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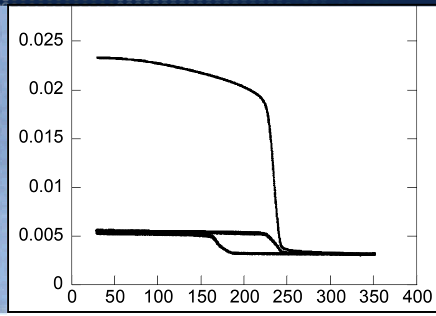

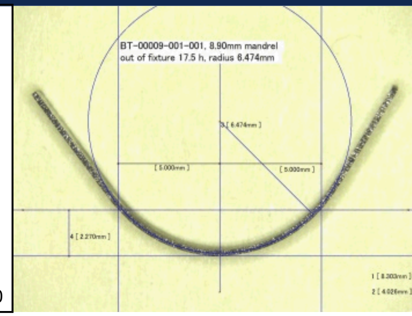

Bend Test Performance of NiTiPt High Temperature Shape Memory Alloys

Thomas E. Buchheit, **Donald F. Susan**, and Donald R. Bradley

Sandia National Laboratories

Albuquerque, NM

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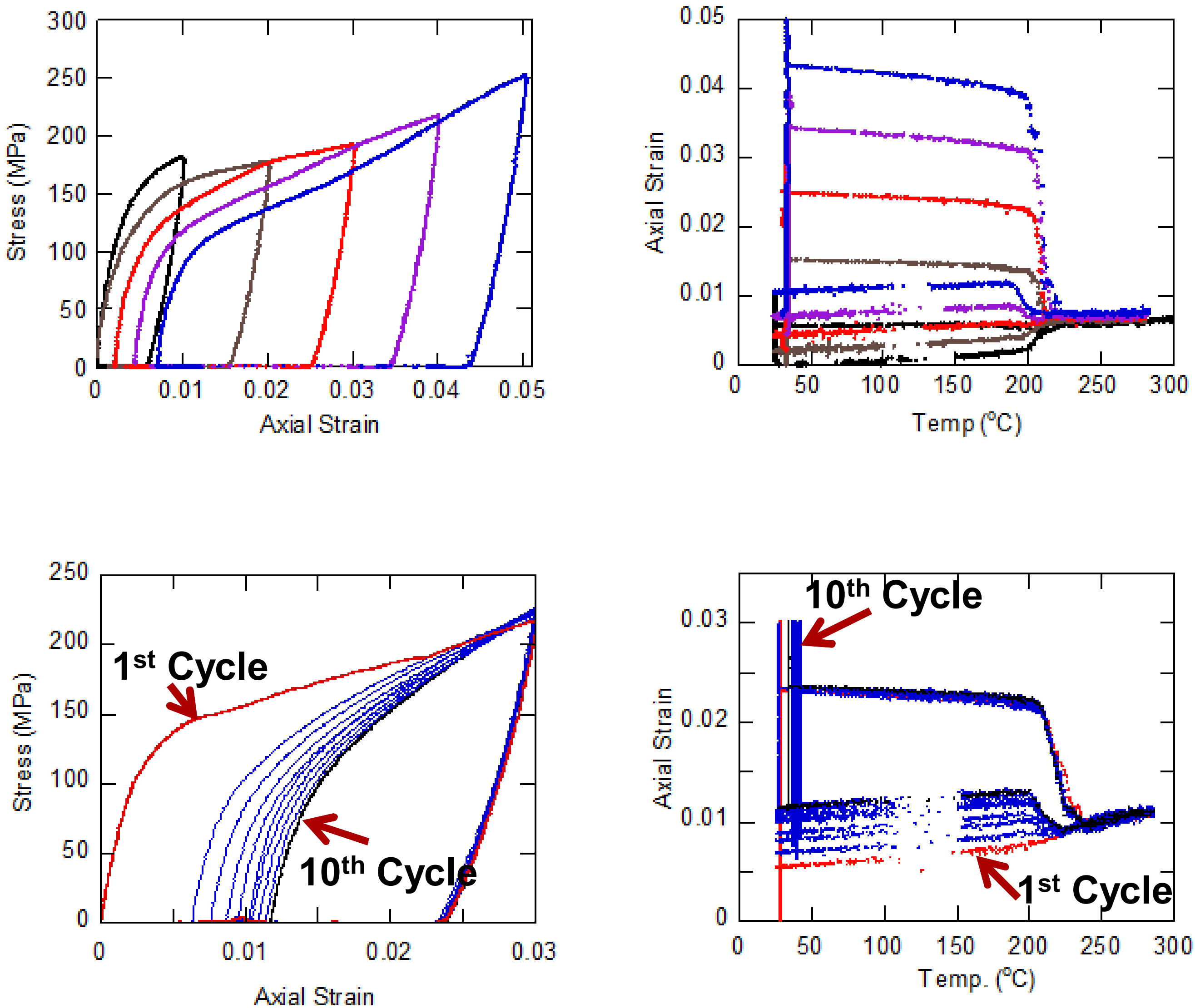
NiTiPt High Temperature SMAs

- Shape memory alloys (SMAs) that exhibit ***shape memory effect <u>and</u> superelasticity at high temperatures*** will enable a new class of mechanical sensors and actuators.
- Substitutional replacement of Ni with Pt (or Pd) in NiTi increases the shape memory transformation temperatures. Pt replacement can increase transformation temperatures up to 1000 °C (TiPt).

- **Our transformation temperature range of interest: 150-250˚C**

Previous Work: Strain Recovery & Cyclic Testing **in Tension**



NiTi16.0Pt
No-load (unbiased)
Incremental Tensile
Strain Recovery
Experiments

SMASIS 2012 (NiTiPt)
SMASIS 2013 (NiTiPd)

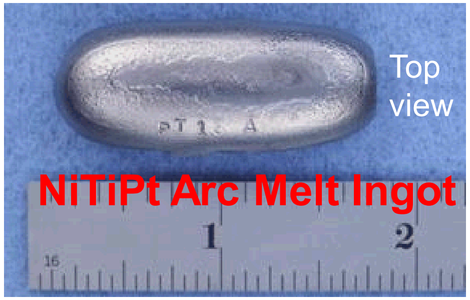
NiTi16.0Pt
No-load (unbiased)
Cyclic Strain
Recovery
Experiments

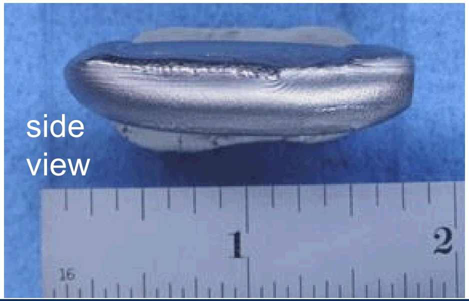
Many SMA applications in Bending Mode

- Shape memory alloy mechanical testing is typically performed in tension or compression.
- Very few bend test studies found in the literature, but applications of SMAs often involve bending mode of deformation.

Alloy Fabrication, DSC, Bend Bars

- Targeted series of Ti-rich NiTiPt ternary alloys.
- Ternary alloys processed via **arc melting** (button melter). Multiple melt processing followed by **homogenization** heat treat.
- **Differential Scanning Calorimetry (DSC)** to determine transformation temperatures.





Target (at.% Ti)	Ingot Mass (g)	Homogenization
50.5	45	1050 °C, 60 hrs

Bend Test Specimens EDM machined from 16.0%Pt ingots:

Pt160-Ti505-20131209-01 (Pt16A)

Bend Bars	Length	Width	Thickness
	25 mm (0.980")	3 mm (0.12")	200 um (0.008")
	25 mm (0.980")	3 mm (0.12")	300 um (0.012")

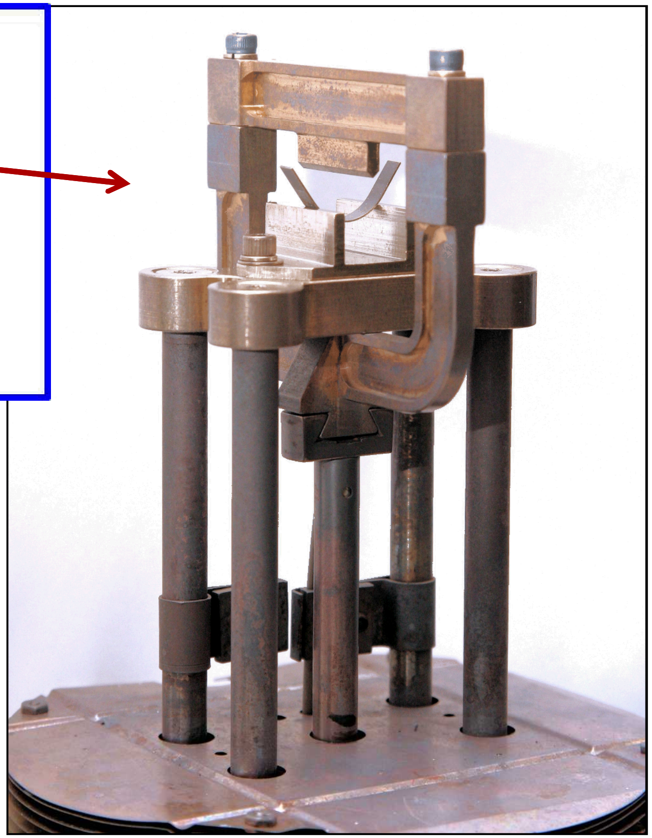
* Note, after EDM machining, all samples were "shape-set" flat above A_f (350˚C, 30 min)

Martensite and Austenite Start & Finish Transformation Temperatures

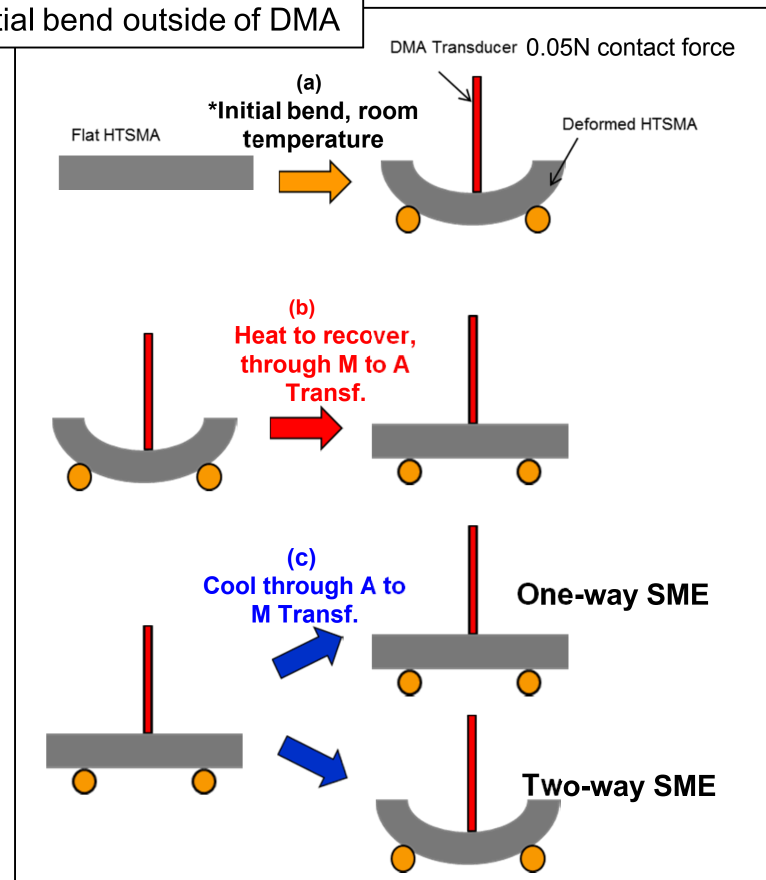
Ingot	M_s (°C)	M_f (°C)	A_s (°C)	A_f (°C)
16Pt-A	227	193	212	241
16Pt-B	218	198	216	230

Dynamic Mechanical Analyzer (DMA)

- Unique method to perform SMA or HTSMA bend testing
- TA Instruments DMA Q800. Commonly used to study the viscoelastic behavior of polymers (dynamic modulus, T_g, etc.)…small bend displacements
- Very sensitive microbalance and displacement measurement. Temperature capability up to 600˚C



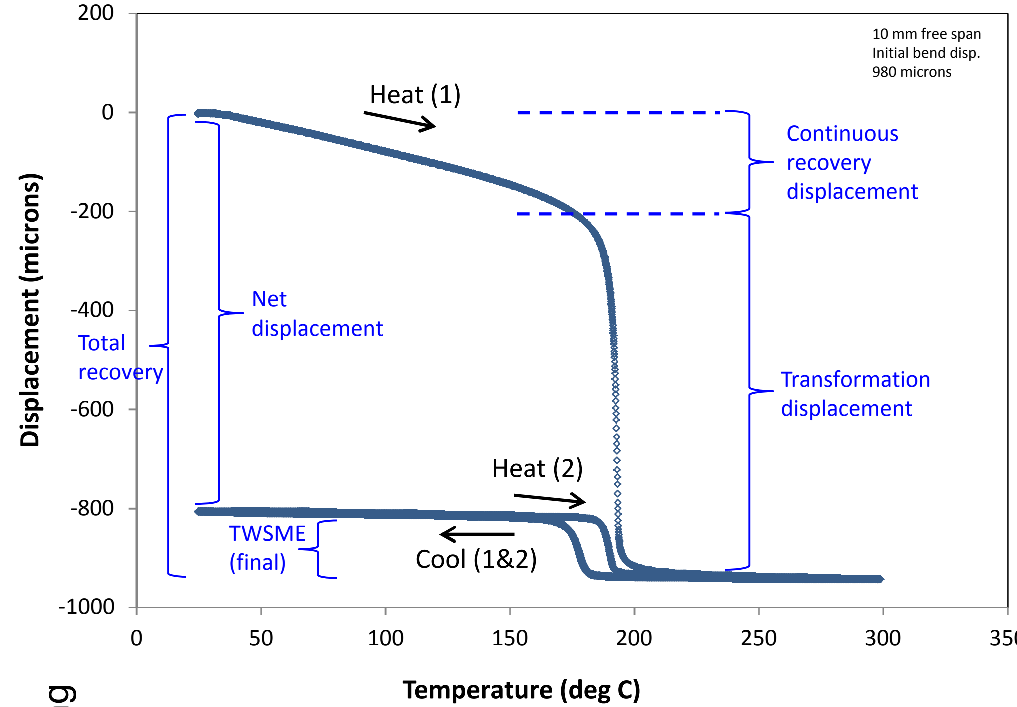
*Initial bend outside of DMA

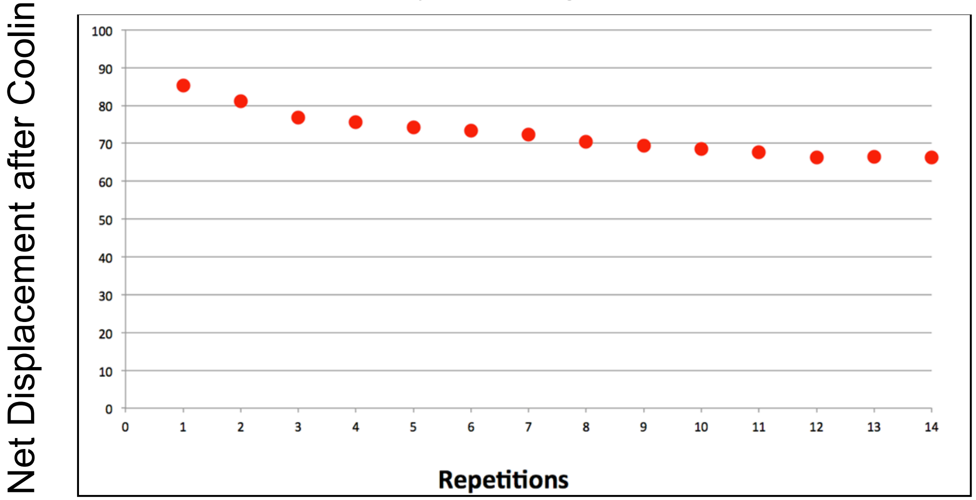


Preliminary Bend Displacement Tests

- Bend displacement data was collected for specific applications. Useful for determining cyclic behavior.

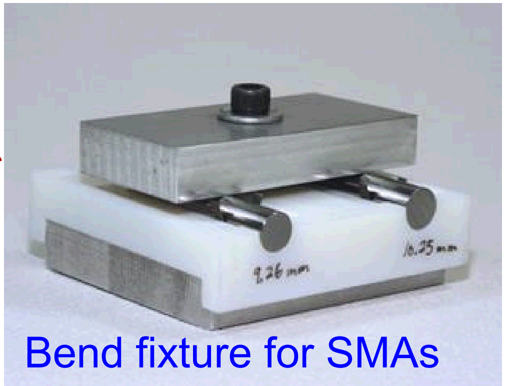
- However, we needed a more general technique, applicable to any design where bending strain can be calculated or estimated. Therefore, we need to measure ***BENDING STRAIN***



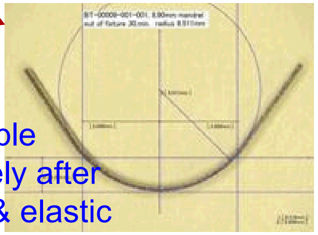


Bend *strain* experiments

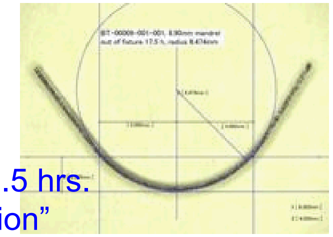
- Pre-bend the sample at room temperature. Semi-circular arc, uniform bend strain
- Measure the radius of curvature carefully with optical microscope, determine initial bend strain.



Bend fixture for SMAs



SMA sample immediately after bending (& elastic springback)



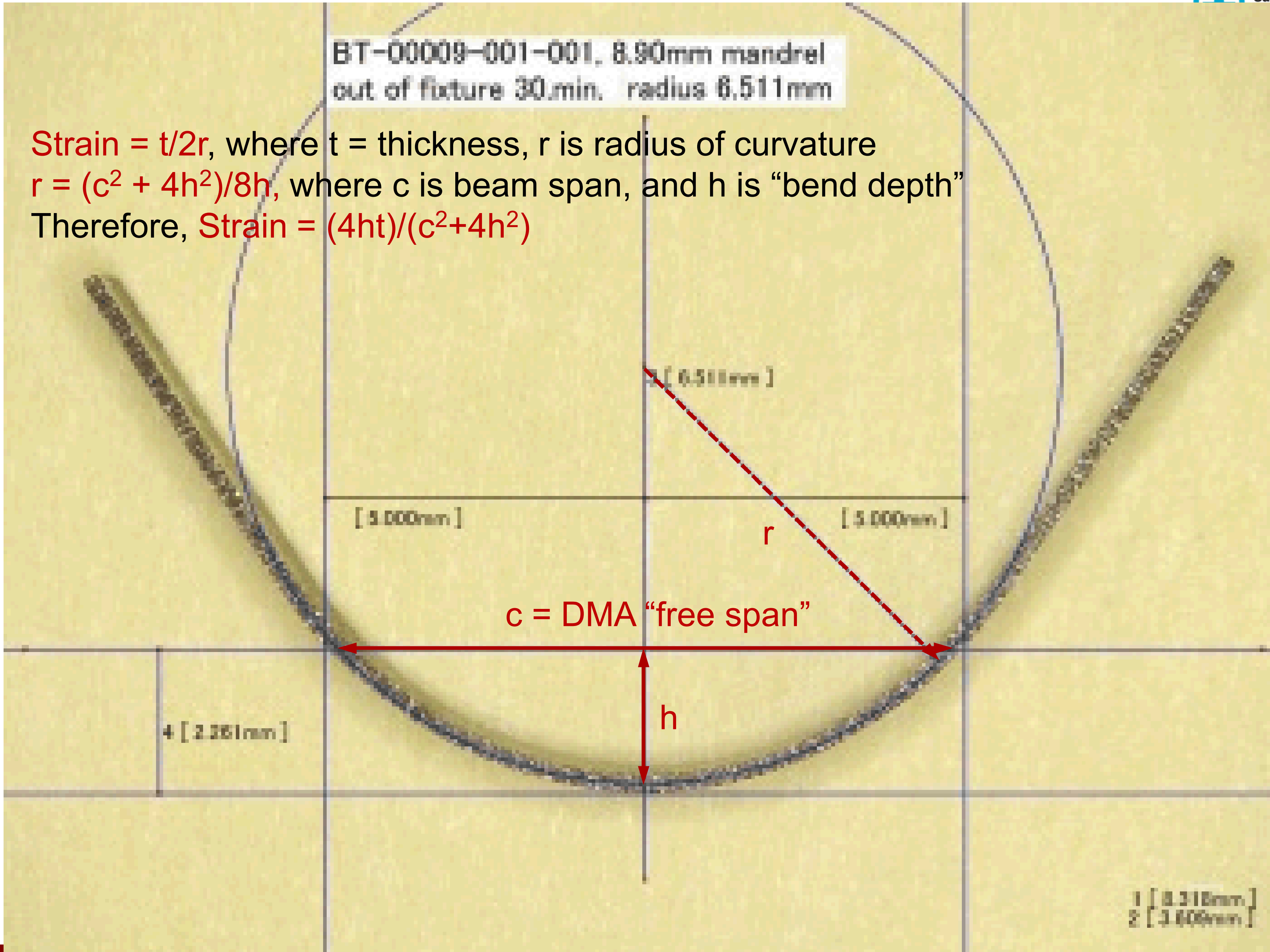
After 17.5 hrs. "relaxation"

- **Thermal Cycle Experiments:** DMA cycle through transformation temperature range, 5˚C/min ramp rate. Leave sample in DMA and repeat thermal cycling…
- **Re-bending Strain Recovery:** DMA cycle through the transformation temperature range, 5˚C/min ramp rate. After cooling, **remove sample and re-bend to same strain level**, repeat no-load thermal cycle…

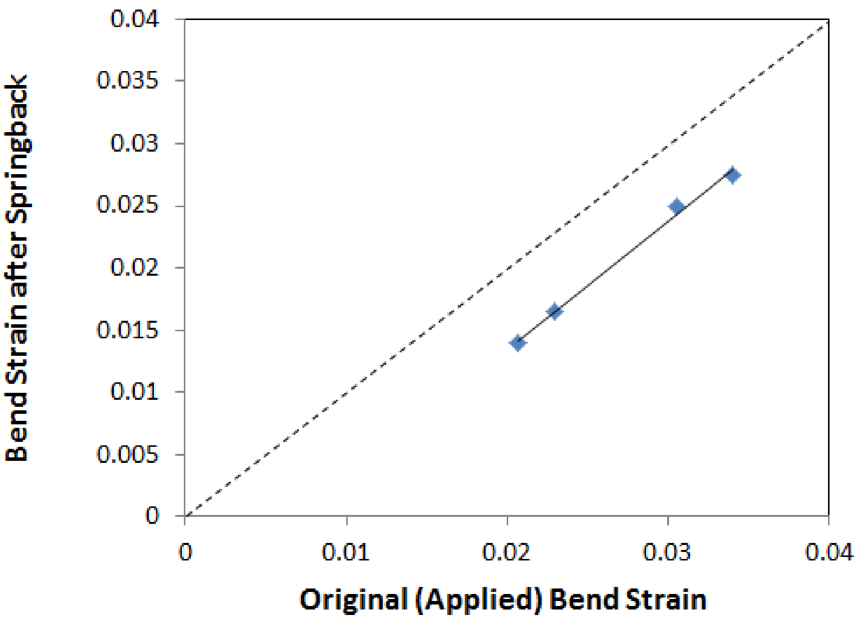
Strain = $t/2r$, where t = thickness, r is radius of curvature

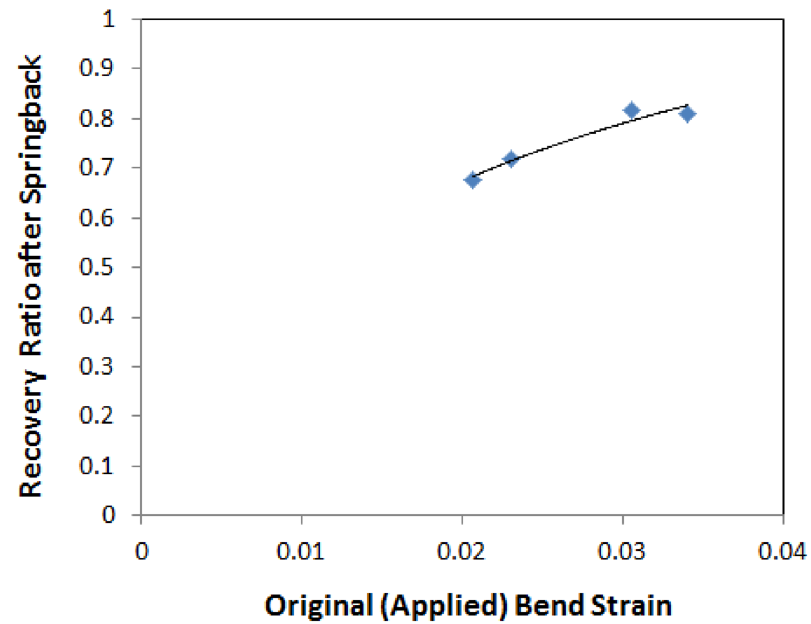
$r = (c^2 + 4h^2)/8h$, where c is beam span, and h is “bend depth”

Therefore, Strain = $(4ht)/(c^2+4h^2)$



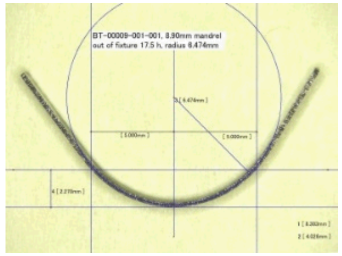
Elastic Springback





- Constant amount of springback after removing from the bend fixture, represents primarily elastic response
- Therefore, higher applied bend strain results in relatively higher initial bend strain prior to DMA testing

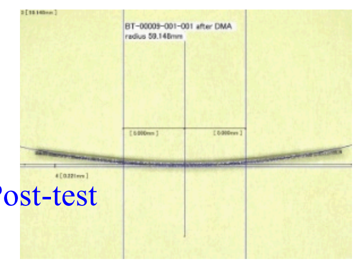
DMA Results in Terms of Bend Strain



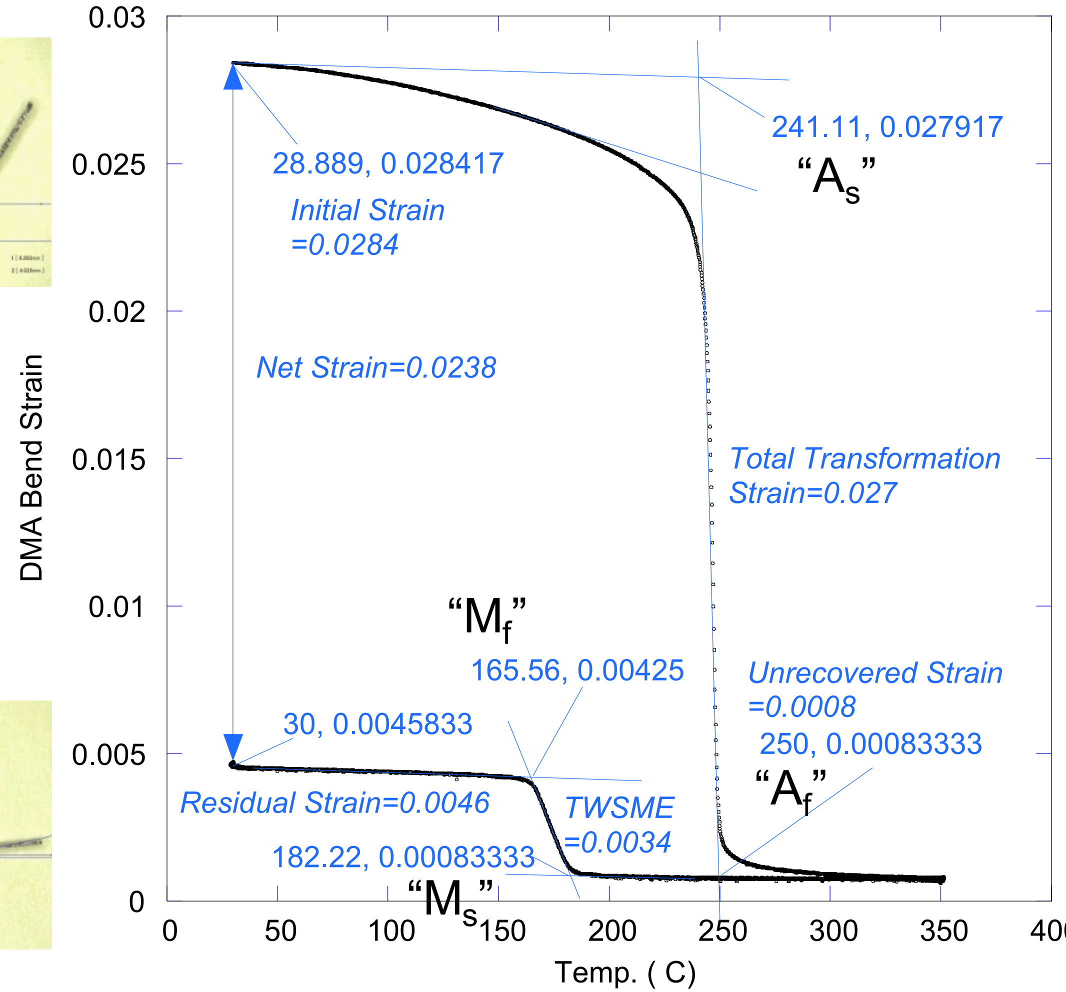
Pre-test

DSC Transf. Temps.

Ingot	M_s (°C)	M_f (°C)	A_s (°C)	A_f (°C)
16Pt-A	227	193	212	241



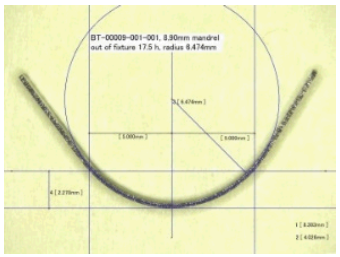
Post-test



Mandrel = 8.9 mm
Beam thickness= 0.308mm
Bend Strain = 0.03402

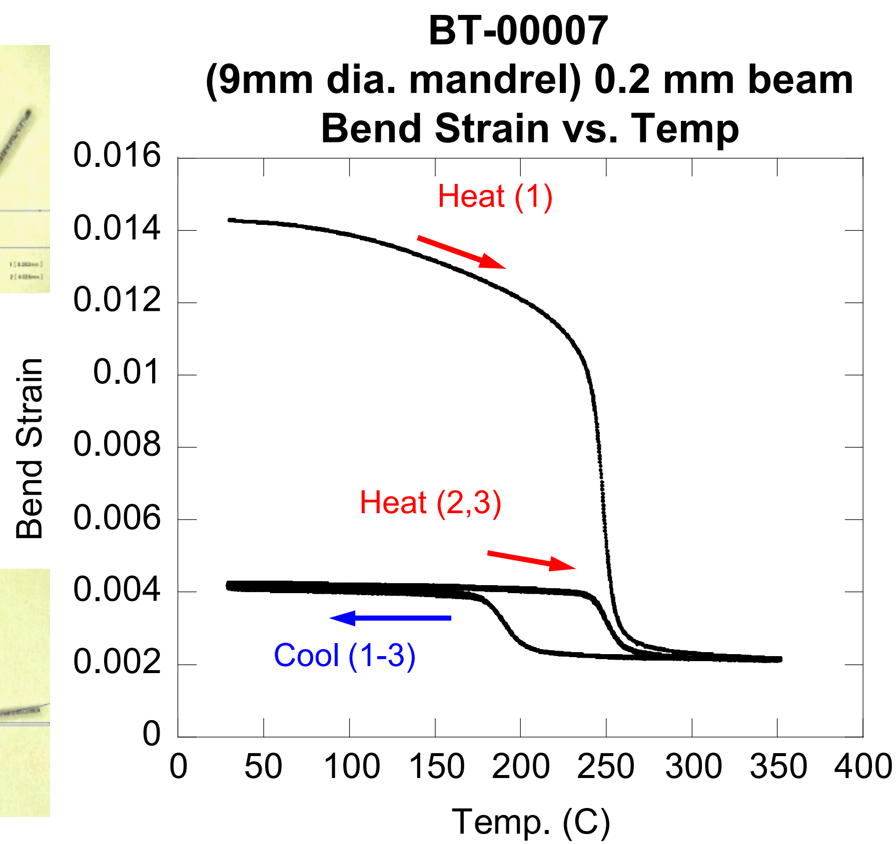
Summary: Thermal Cycle Experiments

- Measured TWSME bend strain is about 12-17% of total applied bend strain. The *fractional* TWSME decreased as the initial bend strain increased.
- Amount of TWSME on cooling stabilizes within 2-3 thermal cycles



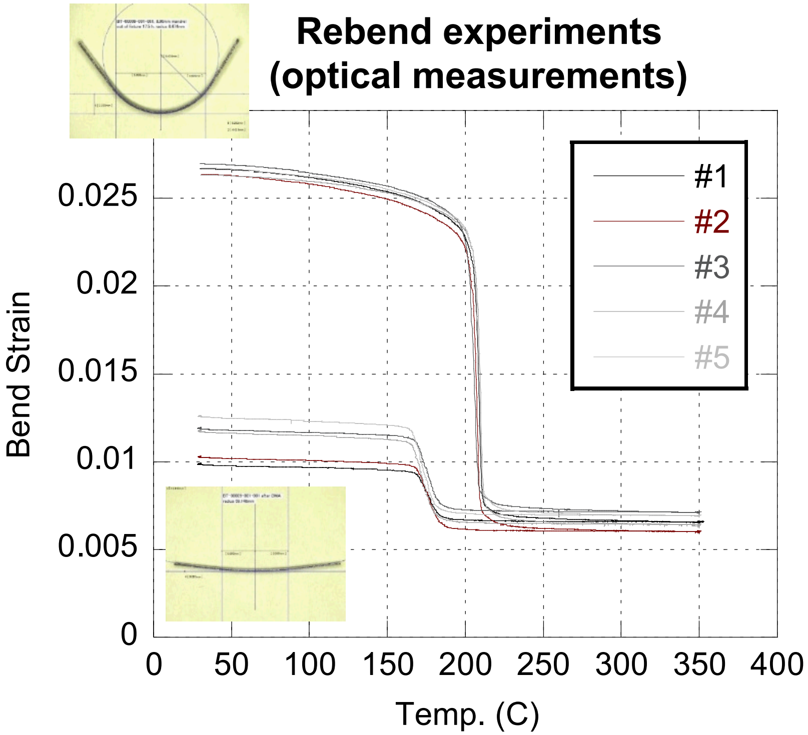
Pre-test

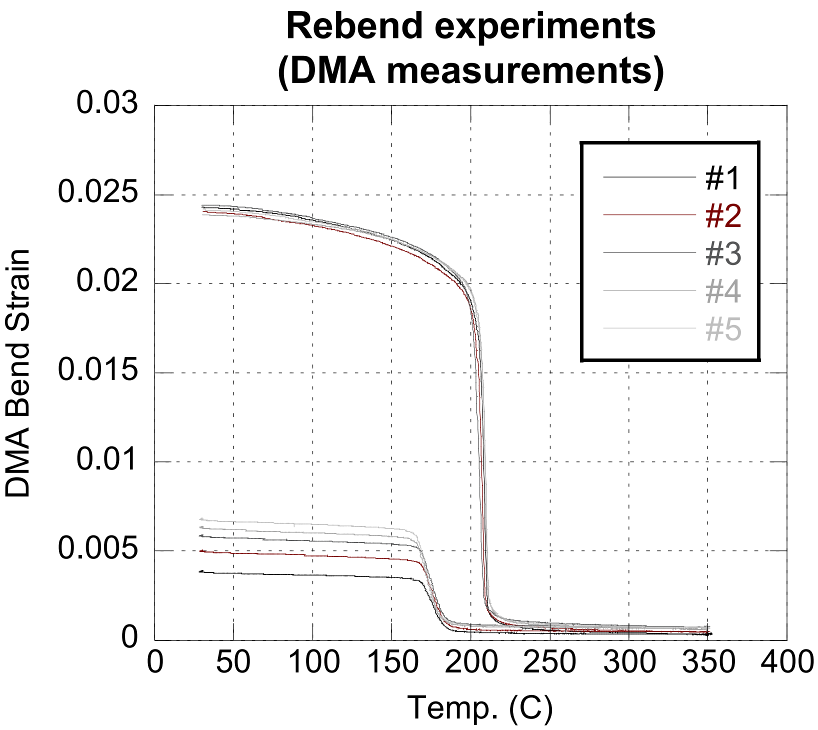
Post-test



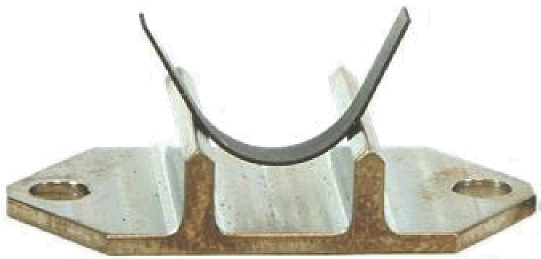
Optical Measurements vs. DMA

- Noticed disagreement between optical measurements (before and after testing) and the DMA bend test results. Final geometry measured optically did not match the DMA measurements.
- Difficult to troubleshoot and understand the issue
- Lessons learned: 1. Check data with multiple techniques, 2. Understand your test equipment as much as possible!!

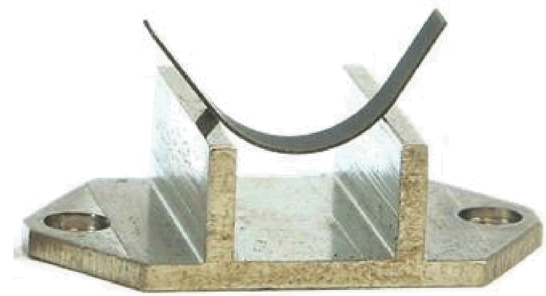




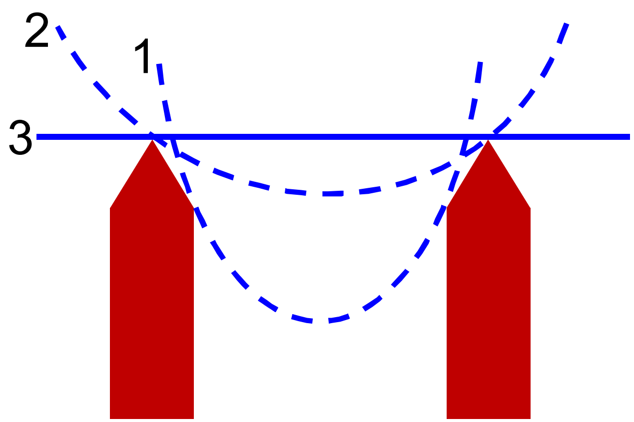
Modified DMA Bend Fixture



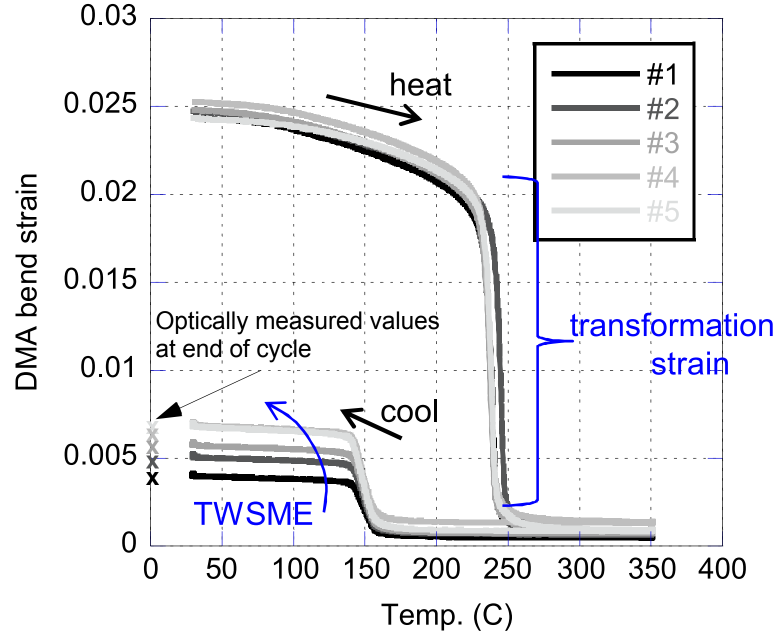
Initial fixture geometry



Modified bend test fixture



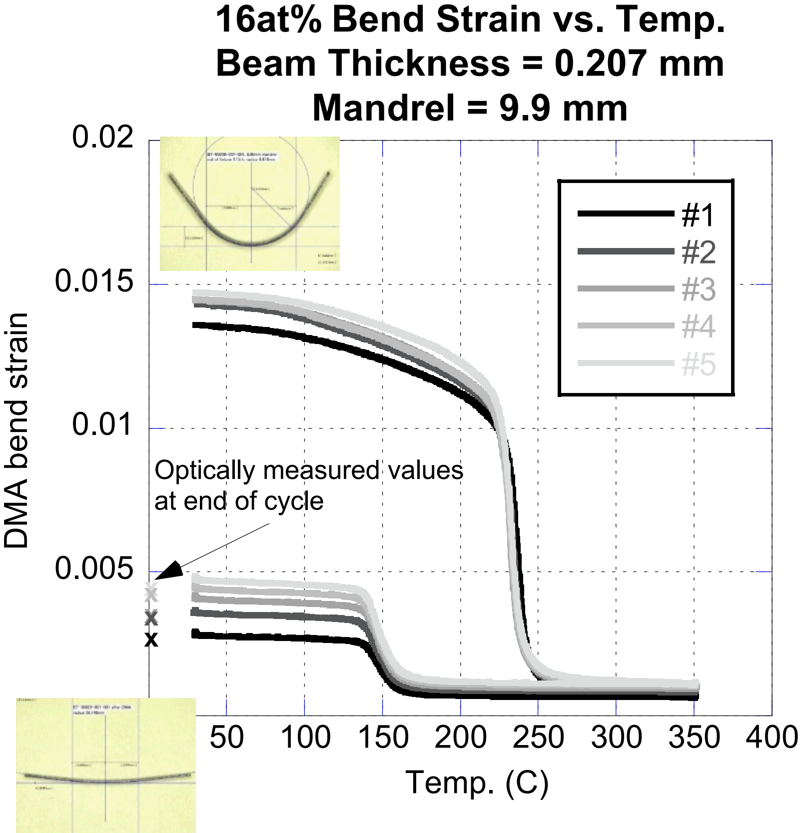
The beam can slide along the inside of the fixture during the test, effectively changing the free span, c, and changing the "bend depth", h, measured by the DMA.



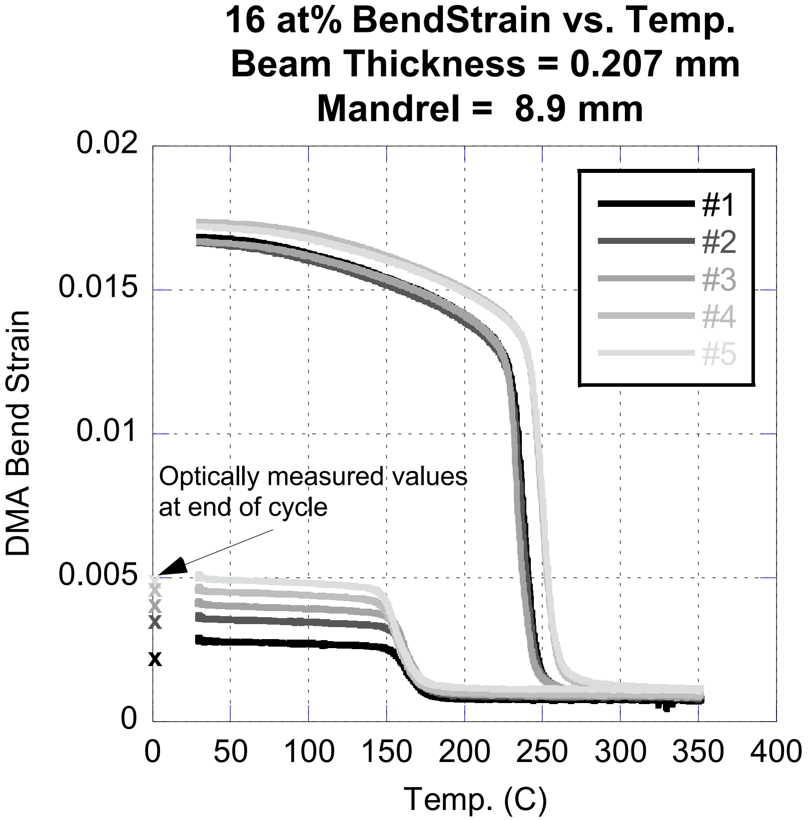
DMA bend test results vs.Optical measurements after simple modification to DMA fixture

Summary: Re-Bend Strain Recovery

Rebound series 5
initial bend strain = 0.0207
cycle #1 recovery ratio = 0.663



Rebound series 3
initial bend strain = 0.0230
cycle #1 recovery ratio = 0.740

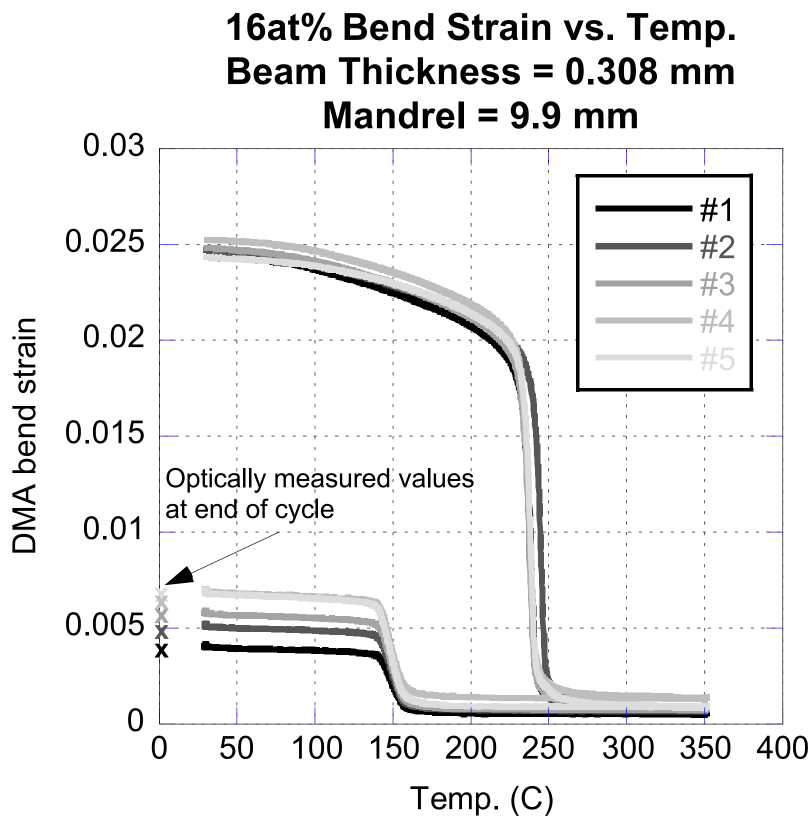


Note good agreement between DMA and optical measurements

Rebound series 4

initial bend strain = 0.0306

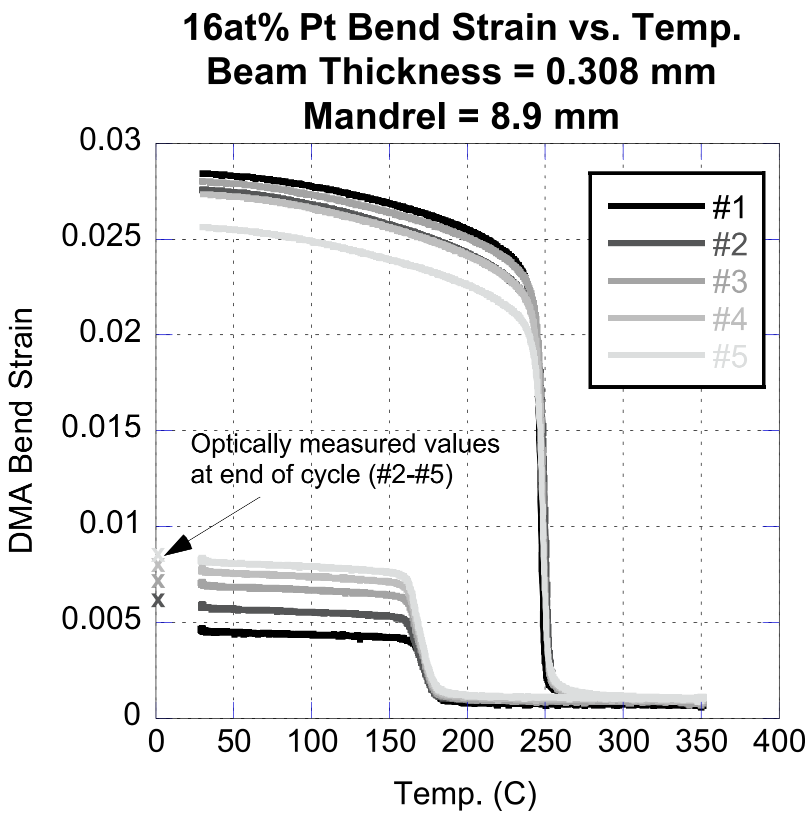
cycle #1 recovery ratio = 0.806



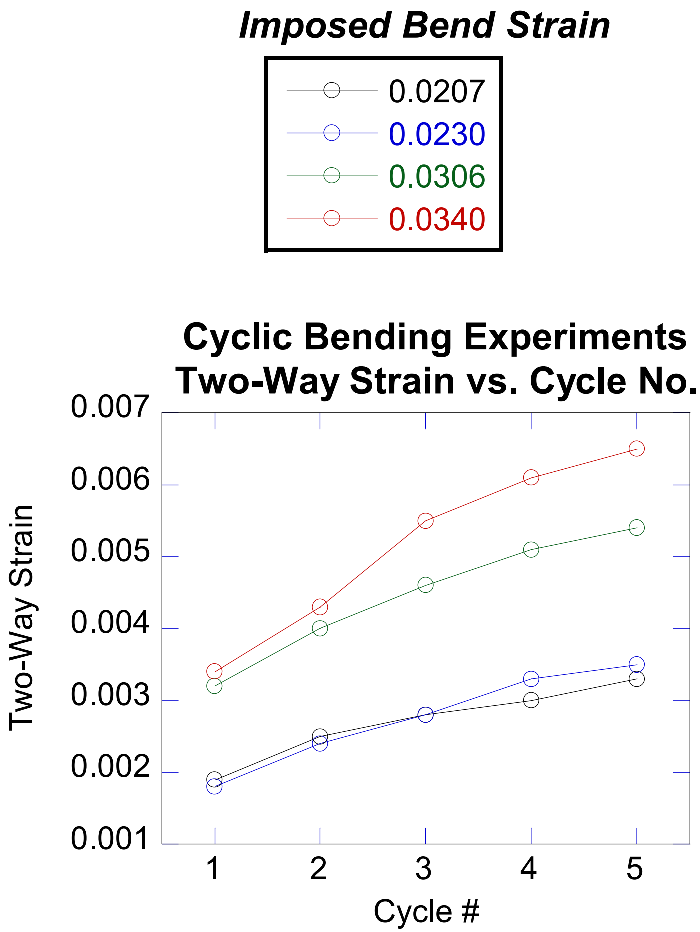
Rebound series 2

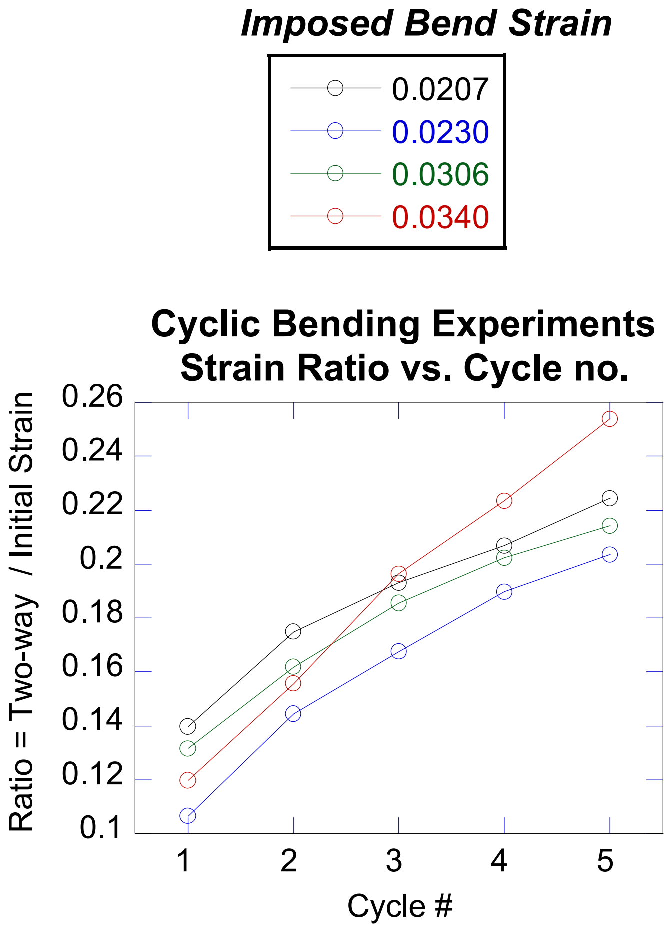
initial bend strain = 0.0340

cycle #1 recovery ratio = 0.823



Cyclic Behavior: Two-Way SME in Bending

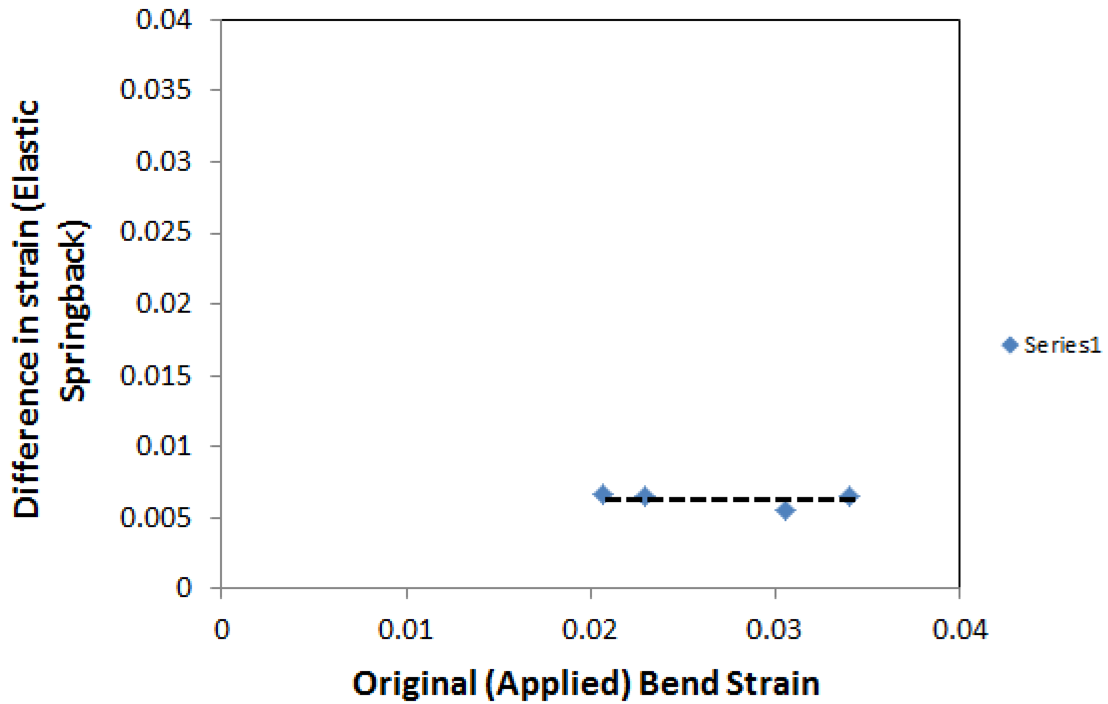




Concluding Remarks

- NiTiPt HTSMAs with 16% Pt were produced with (DSC) A_s transformation temperatures ~210-215˚C.
- Thin rectangular beams were bend tested in a dynamic mechanical analyzer (DMA). For semi-circular bends, the DMA can be used to obtain precise *bend strain* data during dynamic thermal-mechanical testing. With combinations of beam thickness and initial bend mandrel, we analyzed a range of bend strains between 1-3% (after springback).
- For thermal cycle tests, the behavior stabilized within 2-3 cycles. The amount of TWSME strain was ~12-17% of initial bend strain.
- For re-bend strain recovery experiments, good shape memory behavior was shown (good bend recovery) at temperature, with 10-24% two-way shape memory (TWSME) strain on cooling, depending on initital applied strain and cycle number. The amount of TWSME increased, but at a decreasing rate, during five test cycles, approaching stabilization.

- Backup slides

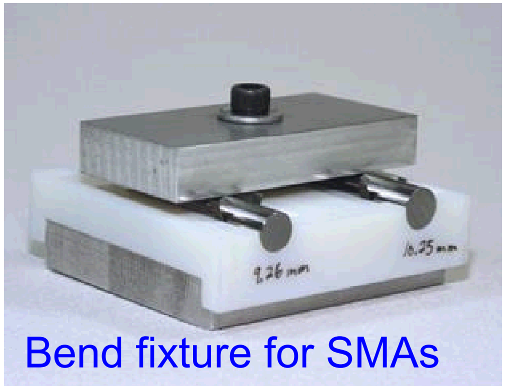


Bend Recovery Experiments: Four Levels of Initial Bend Strain

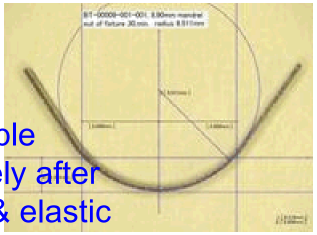
Initial strains between 1-3% were achieved

(Combinations of bend mandrel and sample thickness)

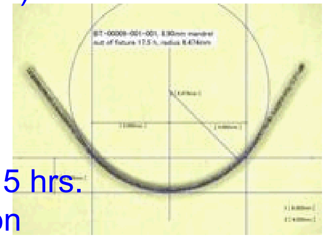
Mandrel Dia.	Beam Thickness	Applied Strain	Resultant bend strain
8.9 mm	0.207 mm	0.0230	0.0165
9.9 mm	0.207 mm	0.0207	0.0140
8.9 mm	0.308 mm	0.0340	0.0275
9.9 mm	0.308 mm	0.0306	0.0250



Bend fixture for SMAs

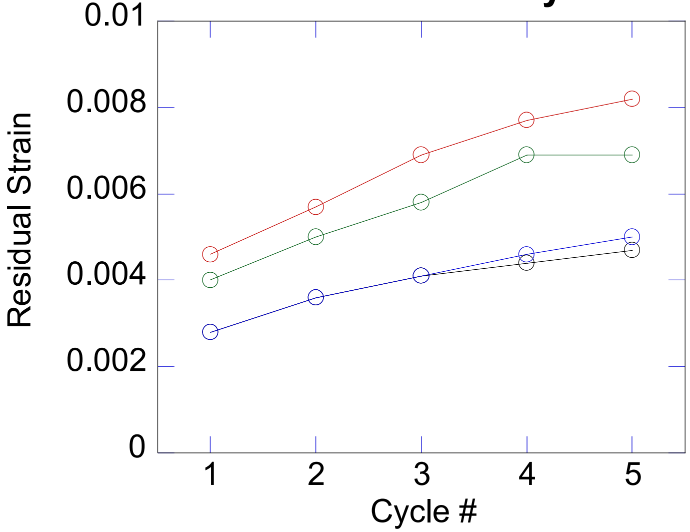


SMA sample immediately after bending (& elastic springback)

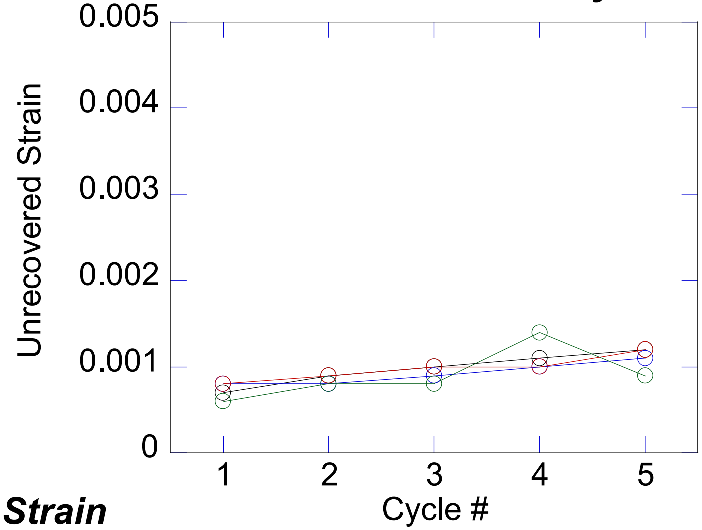


After 17.5 hrs. relaxation

Cyclic Bending Experiments Residual Strain vs. Cycle No.



Cyclic Bending Experiments Unrecovered Strain vs. Cycle no.



Imposed Bend Strain