

SHAPE MEMORY ALLOYS

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SHAPE MEMORY ALLOYS – NOT YOUR ORDINARY METAL

Prepared by

Othmane Benafan, Ph.D.

High Temperature and Smart Alloys Branch NASA Glenn Research Center U.S.A

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CONTRIBUTORS

LIST OF SYMBOLS

BIOGRAPHY



When the Wire Gets Warm!



1962

W. J. Buehler⁵ and F. Wang⁶ (Naval Ordnance Laboratory)

First discovery of shape memory in NiTi alloy

William J. Buehler in 1968, pictured with a demonstration of nitinol wire. Electricity was passed through a straight piece of wire, and the wire would change into the word "innovations." The oak leaf, U.S. Naval ordnance laboratory, White Oak, Maryland, June 1968. ^{7,9}







Applications of Shape Memory Alloys in Aeronautics The first commercial application of SMAs was pipe connectors in a hydraulic system of the F–14 military airplane (by Raychem Corporation⁷)



Applications of Shape Memory Alloys in Space First demonstrations in 1968 using NiTi by Astro Research Corporation for NASA⁸

CHAPTER 1: Shape Memory Alloy Introduction 1.2 Material Science—Just What You Need To Know

Variant selection (Change in crystal structures)



Shape memory alloys (SMA):

- Alloys that have a "memory." These materials have the ability to remember and recover their original shapes with load or temperature.
- SMAs exhibit a solid-to-solid, reversible phase transformation

CHAPTER 1: Shape Memory Alloy Introduction | 1.2 Material Science—Just What You Need To Know

Shape Memory Alloys Conventional Metals







1. Elastic Deformation (**REVERSIBLE**)



CHAPTER 1: Shape Memory Alloy Introduction 1.2 Material Science—Just What You Need To Know

Shape Memory Alloys Conventional Metals



Stress Plastic region **Elastic and Plastic** Deformation **Elastic limit Elastic region** Strain

2. Plastic Deformation (PERMANENT)

3. Inelastic Deformation (**REVERSIBLE**)—SMAs

How?

- Twinning
- Bain strain \rightarrow (lattice deformation)
- Lattice invariant shear \rightarrow (accommodation)



CHAPTER 1: Shape Memory Alloy Introduction 1.2 Material Science—Just What You Need To Know

Cold state: Also referred to as "*Martensite*"



Solid-to-solid, martensitic phase transformation between a high temperature, high symmetry austenite phase (generally cubic) and a lower temperature, low symmetry martensite phase (e.g., monoclinic, tetragonal, ororthorhombic).

Hot state:

Also referred to as "Austenite"









- $(0 \rightarrow 1)$: Austenite phase transforms to martensite variants when cooled
- $(1\rightarrow 2)$: Twinned martensite deforms (elastic + reorientation + detwinning (some plasticity may occur))
- $(2\rightarrow 3)$: Unloading (elastic spring back)
- (3→0): Unloading (elastic spring back)





- Constant-force thermal cycling (actuator response)
- Determine actuation specific properties (transformation strain, work output, residual, strain, transformation temperatures, and hysteresis)

• On the heating portion, martensite starts to transform to austenite at the austenite start temperature (A_s) and completes transformation at the austenite finish temperature (A_f) . During cooling, the forward transformation initiates at the martensitic start temperature (M_s) and finishes at the martensitic finish temperature (M_f) .

1. Shape Memory Effect (Temperature-induced transformation)



- Constant-force thermal cycling (actuator response)
- Determine actuation specific properties (transformation strain, work output, residual, strain, transformation temperatures, and hysteresis)

• On the heating portion, martensite starts to transform to austenite at the austenite start temperature (A_s) and completes transformation at the austenite finish temperature (A_f) . During cooling, the forward transformation initiates at the martensitic start temperature (M_s) and finishes at the martensitic finish temperature (M_f) .

2. Superelasticity/Pseudoelasticity (Stress/load-induced transformation)



- Strains are generated and recovered mechanically through a reversible stress-induced transformation
- Occurs when deforming some SMAs at temperatures above A_f

Going from: SHAPE MEMORY EFFECT to SUPERELASTICITY to PLASTICITY



3. Magnetic/Ferromagnetic

(Magnetically-induced transformation)^{15, 16}



• In single crystalline Ni_2MnGa bulk material, strains as large as 10% have been realized

• Short response times

• Minimum magnetic flux density for max strain ~6200 G (0.6 Tesla)

4. Shape-Memory Polymers (SMP)(Light-induced or electro-active transformation)

5. Shape-Memory Ceramics (SMC)

Shape Setting

- Make new forms/shapes
- Procedure:
 - i. Pre-strain or deform the raw material (wire, sheet, tube, etc.) in a fixture, die, or mandrel with the desired form
 - ii. Constrain the material in all directions (displacement and rotation)
 - iii. Heat treat at some temperature in the proper environment for a certain time (e.g., 450 °C, 5 min, water quench)
 - iv. Cool the material using a specified cooling procedure
 - v. Optimize the final geometry by subsequent shape sets or additional cutting or machining operations



Shape Setting (helical spring example)



Spring fabrication Coil wire around a solid mandrel with a grooved helical channel

Shape setting Heat treatment at 500 °C for 25 min., followed by an ice-water quench

Finishing Electrical Discharge Machining (EDM) to make flat ends.

Actuator: A machine component used to move and/or control a system

Examples:Electric motorsEngines (fuel – gas)HydraulicsPneumaticsMechanical (rack and pinion)Thermal (e.g., SMA)

Comparison of a "Simplified" Actuation System (Part Count)



Hydraulic



Pneumatic





Advantages of SMA-based actuators:

- Reduced complexity (fewer part count, cost)
- Compact form (smaller footprint, package)
- Lightweight
- Silent operation
- Sensor and actuator in a single element
- High power/weight and stroke/weight ratios
- Clean, debris-less, spark-free operation (for high risk application)
- No electro-magnetic interference (EMI) (if not magnetic SMA)
- Flexibility in design integration
- Remember: Inelastic reversibility = large deformation

Weight/power comparison¹⁷



Weight/output comparison¹⁸



Stress-Strain comparison¹⁹⁻²¹



Bandwidth comparison²⁰



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CHAPTER 1: Shape Memory Alloy Introduction | Hands On-LAB 1

GET TO KNOW YOUR SPRINGS

(Group exercise)

- 1. From the provided springs, identify:
 - Superelastic spring
 - Shape memory effect spring
 - Two-phase region spring
 - Low-temperature activation spring
- 2. Make your own spring, "Shape setting":
 - Form a spring on the given mandrel
 - What temperature and time should be used? Why?
 - Try different shape setting temperatures

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CHAPTER 2: Shape Memory Alloys To Mechanisms | 2.1 Functional Variables



- **Define Engineering Requirement(s):**
 - System: mass, footprint, environments, integration, risk...
 Interfaces: structural to thermal to electrical to...
- □ Component: functions, pitfalls, supply chain, kinematics, fabrication, analyses (static, dynamic)...
- □ Material: durability, strength, form, surface protection

CHAPTER 2: Shape Memory Alloys To Mechanisms 2.1 Functional Variables

SMA constraints and requirements

Need to define:

- Type of motion: linear, rotary...
- Required output: force, displacement, torque, bending...
- Available energy source (directed power, collected power)
- Transition temperatures
- Form factor (footprint, weight, packaging, interfaces)
- Actuation time
- Control scheme: e.g., two state system, multi-step actuation...
- Cycle count
- Others: efficiency, cost, manufacturing, energy density...

States and the second se	
Need	
Requirements	
Functions	
Evaluation	
	Need Requirements Functions Evaluation

CHAPTER 2: Shape Memory Alloys To Mechanisms | 2.2 Thermal and Mechanical Variables

Additional variables with SMAs



CHAPTER 2: Shape Memory Alloys To Mechanisms | 2.2 Thermal and Mechanical Variables



- a) Thermal response: typically obtained using differential scanning calorimetry (DSC). Measure transformation temperatures, hysteresis, enthalpy... (under no stress)
- **b) Isobaric response**: typically obtained using thermomechanical load frames. Measure stroke, rotation, strains, loads, torques, stresses, work input, load effect on transformation temperatures...
- c) **Resistivity**: typically done using a current input. Measure electrical resistance, ideal for sensing applications...
- d) Isothermal response: typically obtained using thermomechanical load frames. Measure moduli, ductility, superelastic behaviour, reversibility...

CHAPTER 2: Shape Memory Alloys To Mechanisms 2.2 Thermal and Mechanical Variables

Property Name	Nom.	Units
Austenite start temperature	A _s	°C
Austenite finish temperature	A _F	°C
Martensite start temperature	M _s	°C
Martensite finish temperature	M _F	°C
Hysteresis (A _F - M _S)	$\Delta T_{\rm H}$	°C
Full width $(A_F - M_F)$	ΔT_{FW}	°C
Yield strength	σ_{YS}	MPa
Maximum-strain/elongation	$\epsilon_{Max}/\epsilon_{Elong}$	%
Maximum-stress/UTS	$\sigma_{Max}^{}/\sigma_{UTS}^{}$	MPa
Unloading strain	ϵ_{Unload}	%
Austenite start strain	ϵ_{AS}	%
Austenite finish strain	ϵ_{AF}	%
Martensite start strain	ε _{MS}	%
Martensite finish strain	$\epsilon_{\rm MF}$	%
Austenite slope	n/a	%/°C
Transformation slope	n/a	%/°C
Martensite slope	n/a	%/°C
Cooling trans. strain (ϵ_{MF} - ϵ_{MS})	ϵ_{Cool}	%
Heating trans. strain (ϵ_{AS} - ϵ_{AF})	ϵ_{Heat}	%
Lower cycle temperature strain	ε _{LCT}	%
Upper cycle temperature strain	ϵ_{UCT}	%
Residual martensite strain	٤ _{MRes}	%
Residual austenite strain	ε _{ARes}	%
Work [($\epsilon_{AS} - \epsilon_{AF}$) * σ_{App} * 100]	n/a	J/cm ³
Actuation strain (ϵ_{LCT} - ϵ_{UCT})	ε _{Act}	%


CHAPTER 2: Shape Memory Alloys To Mechanisms | 2.2 Thermal and Mechanical Variables

- 1. austenite finish temperature (Af)—The temperature at which the martensite to austenite transformation is completed on heating in a single-stage transformation or the temperature at which the R-phase to austenite transformation is completed on heating in a two-stage transformation
- 2. austenite start temperature (As)—The temperature at which the martensite to austenite transformation begins on heating in a single-stage transformation or the temperature at which the R-phase to austenite transformation begins on heating in a two-stage transformation.
- 3. martensite start temperature (Ms)—The temperature at which the transformation from austenite to martensite begins on cooling in a single-stage transformation (Fig. 1) or the temperature at which the transformation from R-phase to martensite begins on cooling in a two-stage transformation.
- 4. martensite finish temperature (Mf)—The temperature at which the transformation from austenite to martensite is completed on cooling in a single-stage transformation or the temperature at which the transformation from R-phase to martensite is completed on cooling in a two-stage.
- 5. transformation (Fig. 2).
- 6. actuation strain (e_{act}) —The full strain recovery obtained when heating from LCT to UCT at a specified stress. It includes the thermal expansions of martensite and austenite as well as the phase transformation strain. $e_{act} = e_{LCT} \cdot e_{UCT}$
- 7. *austenite* 50% (A_{50})—Temperature at which the transformation from martensite to austenite is 50% completed. $A_{50} = (A_s + A_f) / 2$.
- 8. *austenite finish strain* (e_{Af}) —Strain at the austenite finish temperature.
- 9. austenite start strain (e_{As}) —Strain at the austenite start temperature.
- 10.hysteresis width (HWIDTH)—Width of the thermal hysteresis curve in degrees centigrade. Distance on the temperature axis between a vertical line drawn through the A_{50} point and a vertical line drawn through the M_{50} point.
- 11. initial strain (e_0) —Specimen strain at UCT after normalizing and prior to loading the specimen.
- 12.lower cycle temperature (LCT)—Minimum temperature of the thermal cycle. It is selected to be 10 to 30 °C lower than M_f determined by a DSC test per ASTM F2004. However, the DSC test shall be done on the sample material in the same condition as the UCFTC test material.

Refer to ASTM <u>E3097-17</u> and <u>E3098-17</u>

- 13.martensite 50% (M_{50})—Temperature at which the transformation from austenite to martensite is 50% completed. $M_{50} = (M_s + M_f)/2$.
- 14. *initial loading strain* (e_i) —Initial specimen strain after normalization and before cooling when loaded at the UCT.
- 15. residual strain (e_{res}) —The final strain at the upper cycle temperature minus the initial strain at the upper cycle temperature. $e_{res} = e_{UCT} e_i$
- 16.strain at the lower cycle temperature (e_{LCT}) —Specimen strain at the LCT after cooling from the UCT to the LCT under the specified stress.
- 17. strain at the upper cycle temperature (e_{UCT}) —Specimen strain at the UCT after cooling to the LCT and heating to the UCT at the specified stress.
- 18.thermal transformation span (TSPAN)—Thermal transformation span in degrees centigrade at a specified stress. Distance on the temperature axis between a vertical line drawn through the A_f point and a vertical line drawn through the M_f point. TSPAN = $A_f M_f$.
- 19.transformation strain (e_t) —The strain recovery due to the austenitic transformation obtained when heating at a specified stress. $e_T = e_{As} e_{Af}$
- 20.upper cycle temperature (UCT)—The maximum temperature of the thermal cycle. It is selected to be higher than the A_f determined by a DSC test per ASTM F2004. For example, a temperature between 10 to 100 °C above A_f may be selected in consideration of the stress applied to the specimen. The DSC test shall be done on the sample material in the same condition as the UCFTC test material.
- 21.initial strain (e_0) —Specimen strain at LCT after normalizing (see section 11.1) and prior to pre-straining the specimen.
- 22.*maximum loading strain* (e_i) —Maximum specimen strain during pre-straining at the LCT.
- 23. recovery strain (e_{rec}) —Is the amount of residual strain that is recovered in the specimen after heating to the UCT and cooling to the LCT following pre-straining, it is equal to the unloaded strain (e_u) minus strain at lower cycle temperature (e_{LCT}) after cooling from the UCT.
- 24. two way strain (e_{TW}) —Specimen strain at the LCT after cooling from the UCT minus the strain at the UCT. This is the strain induced in the shape memory alloy specimen when it is cooled from UCT to LCT with an applied tensile stress of 7 MPa or less. e_{TW} = $e_{LCT} - e_{UCT}$
- 25. unloaded strain (e_u) —Specimen strain at LCT after pre-straining and then unloading, but prior to heating.
- 26.superelasticity—Nonlinear recoverable deformation behavior at temperatures above the austenite finish temperature (Af).

CHAPTER 2: Shape Memory Alloys To Mechanisms | 2.3 What/Where/How to Measure

Example of thermomechanical frame



CHAPTER 2: Shape Memory Alloys To Mechanisms | 2.3 What/Where/How to Measure

To measure properties, you need:

- Force measurements: load/torque cells, grips
- Stroke/rotation measurements: LVDT/RVDT, potentiometers...
- Temperature measurements: heaters, coolants, thermocouples...
- Strain measurements: extensometers cameras...







Constituent of an SMA Actuation System

















Power

Heating/cooling methods^[24]

Table 1. Potential heating and cooling methods for shape memory
alloys.HeatingCooling

IncludingEcoloringDirect resistiveFree convection (air)Capacitance-assisted resis-
tiveLiquid immersionConductiveForced air/liquid convec-
tionConvectivePeltier effectRadiative (including
laser)Heat sinking
cool Chips technology^a

^a Electron transport across a vacuum diode. Suitable for miniaturized applications such as micro-robotics.



Heating/cooling methods

Things to watch for:

- Thermal gradients (e.g., may reduce strain output)
- Over temperatures (e.g., may deteriorate training)
- Heating/cooling rate:
 - \checkmark Trade-offs based on system
 - Joule heating for small wires may work, but won't be feasible for big torque tubes
 - ✓ Induction heating may work for big rods, but require high power
 - ✓ Don't forget about passive actuation (sun power, exhaust heat...)



Control of SMA actuation system can be challenging:

- Nonlinear nature and multiple dependencies of SMAs (stress, temperature, hysteresis...)
- Heating and cooling (overruns, overshoots, minor loops...)
- Number of unknown state variables (phase fractions...)

Controls

It is not just on-off system (2 state), feedback control is doable.



Instrumentation

Sensors SMA sensory function (example)

What sensors, where to place them and how many?

- Thermocouples (or similar) to monitor temperatures.
 - Need to monitor the SMA elements and possible heat leak to surrounding structures
- Position sensors to monitor stroke and/or angular displacement
- Strain gauges or load cells
- Power monitoring (voltage, current)
- Wire routing and management

Can SMA be the "sensor"? YES

- Self-sensing (e.g., resistivity)
- Health monitoring



https://engineering.tamu.edu/news/2017/08/01/embedded-shape-memory-alloy-sensory-particles-may-detect-damage-in-aircraft-and-spacecraft.html

Mainly:

Interfaces

- How to transfer the SMA-load to the structure
- The bias-load:
 - Can be an external element (e.g., springs)
 - Can be part of the structure (e.g. weight)
 - Can be part of the environments (e.g., aero loads)
 - Can be part of the SMA itself (two-way shape memory effect)
- Attachment, joining, welding

Mechanisms:

- Material \rightarrow motor \rightarrow actuation system
 - Bearing structures
 - Locking features
 - Mounts...

Constituent of an SMA Actuation System



CHAPTER 1: Shape Memory Alloy Introduction | References

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CHAPTER 2: Shape Memory Alloys To Mechanisms | Hands On-LAB 2

Linear and Rotational Motions—Build your first SMA model

(Group exercise)

- 1. From the provided kit
 - Identify type of SMA element
 - Identify type of mechanism
 - Identify input parameters (power...)
 - Identify output motion/force
- 2. Build your kit.

Stress-temperature relationship



This is how you obtain it

Stress-temperature relationship



This is how you obtain it

Understanding load-lines



- Stroke limiter (example: mechanical stop...)
- Constant force (example: dead weight...)
- Spring force (example: variable loading, change in CG, pressure drops...)

Case study

Comparison of a "Simplified" Actuation System (Weight and Size)

*Assume the need for 100,000 in-lbf actuator

HYDRAULIC ACTUATORS



PNEUMATIC ACTUATORS



	Model #150000	Model #HTR150		
Rotation (°)	90	90		
Footprint (in)	25" x 9" x 12', 2700 in ³	27" x 11.5" x 13', 4036 in ³		
<u>Output Torque</u> (in-lbs)	100,000 in-lbs @ 2000psi	100,000 in-lb @ 2000psi		
<u>Operating</u> temperature (F)	0 to 200 F	-40 to 250 F		
<u>Weight</u> (lbs)	(330 lbs) (321 lbs)		

Case study

Comparison of a "Simplified" Actuation System (Weight and Size)

*Assume the need for 100,000 in-lbf actuator

SMA Actuator** Model # AMS2018

- Size $\sim 450 \text{ in}^3$
- Weight ~<u>58.5 lbs</u>
- Temperatures~ tunable based on alloy used
- Torque ~ 100,000 in-lbs
- Angle $\sim 90 \text{ deg}$
- <u>20%</u> the weight and <u>15%</u> the size of comparable hydraulic system

**Modeled after: NiTi, 3% strain, 1" OD torque tubes

Does SMA make sense for my application?^[27]

- Why use shape memory alloys?
 - o Identify potential advantages over other systems
- What are the application requirements?
 - Required properties and performance characteristics of SMA element
 - Lifecycle, response time, conditions
 - Choice of material, form, size, and control methods
- What are the cost/expenditure limits?
 - Raw SMA material, processing, and fabrication
 - Cost per device is critical to the business case
- What is the availability and size of the SMA element?
 - Input (power) and required output (work) of the SMA element
 - Forms (e.g., strips, rods, sheets, wires, springs, tubes, etc...) in various sizes
 - Availability and required volume of the material from a commercial supplier or other source

- What efficiency and response time is needed?
 - Energy and mechanical efficiencies of SMA components
 - Weight savings (mass efficiency) may be of higher priority
 - Cyclic frequency
- What is the proposed environment?
 - Environment and thermal conditions
 - Commercial availability of alloys, transformation temperatures are limited to ~115 °C
 - Vibration, humidity, corrosive elements, and bio-compatibility
- What relevant standards and documents are available?
 - Required for certification
 - Examples include ASTM standards: application specific documents, certification documentation, and supplier data
- What other components/system will be required?
 - System components









Wire Design Tool^[28]

• User-input martensite and austenite stress-strain responses

Solve for strokes, loads, and predicted life



Wire Design Tool^[28]

• Wire is rigidly anchored at one end and attached to a linear bias spring at the other



Wire Design Tool^[28]

• Required Input Parameters for Wire Design Tool

Name	Unit	Туре	Description and range for input	Reset	Symbo	×
				value	1	
OneWayLength	mm	Input: wire	>0, length of one or more wires	100	L	Intercept of M and Bias: strain= 0.0500
			mechanically in series			stress(Mpa)= 172.2 Intercept of A and Bias: strain= 0.0053
Diameter	mm	Input: wire	>0, wire diameter	0.25	d	stress(Mpa)= 263.3 Relative to min of CollSton & DiscM. Bias. Met. extra strain is: 0.0247
# of ParallelWires	unit	Input: wire	>0, # of mechanically parallel wires	1	n	Interpret of M and Bios: disp(grap)= 6.00
DispM_Bias_Met	mm	Input: system	>0, displacement where martensite	5% of L	D _{int}	load(N)= 8.5
			curve and linear bias spring intercepts			load(N)= 12.9
SpringConstant	N/m	Input: system	Must be a number	1	k	Relative to min of ColdStop & DispM_Bias_Met, extra stroke(mm) is 2.47
	m					
ColdStop	mm	Input: system	Wire stop position at cold	D _{int}	D _{cold}	Solution strain= 0.0300 Solution stress(Mpa)= 212.9
TargetStroke	mm	Input: system	>0, total motion amount left of	2% of L	D	Strain @ Max wire stress= 0.0300 Max wire stress(Mpa)= 212.9
			minimum of D _{int} or D _{cold}			Solution disp(mm)= 3.00
Volume	mm ³	Output			V	Solution load(N)= 10.5 Disp(mm) @ Max wire stress= 3.00
			-			Max wire load(N)= 10.5
MaxWireStress	MPa	Output	Maximum stress the wire experiences		S _{max}	Predicted Life= 333038 cycles

• Example output or solution message of the wire design tool

Wire Design Tool



Wire Design Tool^[28]

- Input parameters that describe the material and actuator application
- Output deflection and stress in austenite and martensite as a function of applied load

Solve for strokes, loads, as a function of geometries


Wire Design Tool^[28]

- Input parameters that describe the material and actuator application
- Output deflection and stress in austenite and martensite as a function of applied load

Input unit | Input type Input value Symbol Wire diameter Spring geometry d mm Mean coil diameter Spring geometry D mm Free length Spring geometry L_o mm Number of coils Spring geometry N_t End condition Spring geometry EC -----Shear modulus GPa Material property G_A, G_M Young's modulus Material property E_A, E_M GPa Poisson's ratio Material property v_A, v_M Material property Density g/cm³ ρ Applied force F Ν Actuator property Load evolution N/mm Actuator property ΔF Cold position Actuator property mm x_M

Required input parameters



Input values for various spring end conditions. (a) Plain. (b) Ground. (c) Squared. (d) Squared and ground.

Wire Design Tool^[28]



Graphical Output

(a) Force-deflection curves.

(b) Force-stress curves.

Spring Design Tool



Torque Tube Design Tool^[28]

- GUI-based version to predict the actuation stroke
- Code-based version that utilizes a design of experiments (DoE) to select an optimal torque tube design

Solve for strokes, loads, as a function of geometries



Torque Tube Tool^[28]

- GUI-based version to predict the actuation stroke
- Code-based version that utilizes a design of experiments (DoE) to select an optimal torque tube design

Required input parameters

Input value	Input unit	Input type	Symbol				
Tube thickness	mm	Tube geometry	t				
Tube radius	mm	Tube geometry	R				
Tube length	mm	Tube geometry	L				
Available power	W	System	Р				
Heating time	S	System	time _{heat}				
Applied torque	N∙m	System	<i>Torque_{app}</i>				
Load increase	(N·m)/deg	System	$\Delta Torque$				
Shear moduli	GPa	Material property	G_A , G_M				
Minimum	mm/mm	Material property	H_{min}				
transformation							
strain							
Maximum	mm/mm	Material property	H _{sat}				
transformation							
strain							
Transformation		Material property	k				
strain evolution							
parameter							
Poisson's ratios		Material property	v_A, v_M				
Density	g/cm ³	Material property	ρ				
Transformation	Κ	Material/thermal property	$M_f, M_s,$				
temperatures			A_f, A_s				
Transformation	K/MPa	Material/thermal property	C_M, C_A				
temperature							
evolution							
Thermal emissivity		Thermal property	е				
Initial temperature	K	Thermal property	T _e				
Specific heat	J/g	Thermal property	С				
Heating increment	S	Modeling setting	Δt				

Torque Tube Tool^[28]

- GUI-based version to predict the actuation stroke
- Code-based version that utilizes a design of experiments (DoE) to select an optimal torque tube design

Torque Tube Calibration Data (NiTiHf)



Torque Tube Tool^[28]

Graphical Output



Simulated actuation strain from torque tube modeling tool calibration compared with experimental results.

Torque Tube Tool^[28]



Torque Tube Design Tool



Are you looking for what material to use?

Temperature?

Strains?

Cost?

Look no more, the Shape Memory Material Database is here for you.



Shape Memory Material Database, how does it work?



Collect

Collect and organize all existing publications for Shape memory materials (SMM)

Belyaev_2015_Pseudoelasticity effect in amorphous—crystalline Ti 40.7 Hf 9.5 Ni 44.8 Cu 5 shape mem...
 Benafan_2012_Deformation and phase transformation processes in polycrystalline NiTi and NiTiHf hig...
 Benafan_2012_Microstructural Response During Isothermal and Isobaric Loading of a Precipitation-Str...
 Benafan_2014_Mechanical and functional behavior of a Ni-rich Ni50.3Ti29.7Hf20 high temperature sh...
 Benafan_2016_Ontsent-Strain Thermal Cycling of a Ni50.3Ti29.7Hf20 High Temperature Shape Memory Alloy
 Benafan_2016_Constant-Strain Thermal Cycling of a Ni50.3Ti29.7Hf20 High Temperature Shape Memory Alloy
 Benafan_2017_High temperature shape memory alloy Ni50.3Ti29.7Hf20 torque tube actuators
 Beseghini_1999_Ni-Ti-Hf shape memory alloy effect of aging and thermal cycling
 Beyer_1995_Recent developments in high temperature shape memory alloys
 Biglow_2011_Load-biased shape-memory and superelastic properties of a precipitation strengthened...
 Biglow_2015_Diffusion of hydrogen in the shape memory alloy Ni50.4Ti20 Pint/140Hf10Cu3

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Extract

Extract and consolidate data from literature into a standard-format.

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							Viokor: Hardner: (UV)								Lonst	ADC I						
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19.5	50.5	38.0			100.0	LBTC	VIM-homegenized: estruded/900C	VM							100	500	20	24	284.0	298.5	268.7	7
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45	297		20	H	110	LBTC.	Bridsman techniques 1050HBv/V/D 800C73v/V/D	Rider	1050		600	2			25	200	10		82.0	152.9	107.5	ā.
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Design

Integrate data into a graphical user interface (GUI) to explore the SMM system.



Shape Memory Material Database, select a material system.



Shape Memory Material Database, Example: Alloys

Select an alloy (or multiple) from the periodic table)

- Can consider weight
- Cost
- Processability



Shape Memory Material Database, Example: Alloys

Select properties of interest to examine (binary or ternary plot)

- Transformation temperatures
- Yield strength/strains
- Hardness



Shape Memory Material Database, Example: Alloys

Apply filters to narrow search

- Processing methods
- Types of loading (torsion, tension, compression)
- Ranges



Shape Memory Material Database, Example: Alloys

Get all the data you need

- Plot trends
- Hover around data points for source information
- Output data

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Shape Memory Material Database, Ternary Diagrams:

Ternary diagrams:

- a) Plotting a single ternary SMA system
- b) Plotting quaternary SMAs
- c) Plotting multiple ternary SMA systems at once



Shape Memory Material Database, Case Study:

a) I need a material with an austenite finish temperature of 250 °C and a martensite finish temperature of 150 °C.



Shape Memory Material Database, Case Study:

a) I need a material with an austenite finish temperature of 250 °C and a martensite finish temperature of 150 °C.

b) I need actuation strains of ~ 4 to 6%.



Shape Memory Material Database, Case Study:

- a) I need a material with an austenite finish temperature of 250 °C and a martensite finish temperature of 150 °C.
- b) I need actuation strains of ~4 to 6%.
- c) Cannot afford precious metals.



Shape Memory Material Database, Web Tool

a) Access to this tool will be publicly available on or before September 2018.

b) If interested, contact <u>othmane.benafan@nasa.gov</u>.

Choosing the right material for the right applications

High Temperature Shape Memory Alloys (HTSMAs)



Choosing the right material for the right applications

High Temperature Shape Memory Alloys (HTSMAs)

Engines



Active Jet Engine Chevron (LaRC)



Variable Area Fan Nozzles (Boeing)

Choosing the right material for the right applications

High Temperature Shape Memory Alloys (HTSMAs)

Shape Memory Alloy Rock Splitters (SMARS)— When SMAs meet rocks









Choosing the right material for the right applications

Low Temperature Shape Memory Alloys (LTSMAs)



Choosing the right material for the right applications



300 K

Choosing the right material for the right applications

Low Temperature Shape Memory Alloys (LTSMAs)



Adaptive Thermal Management System (KSC)



Choosing the right material for the right applications



Application of Shape Memory Alloys | Biomedical

Implants• Jaw Plates• Bone Staples• Hip Implants• Pedicle Screws

Medical Devices

Targeted Inhalers
Catheter Tubes
Instruments

Stents

Consumer Products

Eyeglasses Orthodontics

101

Application of Shape Memory Alloys | Aeronautics

Variable Area Nozzle -

- High bypass turbofan
- SMA torque tubes provide flap rotation
- Engine noise reduction

SMA Cellular Structures -

- Airframe and engine components
- Morphing airfoils
- Lightweight trusses





Adaptive Fan Blade

- Embedded SMA actuators
- Aerodynamic efficiency
- Specific fuel consumption reduction

Variable Geometry Chevron

- SMA actuators morph the chevron
- Noise reduction at takeoff
- Shock cell noise reduction at cruise



Application of Shape Memory Alloys | Space



SMA Spring Tire

Superelastic technology
Lunar and Martian rovers
Non-Pneumatic

- NiTi Bearings
- Corrosion resistant
- Non-galling properties
- \circ High yield
- Provides drinking water to astronauts

Application of Shape Memory AlloysConsumer Goods



Application of Shape Memory AlloysOil and Gas

Deep-Water Platforms

- Deep-water shutoff valves
- Underwater connectors
- Self-torqueing fasteners
- o Seals

Down-hole Drilling

- Abrasion-resistant components
- o Actuators
- Vibration damping



Crude Extraction SmartRAMTM actuators (*LMP*) SMA couplings

ASTM Standards

For biomedical and or superelastic

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

For SMA Actuation

- E3097-17
- E3098-17

CHAPTER 3: Mechanism Design With Shape Memory Alloys 3.5 Help: Handbooks, ASTM Standards, References



Standard Test Method for Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys (UCFTC)

Examples:

- Determine material properties
- Multi-cycle actuator



Standard Test Method for Uniaxial Pre-strain and Free Recovery of Shape Memory Alloys (UPFR)

Examples:

- Determine material properties
- One time actuation
- Release mechanism, deployment devices

Vendor material data sheets

- Dynalloy, Inc \rightarrow <u>http://www.dynalloy.com/</u>
- Fort Wayne Metals → <u>https://fwmetals.com/</u>
- Johnson Matthey \rightarrow <u>http://jmmedical.com/</u>
- SAES Group → <u>https://www.saesgetters.com/products-functions/products</u>
- TiNi aerospace \rightarrow <u>https://tiniaerospace.com/</u>
- Ultimate R&D: \rightarrow <u>http://www.ultimateniti.com/</u>
- Others...
CHAPTER 3: Mechanism Design With Shape Memory Alloys *3.5 Help: Handbooks, ASTM Standards, References*

Other Useful Resources

- CASMART—Consortium for the Advancement of Shape Memory Alloy Research and Technology <u>http://casmart.tamu.edu/</u>
- SMST—Shape Memory and Superelastic Technologies <u>https://www.asminternational.org/web/smst/home?doAsUserId=vzMatAB%2FAxI%3D</u>
- SMA journals <u>https://www.springer.com/materials/characterization+&+evaluation/journal/40830</u>
- SMA Conferences Materials and applications
 - <u>https://www.asminternational.org/web/smst2017</u>
 - https://www.asme.org/events/smasis
 - <u>https://htsmas2018.dgm.de/home/</u>

Material Science

- <u>https://icomat2017.northwestern.edu/</u>
- <u>http://www.lem3.univ-lorraine.fr/ESOMAT2018/</u>

CHAPTER 3: Mechanism Design With Shape Memory Alloys | References

27) Benafan, O., Brown, J., Calkins, F.T., Kumar, P., Stebner, A.P., Turner, T.L., Vaidyanathan, R., Webster, J., Young, M.L.: Shape memory alloy actuator design: CASMART collaborative best practices and case studies. International Journal of Mechanics and Materials in Design 10, 1–42 (2013)

28) Wheeler RW, et al. Engineering Design Tools for Shape Memory Alloy Actuators: CASMART Collaborative Best Practices and Case Studies. ASME. Smart Materials, Adaptive Structures and Intelligent Systems, *Volume 1: Multifunctional Materials; Mechanics and Behavior of Active Materials; Integrated System Design and Implementation; Structural Health Monitoring* doi:10.1115/SMASIS2016-9183.

CHAPTER 3: Mechanism Design With Shape Memory Alloys | Hands On-LAB 3

The Power of SMAs—Seeing is Believing

(Group exercise)

- 1. Subjects covered: Electrical heating; relationship of resistance to heating rate; heat versus temperature; how current divides, when given alternative paths; relationship of voltage to heating rate; relationship of transition temperatures to bias or return forces; leverage; moment arms; battery voltages; elasticity; spring dynamics; and more.
- 2. Sets of 3 diameter sizes wires, consisting of 2 different transition temperature wires for each wire size.

CHAPTER 3: Mechanism Design With Shape Memory Alloys | Hands On-LAB 4

Ready to test your SMA knowledge?

(Group exercise)

- 1. Form team
- 2. Brainstorm to determine application for smart/adaptive structure
- 3. Determine requirements/define functions
- 4. Select methods to fulfill functions
- 5. Make sketch that shows configuration
- 6. Make sketch that shows interfaces
- 7. Present concept

Many thanks to contributions from:











NASA GRC SMA Team

List of Symbols

Af	Austenite finish
As	Austenite start
DSC	Differential Scanning Calorimetry
EDM	Electrical Discharge Machining
GRC	Glenn Research Center
HTSMA	High Temperature Shape Memory Alloy
Md	Martensite desist
Mf	Martensite finish
Ms	Martensite start
NASA	National Aeronautics and Space Administration
SE	Superelasticity
SMA	Shape Memory Alloy
SME	Shape Memory Effect
TWSME	Two-Way Shape Memory Effect

Othmane Benafan, Ph.D. | Course Instructor



Othmane Benafan, Ph.D.

The instructor for this course is Dr. Othmane Benafan. Dr. Benafan is a materials research engineer in the High Temperature and Smart Alloys Branch at NASA Glenn Research Center. He received his Ph.D. in Mechanical Engineering from the University of Central Florida in 2012. Since joining NASA Glenn, his work entails developing novel shape memory alloys (SMAs) with high and sub-zero actuation temperatures to enable new, lighter weight aerospace mechanisms and shape-changing components for temperature ranges beyond the limits of commercial SMAs. His work is continuing to develop the alloys, address scale-up issues, assess durability, and develop specifications and standards, all of which are critical to enable the technology to be adopted for flight. Othmane is currently the Executive Chairman of the joint industry-government-academia Consortium for the Advancement of Shape Memory Alloy Research and Technology (CASMART), and the Vice President of the ASM International Organization on Shape Memory and Superelastic Technologies (SMST).

NASA Glenn Research Center | Materials and Structures Division | 21000 Brookpark Road | Mail Stop 49-3 | Cleveland, OH 44135 Phone: 216-433-8538 Fax: 216-977-7133 Email:

othmane.benafan@nasa.gov

