An Introduction to a Porous Shape Memory Alloy Dynamic Data Driven Application System

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What are Shape Memory Alloys?

• Shape Memory Alloys (SMAs) are metallic alloys that undergo a solid-to-solid phase transformation which can exhibit large recoverable strains.

• **Austenite**
  – High temperature phase
  – Cubic Crystal Structure

• **Martensite**
  – Low temperature phase
  – Monoclinic Crystal Structure
Shape Memory Alloys

- Shape Memory Alloys are materials that change their internal structure due to changes in temperature and/or externally applied loads:
  - At high temperatures the crystal lattice is in the high symmetry austenite phase (A).
  - At low temperatures the material exists in a low symmetry martensite phase (M).
  - The austenite to martensite phase transition is diffusionless and is characterized by shear deformations of entire regions inside the material.
History of SMAs

- **1932**: discovery of reversible marstensite-austenite transformation in Au-Cd (gold-cadmium) based alloys.
- **1951**: discovery of recovery of deformed shape in Cu (copper) based alloys.
- **1962**: discovery of shape memory effect in Ni-Ti (nickel-titanium) alloys.
- **1970**: first commercial use of Nitinol in F14 Tomcat aircraft.
SMAs in Aerospace

• Release mechanisms
  – Bolts that expand and contract

• In space
  – Solar panel deployment
  – Space station component joining
  – Space vehicular docking
  – Mars rover components

• Airplanes/drones
  – Smart wings
  – Jet engine variable intakes
  – Helicopter blade vibration control
SMAs and Vibration Isolation

- SMAs can be incorporated in vibration isolation devices:
  - They can sustain large recoverable inelastic strains and dissipate high levels of energy.
  - Can actively tune and damp resonance frequencies.

- The porous SMA variety:
  - Has similar macroscopic hysteretic response as their dense counterparts.
  - Offers significant weight advantages for aerospace applications.
  - Flow of a viscous phase in the pore space can be used for temperature control and additional tuning of vibration isolation characteristics

Porous SMA bar (courtesy of Active Materials Lab, Texas A&M University)
Plan for Year I

- Develop a virtual shaker setup.
- Generate a set of porous SMA unit cells with realistic characteristics.
- Develop a Multiscale Finite Element Method (MsFEM) to solve forward problems on a given porous geometry.
- The basic dense SMA model at the microscale is a three internal variable, rate independent constitutive model (Popov and Lagoudas, 2007).
- Incorporate the MsFEM into a global solver which simulates a porous SMA on a shaker device.
- Use a massively parallel environment to speed up the MsFEM.
Virtual Shaker Setup

A Forward FEM Model simulates the loading of the payload/SMA device configuration.

MsFEM provides effective material response at selected locations.

Fine scale FEM discretization and mesh.
**Dense SMA Model: Summary**  
(Posov and Lagoudas, 2007)

**Approach:** Make a distinction between twinned and detwinned martensite. This allows for:

- The introduction of different transformation surfaces, evolution equations and hardening laws for the three phases - Austenite (A), Twinned Martensite ($M^t$) and Detwinned Martensite ($M^d$) in a natural way.
- Model conforms to a realistic phase diagram
- The use of a different hardening laws for the detwinning deformation and phase transformation to accurately capture the stress-strain response at different temperatures

SMA Phase diagram showing the different transformation regions in stress-temperature space. The diagram is extended in comparisons to previous works in order to achieve a consistent and robust model.
The mass fractions of the three phases are introduced:

- $c_1$: self-accommodated martensite
- $c_2$: detwinned martensite
- $c_3$: austenite

where $c_1 + c_2 + c_3 = 1$, $0 \leq c_i \leq 1$, $i = 1, 2, 3$

The transitions between the different species are accounted for by three independent internal variables $\xi_1, \xi_2, \xi_3$ which satisfy:

\[
\begin{align*}
    c_1 &= c_{10} + \xi_1 - \xi_3 \\
    c_2 &= c_{20} + \xi_2 + \xi_3 \\
    c_3 &= c_{30} - \xi_1 - \xi_2
\end{align*}
\]

where the 0 subscript indicates initial values.
Dense SMA Model: Free Energy

- A general form of the Gibbs free energy for a polycrystalline SMA which at any instance can contain all three species is selected:

\[
G = c_1 G^{(1)}(\sigma, T) + c_2 G^{(2)}(\sigma, T) + c_3 G^{(3)}(\sigma, T) + G^{MIX}(\sigma, T, c_1, c_2, \varepsilon^{in})
\]

where, \(G^{(1)}\), \(G^{(2)}\) and \(G^{(3)}\) are given by

\[
G^{(1)}(\sigma, T) = G^{(2)}(\sigma, T) = -\frac{1}{2\rho} \sigma : S^M : \sigma - \frac{1}{\rho} \sigma : \left[ a^M (T - T_0) + \varepsilon^{in} \right] + c \left[ T - T_0 - T \ln \left( \frac{T}{T_0} \right) \right] - s_0^M (T - T_0) + u_0^M
\]

\[
G^{(3)}(\sigma, T) = -\frac{1}{2\rho} \sigma : S^A : \sigma - \frac{1}{\rho} \sigma : \left[ a^A (T - T_0) + \varepsilon^{in} \right] + c \left[ T - T_0 - T \ln \left( \frac{T}{T_0} \right) \right] - s_0^A (T - T_0) + u_0^A
\]

and the mixing energy is assumed to have the form:

\[
G^{MIX}(c_1, c_2) = \frac{1}{2} b_1(\varsigma_1)c_1^2 + \frac{1}{2} b_1(\varsigma_2)c_2^2 + b_1 b_2 c_1 c_2 + \text{sgn}(\varsigma_1)\mu_1 c_1 + \text{sgn}(\varsigma_2)\mu_2 c_2
\]

\[
b_1(\varsigma) = \begin{cases} b_1^A & \text{for } \varsigma > 0 \\ b_1^M & \text{for } \varsigma < 0 \end{cases} \\

b_2(\varsigma) = \begin{cases} b_2^A & \text{for } \varsigma_2 > 0 \\ b_2^M & \text{for } \varsigma_2 < 0 \end{cases}
\]
Dense SMA Model: Second Law and Constitutive Equations.

- The total inelastic strain $\varepsilon^{in}$ is assumed to be generated only by the phase transformation and the detwinning of martensite:

$$\varepsilon^{in} = \varepsilon^t + \varepsilon^d$$

$$\& = \Lambda^t \xi^2$$

$$\varepsilon^d = \Lambda^d \xi^3$$

$$\Lambda^t = \begin{cases} \sqrt{\frac{2}{3}} H \frac{\text{dev}(\sigma)}{||\text{dev}(\sigma)||}, & \xi^2 > 0 \\ \sqrt{\frac{2}{3}} H \frac{\text{dev}(\varepsilon^{in})}{||\text{dev}(\varepsilon^{in})||}, & \xi^2 < 0 \end{cases}$$

$$\Lambda^d = \sqrt{\frac{2}{3}} H \frac{\text{dev}(\sigma)}{||\text{dev}(\sigma)||}, \quad \xi^3 > 0$$

where $\varepsilon^{in}$ is decomposed additively, and the tensors $\Lambda^t$ and $\Lambda^d$ specify the flow rate for the phase transformation ($A \leftrightarrow M^d$) and the detwinning of martensite ($M^t \rightarrow M^d$) respectively. The second law of thermodynamics then takes the form:

$$T \& = - \left( \varepsilon - \varepsilon^{in} + \rho \frac{\partial G}{\partial \sigma} \right) : \& - \rho \left( s + \rho \frac{\partial G}{\partial T} \right) : \& - \rho \frac{\partial G}{\partial \xi^1} \xi^1$$

$$+ \left( \sigma : \Lambda^t - \rho \frac{\partial G}{\partial \xi^2} \right) \xi^2 + \left( \sigma : \Lambda^d - \rho \frac{\partial G}{\partial \xi^3} \right) \xi^3 \geq 0$$
**Multiscale FEM for Porous SMAs**

- One defines a multiscale mapping linking the coarse fields (displacement, stress, internal variables) to the fine scale quantities (e.g. homogenization motivated correctors, etc).
- Coarse level fields are initialized.
- Each coarse-scale integration point is mapped to the fine scale (via a local solution to a PDE)
- Once fine scale quantities are computed, appropriate averages are taken and transferred back to the coarse scale.
- Conservation of linear momentum is solved with those averages producing a new iterate for the coarse fields.
DDDAS

• DDDAS will be realized primarily via
  – Changing the temperature of the specimen dynamically to modify its general hysteresis properties:
    • Resistive heating
    • Fluid flow rate
  – Changing the effective mechanical response by modifying the fluid pressure
  – Responding to long-term fatigue changes in dense SMA model parameters
  – Calibrating and improving microscale (dense) SMA model parameters based on dynamic data
    • Maximum transformation strain, transformation temperatures, etc.
• Forward simulations of the shaker/device setup will be used to manage datastreams and feedback control.
To Date

- Creating prototype of virtual shaker
  - Simulate the response of a SMA specimen and create a CAD model of the vibration isolation device that will be used with the virtual shaker.
  - Arrange for cooperation with Prof. Dmitris C. Lagoudas’ lab at Texas A&M to provide data from an actual vibration isolation device.

- Creating DDDAS protocols for interacting with device.

- Time to make decision on using dusty deck or a new streamlined code.