Effect of Upper-Cycle Temperature on the Load-biased, Strain-Temperature Response of NiTi

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Abstract

Over the past decade, interest in shape memory alloy based actuators has increased as the primary benefits of these solid-state devices have become more apparent. However, much is still unknown about the characteristic behavior of these materials when used in actuator applications. Recently we have shown that the maximum temperature reached during thermal cycling under isobaric conditions could significantly affect the observed mechanical response of NiTi (55 wt% Ni), especially the amount of transformation strain available for actuation and thus work output. This investigation extends that original work to ascertain whether further increases in the upper-cycle temperature would produce additional improvement in the work output of the material, which has a stress-free A_f of 113 ^oC, and to determine the optimum cyclic conditions. Thus, isobaric, thermal-cycle experiments were conducted in the aforementioned alloy at various stress levels from 50-300 MPa using upper-cycle temperatures of 165, 200, 230, 260, 290, 320 and 350 ^oC. The data indicated that the amount of applied stress influenced the transformation strain available in the system, as would be expected. However, the maximum temperature reached during the thermal excursion also plays a role in determining the transformation strain, with the maximum transformation strain being developed by thermal cycling to 290 ^oC. In situ, neutron diffraction showed that the differences in transformation strain were related to differences in martensite texture within the microstructure when cycling to different upper-cycle temperatures. Hence, understanding this effect is important to optimizing the operation of SMA-based actuators and could lead to new methods for processing and training shape memory alloys for optimal performance.

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Interest in SMAs as an Enabling Technology

Purpose of this Work

Determine if any differences in macroscopic strain would result if the highest temperature reached during a thermal cycle of the actuator is varied.

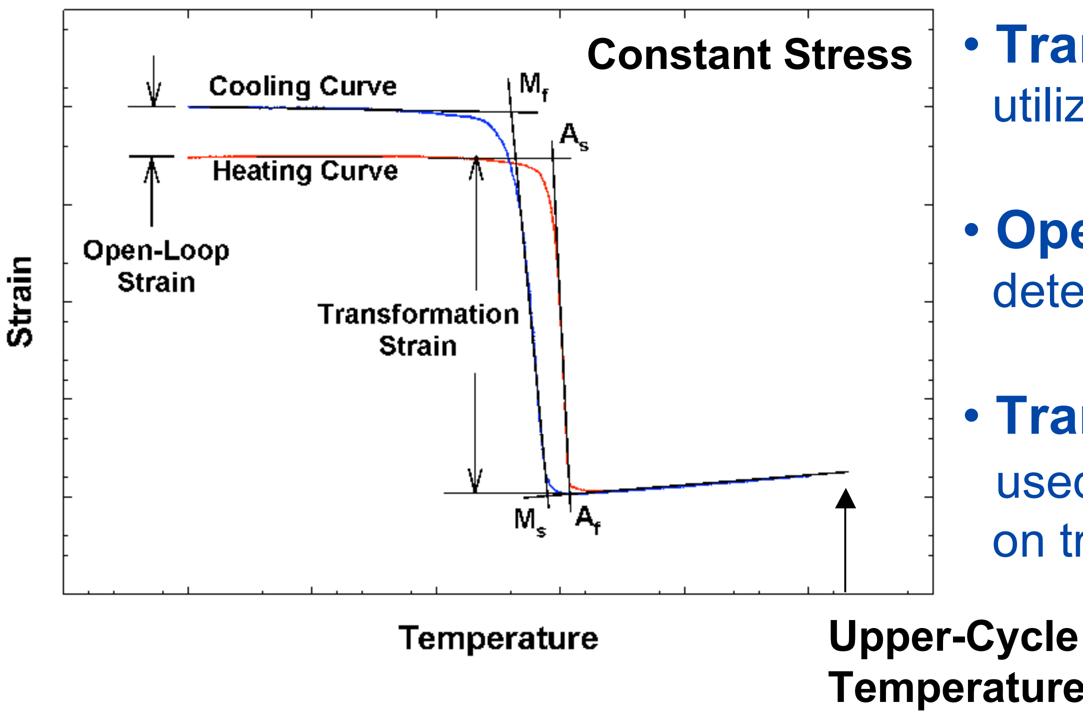
Use constant-stress, thermal-cycling experiment

- Change the highest temperature reached during the thermal cycle (Upper-Cycle Temperature)
- Assess effects of temperature change on observed response:
  - ✓ Absolute strain levels
  - ✓ Transformation strain
  - ✓ Open-Loop strain
  - ✓ Transformation temperatures

Use select *in-situ*, neutron diffraction experiments

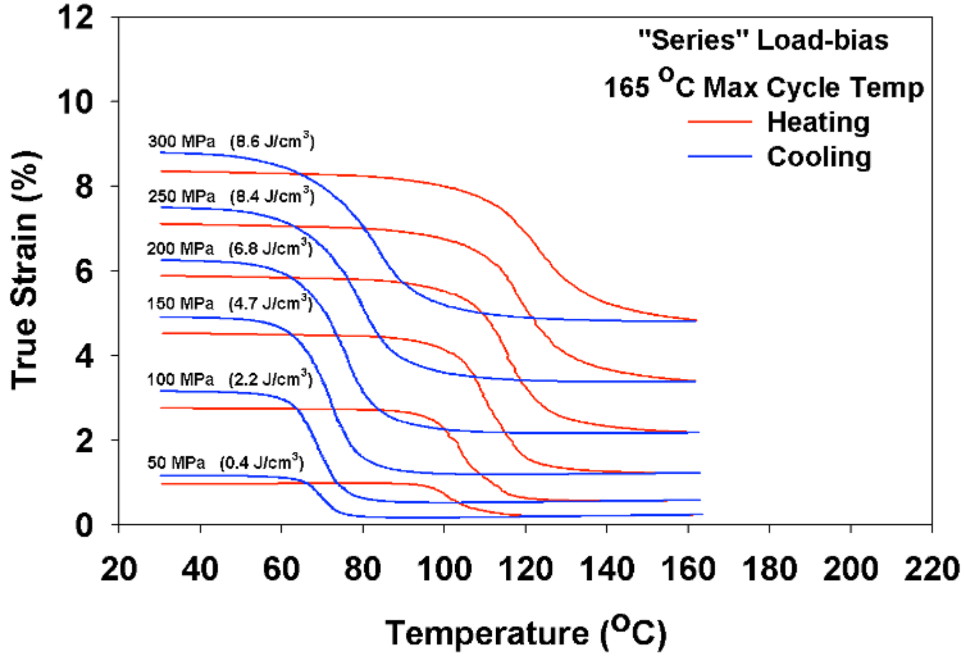
- Understand underlying mechanisms associated with any observed differences

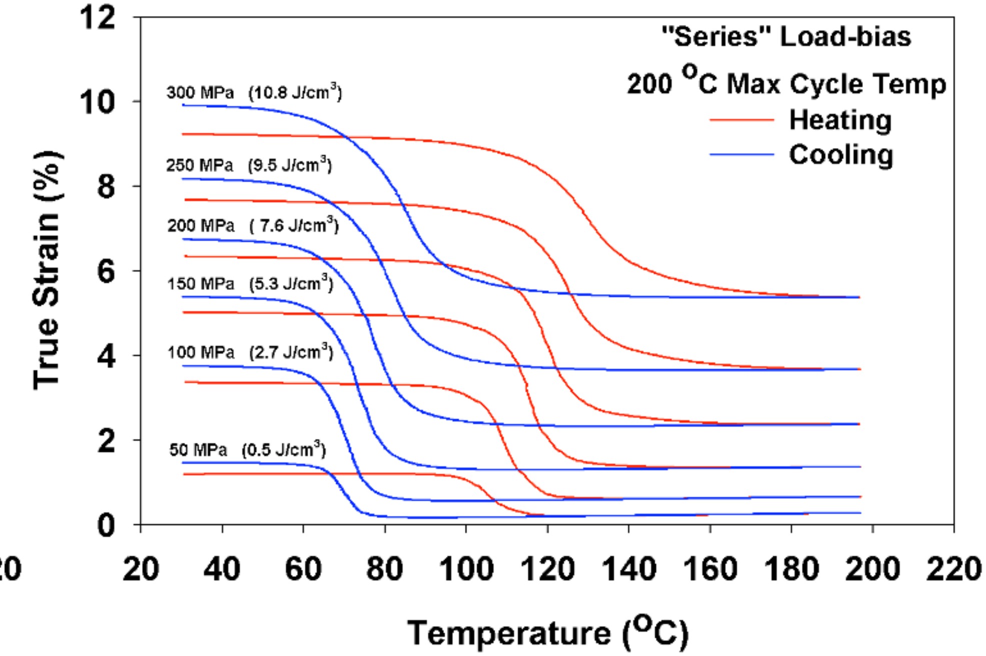
Parameters Assessed from Constant-Stress, Thermal-Cycle Experiment ("Load-Bias" Experiment)



- **Transformation strain** – directly utilized to determine work capability
- **Open-Loop strain** – used to determine dimensional stability
- **Transformation temperatures** – used to assess effect of stress on transformation

Upper-Cycle Temperature Influences “Load-bias” Response

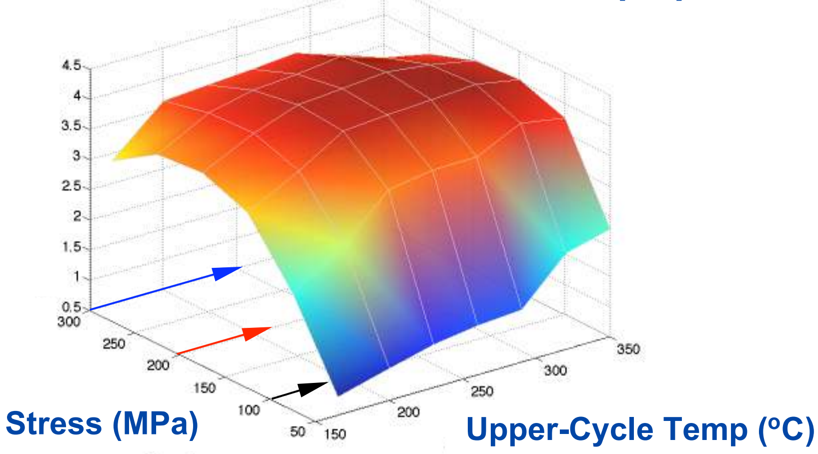


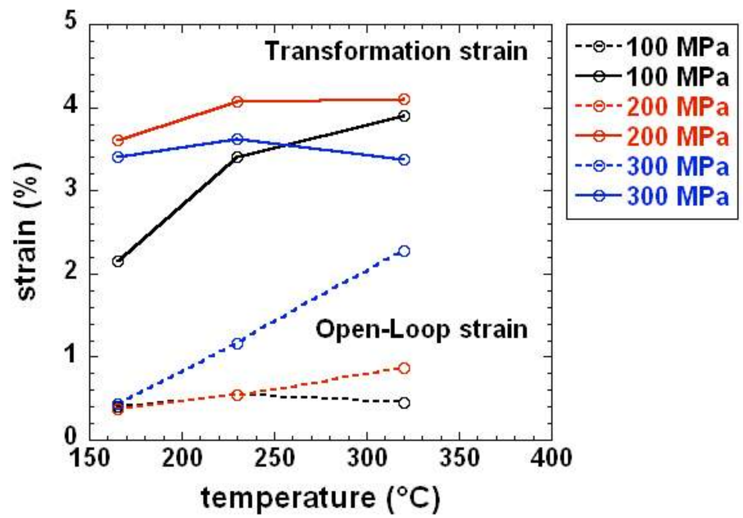


- ✓ **Alters the absolute end levels, especially at the higher stresses**
- ✓ **Has an effect on open-loop strain at the higher stresses**

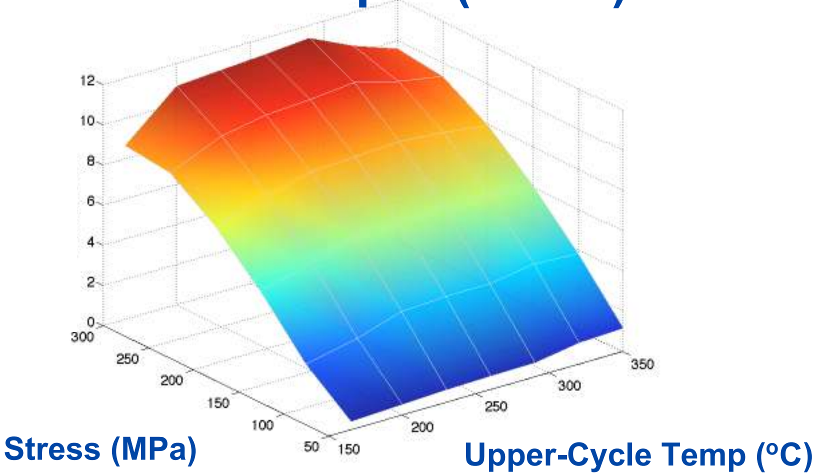
Stress and Upper-Cycle Temperature Influence Stroke and Dimensional Stability

Transformation Strain (%)

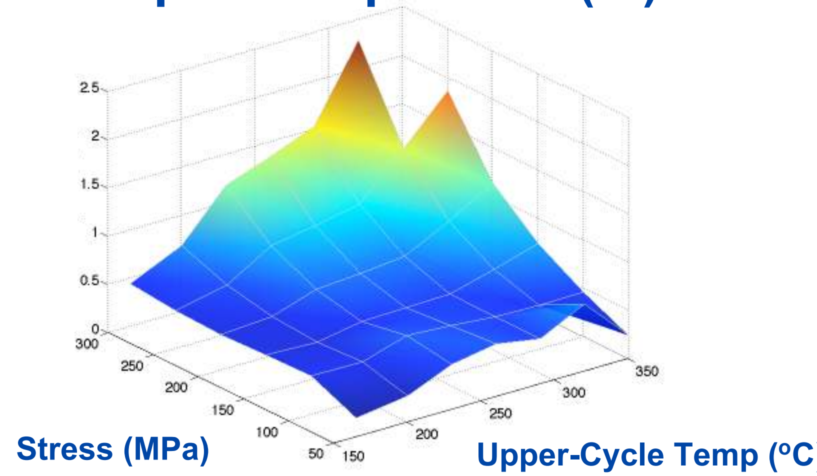




Work Output (J/cm³)

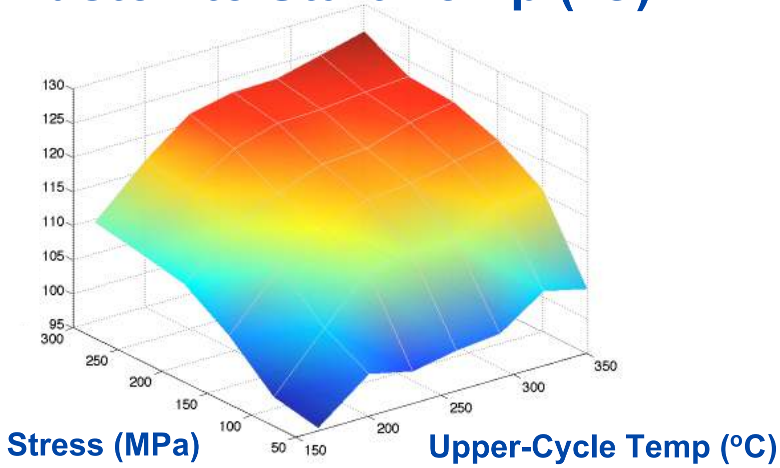


Open-Loop Strain (%)

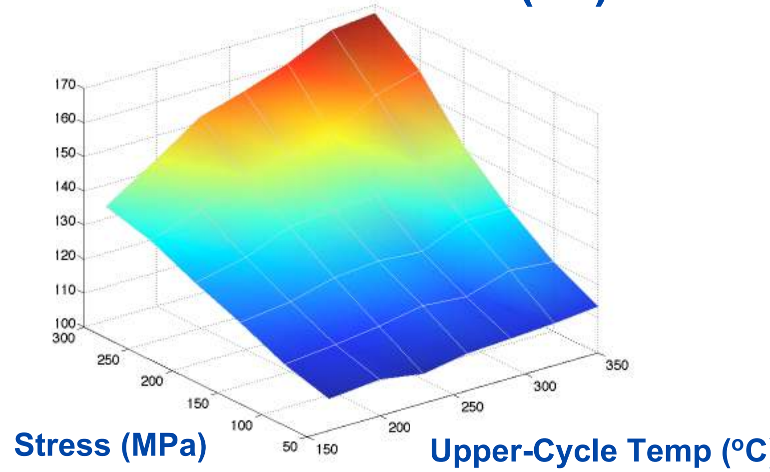


Stress and Upper-Cycle Temperature Affect Transformation Temperatures

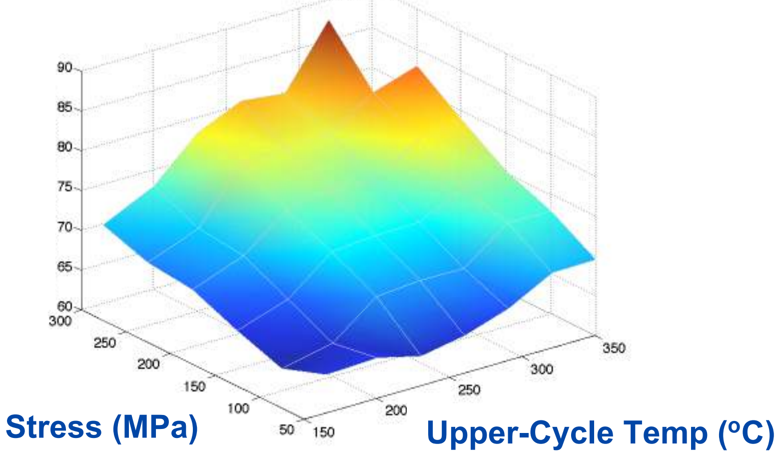
Austenite Start Temp (°C)



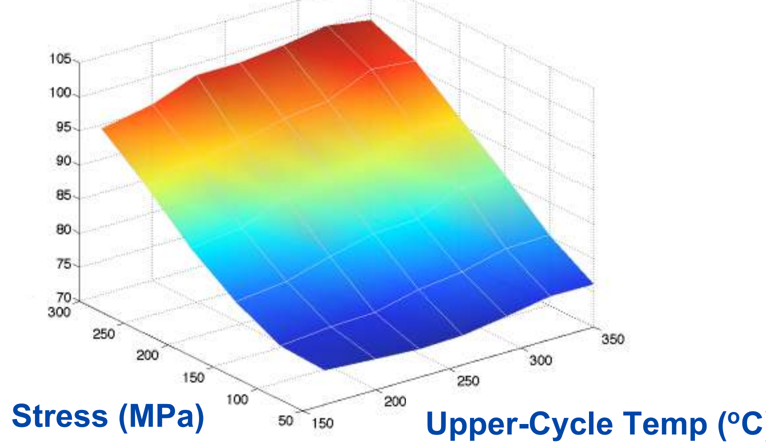
Austenite Finish (°C)



Martensite Finish (°C)



Martensite Start (°C)



Commonly Understood Stress →

Affected Properties

- ✓ Absolute strain level
- ✓ Transformation strain
- ✓ Open-Loop strain
- ✓ Transformation temperatures

← **Not Commonly Understood Upper-Cycle Temperature**

What is causing the observed behavior?

- ✓ Microstructure Changes
- ✓ Throughout Bulk (Not Just Surface)
- ✓ In-situ

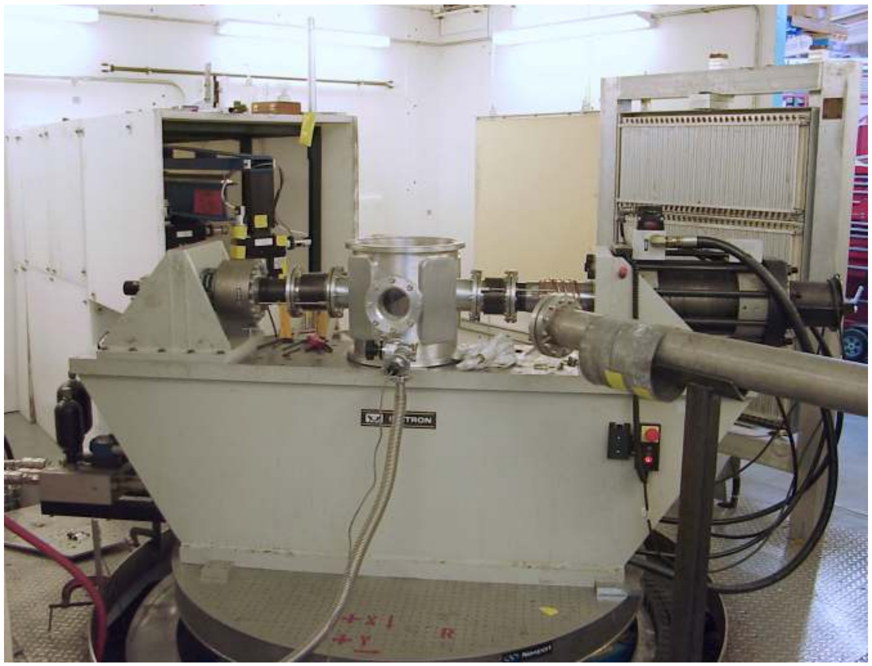
↓

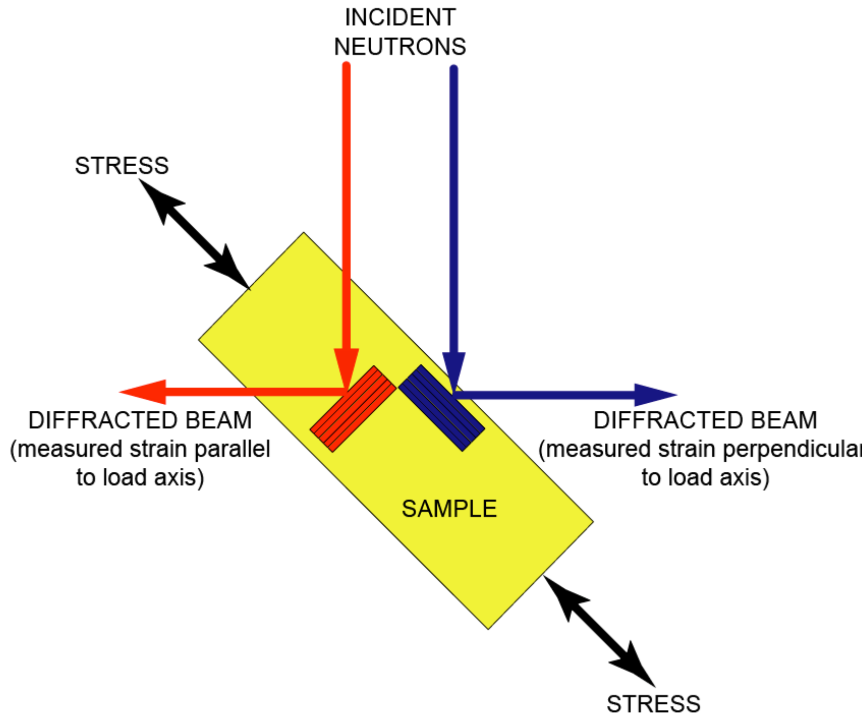
Neutron Diffraction

In-situ Neutron Diffraction

Performed select constant-stress, thermal-cycling experiments:

- Stress Levels: 100, 200 and 300 MPa
- Upper-cycle Temperatures: 165, 230 and 320 °C



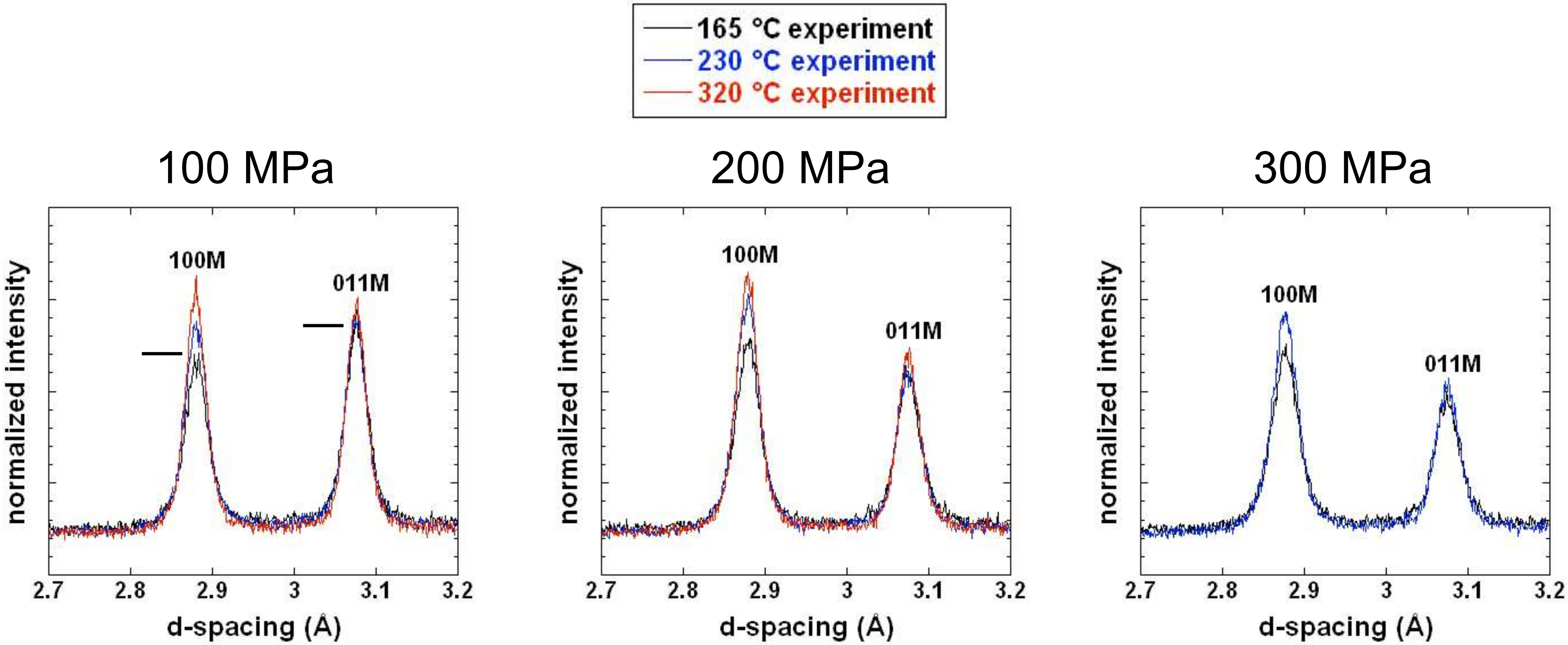


SMARTS at Los Alamos National Laboratory

(Spectrometer for Materials Research at Temperature and Stress)

Stress and Upper-Cycle Temperature Affect Martensite Texture

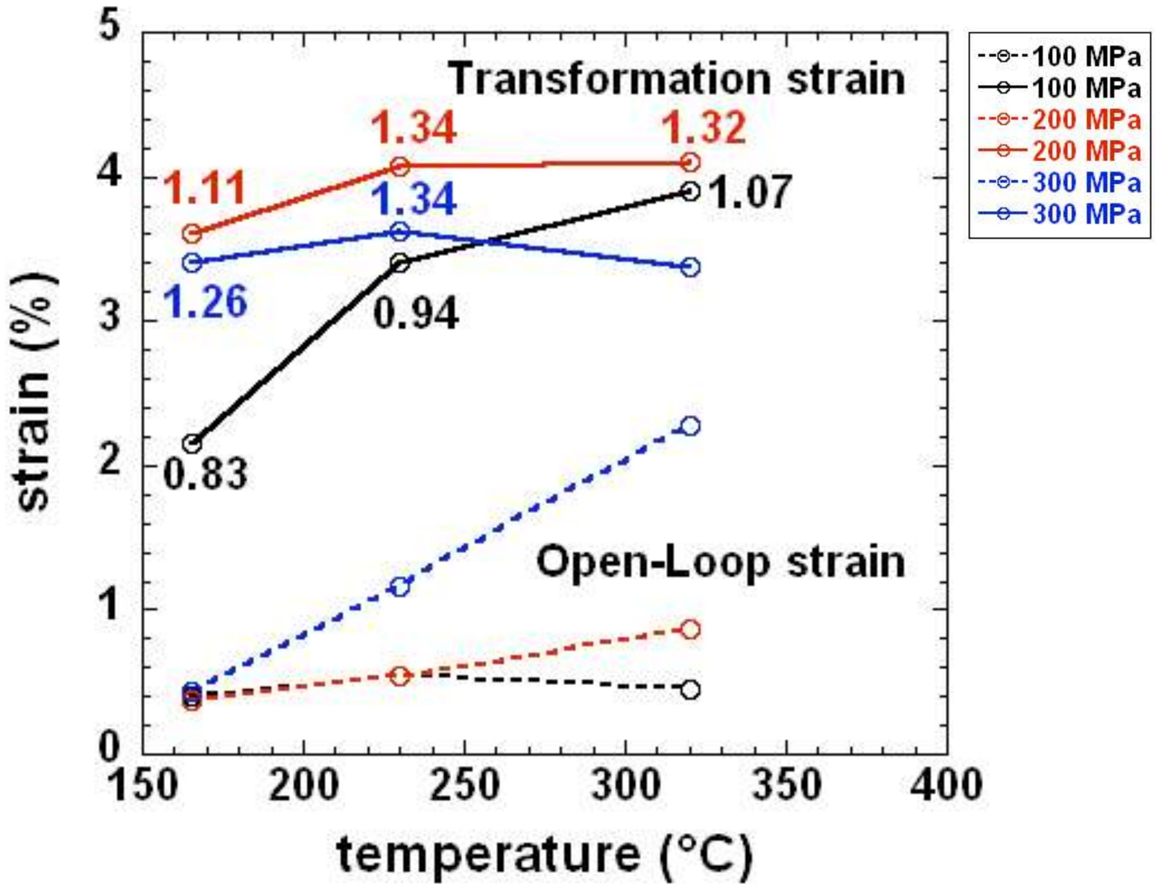
(Determined by looking at changes in 100M/011M peak ratios)



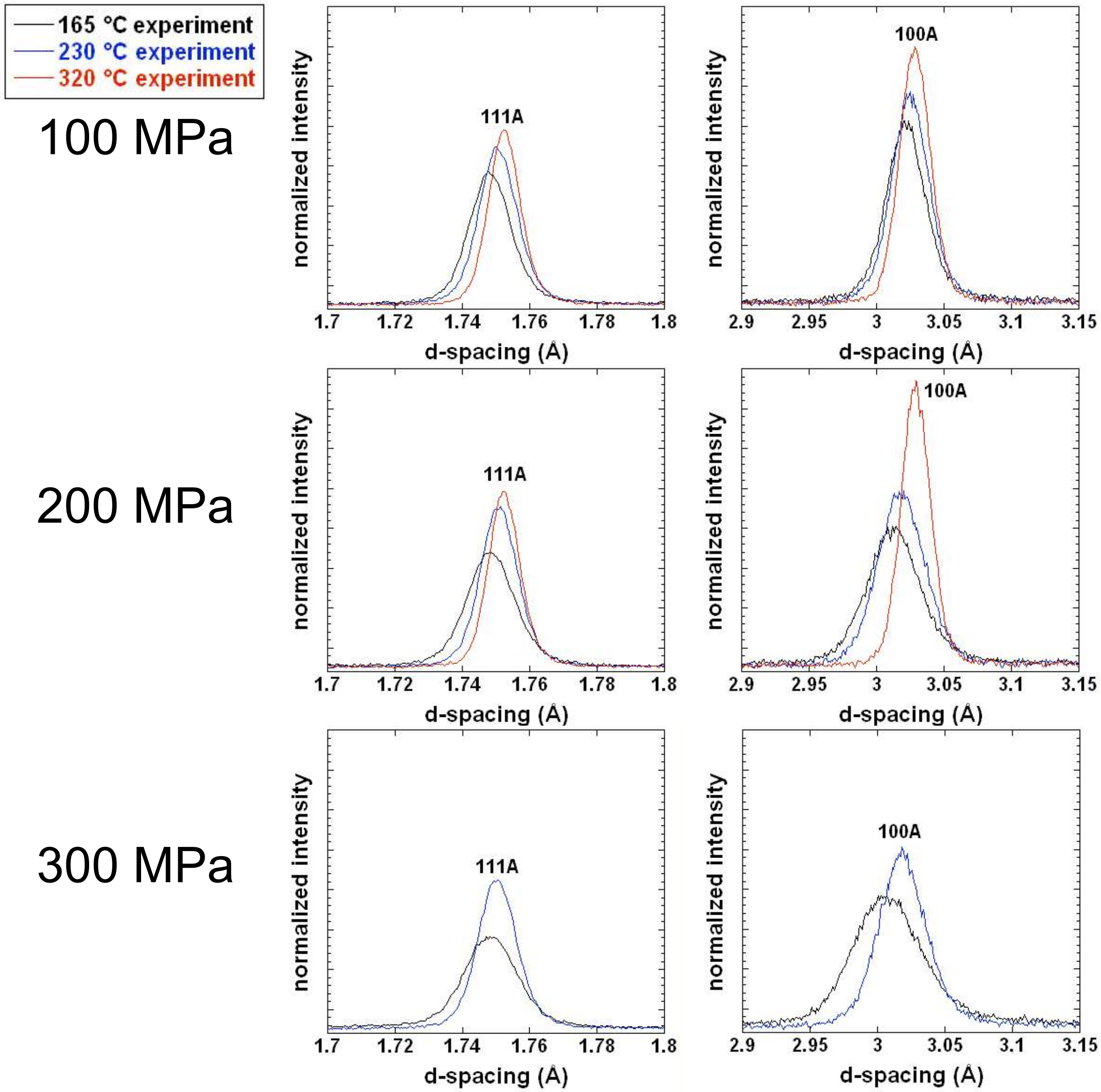
100M/011M Ratios	100 MPa	200 MPa	300 MPa
165 °C	0.83	1.11	1.26
230 °C	0.94	1.34	1.34
320 °C	1.07	1.32	Specimen broke

Stress and Upper-Cycle Temperature Play Separate Roles in Influencing Properties

- ✓ Both affect texture "evolution" of martensite
- ✓ High stresses lead to increased dimensional instability

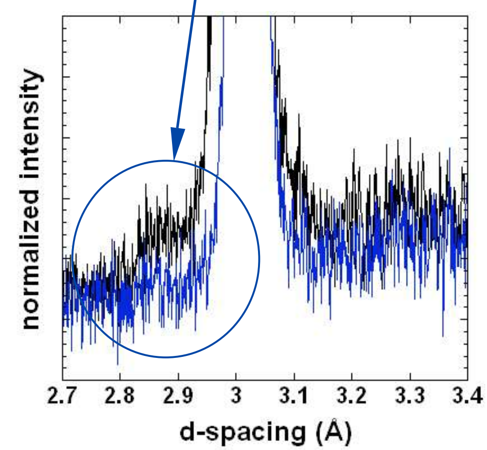


Changes Occur within “Austenite” State



- ✓ Texture evolution @ higher temperature
- ✓ Retained martensite present @ higher stress levels
- ✓ Internal strain changing with temperature

Evidence of retained martensite @ 300 MPa



Summary

- ***Upper-Cycle Temperature* and *Applied Stress* affect observed macroscopic strain through changes in texture (both of the martensite and austenite phases)**

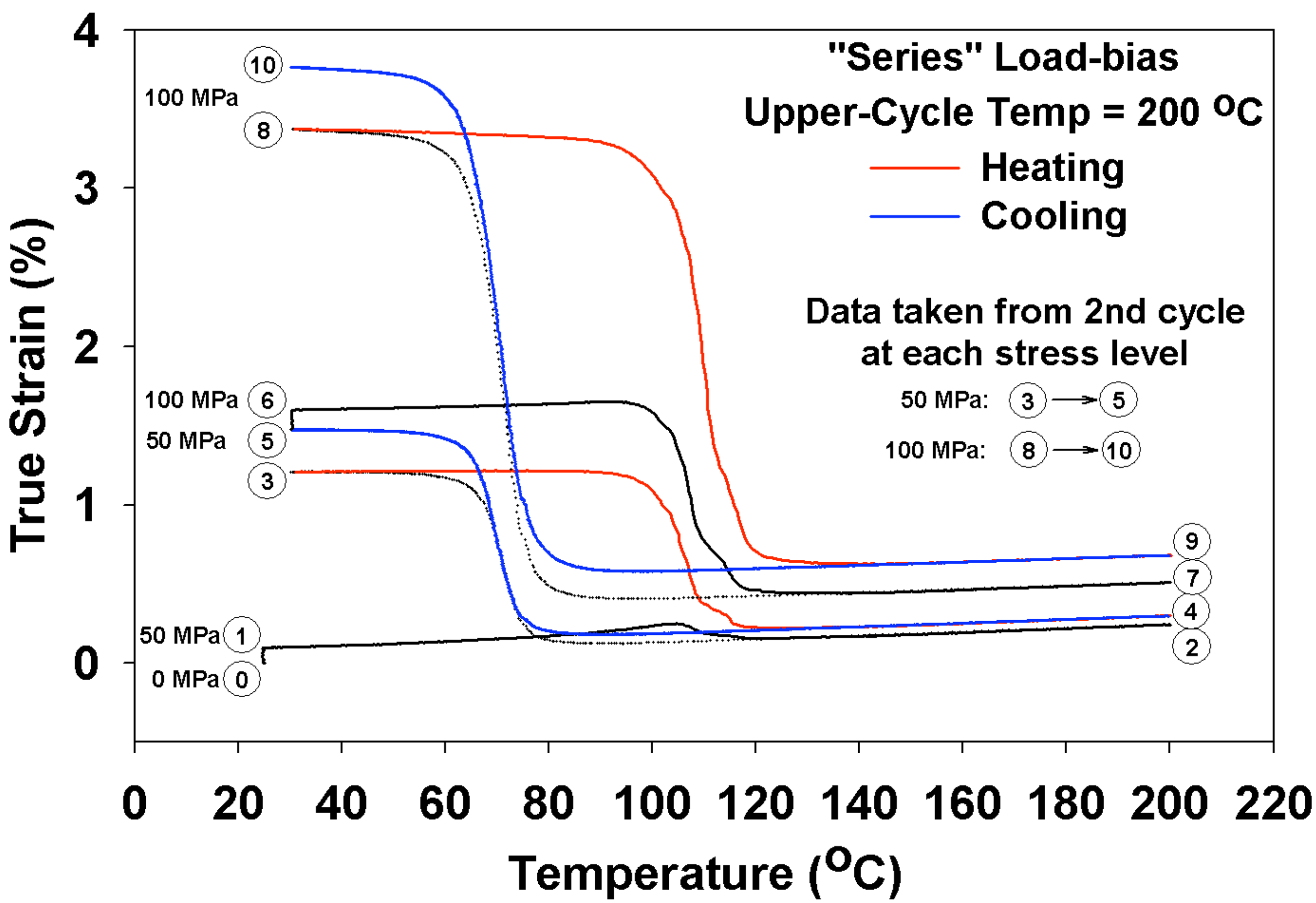
- ***Stress* and *Temperature* also influence other observed properties including the transformation temperatures of the material**

- ***In-situ Neutron Diffraction* plays a key role in helping us understand the complex microstructural developments that lead to observed response**

Questions

Questions

Constant-Stress, Thermal-Cycle Experiment ("Load-bias" Experiment)



- Load applied in martensite state (convenience/ probable method for real actuators)
- Any # of Cycles @ each stress level (typically 2 for exploratory work)
- Multiple stress levels run on same specimen (so-called "series" test)