Cellular Shape Memory Alloy Structures: Experiments & Modeling

J. Shaw (UM), N. Triantafyllidis (UM), D. Grummon (MSU)

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**Report Documentation Page**

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
Outline

- Background
- Honeycomb specimen fabrication
- Honeycomb characterization
- SMA bending
Background
Compression of Al honeycomb

[Papka/Kyriakides, 1998]
Nitinol (SM) wire: shape memory & superelasticity

Shape memory & superelasticity

NiTi wire
Temperature, T (thermocouple)
Strain, $\varepsilon_e$ (extensometer)

$L$

$\sigma$ (GPa)

$T$ (°C)

$\varepsilon_e$ (%)
Thin-walled honeycomb: scaling laws

Comparison of Aluminum & NiTi honeycomb for same recoverable global strain

<table>
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<tr>
<th>Property</th>
<th>Al</th>
<th>NiTi</th>
<th>NiTi/Al</th>
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<tr>
<td>$\varepsilon_{\text{dense}}^*$</td>
<td>-50%</td>
<td>-50%</td>
<td>1</td>
</tr>
<tr>
<td>$\varepsilon_{s,\text{max}}$</td>
<td>0.5%</td>
<td>5%</td>
<td>10</td>
</tr>
<tr>
<td>$t/h$</td>
<td>$10^{-2}$</td>
<td>$10^{-1}$</td>
<td>10</td>
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<tr>
<td>$</td>
<td>\sigma_0^*</td>
<td>/\sigma_{s,0}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$E^*/E_s$</td>
<td>$10^{-6}$</td>
<td>$10^{-3}$</td>
<td>1000</td>
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Relative density

$$\frac{\rho^*}{\rho_s} \propto \frac{t}{h}$$

Global/local bending strain

$$\left| \varepsilon_{\text{dense}}^* \right| \frac{\varepsilon_{s,\text{max}}}{\varepsilon_{s,0}} \propto \left( \frac{t}{h} \right)^2$$

Global/local plateau stress

$$\frac{|\sigma_0^*|}{\sigma_{s,0}} \propto \left( \frac{t}{h} \right)^3$$

global/local modulus

$$\frac{E^*}{E_s} \propto \left( \frac{t}{h} \right)^3$$

[Gibson/Ashby, 1997]
Advantages of SMA honeycombs

Combine benefits of light-weight cellular structures with Shape Memory Alloy (SMA) adaptive behavior

Metallic honeycombs

- Low density
- High specific stiffness
- Large specific energy absorption

NiTi SMA

- Shape memory effect & superelasticity
- High strength, ductility,
- Corrosion resistance, biocompatibility

Combination

- Amplified strain recovery
  - 5% ➔ 50%
- Reduced thermal lag
  - $\tau$ ➔ $\tau/10$

NiTi hexagonal honeycomb
(5.7% dense, 0.37 g/cc)
Potential applications of NiTi Cellular Structures

Overload protection
- Amplified superelasticity, reusable energy absorber
- Lightweight, resilient, damage tolerant

Vibration isolation
- Adaptive damping

Thermal actuators & adaptive structures
- Improved response time, amplified stroke

Thermal & acoustic management
- Adaptive thermal conductivity & acoustic impedance

Biomedical implants & devices
- Lightweight, sparse, tailorable properties, deployable
Fabrication & Metallurgy
Prior Attempts: Powder Metallurgy

Porous SMAs

- 50% dense NiTi bar
- Hot isostatic pressing of elemental powders
  [Naval Research Lab, V. DeGiorgi]

- 40% dense NiTi bar
- Combustion synthesis
  [Li Rong, China]

SMA foam

- 5% dense NiTi open-cell foam
- Powder process with sacrificial precursor
  [Grummon/Shaw, 2002]
Technological Barrier Overcome

Long-standing difficulty:

- Joining NiTi to itself or anything else
- Usually requires mechanical attachment/crimping
- Gluing is a very low strength option

Metallurgical bonds:

- Sensitive to interstitial contaminants (C, O, N).
- Laser welding in inert gas
  - Tricky (& proprietary), but some recent success.
  - Requires line-of-sight access.
- Soldering
  - Requires very aggressive fluxes to remove Ti-oxides.
  - Low strength
- Nb-reactive bonding (our process)
  - Discovered in 2004
  - Self-fluxing
  - Strong, ductile joints
  - Vanadium also works well
Cellular Shape Memory Structures: Experiments & Modeling
N. Triantafyllidis (UM), J. Shaw (UM), D. Grummon (MSU)
Discovery of a Nb-based braze for joining wrought NiTi

[Shaw/Grummon (UM/MSU) U.S. patent 7,896,222, issued March 1, 2011]

60 NiTi-tube array (32 % dense)
Some Metallurgy

Ternary Isotherm

Ni-Ti Binary

NiTi

Ti

Nb

at% Ni

at% Nb

T (°C)

500

1000

1500

2000

2500

Liquid

bcc-Ti

882

942

984

1670

1310

1380

1455

fcc-Ni

Ni

NiTi

Ni

Ti

TiNi

Ni3Ti

Ni3Ti2

Ni4Ti3

hcp-Ti

Titanium

Nickel

N. Triantafyllidis (UM), J. Shaw (UM), D. Grummon (MSU)
Some Metallurgy

Ternary Isotherm

Ni-Nb Binary

NiTi

Liquid

fcc-Ni

Ni$_3$Nb

Ni$_6$Nb$_7$

Ti

at% Ni

at% Nb

Ni

Nb

T (°C)

Ternary Isotherm

Ni-Nb Binary

NiTi

Liquid

fcc-Ni

Ni$_3$Nb

Ni$_6$Nb$_7$

Ti

at% Ni

at% Nb

Ni

Nb

T (°C)

Ternary Isotherm

Ni-Nb Binary

NiTi

Liquid

fcc-Ni

Ni$_3$Nb

Ni$_6$Nb$_7$

Ti

at% Ni

at% Nb

Ni

Nb

T (°C)

Ternary Isotherm

Ni-Nb Binary

NiTi

Liquid

fcc-Ni

Ni$_3$Nb

Ni$_6$Nb$_7$

Ti

at% Ni

at% Nb

Ni

Nb

T (°C)
Some Metallurgy

Ternary Isotherm

Ni

at% Ni

NiTi

at% Nb

Ti

T (°C)

Liquid

bcc-Nb

bcc-Ti

hcp-Ti

882

1670

2469

at% Ni

at% Nb

Ti-Nb Binary

Ti-Nb

Ternary

NiTi

bcc

hcp

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Some Metallurgy

Ternary Isotherm

NiTi-Nb Quasi-Binary

Liquid

(Ni₃₈Ti₃₆Nb₂₆)

NiTi

bcc-Nb

Ni

Ti

at% Ni

at% Nb

Some Metallurgy
Quasi-binary Eutectic

900 °C Isotherm
(Yang and Hao, 2000)

1170 °C Isotherm
(estimated)

900 °C Isotherm
(Yang and Hao, 2000)

1170 °C Isotherm
(estimated)
**Fabrication Procedure**

1. Corrugate SMA strips at 500 °C by shape set die
2. Lay up corrugation layers & Nb foils
3. Vacuum furnace at 1170 °C, 5 min
4. Age at 500 °C, 10 min

Shape-set of corrugated strips (500 °C)
Low-density NiTi cellular specimens

NiTi wavy corrugations

NiTi hexagonal honeycomb
(5.7% dense, 0.37 g/cc)
Cellular Shape Memory Structures: Experiments & Modeling
N. Triantafyllidis (UM), J. Shaw (UM), D. Grummon (MSU)
NiTi-Nb multilayer braze foil cross-section (127 layers, 34 micron thickness total)

Braze microstructure using multilayer foil
Other Heterobonds with NiTi

Pure tungsten (W) wire bonded to NiTi alloy

Sputtered Nb layer bonded between NiTi and Ti-6Al-4V
Possible Braze for High-temperature SMAs

Braze Joint between two wrought pieces of a Ni$_{24.5}$Pd$_{25}$Ti$_{50.5}$ HTSMA (HTSMA from R. Noebe’s group, NASA Glenn Research Center)
Fabrication of SMA cellular structures

APPROACH:

- Built-up, low density SMA corrugated structures
- Commercially-available wrought NiTi materials
- Nb-based brazing process

ACCOMPLISHMENTS:

- Fabricated NiTi SMA specimens:
  - hexagonal honeycombs (~5% dense)
  - wavy corrugations (~5% dense)
  - close-packed tube array (~32% dense)
- Demonstrated robust braze joints:
  - Up to ~800 MPa tensile strength (butt-joints)
- Preserved adaptive properties of NiTi base material
- Improved layup with self-indexing geometry
- Multi-layer foils improve control of braze stoichiometry
- Positive indications that braze process can be used to join other metal alloys and high-temperature SMAs
Possible topologies & geometries

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