DEVELOPMENT OF SHAPE MEMORY ALLOYS-
CHALLENGES AND SOLUTIONS

Othmane Benafan– NASA Glenn
High Temperature & Smart Alloys Branch
Materials and Structures Division

Presentation for: The Boeing Company, Berkeley, MO
Sept. 09, 2016
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.
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.

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
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
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
- AgCd
- AuCd
- CoNiAl

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

(strain, °C)

temperature (°C)

σ = 100 MPa

Heating

Cooling

1st heat
Development of Shape Memory Alloys: HTSMAs Summary

- NiTiHf(X)
- NiTiPt
- NiTi30Pd
- 55NiTi
- NiTiPd
- NiTiAu

Maximum Work Output (J/cm³) vs. Transformation Temperature (°C)
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
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…)
Microstructural Control towards Stability

Electron diffraction

In situ diffraction

Outcome

55NiTi

Outcome

In situ diffraction

Electron diffraction

55NiTi

NiTiPd

NiTiHf

55NiTi

55NiTi

55NiTi
Development of Shape Memory Alloys: Challenges and Lessons Learned

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

Dimensional stability
- Cyclic stability
- Stress-strain relationship

Modeling
- Micromechanics
- Phenomenological
- Evolutions/transients

Durability
- Loading history
- Functional fatigue
- Structural fatigue

Workability/Processing
- Ductility
- Composition control
- Heat treatment

Certification
- Testing standards
- Material certification
- Database
Development of Shape Memory Alloys: How about Durability/Fatigue?

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

![Graph showing strain and temperature relationships for Shape Memory Alloys.](image)
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)
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
Processing and Workability of HTSMAs

NiTiPt

Induction Melt + Homogenization

Extrusion

Wire Grinding

44 & 5 mil NiTiPt

Wire Drawing

5 mil NiTiPt wire

Multiple-Pass Extrusion

60 mil NiTi-20Pt rod
Processing and Workability of HTSMAs

NiTiHf

Successful hot rolled button (C. Wojcik 2008)

Successful hot extrusion (rods and tubes)

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

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

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....
Development of Shape Memory Alloys: Challenges and Lessons Learned

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
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

FS5 HT 0.100" Wall Tubes
(After 20 Thermal Cycles to 300°C)

Calculated Shear Strain (°/L)

Outer Fiber Shear Stress (MPa)

.5" Ø

.375" Ø

.2" Ø

FS5 HT 2.5" Long Tube x .375" Diameter
(After 20 Thermal Cycles to 300°C)

Angle of Twist (°)

Outer Fiber Shear Stress (MPa)

Solid

0.100" Wall

0.075" Wall

0.050" Wall

0.038" Wall
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

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

[Logos of various universities and organizations]
Thank You