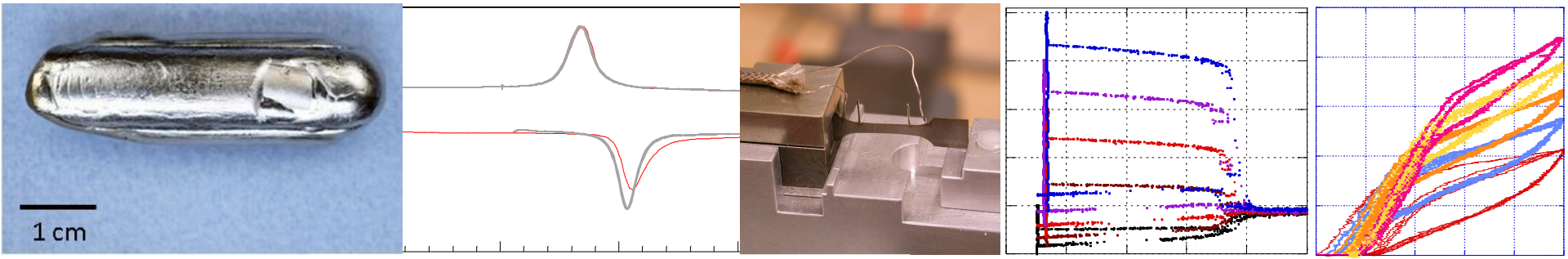
SAND2017-1659PE




# Introduction to Shape Memory Alloys

Don Susan, FASM

ASM Chapter Meeting

February 16, 2017

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# Nitinol Experiments & Videos

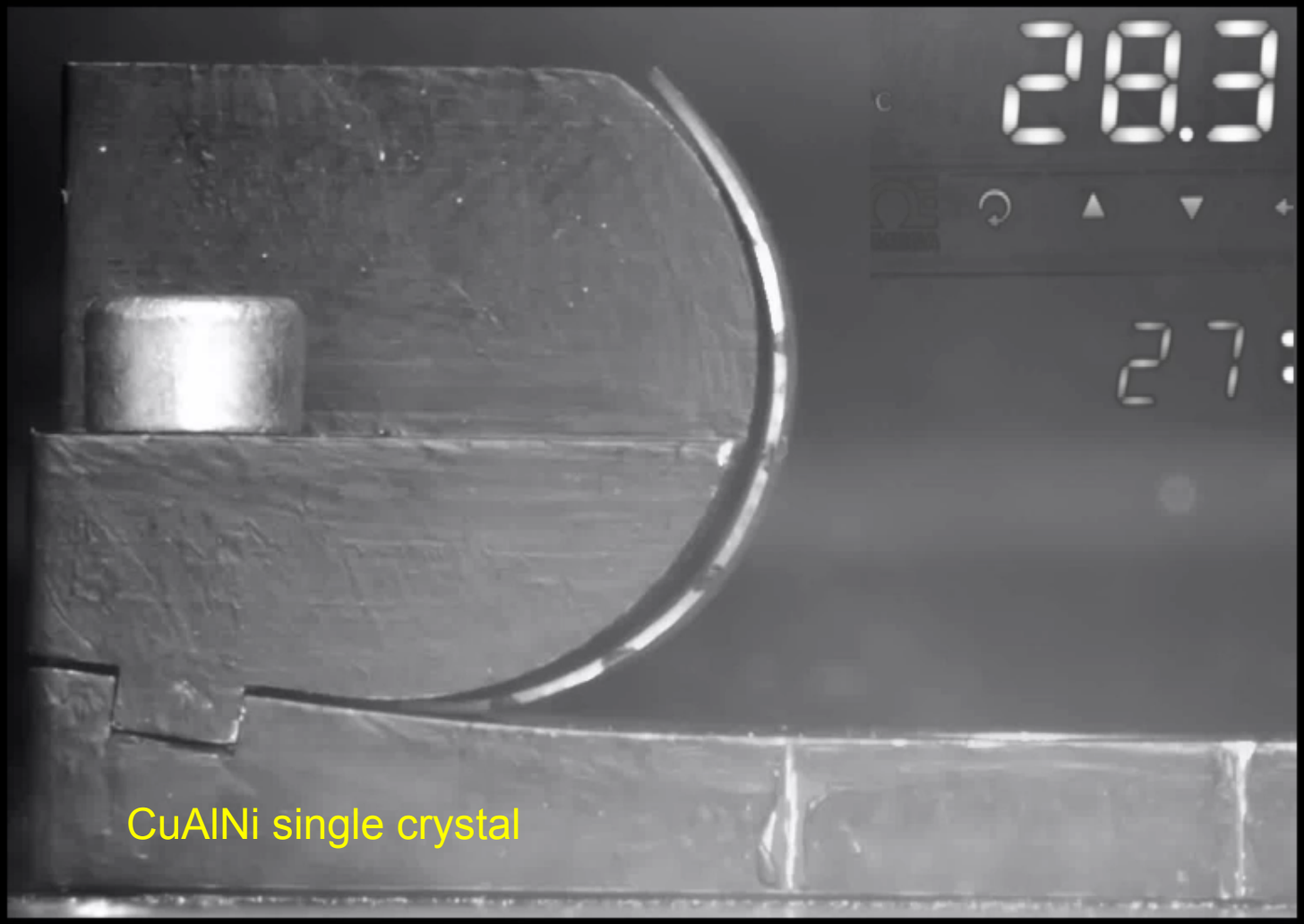
The most common shape memory alloy (SMA) is NITINOL

Discovered in 1959 at the Naval Ordnance Laboratory:

Nickel-Titanium Naval Ordnance Laboratory

Other SMAs include CuAlNi (single crystal), AuCd, some Fe-base alloys


SMA NASA Wire
Shape Memory Effect


28.3
CuAlNi single crystal

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# SMA CONTACT FLAP ACTIVATION TRIAL 1 (COMMERCIAL SMA)

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# SMA CONTACT FLAP ACTIVATION TRIAL 2 (SNL MATERIAL D)

Sandia National Laboratories

# Applications of Shape Memory Alloys

# Traditional SMA Applications

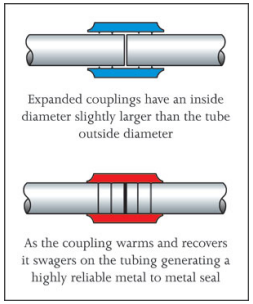
Sandia National Laboratories

## Cell Phones

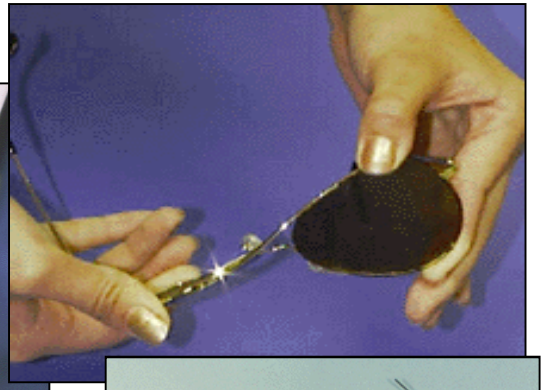
## Stents

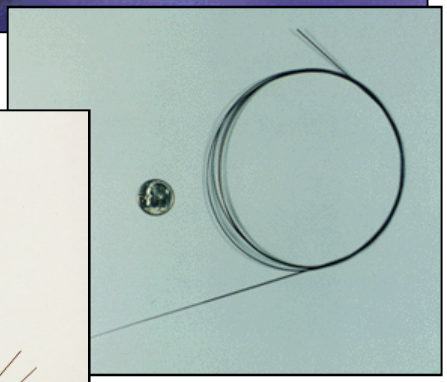

## Automotive

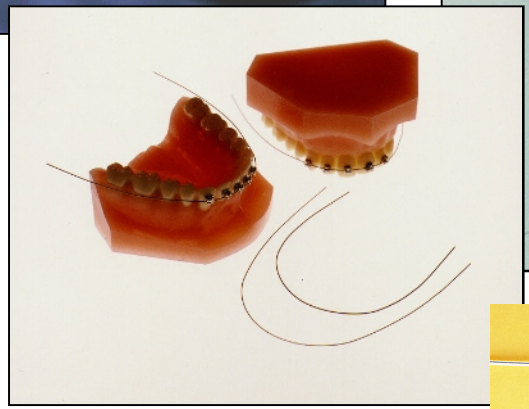
Cryofit couplers

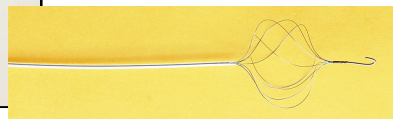



## Sports, Style, Health









Memry Corp., www.memry.com, 2003.

# Maturing Aerospace SMA Application

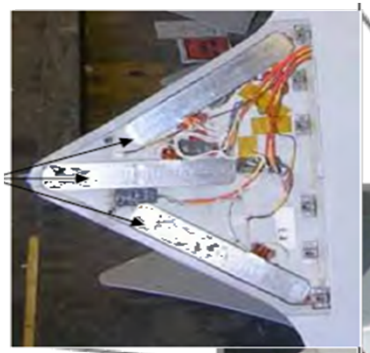
Sandia National Laboratories


60NiTi Bearing Race

## Variable Geometry Chevrons

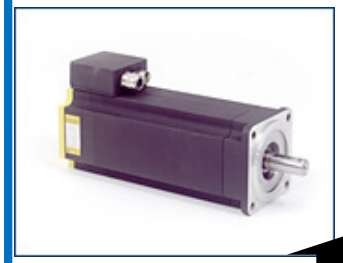
- SMA enables morphing chevron.
- Chevron shape optimizes engine performance
  - noise reduction;
  - cruise performance.

SMA

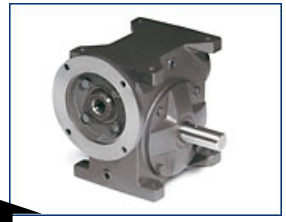


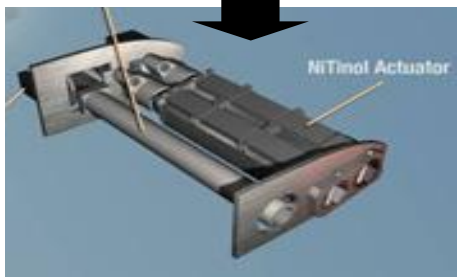

The Boeing Co., T. Calkins, 2007.

**Motor:**
**Torque 66 in-lbs**
**25 lbs**



**Gear box :**
**190 in-lbs**
**16 lbs**






**SMA Rotary Actuator :**
**150 in-lbs**
**1 lbs**

$Ni_{60}Ti_{40}$

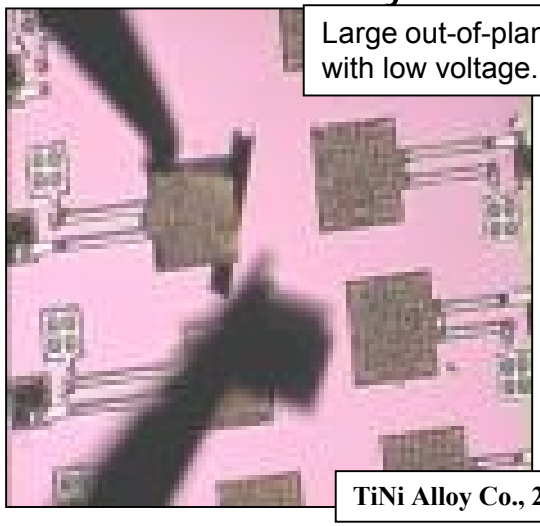
**IDEAL FOR HIGH FORCE, LARGE STROKE, LOW CYCLE OPERATION**

Ron Noebe, NASA Glenn

# Thin Film SMA Applications

Sandia National Laboratories

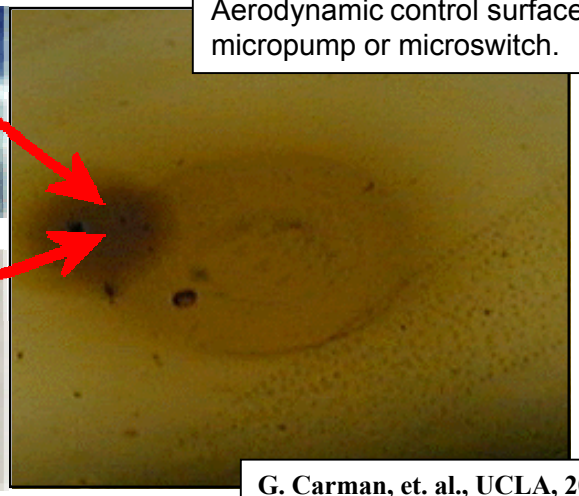
## Micromirror Array



Large out-of-plane motion with low voltage.

TiNi Alloy Co., 2001

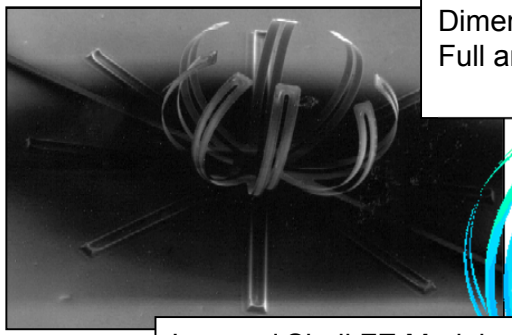
## Microbubble



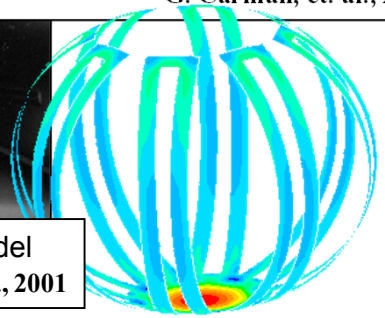
Aerodynamic control surface, micropump or microswitch.

G. Carman, et. al., UCLA, 2001

## Microclaw

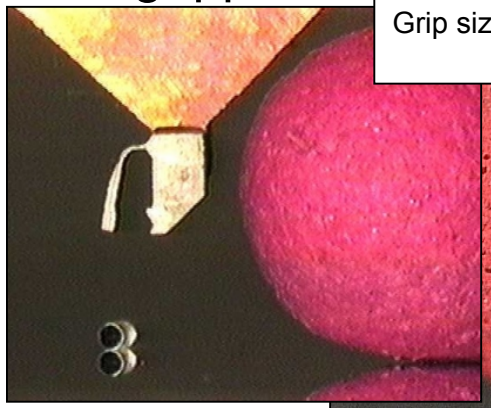


Dimensions: 10 x 100 $\mu m^2$ (arm)
Full arm closure in milliseconds.
G. Carman, et. al., 2001



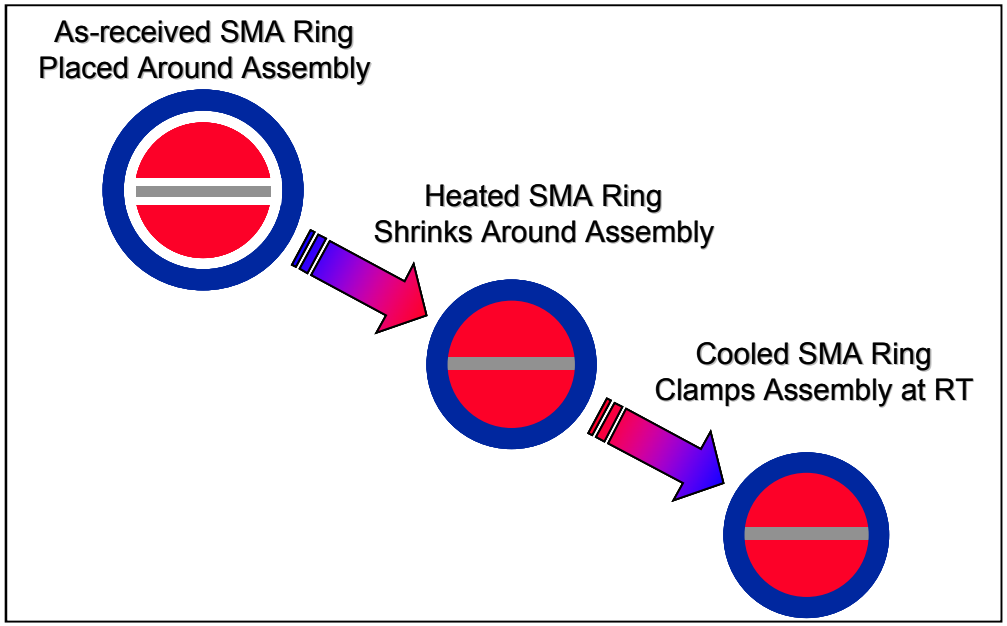
Layered Shell FE Model
J. Redmond, et. al., 2001

## Microgripper



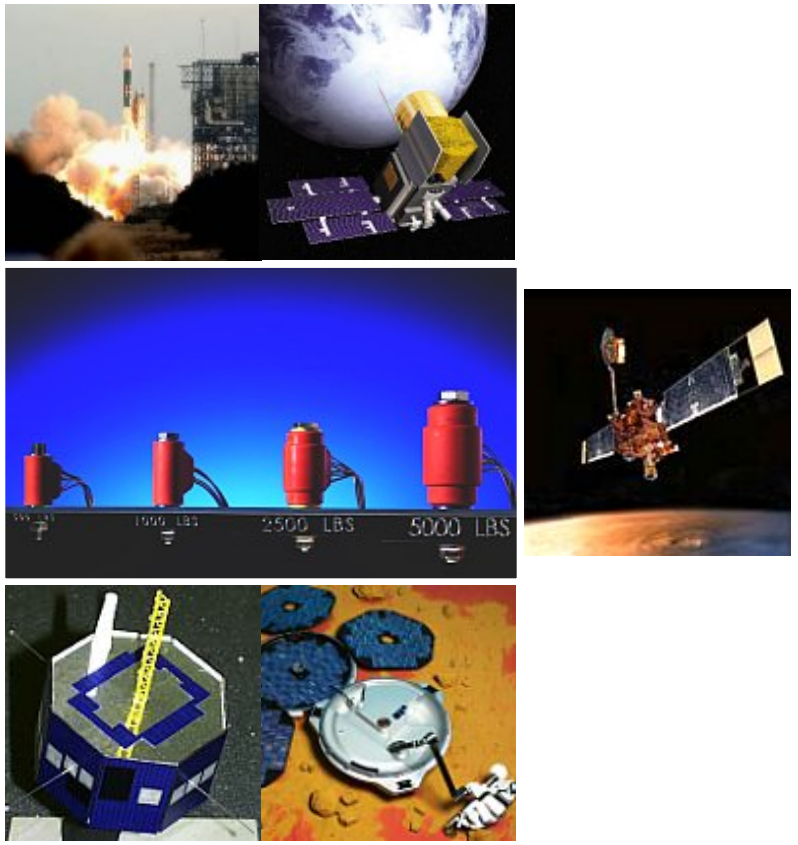
Dimensions: 1.4 x 1.8 $mm^2$, 10$\mu m$
Grip size of 160$\mu m$, 35mN force.
Y. Bellouard, et. al., 1999

# Sandia Applications




Ni-Ti-Nb alloy

## Space Applications




"Frangibolts"

TiNi Aerospace, Inc. www.tiniaerospace.com, 2003

# How do SMAs Work?

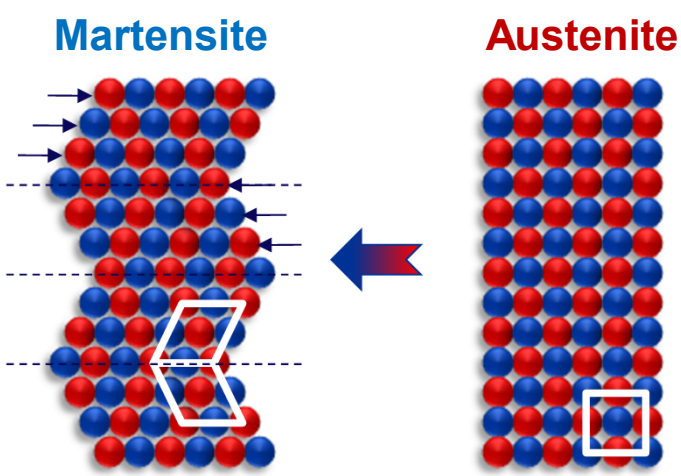
1. Shape Memory Effect

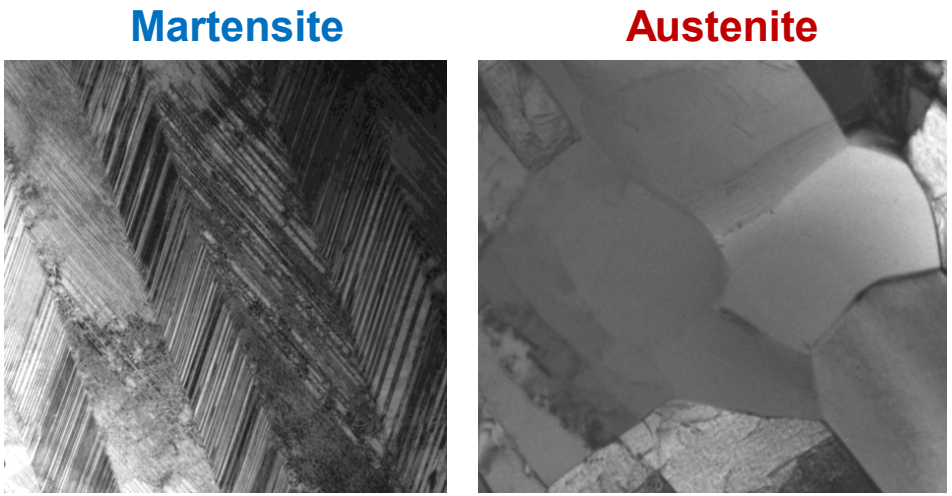
2. Superelasticity

3. High-temperature SMA research at Sandia
   - Ni-Ti-Pt, Ni-Ti-Pd, Ni-Ti-Hf: DSC and transformation temperatures
   - Tensile shape memory effect and superelasticty
   - Bending behavior

# Shape Memory Alloys

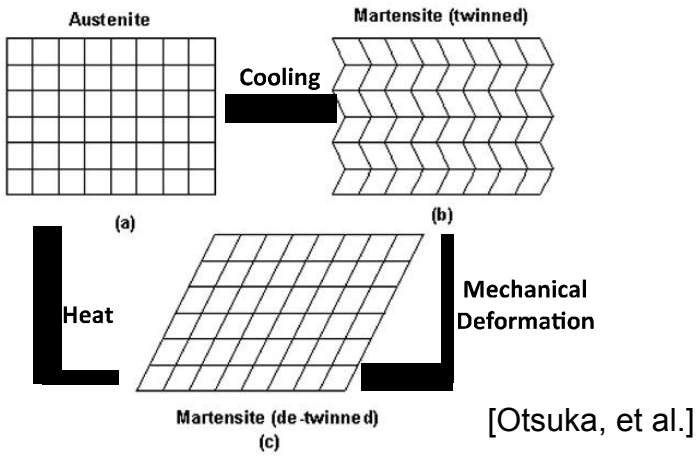
- **Shape memory alloys (SMAs) exhibit a solid-to-solid, reversible phase transformation of martensite (low temp)/austenite (high-temp)**
- **Can accommodate large strains (e.g., 8% strain) through either shape memory effect or superelasticity.**
- **Shape change can generate stresses (up to 500 MPa)**
- **Ability to do work and hence used as actuators (e.g., $10^7$ J/m$^3$)**



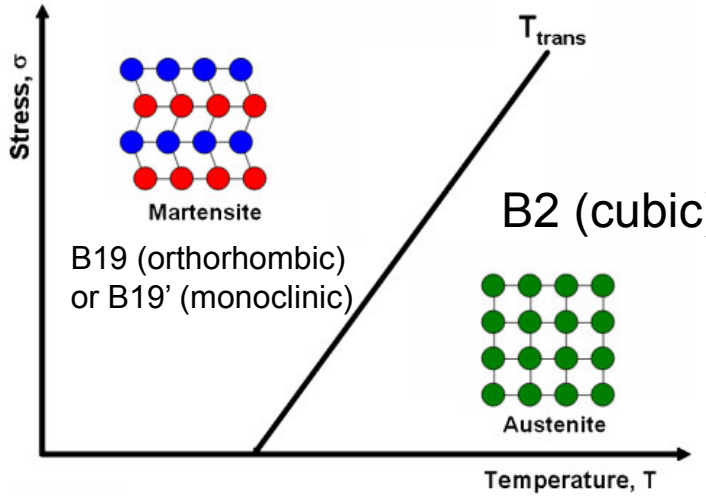



# Shape Memory Effect

- **When deformed at low temperature, SMAs exhibit shape change when heated -- associated with the martensite/austenite phase transformation.**
- **The alloy "remembers" its original shape that was previously set in austenite.**
- **Commercial binary NiTi (Nitinol) used for medical stents, connectors/couplers, actuators, etc.; transformation temperatures are ≤ 100°C.**



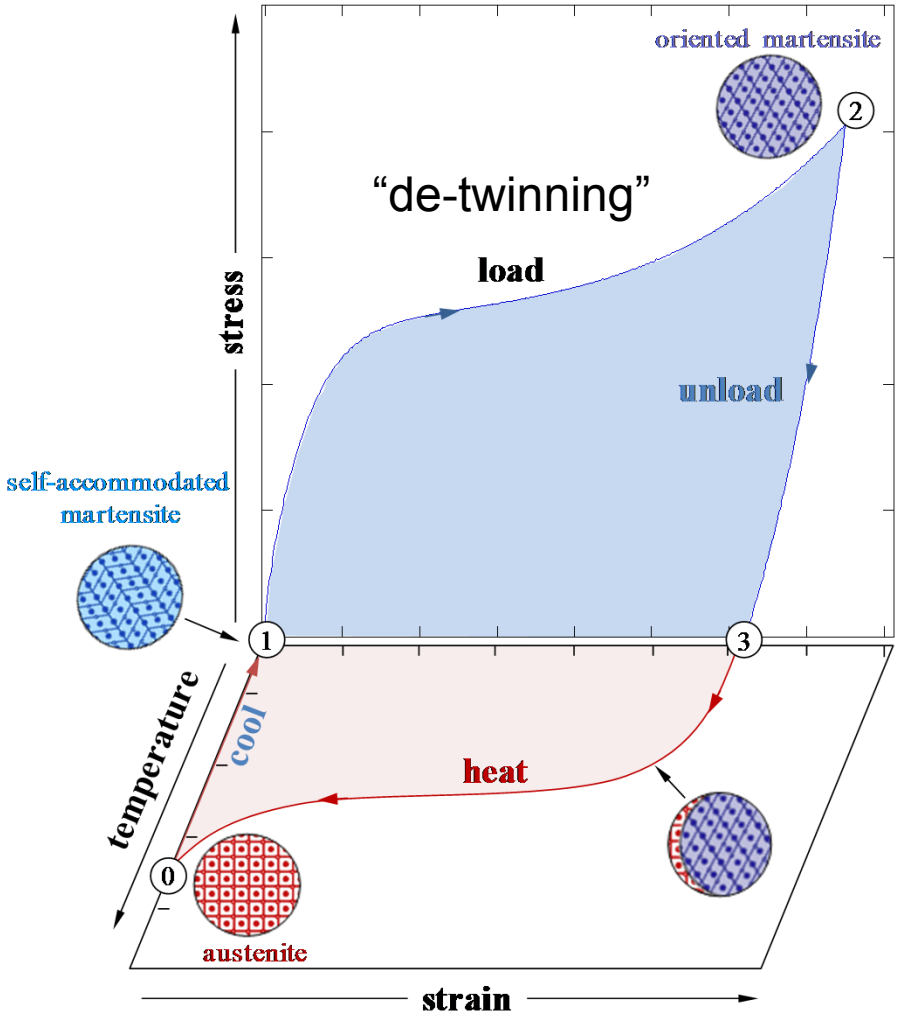

[Otsuka, et al.]

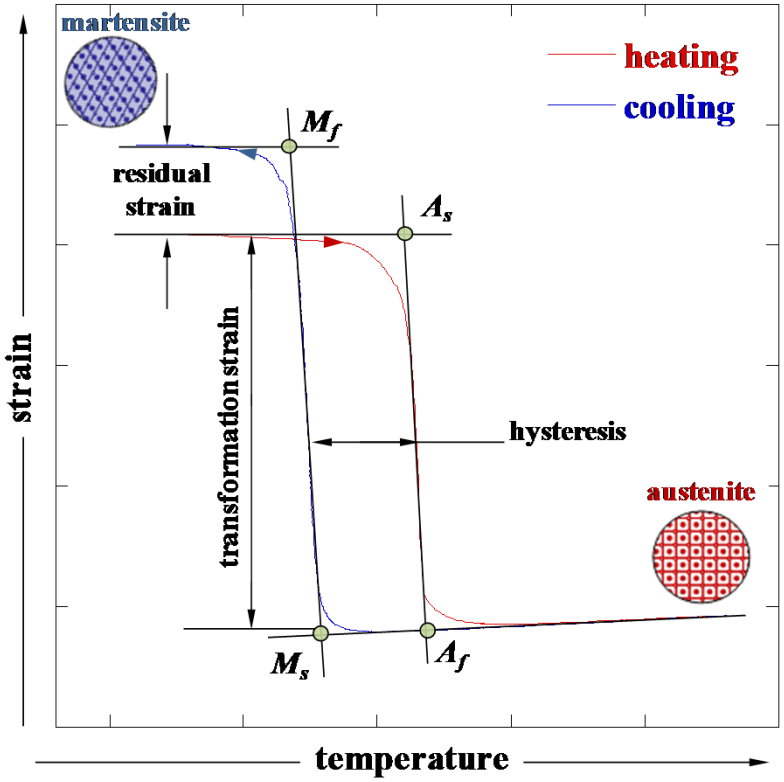



[Ma, et al.]

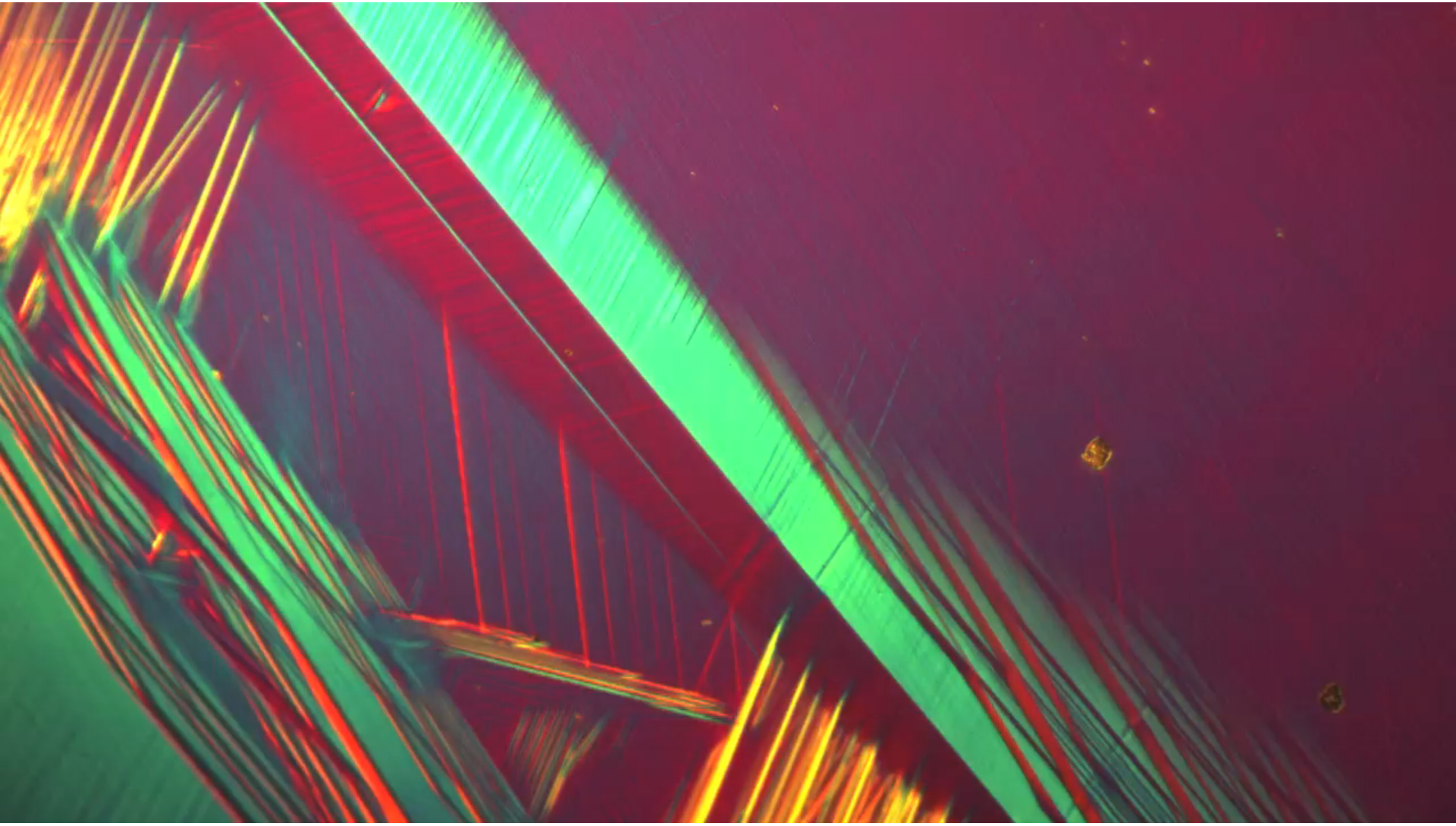
# Shape Memory Effect

## Temperature-induced transformation




- Transformation temperatures
- Transformation strain (work output)
- Residual strain (dimensional stability)
- Hysteresis (active control)



[Song et al., Nature Letters, Vol. 502, 2013, 85-88.]

# Superelasticity

Stress (strain)-induced transformation Superelasticity

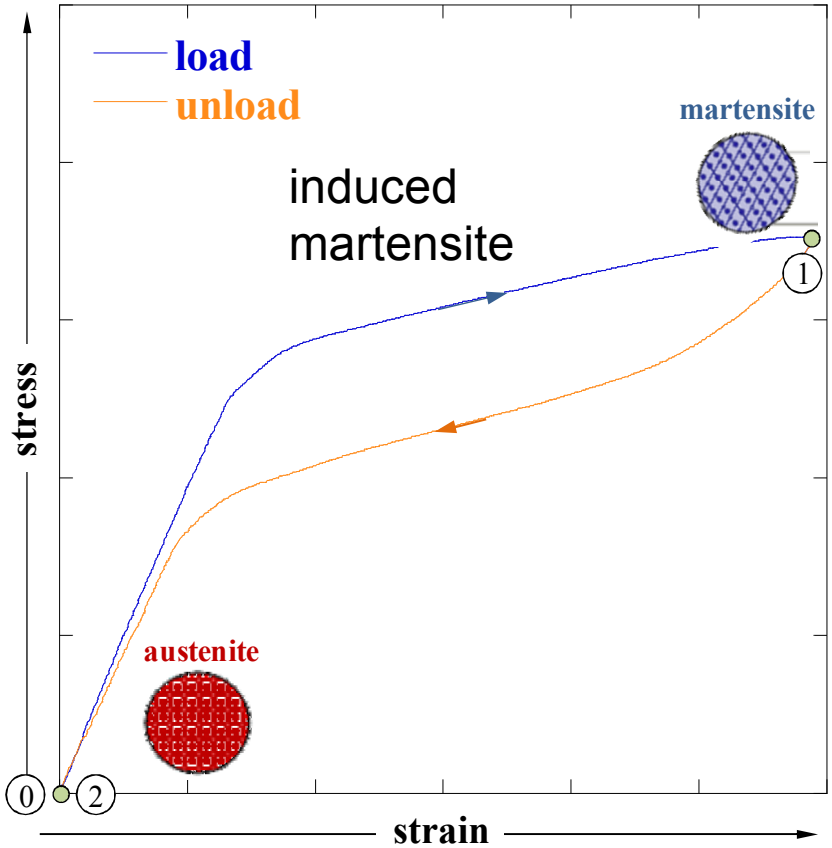
"non-linear elastic"?

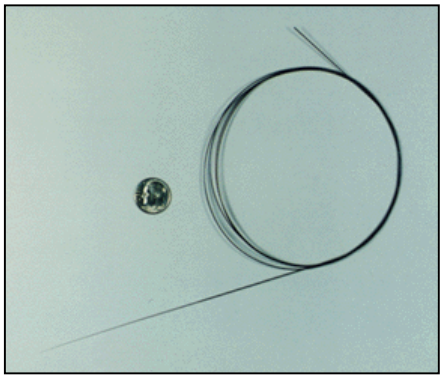
"recoverable plastic"?

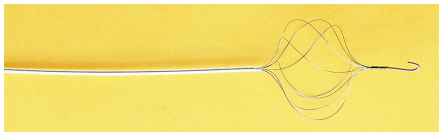
Superelastic

Pseudoelastic

"rubber-like"



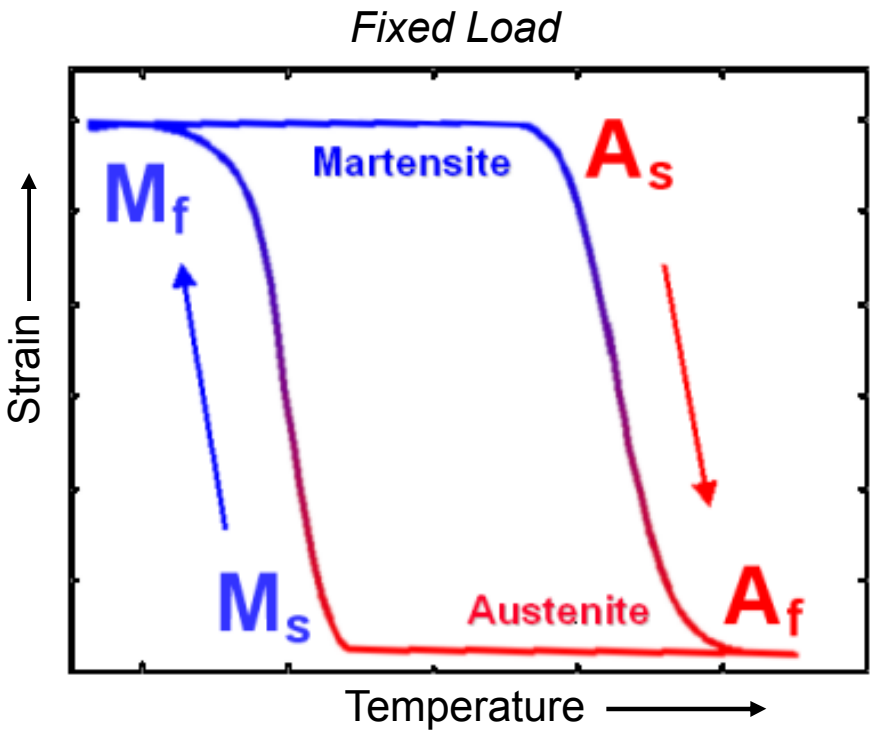





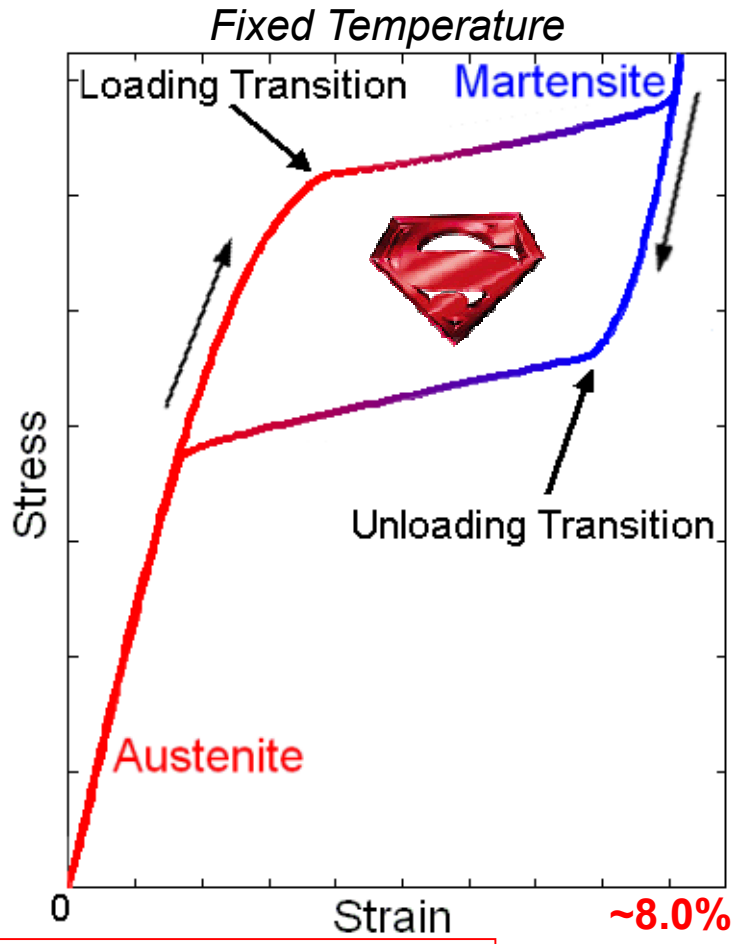
# Shape Memory Measurements

Sandia National Laboratories

### *Shape Memory Effect*

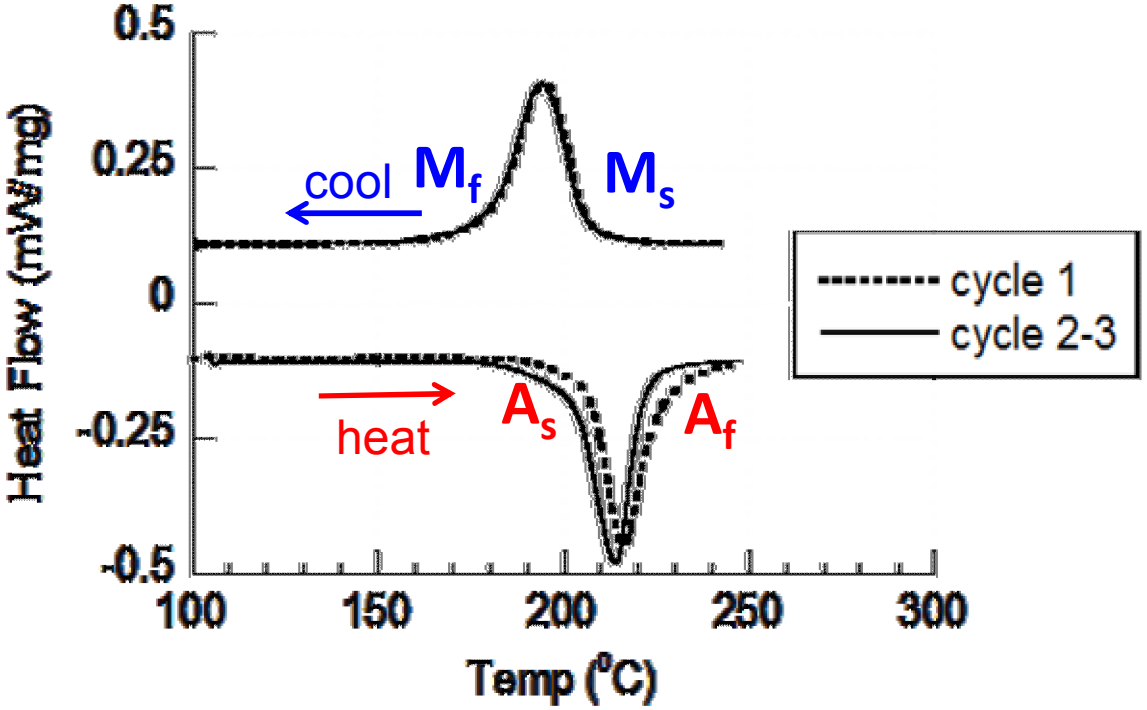


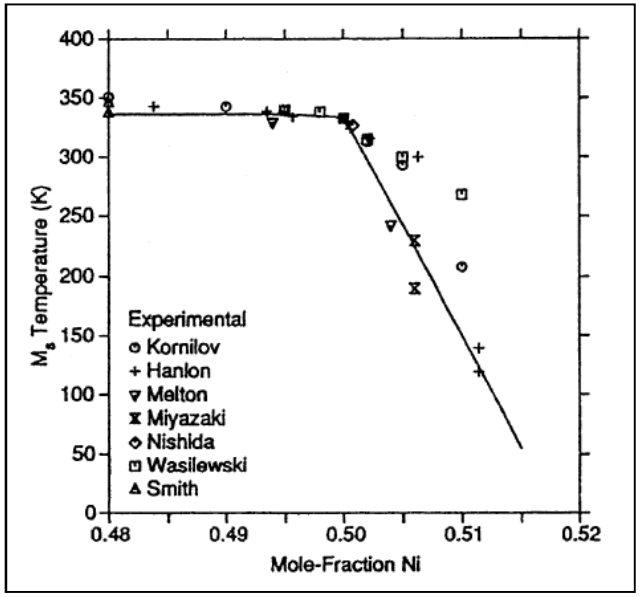

### *Superelasticity*




Thermomechanical behavior is *nonlinear* & *hysteretic*.

# Differential Scanning Calorimetry (DSC) to Determine Transformation Temperatures

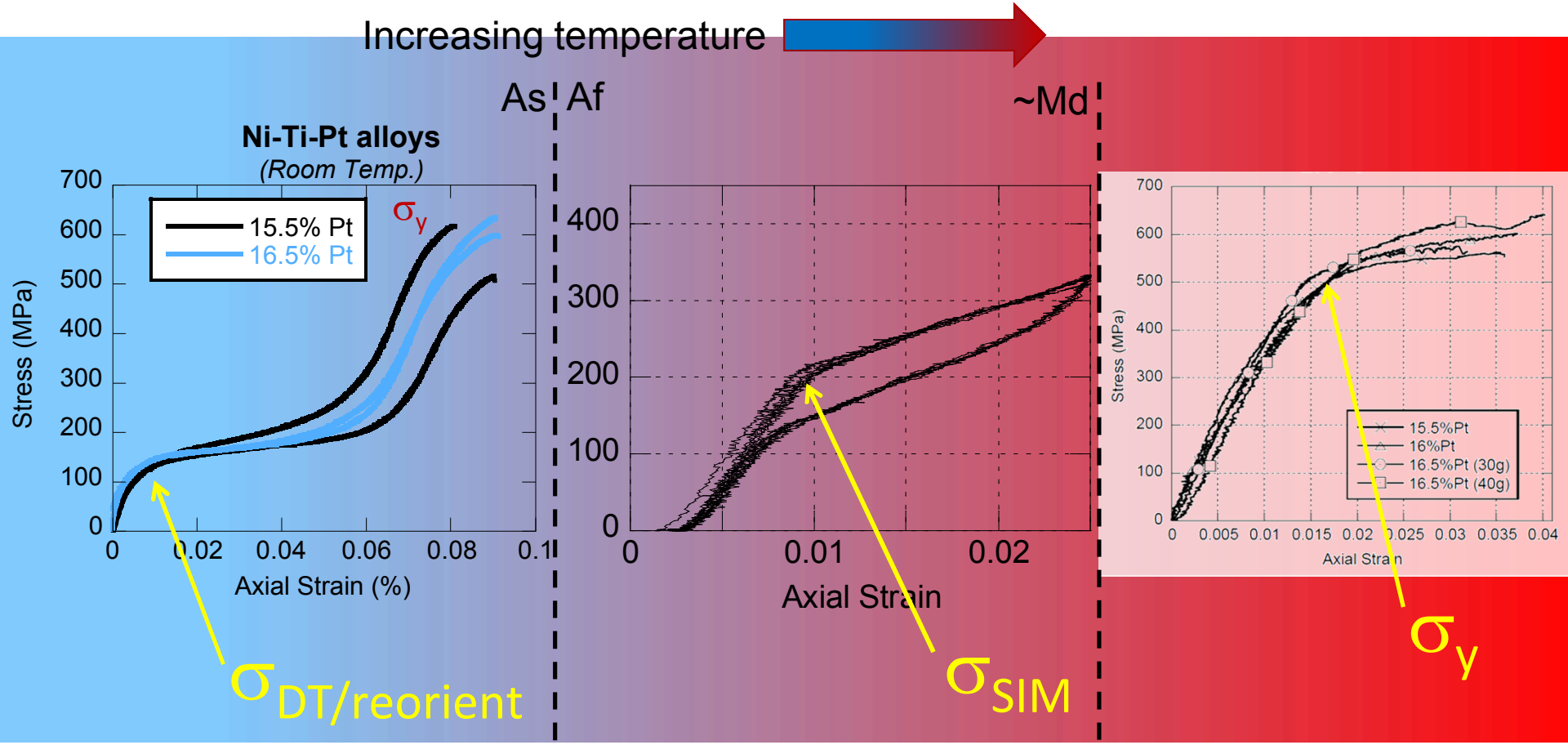



K. Otsuka and X. Ren, *Prog. Mat. Sci.*, Vol. 50, 511-678, 2005

- Hysteresis: difference between austenite formation temps. on heating and martensite formation temps. on cooling
- These are *stress-free (unbiased)* transformation temperatures

# Summary: SMA Mechanical Behavior



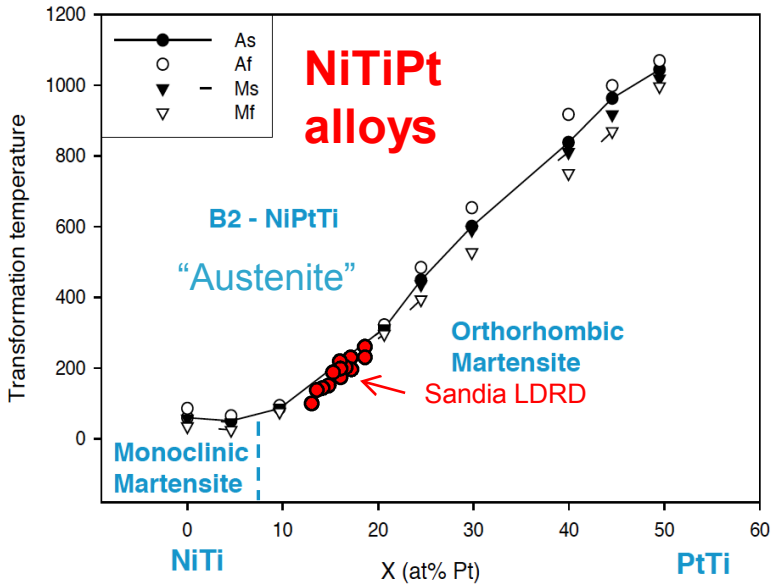

- At low temperature (martensite), the material "detwins", produces significant strain.
- Just above the M/A transf. temp, strain-induced martensite can form (superelasticity).
- At high temperature, in the austenite phase, yielding occurs like a "normal" metal.

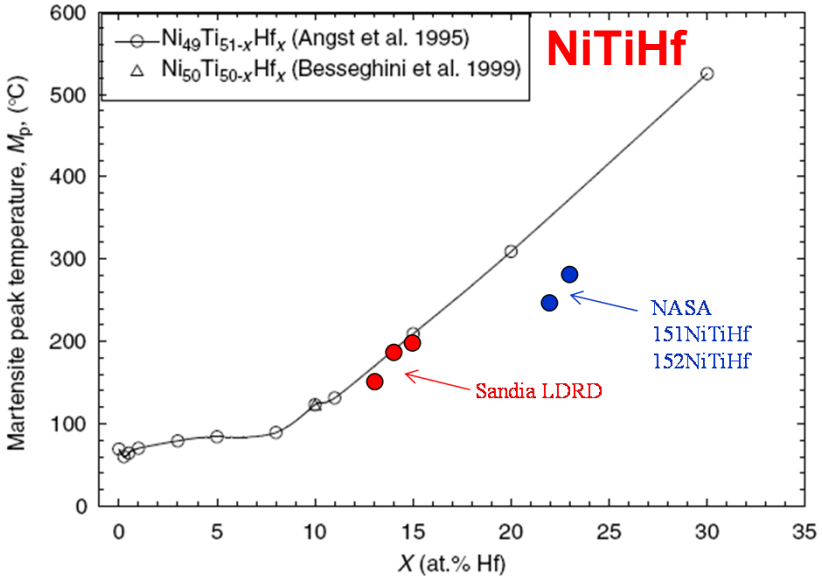
# Sandia Research: High Temperature Shape Memory Alloys (HTSMAs)

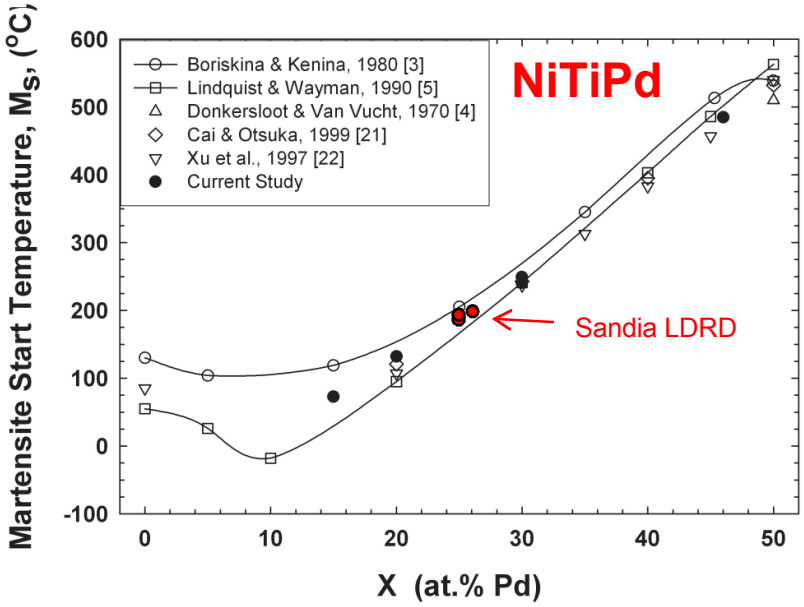
- Substitutional replacement of Ni with Pt, Pd or Ti with Hf in NiTi can increase shape memory transformation temps.
- Previous work by others has focused primarily on alloys with ≥20 at.% Pt and transformation temperatures >250 °C.
- Collaboration with NASA-Glenn Research Center

**Desired Transformation Temperature Range 180-220 °C**

# HTSMA alloys produced at Sandia




- Colored data points represent new alloys produced at Sandia (and NASA-Glenn)

# HTSMA Characterization

Sandia National Laboratories

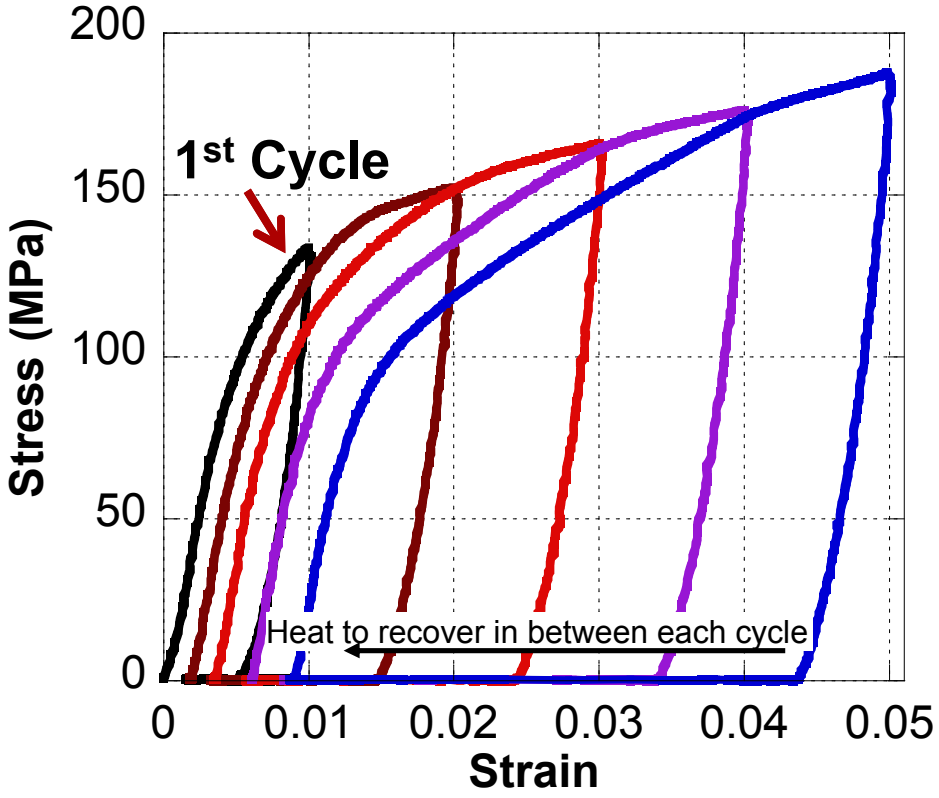
**How do NiTiPt and NiTiPd HTSMAs recover shape under thermomechanical conditions?**

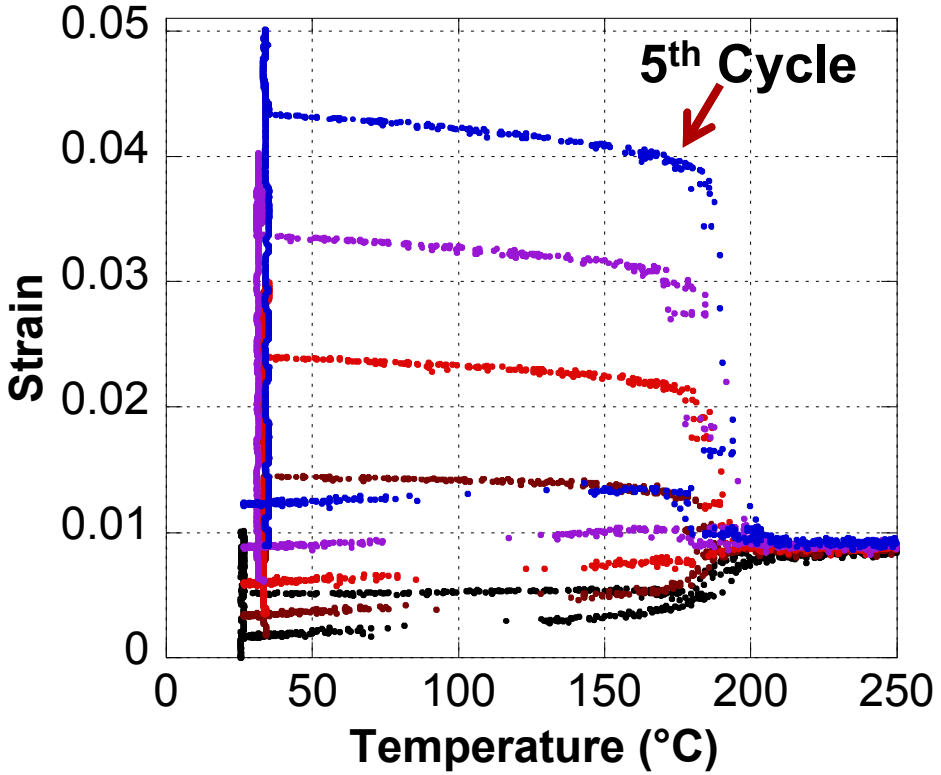
- Shape Memory Effect (SME) Experiments
  - Determine how much tensile strain material can recover under no load via heating through transformation.
- Superelasticity Experiments
  - Determine whether high-temp. superelasticity is possible and over what temperature window

# SME Experiments (NiTiPt)

| Test Program | Effective Strain Rate (1/s) | Heat Rate (°C/min) |
|---|---|---|
| Pull to X% strain (stroke control) @RT; unload to 0 N; heat to $A_f$+30 °C @0 N, hold; cool. | $4 \times 10^{-4}$ | 5-10 |

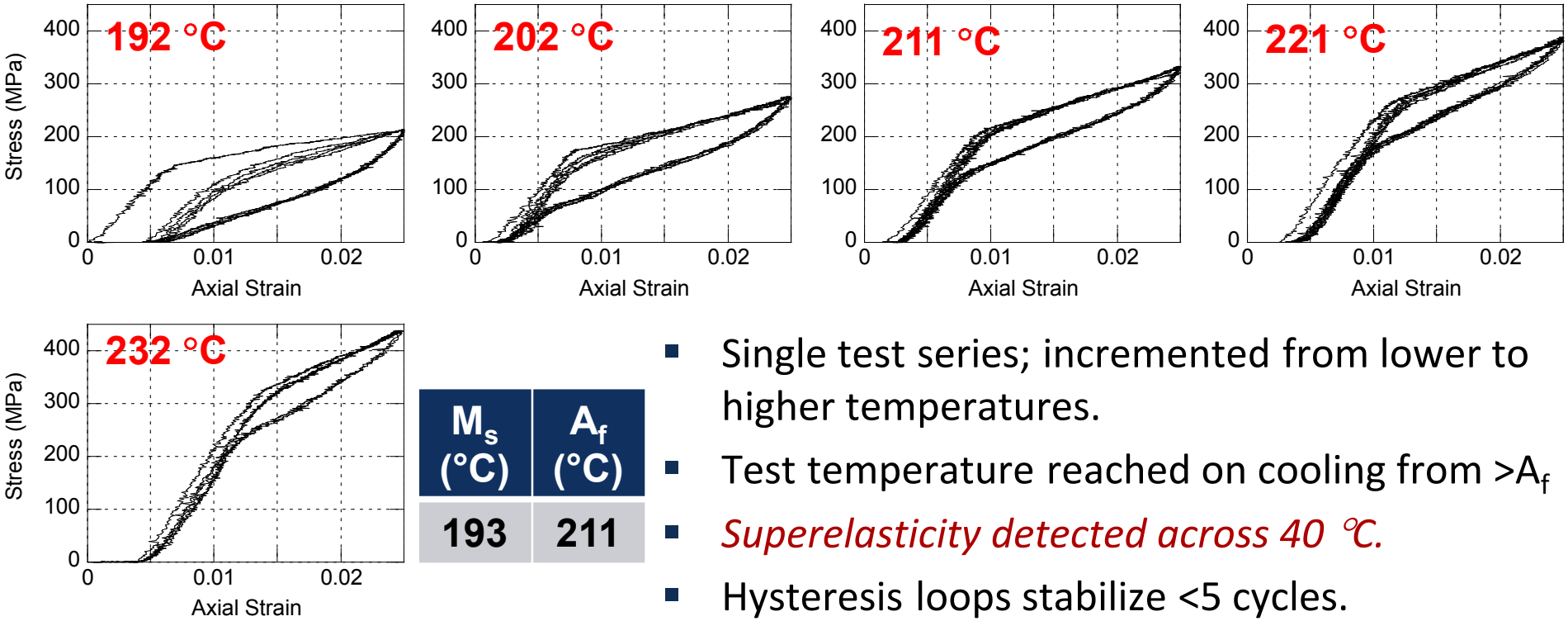
**16 at.% Pt**



# Superelasticity Experiments (NiTiPt)

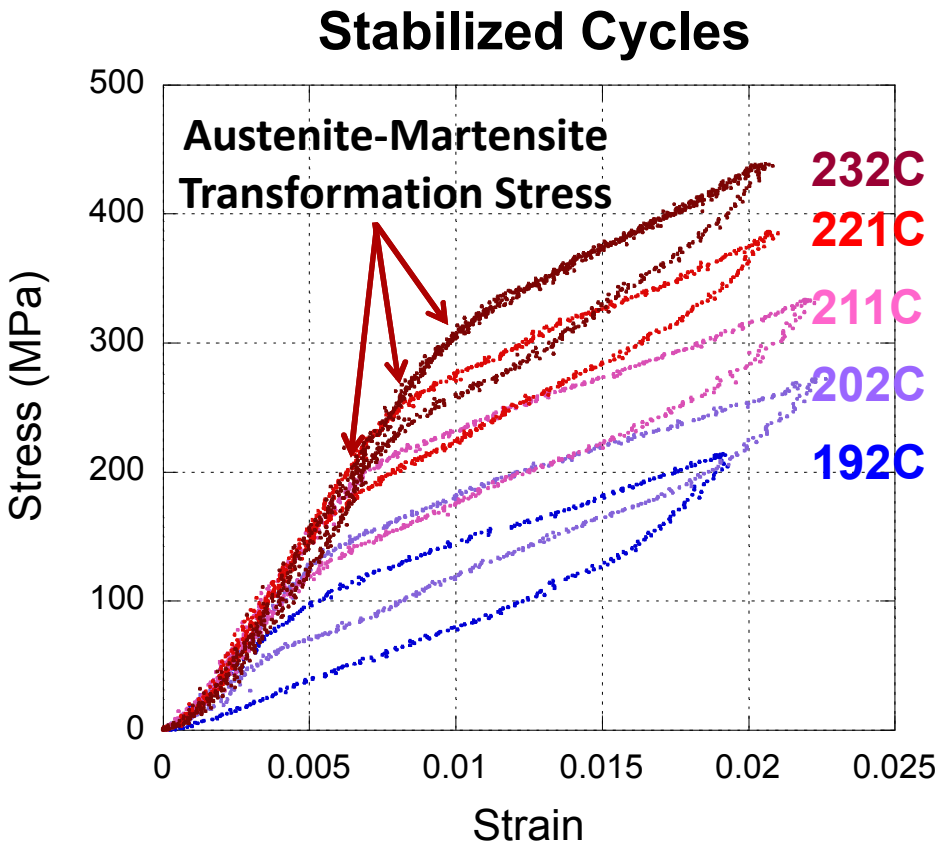
| Test Program | Effective Strain Rate (1/s) |
|---|---|
| Heat to $A_f$+40 °C; cool to test temperature; hold; pull to 2.5% strain (stroke limit); unload to 0 N; cycle load-stroke 4 more times; repeat. | $2 \times 10^{-4}$ |

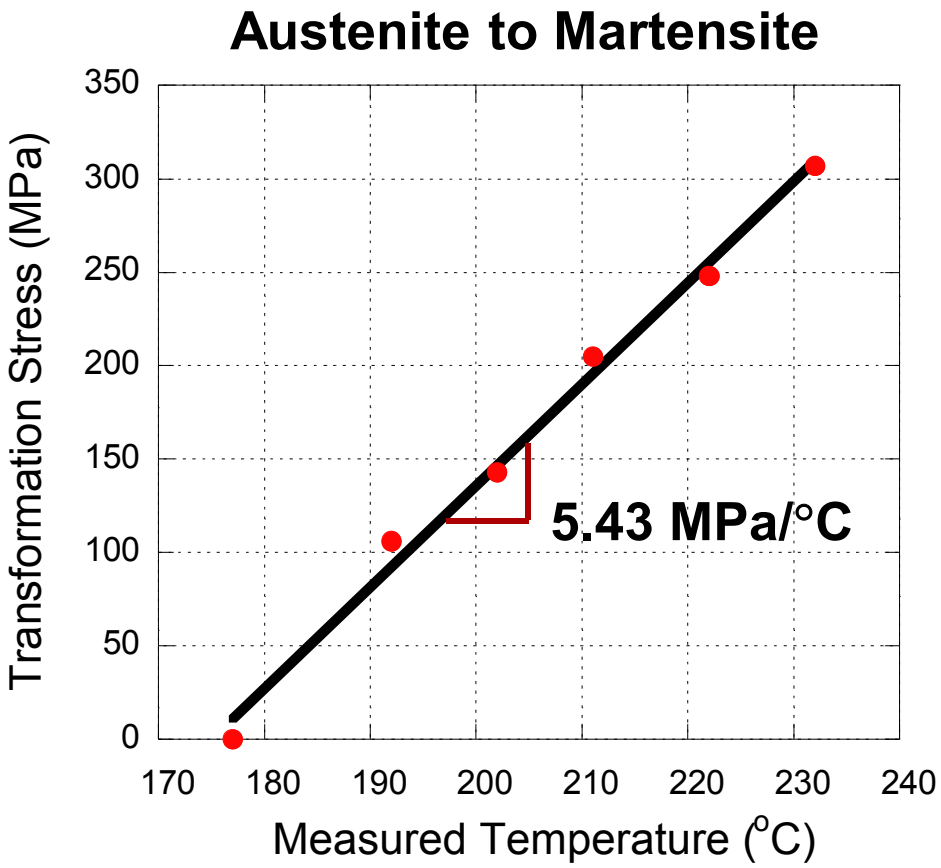



| $M_s$ (°C) | $A_f$ (°C) |
|---|---|
| 193 | 211 |

- Single test series; incremented from lower to higher temperatures.
- Test temperature reached on cooling from >$A_f$
- *Superelasticity detected across 40 °C.*
- Hysteresis loops stabilize <5 cycles.

# Transformation Stress (strain-induced martensite)

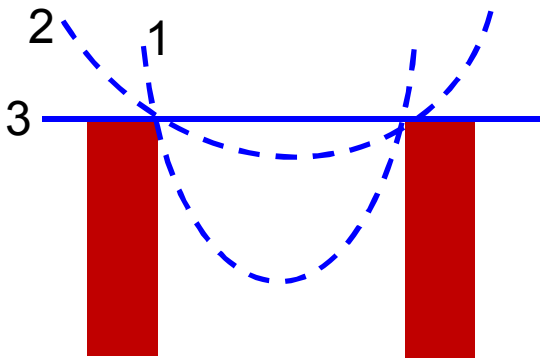


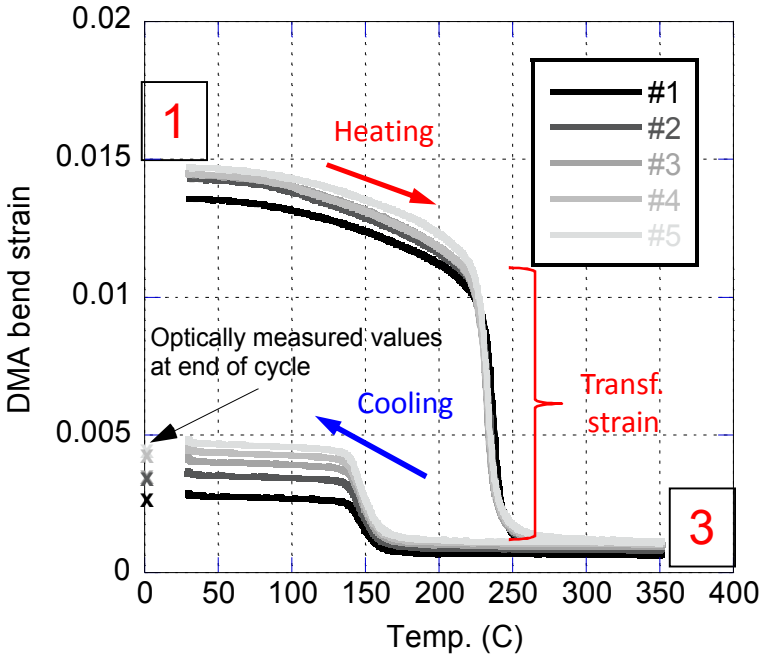



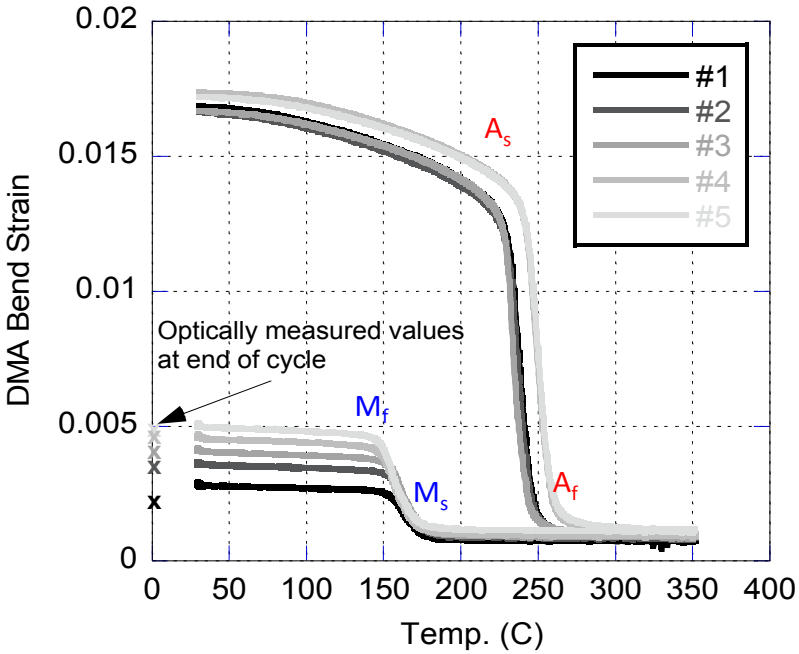

- Characteristic flag-shape superelasticity observed.
- Full recovery of ~2.25% strain.
- Transformation stress increases linearly with temperature.

# Bending Behavior (Dynamic Mechanical Analyzer)

NiTiPt SMA bend bar and DMA fixture



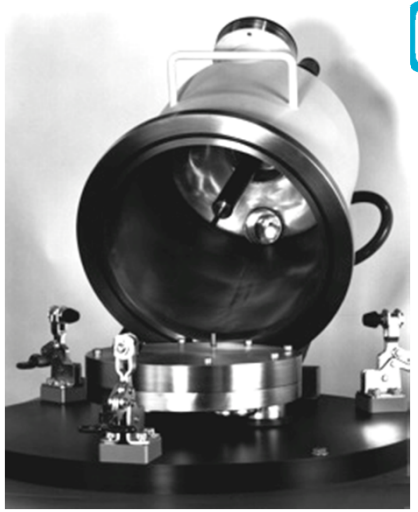
# Concluding Remarks

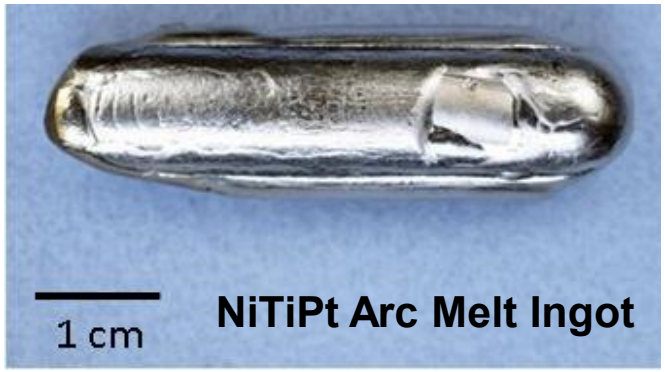
- Shape memory alloys such as Nitinol are used in many applications including medical, aerospace, consumer products, etc.
- To appreciate SMA behavior, we must understand SHAPE MEMORY EFFECT AND SUPERELASTICITY.
- Research on a new range of Ni-Ti-Pt , Ni-Ti-Pd, and Ni-Ti-Hf SMAs fabricated with $A_s$ ranging 150 °C to 250 °C. NiTiPt and NiTiPd alloys show good SME behavior, reasonable ductility, and high-temperature superelasticity.

- Extra slides

# Alloy Processing

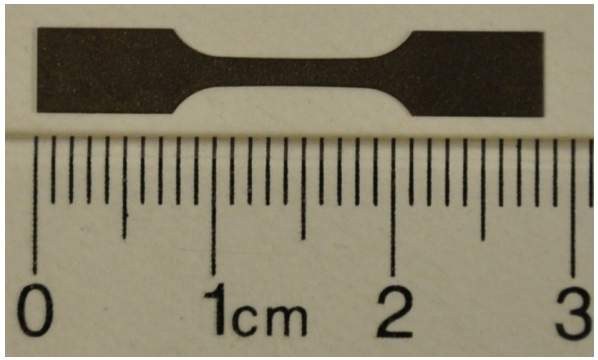
- Targeted series of Ti-rich NiTiPt, NiTiPd, and NiTiHf alloys.
- Ternary alloys processed by vacuum **arc button melting.** Followed by **homogenization**: 60hrs, 1050C.



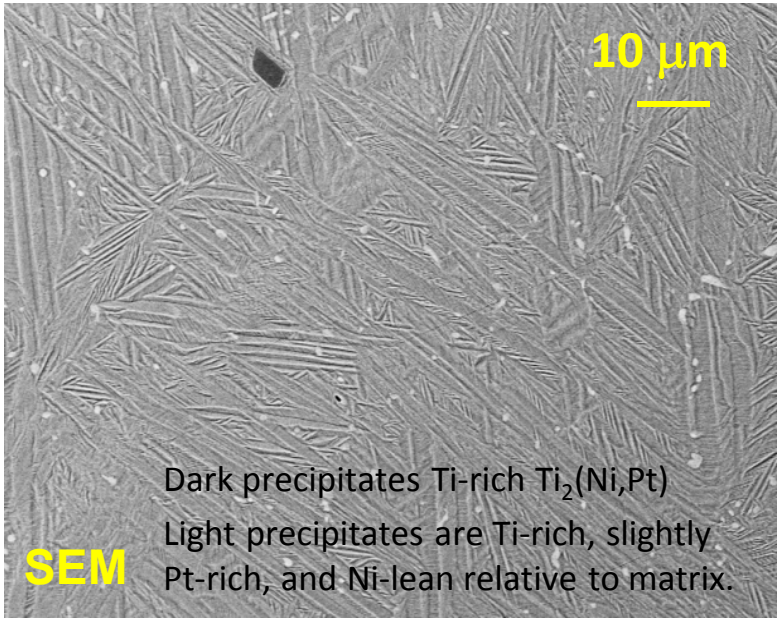


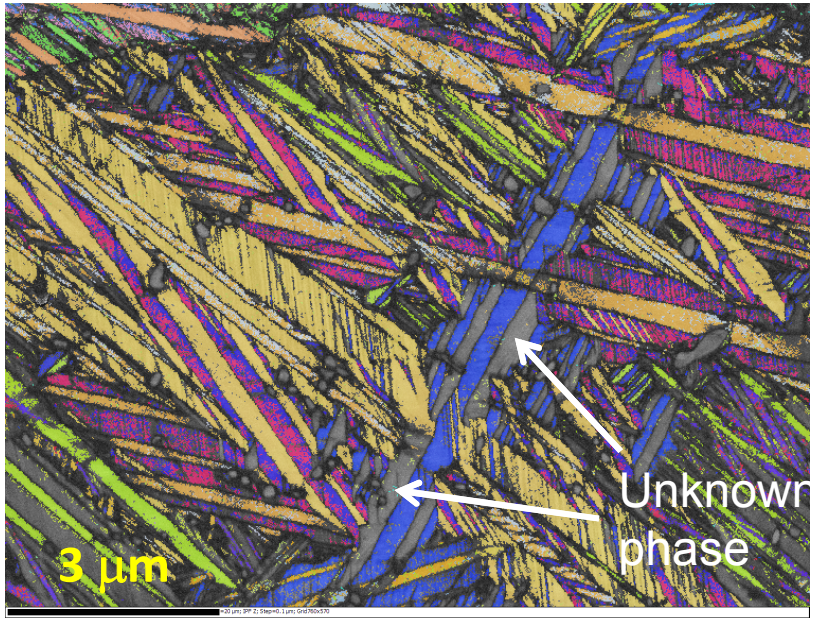

Examples of target chemistries for HTSMAs

| Sample | At.% Ni | At.% Ti | At.% 3rd element |
|---|---|---|---|
| Ni-Ti-16Pt | 33.5 | 50.5 | 16.0 Pt |
| Ni-Ti-25Pd | 24.5 | 50.5 | 25.0 Pd |
| Ni-Ti-15Hf | 49.5 | 35.5 | 15.0 Hf |



# Microstructural Characterization



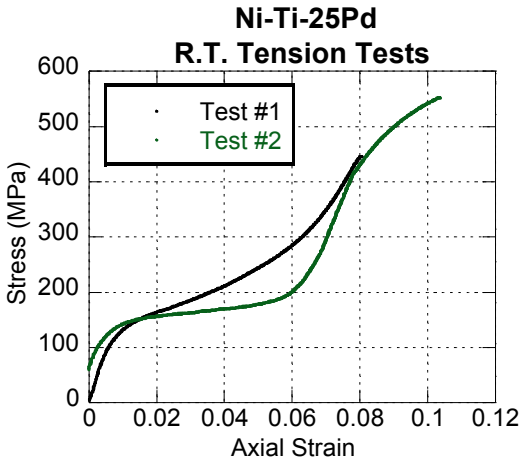



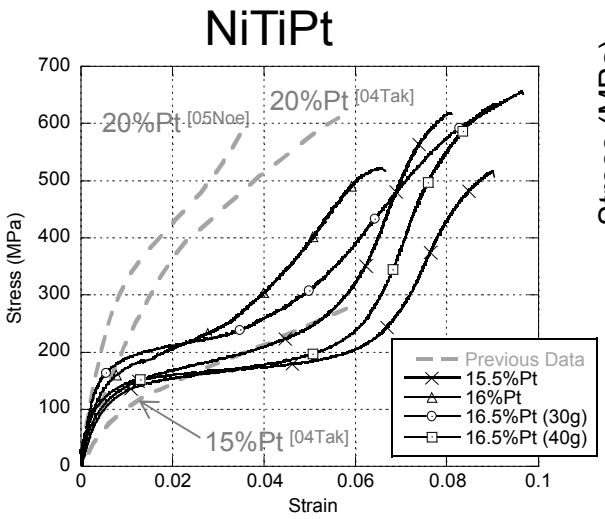


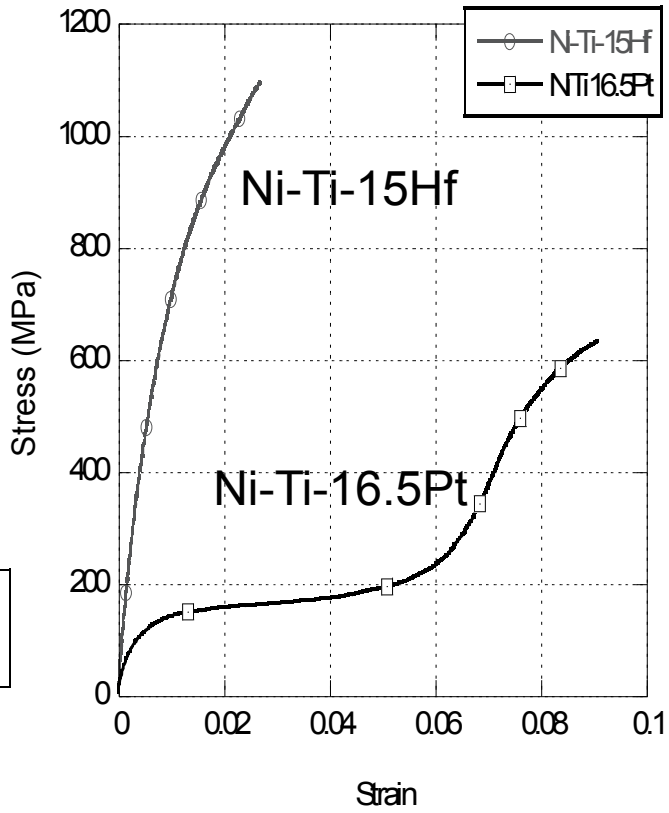
EBSD orientation map of martensite overlay on BC image

- EBSD shows the crystallographic orientation of the martensite laths
- Applied the technique to experimental tensile samples to show de-twinning and re-orientation of martensite during straining

# Room Temperature Tensile Testing (Martensite)

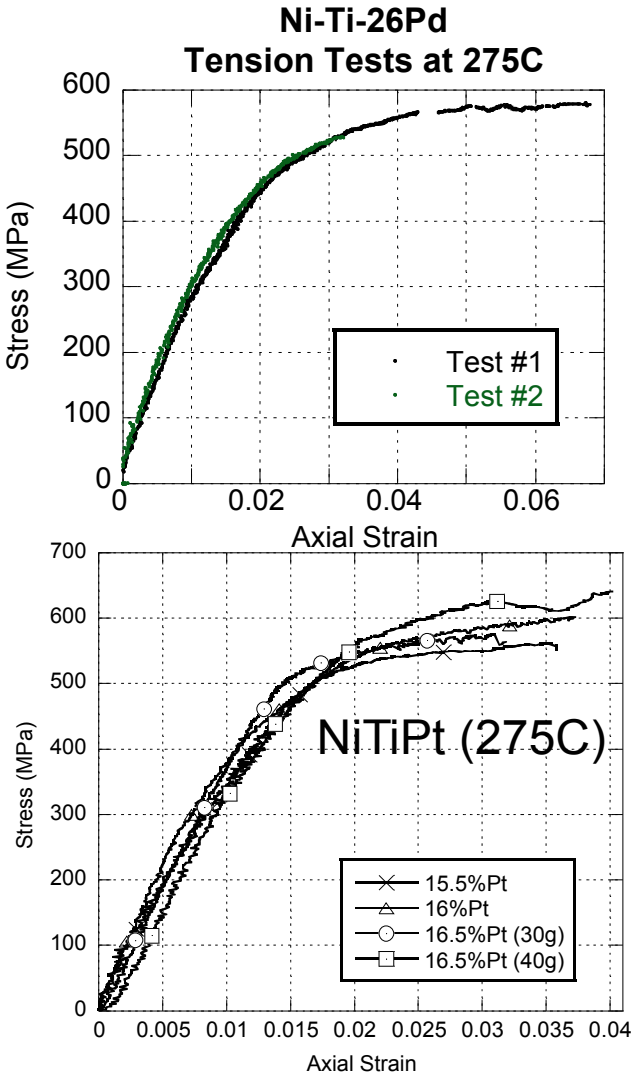


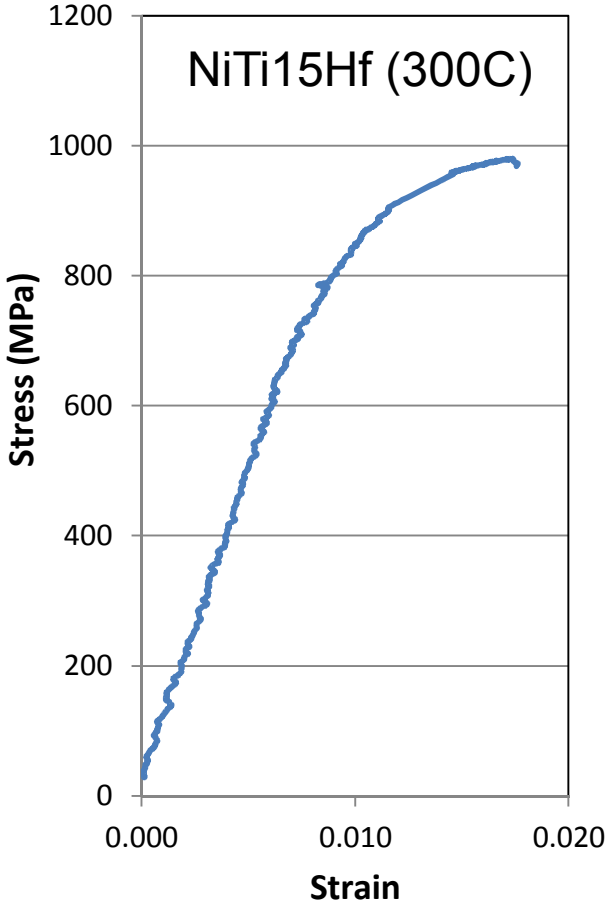




- NiTiPt and NiTiPd show relatively low de-twinning/reorientation stress and reasonable overall ductility
- Ni-Ti-Hf is a low cost alternative to Pt and Pd alloys-- Much higher strength than NiTiPt or NiTiPd. However, NiTiHf ductility is low.

# High Temperature Tensile Tests (Austenite)




- Similar relationships between NiTiPt, NiTiPd, and NiTiHf at high temperature in the austenite phase

# Interesting Behavior in Bending

Much larger hysteresis in bendgin compared to tension.

Mainly due to suppression of martensite transformation on cooling