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
Constant-strain thermal cycling procedure

1. Heat
2. Cool
3. Heat
4. Cool
5. Heat
6. Cool

[Diagram showing constant-strain thermal cycling procedure with strain and temperature graphs, and corresponding stages with heat and cool symbols.]
**Training I**: Isothermal loading within the fully reversible region (*No plastic deformation*)

![Graph showing tension and stress relationship with strain at T = 25 °C](image)
Training I: Isothermal loading within the fully reversible region (*No plastic deformation*)

**Tension**

\[ T = 25 \, ^\circ\text{C} \]

- Stress vs. strain graph showing:
  - Strains: \( \varepsilon = 0.2\% \), \( \varepsilon = 0.4\% \), \( \varepsilon = 0.5\% \), \( \varepsilon = 0.8\% \), \( \varepsilon = 1.0\% \), \( \varepsilon = 1.2\% \), \( \varepsilon = 1.5\% \)

**Compression**

- Stress vs. strain graph showing:
  - Strains: \( \varepsilon = -0.2\% \), \( \varepsilon = -0.4\% \), \( \varepsilon = -0.6\% \), \( \varepsilon = -0.8\% \), \( \varepsilon = -1.0\% \), \( \varepsilon = -2.0\% \)
Training I: Isothermal loading within the fully reversible region (No plastic deformation)

- **Tension**
  - Graph showing stress (MPa) versus strain (%) for T = 25°C.
  - Labels indicate strain values: ε = 0.2%, ε = 0.4%, ε = 0.5%, ε = 0.8%, ε = 1.0%, ε = 1.2%, ε = 1.5%.

- **Compression**
  - Graph showing stress (MPa) versus strain (%) for T = 25°C.
  - Labels indicate strain values: ε = -0.8%, ε = -0.6%, ε = -0.4%, ε = -0.2%, ε = -2.0%, ε = -1.0%.

- **Recovery**
  - Graphs showing temperature (°C) versus strain (%) for both cooling and heating cycles.
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)
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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)

(a), (b), (c), (d), (e), (f) show graphs with temperature on the x-axis and stress on the y-axis. Each graph represents a different strain level: ε = -0.2%, ε = -0.4%, ε = -0.6%, ε = -0.8%, ε = -1.0%, and ε = -2.0%. The graphs are divided into Heating and Cooling phases, with multiple cycles indicated.
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](image-url)
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)
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Tension

Compression

\[ \sigma = 100 \text{ MPa} \]

\[ \sigma = -100 \text{ MPa} \]
Training II: Constant-force thermal cycling (No residual strains)

Tension

![Tension graph with strain vs. temperature plots for heating and cooling cycles.

Compression

![Compression graph with strain vs. temperature plots for heating and cooling cycles.

Strain capability

![Strain capability plots showing actuation strain vs. stress at different levels of stress and strain.]}
Constant-strain thermal cycling: Resultant recovery stress
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 ~1.1GPa (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

(a)
Training III: Cyclic isothermal deformation (load-unload)

9 sequences

![Stress-strain diagram](image)
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
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?