Overview of Smart Materials

Bishakh Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur
LECTURE 7:

Smart Muscles based on Shape Memory Alloys and Electro-active Polymer
Organization

- What is Shape Memory Effect?
- Metallic alloys that show Shape Memory Effect
- The Constitutive Relationship
- Actuators Developed using SMA
- Sensors Developed using SMA
- Future of SMA
What is Shape Memory Effect?

• There are two common shape memory effects - One Way and Two Way effects.

• In the case of One Way effect, the material always remembers the shape at Parent State (Austenite Phase)

• In the case of Two Way effect, the material is trained to remember two shapes, one at the Parent Austenite phase and the other at the Martensite Phase
Hysteresis Curve of SMA

\( M_s \): Martensite start temperature, \( M_f \): Martensite finish temperature, \( A_s \): Austenite start temperature and \( A_f \): Austenite finish temperature
Crystal Structure Depicting SME
One-Way SME

Diagram of the One-Way SME process with labeled stages:

1. Cooling
2. Detwinning
3. Heating
4.
Pseudo-elasticity
Metallic Alloys that show SME

• SME was first observed in 1932 in Silver Cadmium Alloy

• Three types of SMA are currently popular
  – Cu Zn Al
  – Cu Al Ni and
  – Ni Ti

• The last one is commercially available as NiTiNOL (NOL – Naval Ordinance Laboratory)
Space Application of SMA:

- Control of aerodynamic surfaces
- Micro-coils for vibration isolation
- Grasping by robotic fingers
- Space exploration: rock splitting by ESA
- Nitinol filter
- Deployment of Solar Array Hinges (EMC)
Reconfigurable Systems:

Reconfigurable systems composed of modular units have been investigated intensively for their versatility, flexibility, and fault-tolerance.

Conventional electric motors used in these studies impose a limitation on miniaturization of the size of the system, due to their poor power/weight ratio.
Vibration generation using SMA wires
SMA based Tuned Mass Damper
SMA Constitutive Relationship

• Phenomenological Model
• Based on experimentally observed phase kinetics of SMA
• First model developed by Tanaka, later modified by Rogers et al. and finally by Brinson (1993)
• Constitutive relation

\[
\sigma - \sigma_0 = D(\xi)\varepsilon - D(\xi_0)\varepsilon_0 + \Omega(\xi)\xi_s - \Omega(\xi_0)\xi_{s0} + \Theta(T - T_0)
\]

\[
D(\xi) = D_M + (1 - \xi)D_A = \text{Elastic Modulus}
\]

\[
\Omega(\xi) = -\varepsilon_L D(\xi) = \text{Transformation Modulus}
\]

\[
\Theta = \text{Elastic Thermal Coefficient}
\]
Brinson Model

• Phase Kinetics
• Reverse Transformation: Conversion of Martensite to Austenite
  for \( T > A_s \) and \( C_a(T - A_f) < \sigma < C_a(T - A_s) \)

\[
\xi = \frac{\xi_0}{2} \left\{ \cos \left[ \frac{\pi}{A_f - A_s} \left( T - A_s - \frac{\sigma}{C_a} \right) \right] \right\}
\]

\[
\xi_s = \xi_{s0} - \frac{\xi_s}{\xi_0} (\xi_0 - \xi)
\]

• Forward Transformation: Conversion of Austenite to Martensite
  for \( T > M_s \) and \( \sigma^r_s + C_m(T - M_s) < \sigma < \sigma^r_f + C_m(T - M_s) \)

\[
\xi_s = \frac{1 - \xi_{s0}}{2} \cos \left\{ \frac{\pi}{\sigma^r_s - \sigma^r_f} \left[ \sigma - \sigma^r_f - C_m(T - M_s) \right] \right\} + \frac{1 + \xi_{s0}}{2}
\]

\[
\xi_t = \xi_{t0} - \frac{\xi_t}{1 - \xi_{s0}} (\xi_s - \xi_{s0})
\]
# Beam and SMA Specifications

**SMA: Flexinol 125µm from Dynalloy Inc.**

<table>
<thead>
<tr>
<th>Moduli</th>
<th>Transformation Temperature</th>
<th>Transformation Constants</th>
<th>Maximum residual strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_a = 75,GPa$</td>
<td>$M_s = 44.99^\circ C$</td>
<td>$c_m = 20,MPa/^\circ C$</td>
<td>$\varepsilon_L = 0.06$</td>
</tr>
<tr>
<td>$D_m = 28,GPa$</td>
<td>$M_f = 25.08^\circ C$</td>
<td>$c_a = 28,MPa/^\circ C$</td>
<td></td>
</tr>
<tr>
<td>$\Theta = 0.55,MPa/^\circ C$</td>
<td>$A_s = 65.73^\circ C$</td>
<td>$\sigma_s^{cr} = 70,MPa$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$A_f = 83.50^\circ C$</td>
<td>$\sigma_f^{cr} = 170,MPa$</td>
<td></td>
</tr>
</tbody>
</table>

**Beam Properties**

<table>
<thead>
<tr>
<th>No.</th>
<th>Beam Material</th>
<th>Elastic Modulus</th>
<th>Beam Thickness</th>
<th>Beam Width</th>
<th>Flexural Rigidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acrylic</td>
<td>1.78</td>
<td>1.1</td>
<td>15.5</td>
<td>$3.06 \varepsilon^3$</td>
</tr>
<tr>
<td>2</td>
<td>Acrylic</td>
<td>2.38</td>
<td>1.8</td>
<td>10</td>
<td>$1.16 \varepsilon^4$</td>
</tr>
<tr>
<td>3</td>
<td>Acrylic</td>
<td>2.38</td>
<td>1.8</td>
<td>18</td>
<td>$2.08 \varepsilon^4$</td>
</tr>
<tr>
<td>4</td>
<td>Acrylic</td>
<td>2.38</td>
<td>2.8</td>
<td>11</td>
<td>$4.78 \varepsilon^4$</td>
</tr>
</tbody>
</table>
Experimental Setup

- Laser Displacement Sensor
- Displacement Display
- SMA Attached Beam
- SMA Power Amplifier
- SMA Wire
- Cantilever Beam
- Support
The effect of change of offset distance on deflection by an SMA wire

Variation of end deflection with offset for Beam-2:

Engineering Model of SMA (Equivalent Coefficient of Thermal Expansion / ECTE) is recently developed by Turner based upon Nonlinear Thermo-Elasticity.

The most fundamental feature of ECTE model of SMA is the axial constitutive relation for SMA in which non-mechanical strain is represented by effective thermal strain.
The fundamental equation developed for the SMA element in the longitudinal direction is:

\[ \sigma_1 = E_1(T) \left[ \varepsilon_1 - \int_{T_0}^{T} \alpha_1(T) dT \right] \]

Here, \( \sigma_1 \) is the stress induced in SMA, \( E_1 \) is the Young’s modulus, \( \varepsilon_1 \) is total axial strain in SMA and \( \alpha_1 \) is the effective coefficient of thermal expansion (ECTE).
actuators developed: 1

- natural length of SMA spring 60mm
- bias spring length 45 mm
- displacement achieved 12mm

Actuator in action
Amplified SMA Actuator
mechamatronics model developed:

Ready to take a SMArt turn
An SMA based Rotational Sensor
An SMA based Trajectory Tracking System
References

END OF LECTURE 7