DEVELOPMENT OF SHAPE MEMORY ALLOYS - CHALLENGES AND SOLUTIONS

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Materials and Structures Division

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Our Goals – Materials, Infrastructure, Applications

• **Materials:**
  – Develop new shape memory alloys ranging from cryogenic to high temperature for use in adaptive structures, and lightweight, solid-state actuation systems.
  – Adjust material properties through alloying, processing, and thermo mechanical understanding.
  – Identify methods to establish good stability, durability, workability, and work output amongst others.

• **Infrastructure:**
  – Develop laboratory testing capability and methods to evaluate and characterize SMA properties/performance.
  – Generate material(s) data sheets and databases
  – Determine test standards/methodologies
  – Component or subcomponent testing/modeling

• **Applications:**
  – Identify/build applications to benefit the aeronautics and space design challenges
  – Design methodologies
  – Commercialization
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Design “**The**” material

Design “**WITH**” material
SMA Labs: Thermomechanical Testing

Cold Temperature Testing

Capabilities:
- 5-22 kip load capacity
- Temperature: -125 °C to 500 °C
- Servohydraulic & electromechanical
- Load, stroke, strain control
- Tension and compression

Multiaxial Testing

Capabilities:
- Axial-Torsion loading
- Optical strain measurement
- Temperature > 600 ° C
- Torque rating : 220 N-m
- Force rating: 22 kN

Durability Testing

- Uniaxial loading (tensile loading)
- Torsion (torque tubes)
- Fast cycling times (5 minutes cycle)

Uniaxial High Temperature Testing

Capabilities:
- Laser strain measurement
- High temperature extensometers
- Tension/compression
- Force rating: 5-22kip
Melting & Processing

Mechanical Alloying

Vacuum Induction Melting

Vacuum Hot Press

Welding and Joining
Development of Shape Memory Alloys: Challenges and Lessons Learned
Development of Shape Memory Alloys: Challenges and Lessons Learned

High transformation temperatures
- Above 100 °C
- Good work output
- Thermal stability

Modeling
- Micromechanics
- Phenomenological
- Evolutions/transients

Dimensional stability
- Cyclic stability
- Stress-strain relationship

Durability
- Loading history
- Functional fatigue
- Structural fatigue

Workability/Processing
- Ductility
- Composition control
- Heat treatment

Certification
- Testing standards
- Material certification
- Database
55 Years after Nitinol Discovery

**Metals**
NiTi, NiTiFe, NiTiNb, NiTiCu, NiTiPd, NiFeGa, NiTiCo CuZn, CuZnAl, CuAlNi, CuAlNiMn, CuSn, FePt, FeMnSi, FeNiC
NiTiHf, NiTiZr, TiNiPd, TiNiPt, ZrRh, ZrCu, ZrCu NiCo,
AgCd, ZrCuNi CoTi, TiMo, TiNb,
AuCd, TiTa, TiAu, UNb, TaRu, NbRu,
CoNiAl, FeMnSi

**Magnetic/Ferromagnetic**
NiMnGa, FePd, NiMnAl,
FePt, Dy, Tb, LaSrCuO,
ReCu, NiMnIn, CoNiGa

**Ceramics**
ZrO2 (PSZ), MgO,
CeO2, PLZT, PNZST

**Polymers**
PTFE, PU, Poly-caprolactone, EVA + nitrile rubber, PE, Poly-cyclooctene, PCO–CPE blend
PCL–BA copolymer, Poly(ODVE)-co-BA, EVA + CSM, PMMA, Copolyesters, PET-PEG

**Others**
Thin films, hybrids…
Development of Shape Memory Alloys: High Temperature Shape Memory Alloys (HTSMAs)

Ma et al. (2010)
Development of Shape Memory Alloys: **NiTi** –Based HTSMAs

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>NiTiHf</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing deformation behavior](image)
Development of Shape Memory Alloys:

**HTSMAs Summary**

![Graph showing the relationship between maximum work output (J/cm³) and transformation temperature (°C) for various NiTi alloys.

- **NiTiHf(X)**
- **NiTiPt**
- **NiTi-30Pd**
- **NiTiPd**
- **55NiTi**
- **NiTiAu**

The graph indicates that NiTiHf(X) has the highest maximum work output at a specific transformation temperature, while NiTi-30Pd has the lowest. NiTiAu and NiTiPd fall in between these extremes.

The x-axis represents the transformation temperature in °C, ranging from 0 to 700, while the y-axis represents the maximum work output in J/cm³, ranging from 0 to 20.
Development of Shape Memory Alloys: Challenges and Lessons Learned

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How to make the material/actuator stable?

- Solution 1: Thermomechanical “training” (e.g., cycling, reverse loading…)
- **Solution 2: Alloying and microstructural control** (e.g., precipitation hardening, Ni-content…)

![Graph showing strain vs. temperature for cooling and heating cycles.](image)
Microstructural Control towards Stability

Electron diffraction

In situ diffraction

Outcome

55NiTi

55NiTi
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Development of Shape Memory Alloys: How about Durability/Fatigue?

- Loss of actuation strain
- Shifts in transformation characteristics (Hysteresis, temperatures…)

![Graph showing cyclic deformation over temperature](image-url)

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www.nasa.gov
Durability Assessment Underway…

Data exists up to 1000’s of cycles, how about 1M cycles?

Currently collecting durability data on NiTiHf tubes
Durability Assessment Underway…

\[ \text{Austenite Angle} - \text{Martensite Angle} = \text{Actuation Angle} \]

Strain Actuation \(1/\alpha\) (Cycle Count \(\times\) MPa per load)
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Processing and Workability of HTSMAs

**NiTiPt**

- Induction Melt + Homogenization
- Extrusion
- Wire Grinding
- Wire Drawing

**Examples:**
- Multiple-Pass Extrusion: 60 mil NiTi-20Pt rod
- 44 & 5 mil NiTiPt
- 5 mil NiTiPt wire
Processing and Workability of HTSMAs

NiTiHf

High temperature extrusion proved to be problematic (C. Wojcik 2008)

Successful hot extrusion (rods and tubes)

Successful hot rolled button (C. Wojcik 2008)
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Certification and Test Standards

ASTM Standards for biomedical and or superelastic

- F2004-05
- F2005-05
- F2063-05
- F2082-06
- F2516-07
- F2633-07

ASTM Standards for SMA Actuation

- None
Certification and Test Standards

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ASTM Standards for SMA Actuation
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Deliver the first ever regulatory agency-accepted material specification and test standards for shape memory alloys as employed as actuators for commercial and military aviation applications
Promoting Growth of SMA Technologies....
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Research and Understanding of Shape Memory Alloys

1. Applied Research
2. Alloy Processing & Development
3. Testing and Modeling
4. Applications
Complex Responses, Many Responses

Uniaxial (tension/compression)

- Isothermal monotonic
- Isothermal cyclic
- Isobaric cyclic
- Isostrain cyclic

Multiaxial

- Proportional/non-proportional loading
- 3D strain measurement
- Torque/force/twist/displacement control capability

Geometries

Torsion

Durability

- New frames for durability testing are underway
  - Durability analysis of sample and components
  - Generate data for existing materials

Hot grip testing
Materials – High and Low Temperature SMA

Low Temperature SMAs
- NiTi
- NiTiFe
- NiTiCo/Cr
- NiTiCu
- NiTiHf/Zr

High Temperature SMAs
- NiTiHf
- NiTiZr
- NiTiPd
- NiTiPt
- NiTiAu
Design of Actuators - Torque tubes example

Material and geometry effects

Possible Stress Gradients
Some SMA Components
Shape Memory Alloy Applications

Space

SMA Bellows
- Dynamic sealing
- Fluid handling
- Flexibility (structure alignment)

SMA Spring Tire
- Superelastic technology
- Lunar rovers
- Terrestrial tires

SMA Docking Coupling
- Cryogenic transfer coupling
- Orbital propellant depots
- Propellant handling/protection

SMA Thermal Switch
- Thermal management
- Clean & spark-free operation
- Passive or active control

SMA rock splitters

SMA Bearings
- Corrosion resistant
- Non-galling properties
- High yield
Shape Memory Alloy Applications

Aeronautics

Adaptive Fan Blade
- Embedded SMA actuators
- Aerodynamic efficiency
- Specific fuel consumption reduction

SMA Cellular Structures
- Airframe and engine components
- Morphing airfoils
- Light weight trusses

The Mars Atmosphere and Volatile Evolution (MAVEN) mission.
- SMA Pinpullers (From TiNi Aerospace) were used to secure and release deployables

Variable Area Nozzle
- High bypass turbofan
- SMA torque tubes provide flap rotation
- Engine noise reduction
Shape Memory Alloy Applications
Non-Aerospace Potential

Oil and Gas Industry
- SmartRAM™ actuators (LMP)
- SMA couplings (Aerofit Inc)
- Deep-water valves/shut off valves
- Self-torquing fasteners

Other Applications
- Home appliances
- Electronics
- Transportation
- Air conditioners

Medical Industry
- Surgical tools
- Stents and implants
- Glasses frames

Automotive Industry
- Louvers
- Quiet actuators
- Door handle
NASA SMA Team and Collaborators

SMA Team at NASA GRC

• Othmane Benafan
• Santo Padula II
• Glen Bigelow
• Anita Garg
• Darrell Gaydosh
• Timothy Halsmer
• Ron Noebe
• (Branch Chief: Joyce Dever)

Collaborators
Thank You