Characterization and 3-D Modeling of Ni60Ti SMA for Actuation of a Variable Geometry Jet Engine Chevron

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Overview

• Introduction
• Experimental Characterization
• Calibration and Validation of Model
• Finite Element Analysis of Variable Geometry Chevron (VGC)
• 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
- Nickel rich → additional precipitates
- Leads to the following attributes:
  - Thermomechanical stability
  - Transformation temperatures set by heat treatments
  - No initial cold work required to promote the shape memory effect → complex shapes

Mabe, Ruggeri, & Calkins, Int’l Conf Shape Memory & Superelast., 2006; Clingman, Calkins, & Smith, SPIE, 2003
Introduction – SMA Behavior

![SMA Phase Diagram (Schematic)](image)
Thermomechanical Characterization (1)

I. Plates of various thickness received
II. ASTM “subsized” dogbone specimens prepared
III. Thermomechanical loading paths applied

4.3mm thick
Thermomechanical Characterization (2)

III.a. Untrained material specimens tested (generation of plastic strains evident)

III.b. Material trained (stabilized)

III.c. Testing repeated for trained specimens (model parameters calibrated)
Calibration of the Unified Model (1)

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

Gibbs Free Energy:
(Includes elastic terms)

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

Thermoelastic Stress/Strain:

\[ \varepsilon'^e = -\rho \frac{\partial G}{\partial \sigma} = S : \sigma + a \Delta T \]

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

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

where

\[ \Lambda = \begin{cases} H^{cur} \frac{\sigma_{eff}'}{\sigma_{eff}}, & \dot{\xi} > 0 \\ H^{cur} \frac{\varepsilon'}{\varepsilon}, & \dot{\xi} < 0 \end{cases} \]

\[ H^{cur}(\sigma) \]
Calibration of the Unified Model (2)

Kuhn-Tucker Conditions:
(Defines transformation surfaces)

Transformation Surfaces:
\[ \Phi = \pm \left\{ \frac{1}{2} \sigma : \Delta S : \sigma + \sigma : [\Delta a \Delta T + \Lambda] + \rho \Delta s_0 \Delta T \right\} - \rho \Delta u^B_0 - \frac{df}{d\xi} - Y = 0 \quad \xi > 0 \]

\[ \Phi = \begin{cases} \pi - Y = 0, & \xi > 0 \\ -\pi - Y = 0, & \xi < 0 \end{cases} \]

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

Example transformation surface for cosine hardening:
(forward transformation)

\[ \xi = \frac{1}{2} \left\{ \cos \left[ a^M \left( T - M_f \right) \right] - \frac{a^M}{HC^M} \left( \sigma \Lambda + \frac{1}{2} \sigma \Delta S \sigma + \Delta a \Delta S \sigma \right) \right\} + 1 \]
Model Calibration: Trained Material

### Parameter | Value
---|---
\( E^A \) | 90GPa
\( E^M \) | 47GPa
\( \nu \) | 0.33
\( \alpha^A, \alpha^M \) | 10.0E-6/°C
\( H \) | \( =0.015[1-e^{-7.0E-9*\sigma_{VM}}] \)
\( M_s \) | 34°C
\( M_f \) | -17°C
\( A_s \) | 23°C
\( A_f \) | 57°C
\( \rho \Delta s_{0}^A \) | 0.300MPa /°C
\( \rho \Delta s_{0}^M \) | 0.212MPa /°C
\( \rho C_{M}^A \) | 14.9MPa/°C
\( \rho C_{M}^M \) | 10.6MPa/°C
Simulation of Experiments

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

Model/Experiment Matching
The FEA Model (1)

Chevron Substrate
- Laminate structure
- Linearly elastic
- 5494 6-Node triangular shell (STRI65) elements used
- Constrained along forward edge

SMA Curved Beam
- 3 instances used
- SMA material behavior - UMAT
- 2100 Quadratic brick elements w/ reduced integration (C3D20R) used (6 thru thick)
- “Fastened” to chevron via ABAQUS connector elements
The FEA Model (2)

Assembly
- SLOT connectors used to “bolt” down SMA beams
- SLIDE-PLANE connectors used to prevent beam rotation
- Contact enforced between SMA beam edge nodes and chevron elements (no friction)

Loading Steps
1. Clamp beams \((T < A_s)\)
2. Heat beams \((T > A_f)\)
3. Cool \((M_f < T < M_s)\)
4. Heat beams \((T > A_f)\)
Results of Analysis (1)

1) Initial Condition

2) Clamp SMA beams
   \(T < A_s\)

Von Mises
   (MPa)

3) SMA beams heated
   \(T > A_f\)

4) SMA beams cooled
   \(M_f < T < M_s\)
Results of Analysis (2)

Deflection Contours

Tip Immersion Time History

Centerline Profile
Results of Analysis (3)

Comparison of flight test data with analysis; Take-off condition

(Calkins, Butler, Mabe: AIAA 2006-2546)
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 consisting of the Boeing VGC has been analyzed using the calibrated model

- Future work:
  - Detailed validation
  - Extension to other applications
Use of Analysis Tools for Modeling of VGC Actuation Cycles

Legacy Method: Design, Build, Test, Iterate → Optimize

Preferred Method: Characterize, Analyze → Optimize