UAM Fabrication of Metal-Matrix Smart Material Composites

Authors: Ryan Hahnlen, Prof. Marcelo Dapino

Collaborators:
- Karl Graff, Matt Short & group
- Suresh Babu & group

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www.SmartVehicleCenter.org

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Research Objective and Talk Overview

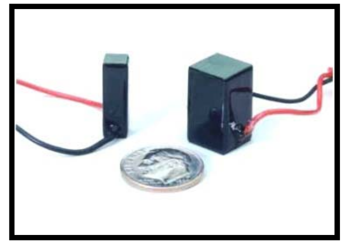
Objective: Develop multifunctional metal-matrix composites through an emerging rapid prototyping technique called Ultrasonic Additive Manufacturing (UAM)

Talk Overview:

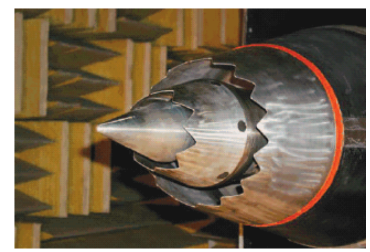
- Background
- Active metal-matrix composites
  - NiTi-Al composites
    - Strain sensing
      - Electrical insulation tests
    - Stiffness tuning tests
    - Thermomechanical deformation tests
  - Galfenol-Al composites
    - Magnetic actuation
  - PVDF-Al composites
    - Initial results

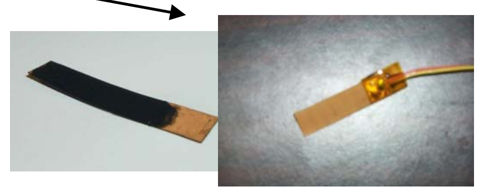
Background: Smart Materials

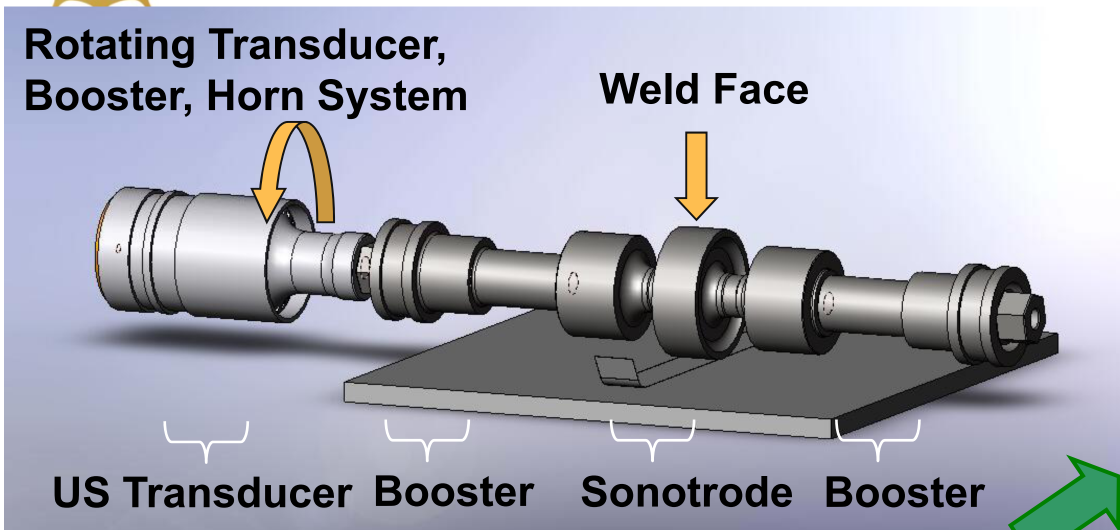
- An active or “smart” material is one that exhibits controllable changes in shape and properties in response to external excitations
- Smart materials are used to create solid state actuators and sensors, and adaptive structures and systems



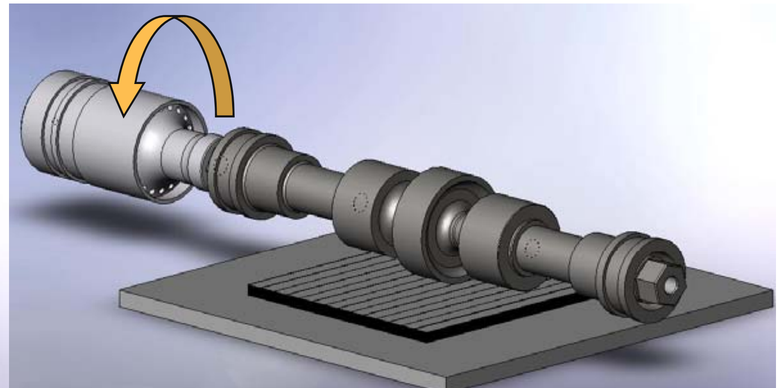
Material Type	Activation
Piezoelectric	Electrical
Magnetostrictive	Magnetic
Shape Memory	Thermal
Magnetorheological fluid	Magnetic
Electroactive polymers	Electrical



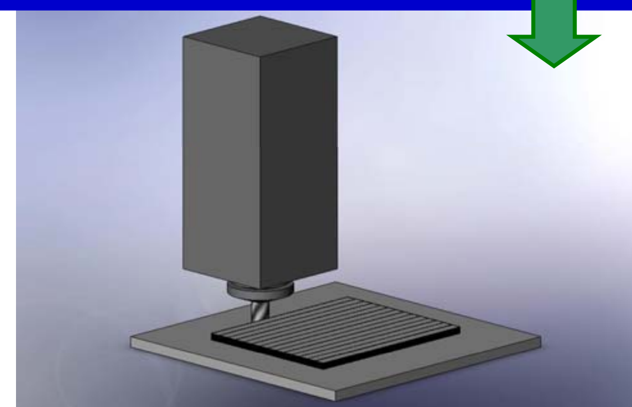




(1) Ultrasonic welding system with rolling horn welds Al tape to base plate



(2) Applying successive layers of Al tape builds feature



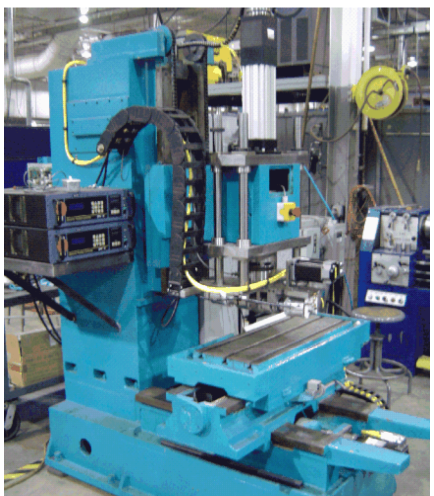
(3) Periodic machining operations to shape features and maintain uniform welding surface

- **UAM**: Based on **ultrasonic metal welding** and can create metal parts from Al, Ti, and Cu
- **Low-temperature** process
- Unprecedented opportunity to embed both **active materials** and **electronics in metals**

Background: Expanding the State of the Art of UAM

Solidica Beta System

Photograph courtesy of Solidica, Inc.



10 kW UAM Test Bed

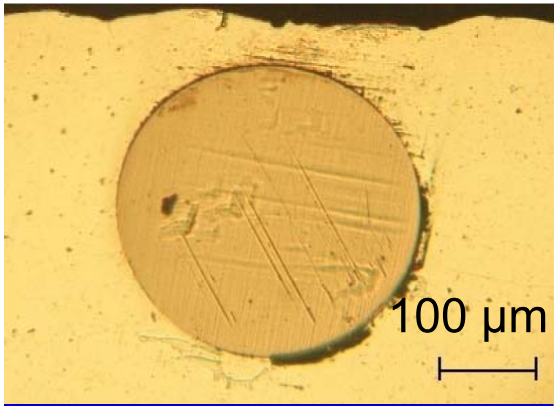
- Solidica Beta system has 1.5 kW of ultrasonic power and integrated CNC capabilities
- UAM test bed system at Edison Welding Institute has 10 kW of ultrasonic power. Increased power creates more plastic flow and allows for the embedding of larger diameter wires.
- 3-D High Power UAM system under development will create multifunctional parts with the ability to **embed sensors and actuators in three dimensions**

Image courtesy of EWI

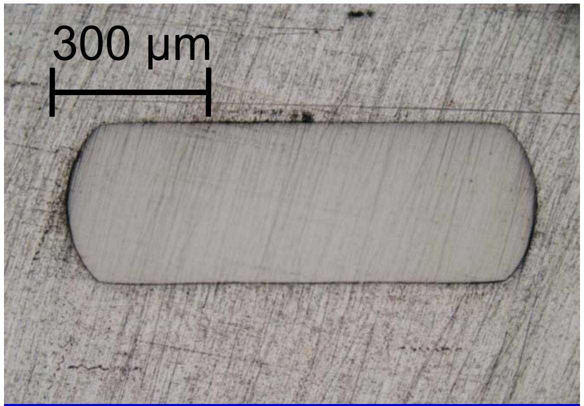
High Power UAM Developed under Wright Project

Embedding Materials via UAM

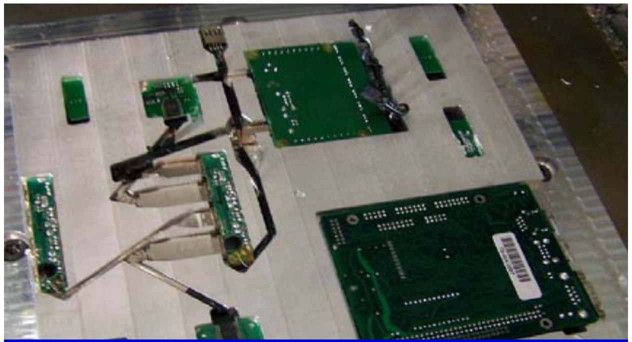
- UAM can be used by "welding over" the material to be embedded, allowing **plastic flow of the matrix** to envelop the material
  - Current capabilities allow for embedding up to **381 μm wires** and **245 μm ribbons** through plastic flow only
  - Previous research embedded up to 100 μm wires
- **Subtractive processes** involve machining pockets or grooves
  - Used to embed larger diameter wires or **large, arbitrary shaped materials** or objects



381 μm Dia NiTi Wire



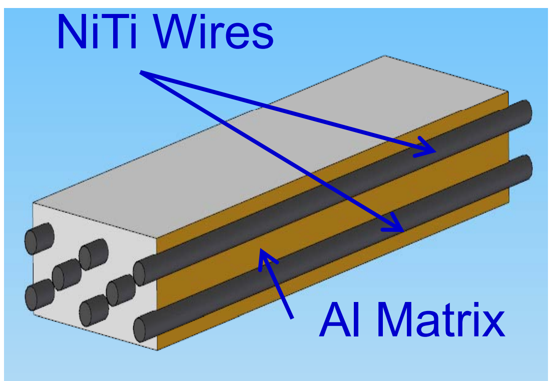
Embedded NiTi Ribbon



Electronics Positioned for Embedding*

*Siggard, E., "Investigative Research into the Structural Embedding of Electrical and Mechanical Systems using Ultrasonic Consolidation," M.S. Thesis, Utah State University, (2007).

- **Embedded stress and strain sensing** for real time health monitoring
  - NiTi-Al: electrical resistance; FeGa-Al: magnetic; PVDF-Al: piezoelectric
- **Stiffness tuning** for noise and vibration attenuation
  - NiTi-Al: changes in elastic modulus between martensite and austenite phases
- **Dimensional stability** for in high temperature environments
  - NiTi-Al: recover thermally induced strain via Shape Memory Effect (SME)



Seamlessly Embedded Sensors

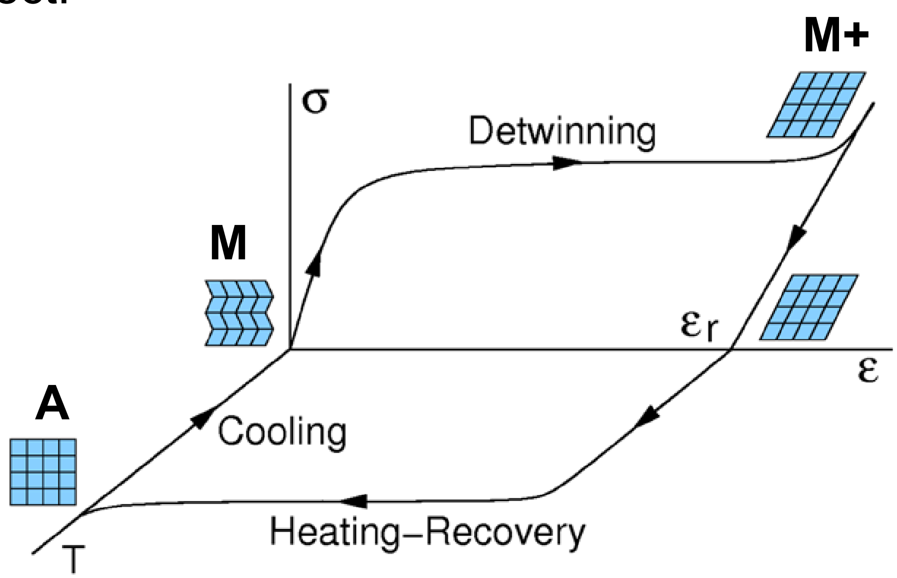
Change in Local and Global Mobility Paths*

Dimensional Stability: Jet Engine Components**

*Book, W, "FLUID POWER RESEARCH CENTRES WORLD-WIDE," Fluid Power Net, 17, (2005). http://journal.fluid.power.net/issue17/fprcentre17.html
**GE Reports, June 16, 2009 http://www.gereports.com

Shape Memory Alloys (SMAs)

- NiTi (nickel-titanium or "Nitinol") is an SMA which exhibits up to 8% no-load strain recovery when **heated** through its martensite-austenite transition temperature
- This strain recovery is possible due to **stress and temperature induced transformations** between the martensite and austenite phases of NiTi
- Shape Memory Effect:



- Phase transition induces changes in **elastic modulus, ~160%,** and **electrical resistivity, ~16%**

Active NiTi-Al Composites

Sample	NiTi Elements	NiTi Form	Percent NiTi	Test Type
#1	1	254 µm X 6350 µm	-	Electrical Insulation
#2	8	100 µm Dia.	4.5%	Stiffness Tuning
#3	6	203 µm Dia.	13.4%	Stiffness Tuning
#4	8	203 µm Dia.	22.3%	Stiffness Tuning
#5	6	203 µm Dia.	13.4%	Thermomechanical Strain Testing
#6	1	381 µm Dia.	-	System Capability Testing

NiTi-Al Composite #3 with 6 X 203 µm NiTi Wires

4 X 100 µm Diameter NiTi Wires Embedded in Al Matrix

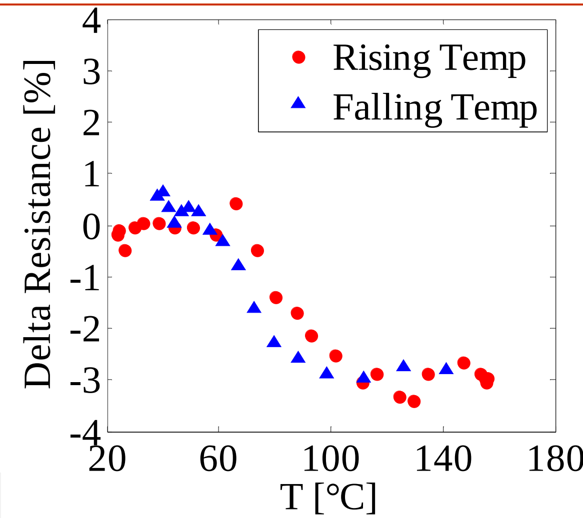
Characterization of NiTi Wire for Sensing

- **381 μm diameter NiTi** wire tested with **0 N and 12 N axial load** and thermally cycled to **demonstrate the sensing concept** and **provide material properties**

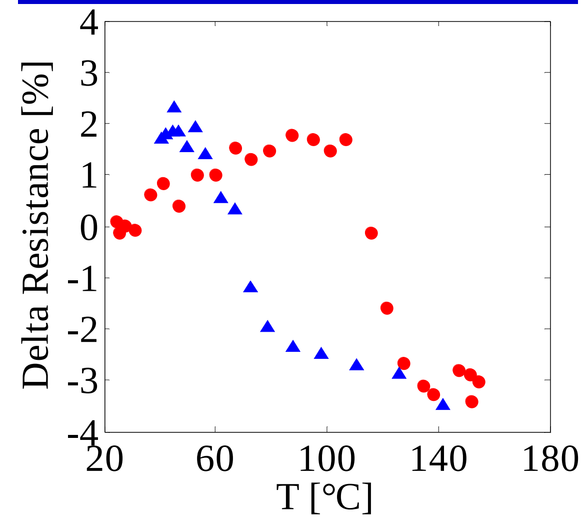
- Wheatstone bridge measurements:
  - Temperature causes up to a **-3% resistance change** from room temperature

Experimentally Derived Properties		
M_f	Martensitic Finish Temperature	55 °C
M_s	Martensitic Start Temperature	90 °C
A_s	Austenitic Start Temperature	65 °C
A_f	Austenitic Finish Temperature	100 °C
C_M	Stress Influence Coefficient for Martensite	1000 MPa/°C *
C_A	Stress Influence Coefficient for Austenite	3MPa/°C
ρ_M	Electrical Resistivity of Martensite	1.07 μOhm-m
ρ_A	Electrical Resistivity of Austenite	0.92 μOhm-m

* Value estimated to reflect no noticeable change from applied stress



0 N Load



12 N Load

NiTi-Al Composite Resistance Change Model

- **Brinson model** with material properties obtained from our experiment and literature:

Martensitic Volume Fraction

$$\rho_{NiTi}(\xi,T)=\xi\left[\rho_M+\kappa_M(T-T_o)\right]+(1-\xi)\left[\rho_A+\kappa_A(T-A_f)\right]$$

Resistivity Temperature Coefficient, Martensite

Resistivity Temperature Coefficient, Austenite

Reference Temperature

Model Parameters	
κ_M	1.75 nOhm-m/°C*
κ_A	0.50 nOhm-m/°C*
ξ	Between 0 and 1
T_o	20 °C

$$R_{NiTi}=\frac{\rho_{NiTi}(\xi,T)L}{A}$$

NiTi Resistance

$$R_{comp}=\left[\frac{1}{R_{NiTi}}+\frac{1}{R_{Al}}\right]^{-1}$$

Composite Resistance

$$\Delta R_{NiTi}=\frac{R_{NiTi}(T)-R_{NiTi}(T_o)}{R_{NiTi}(T_o)}\times 100$$

Change in NiTi Resistance

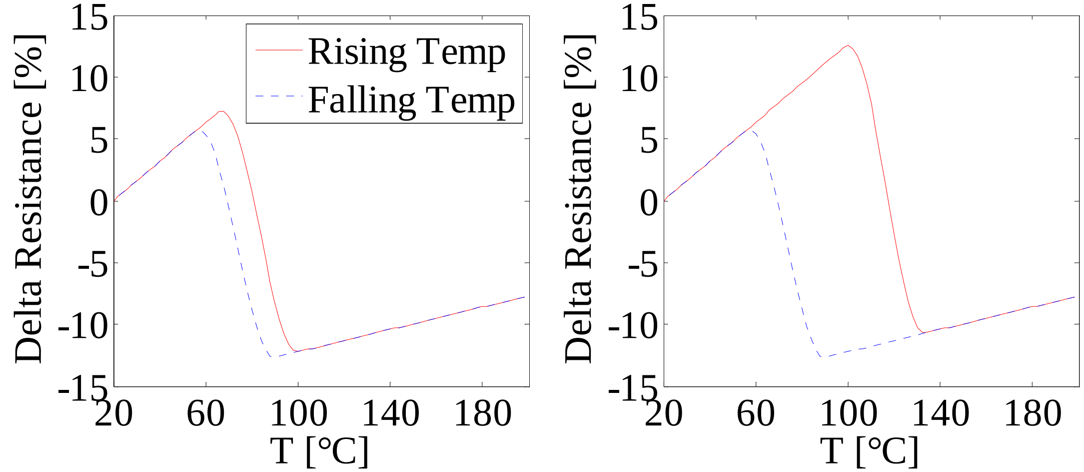
$$\Delta R_{comp}=\frac{R_{comp}(T)-R_{comp}(T_o)}{R_{comp}(T_o)}\times 100$$

Change in Composite Resistance

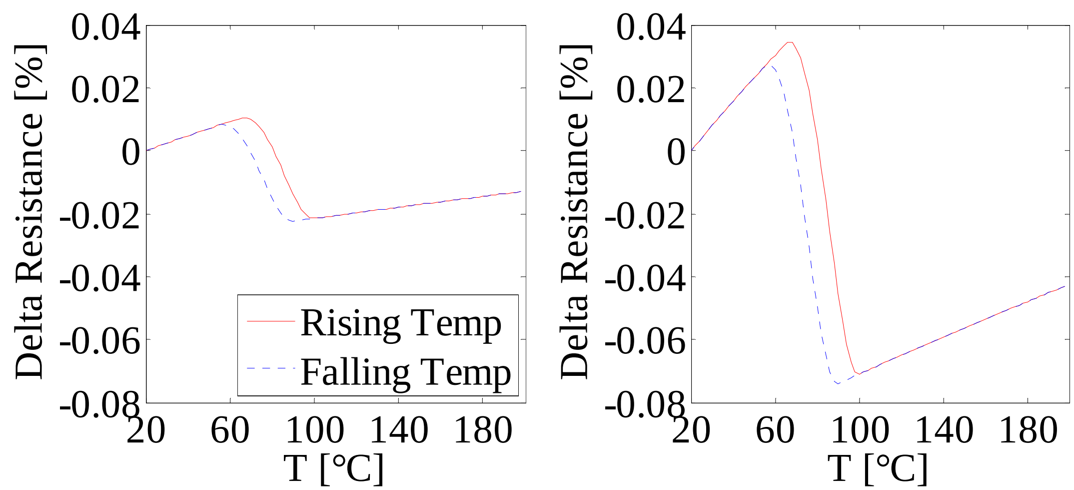
Brinson, L., "One Dimensional Constitutive Behavior of Shape Memory Alloys," Journal of Intelligent Material Systems & Structures, 4, 2, 229-242, (1993).
* Matsumoto, H., "Electrical resistivity of NiTi with a high transformation temperature," Journal of Materials Science Letters, 11, 367-368, (1992).

Insulation Tests: Motivation and Methods

- Can utilize change in resistance for **stress/strain sensing**
  - Resistivity of Al matrix is **much less than NiTi**
  - NiTi-Al models **exhibit less than 0.05% resistance change** due to electrical continuity with Al matrix
- Candidate methods for insulating NiTi from Al matrix:
  - Coatings include **thick oxide layer** through anodization, **PTFE (Teflon), commercial spray enamel, polyimide varnish, and polyimide tape (Kapton)**



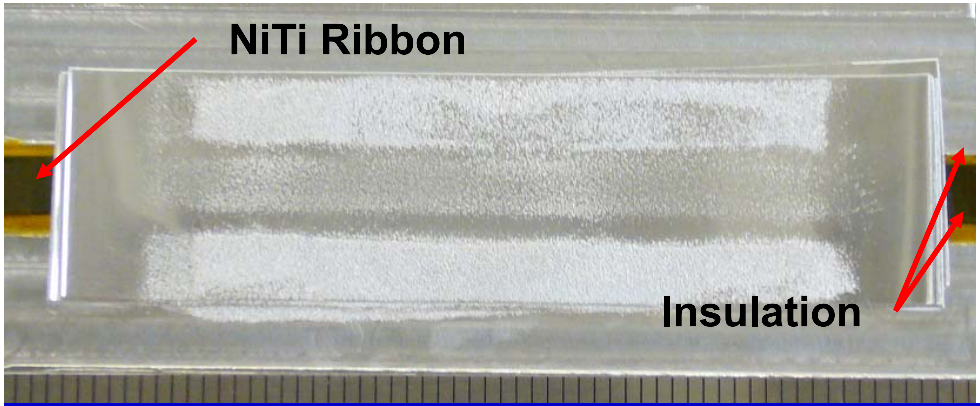
0 N Load and 12N Load NiTi Wire Model



4.5% and 13.4% NiTi-Al Composite Model

Insulation Tests: Results

- Insulated samples: tested **resistance and coating adhesion** before embedding
  - **Oxide coating and PTFE** did not adhere well to NiTi
- Remaining samples embedded in Al matrix - resistance measured after embedding
  - **Commercial spray** and **polyimide varnish resistance <1 ohm**
    - Insulation coatings **did not withstand the embedding process**
  - **Polyimide tape** maintains high **electrical resistance** between NiTi and Al
    - Enables NiTi **embedded stress/strain sensing** and **actuation**



NiTi-Al Composite #1 with Kapton Insulation

NiTi-Al Composite Stiffness Tuning: Modeling

- **Brinson model** with material properties obtained from literature:

Martensitic Volume Fraction

Elastic Modulus, Austenite

$$E_{NiTi}(\xi) = \xi E_M + (1-\xi)E_A$$

Elastic Modulus, Martensite

Elastic Modulus, Aluminum

E_M	26 GPa*
E_A	67 GPa*
E_{Al}	68 GPa**
ξ	Between 0 and 1
T_o	20 °C

$$k_{comp} = \frac{\left(E_{NiTi}A_{NiTi} + E_{Al}A_{Al}\right)}{L}$$

Composite Stiffness

$$\Delta k_{comp} = \frac{k_{comp}(T) - k_{comp}(T_o)}{k_{comp}(T_o)} \times 100$$

Change in Composite Stiffness

Build with 6 X 203 µm NiTi Wires

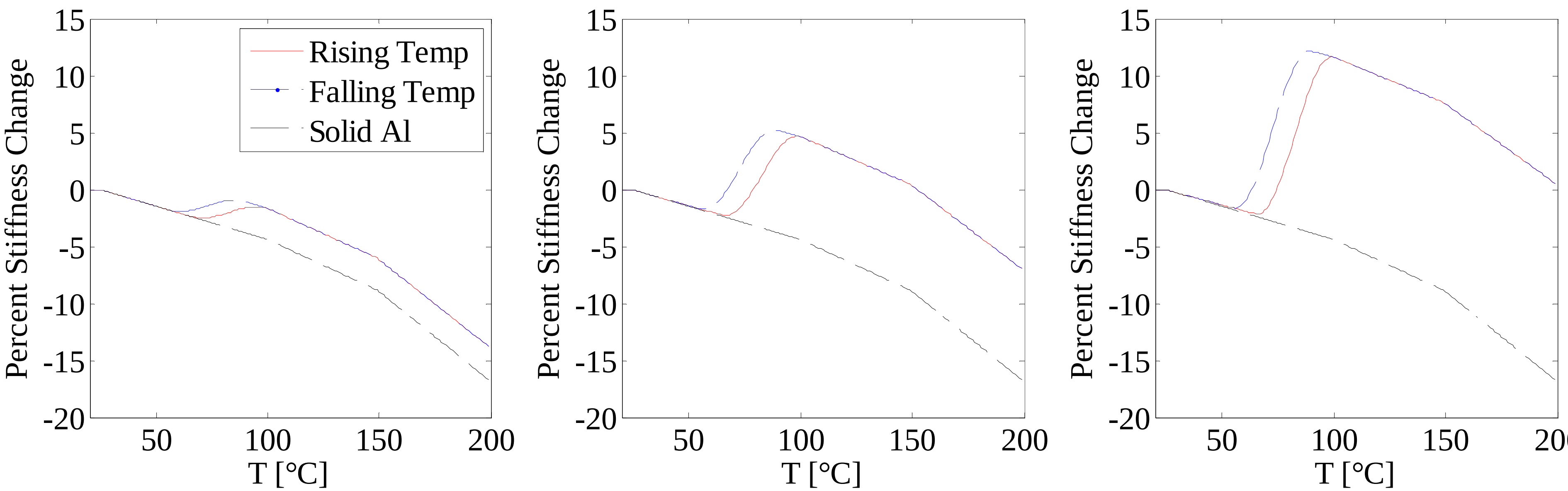
Brinson, L., "One Dimensional Constitutive Behavior of Shape Memory Alloys," Journal of Intelligent Material Systems & Structures, 4, 2, 229-242, (1993).

*Dynalloy Inc. http://www.dynalloy.com, (2008).

**Kaufman, "Aluminum Alloy Database," Knovel, 2004. http://knovel.com

NiTi-Al Composite Stiffness Tuning: Modeling cont.

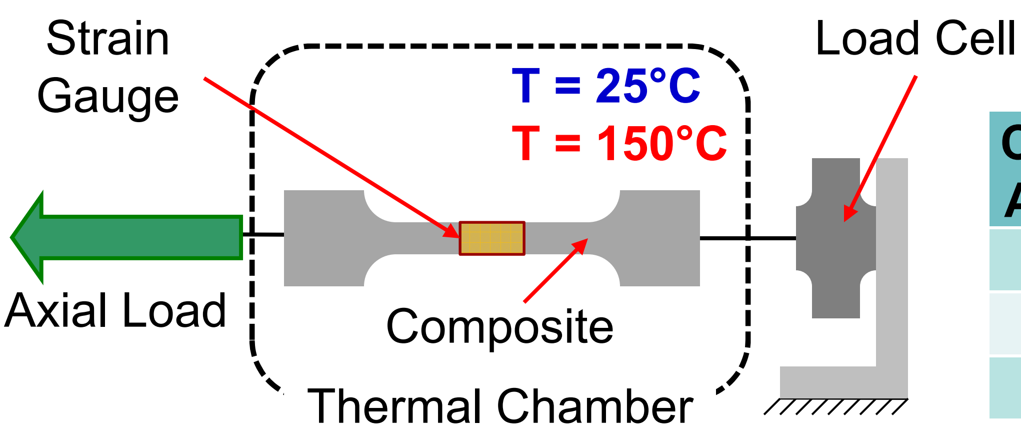
- **Model Key Points:**
  - **Initial softening** due to Al matrix becoming soft with higher temperature
  - **Sharp increase** during martensite to austenite transformation
  - **After transformation** to austenite**, composite softens** with Al matrix
  - **Increase in NiTi yields increase in stiffness change:** 4.5% exhibits -1% change; 13.4% exhibits 5% change; 22.3% exhibits 12% change



Modeled Stiffness Change of 4.5% , 13.4%, and 22.3% NiTi Area Ratio Composites

NiTi-Al Composite Stiffness Tuning: Results

- NiTi composites **axially loaded at room temperature** and at **elevated temperatures ~150°C**
- Composite strain measured with surface mounted **strain gauge**, temperature measured with **surface mounted thermocouple**
- **4.5% NiTi** composite experiences **-6% stiffness change** – **similar to model**
- **13.4% NiTi** composite experiences **5.5% stiffness change** – **similar to model**
- **22.3% NiTi** composite experiences **-22% stiffness change** – **contrary to model**
  - Magnitude of decrease typical of a **solid Al sample**

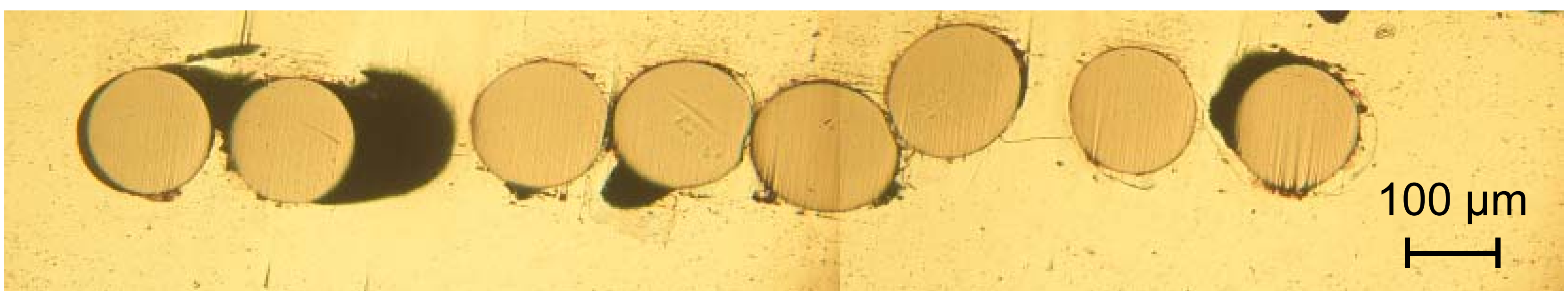


Composite Area Ratio	Stiffness Change	Model Prediction
4.5%	-6%	-1%
13.4%	5.5%	5%
22.3%	-22%	12%

NiTi-Al Composite Stiffness Testing Diagram

NiTi-Al Composite Stiffness Tuning: Results cont.

- NiTi-Al composite was sectioned and polished for **optical microscopy**
- Microscopy indicates **wires interacted** possibly rolling over each other during embedding **due to ultrasonic vibrations**
- Poor mechanical coupling **caused thermal softening** of the composite
  - **Wires allowed to transform without carrying any applied load**
- **Wire proximity** is new concern with higher area ratios
  - Other wire forms, i.e. **ribbons**, not as mobile

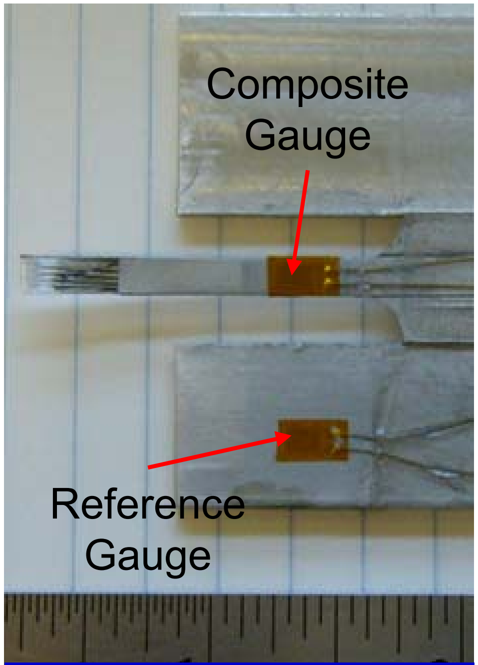


Material Section of 22.3% NiTi-Al Composite

Thermomechanical Deformation Tests: Methods

- 13.4% NiTi composite thermally cycled, unloaded, to **observe thermomechanical deformation**
- Cycled multiple times from **room temperature** to **~150°C**
- **Temperature monitored** by surface mounted thermocouple
- Strain monitored by **strain gauges on composite and on base plate**
  - Base plate gauge acts as **reference to nullify thermal output** from the gauges
  - Obtain CTE of composite using reference gauge*:

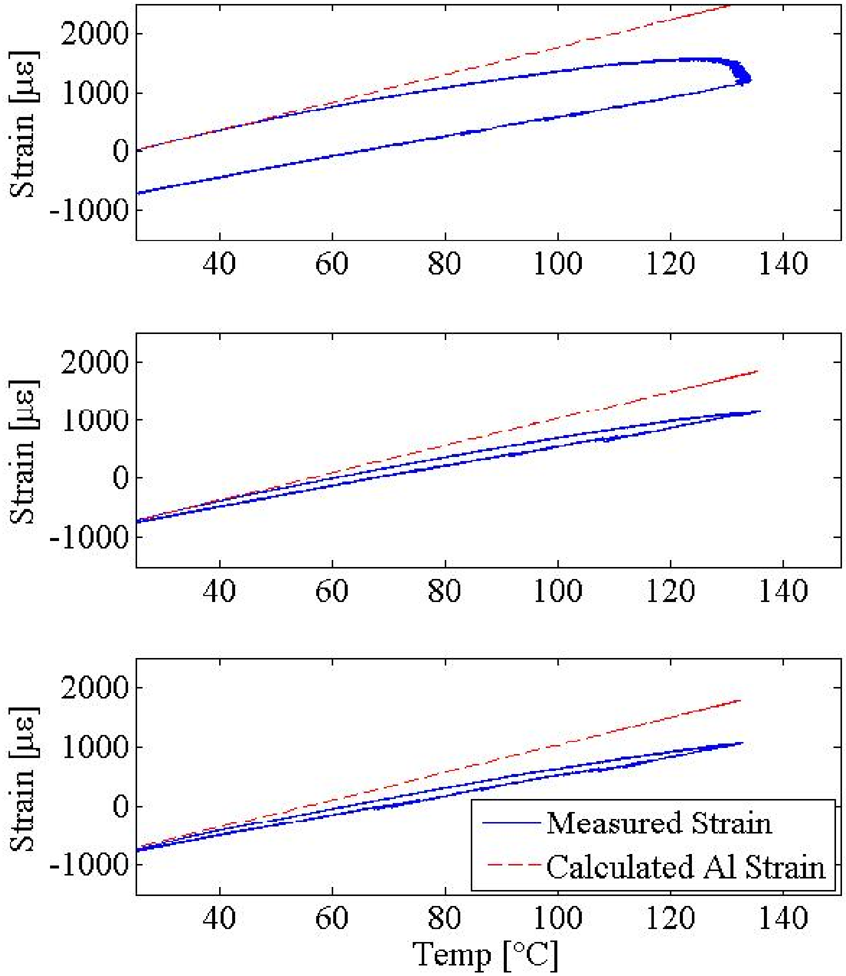
$$\alpha_{comp} = \alpha_{ref} + \frac{\varepsilon_{comp} - \varepsilon_{ref}}{\Delta T}$$



NiTi-Al Composite #5

*Scalea, F. L., “Measurement of thermal expansion coefficients of composites using strain gauges," Experimental Mechanics 328, 233{241 (December 1998).

Thermomechanical Deformation Tests: Results



Strain vs. Temperature for 13.4% NiTi-Al Composite #5

- Initial thermal cycle shows **large strain recovery: -721 με**
  - Initial recovery **due to detwinned NiTi** embedded in composite
  - **Demonstrates thermal actuation**
- Subsequent cycles **return to respective initial strain**
- In all cycles, composite expands **significantly less than a solid Al piece** (CTE: **~15 με/°C** vs. **23.2 με/°C**)

Magnetostrictive Materials

- Magnetostrictive materials enable **high frequency** sensing and actuation
  - **Sensing:** generate magnetic fields in response to applied strain
  - **Actuation:** exhibit strain in response to magnetic fields

- Embedding **Galfenol (FeGa)** in UAM active composites for **non-contact magnetic sensing and actuation**
  - **Mechanical properties similar to steel**
  - **Structural material**
  - **Machinable and formable using conventional methods**

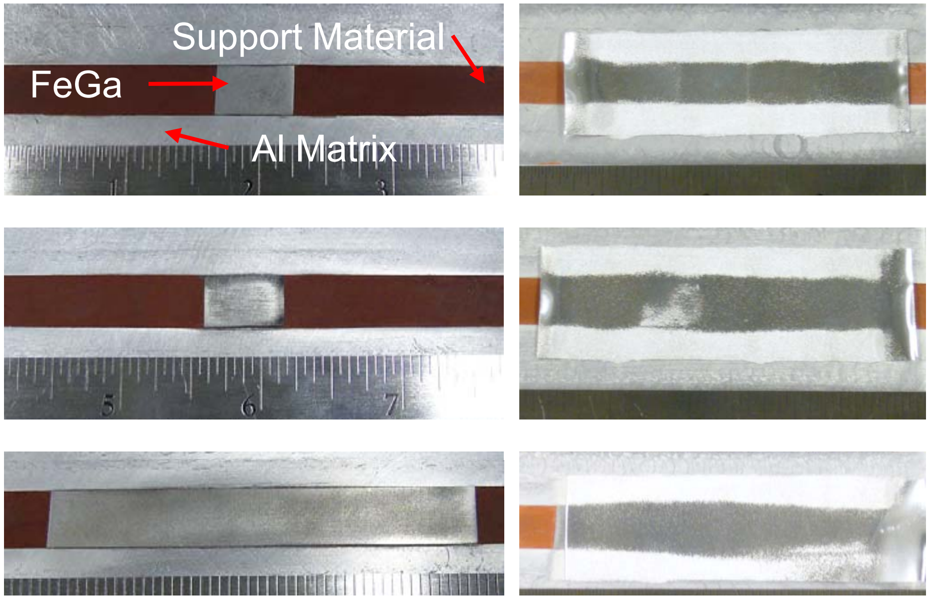
Rolled Galfenol Strip

Galfenol Formed into Ring

FeGa-Al UAM Composites

Constructed three FeGa-Al composites:

- Composite #1 and #2 to **test embedding methodology** and **observe interface**
  - Interface shows intimate contact, suggests good **mechanical coupling** to matrix
- Composite #3 used for **actuation testing**

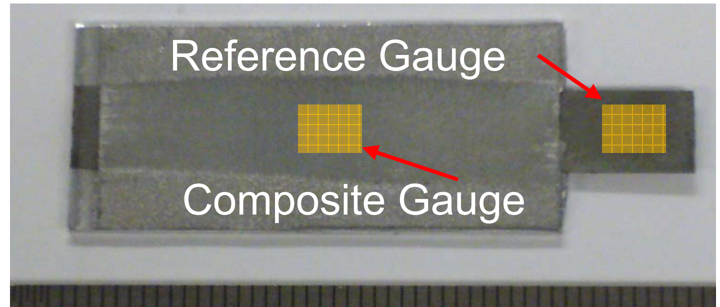


FeGa-Al Composites Before and After Embedding

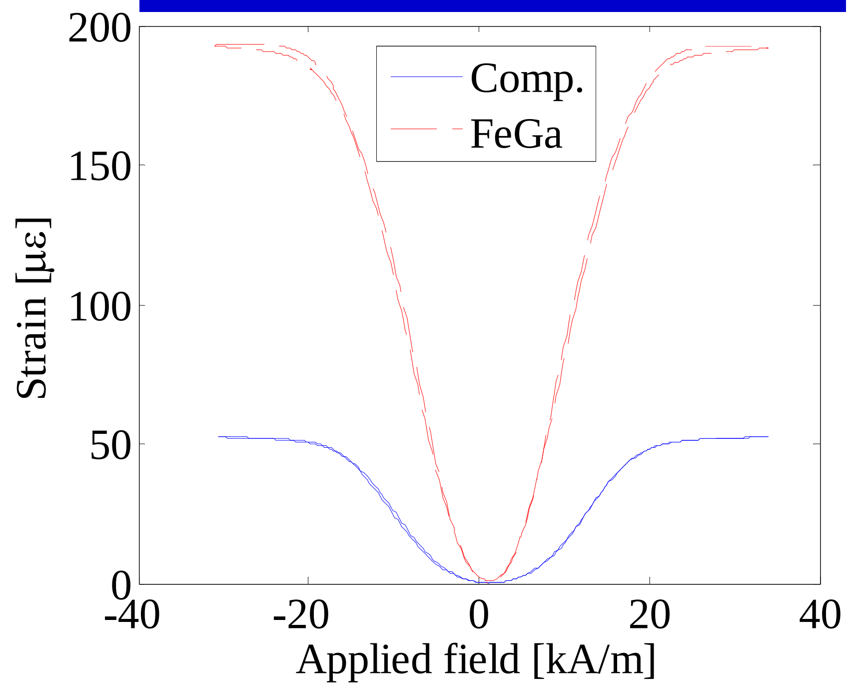
Microsection of FeGa-Al Interface

FeGa-Al Composites: Actuation Experiment

- FeGa-Al Composite #3 machined to **1.27 mm thick** with a section of **exposed FeGa for reference**
- **Strain gauges** mounted to **composite surface** and **exposed FeGa**
- Composite #3 suspended in electromagnetic drive coil **excited with ±30 kA/m AC field**
- Observed exposed **FeGa response 193.5 με**, nominal
- Observed **52.4 με response** on the composite surface
  - **Reduction in magnetostriction** likely due to **loading of FeGa** or **coupling losses**



FeGa-Al UAM Composite #3



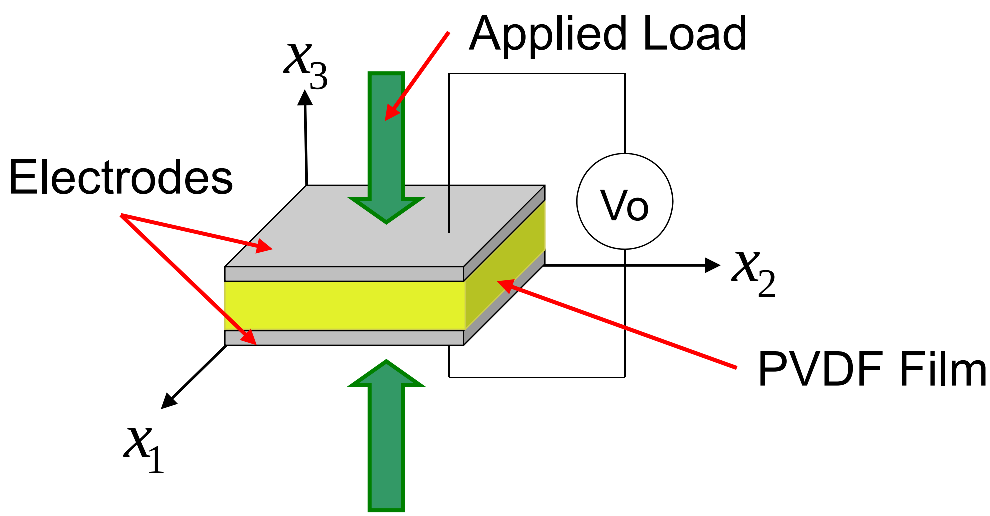
FeGa and FeGa-Al Composite Strain Response to Applied Field

Electroactive Polymers

- Electroactive **Polyvinylidene Fluoride (PVDF)** is a piezoelectric polymer
  - **Sensing:** induced stress creates an electric charge
  - **Actuation:** electric charge induces strain
- High electromechanical coupling – **high sensitivity**
- Available as sheets, tubing, films, plates, etc.

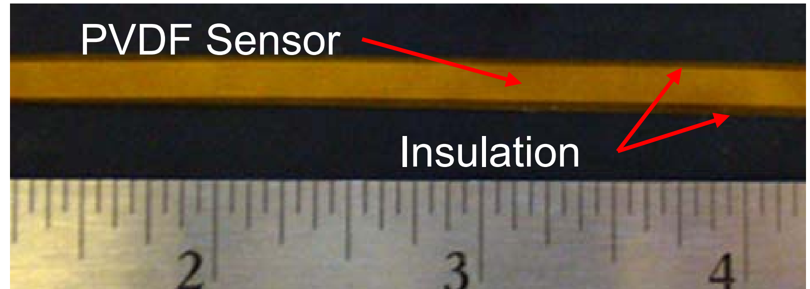
•Utilize pieces cut from **25.4 μm thick PVDF film** for active composites

•**Temperature sensitive** – will de-pole (loose electroactive properties) above 195° C

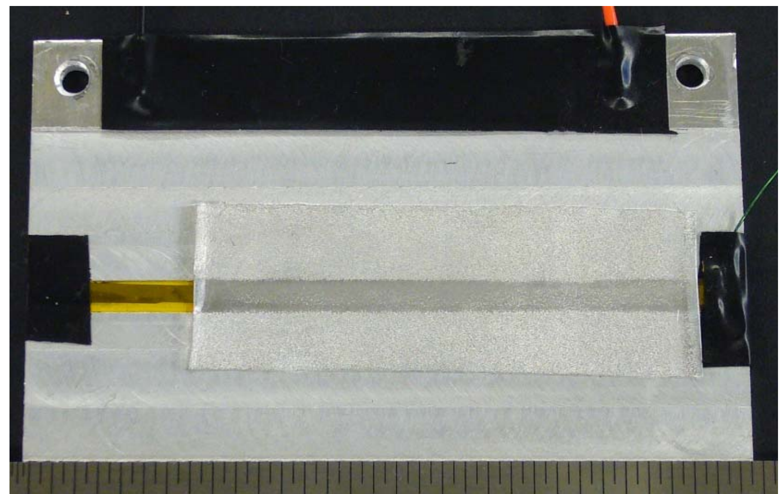


PVDF-Al Composite Sensor

- Sensor created by cutting electroactive **PVDF film** with deposited electrodes cut into a 3.175 mm wide strip
- Sensor **encapsulated with Kapton** to provide electrical insulation
- **Sensor placed in machined groove** to lay flush with Al surface and embedded via UAM
- **Electrical resistance** between sensor and matrix and **sensor capacitance** remained unchanged after embedding
- Preliminary tests show **composite response to impact and vibration**
- **UAM process temperature below 195°C**



PVDF Sensor Before Embedding

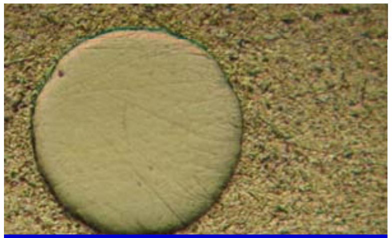


Completed PVDF-Al UAM Sensor

Concluding Remarks

NiTi-Al UAM composites:

- **Polyimide film** provides durable, **electrically insulated** coating for UAM embedded material
  - Enables NiTi based embedded **stress/strain sensors**
- **Stiffness tuning** models predict **stiffness changes** for **4.5% and 13.4% NiTi composite**
  - 22.3% NiTi-Al Composite: poor NiTi/Al coupling due to wire interaction results in softening at high temperature
- 13.4% NiTi-Al Composite: **thermal actuation** via SME and significantly **lower CTE compared to Al** (~15 με/° C vs. 23.2 με/° C)
  - Ongoing work to **model these behaviors**



Embedded NiTi Wire

NiTi-Al UAM Dogbone

Concluding Remarks cont.

<u>FeGa-Al UAM Composites:</u>

- Composite exhibits **magnetic actuation**
- Ongoing work to test magnetic based **non-contact magnetic sensing**
- Modeling will aid construction of future composites

FeGa Strip Prior to Embedding

<u>PVDF-Al UAM Composite:</u>

- Composite exhibits **embedded sensing capabilities**
  - **Demonstrates interface temperature <195° C**
- Ongoing work to test the **frequency response**

PVDF-Al Composite