High Temperature Shape Memory Alloys: From Materials Design to Device Reliability

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How SMAs work?

Zn$_{45}$Au$_{30}$Cu$_{25}$

Courtesy of R.D. James
How SMAs work?

- Define shape at high temperature (austenite)
- Cool to low temperature (martensitic twinning)
- Mechanically deform at low temperature (martensite)
- Heat to high temperature (austenite)
- Cool to low temperature (martensitic twinning)

Austenite phase | Twinned domains of martensite phase

Courtesy of Dr. Y. Liu

www.adaptamat.com
SMA-Enabled Applications and History

Variable Geometry Chevron (2005 Flight Test). Noise reduction and fuel economy

Variable Area Fan Nozzle (2008) Farnborough

Future Applications, supersonic aircrafts (?)

2000 2010 2020

- Compact (large energy density)
  - large shape change
  - large actuation force
- Lightweight
- High Temperature
- Relatively inexpensive
- Reliable

High temperature shape memory alloys: defining transformation temperature above 100 °C

Practically: something that works at a higher temperature than NiTi

Actuation fatigue is a problem - Not reliable

Ni$_{50}$Ti$_{50}$

- Easy dislocations generation during reversible transformation, poor stability
- Thermo-mechanical training is needed to stabilize shape memory response!

Atli, Ph.D. Dissertation, Texas A&M University, 2012
NiTiX alloys are less prone to actuation fatigue

Ni$_{24.5}$Ti$_{50.5}$Pd$_{25}$

150 MPa Training

UCT = 280 °C

How can we improve the actuation response of HTSMAs?

• Use conventional metallurgy approaches
  
  — Solid Solution Hardening (quaternary additions)

  — Work hardening (thermo-mechanical processing)

  — Precipitation hardening

  — Grain size refinement
Nano-precipitates in SMAs form hierarchical microstructures
Demonstrated formation of coherent nanoprecipitates in NiTi(Hf,Zr)

Ni-rich NiTi SMA, Ni$_{52}$Ti$_{48}$

Ni$_4$Ti$_3$ (Ni$_{57}$Ti$_{43}$)

• The initial compositions should be Ni-rich
• The precipitates are richer in Ni than the matrix
Ni$_{50}$Ti$_{50}$

$\sigma = 150$ MPa

Ni$_{50.3}$Ti$_{20}$

Under 200 MPa

Significantly improved actuation fatigue response

100 Cycles

Aged at 550$^\circ$C, 3 hrs
Nano-precipitates in SMAs form hierarchical microstructures

Design of nano-precipitates provides new opportunities in SMAs for functional stability and superelasticity

Ni-rich NiTi SMA, Ni$_{52}$Ti$_{48}$

Ni$_4$Ti$_3$ (Ni$_{57}$Ti$_{43}$)

NiTiHf high temperature SMAs

FeMnNiAl SMAs

CoNiGa and CoNiAl-based shape memory super alloys
Size and Morphology of Precipitates in NiTiHf and NiTiZr

Fine precipitates $\rightarrow$ Large variants
Aging at low temperatures or for short durations

Large precipitates $\rightarrow$ Refined variants
Aging at high temperatures or for long durations
Evolution of $M_s$ and $A_f$ with precipitation

- Great flexibility to modify transformation temperatures (same trend in $A_f$), and hysteresis (dissipative mechanisms)

Time-Temperature-Property Diagrams: Two different regimes - Ni$_{50.3}$Ti$_{34.7}$Hf$_{15}$

Nanoprecipitates suppress functional degradation

New NiTiHf and NiTiZr alloys are less prone to actuation fatigue

Work Output of Comparison

Atli, Karaman, Noebe, Smart Materials and Structures, 2015
Model Specifics

Microstructure generation
- Multiple RVEs of SMA matrix and elastic Ni₄Ti₃ precipitates

Micromechanics
- Periodic boundary conditions for stress, strain, and Ni-concentration
  \[ u(x_1, x_2, 0) - u_3 = u(x_1, x_2, L) \]
  \[ u(x_1, 0, x_3) - u_2 = u(x_1, L, x_3) \]
  \[ u(0, x_2, x_3) - u_1 = u(L, x_2, x_3) \]

Coherency stress field
- Mismatch between the lattice parameters of the two phases

Ni-depletion (3D Fick’s law)
- Representative of precipitate formation

Thermo-mechanical response prediction
- Thermal cycle microstructure and obtain response

Ni-content distribution

Typical stress field under macroscopic load
Current work

- Given solutionized material response and calorimetric data after heat treatment,
  Predict precipitated material response

Solutionized Material Response

Precipitation Relations

Response Prediction
What is next?

• Design of HTSMAs with operating temperatures between 500°C to 800°C
  – Discovered a new class of materials that works around 600°C

• Better understanding of fatigue and fracture mechanisms in HTSMAs

• Accelerated Alloy and Processing Design

• Ultra-high temperature shape memory ceramics