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 though 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, stoke, strain control
- Tension and compression

Uniaxial High Temperature Testing

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

Multiaxial Testing

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- Axial-Torsion loading
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Durability Testing

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

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
Analytical Sciences

Hitachi S4700-FESEM

AURIGA™ Cross-Beam Microscope

Philips CM200 TEM

JEOL 8200 Electron Probe
Development of Shape Memory Alloys: Challenges and Lessons Learned
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High transformation temperatures
- Above 100 °C
- Good work output
- Thermal stability

Durability
- Loading history
- Functional fatigue
- Structural fatigue

Modeling
- Micromechanics
- Phenomenological
- Evolutions/transients

Workability/Processing
- Ductility
- Composition control
- Heat treatment

Dimensional stability
- Cyclic stability
- Stress-strain relationship

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
- ZrCuNi CoTi, TiMo, TiNb, CoNiAl
- TiTa, TiAu, UNb, TaRu, NbRu, 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

NiTiHf

(a)
Development of Shape Memory Alloys: HTSMAs Summary

![Graph showing the relationship between Transformation Temperature (°C) and Maximum Work Output (J/cm³) for various NiTi alloys.](image)
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Development of Shape Memory Alloys: How about Dimensional Stability?

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…)

[Graphs showing strain vs. temperature for cooling and heating cycles]
Microstructural Control towards Stability

**Electron diffraction**

**In situ diffraction**

**Outcome**

- 55NiTi
- Neutron
- 55NiTiPd
- NiTiHf

Outcome

In situ diffraction

- Electron diffraction

- 10 nm precipitates
- 20 nm precipitates

- 114M,T
- 110T
- 002T
- 112T
- 110M
- 002M
- 112M

- 15
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Development of Shape Memory Alloys: How about Durability/Fatigue?

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

![Graphs showing strain and temperature relationships for shape memory alloys.](image-url)
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…

Austenite Angle - Martensite Angle = 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

Multiple-Pass Extrusion
60 mil NiTi-20Pt rod

Wire Grinding

44 & 5 mil NiTiPt

Wire Drawing

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)
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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

Durability

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

Torsion

- Control mode: torque/load
- Geometries
- Hot grip testing

www.nasa.gov
Materials – High and Low Temperature SMA

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

High Temperature SMAs
- NiTiHf
- NiTiZr
- NiTiPd
- NiTiPt
- NiTiAu

Cold
0 °C
Hot
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 Bearings**
  - Corrosion resistant
  - Non-galling properties
  - High yield

- **SMA rock splitters**
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

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