN ADVANCED COMPOSITE MATERIALS

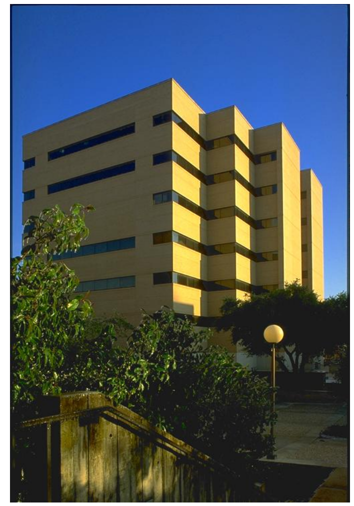
2-6 July



TEI Serres

Texas A&M University




Aerospace Engineering

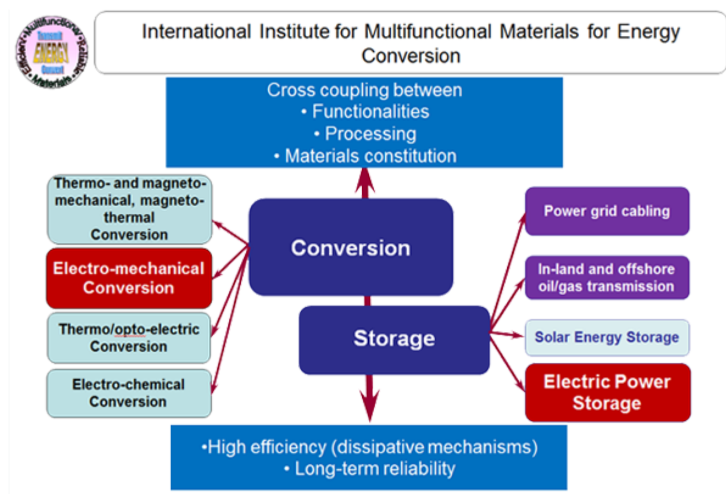

Administration Building


Academic Plaza

IIMEC

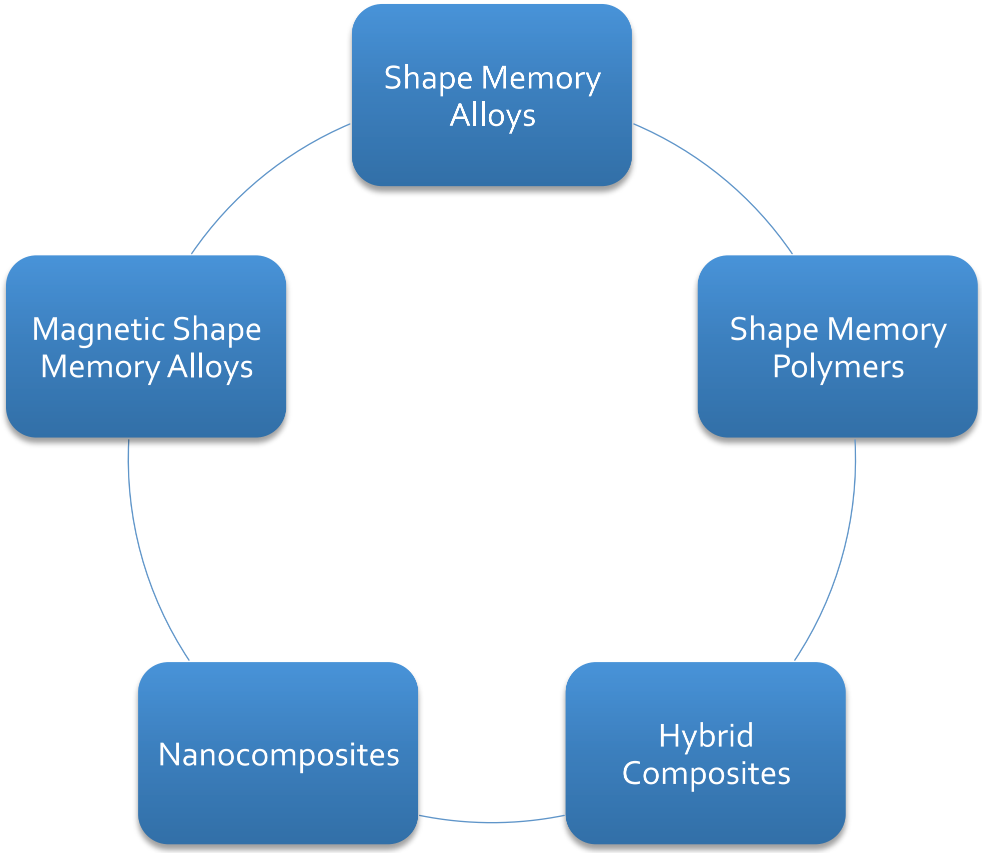
- **What is the IIMEC**
  The International Institute for Multifunctional Materials for Energy Conversion (IIMEC) is an NSF-funded International Material Institute
- **What is our Mission as a research group?**
  The mission of IIMEC is to establish a communications, knowledge-base and computational/laboratory grid that will advance research in multifunctional materials for efficient energy conversion
- **Specific research theme areas:**
  - Coupling of thermal/magnetic and mechanical properties
  - Coupling of electrical and mechanical properties
  - Thermal and electrical, and optical and electrical coupling

Participating Universities in US and worldwide



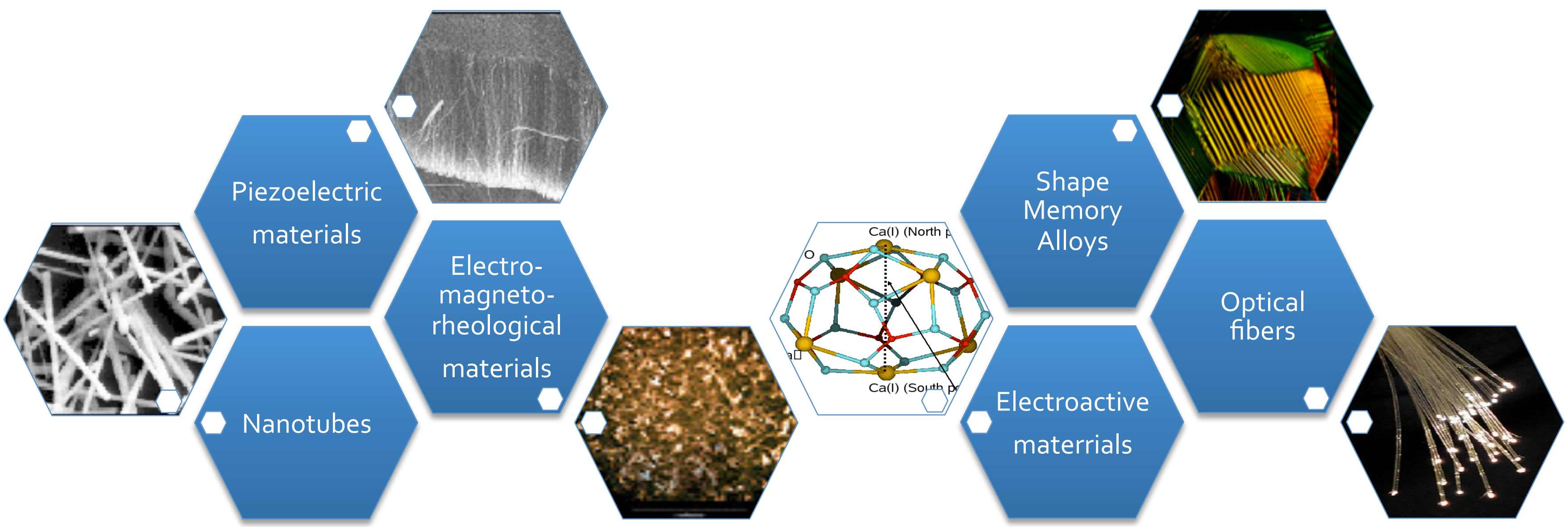
Research in our Group

Characterization, model development, and analysis of



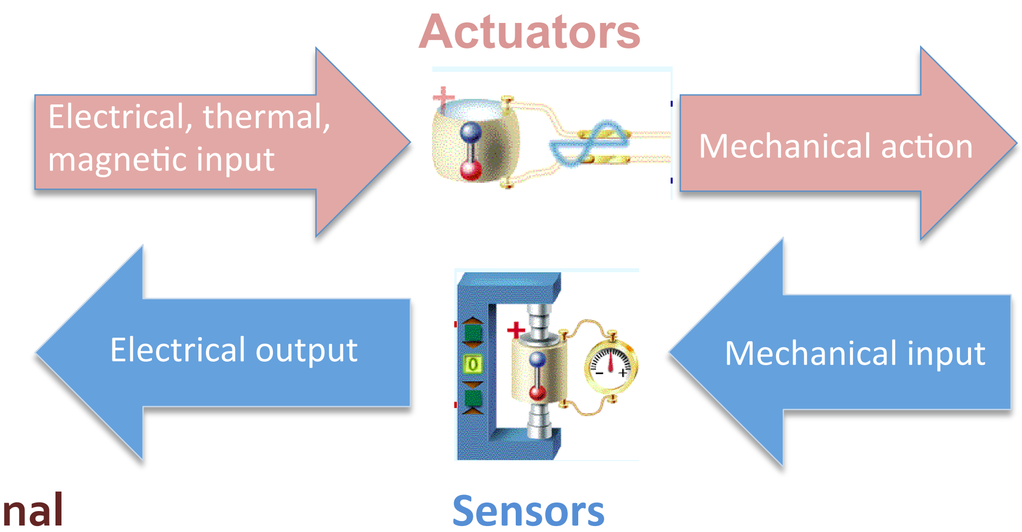
What are Multifunctional Composites?

- Multifunctional Composites are structural materials with added functionality, e.g., energy absorption, electromagnetic properties, sensing and actuation, power harvesting and repair.
- Development of Multifunctional Composites involves the integration of active and passive material systems, often including the coupling of relevant mechanical, electrical, magnetic, thermal, optical, or other physical properties
- Active materials include piezoelectrics, electrostrictives, magnetostrictives, electroactive polymers (EAPs), shape memory alloys (SMAs), shape memory polymers (SMPs) and magnetic shape memory alloys (MSMAs)



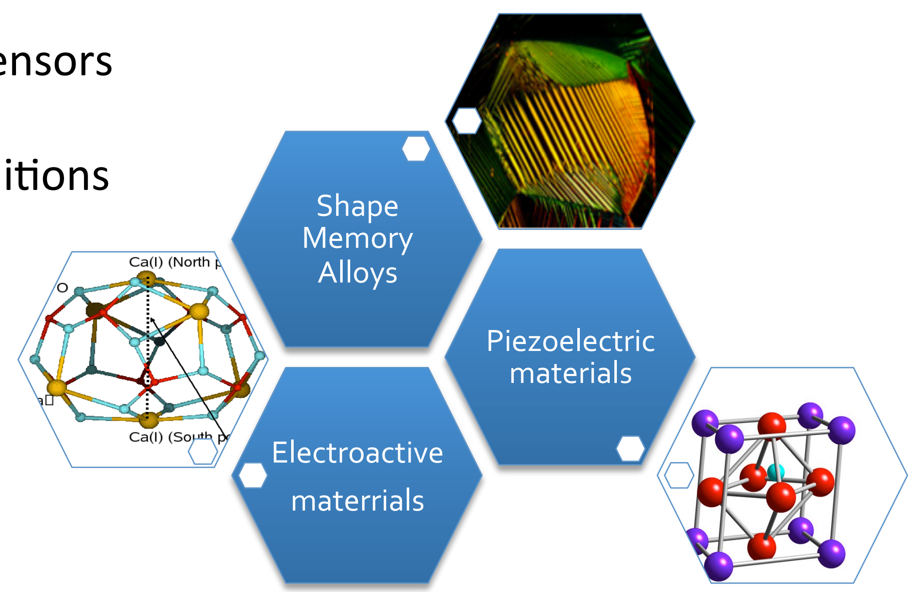
Active Materials

Active materials are able to modify their functional characteristics if stimulated with electrical or magnetic fields, temperature, light, etc…

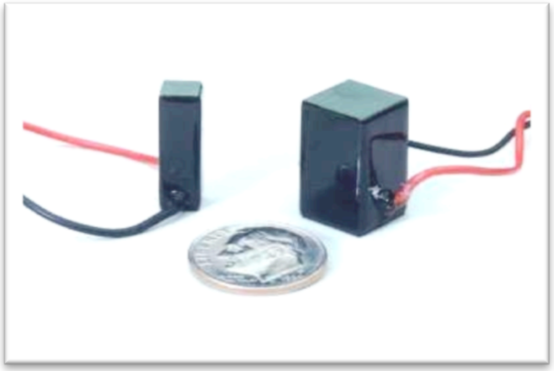


Main advantages with respect to traditional components:

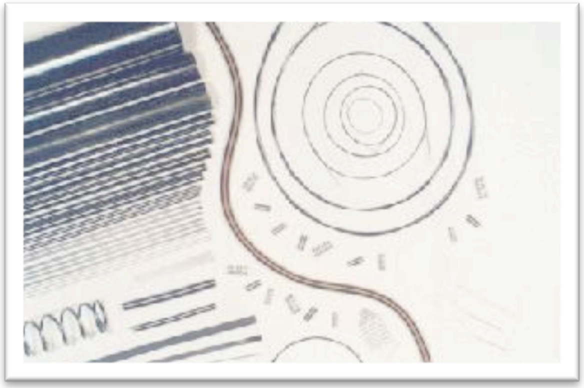
- Act simultaneously as actuators and sensors
- Perform controlled mechanical action
- Are adaptive with environmental conditions
- High level of miniaturization



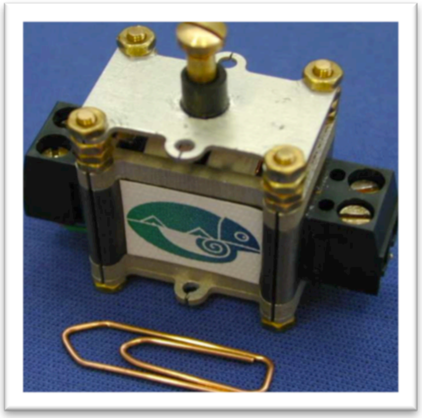
Types of Coupling in Active Materials



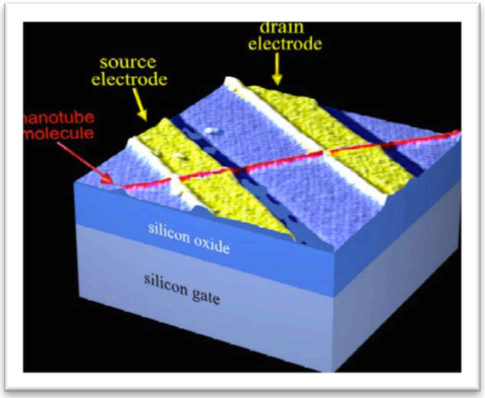
Piezoelectrical Polymers and Ceramics:
Electromechanical coupling



Shape memory alloys:
Thermomechanical coupling

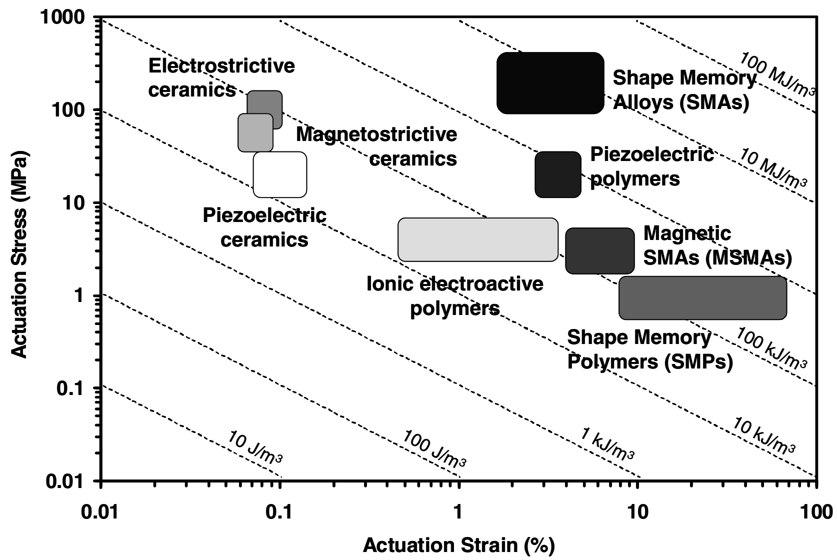


Magnetic shape memory alloys:
Magnetomechanical coupling

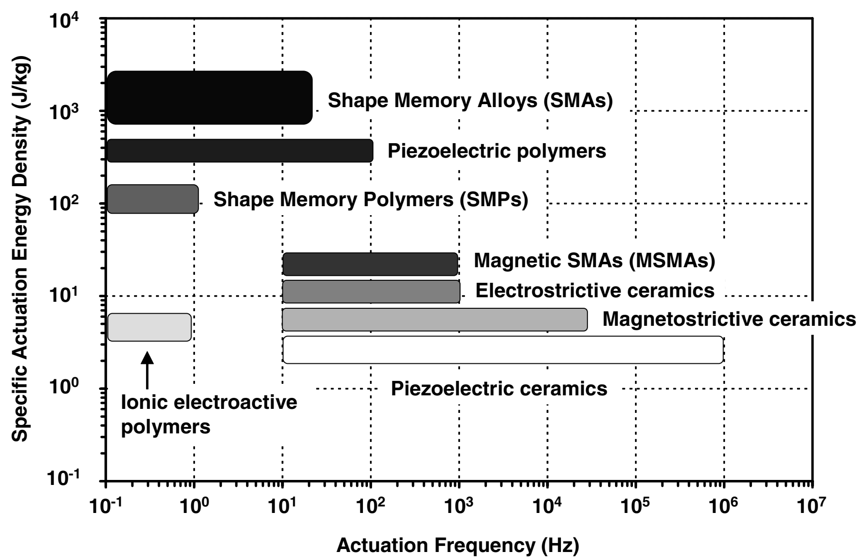


CNT-based devices:
Electrothermal coupling

Mechanical Response of Active Materials

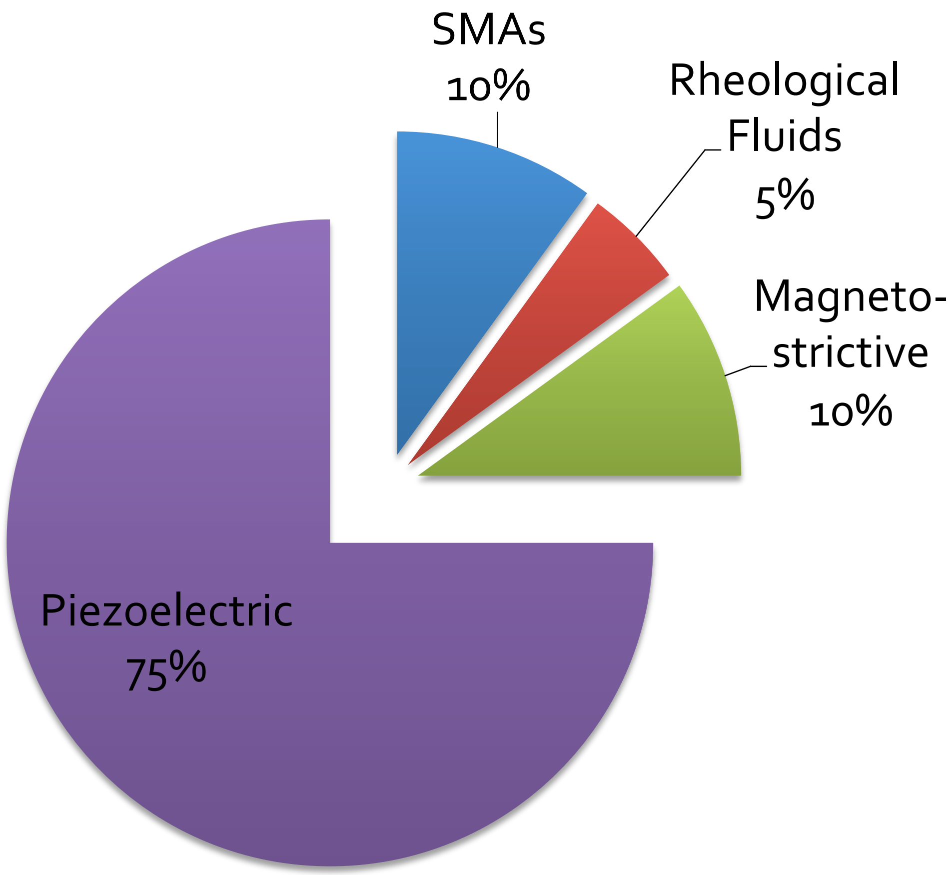


actuation energy density



actuation frequency

Active Materials Market Share



excludes Fiber Optic

Shape Memory Alloys (SMAs)

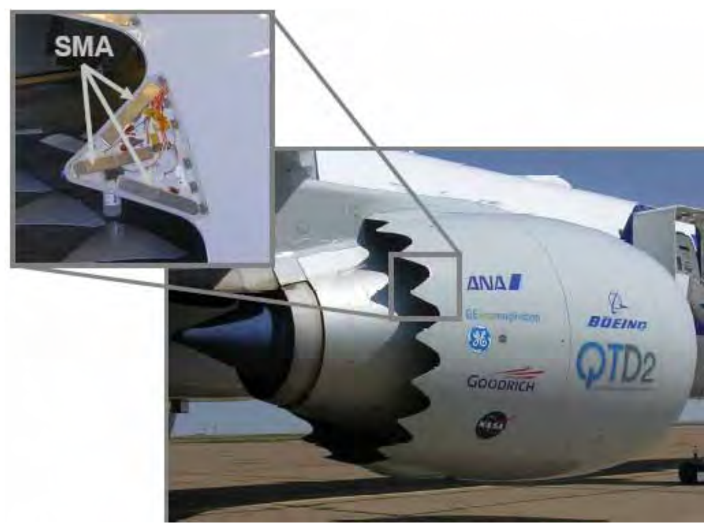
- Shape Memory Alloys (SMAs) are active materials, capable of converting thermal to mechanical work and *vice versa*
- SMAs are desirable in a wide range of actuator, energy absorption and vibration damping applications

Advantages:

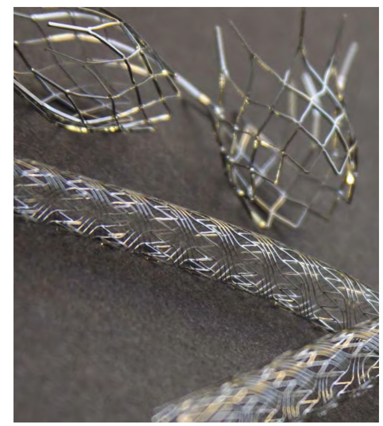
- High Strength
- High Strain
- High Actuation Energy

Disadvantages:

- Low Frequency
- Low Efficiency



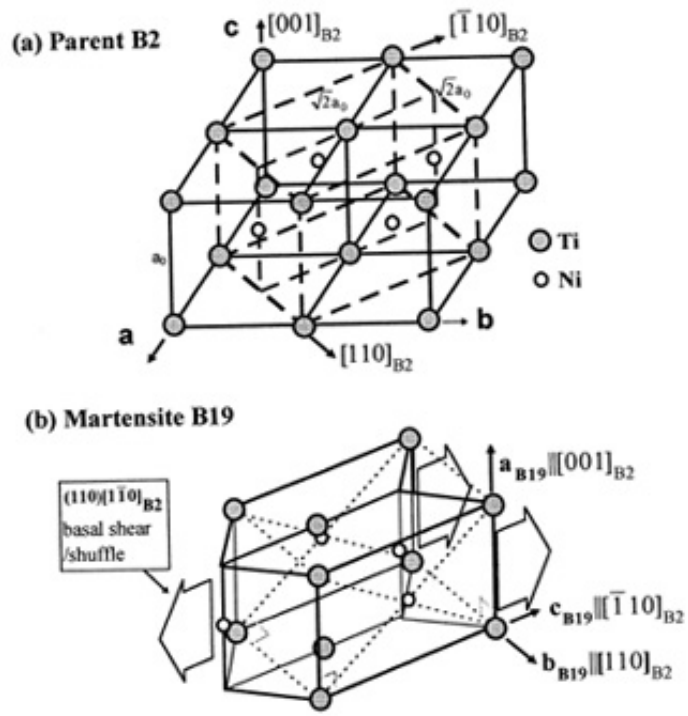
Variable Geometry Chevrons



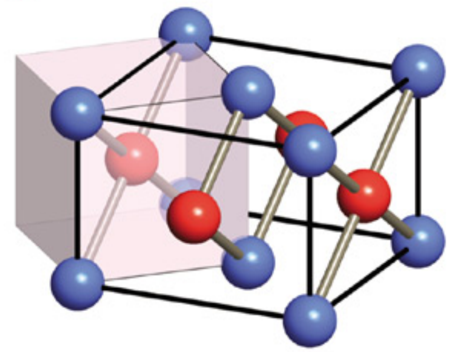
Bomedical devices

Burpee Materials Technology, LLP

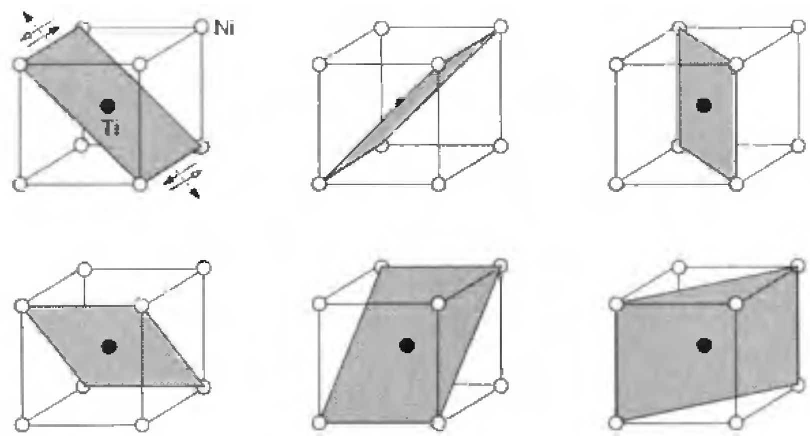
Phase Transformation



Diffusionless, shear driven transformation from austenite to martensite and vice-versa

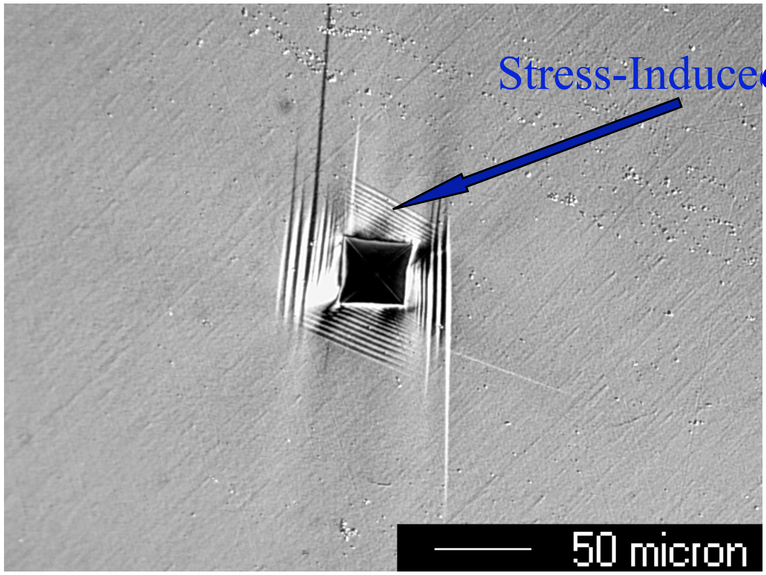


The relation between the cubic *B*2 cell (shaded box) and the undistorted (tetragonal) *B*19 cell

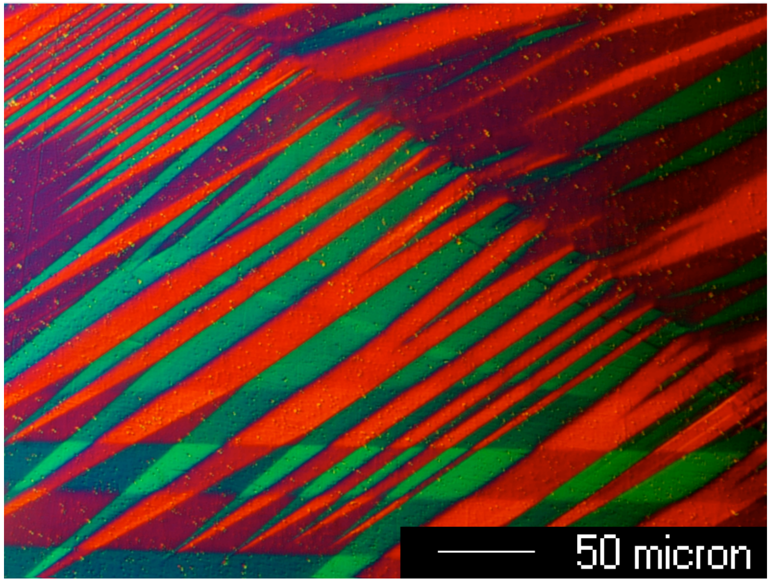


Face-diagonal planes. Martensite variants

Phase Transformation (cont.)



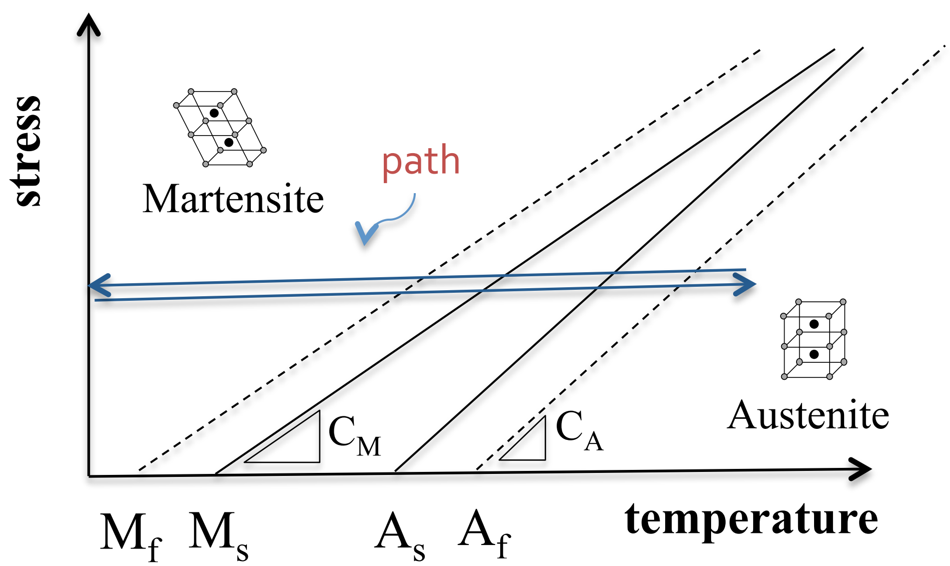
Stress-Induced martensite



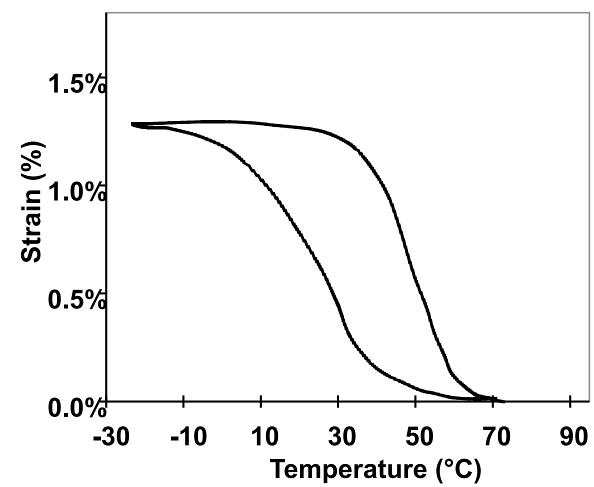
Thermally-Induced martensite

Mechanical Response of SMAs

shape memory effect



stress vs temperature phase diagram



strain vs temperature

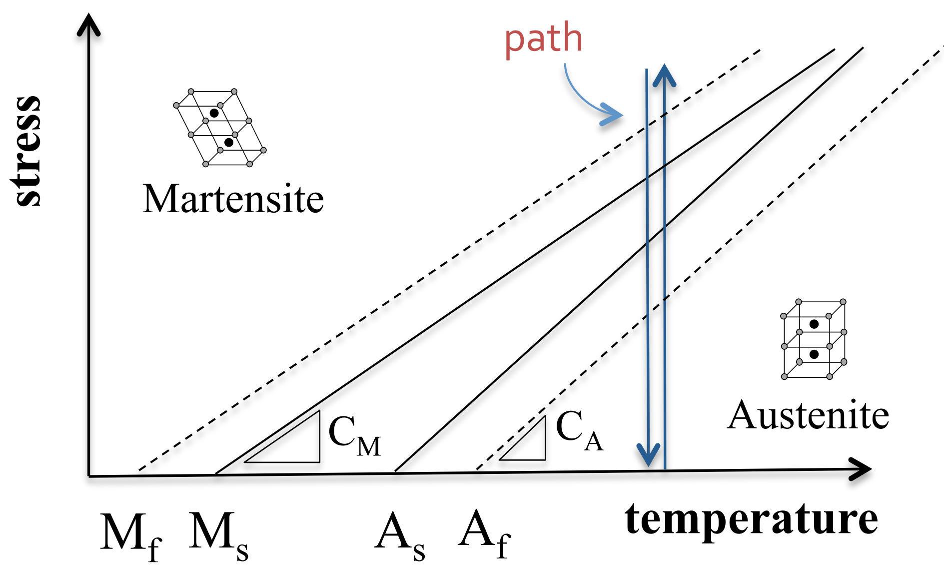
- SMAs can recover their shape when the temperature is increased even under high applied loads (*Shape Memory Effect*)

Shape memory effect

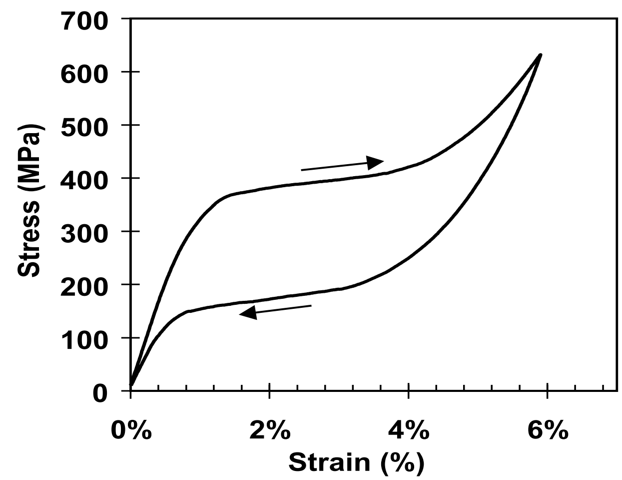
Pseudoelastic effect

Mechanical Response of SMAs

pseudoelastic behavior



stress vs temperature phase diagram



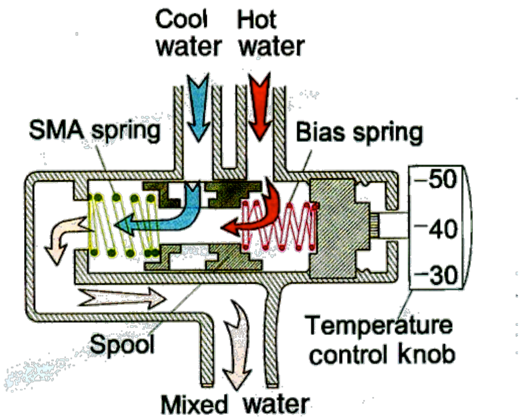
stress vs strain

- Transformation can also be induced by applying a sufficiently high mechanical load to the material in the austenitic phase (*Pseudoelastic Effect*)

Shape memory effect

Pseudoelastic effect

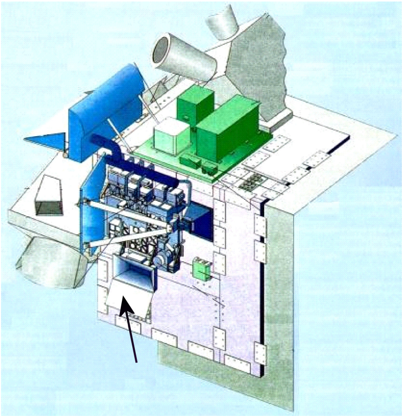
Applications



mix

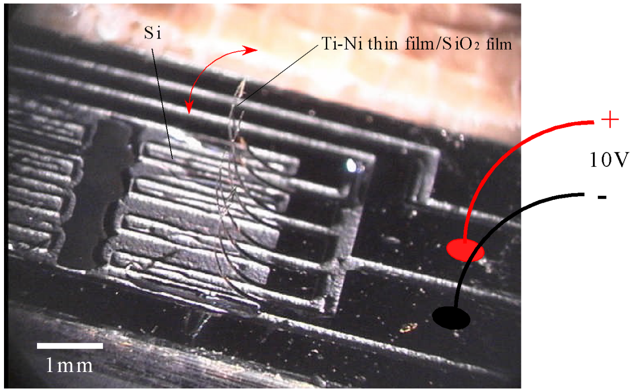
Otsuka (NIMS) 2002

open

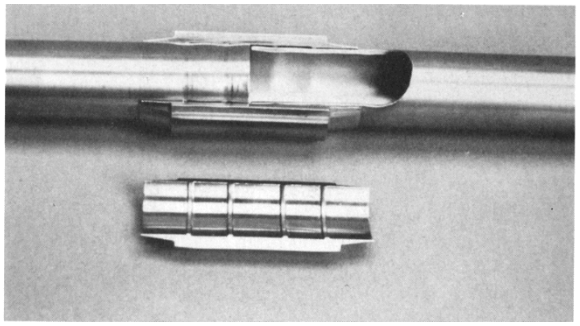


Voggenreiter (EADS) 2001

move

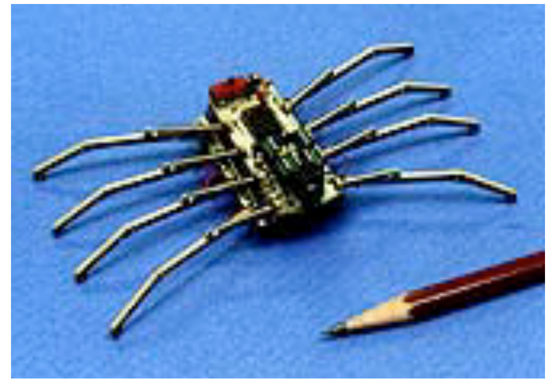


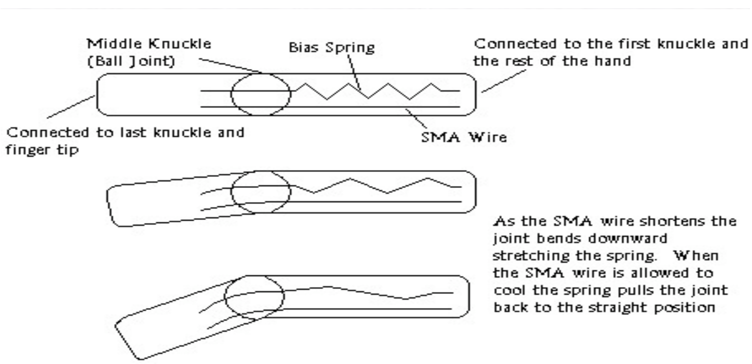
connect

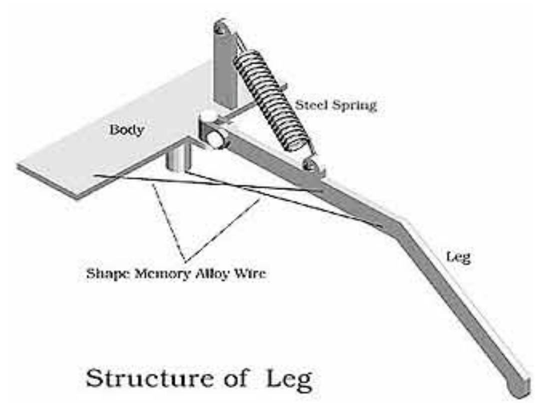


F-14 Raychem 1971

SMA Devices







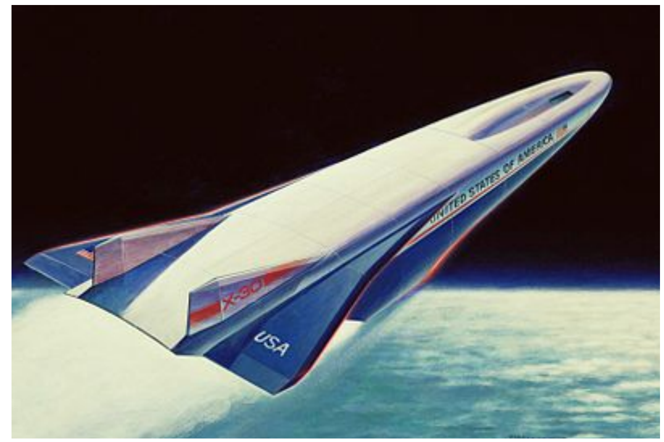
http://www.cs.ualberta.ca/~database/MEMS/sma_mems/muscle.html

http://www.toki.co.jp/MicroRobot/_8LegRobot.html

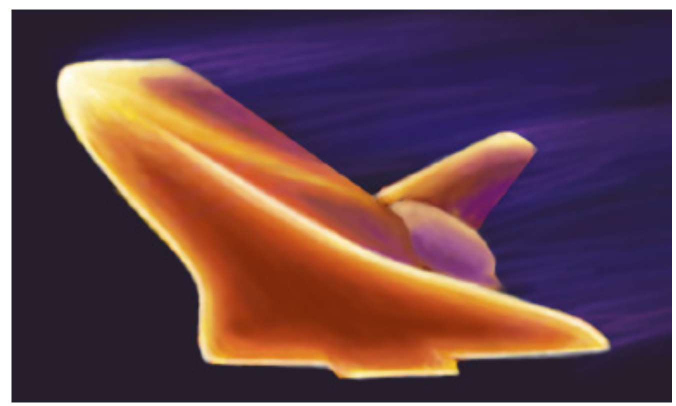
An Application…

- Common problem for many aerospace applications:
  - Lack of materials capable of handling extreme environments
  - High Temperature Regimes

- Past solution was metal-ceramic composites
  - Brittleness of ceramics often lead to failure



http://en.wikipedia.org/wiki/National_Aerospace_Plane

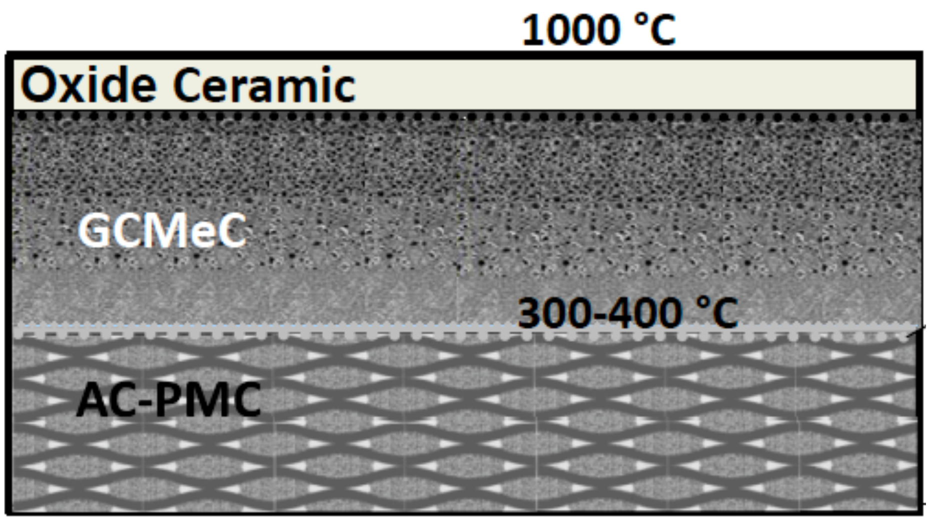


http://en.wikipedia.org/wiki/File:Stsheat.jpg

New FG Hybrid Composite

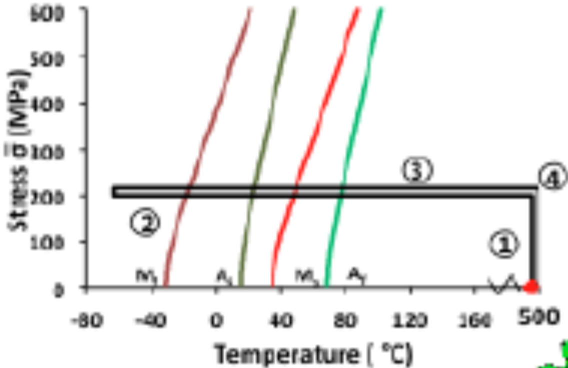
- **New Solution:** New *Functionally Graded Hybrid Composite*

- Top: Oxide Ceramic Thermal Barrier Coating
- Middle: Graded Ceramic-Metal Composite
- Bottom: Actively Cooled Polymer Matrix Composite

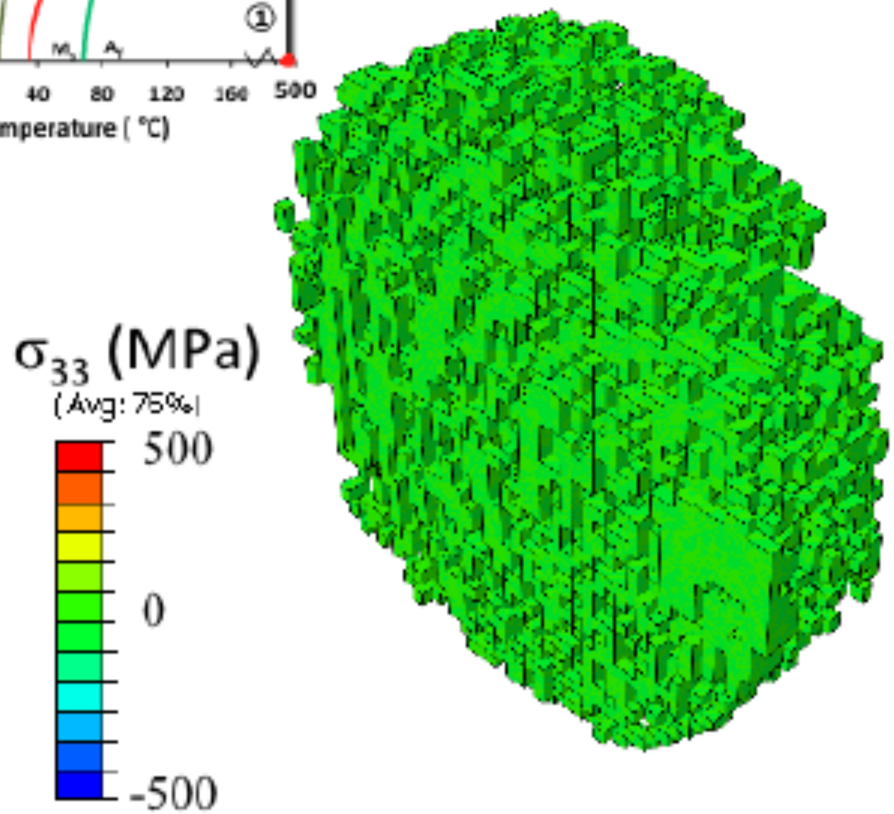


Problem: How to improve mechanical behavior of GCMeC

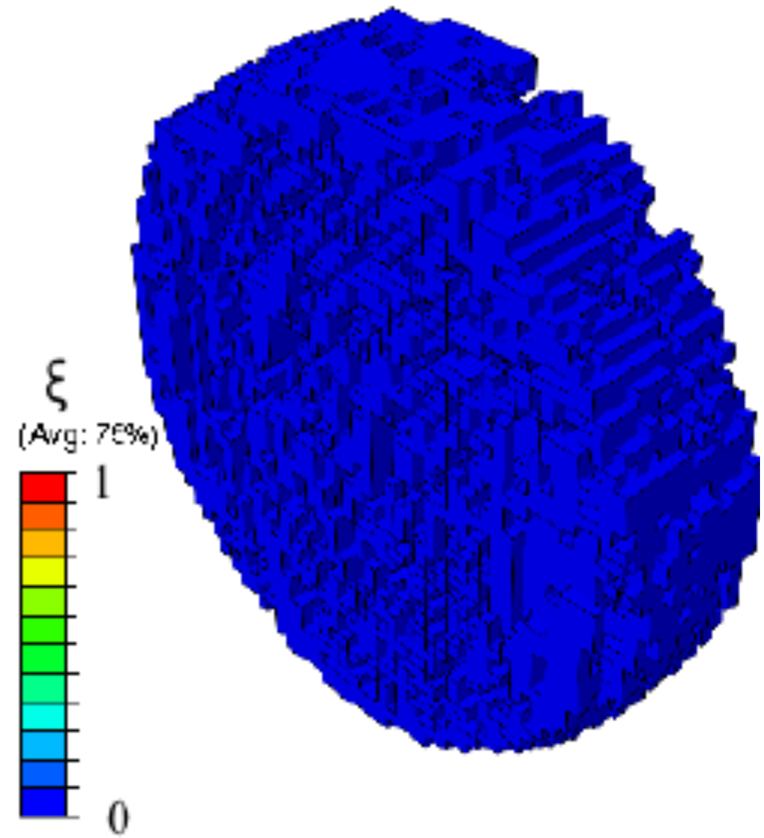
Ceramic Stress State



Stress in Ceramic Phase

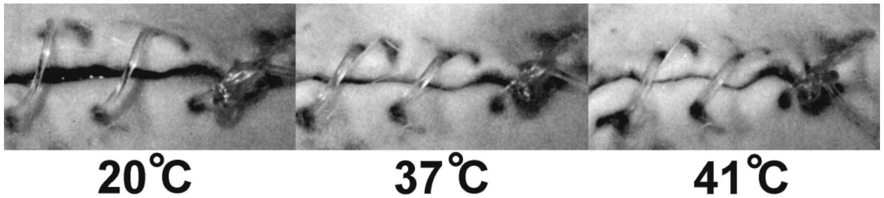


Martensitic Volume Fraction, ξ, in SMA Phase

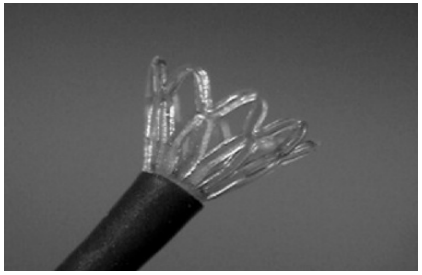


Shape Memory Polymers

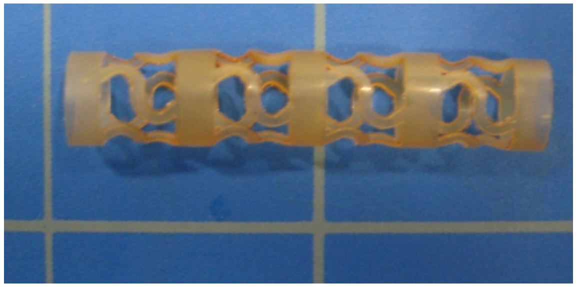
- SMPs present a relatively low-force, high-elongation alternative compared to shape memory alloys (SMAs)
  - Reported strains up to 800% (Liu et al. 2007)
  - Ability to significantly tune material properties
- Potential applications
  - Aerospace devices
  - Biomedical devices



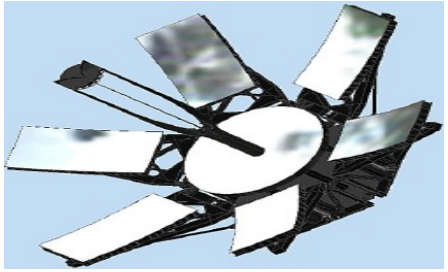
Lendlein and Langer (Science 2002)



Thrombectomy Devices [1]



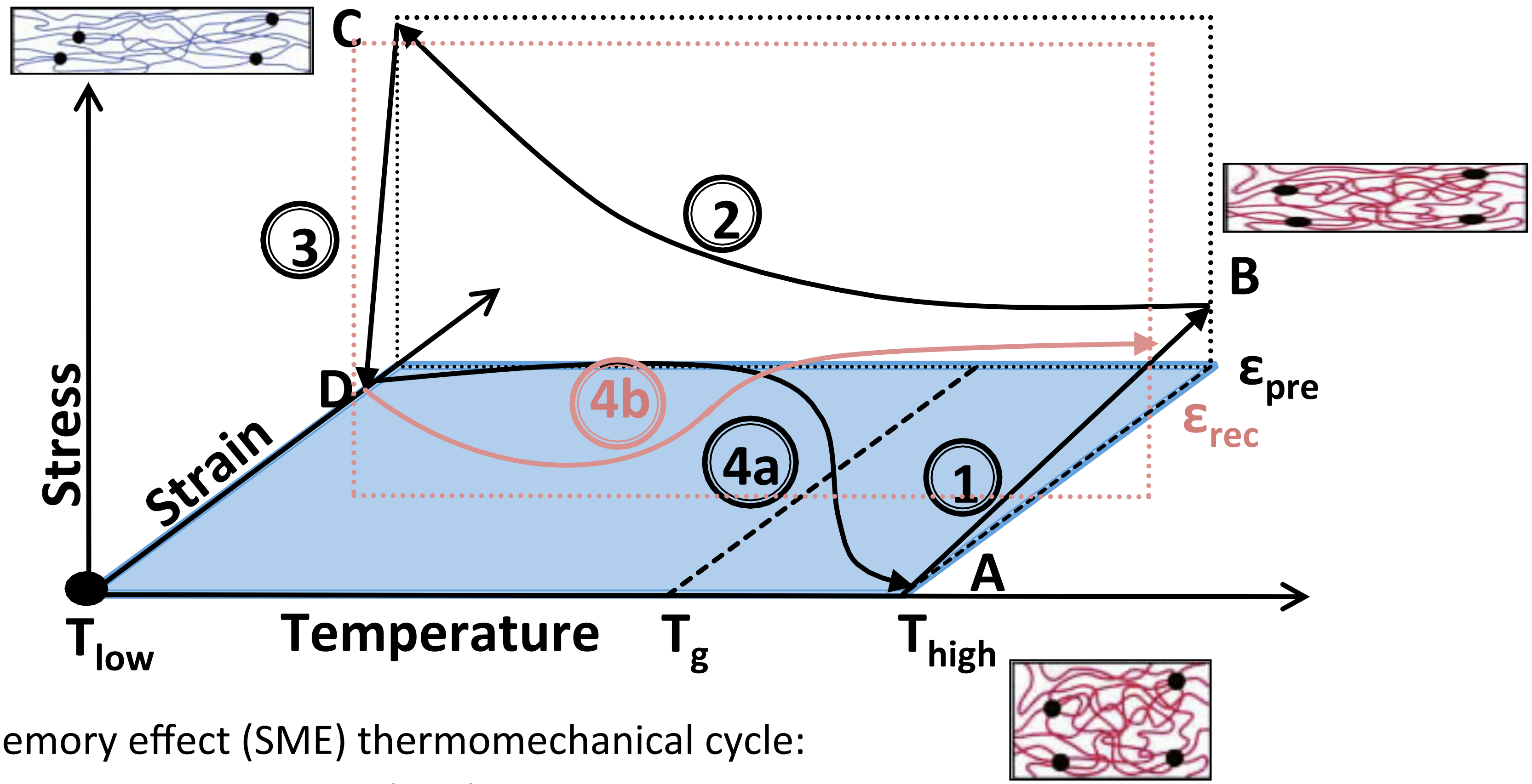
Cardiovascular Stents [2]



Deployable Space Structures [3]

[1]Buckley, P.R., et al., *IEEE Transactions on Biomedical Engineering, 2006.*
[2]Courtesty of Landon Nash
[3]Lake, M.S., et al., *Proceedings of SPIE,* 1999.

Thermomechanical Cycle



Shape memory effect (SME) thermomechanical cycle:

1. Load in rubbery phase ($T>T_g$)
2. Cool at fixed deformation
3. Unload in glassy phase (T<Tg)

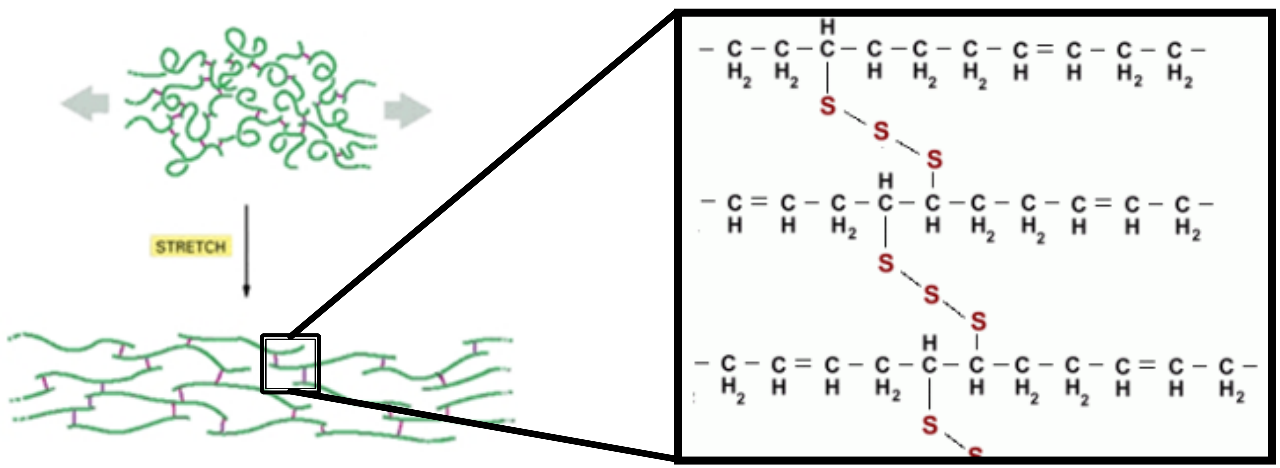
4a. Free recovery (heat at zero stress)

4b. Constrained recovery (heat at constant displacement)

Loading at High Temperature ($T>T_{trans}$)

- Large deformations possible
  - Polyurethane SMPs stretched to 100% strain (Baer et al., 2006; Tobushi et al. 1997)
  - Polystyrene-based SMPs stretched to 75% (Atli et al. 2009) and 100% strain (Volk et al. 2010)

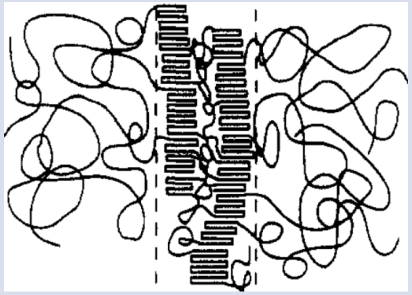
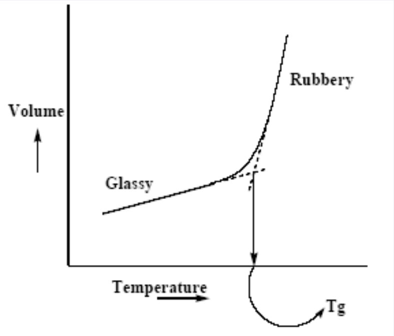
- Deformation mechanism (stretching chains + netpoints) similar to that of stretching vulcanized rubber



(http://www.ncbi.nlm.nih.gov) (http://www.worsleyschool.net)

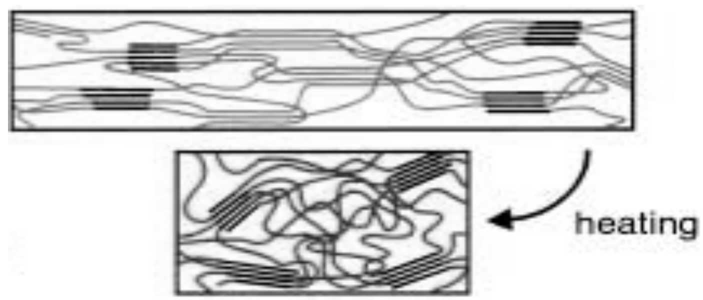
Cooling to $T<T_{trans}$ and Unloading

- 'Freeze' the deformation of the material by cooling while maintaining a constraint (e.g., constant strain)

Type of Switching ('Soft') Segment	'Freezing' Mechanism
Semi-crystalline ($T_{trans}=T_m$)	Formation of crystalline regions prevents long range motion of amorphous molecules  Rangarajan et al. (Macromolecules 1998)
Amorphous ($T_{trans}=T_g$)	Transformation from rubber phase to glass phase. Lack of thermal energy results decreases long range motion of molecules.  (http://www.ejpau.media.pl/)

Recovery at High Temperature ($T>T_{trans}$)

- Heating at zero load to observe shape recovery
  - Stretched polymer chains inherently want to return to their randomly oriented, coiled configurations (entropic gain)



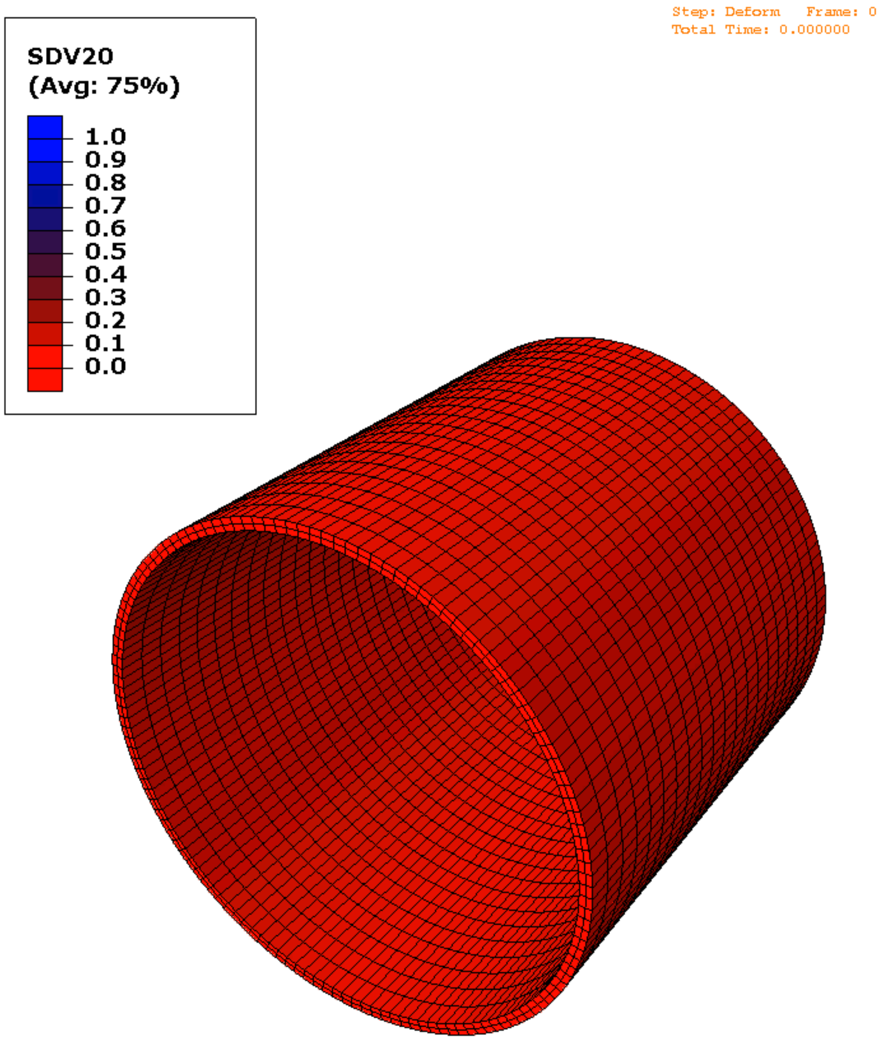
Lendlein and Kelch (Angew Chem. Int. Ed. 2002)

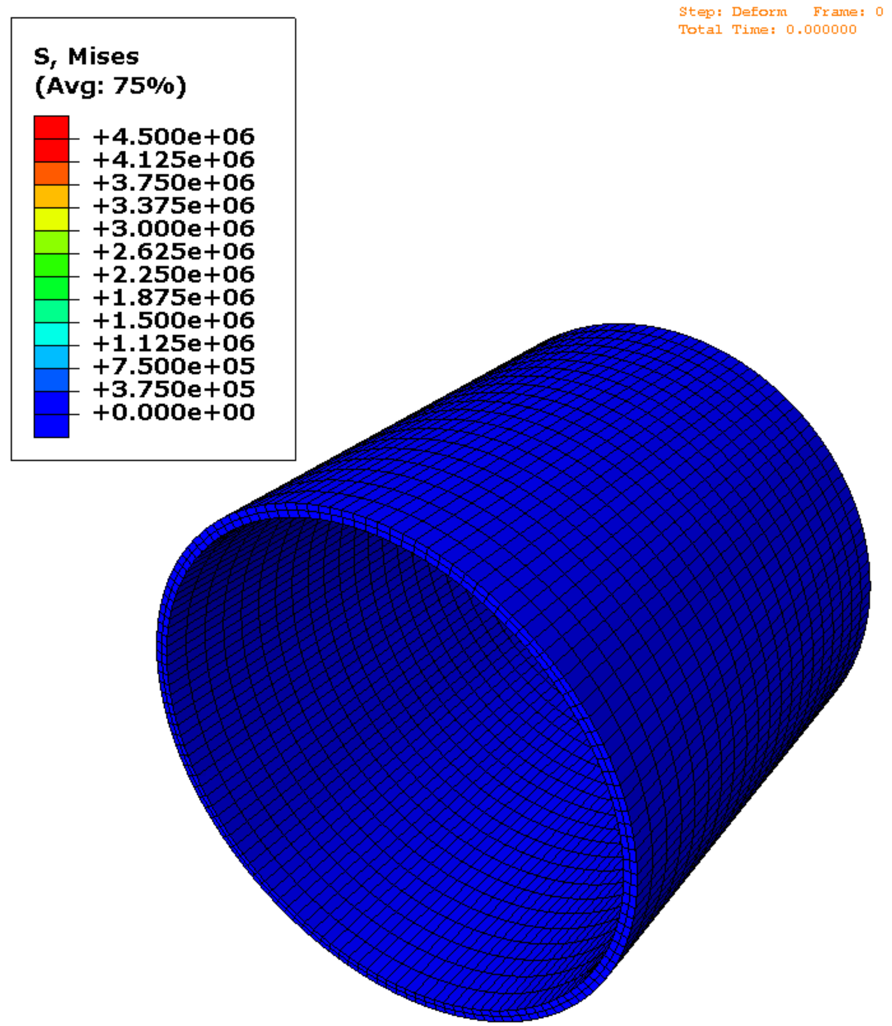
  - Thermodynamically consistent:

$$\Delta G = \Delta H - T\Delta S$$

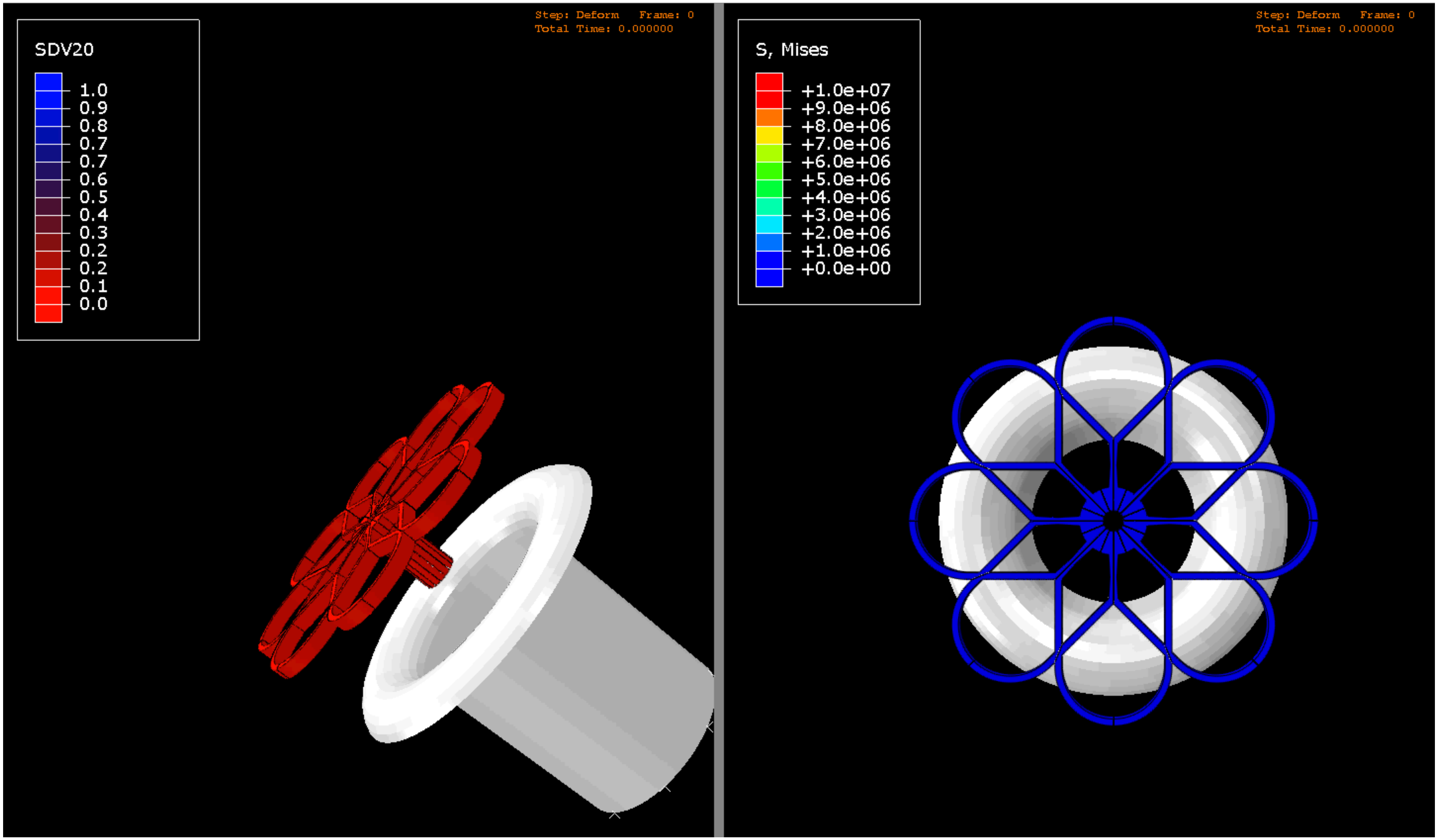
Swalin (Thermodynamics of Solids, 1972)

SMP Cardiovascular Tube



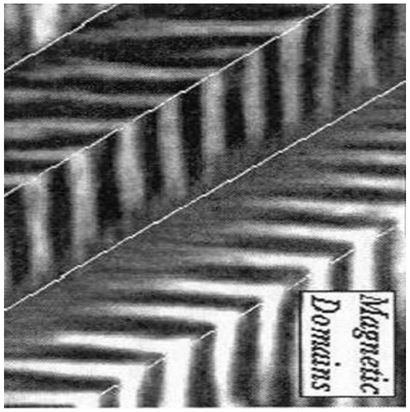


SMP Thrombectomy Device

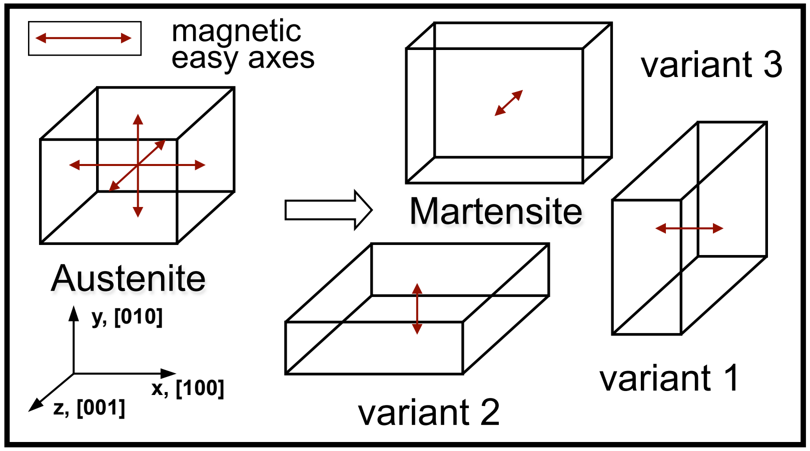


Magnetic Shape Memory Alloys

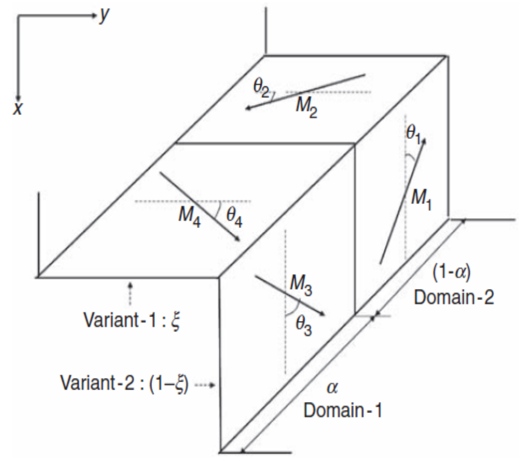
Magnetic Shape Memory Effect



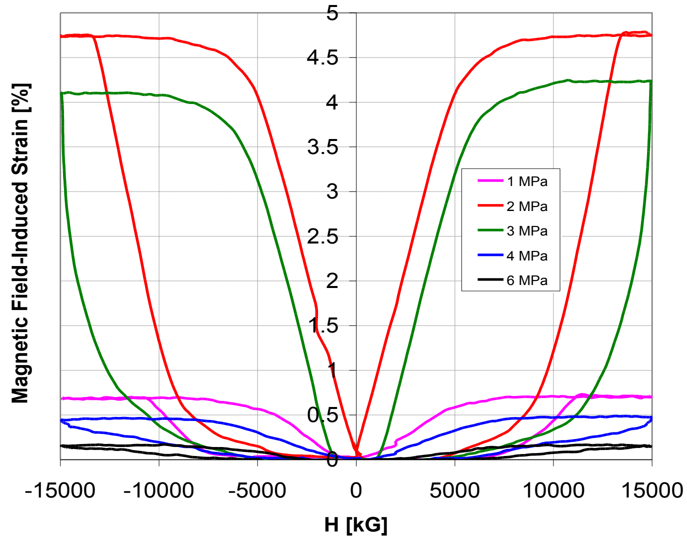
Magnetic Domain Structure



Martensitic Phase Transformation in MSMAs



4 possible magnetic domains in tetragonal martensite

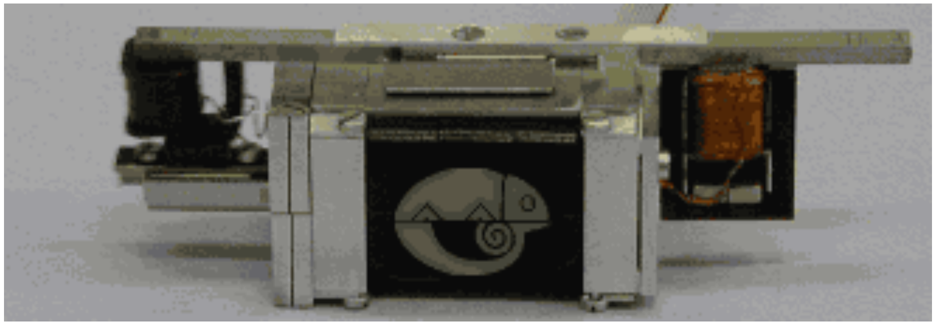


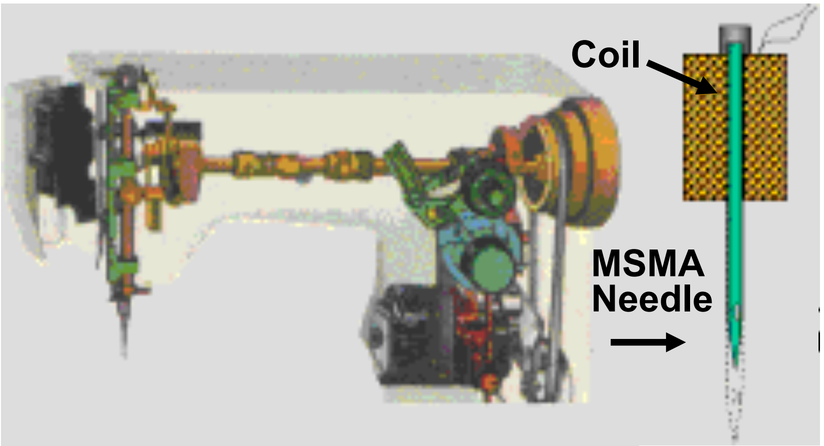
Large magnetic field-induced strains in MSMA single crystals

Applications of MSMAs

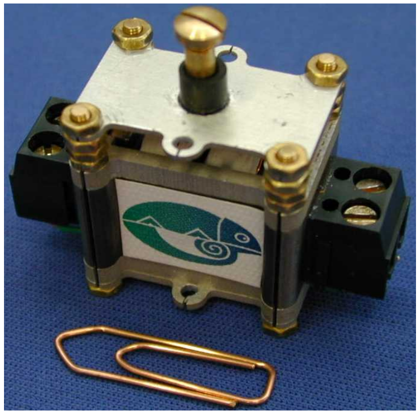
Design of High Frequency MSMA Actuators

- High mobility of twin boundaries that separate martensitic variants
- High Frequency Actuation





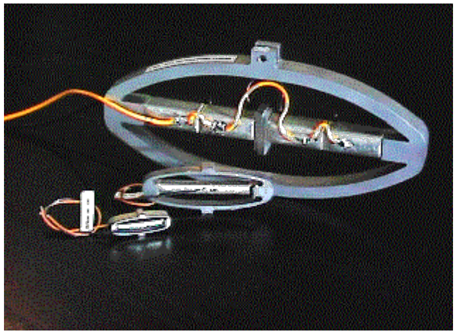
Potential application: Replacement of Motor, Gears and Belts in Sewing Machine with Magnetically Actuated MSMA Needle



Commercially available MSMA Actuators:
(source: http://www.adaptamat.com)

Ferroelectric Materials

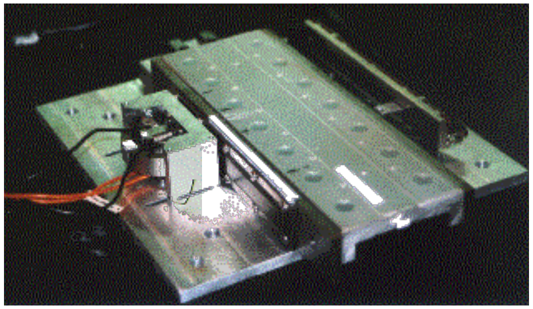
- Ferroelectic materials are defined as those which exhibit, at temperatures below the Curie point, a domain structure and spontaneous polarization which can be oriented by applied electric fields ($BaTiO_3$, $Pb(Zr, Ti)O_3$, $Pb(Mg, Nb)O_3$)



Piezoelectric actuator

Advantages:
- Very High Actuation Frequency
- Direct Electric-Strain Coupling

Disadvantages:
- Low Energy Output

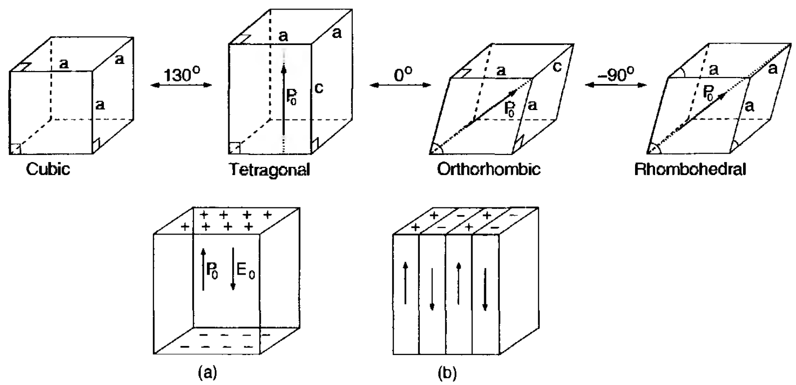


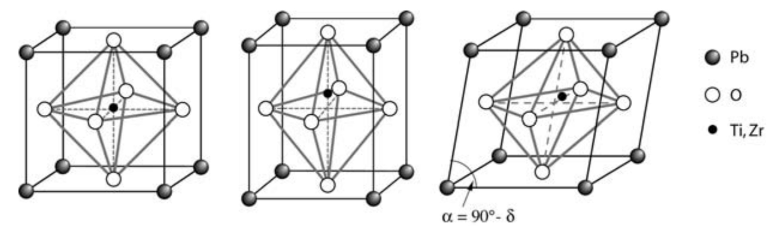
Piezomotor

http://www.micromega-dynamics.com/piezo-products.htm

Direct and Converse Piezoelectric Effects

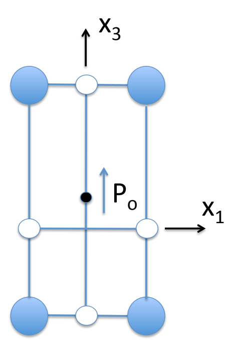
- The *converse piezoelectric effect* constitutes of linear reversible strains generated in ferroelectric materials in response to an applied electrical field
- The *direct piezoelectric effect* designates the opposite phenomenon in which low stress inputs produce changes in the dipole configuration or polarization



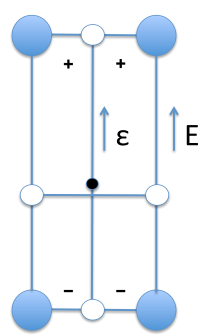


centrosymmetric structure

noncentrosymmetric structures

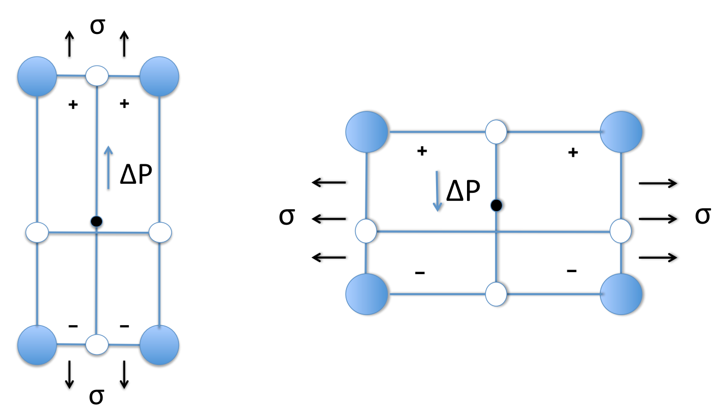


Tetragonal form of $PbTiO_3$



Converse piezoelectric effect

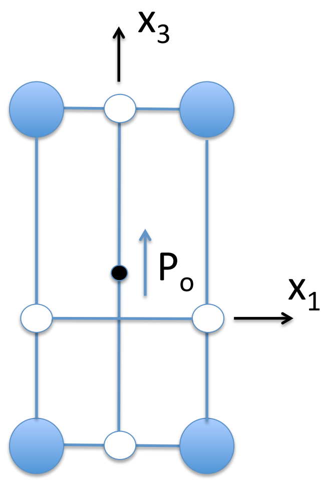
$\varepsilon = d_{33}E$



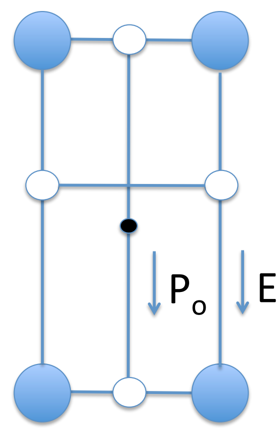
Direct piezoelectric effects

(left) $\Delta P = d_{33}\sigma$ (right) $\Delta P = d_{31}\sigma$ for $\sigma < \sigma_c$

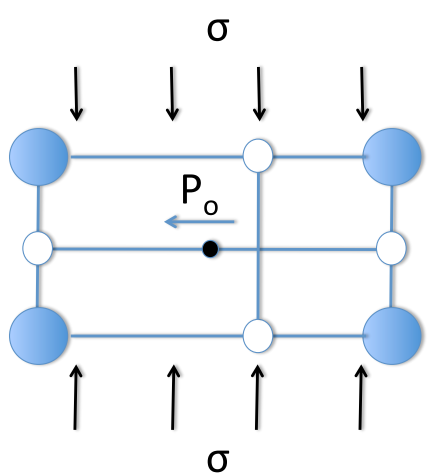
Ferroelectric and Ferroelastic switching



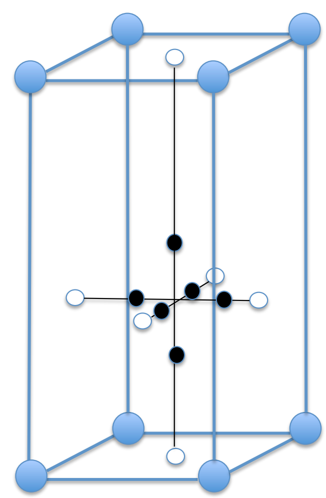
Spontaneous polarization



Ferroelectric 180° polarization switch

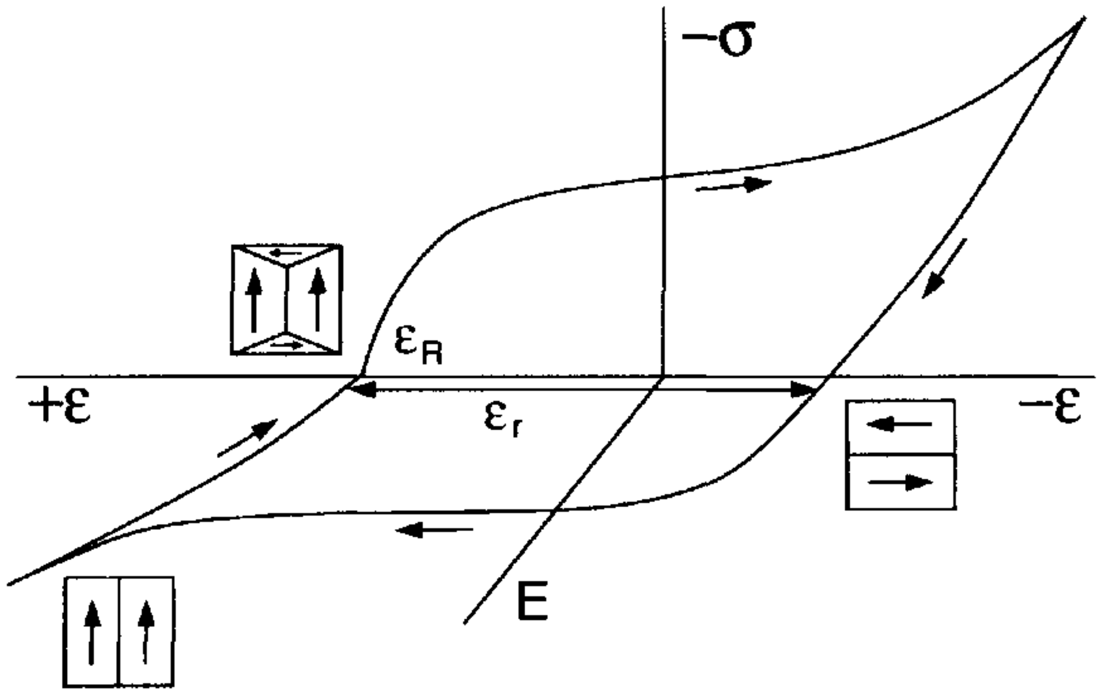


Ferroelastic 90° switch due to compressive stress greater than the coercive stress ($\sigma > \sigma_c$)



Six possible switching mechanisms

Shape Memory Effect



Constitutive Equations for Linear Piezoelectricity

$$\varepsilon_{ij} = s^E_{ijkl}\sigma_{kl} + d_{nij}E_n$$

$$P_n = d_{nij}\sigma_{ij} + \epsilon^T_{nm}E_m$$

σ_{ij} components of the stress tensor

ε_{ij} components of the strain tensor

P_i components of the electric displacement vector

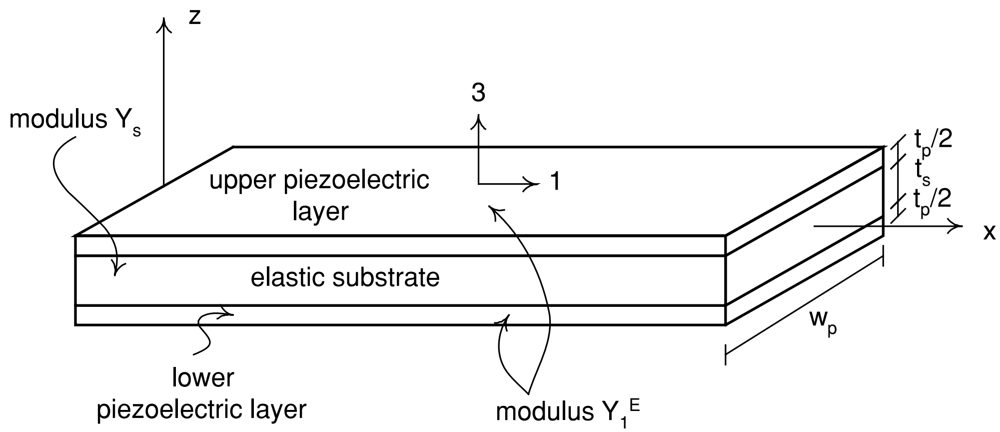
E_i components of the electric field vector

s^E_{ijkl} components of the elastic compliance tensor

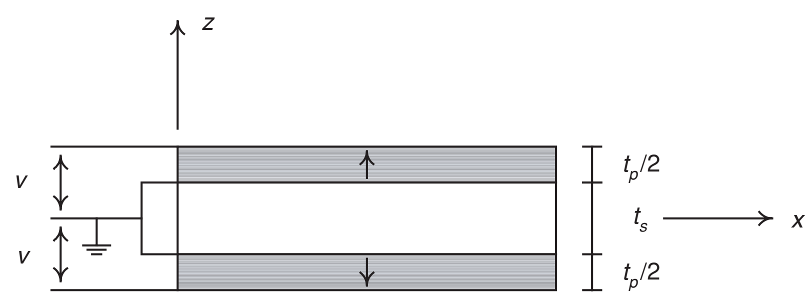
d_{nij} piezoelectric strain coefficients

ϵ^T_{ij} components of the permittivity tensor

Extensional Piezoelectric Device



Composite actuator consisting of an elastic substrate and two piezoelectric layers



Electrical connections for a piezoelectric extender actuation. A voltage is applied to the piezoelectric layers aligned with the poling direction of both piezoelectric layers

Extensional Piezoelectric Device (cont.)

The deflection u_1 of a piezoelectric extender of total length L can be expressed as

$$u_1 = \varepsilon_{11} L$$

and the electric field is equal to the applied voltage divided by the piezoelectric layer thickness

$$E_3 = \frac{2v}{t_p}$$

Constitutive relationships for the three layers

$$\varepsilon_{11} = \begin{cases} \frac{1}{Y_1^p}\sigma_{11} + d_{13}E_3, & \frac{t_s}{2} \leq z \leq \frac{1}{2}(t_s + t_p) \\ \frac{1}{Y_s}\sigma_{11}, & -\frac{t_s}{2} \leq z \leq \frac{t_s}{2} \\ \frac{1}{Y_1^p}\sigma_{11} + d_{13}E_3, & \frac{1}{2}(t_s + t_p) \leq z \leq -\frac{t_s}{2} \end{cases}$$

Extensional Piezoelectric Device (cont.)

Integrating over the y and z directions for the respective domains gives

$$\frac{w_p t_p}{2} Y_1^p \varepsilon_{11} = \int_{y,z} \sigma_{11} dydz + \frac{w_p t_p}{2} Y_1^p d_{13} E_3$$

$$w_p t_s Y_s \varepsilon_{11} = \int_{y,z} \sigma_{11} dydz$$

$$\frac{w_p t_p}{2} Y_1^p \varepsilon_{11} = \int_{y,z} \sigma_{11} dydz + \frac{w_p t_p}{2} Y_1^p d_{13} E_3$$

Assuming that the strain in all three regions is the same, by adding one obtains

$$(w_p t_p Y_1^p + w_p t_s Y_s)\varepsilon_{11} = \int_{y,z} \sigma_{11} dydz + w_p t_p Y_1^p d_{13} E_3$$

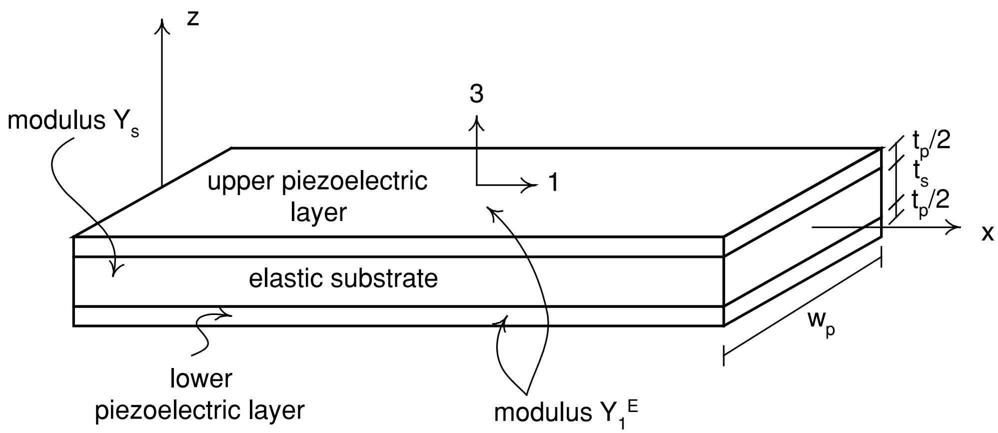
Extensional Piezoelectric Device (cont.)

Thus

$$u_1 = \frac{2}{1+\Psi_e} \frac{d_{13} L v}{t_p}$$

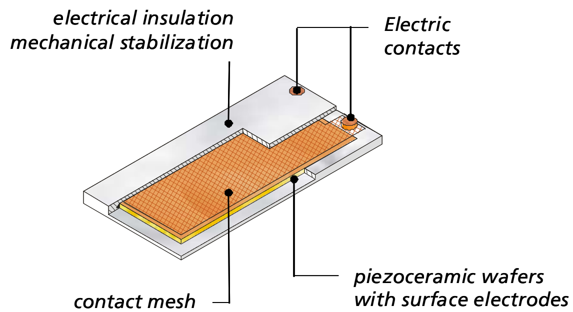
where

$$\Psi_e = \frac{Y_s t_s}{Y_1^p t_p}$$

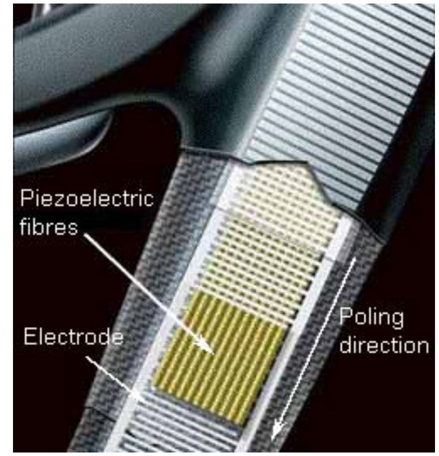


Applications of Ferroelectrics

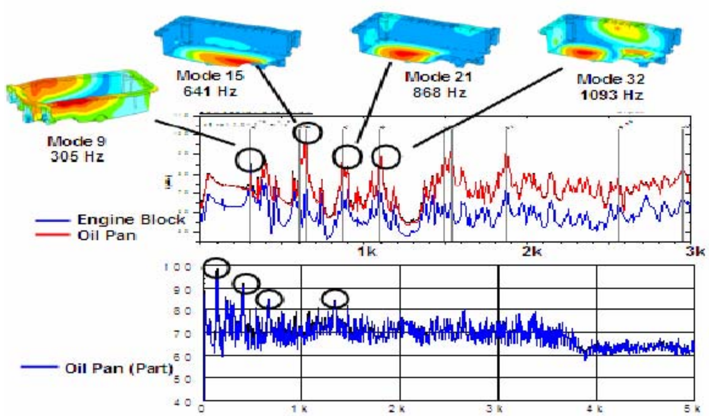
- Medical Ultrasound Imaging
- Transducers
- Hydrophones
- Micro pumps
- Vibration control
- Actuators



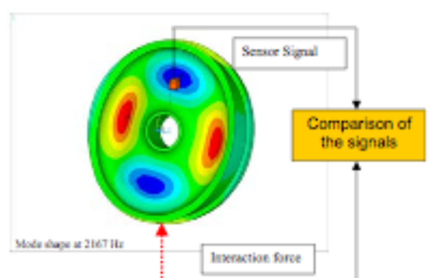
High temperature piezoelectric composites. An active damping concept



Vibration damping (University of Bath)



Significant noise reduction can be achieved with the use of piezoelectric patches



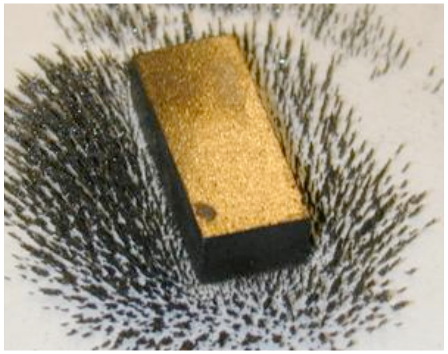
A piezoelectric sensor detects the vibrations of the wheel, leading to an assessment of its wear status

Ferromagnetic Materials

- At temperatures below the Curie point, ferromagnetic materials exhibit a domain structure and spontaneous magnetization which can be oriented by applied magnetic fields (Fe, Ni, Co)

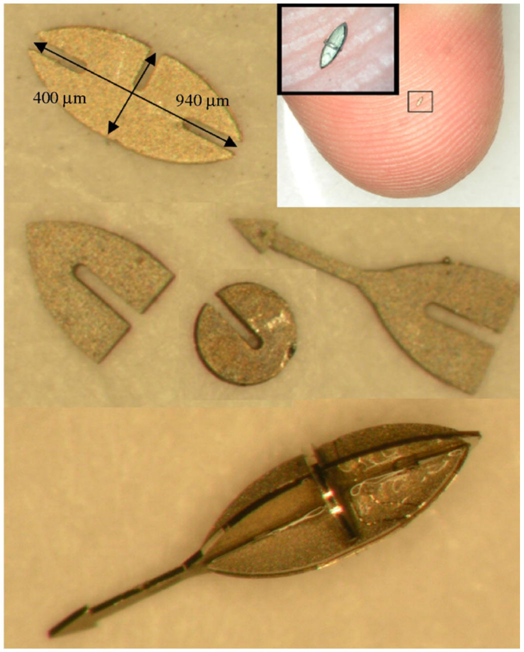
Advantages:

- Moderate Strains
- Moderate Force
- High frequency



Ferromagnetic sensor

http://research.microsoft.com/en-us/projects/ferromag/

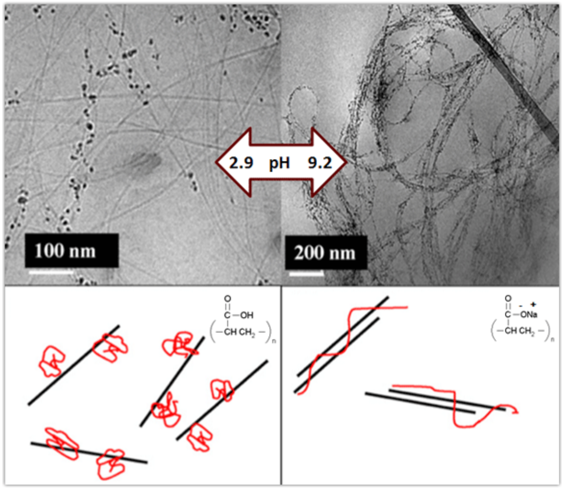


Source: ETH, Zurich

Miniature ferromagnetic prototype devices can be made to move within fluids by applying an external magnetic field

Polymer Nanocomposites

Polymer nanocomposites consist of a polymeric material (e.g., thermoplastics, thermosets, or elastomers) with reinforcement of nano-particles

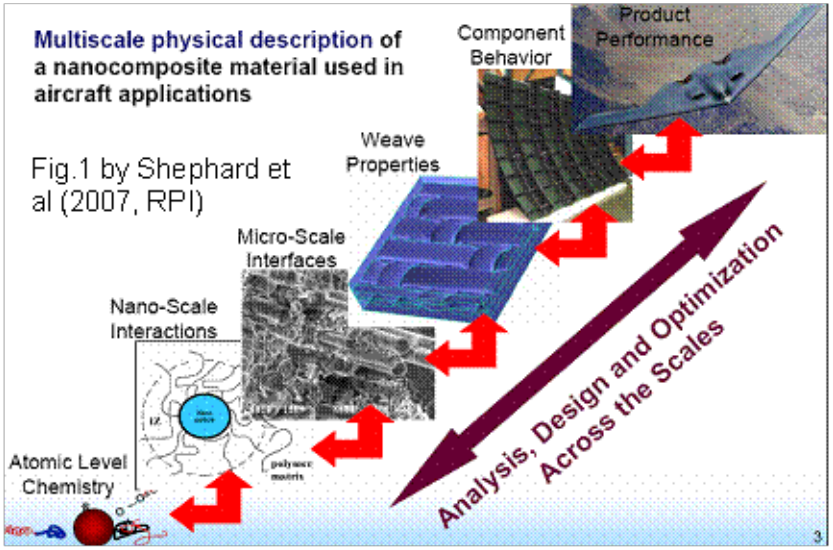


Most commonly used nano-particles include:

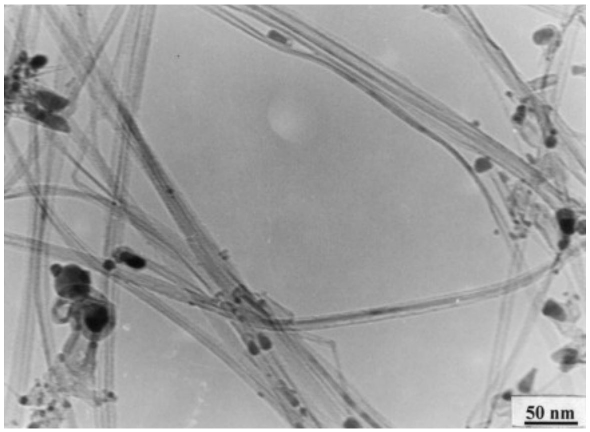
- Carbon nanofibers (CNFs)
- Carbon nanotubes [multiwall (MWNTs), small-diameter (SDNTs), and single-wall (SWNTs)]
- Nanosilica (N-silica)
- Nanoaluminum oxide (Al2O3)
- Others

Thermosets and thermoplastics used as matrices for making nanocomposites include:

- Nylons
- Polyolefin, e.g. polypropylene
- Polystyrene
- Ethylene-vinyl acetate (EVA) copolymer
- Epoxy resins

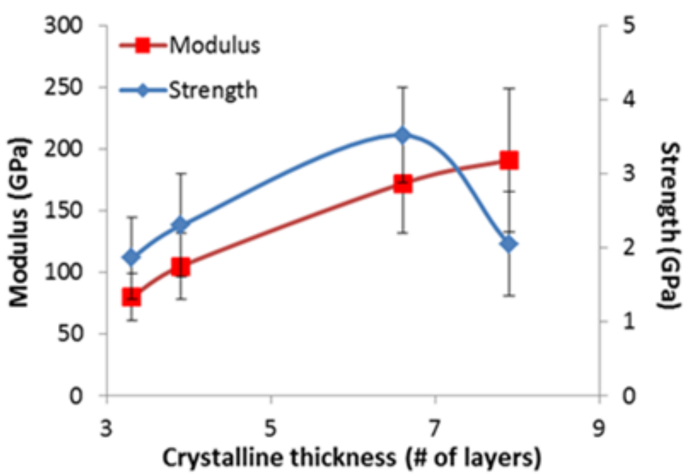


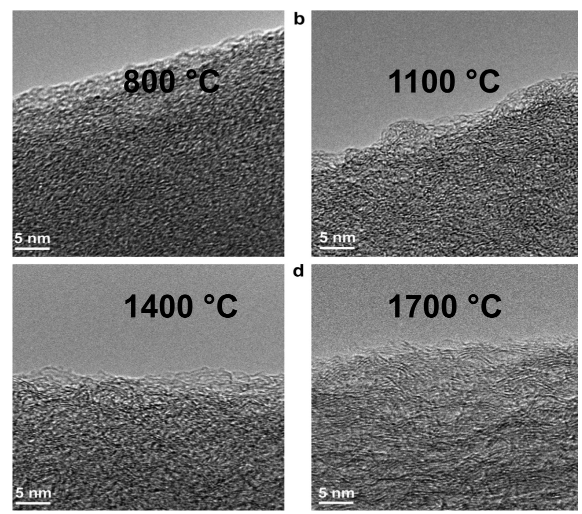
CarbonNanoFibers



TEM image of several CNFs

- Due to the remarkable mechanical properties, high thermal stability and electrical properties, CNFs offer opportunities to develop multifunctional materials
- Role of the interphase around the inclusion:
  - Polymer with restricted chain mobility
  - Higher Tg, Stiffness, Strength





Thermal stability of CNFs

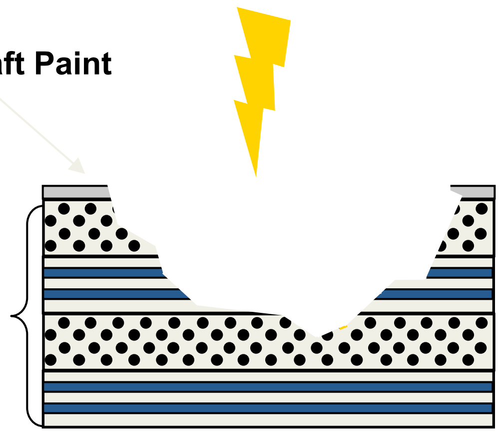
An Application of Polymer Nanocomposites

- Lightning strikes cause:
  - resin melting, vaporization, and ply delamination in composites
    - Increase in affected area
    - Compromise structural integrity of aircraft
    - Difficult to repair
  - damage to onboard electronics without EM shielding
- Current LSP system protects composites from complete failure
  - But large damage still present
- Avoiding weather not always an option

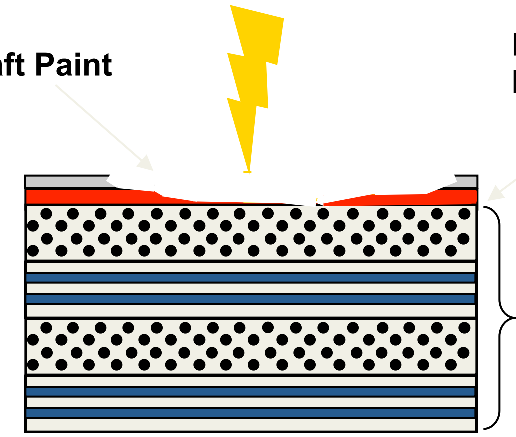


1. http://abcnews.go.com/Travel/Story?id=3994564&page=1
2. http://www.lightningtech.com/d~ta/faq1.html
3. http://www.boeing.com/commercial/aeromagazine/aero_10/loop.pdf

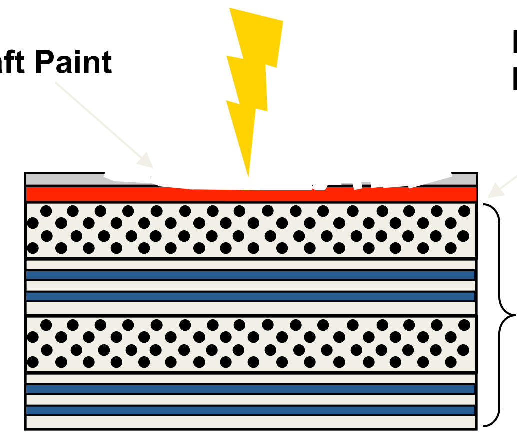
Motivation



Unprotected Composite



No composite damage, some LSP repair / repaint

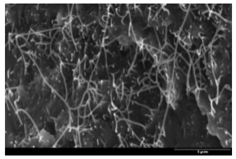


Ideal System – repaint only

- Composite structures are significantly less electrically conductive than aluminum structures
- Lightning Strike Protection (LSP) major concern for composites
- The initial lightning strike must be dispersed quickly around the skin to prevent concentrated damage

Fabrication

- Carbon nanotube thin film fabrication

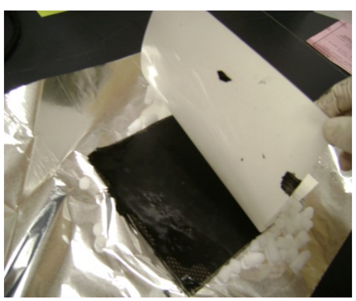


Oxidized CNTs
+ Epon 862/W

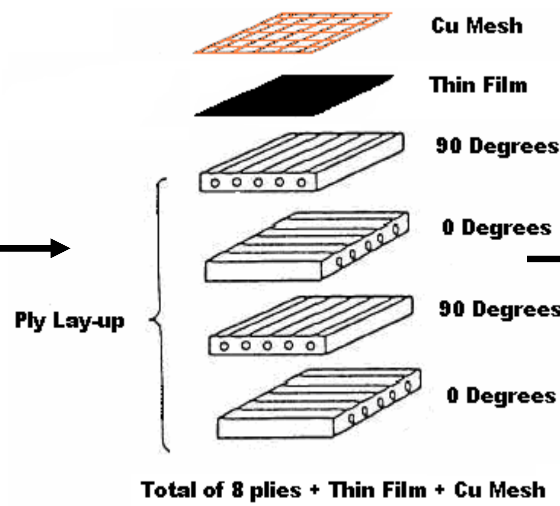
Film Applicator

Thin Film

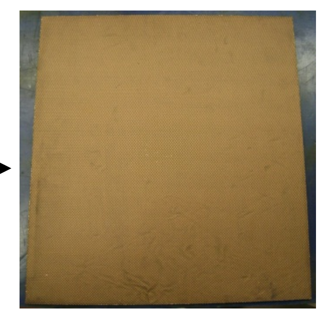
- Incorporate thin films into composite laminate structure
  - Embody CNT loaded resin thin film on top carbon fiber ply
  - Lay-up rest of carbon fiber and Cu mesh
    - T650-135 carbon fiber plies
    - Astrostrike Cu mesh
  - Autoclave



Thin film incorporated into top ply



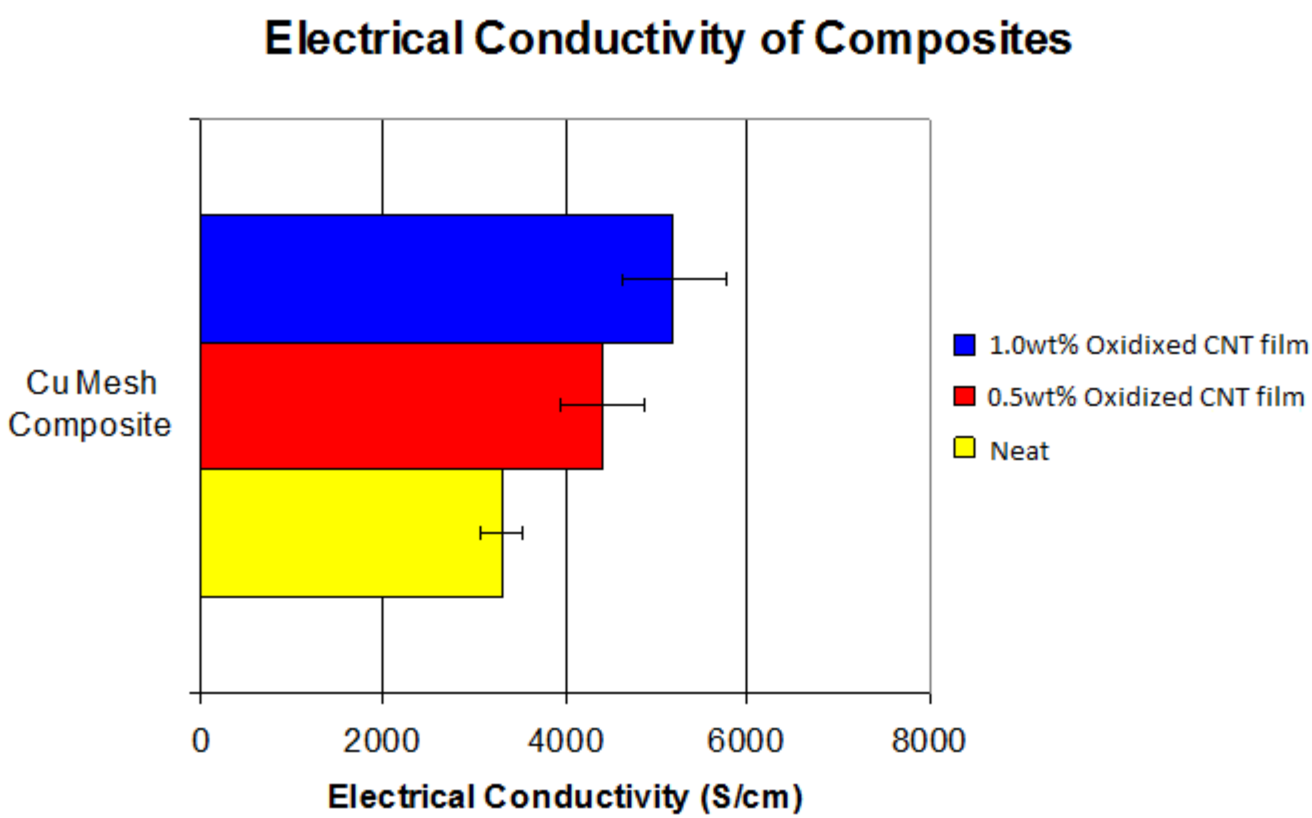
Autoclave



Cu-Mesh Composite

Electrical Conductivity

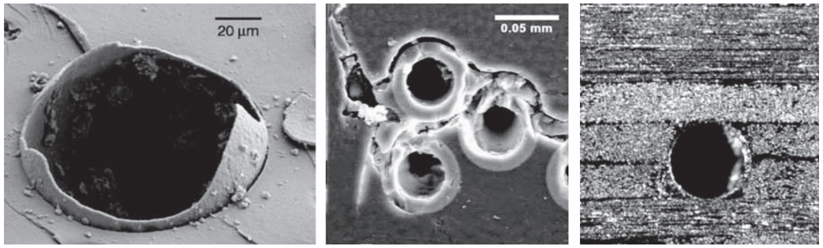
- Composite Electrical Conductivity



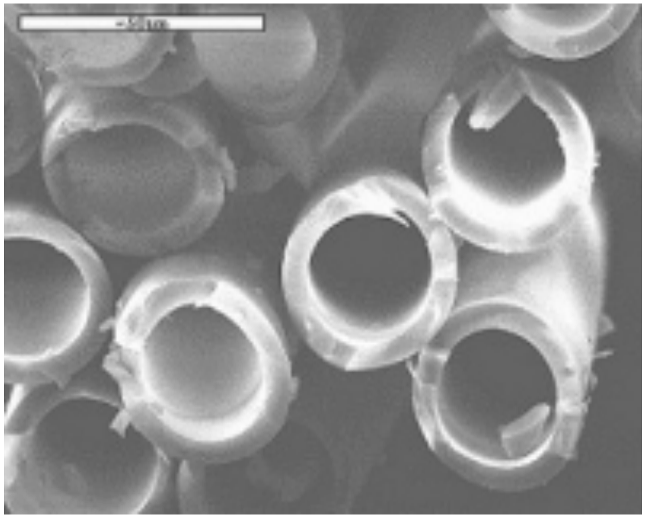
- Increase of about 1000 S/cm from control to 0.5 wt% and from 0.5 to 1.0 wt%

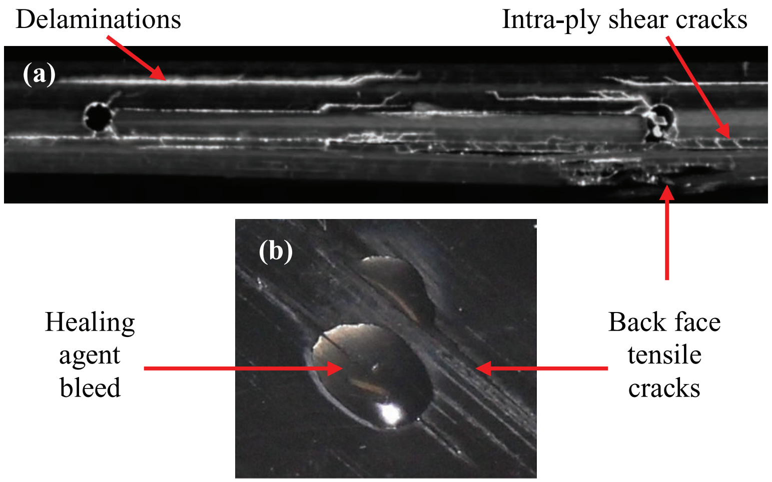
Self-Healing Composites

- Self healing can be described as mechanical, thermal or chemically induced damage that is repaired by materials already contained within the structure
- The release of repair agent from embedded storage reservoirs mimics the bleeding mechanism in biological organisms. Once cured, the healing resin provides crack arrest and recovery of mechanical integrity
- Experiments have shown as much 75% recovery of the original strength



storage reservoirs





Self-Healing Fibre Reinforced Composites via a Bioinspired Vasculature
DOI: 10.1002/adfm.201101100
Christopher J. Norris, Gregory J. Meadway, Michael J. O'Sullivan, Ian P. Bond, and Richard S. Trask