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 (%)**
  - \( \varepsilon_{\text{end}} \)
  - \( \varepsilon_0 \)

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

- **TIME (s)**
  - \( t_0 \)
  - \( t_1 \)
  - \( t_{\text{end}} \)

- **Heat**
  - **Cool**

- **Steps**
  1. Constant
  2. \( \delta_{\text{constant}} \)
  3. \( \varepsilon_{\text{pr}} \)
  4. Heat
  5. Cool
  6. Heat

- **Images**
  - Shape of objects at different stages:
    1. Initial state
    2. State after heat application
    3. State after cooling
    4. State after another cycle of heat application
    5. State after another cycle of cooling
    6. State after final cycle of heat application
**Training I:** Isothermal loading within the fully reversible region (*No plastic deformation*)

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

![Graph showing tension and stress relation](image)
Training I: Isothermal loading within the fully reversible region (No plastic deformation)

Tension

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

Compression

\varepsilon = 0.2 \% \\
\varepsilon = 0.4 \% \\
\varepsilon = 0.5 \% \\
\varepsilon = 0.8 \% \\
\varepsilon = 1.0 \% \\
\varepsilon = 1.2 \% \\
\varepsilon = 1.5 \% \\
\varepsilon = -0.8 \% \\
\varepsilon = -0.6 \% \\
\varepsilon = -0.4 \% \\
\varepsilon = -0.2 \% \\
\varepsilon = -2.0 \%
Training I: Isothermal loading within the fully reversible region (No plastic deformation)

Tension

\[ T = 25 \degree C \]

Compression

Recovery

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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)

(a) $\varepsilon = 0.2 \%$
(b) $\varepsilon = 0.5 \%$
(c) $\varepsilon = 0.8 \%$
(d) $\varepsilon = 1 \%$
(e) $\varepsilon = 1.2 \%$
(f) $\varepsilon = 1.5 \%$

Stress (MPa) vs. Temperature (°C) for different strain levels.
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 +...)

Graphical data showing:
- Cycle number (#) vs. end stress at 300 °C (MPa)
- Applied strain (%) vs. end stress at 300 °C (MPa)

Key points:
- ε = -0.2%
- ε = -0.4%
- ε = -0.6%
- ε = -0.8%
- ε = -1.0%
- ε = -2.0%
- 1st cycle
- 20th cycle
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)

**Tension**

![Graph showing tension vs. temperature](image)

- **σ = 100 MPa**
- **Strain (%)**
- **Temperature (°C)**
- **Load**
- **Unload**
- **1st heat**
- **Heating**
- **Cooling**
**Training II:** Constant-force thermal cycling
(No residual strains)

Tension

![Graph showing strain vs. temperature for tension](image)

- **σ = 100 MPa**
- Heating vs. Cooling

Compression

![Graph showing strain vs. temperature for compression](image)

- **σ = -100 MPa**
- Heating vs. Cooling

The diagrams illustrate the change in strain (in %) with respect to temperature (in °C) under tension and compression loads. The graphs show the heating and cooling cycles with peak points indicating the 1st heat.
Training II: Constant-force thermal cycling (No residual strains)

Tension

Compression

Strain capability
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 ~1.1 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
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?