Thermomechanical Characterization and Modeling of Ni60Ti40 SMA for Actuated Chevrons

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Overview

• Introduction
• Experimental Characterization
  – Preparation
  – Results
• Calibration and Validation of Model
• Finite Element Analysis of Active Structural System Motivated by VGC
• Work in Progress and Conclusions
Introduction-The Boeing VGC

Calkins, Mabe, & Butler, SPIE, 2006

Mabe, Calkins, & Butler, 47th AIAA, 2006
Introduction-Ni60Ti40

- Ni60-Ti (wt %) = Ni55-Ti (at %)
- Boeing chevrons pioneered use in aerospace applications
- Chosen for following attributes:
  - Thermomechanical stability
  - Transformation temperatures set by heat treatments
  - No initial cold work required to promote the shape memory effect → complex shapes
- Nickel rich → additional precipitates

Mabe, Ruggeri, & Calkins, Int’l Conf Shape Memory & Superelast., 2006;
Clingman, Calkins, & Smith, SPIE, 2003
Introduction - Calibration of the Unified Model

“UNIFIED MODEL”
- proposed by Qidwai and Lagoudas; implemented in ABAQUS
- here modified to account for variable transformation strain
- includes the following three key attributes:

Gibbs Free Energy: (Includes elastic terms)

\[
G(\sigma, T, \xi, \xi') = -\frac{1}{2\rho} \sigma : S : \sigma - \frac{1}{\rho} \sigma : \alpha \Delta T
+ c \left[ \Delta T - T \ln \left( \frac{T}{T_0} \right) \right] - s_0 \Delta T + u_0 + f(\xi)
\]

Thermoelastic Stress/Strain:

\[
e^{\varepsilon}_{\text{eff}} = -\rho \frac{\partial G}{\partial \sigma} = S : \sigma + \alpha \Delta T
\]

Evolution Equation:
(Relates internal state variable and observable quantity, i.e. strain)

\[
\dot{\xi}' = \Lambda \ddot{\xi}
\]

where

\[
\Lambda = \begin{cases} 
\xi' H^{\text{cur}} \sigma^{\text{eff}} / \sigma^{\text{eff}}, & \dot{\xi} > 0 \\
H^{\text{cur}} \xi' / \dot{\xi}', & \dot{\xi} < 0
\end{cases}
\]

\(H^{\text{cur}} \text{ or } H^{\text{cur}}(\sigma)\)
**Introduction - Calibration of the Unified Model**

**Kuhn-Tucker Conditions:**
(Defines transformation surfaces)

\[
\xi > 0, \; \Phi \leq 0, \; \Phi \xi = 0
\]

\[
\xi \leq 0, \; \Phi \leq 0, \; \Phi \xi = 0
\]

where

\[
\Phi = \left\{ \begin{array}{ll}
\pi - Y = 0, & \xi > 0 \\
-\pi - Y = 0, & \xi < 0
\end{array} \right.
\]

and

\[
\pi = -\rho \frac{\partial G}{\partial \xi}
\]

**Transformation Surfaces:**

\[
\Phi = \pm \left\{ \frac{1}{2} \sigma : \Delta S : \sigma + \sigma : [\Delta a \Delta T + \Lambda] + \rho \Delta s_0 \Delta T - \Delta u_{0s} \frac{df}{d\xi} \right\} - Y = 0, \; \xi > 0
\]

\[
C^A, C^M
\]

\[
M^{0s}, M^{0s}
\]

\[
A^{0s}, A^{0s}
\]

**Other Important Information:**

- Trained vs. untrained
  - Intended stress level of operation
  - Stability of trained material
Experimental Preparation - Planning

Experimental Plan:
• As-Received Material
  – DSC test
  – SME test
  – Characterize isobaric behavior
  – Cyclic behavior repeatable?
• Perform Training (1 thickness)
• Trained Material
  – Characterize isobaric behavior
  – Cyclic behavior repeatable?
  – **Calibrate model**
Experimental Preparation – Setup

Extensometer/Furnace configuration for isobaric characterization

Extended-exposure image of liquid nitrogen cooling of specimen

Extensometer/Furnace configuration for isobaric training
Experimental Results: As-Received Material

- Tensile testing, two thicknesses: 4.3mm & 1.8mm
- Verify operation of testing equipment; preliminary material data

Isobaric testing of 4.3mm thick specimens

Preliminary phase diagram, 1.8mm thickness specimens (as-received)
Experimental Results: Training (Stabilization)

1.8 mm specimen stabilized
- Isobaric loading
- 300 MPa
- 100 thermal cycles (-10 to 160°C)

(Above): Strain vs. Temperature Graph for Isobaric Thermal Cycling.

(Right): Evolution of Strain vs. Number of Thermal Cycles.
**Experimental Results: Trained Material**

\[ H = H_{\text{max}} [1 - \exp(-C \sigma_{\text{eff}})] \]

\[ H_{\text{max}} = 1.5\% \]

\[ C = -7.0 \times 10^{-9} \]

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>( E_A )</td>
<td>90GPa</td>
</tr>
<tr>
<td>( E_M )</td>
<td>47GPa</td>
</tr>
<tr>
<td>( \nu )</td>
<td>0.33</td>
</tr>
<tr>
<td>( \alpha_A )</td>
<td>10.0E-6/°C</td>
</tr>
<tr>
<td>( \alpha_M )</td>
<td>10.0E-6/°C</td>
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<tr>
<td>( M_{0s} )</td>
<td>28°C</td>
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<tr>
<td>( M_{0f} )</td>
<td>-10°C</td>
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<td>( A_{0s} )</td>
<td>27°C</td>
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<tr>
<td>( A_{0f} )</td>
<td>53°C</td>
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<tr>
<td>( C_A )</td>
<td>20MPa/°C</td>
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<tr>
<td>( C_M )</td>
<td>14MPa/°C</td>
</tr>
<tr>
<td>( H )</td>
<td>(0.015[1 - \exp(-7.0 \times 10^{-9} \sigma_{\text{VM}})])</td>
</tr>
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Simulation of Experiments

1-D Loading of 3-D BVP to validate material parameters chosen

Validation results
Preliminary BVP Motivated by VGC

SMA bending component in fastened to elastic aluminum substrate
FEA: Thermomechanical Loading Path

1. Load in a fully martensitic state
2. Heat to 100ºC
3. Cool to 0ºC
4. Repeat (cycle should be repeatable)

Stress/Temperature response of characteristic surface element (schematic)
FEA: Stress Contours

VM Stress

<table>
<thead>
<tr>
<th>Level</th>
<th>Color</th>
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<tbody>
<tr>
<td>100 MPa</td>
<td>Red</td>
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<tr>
<td>50 MPa</td>
<td>Orange</td>
</tr>
<tr>
<td>0 MPa</td>
<td>Blue</td>
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8-node (quadratic), plane strain, reduced-integration elements

Clamp

Actuated (Hot)

Non-actuated (Cold)
FEA: Beam Profile Results - Actuation

Profile of upper surface of SMA beam heated and cooled: experimental and FEA
Work in Progress

Symmetric Problem
10276 elements
(75% nonlinear)
42524 nodes
155304 variables
(DOFs + contact)

Modeling of full 3-D chevron including constitutive behavior of Ni60Ti40 material
Work in Progress, Cont’d
Conclusions

• Ni60-Ti (wt %) SMA has been characterized for use as an actuator

• Unified Model (as implemented in ABAQUS) has been successfully calibrated using the experimental data

• BVP inspired by the Boeing VGC has been analyzed using the calibrated model

• (Simple 1-D tensile test results) + (straightforward model) + (powerful nonlinear FEA software) = effective predictive capability = powerful design tool
Acknowledgments

- National Defense Science and Engineering Grant (NDSEG)
- The Boeing Company, for their support of this work
- Material and Structures Lab staff, for providing a productive testing atmosphere