DEVELOPMENT OF SHAPE MEMORY ALLOYS - CHALLENGES AND SOLUTIONS

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High Temperature & Smart Alloys Branch
Materials and Structures Division

Presentation for: The Boeing Company, Berkeley, MO
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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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  - 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

Uniaxial High Temperature Testing

Uniaxial Loading (tensile loading)
- Force rating: 22 kN

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

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

Capabilities:
- Laser strain measurement
- High temperature extensometers
- Tension/compression
- Force rating: 5-22 kip
Development of Shape Memory Alloys: Challenges and Lessons Learned
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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,
- ZrCuNi CoTi, TiMo, TiNb,
- 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

![Graph showing strain and temperature for NiTiHf](chart)

- Strain (%)
- Temperature (°C)
- \( \sigma = 100 \text{ MPa} \)

(a)
Development of Shape Memory Alloys: 
**HTSMAs Summary**

![Graph showing Maximum Work Output (J/cm³) vs Transformation Temperature (°C) for various NiTi alloys.](attachment:image.png)
Development of Shape Memory Alloys: Challenges and Lessons Learned

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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…)
Microstructural Control towards Stability

Electron diffraction

In situ diffraction

Outcome

55NiTi

Temperature (ºC)

Heating

Cooling

Outcome

100 MPa - 165 ºC

Intensity (a.u.)

10

8

6

4

2

0

0

20

40

60

80

100

120

140

160

180

Temperature (ºC)

0.5

0

-0.5


0

30

60

90

120

150

180

210

240

270

300

330

{110}A

lattice strain (%)
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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 vs. temperature for cooling and heating cycles.](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)
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Processing and Workability of HTSMAs

NiTiPt

Induction Melt + Homogenization

Extrusion

Multiple-Pass Extrusion
60 mil NiTi-20Pt rod

Wire Drawing

44 & 5 mil NiTiPt

Wire Grinding

5 mil NiTiPt wire
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)
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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....

CONSORTIUM FOR THE ADVANCEMENT OF SHAPE MEMORY ALLOY RESEARCH AND TECHNOLOGY

Government Academia Industry

Texas A&M University
COLORADO SCHOOL OF MINES
UNIVERSITAT DES SAARLANDES
MICHIGAN STATE UNIVERSITY
University of Central Florida
University of North Texas

ATI Wah Chang
DYNALLOY, Inc.
Makers of Dynamic Alloys
FORT WAYNE METALS
Johnson Matthey

NASA Sandia National Laboratories General Motors BOEING Rolls-Royce
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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

**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