On the Recovery Stress of a Ni$_{50.3}$Ti$_{29.7}$Hf$_{20}$ High Temperature Shape Memory Alloy

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Motivation and objectives

- **Recovery stress** obtained during a dimensionally constrained, martensitic phase transformation.

Where is it used?
- Fastening and joining
- Rock splitting
- Safety/release mechanisms
- Medical devices (stents)
- Reinforced composites/concrete confinement
- Shape setting procedures
- Jamming loads

Goals: Investigate the stress recovery capability of a precipitation strengthened, Ni$_{50.3}$Ti$_{29.7}$Hf$_{20}$ (at.%) high temperature SMA in uniaxial tension and compression.
Ni$_{50.3}$Ti$_{29.7}$Hf$_{20}$ processing and testing

**Processing:**
- Induction melted (~60lbs)
- Homogenized at 1050 °C for 72 h
- Extruded to rods (~0.4” in diameter) at 900 °C (7:1)
- Machined to form (dogbone, cylinders…)
- Aged 550 °C/3hrs/AC (Argon)

**Testing**
- Servohydraulic frame
- Induction heating
- Contact extensometer

~grain size = 40 μm

~Ppt. size < 20 nm
Constant-strain thermal cycling procedure

- **STRAIN (%)**
  - $\varepsilon_{end}$
  - $\varepsilon_0$

- **TEMPERATURE (°C)**
  - UCT
  - LCT
  - TIME (s)

- **Diagram Explanation**
  - Constant heat and cool procedure
  - $\delta_{\text{constant}}$
  - $\varepsilon_{pr}$

- **Steps**
  1. Heat
  2. Cool
  3. Heat
  4. Cool
Training I: Isothermal loading within the fully reversible region (No plastic deformation)

T = 25 °C
Training I: Isothermal loading within the fully reversible region (\textit{No plastic deformation})

![Graphs showing stress-strain relationships for tension and compression at 25°C.](#)
**Training I**: Isothermal loading within the fully reversible region (*No plastic deformation*)

- **Tension**
  - $T = 25 \, ^\circ\text{C}$
  - Recovery

- **Compression**
  - $T = 25 \, ^\circ\text{C}$
  - Recovery
Constant-strain thermal cycling: Resultant recovery stress

- Stress buildup on heating
- Relaxed to zero or to a slightly compressive or tensile stress on cooling
- Thermal expansion contribution, against in tension, with in compression
Constant-strain thermal cycling: Resultant recovery stress (Tension)
Constant-strain thermal cycling: Resultant recovery stress (Tension)
Constant-strain thermal cycling: Resultant recovery stress (Tension)

- Stresses in excess of 1 GPa
- Stress evolution for pre-strains > 1% (yielding of B2 phase)
Constant-strain thermal cycling: Resultant recovery stress (Compression)
Constant-strain thermal cycling: Resultant recovery stress (Compression)

- Stresses of ~1.3 GPa
- Stress evolution for pre-strains < -0.8% (yielding of B2 phase + retained martensite +...)

![Graph showing stress evolution vs. cycle number and applied strain](image-url)
Constant-strain thermal cycling: Resultant recovery stress (Compression)

- Stresses of ~1.3 GPa
- Stress evolution for pre-strains < -0.8% (yielding of B2 phase + retained martensite +...)

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Training II: Constant-force thermal cycling
(No residual strains)
Training II: Constant-force thermal cycling (No residual strains)
Training II: Constant-force thermal cycling (No residual strains)

Tension

Compression

Strain capability
Constant-strain thermal cycling: Resultant recovery stress

Tension

pre-trained @ 100 MPa

pre-trained @ 200 MPa

pre-trained @ 300 MPa

(a-1)

(a-2)

(a-3)

stress (MPa)

temperature (°C)

Comression

pre-trained @ -100 MPa

pre-trained @ -200 MPa

pre-trained @ -400 MPa

(b-1)

(b-2)

(b-3)

stress (MPa)

temperature (°C)
Constant-strain thermal cycling: Resultant recovery stress

- Stresses of ~1.0 GPa in tension
Constant-strain thermal cycling: Resultant recovery stress

- Stresses in excess of ~1.5 GPa, saturation at ~1.1 GPa (in compression)
Training I (Isothermal) vs. Training II (Isobaric)

- Isothermal reorientation and detwinning (R&D) of the B19’ is almost unnoticeable.
- Most R&D occurs on the 1st constant-strain cycle.
- Isobaric (R&D) occurs on the very first cycle.
- The majority of transformation occurred before the 1st constant-strain cycle.

Training III: Cyclic isothermal deformation (load-unload)

1 sequence
Training III: Cyclic isothermal deformation (load-unload)

9 sequences
Constant-strain thermal cycling: Resultant recovery stress
Constant-strain thermal cycling: Resultant recovery stress
Constant-strain thermal cycling: Resultant recovery stress

- Recovery stress increases with repeated cycles.
- Approaching 1.1 GPa
Switching from tensile to compressive B19' variants

(a) \( \sigma = 0 \text{ MPa (1) - post thermal cycle} \)

(b) \( \sigma = 0 \text{ MPa (2) - post thermal cycle} \)

(c) \( \sigma = 0 \text{ MPa (3) - post thermal cycle} \)

(d) \( \sigma = 0 \text{ MPa (4) - post thermal cycle} \)

(e) \( \sigma = 0 \text{ MPa (5) - post thermal cycle} \)

(f) \( \sigma = 0 \text{ MPa (6) - post thermal cycle} \)

(g) \( \sigma = 0 \text{ MPa (7) - post thermal cycle} \)

(h) \( \sigma = 0 \text{ MPa (8) - post thermal cycle} \)
Switching from tensile to compressive B19' variants
Summary

- The recovery stresses of a precipitation strengthened, Ni-rich Ni$_{50.3}$Ti$_{29.7}$Hf$_{20}$ (at.%) high temperature shape memory alloy were evaluated in tension and compression.

- Isothermal training resulted in recovery stresses nearing 1 GPa in tension and -1.3 GPa in compression with pre-strains of 1.5 and -2%, respectively.

- Isobaric training, resulted in recovery stresses nearing 1.1 GPa in tension and -1.5 GPa in compression with training stresses of 200 and -400 MPa, respectively.

- Cycling preloading increased the stress capability.

- How does it look in Torsion?